Lab Manual - Teacher Edition

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College Phys-ics for AP® Courses

College Physics for AP® Courses Lab Manual

Teacher Version

OpenStax
Rice University
6100 Main Street MS-375
Houston, Texas 77005

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To the Student:

Congratulations on being accepted into, and having the courage to take, an Advanced Placement physics class! You are about to delve deep into some very detailed physics concepts. This lab manual aims to help you better understand these concepts through hands-on experiences in the laboratory. In addition, it will challenge you to critically think about physics concepts, scientific methods, and experimental design as part of its inquiry-based framework.

Inquiry-based learning involves challenging students to learn through self-discovery. Instead of simply presenting students with facts to memorize, students instead ask their questions about the material that they then answer through their own exploration. By creating your own hypotheses and then planning and carrying out your own experiments on a variety of topics in the lab manual, you will hopefully learn physics by satisfying your own curiosity.

In this AP lab manual, the inquiry-based structure includes the following components:

1) Pre-assessment Section. This section contains a list of questions that you should answer before starting each activity. These are meant to get you thinking about the main concepts of each lab. The pre-assessment questions are designed to connect the concepts in each lab to your experiences in daily life. Whether you realize it or not, you observe physics constantly in the world around you. Therefore, you likely are familiar with more physics topics than you realize! The pre-assessment questions are meant to tap in to the physics knowledge you already have and apply it to what you will learn in each lab. As a result, your answers to these questions may not be graded and you will benefit greatly by discussing your answers as class. This also allows your teacher to measure how familiar you and your classmates are with the material.

2) Structured Inquiry. In this section, you will be introduced to an experimental system by doing a well-laid out experiment with detailed steps. This section is meant to guide you in using the equipment in a “safer” activity before planning and performing an entire experiment. However, you will still be posing questions, predictions and hypotheses in the structured inquiry. You will also critically think about how to achieve the most accurate and reliable results during the structured inquiry, in preparation for creating your own experiments in the guided inquiry.

3) Guided Inquiry. In the guided inquiry, you will use the familiarity you gained during the structured inquiry to perform your own self-investigation. The experimental setup of the guided inquiries is often identical to that used in the structured inquiry. Therefore, you will be working with equipment and methods that you have already tried in the structured inquiry. This time, you will pick a variable to study, create a hypothesis, and fully design an experiment to test your hypothesis. You will determine which equipment and methods you should use to collect accurate and precise data.

Once you have planned your experiment, be sure to have your plan approved by your teacher, who will also ensure that your plan is safe and appropriate for the equipment available. Finally, you will analyze your own data and make conclusions based on your experimental evidence. If time allows, you will then refine and re-run your experiments or test additional hypotheses that find interesting. In many ways, the guided inquiry step is meant to engage you in the same processes that scientists have used to discover information about our world and universe!

Components of Structured and Guided Inquiry Sections

To ensure that an inquiry-based approach is implemented in each activity, both the structured and guided inquiries also contain each of the following steps at least once**:**

Hypothesize/Predict– This is where you will be creating hypotheses, questions or predictions about what will happen during the experiment. Be sure that your hypotheses are clear, specific, and testable.

Good hypothesis: The volume of water in a container will be higher when a 2-gram mass is added compared to when a 1-gram mass is added.

Poor hypothesis: The volume of water in this experiment will increase as larger objects are added.

Good hypothesis: The speed of a vehicle traveling down the 30^{o} ramp will be lower than the speed of the vehicle traveling down the 60^{o} ramp.

Poor hypothesis: The vehicle will travel fast down the ramp with the greater amount of slant.

Student-led Planning- Each inquiry contains at least one step where you and your lab partners plan how to conduct your experiment properly. During the Structured Inquiry, you will generally plan proper techniques for getting the best results possible using the available equipment and described methods. As with many things in life, two or more heads are often better than one, and you and your group members should come to a consensus on a plan before proceeding. This will lay the groundwork for the Guided Inquiry; you and your group will and your group will need to plan an entire experiment in this step.

Critical Analysis-This step typically occurs near the end of each inquiry. Here you will critically analyze your results, judge their validity, and explain why your hypotheses were supported or unsupported by your results. You will also suggest ways that your experimental methods could have been improved to get more accurate or precise data as well as determine new questions to ask related to your results.

A Note About Your Notebook
As part of the challenge of taking an AP course, this lab manual does not contain data tables where you record their findings. Therefore, you will be required to design their own tables, answer assessments, and do any other note-taking in a separate notebook. You should use the same notebook for physics lab throughout the year. This will allow you to easily refer back to previous labs when you need to reference earlier content. Do not put non-physics content in your physics notebook, as your teacher may collect and grade your notebook throughout the year.

Components of a Lab

Main introduction:

Each lab contains an introductory section under the title. This introduces the "big picture" concepts of the lab as well as how they connect to everyday life. They will also introduce the pioneering physicists and experiments that led to our current knowledge of each lab topic. Relevant equations that you will use in the labs are also introduced here, including definition of their variables. Many of the labs involve measuring the value of these variables so that you can later perform your own calculations. Please read the lab and activity introductions carefully before your lab period. Then, ask your teacher about any concepts that you are unsure of before the lab starts.

In this lab you will learn:

This section presents learning objectives for the lab. These are the "take away points" that you should be able to explain or perform after doing the activities. It is helpful to read these objectives before each lab to prime yourself for what you will learn. It is then helpful to reread these at the end of each lab to ensure that you have achieved all of the learning objectives.

Activities:

Each lab is divided into 2-3 activities. Please note that your teacher may or may not have you perform all activities in a given lab so pay close attention to your teacher's instructions throughout the lab.

Safety precautions:

These bullet points list important safety issues that will prevent the injury to yourself or your classmates during the lab activities. Each activity has its own safety precautions section. **<u>Please read and understand all safety precautions before beginning each activity!</u>**

For this activity you will need, section:

This section lists all of the materials needed for each activity. Before you start the lab, make sure that you can identify all items on this list. Also, pay close attention to your teacher's instructions, as you may be using different equipment for these labs than those on this list.

Activity introduction:

These are short introductions relevant to specific activities. As with the main introduction, the activity introductions may contain formulas, equations or other background information that needed to successfully carry out and understand the activities. As with the main introduction, please read these introductions carefully before your lab period, and ask your teacher about any material that you are unsure of.

Process steps:

These are the steps you will perform to carry out the activities. Please read through **all** of the process steps and setup diagrams **before** starting Step 1. Ask your teacher if there are any steps you don't understand prior to starting. This will help you perform the activities correctly the first time, preventing the need to redo activities or having to leave your laboratory period with unusable data.

Assessments:

The assessment sections provide questions that test your knowledge of the lab material. Your teacher will instruct you on how to submit answers to the assessments for grading.

Lab 1: Graphing Motion

Quantitatively describing the motion of objects is a key part of physics. Many objects move in complicated ways, but the mathematical tools used to describe them are the same as those used to describe simple motion. Before you can continue your study of motion, it is important to define and understand these tools.

A moving object starts at one place and ends at another. The distance the object travels, which is measured in meters, is the length of the path the object follows between the start and end points of its motion. The object's speed describes how quickly the object gets from the start point to the end point. Therefore, speed is the distance of travel divided by the time of travel, that is

$$v = \frac{d}{\Delta t},$$

where *d* is the distance the object traveled and Δt is the amount of time it took to travel that distance. The units for the calculated speed are meters per second (m/s). An object that is not speeding up or slowing down is moving at a constant speed, meaning that the speed calculated along any point of its motion is the same.

Accurately measuring an interval of time can be tricky. Although using a stopwatch may seem like a straightforward method, the reaction time between seeing an event and pressing the stopwatch limits the accuracy of the time measurement. Using cameras or photogate timers can improve the accuracy of measurement because they respond much faster and more accurately than a person using a stopwatch can.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- If your students have not yet had experience with the difference operator Δ, give a brief introduction to it. You could give an example where $t_i = 3 \text{ s}$ and $t_f = 10 \text{ s}$. Hence, $\Delta t = t_f - t_i = 10 \text{ s} - 3 \text{ s} = 7 \text{ s}$. Be sure that students understand why the initial time is subtracted from the final time.
- Students may think that speed and velocity are the same. Remind them that speed only has magnitude, and velocity is a vector quantity and, as such, has both magnitude and direction. You may need to review these differences before the lab.

- Review significant figures, especially the detailed rules for dealing with measurements. Students may think that the only significant figures are those that are absolutely certain, but they should also consider the one doubtful digit as a significant figure. Note the rules for this when dealing with photogates and other automatic measuring devices.

In this lab you will learn:

- how to measure the speed of an object traveling at a constant velocity;
- how to differentiate between motion at a constant velocity and motion with acceleration;
- how to use a position or velocity versus time plot to understand motion.

Activity 1: Pre-Assessment

1. **Answer the following questions in your notebook:** Would you expect an object that you set in motion to continue moving at a constant speed? Why or why not?
2. **Discuss the answers to question 1 with the class.**

Activity 1: Constant Velocity

Suppose you graphed the motion of an object using the horizontal axis for the time elapsed, in seconds, and the vertical axis for the distance traveled. For an object traveling at constant speed, the change in distance would be proportional to the change in time. Therefore, when you plot your data on a distance-versus-time graph, the points should fall along a straight line. However, every measurement has some error, so the data points would not be likely to exactly fall on a straight line. Using a line of best fit helps to average these errors and give a more accurate approximation. To draw a line of best fit, you would use a ruler to draw a straight line that follows the trend of the data and comes as close to all of the data points as possible. The slope of that line is given by

$$m = \frac{d}{\Delta t} = v \quad .$$

The slope equals the speed of the object. Because of measurement errors, some points will lie above the best-fit line and some will lie below it. This is because the best-fit line passes through the middle of the data and averages the values. As a result, the slope of the line of best fit provides a more accurate value of the speed than a single pair of data points would.

Safety Precautions

- Keep the cart on the track to avoid damage or injury.

For this activity you will need the following:

- Straight track*
- Cart with spring
- Stopwatch*
- Masking tape*
- Meter stick

For this activity, you will work *in pairs*.

*Note—If you have access to air tracks, using them will improve your approximation of a frictionless system that can move at a constant speed.
**Note—For increased accuracy, photogate timers or other technology can be used in place of the stopwatch and masking tape. The distance between the photogate timers would replace the distance between pieces of masking tape, and the timers instead of a stopwatch would record the time.

Activity 1 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 1:

- Air tracks may be unfamiliar to students, so you may want to give students an introduction to their operation, especially if you plan to use air tracks for other experiments throughout the rest of the year. Be sure to give students enough background so that they can correctly diagnose when their air tracks are malfunctioning.
- Similarly, photogates may be unfamiliar to students, so you should give students an introduction to their operation. Be sure to give students enough background information so that they can test their photogates to be sure that they are working correctly.
- Remind students that they should be sure that their tracks are level. For some air tracks, this may require them to adjust the height screw at one end of the track. Ask students what unwanted effects could result from having an un-level track.
- As an aid to Assessment 1, you may want to reiterate to students the differences between distance and displacement.
- To further build on this activity and prepare students for later labs, you could have students graph the information for Assessment 2 in terms of displacement and velocity. They would need to select a reference frame and orient the runner's path accordingly.

The following are recommendations for the Guided Inquiry for Activity 1:

- To facilitate Step 1, it may be helpful to ask students what an idealized form of this experiment would look like. Then, they can determine how their experimental setup diverges from that idealized form and whether these divergences are acceptable.
- To facilitate Step 2, it may be helpful to remind students of the variables that they can measure and how these variables relate to speed.

Structured Inquiry

Step 1: Place your track with one end against a wall. Rest the cart against the wall, as shown in Figure 1.1, so that releasing its spring can launch the cart. Place one piece of masking tape on the track ahead of the starting position of the cart and another piece of tape further down the track. Measure the distance between the two pieces of tape. Create a data table in your notebook for recording the distance and travel time for the cart's motion. You will be moving the second piece of tape at least three times, so you will need space in the table to record at least four separate times and distances.

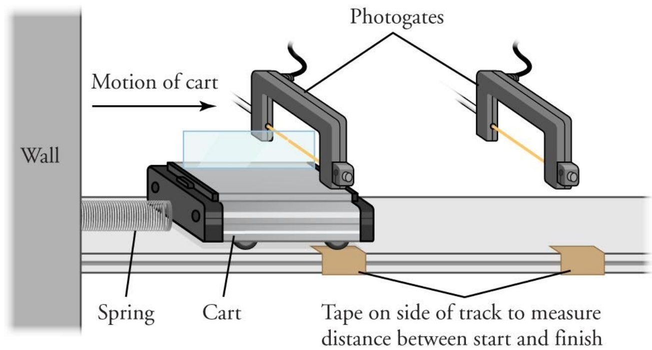


Figure 1.1: The speed of the cart can be measured by using the spring to launch the cart from the wall and then measuring how long the cart takes to travel a fixed distance. This can be done either by having it pass through two photogate timers or by using a stopwatch to measure the time of travel between two pieces of masking tape.

Step 2: Hypothesize/Predict: Knowing that, ideally, the cart should move at a constant speed, predict how your measurements would change as you vary the location of your second tape marker. How would this prediction differ if the cart did not move at a constant speed? Realistically, do you expect your data to resemble the ideal situation?

Step 3: Student-Led Planning: You will now use your photogates, or a stopwatch and meter stick, to measure the speed of your cart. You should vary the position of your second piece of tape or photogate timer to measure the speed for at least four distances. If your class uses photogates, listen closely to your teacher's instructions on how to use them. Discuss with your partner what data you need to collect and how to use the data to determine the speed of the cart.

Step 4: Critical Analysis: Record the time it takes for the cart to travel each distance in the data table in your notebook. Then calculate the speed of the cart for each trial, as well as the average speed across all trials. Were the predictions you made in Step 2 supported by your data? Why or why not? How could you improve your results? Discuss your answers with your partner and then write them in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: Is this experimental setup a good choice for observing motion at a constant speed? What potential issues does it have, and what improvements could you make?

Step 2: Student-Led Planning: Discuss with your partner how to use the data in your table to plot a graph from which you can determine the speed of the cart. Now plot your data and use the graph to find the speed of the cart in your experiment.

Step 3: Critical Analysis: How did the speed you calculated using your graph compare with the speeds you calculated for each trial, and the average speed across all the trials, in your table? Which is a better method for measuring the speed of the cart, and why? Did your graph look as you expected for an object moving at a constant speed? Discuss your answers with your partner and record them in your notebook.

Assessments

1. Consider a baseball player who hits a home run and runs around all of the bases on the field. [EK 3.A.1; SP 2]
    a. Considering that he started and ended at home plate, is the distance he traveled equal to zero? What about the displacement? Explain.
    b. Is the player's average speed over his entire base run equal to zero
    c. Based on this, is it important to know the path an object followed to calculate its speed, or do you only need to know where and when it started and ended? Explain.
2. In a particular city, each block is 50 m long. A runner goes two blocks north in 10 seconds, then five blocks south in 20 seconds, then eight blocks north in 50 seconds. [EK 3.A.1; SP 2]
    a. Plot the runner's distance traveled as a function of time.
    b. Calculate the runner's speed for each interval.
    c. Calculate the runner's average speed for the entire run.

[Solutions]

1. [EK 21.1a; SP 2]
    a. The distance traveled by the player is not equal to zero because it is the length of the path he actually traveled. However, the player's displacement is equal to zero, because he started and ended at the same position. There is no change in position, which is displacement.
    b. Average speed is calculated using the total distance traveled, which is not zero, divided by time, so this would not be zero in this case. However, average velocity uses displacement divided by time, and the displacement is zero, so the average velocity is also zero.
    c. You have to know the path that an object followed to know the length of the path and therefore the distance the object traveled in the given time.
2. [EK 21.1a; SP 2]
    a.

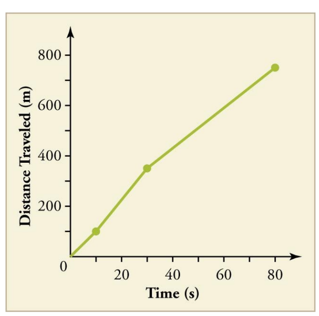


Figure 1.2

b.

$$\text{Interval 1; } v = \frac{(2 \text{ blocks})(50 \text{ m/blocks})}{10 \text{ s}} = 10 \text{ m/s}$$

$$\text{Interval 2; } v = \frac{(5 \text{ blocks})(50 \text{ m/blocks})}{20 \text{ s}} = 12.5 \text{ m/s}$$

$$\text{Interval 3; } v = \frac{(8 \text{ blocks})(50 \text{ m/blocks})}{50 \text{ s}} = 8.0 \text{ m/s}$$

c. $v = \dfrac{750 \text{ m}}{80 \text{ s}} = 9.4 \text{ m/s}$

Activity 2: Pre-Assessment

1. **Answer the following questions in your notebook:** What does it mean for an object to travel at constant acceleration? How could you set an object in motion at constant acceleration?
2. **Answer the following question in your notebook:** Describe at least two different types of accelerated motion.
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 2: Constant Acceleration

An object is **accelerating** if its velocity is changing. The acceleration ***a*** of an object is calculated by dividing Δv, the change in the object's velocity, by Δt, the time over which the velocity changed

$$a = \frac{\Delta v}{\Delta t}.$$

The SI unit for acceleration is m/s^2, or meter per second per second. The slope of a position versus time graph for an accelerating object is still the object's velocity, but by definition, the velocity of an accelerating object is changing. However, for an object with constant acceleration, the slope of the velocity versus time graph is

$$m = \frac{\Delta v}{\Delta t} = a,$$

and the graph should be a straight line whose slope is the acceleration.

Safety Precautions

- Keep the cart on the track to avoid damage or injury.
- Limit the angle of incline of the track to less than 10°, so that the cart reaches the end of the track at a reasonable speed, avoiding damage or injury.

For this activity you will need the following:

- Straight track
- Cart
- Stopwatch*
- Masking tape*
- Meter stick
- Ring stand or blocks

For this activity, you will work *in pairs*.

*Note —For increased accuracy, photogate timers or other technology can be used in place of the stopwatch and masking tape. The distance between the photogate timers would replace the distance between pieces of masking tape, and the timers instead of with the stopwatch would record the time.

Activity 2 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 2:

- Air tracks may be unfamiliar to students, so you may want to give students an introduction to their operation, especially if you plan to use air tracks for other experiments throughout the rest of the year. Be sure to give students enough background so that they can correctly diagnose when their air tracks are malfunctioning.
- Similarly, photogates may be unfamiliar to students, so you should give students an introduction to their operation. Be sure to give students enough background information so that they can test their photogates to be sure that they are working correctly.
- Ask students why they think the angle of incline for the track is limited to small angles less than 10°. In addition to avoiding damage and injury, how would such a steep angle affect the results?
- Students may think there is a single *true* set of coordinates and coordinate axes for a given problem. In fact, coordinates and coordinate axes can be freely chosen, and different parts of a single problem might be easier to solve with different coordinates. Ask students to describe how using a different coordinate system for this activity would make their tasks easier or harder.
- To further build on this activity, have students research Galileo's experiments involving inclined planes. Have them compare their experiment setup to Galileo's and offer suggestions for improving both their setup and Galileo's.

The following are recommendations for the Guided Inquiry for Activity 2:

- To facilitate Step 1, it may be helpful to ask students what exactly they were trying to determine in Activity 1. How does this compare to what they are attempting to find in this activity? Guide them to consider how experimental setups change according to the variables investigated.
- To facilitate Step 2, it may be helpful to remind students of how they used position and time graphs to show the velocity. Ask them how velocity and time relate to acceleration.

Structured Inquiry

Step 1: Position the track so that one end is slightly lifted above the ground, using either the ring stand mounts or blocks. Using your meter stick, place pieces of masking tape along the track to divide the track into five even intervals, as shown in Figure 1.3. Create a data table in your notebook to record the distance and time for the cart's motion.

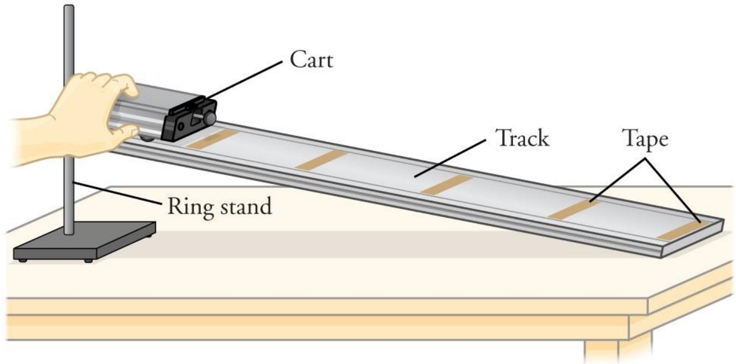


Figure 1.3: A cart that is free to move on an incline will accelerate and will have different velocities at different locations.

Step 2: Hypothesize/Predict: Now that the track is no longer horizontal, predict what should happen to the speed of the cart as it travels down the track. How will this differ from the motion of the cart at constant speed?

Step 3: Student-Led Planning: You will now use your stopwatch to measure the speed of the cart as it travels different distances down the ramp, starting from rest. Discuss with your partner what data you will need to collect in each trial to measure the average speed for the given distance. Explain in your notebook why the final speed at the end of this distance is twice the average speed if the cart starts from rest. Be sure to think carefully about the start and end points you choose for each measurement of the cart's speed. Your procedure may be different if you are using photogates to time the arrival times at several different locations in each trial.

Step 4: Record the time it took for the cart to travel between each marker in the data table in your notebook. Calculate the final speed of the cart at the end of each interval. Given that the cart started at rest, calculate the acceleration of the cart for each interval, and calculate an average value for the acceleration across the trials.

Step 5: Critical Analysis: Were the predictions you made in Step 2 supported by your data? Why or why not? What methods could you have used to improve your results? Discuss with your partner and then write your answers in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: What makes the experimental setup here different from that in Activity 1? How will that make your graphs different from those in Activity 1? What do you expect the position and velocity versus time graphs to look like for your data?

Step 2: Student-Led Planning: Discuss with your partner how the data in the table you created can be used to create position and velocity versus time graphs and how you can use these graphs to determine the acceleration of the cart. Now plot your data and use the graph to find a value for the acceleration of the cart in your experiments.

Step 3: Critical Analysis: Given that gravity accelerated the cart down the ramp, does the value you measured for the acceleration of the cart make sense? Why or why not? Did your graphs look like you expected for an object moving with constant acceleration? Did the value you calculated using your line of best fit agree with the average value from your trials for the acceleration? Discuss your answers with your partner and record them in your notebook.

Assessments

1. How does the acceleration of a cart on an incline relate to the angle of the incline? Give an expression that relates the acceleration of the cart, acceleration due to gravity, and the ramp angle. Assume that friction can be ignored. [EK 3.A.1; SP 2]
2. If a car speeds up from rest to 30 m/s in 6.0 seconds and then returns to rest in 12.0 seconds, what is its acceleration? [EK 3.A.1; SP 2]
    a. While speeding up?
    b. While slowing down?
3. In the first activity, you observed the motion of a cart moving at constant speed. However, the cart started at rest and then began moving. Therefore, the cart did accelerate in Activity 1 because the velocity changed. How did one experimental procedure produce motion at constant speed whereas the other produced accelerated motion? [EK 3.A.1; SP 2]

[Solutions]

1. $a = g\sin\theta$ [EK 3.A.1; SP 2]
2. [EK 3.A.1; SP 2]
    a. $a = \dfrac{30 \text{ m/s} - 0}{6.0 \text{ s}} = 5.0 \text{m/s}^2$
    b. $a = \dfrac{0 - 30 \text{ m/s}}{12.0 \text{ s}} = -2.5 \text{m/s}^2$
3. The cart accelerated from rest to its speed while it was being pushed off the wall by its spring, but once it was pushed off the wall it continued its motion at a constant speed. [EK 3.A.1; SP 2]

Activity 3: Pre-Assessment

1. **Answer the following questions in your notebook:** What physical quantities can be found using position and velocity versus time graphs, and how?
2. **Answer the following question in your notebook:** How would you interpret a negative value for velocity or acceleration calculated from a graph?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 3: Graph Matching

A position or velocity versus time graph can tell you about the motion of an object. Figure 1.4 is an example of a graph with a straight line. The slope, which is the object's acceleration, is therefore constant. The slope is positive, so the object keeps moving faster over time.

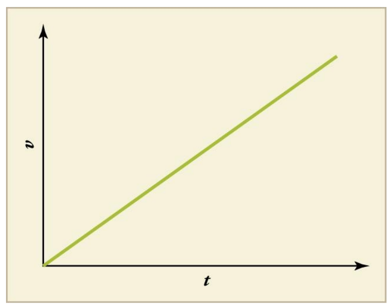


Figure 1.4: An object speeding up with constant acceleration has a straight-line velocity versus time graph.

Safety Precautions

- Keep the cart on the track to avoid damage or injury.
- Limit the angle of incline of the track to less than 10° so that the cart reaches the end of the track at a reasonable speed, avoiding damage or injury.

For this activity you will need the following:

- Straight track
- Cart with spring
- Stopwatch*
- Masking tape*
- Meter stick
- Ring stand or blocks

For this activity, you will work *in pairs*.

*Note—For increased accuracy, photogate timers or other technology can be used in place of the stopwatch and masking tape. The distance between pieces of masking tape would be replaced by the distance between the photogate timers, and the time would be recorded by the timers instead of with the stopwatch.

Activity 3 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 3:

- Remind students to closely examine the labels on the *x*- and *y*-axes of the graphs, and stress the importance of labels for their graphs. To emphasize this, show them a graph of some mysterious variable versus time. Then compare what would be happening to the object if the graph were of distance versus time as opposed to speed versus time.
- As an extension to Assessment 2, you may want to ask students what the area under the graph of an acceleration versus time graph denotes. Ask students under what circumstances this information could be used.
- To further build on this activity, have students draw each graph of velocity versus time as a graph of acceleration versus time. If they are stuck, remind them that acceleration is the change in velocity over time, so an increasing velocity would mean a positive acceleration, and a decreasing velocity would mean a negative acceleration.

The following are recommendations for the Guided Inquiry for Activity 3:

- To facilitate Step 2, remind students to correctly label the axes of their graphs.
- To facilitate Step 3, ask students how the data for an idealized version of these experiments would compare to those that you collected.

Structured Inquiry

Step 1: Hypothesize/Predict: Look at the graphs in Figure 1.5. For each graph, describe the motion shown. Does it describe an object accelerating or one moving at a constant velocity? In what direction is the object moving? If the object is accelerating, is it speeding up or slowing down?

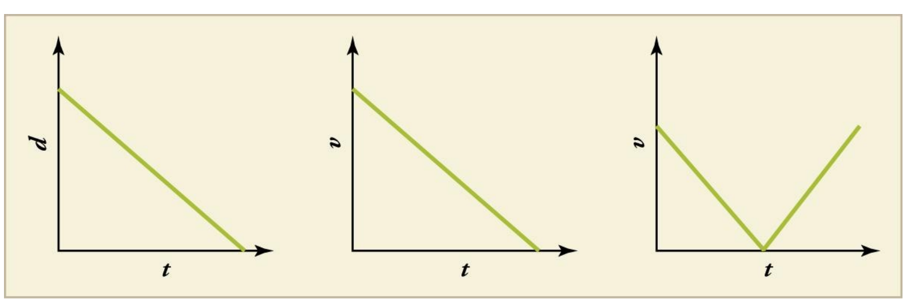


Figure 1.5: Position and velocity versus time graphs describe an object's motion.

Step 2: Student-Led Planning: You will now use the equipment from Activities 1 and 2 to get the cart to move in a way that would produce each of the graphs in Figure 1.5. Discuss with your partner how to do this, and what measurements you will make to recreate the motion described by the graphs.

Step 3: Critical Analysis: Record the appropriate time and distance measurements for the three graphs in data tables in your notebook. Were the predictions you made in Step 1 supported by your data? Why or why not? How could you have improved your results? Discuss your answers with your partner and then write them in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: Did you choose the correct motions for the cart to recreate the motions described in the graphs in Figure 1.5? If not, what could you change to make them better agree?

Step 2: Student-Led Planning: Discuss with your partner how the data in the tables you created can be used to recreate the graphs in Figure 1.5. Now plot your data and compare the graphs with the expected graphs.

Step 3: Critical Analysis: Did your graphs agree with the graphs you were trying to recreate? If they differ, in what ways do they differ? How can you change your experimental procedure to produce better agreement? Discuss your answers with your partner and record them in your notebook.

Assessments

1. An object slows down at a constant acceleration, and then speeds up with the same constant acceleration. [EK 3.A.1; SP 2]
    a. Sketch a velocity versus time plot for this motion.
    b. What experimental procedure could you use to recreate this motion with a cart and tracks?
2. Using dimensional analysis, what quantity would you find by calculating the area under a velocity-versus-time graph? [EK 3.A.1; SP 2]
3. Two velocity versus time graphs have the same shape, but their *y*-intercepts are different. [EK 3.A.1; SP 2]
    a. What must be the same about the motion of the two objects?
    b. What must be different about the motion of the two objects?

[Solutions]

1. [EK 3.A.1; SP 2]
    a.

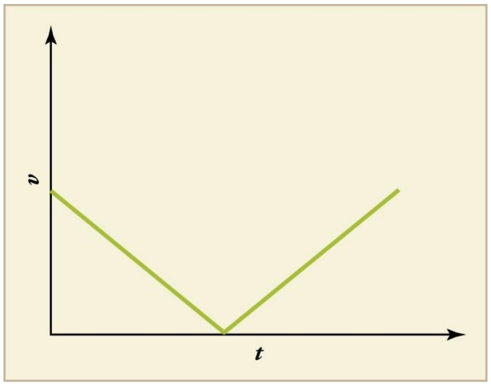


Figure 1.6

    b. You could have the cart go up a ramp until it stops and then slides back down the ramp.
2. [EK 3.A.1; SP 2] The area would be given by height times width. On a velocity-versus-time graph, the height is measured in m/s and the width is measured in seconds, so the area is measured in m/s times s, or in meters only, which is a distance.
3. [EK 3.A.1; SP 2]
    a. The two motions must have the same acceleration because the slopes are the same.
    b. The two motions must have different initial velocities because their velocity at t = 0 is not the same.

Lab 2: Projectile Motion

In your study of one-dimensional **motion**, objects changed position only along one direction (for example, along the *x*-direction). In two-dimensional motion, the position of an object along both the *x*-direction and *y*-direction changes simultaneously. The same variables (displacement, velocity, and acceleration) that describe one-dimensional motion also describe two-dimensional motion. However, the part of the motion along each axis is independent and must be analyzed separately.

In this lab, you will study **projectile motion**, a specific type of two-dimensional motion. Projectile motion is the motion of an object that has been thrown or projected into the air. The object is called a **projectile**, and its path is called its **trajectory**. Projectile movement is, therefore, subject only to the force of gravity. When analyzing the displacement, velocity, or acceleration of a projectile, remember to examine the motion along the *x*-direction and *y*-direction separately, based on the angle of launch. For example, velocity will need to be split into its v_x and v_y components by applying the methods you learned while studying **vectors**. To complete this lab, you will need to use basic **kinematic** and vector analysis equations.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- Be sure the students identify when the initial velocity is zero (dropped object), the initial velocity is positive, and the initial velocity is negative.
- A common student difficulty is recognizing that an object at its maximum height still has an acceleration of $-9.8\ m/s^2$, although its instantaneous velocity is zero.
- Students must be aware that the horizontal and vertical motions are independent of each other. It is useful to illustrate several free-body diagrams of various types of projectile motion.
- Discuss the aspects of projectile motion as it relates to air resistance. Have the students discuss whether air resistance should be considered for these activities.
- This is also a good time to discuss error analysis, as students should not expect every result to match every other result or even those of other groups. Have the students ask why these types of data variations exist, what is responsible for them, and what might be done to minimize them.

In this lab you will learn:

- how to describe the trajectory of a projectile mathematically and graphically;
- how to design an experimental investigation of the trajectory of a projectile;
- how to analyze experimental data describing the trajectory of a projectile mathematically and graphically.

Activity 1: Pre-Assessment

1. **Answer the following questions in your notebook:** How could you calculate the velocity of an object that is travelling horizontally? What lab equipment would you use and what data would you collect?
2. **Answer the following questions in your notebook:** Qualitatively describe the vertical acceleration of a falling object. In which direction does a free-falling object accelerate? How does this acceleration affect the velocity of an object initially moving upward? How does this acceleration affect the velocity of an object initially moving downward?
3. **Discuss your answers to questions 1 and 2 with the class.**

Activity 1: Dart Gun Speed

The introduction pointed out that motions along perpendicular axes are independent; because of this, you need to analyze horizontal and vertical **components** separately from each other. These components are the horizontal and vertical parts of a vector. It is important to remember that the downward component of velocity changes during the dart's motion because of the acceleration due to gravity. In this activity, we fire a dart gun horizontally to determine the velocity at the point at which the dart exits the gun.

Safety Precautions

- Be aware of what is in front of the dart gun. Do not shoot the dart gun if someone could get hit.
- Wear safety goggles at all times while dart guns are being fired.

For this activity you will need the following:

- Dart gun with one dart
- Tape measure or meter stick

For this activity, you will work *in pairs*.

Activity 1 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 1:

- It is important that the launcher be exactly horizontal; use a level for best results.
- Have the students predict how the time of flight of their projectile would change if its initial speed is increased but the angle of launch remains horizontal.
- Have the students predict how the time of flight of their projectile would change if its launch height is increased but the angle of launch remains horizontal.
- Is there a relationship between the launch height and horizontal displacement?
- After the marble leaves the ramp, what force(s) are acting on it horizontally and/or vertically?
- Discuss what it means for an object to have a constant velocity or constant acceleration.

- As a follow-up, once they have determined their dart's initial velocity, challenge the students to predict how high the dart would travel if fired perfectly vertical.

The following are recommendations for the Guided Inquiry for Activity 1:

- Note that no matter how close the dart is to the wall when fired, it will fall some non-zero distance if permitted to leave the gun; gravity is always on and always down!
- Stress that the horizontal and vertical motions of a projectile are independent of each other. This is true both qualitatively (experimentation) and quantitatively (the equations of motion)
- This is a good time for a demonstration that will assist the students in making their predictions:
    - Fire one dart horizontally and the other will drop vertically at exactly the same time. Ask the question as to which will hit the ground first. Ask the students *not* to watch the dart but to listen carefully for the sound of the darts when they hit the floor. The goal is to determine whether they hit at the same time or not.

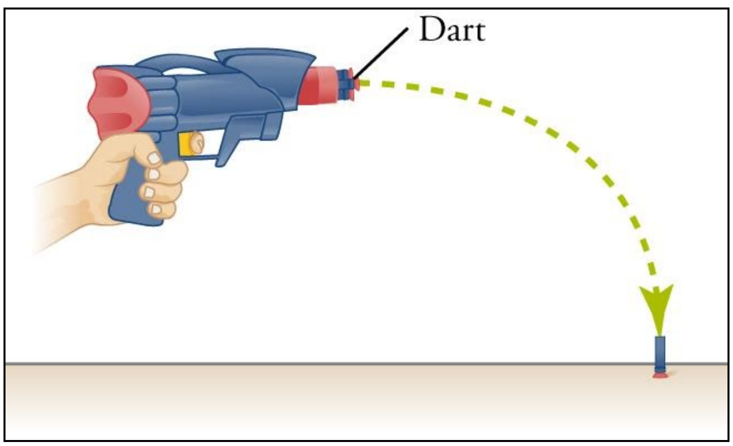


Figure 2.1: As the dart travels horizontally toward the wall, its vertical position changes independently because of the acceleration due to gravity.

Table 2.1: Variables Used in Two-Dimensional Motion

Variable	Horizontal Displacement	Vertical Displacement
Displacement	x	y
Initial velocity	v_{ox}	v_{oy}
Final velocity	v_{fx}	v_{fy}
Acceleration	a_x	a_y
Time	t	t

Table 2.2: Kinematic Equations

$v_f = v_0 + a\Delta t$
$\Delta x = v_0 \Delta t + \frac{1}{2} a t^2$
$\Delta x = \frac{1}{2}\left(v_0 + v_f\right)\Delta t$
${v_f}^2 = v_0^2 + 2a\Delta x$
Where v_0 is the initial velocity, v_f is the final velocity, a is the acceleration, Δt is the time of travel, and Δx is the distance traveled

Structured Inquiry

Step 1: Pick a location where you will fire your dart gun horizontally. The location should be at least 3 meters away from a wall on which the dart will stick. Measure the height of this location from the ground in centimeters and measure how far away from the wall the position you are firing from is in centimeters. Create a data table for your measurements and show your calculations in your notebook.

Step 2: Hypothesize/Predict: Predict where the dart will strike the wall. Why did you make this prediction? What knowledge have you used about motion in the vertical direction to make your prediction? Add your predictions to the data table you created in Step 1.

Step 3: Student-Led Planning: You will now solve for the velocity at which the projectile exits the dart gun in terms of distances you can measure. Start by looking at the kinematic equations listed in Table 2. Discuss with your partner how you can obtain the time of flight of the dart from the distance downward it moves on its way to the wall. Write an equation in your notebook that expresses the time of flight in terms of how far downward the dart strikes the wall if it had traveled horizontally. Next, discuss with your partner how you will use the time of flight and other data you can measure to find how fast the projectile left the dart gun. Write the expression for the speed in terms of the variables you can measure and the time of flight in your notebook. Remember to separate the horizontal and vertical components of motion in obtaining these equations.

Step 4: Critical Analysis: After obtaining the necessary equations, aim the dart gun as close to horizontal as possible, fire the dart, and collect your data. Record your data and use the data to determine the velocity of the projectile. List your results in your data table. Were your predictions in Step 2 supported by your data? Why or why not? How could you have improved your results? Discuss your answers with your partner and then write them in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: How will the time of flight, and the displacement downward of the dart during flight, change if you fire the dart horizontally from a distance closer to the wall? Will it strike higher or lower than before? How will it change if the dart gun is farther from the wall? Why? Write your predictions and your reasoning in your notebook.

Step 2: Student-Led Planning: Assume the dart leaves the gun at the same velocity you determined in the first part of this lab. Work with your partner to use the kinematic equations to obtain an expression for the time of flight of the dart in terms of the distance of the gun from the wall. Write the expression in your notebook. Discuss with your partner how to calculate, in terms of the time of flight, the distance downward that the dart should fall before reaching the wall. Then choose two distances from the wall, one closer and one farther than you used in the first part of the lab. Calculate the expected displacement downward from where the dart strikes the wall. Then carry out the actual measurement of this displacement by firing the dart horizontally from the measured distances. Write your results in your notebook at each step.

Step 3: Critical Analysis: How did the displacement downward of the dart compare with your prediction of whether it would be higher or lower than in the first part of the lab? How well did its precise measured value compare with the value predicted from your calculations? Discuss with your partner the possible sources of any disagreement and write your ideas in your notebook.

Assessments

1. In your notebook, draw a position in the *x*-direction versus time graph, a velocity in the *x*-direction versus time graph, and acceleration in the *x*-direction versus time graph for the dart launch experiment. Repeat this for the *y*-direction for a total of six graphs. You can omit numbers on your *x*- and *y*-axes and just show the shape of each graph line. After each graph, write a brief explanation of why the graph has the shape that it does. [EK 3.A.1; SP 7]
2. A baseball outfielder throws a baseball horizontally with an initial velocity of 38 m/s. If the player releases the baseball from a height of 2.25 m, how far does the baseball travel horizontally before it strikes the ground? Be sure to include a table of horizontal and vertical variables and show all of your work. [EK 3.A.1; SP 5]

[Solutions]

1. [EK 3.A.1; SP 7]

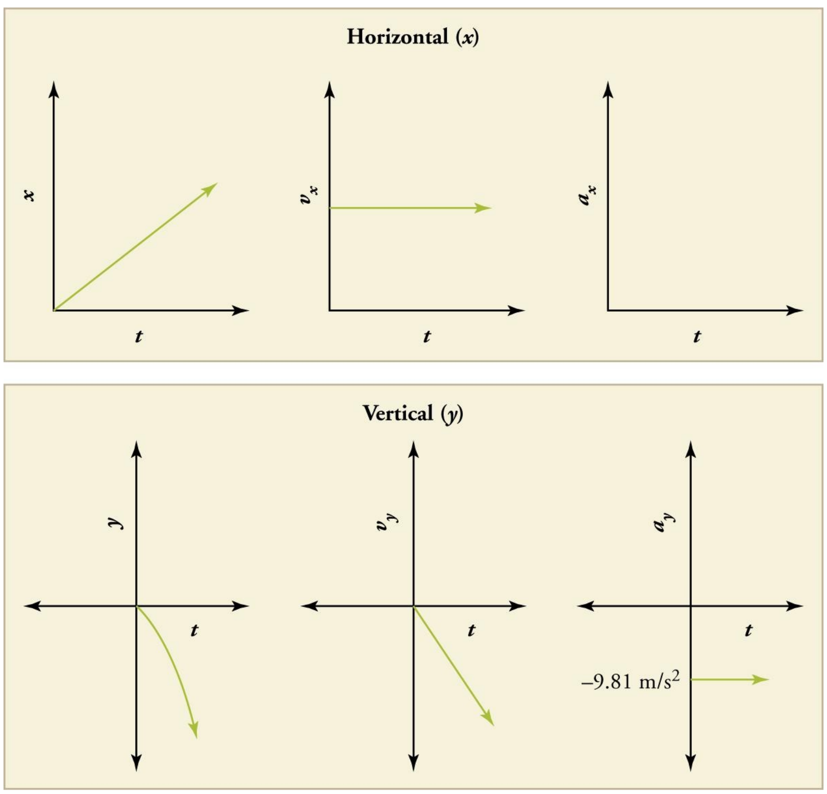


Figure 2.2

Graphs in the Horizontal Direction
Position versus time: The graph has a positive slope because the displacement increases at a constant rate.

Velocity versus time: The graph has no slope because the horizontal component of velocity does not change with time.

Acceleration versus time: There is nothing to draw because the acceleration in the horizontal direction is zero (assuming no air resistance).

Graphs in the Vertical Direction
Position versus time: The graph has an increasing negative slope because the change in position is increasing negatively for each second that passes.

Velocity versus time: The graph has an increasing negative slope because the acceleration due to gravity increases the velocity downward with increasing time.

Acceleration versus time: The graph has a constant negative acceleration because the acceleration downward due to gravity is always –9.80 m/s^2.

2. [EK 3.A.1; SP 5]
   The given data are shown in the table.

$\boldsymbol{x}$		$\boldsymbol{y}$	–2.25 m
$\boldsymbol{v_{ix}}$	38 m/s	$\boldsymbol{v_{iy}}$	0 m/s
$\boldsymbol{v_{fx}}$	38 m/s	$\boldsymbol{v_{fy}}$	
$\boldsymbol{a_x}$	0 m/s^2	$\boldsymbol{a_y}$	–9.80 m/s^2
$\boldsymbol{t}$		$\boldsymbol{t}$	

   To find the time of flight:

$$y = v_{oy}t + \tfrac{1}{2}a_y t^2$$
$$-2.25\text{ m} = 0 + \tfrac{1}{2}\left(-9.80\text{ m/s}^2\right)t^2$$
$$t = 0.678\text{ s.}$$

From this, to find the displacement in the *x*-direction:

x		***x***	–2.25 m
v_{ix}	38 m/s	v_{iy}	0 m/s
v_{fx}	38 m/s	v_{fy}	
a_x	0 m/s^2	a_y	–9.80 m/s^2
t	0.677 s	***t***	0.677 s

$$x = v_{ox}t + ½a_x t^2$$

$$x = (38 \text{ m/s})(0.678 \text{ s}) + ½(0)(0.678 \text{ s})^2$$

$$x = 25.8 \text{ m}.$$

Activity 2: Pre-Assessment

1. **Answer the following questions in your notebook:** If you were provided with the initial velocity and the launch angle, could you predict whether a basketball player will make a free throw? Is there any other information you may need to make this prediction more reliable?
2. **Answer the following questions in your notebook:** How does the launch angle affect the horizontal and vertical velocities of a projectile? If the launch angle increases, how does the horizontal component of velocity change? Does the launch angle affect the acceleration of the projectile along its trajectory?
3. **Discuss your answers to questions 1 and 2 with the class.**

Activity 2: Marble Launch Landing Spot

In the first activity of this lab, you determined the velocity of a **projectile** as it left a dart gun. Each time you performed this activity, the projectile was launched horizontally, so the vertical component of its initial velocity was always zero. In this activity, you will launch your projectile at an angle above the horizontal direction so that its initial velocity has a non-zero vertical **component**. You will predict where this angled shot strikes the floor.

Safety Precautions

- Be aware of what is in front of the marble launcher. Do not shoot the marble if someone could get hit.
- Do not fire the marble into the ceiling or windows of the classroom.
- Wear safety goggles at all times while marble guns are being fired.
- Be sure all breakable objects, including cell phones, are out of range of the marbles.

For this activity you will need the following:

- Marble launcher with one marble
- Tape measure or meter stick
- Protractor or any other tool to determine the angle of launch
- Stopwatch

For this activity, you will work *in pairs*.

Activity 2 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 2:

- Discuss the expected shape of a projectile launched at an angle greater than 0° but less than 90°.
    - If the term "parabolic" does not pop up during the discussion, try breaking up the motion into horizontal and vertical components. What is happening to the vertical velocity? What about the horizontal velocity?

- Provided air resistance is ignored, the velocity and position of a projectile coming to rest at the same height at which it was launched will be symmetrical with respect to the maximum height midpoint.
- Additionally, provided air resistance is ignored, the maximum range of a projectile will be obtained when launched at an angle of 45°.
- Any two launch angles totaling 90° will have the same range.
- So, some open-ended questions to explore would be the following:
    - What angle should cause a projectile to travel the furthest? Highest?
    - Is there a relationship between the launch speed and the maximum height for an angle-launched projectile?
- As a follow-up, once they have determined their marble's initial velocity, challenge the students to a contest by setting the distance from a target elevated on the wall and have them predict (and then test) the setting necessary to hit the target on the first attempt.

The following are recommendations for the Guided Inquiry for Activity 2:

- It is important that the range measurements be taken at the same horizontal level where the projectile leaves the launcher. Typically, with most student-launchers that are placed on a flat surface, the projectile falls past the horizontal and thus appears to travel farther than the equations of motion would suggest.
- Any two launch angles totaling 90° will have the same range.
- What angle should cause a projectile to travel the highest?
    - Is there a relationship between the launch speed and the maximum height for an angle-launched projectile?

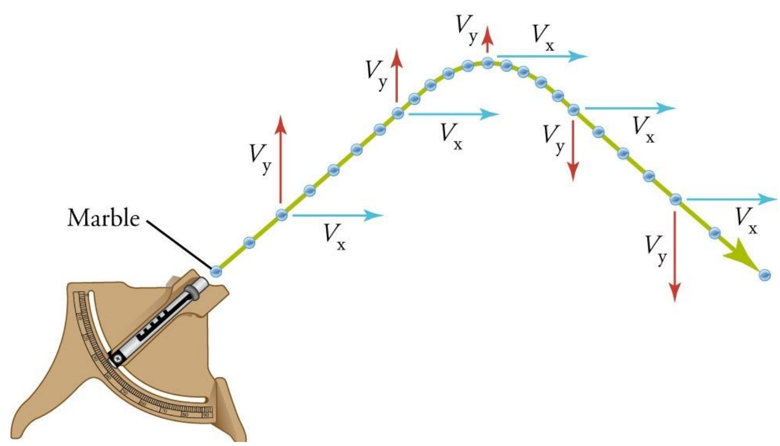


Figure 2.3: As the marble moves through the air, the horizontal component of velocity remains constant, while the vertical component of velocity changes.

Structured Inquiry

Step 1: First you will measure the speed of the projectile as it leaves the launcher. Pick a location where you will fire your marble launcher vertically. Remember all of the safety precautions and only fire the marble when it is safe. Launch your marble straight up. Use the stopwatch to time how long the marble is in the air. From the measured time of flight and the known value of the acceleration due to gravity (g = 9.80 m/s^2), calculate the speed of the projectile as it left the launcher. (Remember that the vertical component of velocity of the marble is zero at the top of its flight.) Create a data table in your notebook to show your measurements and calculations.

Step 2: Hypothesize/Predict: Assuming the marble exits the launcher at the same speed as in Step 1, predict how far you think the marble will travel before hitting the floor if it is launched horizontally from a table. Mark your prediction with a piece of tape or a similar object. Also predict where the marble would land if fired at an angle of 30^o. Add your predictions to the data table you created in Step 1.

Step 3: Student-Led Planning: You will now use the kinematic equations to solve for how far the marble will travel when fired horizontally, given the initial speed you determined in Step 1 and the height of the launcher. Discuss with your partner how you will use your collected and previously known data to solve for the horizontal displacement using the kinematic equations.

Step 4: After you have solved for a displacement, mark that position with a piece of tape or a similar object. Once it is safe, fire the marble launcher and see if your calculated value and observed value are in reasonable agreement. If they aren't, return to your equations to see if you can explain why before moving on to Step 5.

Step 5: Student-Led Planning: You will now solve for the horizontal displacement the marble will travel when fired at an angle of 30^o using the height of the launcher, the initial speed you determined in Step 1, and the kinematic equations. Discuss with your partner how you will use your collected and previously known data to solve for the horizontal displacement using the kinematic equations.

Step 6: Use your protractor or a similar tool to make sure your marble launcher is positioned at the correct angle. Mark that position with a piece of tape or a similar object. When it is safe, fire the marble launcher and see if your calculated value and observed value are in reasonable agreement. If they aren't, return to your equations to see if you can explain why before moving on to Step 7. Repeat this step for two other angles that you choose and create a data table for the angle of launch and horizontal components of initial velocity.

Step 7: Critical Analysis: After completing your calculations, record your collected data in your data table. Also include the initial velocity of the projectile from Step 1 and the displacements solved in Steps 4 and 6. Did your data support your predictions in Step 2? Why or why not? How could you have improved your results? Discuss your answers with your partner and then write them in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: The range of the projectile is how far it lands from the launcher. How does the launch angle affect the range? Discuss with your lab partner what the range of the projectile should be if the projectile is fired straight up and if it is fired horizontally starting just barely above the tabletop. What angle would you predict gives the maximum range? Should the range get smaller or larger if the angle is increased from this maximum-range launch angle? What if the launch angle is decreased? Discuss your answers and your reasoning with your partner and write them in your notebook.

Step 2: Student-Led Planning: Discuss with your partner how you will test the range produced by launch angles of 10°, 30°, 45°, 60°, and 80°. Collect your projectile range data, measured from the exit point of the launcher, for each of the five launch angles. Write the data for each one in your data table.

Step 3: Critical Analysis: Did your data support your prediction of which angle would give the maximum range for the projectile? What does your data show is the effect on the range if the launch angle is made larger than the angle that gave the largest range? How about if the launch angle was made smaller? If you were to choose a distance smaller than the maximum range, how many different launch angles would there be that make the projectile land at this distance? Discuss your answers with your partner and write them in your notebook.

Assessments

1. If you were to know the initial velocity and the angle of launch, could you accurately predict whether or not a basketball player could make a free throw? Explain how you would design an experiment that could determine if a player will make or miss a free throw before the ball reaches the rim. [EK 3.A.1; SP 4]
2. Whether a projectile is launched at 20° or 70°, it will land in the same spot as long as the projectile's initial speed leaving the launcher is the same. How can you explain this phenomenon? [EK 3.A.1; SP 1]
3. Your friend is leaving your house when you discover your friend's wallet in your room. You quickly run to your second-story window. You call out and throw the wallet horizontally from the window, and your friend catches it, 13.0 m away from the house. If your window is 3.5 m above the ground, how fast did you throw the wallet? Be sure to include a table of horizontal and vertical variables and show all of your work. [EK 3.A.1; SP 2]

[Solutions]

1. [EK 3.A.1; SP 4]
   Use the angle of launch to split the initial velocity into its horizontal components and vertical components, and determine the time it will take the ball to get to the rim. Using this time, the vertical component of the initial velocity, and the acceleration due to gravity, determine the predicted vertical displacement of the ball. If the calculated vertical displacement is the same as the difference between the height of the ball when it is released and the height of the rim, the ball will go in. If they are not the same, the ball will not go in. Students do not need to worry about side-to-side motion along the *z*-axis.
2. [EK 3.A.1; SP 1]
   The answer should mention the horizontal and vertical components of the initial velocity being reversed for 20° and 70°. Students should also explain that although the 20° launch results in faster projectile motion in the horizontal direction, the projectile has less time to travel. Students can also answer this question mathematically by showing the horizontal displacements are identical when using the same initial velocity and the two different launch angles.

3. [EK 3.A.1; SP 2]
   The given data are shown in the table.

x	13 m	***y***	–3.5 m
$\boldsymbol{v_{ix}}$		$\boldsymbol{v_{iy}}$	0 m/s
$\boldsymbol{v_{fx}}$		$\boldsymbol{v_{fy}}$	
$\boldsymbol{a_x}$	0 m/s^2	$\boldsymbol{a_y}$	–9.80 m/s^2
t		***t***	

The time of flight can be calculated as the time to reach the ground.

$$y = v_{oy}t + \tfrac{1}{2}a_y t^2$$
$$-3.5 \text{ m} = 0 + \tfrac{1}{2}\left(-9.80 \text{ m/s}^2\right)t^2$$
$$t = 0.845 \text{ s}$$

And the *x*-component of the displacement can then be obtained.

$$x = v_{0x}t + \tfrac{1}{2}a_x t^2$$
$$13 = v_{ox}(0.845 \text{ s}) + \tfrac{1}{2}(0)(0.845 \text{ s})^2$$
$$v_{ox} = 15.38 \text{ m/s}$$

Lab 3: Newton's 2nd Law

Newton's Second Law tells us that the acceleration of an object is directly proportional to the net force acting on it and inversely proportional to the mass of the object. In other words, the harder you push an object, the faster it will accelerate; the heavier it is, the slower it will accelerate. This relationship is expressed in the equation

$$\mathbf{F}_{\text{net}} = m\boldsymbol{a}\ ,$$

where $\mathbf{F}_{\text{net}}$ is the net force acting on the object and *m* and $\boldsymbol{a}$ are the object's mass and acceleration, respectively, Acceleration is defined as the change of velocity per unit time, and acceleration is the slope of a velocity vs. time graph.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- Students should be familiar with Newton's Second Law. Work an example of it on the board.
- Students should be familiar with the definition of velocity and acceleration, including the use of limits as the time interval goes to zero.
- Students should be familiar with building and using free-body diagrams. A simple example of such a diagram should be drawn on the board and briefly discussed.
- Students should be asked questions in the course of this discussion. A teaching tip is to ask students to prepare and introduce the concepts and equations, and lead the discussion.
- It is important to briefly talk about the significance of making accurate and precise measurements. The procedure for finding averages and average deviations should be discussed.

In this lab you will learn:

- how to use free-body diagrams to determine and visualize experimental variables for force and motion;
- how to graph velocity versus time;
- how to measure and calculate velocity;
- how to calculate acceleration.

Activity 1: Pre-Assessment

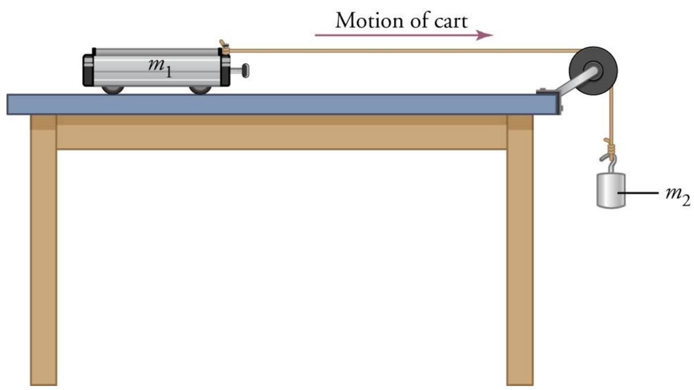


Figure 3.1: The cart of mass m_1 accelerates along the table. Rate of acceleration is directly proportional to mass m^2.

1. **Answer the following questions in your notebook:** Using Figure 3.1, draw a free-body diagram, indicating all the forces acting on the cart and its cargo.
2. **Answer the following questions in your notebook:** Answer the following questions based on Figure 3.1:
    a. What is the strength of the force accelerating the system, in terms of the masses involved?
    b. What is the relationship between the acceleration of mass m_1 and the acceleration of mass m_2?
    c. Does the force accelerating the system change or remain constant until mass m_2 reaches the floor? Does the acceleration itself change?
    d. What total mass does the gravitational force acting on mass m_2 accelerate?
3. **Answer the following questions in your notebook:** Imagine that you placed all the masses you intend to test as cargo in the cart, except the one that is hanging (Figure 3.1). You then exchange the hanging mass with one from the cargo section that is heavier. How will that affect
    a. the mass that is being accelerated, and
    b. the net force causing the acceleration?
4. **Discuss the answers to questions 1–3 with the class.**

Activity 1: Applying Constant Force

When a constant force is applied to an object or system, the object or system will accelerate at a constant rate. If the applied force and mass of the system are known, the acceleration predicted by Newton's Second Law can be calculated.

In this lab, you will measure acceleration of various masses by various forces using the setup shown in Figure 3.1. The lab cart starts at rest and accelerates at a constant rate. According to the kinematic equations, the distance Δx that the cart travels in time Δt is then

$$\Delta x = \frac{1}{2} a \left(\Delta t \right)^2$$

for acceleration *a.* This can provide a useful method for determining the acceleration by timing the motion.

Safety Precautions

- Heavy weights that fall can cause injury. It is safest to use a cart and hanging weight of modest mass whenever possible.
- Make sure your experimental setup includes a means of stopping the cart to prevent it from rolling off the table.

For this activity you will need the following:

- Cart, weights, and pulley and string setup; note—If no pulleys are available, then dental floss over the edge of the table will work
- Scale capable of weighing the cart and weights used
- Meter stick
- Visible tape or chalk for marking positions
- Stopwatch or video capture device

For this activity, you will work *in pairs or small groups*.

Activity 1 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 1:

- This activity is conceptually simple. However, making the actual measurements can require some practice.
- The students should take turns making the practice measurements before they proceed to the runs that will be used to record the results.

The following are recommendations for the Guided Inquiry for Activity 1:

- The students should briefly share their hypothesis with the instructor before proceeding to the measurements.
- The precision of the measurements and how many significant digits have to be recorded should be discussed.
- The students should repeat measurements to obtain acceptable averages. They should present their estimates of the final average error bars to the instructor before concluding this activity.

Structured Inquiry

Step 1: Hypothesize/Predict: Using the notation from your free-body diagram, apply Newton's Second Law to derive an equation predicting the acceleration of the cart for given masses m_1 and m_2. Ignore friction and air resistance as well as the mass of the pulley and string.

Step 2: Student-Led Planning: You will need to determine the acceleration of the cart for several different applied forces. The total mass should be kept the same. Discuss with your partner the details of how to accomplish that goal by timing the travel of the cart between two lines marked by chalk or by visible pieces of tape. What precisely will you measure and how will you analyze your data? Then, discuss with your partner what masses you will use for $m_{2.}$ Using the values for m_2 you selected, create a data table to structure your data. Include in the table the predicted values for each mass that you can calculate using the equation you derived in Step 1.

Step 3: Procedure: Execute the planned experiment, repeating the procedure for each of the selected values of m_2. Record the numerical results in the prepared data table(s). Display your experimental data in a graph of acceleration versus applied force. Plot the theoretically predicted graph line from your equation in Step 1 on the same graph for comparison.

Step 4: Critical Analysis: Were the results from your experiment in reasonable agreement with your calculated predictions? Why or why not? If your experimental results did not reasonably agree with your predictions, what factors do you think affected the results? What, according to your equation in Step 1, is the meaning of the slope of the acceleration versus force graph? Are your experimental data consistent with this? Discuss your answers with your lab partner and write them in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: What do you predict the acceleration vs. applied force for fixed mass should look like? If your experimental results weren't the same as you predicted, what factors do you think affected the results? Consider some of the assumptions that were made about the setup when you did your initial calculations in Step 1. How much do you think those factors affected the results? How could you alter the experiment to test this prediction? Write your ideas in your notebook.

Step 2: Student-Led Planning: Discuss and decide as a team which modifications to the experiment you should make to test your ideas. Check with your teacher before conducting additional experiments.

Step 3: Critical Analysis: Were you able to determine how much impact the setup assumptions have on your experimental results? Could you use this data to improve your predictions for the acceleration of the cart with different values of m_2? How?

Assessments

1. What is velocity? [EK 4.A.2]
2. What is acceleration? [EK 4.A.2]
3. What is the source of the force causing the acceleration of the system? [EK 1.C.2]
4. How did you change the acceleration of the cart? [EK 1.C.1]
5. When you increased the hanging mass, did that increase or decrease the acceleration of the cart? Why? [EK 3.A.3]
6. What measurements did you make that enabled you to calculate acceleration? [EK 3.A.1]

[Solutions]

1. [EK 4.A.2] Velocity is a vector quantity, indicating the rate of change of displacement per unit of time.
2. [EK 4.A.2] Acceleration is a vector quantity, indicating the rate of change of velocity per unit of time.
3. [EK 1.C.2] The source is the force of gravity on the hanging mass.
4. [EK 1.C.1] Changing the hanging mass changes the force due to gravity, which in turn changes the force transmitted to the cart via the string and the acceleration of the system.
5. [EK 3.A.3] Increasing the hanging mass increased the acceleration of the cart and increased the applied force.
6. [EK 3.A.1] Measuring the position of the cart at subsequent time intervals allowed calculation of instantaneous velocity over a series of points. The change in velocity from start to finish is the acceleration.

Activity 2: Effect of Force on Different Masses

Newton's Second Law tells us that the acceleration of an object or system is inversely proportional to the mass of the object or system. The greater the mass of the system for a given force, the smaller the acceleration.

Safety Precautions

- Heavy weights that fall can cause injury. It is safest to use a cart and hanging weight of modest mass whenever possible.
- Make sure your experimental setup includes a means of stopping the cart to prevent it from rolling off the table.

For this activity you will need the following:

- Cart, weights, and pulley and string setup; note—If no pulleys are available, then dental floss over the edge of the table will work
- Meter stick
- Visible tape or chalk for marking positions
- Stopwatch or video capture device

For this activity, you will work *in pairs or small groups*.

Activity 2 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 2:

- This activity includes measurements that are essentially the same as for Activity 1. This is why it is recommended to have a discussion on additional topics before proceeding to the experiment. One of the main questions can be what additional influences and forces affect the accuracy of agreement between the predictions and the measured results. What would be the direction of the deviations? What can be done to minimize them?

The following are recommendations for the Guided Inquiry for Activity 2:

- Once the measurements are completed, the students should roughly assess their accuracy and the error bars, and share these findings with the instructor.
- The instructor should encourage the students to recall the background information discussed before the lab as they are analyzing the final results.

Structured Inquiry

Step 1: Hypothesize/Predict: The experimental setup in Figure 3.1 shows mass m_1 resting on the cart and mass m_2 hanging from the string. Can you predict what will happen when you change mass m_1 while keeping m_2 constant? Choose a value for m_2. Then, choose several values for m_1 to test. Using the equation you derived in Activity 1, calculate your prediction for the acceleration of the cart for each value of m_2. Record your calculations in your notebook.

Step 2: Student-Led Planning: In Activity 1 of this lab, you established a procedure for finding the acceleration of the cart. Using the values for m_1 you selected in Step 1, create a data table to structure your inquiry.

Step 3: Procedure: Execute the planned experiment, repeating the procedure for each of the selected values of m_1. Record the numerical results in the prepared data table(s) and determine the measured acceleration of the cart for each value of m_1.

Step 4: Critical Analysis: Compare the experimental results from Step 4 to your calculated predictions from Step 2. Were the results from your experiment in reasonable agreement with your calculated predictions? Why or why not?

Guided Inquiry

Step 1: Hypothesize/Predict: Based on what you know about Newton's Second Law, what do you expect would happen if you did the experiment with both masses, m_1 and m_2, now 1.5 times larger than before? Or, what if m_1 and m_2 were multiplied by some other number, such as 0.5? By what factor would that multiply the force that accelerates the cart? By what factor would it multiply the total mass being accelerated? Considering the effect of increasing the force along with the effect of increasing the mass, what changes would this cause? Write your prediction and rationale in your notebook.

Step 2: Student-Led Planning: Work with your lab partner to plan an experiment to test your hypothesis on the effect of changing the masses. Describe your planned experiment in your notebook and get your plan approved by your teacher. Then, carry out the experiment.

Step 3: Critical Analysis: Did your results match your prediction? What is the effect on acceleration if both mass and applied force are multiplied by the same factor, per Newton's Second Law? How does that relate to your data? If your results differed from your prediction, try to explain why. Discuss your answers with your lab partner and write the analysis in your notebook.

Assessments

1. When you increased the mass on the cart, did that increase or decrease the acceleration of the cart? Why? [EK 3.A.3]
2. Apply the same idea as in the Guided Inquiry to an object in free fall by considering replacing the object with one *k* times as massive. How will this change in mass (*k*) affect the force of gravity? By what factor does this change the acceleration of the object? How does this account for Galileo's observation that all objects in free fall have the same acceleration regardless of mass? [EK 3.A.3]

[Solutions]

1. [EK 3.A.3] Changing the mass on the cart changed the rate of acceleration in an inversely proportional relationship. Increased mass decreased the acceleration, decreased mass increased the acceleration.
2. [EK 3.A.3] The change in mass multiplies the force of gravity by *k*. This is due to the change in the acting force. The change also multiplies the acceleration by 1/*k*. This is due to changing the response of the mass to a net force. Therefore, both changes combine to leave acceleration unchanged.

Lab 4: Forces

Forces govern the movement of everything, from cars to the stars. Nothing changes velocity without an unbalanced force acting on it. As stated in Newton's First Law, an object at rest stays at rest and an object in motion stays in motion with the same speed and in the same direction unless acted upon by an unbalanced force. These forces take many different forms: gravity, electromagnetic forces, tension, and applied forces, among others. Knowing the net force from forces acting on an object, you can calculate how an object will change its motion.

To determine how an object will move, we need to know the magnitude and direction of the forces that are acting on it. The main force that generally acts against movement is friction. **Friction** is the force that resists the movement of an object that is touching a surface in contact with it. For example, friction brings a baseball player sliding into third base to a stop. As with any force, the force of friction is given in units of newtons.

When the objects are at rest, the friction between the two objects is called **static friction**. When you push an object on a surface, the force of static friction is equal in size and opposite in direction to the force you apply, as long as the applied force is less than the maximum force of static friction. Once the applied force exceeds this limit, the friction force is no longer strong enough to balance the applied force, and the object starts moving. The maximum force of static friction is given by the equation $F_s = \mu_s N$, where F_s is the maximum force of static friction, μ_s is the coefficient of static friction, and N is the normal force. When an object is sliding over another, the friction force between the two objects is called **kinetic friction**. Once the object has overcome static friction and is in motion, the force that applies is kinetic friction. The magnitude of this force is given by the equation $F_k = \mu_k N$, where F_k is the force of kinetic friction, μ_k is the coefficient of kinetic friction and N is the normal force. The direction of the kinetic friction force acting on the object is opposite to the direction the object is moving. Therefore, the friction force opposes the object's motion. To complete this lab, you will calculate both static and kinetic friction.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- Students often have difficulties with the idea that there is a maximum force of static friction. Provide some examples. The first one could be of you trying to push your own desk. Ask a student or two to help you push your desk. Note that you were not able to push it yourself at first, because the maximum force of static friction was greater than the force you supplied.

- To continue the desk example, note that when the desk does start moving, it is overcoming kinetic friction. Provide other examples to ensure that students can differentiate between the two.
- For some students, the idea that the generally vertical normal force is involved in determining the magnitude of a generally horizontal friction force is counterintuitive, especially when considered in the context of vectors. However, to demonstrate this, again try pushing the desk, but this time with weight (e.g., books, students) added to it. Ask students to explain why adding weight would make it more difficult to overcome the force of static friction. Answers may center around Newton's Second Law of Motion, but guide students to consider how the added weight would influence the friction. It may be helpful to give students sandpaper and blocks of wood. They should be able to guide the wood on the sandpaper when only the weight of the block is involved, but when the weight of, say, a student is added, it should become significantly more difficult to move.

In this lab you will learn:

- how to design an experiment for collecting data and determine the relationship between the net force exerted on an object, its inertial mass, and its acceleration;
- how to represent forces in diagrams or mathematically using appropriately labeled vectors with magnitude, direction, and units during the analysis of a situation.

Activity 1: Pre-Assessment

1. **Answer the following questions in your notebook:** What seems to happen when you slide something smooth, like a block, across a smooth surface? What about when you slide the same block across a rough surface? Does the normal force change? What about the coefficient of friction?
2. **Answer the following questions in your notebook:** Can you measure the friction between the block and the lab bench by only measuring the acceleration of the block? Why or why not?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 1: Friction Forces

What is friction? **Friction** is defined as a force that acts to oppose the movement of two objects in contact with each other. In this activity, we will be measuring the friction of a block with a rubber band around it. We will also learn how to calculate the **coefficient of friction**, which is the ratio between the force of friction between two objects and the normal force between the objects.

Safety Precautions

- There are no safety considerations for this lab.

For this activity you will need the following:

- Rubber bands
- Block
- Spring scale or digital force gauge

For this activity, you will work *in pairs*.

Activity 1 Instructor Preparation and Teaching Tips

The following are recommendations for the Structure Inquiry for Activity 1:

- Ideally, the blocks you use will be cubes, so students will not be able to change the surface area of the blocks in contact with the surface. However, if you use rectangular blocks, ask students to consider how the surface area of the block in contact with the surface would affect the friction. They should control for this variable in their lab notes by noting which side they are using in each trial.
- To further build on Step 4 in the Structured Inquiry, you could direct students who finish early (1) to research why the coefficient of static friction is always greater than that of kinetic friction and/or (2) to describe what would happen if the coefficient of kinetic friction were greater than that of static friction.

The following are recommendations for the Guided Inquiry for Activity 1:

- To facilitate Step 1, you may need to encourage students to consider what it is about a rubber band being in contact with a surface that increases or decreases the amount of friction. Specifically, have them compare the surface area in contact when the rubber bands are laid horizontally versus laid vertically if the blocks you are using are rectangular.
- To facilitate Step 3, ask students how they could maximize the amount of static friction using only four rubber bands. If time allows, have them conduct another experimental trial with their friction-maximizing setup.

Structured Inquiry

Step 1. Measure the weight exerted by the block on the lab bench using a spring scale or digital force gauge. How does the weight of the block relate to the normal force? Create a data table for your measurements in your notebook.

Step 2: Hypothesize/Predict: Which will be larger, the force of friction for the block at rest (static friction) or the force of friction while the block is moving (kinetic friction)? Write your predictions in your notebook.

Step 3: Student-Led Planning: You will now measure the maximum force of static friction for the block at rest (static friction) and the force of friction while the block is moving (kinetic friction) using the spring scale or digital force gauge. First, you should measure the weight of the block (and its attached rubber bands) using the spring scale or digital force gauge. Then, you should pull the block across your surface with the spring scale or digital force gauge. Do your best to pull it at a constant speed. In successive trials, attach more rubber bands around your block to increase the friction.

Step 4: Critical Analysis: Calculate and record the coefficient of static friction and the coefficient of kinetic friction in your data table. Were the predictions you made in Step 2 supported by your data? Why or why not? What methods could you have used that would have improved your results? Discuss your answers with your partner and then write them in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: How do you think the number and/or orientation of rubber bands determines the coefficient of friction? What rubber band arrangements would increase the coefficients of friction? Write your ideas in your notebook.
Step 2: Student-Led Planning: Now, pick four arrangements of rubber bands on your blocks. Measure the normal force for a block with each arrangement and then measure the maximum force of static friction and the kinetic friction for each. Calculate the coefficients of static friction and kinetic friction for each. Write your results in your science notebook.

Step 3: Critical Analysis: Which arrangements of rubber bands had larger coefficients of friction? When the coefficient of static friction increased, did the coefficient of kinetic friction also increase? What about the different arrangements of rubber bands that affected friction? Discuss your answers with your partner and write them in your notebook.

Assessments

1. A student pushes a 0.65-kg block along a smooth table. [EK 1.C.1; SP 3]
    a. Does friction occur in this scenario? Where does it occur?
    b. What would the student need to measure to obtain the coefficient of kinetic friction?
2. Friction refers to the force that acts to ________ the movement of one object past another in contact with it. From your observations, describe how static friction does this. [EK 3.A.2; SP 3]
3. An object at rest on a table is subject to a large force. As a result of the large force, the object slides along the table.[EK 3.A.2; SP 3]
    a. Does the object experience static friction? When?
    b. Does the object experience kinetic friction? When?

[Solutions]

1. [EK 1.C.1; SP 3]
    a. Yes, friction occurs in this scenario. The friction is between the block and the smooth table.
    b. The student would need to measure the force that he/she is applying to the block to keep it moving at constant velocity. The normal force can be calculated using the mass and the known acceleration due to gravity.
2. [EK 3.A.2; SP 3] oppose; Friction acts to oppose the movement of an object because it gets *hung up* on the surface it is sliding over. For the case of static friction, the friction force opposes the applied force to give a net force of zero, holding the object in place until the applied force is increased to a large enough value.
3. [EK 3.A.2; SP 3]
    a. Yes, the object experienced static friction when the force was first applied to it, before the object moved. The force was large enough to overcome the force of static friction, and, as a result, it slid along the table.
    b. Yes, the object experienced kinetic friction as it was sliding along the table.

Activity 2: Pre-Assessment

1. **Answer the following questions in your notebook:** When you push an object up an inclined plane, what forces seem to be acting on it? Why?
2. **Answer the following question in your notebook:** What is the direction of the normal force for an object on an inclined plane?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 2: Forces on an Inclined Plane

Think about pushing an object uphill. Why is it harder to push that object up the hill than it would be to push it across a flat surface? On the hill, some of the weight of the object is directed downhill. That is, without the push, the object would likely roll or slide down the hill. In other words, there is a force acting against the force of the push. We can model this situation in this lab by pulling a block up an inclined surface with a hanging weight. Consider a diagram of this situation shown in Figure 4.1.

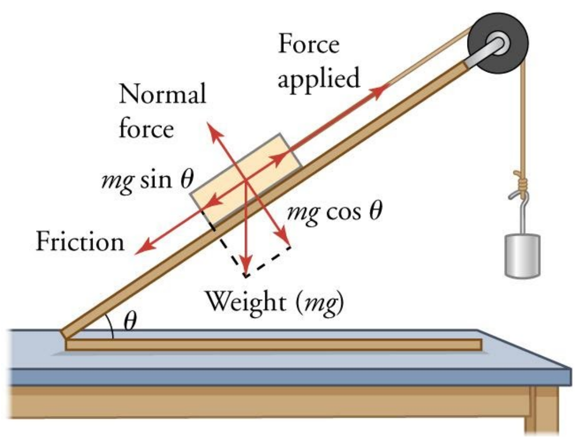


Figure 4.1: Lab model of a cart being pulled up a hill.

Note that part of the weight exerts a force down the incline, namely, $mg \sin \theta$. The $\sin \theta$ component is used to obtain only the part of the weight that is directed down the incline. In this activity, we will be measuring the forces on a cart as it moves up an inclined plane.

Safety Precautions

- Do not roll carts at other students.
- Roll carts only on the table to prevent people from slipping on them.

For this activity you will need the following:

- Carts
- Inclined plane
- Pulley

- String
- Protractor
- Stop watch
- Meter stick
- Spring scale or digital force gauge

For this activity you will work *in pairs*.

Activity 2 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 2:

- Ideally, the blocks you use will be cubes, so students will not be able to change the surface area of the blocks in contact with the surface. However, if you use rectangular blocks, ask students to consider how the surface area of the block in contact with the surface would affect the friction. They should control for this variable in their lab notes by noting which side they are using in each trial.
- If students are setting up their own inclines, encourage them to use values that are easy to work with. It might help to remind students that cos 60° is 0.5 and that an angle of 0° is still an angle.
- To support answers to the questions in Step 3 of the guided inquiry, you may need to direct students to plot their acceleration results against cos θ for each angle.

The following are recommendations for the Guided Inquiry for Activity 2:

- To facilitate Step 1, encourage students to draw a force diagram for their experimental setup. Guide them to mathematically represent the part of the diagram that contributes the acceleration.
- To facilitate Step 2, encourage students to use angles that are easy to work with. It might help to remind students that cos 60° is 0.5 and that an angle of 0° is still an angle.
- To support answers to the questions in Step 3 of the guided inquiry, you may need to direct students to plot their acceleration results against cos θ for each angle.

Structured Inquiry

Step 1: Measure the weight of the cart using a spring scale or digital force gauge. Then, calculate the weight exerted on the inclined plane using this weight measurement and your measurement of the angle of the inclined plane. Create a data table for your measurements in your notebook.

Step 2: Hypothesize/Predict: Predict the value of the acceleration of the cart when a constant force is applied to it as it is moving up the plane. Write your predictions in your notebook.

Step 3: Student-Led Planning: You will need to determine the acceleration of the cart from quantities you can measure, such as the distance and time of travel of the cart. Assuming the acceleration of the cart is constant and that it starts from rest, use the kinematic equations to obtain an equation you can use for this purpose. Write the equation in your notebook. Discuss with your lab partner what you will need to do to measure the acceleration of the cart. Now, measure the velocity of the cart as it moves up the inclined plane under a constant force at numerous places along the plane. From this, you will calculate the acceleration. If the block is started from rest and accelerates at a constant rate, its average velocity is related to its acceleration by $a = v_{ave} / T^2$, where *T* is its time of travel down the incline. Note that under this situation, the final velocity will be equal to twice the average velocity, that is, $v_f = 2v_{\text{ave}}$. Discuss with your partner how best to set up your experiment to measure the velocity and calculate the acceleration.

Step 4: Critical Analysis: Record the acceleration multiple times for each run in your data table. Calculate the acceleration from this data. Were the predictions you made in Step 2 supported by your data? Why or why not? What methods could you have used that would have improved your results? Discuss your answers with your partner and then write them in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: How do you think the angle of the inclined plane affects the acceleration? How would you change the angle to increase the acceleration? Write your ideas in your notebook.

Step 2: Student-Led Planning: Now, pick four angles for the inclined plane. Conduct your experiment again. Again, measure the velocity of each cart and then calculate the acceleration for each. Write your results in your notebook.

Step 3: Critical Analysis: How did the change in the angles affect the acceleration? Did increases in the angle coincide with increases in the acceleration? Why? Discuss your answer with your partner and write it in your notebook.

Assessments

1. A student pushes a 1.2-kg block up an inclined plane. [EK 1.C.1; SP 4]
    a. How would you determine the normal force?
    b. What would the student need to measure to calculate the acceleration of the block?
2. Suppose that your calculations result in a net force measurement of 10 N for an object that has a mass of 5 kg. Give the equation that would allow you to calculate the acceleration and provide the acceleration for this situation. [EK 1.C.1; SP 2]
3. An object is pushed up an inclined plane. [EK 3.A.2; SP 1]
    a. Name the forces that are exerted on the object.
    b. Calculate each of the forces exerted on your cart that you gave to answer the previous question.

[Solutions]

1. [EK 1.C.1; SP 4]
    a. You would measure the angle of the inclined plane. Then you would calculate the normal force as $(1.2 \text{ kg})g\cos\theta$.
    b. The student has a number of options, but the easiest would probably be to measure the force that the student is exerting on the block and, from that, calculate the coefficient of friction between the block and the inclined plane. To obtain the coefficient of friction, use $F_k = \mu_k N$, where *N* is the normal force, as calculated earlier, and F_k is the force applied when the speed is constant. To obtain the acceleration, use *F* = *ma*, where m is the mass obtained by working back from the mass (weight equals *mg*, where *g* is the acceleration due to gravity) and observing the force applied.
2. [EK 1.C.1; SP 2] *F* = *ma*; the acceleration is 2 m/s^2.
3. [EK 3.A.2; SP 1]
    a. Forces on the object are the normal force, applied force, friction force, and force of gravity.
    b. The calculations will depend on the apparatus.

Lab 5: Circular Motion

Newton's First Law tells us that an object in motion will stay in motion, in a straight line, unless acted upon by a net external force. In circular motion, the object stays in motion but not in a straight line. Instead, the object's direction of motion changes continuously, and the path it follows is a circle. This change in direction is an acceleration, and we hypothesize that there must therefore be an unbalanced force acting on the object. We call this center-seeking change in movement centripetal **acceleration** (ac). Acceleration, you will recall, can be measured by the change in velocity for each unit of time that passes and is expressed in units of m/s^2. Angular velocity (ω) is the rate of change of the angle as the object rotates. It is expressed in units of radians per second (rad/s) where one complete rotation is 2π radians, or 360°. The tangential velocity is simply the instantaneous linear velocity (v) in units of m/s. The centripetal acceleration can be calculated from either the angular velocity

$$a_c = r\omega^2 ,$$

or the tangential velocity

$$a_c = \frac{v^2}{r} .$$

The **period of rotation** (*T*) is defined as the amount of time needed for one complete revolution, measured in seconds.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- Review fully with the students the concepts and equations associated with uniform circular motion. Note the difference between angular and tangential velocity, and the mathematical relationship between the two. Make a special point to discuss the direction and magnitude of the related parameters of centripetal acceleration and force, and how these differ from general motion in one and two dimensions. Take special care that the students understand the vector quantities for uniform circular motion. This can be especially useful in helping the students deal with the common misconception of centrifugal force.
- It can be especially useful to review Cartesian and polar coordinate systems, and to show how uniform circular motion is described in the two systems and the relation between them.

In this lab you will learn:

- how to use free-body diagrams to determine and visualize the variables of circular motion;
- how to measure the period and radius of uniform circular motion;
- how to calculate centripetal acceleration from measured variables;
- how to calculate centripetal force from measured variables.

Activity 1 Pre-Assessment

1. **Answer the following questions in your notebook:** What seems to happen when you swing an object attached to a string or rope in a circle? Recall Newton's First Law. What prevents the object at the end of the string from continuing its motion in a straight line? What prevents it from dropping to the ground?
2. **Answer the following questions in your notebook:** If you know the period *T* of the rotation and the radius *r* of the circle, how can you calculate the linear or tangential velocity of the object? From the linear or angular velocity, how can you calculate centripetal acceleration?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 1: Flying Toy

When an object is in circular motion, there is a force on the object toward the center of the circle, preventing it from continuing in the straight-line path that Newton's First Law would otherwise predict. In this activity, you will observe the effects of centripetal acceleration and collect data that will allow you to calculate the centripetal acceleration of a flying pig toy as it moves along a circular path, as shown in Figure 5.1.

Safety Precautions

- Before starting, ensure that the toy will not strike people or surrounding objects while it is in motion.
- If you change the string length by replacing the string, have your teacher check that it is securely fastened before proceeding further.

For this activity you will need the following:

- Toy
- Meter stick
- Stopwatch precise to hundredths of a second

For this activity, you will work *in groups*.

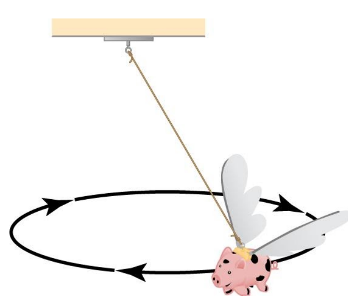


Figure 5.1: The flying pig rotates in a circular path.

Activity 1 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry in Activity 1:

- This type of device is also called a conical pendulum. It is important that the students use their knowledge of the system to derive the key equations that connect the angular velocity, the length of the string, and the angle of the taut string with respect to the vertical.
- Make sure the students make several practice runs with the device so that their data taking is efficient and robust. It may be useful for each student to try using the device in order to find who can operate it in a well-controlled fashion. It is imperative that the students learn to (a) maintain a uniform circular speed and (b) be able to count the number of revolutions in a given time period.

The following are recommendations for the Guided Inquiry in Activity 1:

- Discuss with the students the role of the mass in defining the relationship between the angle of the string and the angular velocity. Ask the students to consider what happens to the angular velocity as the angle approaches the limiting values of zero and 90°. Discuss with them the physical meaning of these results.

Structured Inquiry

Step 1: Measure the length of the string used to suspend the toy pig. In your notebook, draw a free-body diagram, indicating all the forces acting on the pig. Ignore air resistance, although note that the wings on the pig do create air resistance. Use arrows to show the vertical and horizontal components of the forces. Identify in the diagram which force or forces produce the centripetal acceleration.

Step 2: Hypothesize/Predict: Discuss the feasibility of measuring centripetal acceleration directly. What experimental information will you need to collect in order to determine the centripetal acceleration? What intermediate calculations will you need to carry out along the way? Create a data table to structure your inquiry. Include space for gathering data and for making intermediate calculations.

Step 3: Student-Led Planning: You will now measure the period and radius of rotation of the flying pig. Discuss with your classmates how best to measure these, maximizing accuracy and precision. Also, discuss how you will use these data to determine the centripetal acceleration. Create a data table to record these measurements.

Step 4: Set the pig in motion and record the period of rotation and the radius of rotation in your data table.

Step 5: Critical Analysis: Were you able to calculate the centripetal acceleration? Why or why not? What methods could you have used to improve your results? Discuss with the class and then write your answers in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: How do you predict the centripetal acceleration would change if you increase the angular speed (in revolutions per second) of the flying pig? How about if you change the length of the string but keep the angular speed the same? Write the name of each variable you can directly control in the flying pig experiment in your notebook. Then, record your prediction of how changing each variable would change the centripetal force.

Step 2: Student-Led Planning: To test your predictions, you will need a way to observe whether the centripetal force has been increased or decreased. Draw a free-body diagram, showing all the forces acting on the flying pig when it is in motion. Label the angle θ that the string makes with the vertical. Keep in mind that the horizontal component of the tension force is the centripetal force, and the vertical component of the tension force must balance the weight of the pig toy to keep it at the same height. Discuss as a class, using free-body diagrams, how the angle of the string must change if the centripetal force is increased. Write a summary of your arguments in your notebook.

Step 3: Student-Led Planning: Decide how you will use your observations of θ to test your predictions. After your procedure has been approved by your teacher, carry out your experiment.

Step 4: Critical Analysis: Did your observations confirm your prediction in Step 1? If not, what may have caused the discrepancy?

Assessments

1. a. Compare the effect of an acceleration for a very short time Δt in the direction of the instantaneous velocity with the main effect if the acceleration is perpendicular to the velocity.
   b. Justify your answer with a vector diagram showing the small vector change in velocity (Δv) from the acceleration being added to the instantaneous velocity vector of the flying pig. [LO1][EK 4.A.2b]
2. In your free-body diagram from Step 1 of the Structured Inquiry, what force acting directly on the flying pig is the centripetal force causing the motion to be circular? [LO 1][SP 1][EK 3.B.1]
3. a. Why were you unable to measure centripetal acceleration directly?
   b. What measurements enabled you to calculate centripetal acceleration? What intermediate calculations did you have to carry out to calculate centripetal acceleration? [LO 3][SP 1][SP 2][EK3.B.1]

[Solutions]

1.
   a. The acceleration in the direction of the instantaneous velocity causes a change in speed, while the acceleration perpendicular to the instantaneous velocity causes a change in direction of motion.
   b.

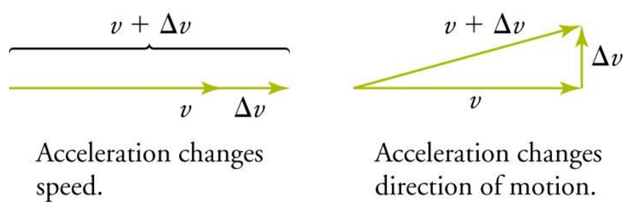


Figure 5.2: A small change is added to the velocity from a brief acceleration.

2. The horizontal component of the tension in the string that supports the flying pig toy points toward the center of the circle forming the path of the pig and is the centripetal force.
3.
   a. The changes in velocity and time are too small to measure accurately with a stopwatch and ruler. Therefore, it is impossible to directly calculate instantaneous acceleration.
   b. Measuring the period of rotation and the radius of rotation enabled calculation of the instantaneous velocity ($v = 2\pi r / T$) and then the centripetal acceleration ($a_c = v^2/r$).

Activity 2 Pre-Assessment

Answer the following question in your notebook: If you know the centripetal acceleration of an object in circular motion, how can you determine the centripetal force? Remember the simple equation $F = ma$.

Activity 2: Stopper on a String

Centripetal force is the name we use to denote the net force that pulls an object engaged in circular motion toward the center of the circle. In the case of an object being swung on a string, the centripetal force is the horizontal part of the tension force from the string. In the previous section, we calculated centripetal acceleration, which is related to centripetal force through Newton's Second Law, $F = ma$, where the force *F* can be expressed in units of newtons (N).

In this experiment, we will examine centripetal force and how it is related to the rotational period and radius of the circular motion. The experimental apparatus shown in Figure 5.3 allows a rubber stopper to travel easily in a horizontal plane. The stopper is pulled inward by a string that supports an adjustable amount of weight. The apparatus allows the string to move freely through the tube to change the radius of the stopper's circular motion.

Safety Precautions

- Before beginning, ensure the rotating stopper will not come in contact with people or surrounding objects when in motion.

For this activity you will need the following:

- Smooth-edged glass tube
- Stopper
- String
- Meter stick
- Stopwatch precise to hundredths of a second
- Mass scale
- Marking pen

For this activity, you will work *in pairs*.

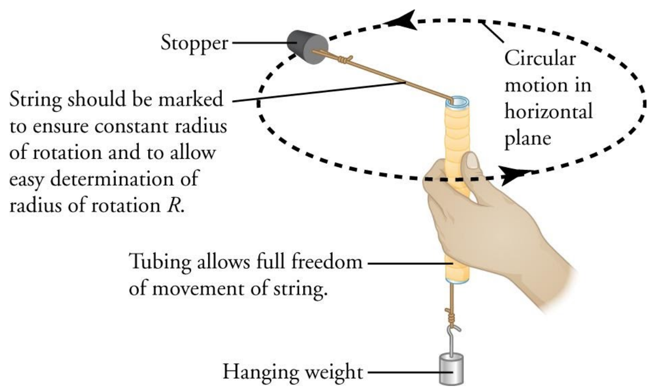


Figure 5.3: The weight hanging from the string provides the centripetal force that causes the motion of the stopper to be circular.

When using the stopper-on-a-string apparatus for this experiment, be sure to keep the stopper rotating in as horizontal a plane as possible. The plane in which the stopper travels should not be slanted, because there should be no vertical changes in the motion of the stopper. Also, the length of the string between the plastic tubing and the stopper should stay constant while swinging, because the period of rotation depends on the radius.

Activity 2 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry in Activity 2:

- Make sure the students practice using the device. This will help ensure proper operation of the device and allow proper data taking.
- As with the previous activity, it is important that the student learns to maintain a uniform circular speed and to be able to count the number of revolutions in a given time period. A recommended method would be to have one student operate a timer and the other operate the device while counting (and calling out loud) complete revolutions. When a set number of complete revolutions is made (e.g., 30), the student with the timer could stop the timer at the final count. Clearly, some practice is necessary, and one student should be recording the attempts so that one can examine the trend in the data.

The following are recommendations for the Guided Inquiry in Activity 2:

- Discuss with the students the key equations that relate the circular motion, the centripetal force, and the masses at each end of the string. This will form the guide they need in their inquiry.

Structured Inquiry

Step 1: In your notebook, draw a free-body diagram, indicating all the forces involved. Ignore air resistance. Identify which force or forces in the free-body diagram constitute the centripetal force.

Step 2: Write the mathematical equation giving the force F that the hanging weight exerts on the string in terms of the hanging mass m. Similarly, write the mathematical expression for the centripetal force in terms of the mass of the stopper and the centripetal force needed to keep it moving in a circle. Why does the radius of rotation change when you change the rate of rotation of the stopper, and what does that imply about the relationship between mass, centripetal acceleration, and centripetal force? Express this as an equation.

Step 3: Hypothesize/Predict: From the first activity, the pre-assessment, and the equation you derived in Step 2, predict how the radius of the stopper's motion will change if the applied force is increased by increasing the mass hanging at the other end of the string. Write your prediction and your reasoning in your notebook.

Step 4: Student-Led Planning: You will now measure the period and radius of rotation of the stopper on the string. Discuss with your partner how best to measure these, maximizing accuracy and precision. How can you change the centripetal force applied to the rotating stopper? Test at least three different applied forces. Ensure that for each measurement, you maintain a constant radius of rotation. Add to the data table you created in Step 2 to record these measurements.

Step 5: Record the period of rotation and the radius of rotation of the stopper in your data table for each of the three variations of applied force. You can measure the period by measuring how long it takes for a few complete rotations and then divide by the number of rotations to obtain the period of rotation.

Step 6: Critical Analysis: Were you able to calculate the centripetal force from the period and radius of rotation? Why or why not? Does your data support your prediction in Step 3? What methods could you have used to improve your results? Discuss with your partner and then write your answers in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: What factors do you think would increase or decrease the centripetal force? How could you alter the experiment to test these factors? Write your ideas in your notebook.

Step 2: Student-Led Planning: Discuss and decide with your partner how to alter the experiment to test your ideas. Get approval from your teacher before proceeding.

Step 3: Critical Analysis: Which factors increased or decreased the centripetal force? Which factors have no effect? Do these observations match your prediction?

Assessments

1. What is the source of the force causing the centripetal acceleration? How did you change the centripetal acceleration? [SP1][EK 3.B.1][EK 4.A.3]
2. What measurements enabled you to calculate centripetal force when the radius could change as you twirled the stopper? What intermediate calculations did you have to make in order to ultimately calculate centripetal force by this method? [SP1][SP2][SP4][EK 3.B.1]
3. How were you able to measure the centripetal acceleration from just the period and radius of the motion? What intermediate calculations did you have to make to ultimately calculate centripetal force by this method?

[Solutions]

1. The hanging mass created tension in the string supporting the rotating stopper. Changing the mass changed the force applied, which changed the centripetal force and acceleration. [SP1][EK 3.B.1][EK 4.A.3]
2. Measuring the mass of the stopper and the hanging mass gives the centripetal acceleration using the relationship

$$m_{\text{stopper}} a_{\text{c}} = m_{\text{hanging}} g ,$$

   where $g = 9.8\ \text{m/s}^2$. [SP1][SP2][SP4][EK 3.B.1]
3. Measuring the period T, the radius of rotation r, and the mass of the stopper enabled calculation of instantaneous velocity, centripetal acceleration, and centripetal force, using the relationship

$$a_{\text{c}} = \frac{v^2}{r} = \frac{\left(\frac{2\pi r}{T}\right)^2}{r} .$$

Lab 6: Hooke’s Law and Spring Energy

Energy exists in a variety of forms. The mechanical energy of an object is the energy of both its motion (**kinetic energy**) and its position (**potential energy**). The law of **conservation of energy** states that energy can neither be created nor destroyed but can be converted only from one form to another. Friction, for example, can convert some of the mechanical energy of an object into thermal energy. When friction can be neglected, the total mechanical energy of an object stays the same.

These energy transformations can be seen in real life. As a gymnast springs vertically from a trampoline, the gymnast’s kinetic energy is converted to gravitational potential energy. In a moving car, some of the chemical energy in gasoline is converted to kinetic energy to turn the wheels, but some is converted also to electrical energy to operate the headlights and air conditioning. During the process of cooking food, an electric stove converts electrical energy to thermal energy. A hydroelectric plant uses the mechanical energy of flowing water to generate electrical energy. Learning how to convert energy efficiently from one form to another form is an important goal of modern science and technology. In this lab you will explore several energy transformations of a spring bumper cart on an inclined ramp.

Instructor Introduction Notes

The following are recommendations for introducing this lab’s background content to your students:

- In order for students to better understand the concepts, provide explanation of key terms: elasticity (property of an object that allows it to be restored to its original shape after becoming distorted), elastic limit, elastic potential energy (energy that is stored by applying force to an elastic object), Hooke’s law and the formula for Hooke’s law ($F=kx$), potential energy, kinetic energy, and mechanical energy.
- In order for students to understand better the concept of spring energy, demonstrate to the students how the force required to stretch a spring will be directly proportional to the amount of the stretch. Set up a demonstration with hanging a spring from a rod, adding weights to the end of the spring, and measuring the length of the stretch. Deduce how the extension of the spring is directly proportional to the weights attached to it.
- In order for students to visualize the relation between force and extension of the spring, have students draw graphs to plot the relation between the force and extension using springs of different strengths.
- In order for students to understand the application of Hooke’s law, provide real life examples: coil springs used in mattresses, flat bar springs used in automobile suspensions, and tension springs used in garage doors.

- In order for students to better understand the concept of elastic potential energy, using a spring, demonstrate to the students how the energy of a spring exists only when it is compressed or stretched.
- In order for students to understand the concept of elastic potential energy, provide other examples including bungee cords, bow and arrow, rubber bands and trampolines where potential energy exists only when stretched or compressed – the more the amount of the stretch, the greater the energy stored.
- In order for students to understand the concept of transformation of energy, explain what is the initial energy and final energy in the following examples:
    - a ball falls from a height, assume there is no air resistance (answer: gravity transforms potential energy, due to height, to kinetic energy, speed—as the ball increases in speed as it falls to the ground)
    - a baseball is thrown up in the air (answer: the ball is gaining in height and losing speed or slowing down as it goes higher – here gravity transforms kinetic energy, speed, to potential energy, due to height)
- In order for students to understand the concept of mechanical energy in relation to kinetic and potential energy, explain to the students using a roller coaster as an example, how the kinetic energy of a car—as it moves to the top position—is converted to potential energy—as it comes to a momentary stand still at the very top. Explain also how the mechanical energy of the car is always a constant (even though the kinetic and potential energies may vary at different points) and is a sum of the kinetic and potential energies.

In this lab you will learn:

- how to measure a spring constant on a spring bumper of a cart; and
- how to determine the energy of a compressed spring bumper on a cart using the law of conservation of energy.

Activity 1: Pre-Assessment

1. **Answer the following questions in your notebook**: What is meant by the term *ideal spring*? What factors could affect the strength of the spring? Are shorter springs stiffer? For example, if a spring is cut in half, will each half-spring be stronger or weaker than the original spring?
2. **Answer the following questions in your notebook.** How could you measure and compare the strengths of two or more springs qualitatively? Describe a simple experimental procedure illustrating the qualitative behavior of an ideal spring when stretched to different lengths.
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 1: Hooke's Law

Most springs exhibit linear elastic behavior, provided that applied force is not large enough to permanently deform the spring. In a linearly elastic spring, the stretch (or compression) of the spring, measured as displacement from its unstrained length, is directly proportional to the applied force. This is expressed in the equation

$$F = kx\ ,$$

where *F* is the applied force in newtons*, k* is the spring constant, and *x* is the spring extension distance in meters. This relationship is derived from **Hooke's law**, named after the British physicist, Robert Hooke, who researched oscillatory motion in the mid-seventeenth century.

A spring that behaves according to Hooke's law is called an **ideal spring**. If an elastic material is stretched or compressed beyond a certain point, it will not return to its original state and will remain permanently deformed. Therefore, it will no longer obey Hooke's law. The displacement beyond which permanent deformation occurs is called the **elastic limit**.

Safety Precautions

- Do not place the carts on the floor where someone could slip on one.
- Be careful when stretching the springs, because you could hurt someone if the spring is released near the body, especially near someone's eyes or face.

For this activity you will need the following:

- Spring bumper provided with the cart
- Mass set with hanger
- Ring stand
- Table clamp (C-clamp)
- Ring-stand clamp
- Ruler in cm

For this activity you will work *in pairs*.

Activity 1 Instructor Preparation and Teaching Tips Structured Inquiry

The following are recommendations for the Structured Inquiry for Activity 1:

- In advance of the lab, show the students all of the different items that will be used for this activity. If students need to bring any of the items, provide them with a list and instructions on where to get them. Provide specific details about the type of spring bumper, cart, mass, ring stand, and table clamp.
- Since the students are to be working in pairs, explain what each student needs to do so that both students equally contribute to the activity. For example, to begin with, both students can help set up the apparatus. When the activity starts, one student can conduct the activity, and the other student can record the results.

The following are recommendations for the Guided Inquiry for Activity 1:

- The data collected can be expanded to include three trials for different springs of different thickness and length. Repeat the experiment for both the stretch and compression of the spring. The data can be graphed to understand the relation between the force and the extension of the spring.
- Repeat the experiment with different kinds of springs and additional weights to determine the elastic limit of the spring.

Structured Inquiry

Step 1: Hypothesize/Predict: Examine the spring bumper provided with the cart. Predict whether the bumper is an ideal spring. Explain why you made this prediction.

Step 2: Detach the spring bumper from the cart. Measure the length of the unstrained spring and record that in your notebook. Set up your experiment as shown in the diagram. (Figure 6.1)

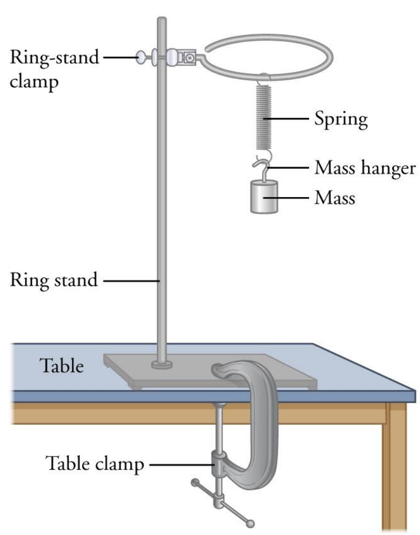


Figure 6.1: An experimental setup to investigate whether the spring obeys Hooke's law.

Step 3: Student-Led Planning: Measure the stretch of the spring for different weights you place on the spring. Discuss with your partner how best to take the measurements of the spring stretch for different weights. Create a data table for your measurements. Carry out the measurements following the procedure you decided on. Determine the spring constant based on your data, and show your calculations in your notebook. Remember to include units in all measurements and calculations.

Step 4: Critical Analysis: Did your data support the prediction you made in Step 1? Why or why not? What methods could you have used to improve your results? Discuss these improvements with your partner, and then write your answers in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: Recall that Hooke's law can be applied both to the stretch and the compression of a spring. Predict whether Hooke's law holds true if you compress the spring of a bumper. Write your ideas in your notebook.

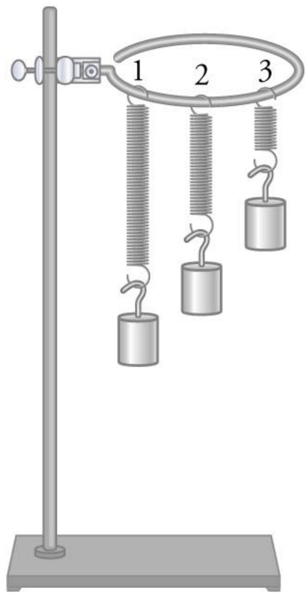
Step 2: Student-Led Planning: How can you alter your procedure to test your hypothesis in Step 1? What information will you collect, and how will you display your experimental data? Write your ideas in your notebook.

Step 3: Show your proposed procedure for testing your hypothesis from Step 1 to your teacher for approval. Revise your procedure, if needed, and complete the experiment. Record your measurements and observations in your notebook. Determine the spring constant based on your data, and show your calculations in your notebook. Make sure to indicate units for all measurements and calculations.

Step 4: Critical Analysis: Compare and contrast the behavior of the spring when it was stretched (structured inquiry) and when it was compressed (guided inquiry). What was similar in compressing and in stretching the spring, and what was different? Discuss your answers with your partner, and write them in your notebook.

Assessments

1. Three different springs have the same length before being stretched. The same mass is attached to each of the springs, as shown in the figure. [EK 3.A.3; SP 3]



   a. Which spring has the greatest spring constant? Which one has the smallest spring constant?
   b. Explain your reasoning.

2. A student measures the length of a spring with several different masses attached and records the measurements as shown in Table 6.1. Using the data, determine whether the spring is an ideal spring. Justify your answer. [EK 3.A.3; SP 5]

Table 6.1

Mass on the Spring (g)	Length of the Spring (cm)
40	5.5
60	6.0
80	6.5
100	7.0
120	7.5
140	8.0
160	8.5
180	9.0

3. Figure 6.3 shows a graph of a force F in newtons exerted on an ideal spring, versus the displacement x from the spring's unstrained length, measured in meters. At the end of the experiment, the spring did not return to its original shape. [EK 3.A.3; SP 2; SP 5]

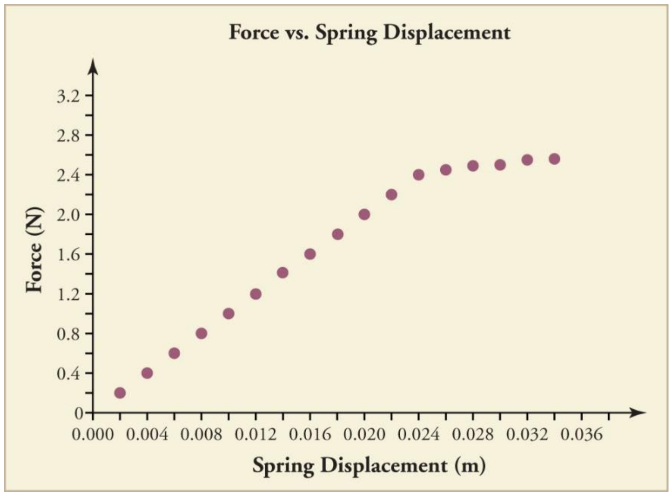


Figure 6.3: Force exerted on a spring as a function of how it is stretched.

   a. What is the range of force for which Hooke's law applies? What is the spring constant for this range?
   b. What is the spring's elastic limit? What happens when the spring is stretched beyond this limit?

[Solutions]

1. [EK 3.A.3; SP 3]
   a. Spring 1 is weakest, because it stretches the most under the same weight, and spring 3 is strongest, since it stretches the least. Therefore, spring 3 has the largest spring constant and spring 1 has the smallest spring constant.
   b. The spring constant is defined as the ratio of applied force to displacement. Because the applied force is the same, the spring constant is larger for a smaller displacement.
2. [EK 3.A.3; SP 5] For each 20 g added to the spring, the spring stretches an extra 0.50 cm, so the stretch of the spring is proportional to the applied force. Thus, this spring behaves according to Hooke's law and is ideal, within the accuracy of the listed data**.**
3. [EK 3.A.3; SP 2; SP 5]
   a. The force is proportional to the displacement until its value is about 2.6 N. The spring constant for this range can be found as the slope of the graph

$$k = \frac{\Delta F}{\Delta x} = \frac{2.6\text{ N} - 0.4\text{ N}}{0.024\text{ m} - 0.02\text{ m}} = 100\text{ N/m}.$$

   b. The spring elastic limit is 0.024 m. Beyond this length, the spring becomes deformed, and it takes much less force to stretch the spring farther.

Activity 2: Pre-Assessment

1. **Answer the following questions in your notebook**: Does a spring have energy when compressed or stretched from its unstrained length? If so, is the energy potential, kinetic, or both? How do you know? What could the elastic potential energy of the spring depend on?
2. **Answer the following questions in your notebook.** A cart with a spring bumper is placed at the base of an inclined ramp, the spring is compressed, and the cart is released to go up the ramp. Assuming there is no friction between the cart and the ramp, what happens to the mechanical energy of the cart as it travels? Describe transformations of energy of the cart as it moves up the incline.
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 2: Spring Energy

According to the law of conservation of energy, the total energy of a closed system (its internal energy) remains constant. In this activity, you will use a cart with a spring bumper placed on an inclined ramp. The cart is positioned on the ramp so that its spring is compressed against a wall (See Figure 6.4). The Earth-cart-spring system is closed and energy exists in the compression of the spring, in the movement of the cart, and in the cart's gravitational interaction with Earth. Thermal energy is also present, but we can assume that it is negligible.

Initially, all of the mechanical energy is in the compressed spring, which pushes the cart up the slope. The cart momentarily reaches its highest point where its gravitational potential energy is at its maximum. If mechanical energy is conserved for this system, then the original spring potential energy must equal the increase in gravitational potential energy. The gravitational potential energy of the cart is

$$\mathrm{PE}_g = mgh,$$

where *m* is the mass of the cart, $g = 9.8\ \mathrm{m/s^2}$ is acceleration due to Earth's gravity, and *h* is the height of the cart above its starting position. The potential energy of the spring is

$$\mathrm{PE}_s = \frac{1}{2}kx^2,$$

where *k* is the spring constant and *x* is the stretch or compression of the spring.

In this lab, you will measure the spring potential energy of the compressed spring and the gravitational potential energy of the cart when it comes to rest on the incline. Then you will compare the two energies to see if mechanical energy was indeed conserved.

Safety Precautions

- Do not place the carts on the floor where someone could slip on them.
- Be careful when stretching the springs, because you could hurt someone if the spring is released near the body, especially near someone's eye or face.
- Flip the cart over when it is on the table to prevent it from accidentally rolling off the table.

For this activity you will need the following:

- Cart with spring bumper
- Track or ramp with end stop
- Meter stick
- Protractor
- Stopwatch
- Masking tape or marker

For this activity you will work *in pairs.*

Activity 2 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 2:

- In advance of the lab, show the students all of the different items that will be used for this activity. If students need to bring any of the items, provide them with a list and instructions on where to get these. Provide specific details about the type of spring bumper, cart, protractor, and stopwatch. Demonstrate to the students how each of the items will be used.
- Since the students are to be working in pairs, explain what each student needs to do so that both students equally contribute to the activity. For example, to begin with, both students can help set up the apparatus. When the activity starts, one student can conduct the activity, and the other student can record the results.

The following are recommendations for the Guided Inquiry for Activity 2:

- The data collected can be expanded to include trials for different springs of different thickness and length and objects of different weights, instead of the cart. The data can be graphed to understand the relation between the spring compression and the maximum height of the cart.

Structured Inquiry

Step 1: Hypothesize/Predict: How would you predict the compression x of the spring to be related to the greatest height the cart reaches on the incline? Use conservation of mechanical energy to write an equation relating the potential energy of the spring, in terms of its compression, to the gravitational potential energy of the cart, in terms of the greatest height h it reaches, including other variables as needed. Rearrange the equation so that it predicts the change in height of the cart from the compression of the spring. Then use the equation to predict how the maximum height changes if the spring compression is larger or smaller.

Step 2: Student-Led Planning: You will need to know the spring constant of the spring to determine the energy stored in the compressed spring. Decide with your lab partner how to measure the spring constant of the spring by hanging a known mass from it. Write your answer in your notebook, along with the equation for the spring constant in terms of what will be measured. Measure the spring constant, and write your result and how you calculated it in your notebook.

Step 3: Place the cart on the inclined ramp with the spring against the end stop as shown in Figure 6.4. For each trial, you should be able to compress and release the spring to propel the cart up the incline.

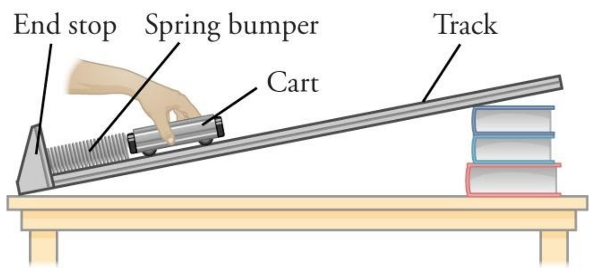


Figure 6.4: The setup for this experiment should allow you to propel the cart up the incline.

Step 4: Student-Led Planning: You will now need to collect data to test how well your energy conservation equation from Step 1 predicts experimental results. Which variables will you adjust, and which will you merely observe and record? Discuss with your partner how best to take the measurements of these variables. In your notebook, create a data table for your measurements. Include in your table a column for the spring compression, a column for the change in height of the cart, a column for the spring potential energy, and a column for the maximum gravitational potential energy of the cart. Show your calculations in your notebook. Make sure you include appropriate units and carry out any unit conversions needed. Proceed to carry out your planned experiment.

Step 5: Critical Analysis: Were the predictions you made in Step 1 supported by the data? Why or why not? If there was a significant difference between the initial energy of the spring and the final gravitational potential energy of the cart, does the difference represent a loss or gain of mechanical energy? How can you account for the energy gain or energy loss you observed? Discuss your answers with your lab partner, and write them in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: What is the mathematical relationship between the energy of a spring and the compression of the spring when Hooke's law applies? What is the relationship between the height the cart rises and its gravitational potential energy? Use these relationships to predict the general shape of a graph of maximum cart height versus spring compression. Discuss your answers with your lab partner and write your predictions in your notebook, including a sketch showing the shape of the graph you expect.

Step 2: Student-Led Planning: Discuss with your lab partner how best to collect your data. Measure the maximum height reached by the cart for several different measured values of spring compression. Record your measurements and observations in your notebook. Plot a graph of observed height versus compression as part of your work.

Step 3: Critical Analysis: How well did your experimental results agree with your predictions? Discuss with your partner what may have caused any disagreement between your results and your predictions. Write your answers and explanations in your notebook.

Assessments

1. The same low-friction cart is placed against the same spring on three different ramps. The spring is compressed by the same amount each time and then released. Assume that spring mass is negligibly small compared to the mass of the cart. [EK 4.C.1; EK5.A.2; SP 3]
    a. In Figure 6.5, draw the cart in its highest position on each ramp.
    b. Provide an explanation for your drawings.

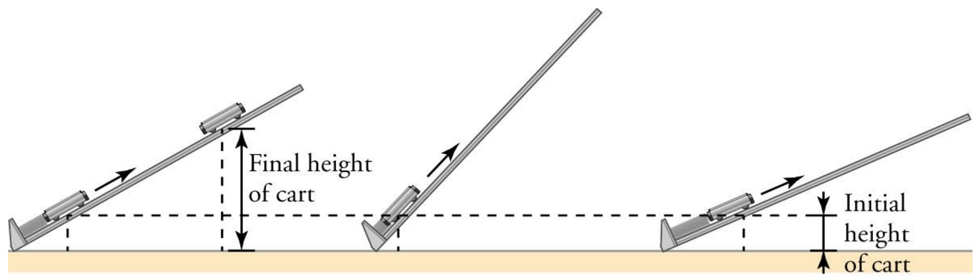


Figure 6.5: Three ramps with different slopes.

2. A low-friction cart descends the ramp from a height of 40 cm and hits an ideal spring at the bottom of the ramp, compressing it by 2.0 cm. [EK 4.C.1; SP 2]
    a. In the second experiment, the compression of the spring is doubled. What was the initial height of the cart?
    b. In the third experiment, the compression of the spring is halved. What was the initial height of the cart?
    c. Explain your answers.

3. A 100 g ball is dropped from several different heights onto a vertical spring with a spring constant k = 200 N/m, as shown in Figure 6.6. [EK 4.C.1; SP 2; SP 5]

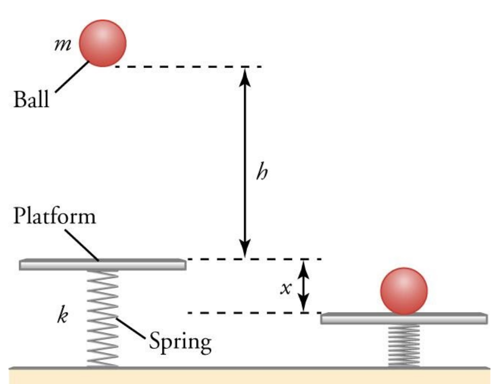


Figure 6.6

a. Given Table 6.2, listing measurements of the heights *h* for each compression *x* from this experiment, calculate the spring energy, PE_s, and plot it as a function of compression, *x*. Use g=10 m/s^2 to simplify calculations. What type of graph represents this relationship?

Table 6.2

h (cm)	*x* (cm)
2.0	2.0
6.0	3.0
12.0	4.0
20.0	5.0
30.0	6.0
42.0	7.0

b. Obtain the equation giving the spring energy in terms of compression, *x*, and spring constant, *k*. Show details of your calculations.

[Solutions]

1. [EK 4.C.1, EK5.A.2; SP 3]
   a. The expected drawing is shown in Figure 6.7.

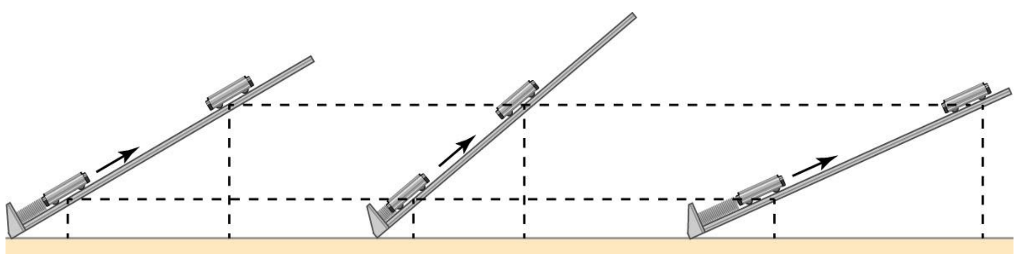


Figure 6.7

   b. Because friction is negligible, and the Earth-cart-spring system is closed, the mechanical energy of the system is conserved. Therefore, the mechanical energy of the system, which remains constant, is the sum of the spring potential energy, the kinetic energy of the cart, and the gravitational potential energy of the cart. Initially, all of this energy is in the potential energy of the spring. At the highest point, all the energy is in the gravitational potential energy of the cart. Because the initial spring energy is the same in all three cases, the final gravitational potential energy will also be the same. The gravitational potential energy depends on the height, not the slope, of the incline, and the final height is therefore the same for all three cases.

2. [EK 4.C.1; SP 2]
    a. If the compression of the spring is doubled to 4.0 cm from 2.0 cm, the initial height of the cart must have been four times higher, or 160 cm instead of 40 cm.
    b. If the compression of the spring is halved from 2.0 cm to 1.0 cm, then the initial height of the cart should decrease by a factor of 1/4, from 40 cm to 10 cm.
    c. According to the law of conservation of energy, the gravitational potential energy of the cart is transformed into the elastic potential energy of the spring, which is proportional to the square of spring compression.
3. [EK 4.C.1; SP 2; SP 5]. Based on the law of conservation of energy, the initial gravitational potential energy of the ball is transformed into the elastic potential energy of the spring.

    Therefore, $\mathrm{PE}_s = \mathrm{PE}_g = mg(h+x)$. The height needs to be converted to meters, and the mass needs to be converted to kilograms.
    a. Calculations are shown in Table 6.2. The graph in Figure 6.8 shows a quadratic relationship between the energy of the compressed spring and its compression.

Table 6.2

h (m)	PE_s (J)	*x* (m)
0.020	$(0.020\text{ m}+0.020\text{ m})\left(9.8\text{ m/s}^2\right)\left(0.100\text{ kg}\right) = 0.040\text{ J}$	0.020
0.060	$(0.06\text{ m}+0.030\text{ m})\left(9.8\text{ m/s}^2\right)\left(0.100\text{ kg}\right) = 0.090\text{ J}$	0.030
0.120	$(0.12\text{ m}+0.040\text{ m})\left(9.8\text{ m/s}^2\right)\left(0.100\text{ kg}\right) = 0.16\text{ J}$	0.040
0.200	$(0.20\text{ m}+0.050\text{ m})\left(9.8\text{ m/s}^2\right)\left(0.100\text{ kg}\right) = 0.25\text{ J}$	0.050
0.300	$(0.30\text{ m}+0.060\text{ m})\left(9.8\text{ m/s}^2\right)\left(0.100\text{ kg}\right) = 0.36\text{ J}$	0.060
0.420	$(0.42\text{ m}+0.070\text{ m})\left(9.8\text{ m/s}^2\right)\left(0.100\text{ kg}\right) = 0.49\text{ J}$	0.070

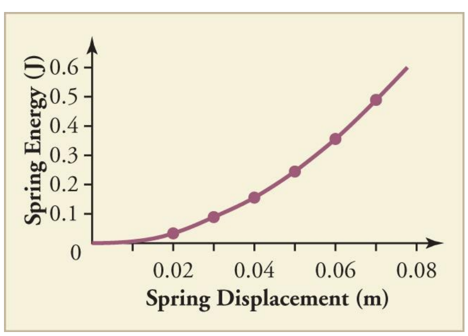


Figure 6.8

b. Because the relationship is quadratic, we can write $\mathrm{PE}_s = ax^2$. Calculating the value of coefficient *a* from the data leads to

$$a = \frac{0.04\ \mathrm{N}}{(0.02\ \mathrm{m})^2} = \frac{0.09\ \mathrm{N}}{(0.030\ \mathrm{m})^2} = \frac{0.16\ \mathrm{N}}{(0.040\ \mathrm{m})^2} = \frac{0.25\ \mathrm{N}}{(0.050\ \mathrm{m})^2} = \frac{0.36\ \mathrm{N}}{(0.060\ \mathrm{m})^2} = \frac{0.49\ \mathrm{N}}{(0.070\ \mathrm{m})^2} = 100\ \mathrm{N/m^2}.$$

c. The spring constant is 200 N/m, which suggests that $a = \frac{1}{2}k$. Substituting into the equation, we obtain the formula for elastic potential energy of the spring:

$$\mathrm{PE}_s = \frac{1}{2}kx^2.$$

Lab 7: Impulse and Momentum

When two objects collide in real life, the velocity and size of the object can both play important roles in determining the outcome of the collision. There are many more possible factors involved in collisions, but for this activity, you will focus on just the mass and the velocity of the objects in question.

There are two major concepts involved in analyzing the collision of two objects. The object's **momentum** is its mass times its velocity. When a force acts on an object, the **impulse** is the average force times the time it acts, which can be shown from Newton's second law to be the change in momentum the force produces. A change in momentum of an object requires a change in its velocity. Therefore, acceleration is also involved in the collision. In the first lab activity, you will determine the relationship between mass, velocity, and momentum. In the second lab activity, you will find the components of impulse.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- The students should know the difference between the different types of collisions: elastic, inelastic, and explosion.
- Students should be able to use projectile equations to predict the landing position of a projectile.
- Review potential and kinetic energy. If you have not discussed rotational kinetic energy, discuss with your students how a rolling object has translational kinetic energy and rotational kinetic energy. An energy diagram on the board may help students understand how energy is being transferred throughout the experiment.
- Students should know about the impulse of collisions and be able to relate the force of a collision to the time of impact. They should understand that shorter impact times lead to greater force, and longer impact times lead to a smaller force.

In this lab you will learn:

- how to predict the dynamic properties of an elastic collision using the principle of conservation of linear momentum and the principle of conservation of energy;
- to qualitatively predict, in terms of linear momentum and kinetic energy, how the outcome of a collision between two objects changes depending on whether the collision is elastic or inelastic.

Activity 1: Pre-Assessment

1. **Answer the following questions in your notebook**: What do you notice happens when objects collide (like car accidents and athletes colliding on the field) in terms of energy and direction of travel? How does this change if the objects have the same mass? What if they have different masses?
2. **Answer the following questions in your notebook:** Can you predict how various objects will move after a collision? What do you need to know about the objects to predict their motion? Why is this information important?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 1: Momentum

Just as objects with mass and velocity all have kinetic energy, they also all have momentum. One way to study this momentum is to observe how the objects transfer or lose that momentum during a collision. A fast change in momentum can cause serious harm to a living being, so learning about momentum helps us design machines, play sports more safely, and even understand future technologies that will allow for space travel.

Before you can perform calculations with momentum, however, you must first determine if the collision is elastic or inelastic. An **elastic** collision conserves internal kinetic energy; that is, no kinetic energy is lost or gained by the system. In an **inelastic** collision, the internal kinetic energy changes (it is not conserved). For the purposes of this experiment, we will assume our collisions are elastic.

Safety Precautions

- Marbles may create a hazard on the floor. Take precautions when moving around.

For this activity you will need the following:

- Two marbles of approximately the same size
- Track or wrapping paper tube
- Masking tape

For this activity, you will work *in groups of 2 to 3*.

Activity 1 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 1:

- It is best to complete this activity in groups of two or three so students can better observe everything that happens.
- The best results will occur when the ramp is smooth with the table, using a thin ramp, like a wrapping paper tube, will be closest to the table.
- Check students' equations before continuing on to Step 4; if this equation is not correct it will alter their results for the rest of the lab.
- Remind students to release the ball at the same position in Step 5; otherwise the speed of the ball will change and it will land in a different place.
- Before the guided inquiry activity, discuss the results of the structured activity so you can clear up misunderstandings before proceeding.

The following are recommendations for the Guided Inquiry for Activity 1:

- Complete this activity in groups of two or three so each student can observe, since the action happens very quickly.
- Make sure that the students' measurements for the horizontal distance are accurately measured; students can use a plumb line from the edge of the table to determine exactly where the ball is.
- Check students' calculations before allowing students to launch the marble. It may be best to keep the marbles and give the marbles to students after they have completed the calculations correctly.
- Carbon paper can be placed on the floor to help students track where the ball actually lands; the carbon paper will make a darker mark on the target where the ball lands the first time, but may make lighter marks on secondary bounces.

Structured Inquiry

Step 1: Find the mass of each marble given to you by your instructor. Set up the track so that it is held at a fixed angle, approximately 30°, with the second marble centered at the very bottom of the ramp, as illustrated in Figure 7.1. Make a drawing of the setup in your notebook.

Step 2: Calculate the velocity of the first marble right before it collides with the second marble, if it is released from rest at the top of the track. At a height, *h*, higher than the bottom of the ramp, the potential energy of the marble of mass, *m*, is $\mathrm{PE} = mgh$. At the bottom of the ramp, this potential energy has been converted into kinetic energy, given by $\mathrm{KE} = \frac{7}{10}mv^2$. The factor of $\frac{7}{10}$ in place of $\frac{1}{2}$ results from some of the kinetic energy of the rolling marble going into rotational motion. Equate the two energies and solve for the velocity of the marble at the bottom of the ramp in terms of its height at the top of the ramp.

Step 3: Obtain equations for the distance, *d,* from the end of the table to where it strikes the ground of the second marble in terms of the velocity, *v*. Record these equations in your notebook.

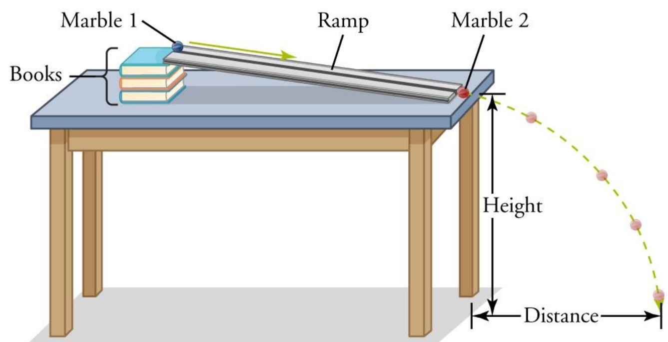


Figure 7.1: The setup shown will allow you to control the side-to-side movement of the marble and the initial energy of the system. Be sure to use more or fewer books to adjust the height in your own setup.

Step 4: Hypothesize/Predict: What will happen when the two marbles of equal mass collide at the bottom of the ramp? How do you think mass and velocity are related to momentum? Suppose the velocity of the first marble at the bottom of the ramp is transferred completely to the second marble. Use the kinematic equations to determine the horizontal distance the second marble will travel before it hits the floor. Add your predictions and calculations to your notebook. Create a data table to hold the values you recorded and calculated in this and previous steps.

Step 5: Student-Led Planning: Perform three trials of the experiment. Be sure to release the marble from the same height each time. Then change the angle of elevation of the ramp, calculate new velocities and distances, and perform three more trials at the new angle. Discuss with your partner how to minimize differences between trials.

Step 6: Critical Analysis: Using the data you have collected, derive an equation that relates the mass and velocity of both objects, just before the collision, to the mass and velocity of both objects just after the collision. Were the predictions you made in Step 3 supported by your data? Why or why not? What methods could you have used to improve your results? Why is the collision not perfectly elastic? Where is energy lost? Discuss these questions with your partner, and then write your answers in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: Your instructor will now mark a spot on the floor on a sheet of paper placed at the bottom of the ramp. With your partner, hypothesize an angle, and a 20° range of angles around it, at which you could set the ramp so that the second marble lands on the paper. Write your ideas in your notebook.

Step 2: Student-Led Planning: Using the formula you derived in Step 3 of the Structured Inquiry and your data, calculate the angle at which you would need to place the ramp to ensure the second marble lands within the edges of the paper. Write your results in your notebook.

Step 3: Critical Analysis: Was your team successful in landing your marble in the zone? If yes, how accurate was your predicted range for the angle of the ramp? Calculate the distances the marble would travel if the angle were at each end of your selected range. If not, recalculate and try again until you are successful, and, again, calculate the accuracy of your range. Discuss your answer with your partner and write it in your notebook.

Assessments

1. A student measures several variables during a collision between two objects of equal mass and gets these results: $v_{1i} = 10.0 \text{ m/s}, v_{2i} = 0, v_{1f} = 5.0 \text{ m/s}, v_{1f} = 5.0 \text{ m/s}$ [EK 4.B.1; SP 5.1]
   a. Calculate whether kinetic energy and momentum are conserved in the collision. Show all of your work.
   b. Does this scenario describe an elastic or inelastic collision? Explain how you know.
2. What happens to the kinetic energy lost in an inelastic collision? Since energy cannot be created or destroyed, what new form does the lost kinetic energy take? [EK 5.D.2; SP 7.2]
3. Would a person in a car colliding with a wall feel the change in momentum more when the car's acceleration is large or small? Why? [EK 3.D.2; SP 6.4]

[Solutions]

1. [EK 4.B.1; SP 5.1]
   a. $m_1 = m_2 = m$

Total momentum before:

$$mv_{1i} + mv_{2i} = m(10 \text{ m/s}) + m(0) = (10 \text{ m})m$$

Total momentum after:

$$mv_{1f} + mv_{2f} = m(5 \text{ m/s}) + m(5 \text{ m/s}) = (10 \text{ m})m$$

Total kinetic energy before:

$$\tfrac{1}{2}mv_{1i}{}^2 + \tfrac{1}{2}mv_{2i}{}^2 = \tfrac{1}{2}m(10 \text{ m/s})^2 + \tfrac{1}{2}m(0)^2 = (50 \text{ m}^2/\text{s}^2)m$$

Total kinetic energy after:

$$\tfrac{1}{2}mv_{1f}{}^2 + \tfrac{1}{2}mv_{2f}{}^2 = \tfrac{1}{2}m(5 \text{ m/s})^2 + \tfrac{1}{2}m(5 \text{ m/s})^2 = (25 \text{ m}^2/\text{s}^2)m$$

   b. The experiment describes an inelastic collision because momentum is conserved but kinetic energy is not conserved.
2. [EK 5.D.2; SP 7.2] It is converted to other forms of energy, such as sound and thermal energy.
3. [EK 3.D.2; SP 6.4] The passenger would feel a smaller momentum change if the collision involved a smaller acceleration. This is because the velocity change would be smaller over the time of collision. Because the change in momentum equals the object's mass times its change in velocity, the momentum change would be smaller than if the car's acceleration were smaller.

Activity 2: Pre-Assessment

1. **Answer the following questions in your notebook**: Using the outcome of Activity 1, what can affect the motion of objects after a collision? What parts of a collision can we control when designing a bumper?
2. **Answer the following questions in your notebook:** Think about at least three different styles of bumpers you have seen on automobiles. Explain several advantages and disadvantages to each design.
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 2: Bumper Design

How do car bumpers work to save the passengers of a car? Have bumper designs changed over the course of automotive history? Look at the pictures provided here in Figure 7.2 and think about the bumpers you have seen on cars and trucks. What makes them different? How are they the same? Now that you are thinking about momentum and how bumpers are designed, work with a partner to brainstorm how momentum, and the related concept of impulse, is involved in bumper design and car safety.

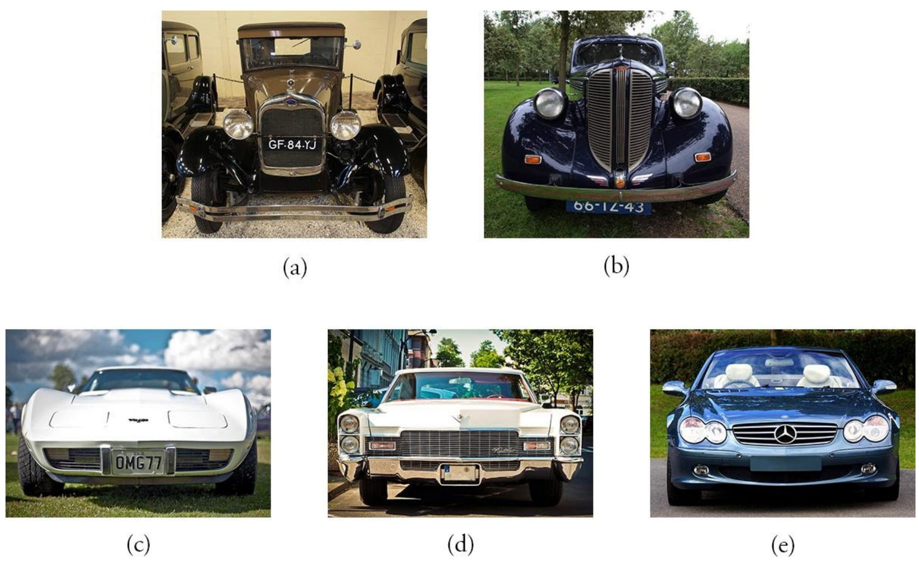


Figure 7.2: Car bumpers have changed over time and come in many shapes, styles, and materials.

Safety Precautions

- Keep the cart under control at all times. Also, do not leave the cart on the floor when not in use or anywhere else where someone could fall because of it.

For this activity you will need the following:

- Cart
- Tape
- Paper
- Force sensor

For this activity, you will work *in pairs*.

Activity 2 Instructor Preparation and Teaching Tips

The following are recommendations for the Guided Inquiry for Activity 2:

- It is best to do this in pairs so each student can contribute; working in pairs also allows students to brainstorm together and come up with more ideas than if they were working alone.
- Make sure bumpers are securely attached to their vehicles before testing in order to get the best results from the force sensor.
- Review Newton's Third Law, which explains that the force applied to the bumper is equal to the force measured by the force sensor but will be the opposite direction. Since the measured force is in opposite directions, the sensor may show a negative force depending on how the force sensor is set up.
- Set up the force sensor to be stationary at the end of the track, so when the student pushes the car the bumper hits the stationary sensor in the correct location.
- As students are building their bumpers, check that the height of the bumper is appropriate to hit the force sensor. If the bumper does not hit the force sensor, you will not be able to test the force applied to the car.
- Popsicle sticks and rubber bands are also good materials to use. Since popsicle sticks do not bend, they will not work as well as a bumper. However, the use of a variety of materials can stem good classroom discussion of the different advantages and disadvantages of each.
- To add a variety, you can require each pair to use a different set of materials.
- After discussing the best designs for bumpers, you can show videos of crash testing for older cars and newer cars and discuss the benefit of crumple zones and airbags. In today's cars the bumper is only part of what protects the passengers in the event of an accident. All of these safety features lead to a longer impact time which decreases the force on the passengers.

Guided Inquiry

Step 1: Hypothesize/Predict: How do you think the shape of the bumper and the material it is made of determine how it functions during a collision? Using the formulas you derived in the first activity, think about what elements of the collision you can control by designing your own bumper. Write your ideas in your notebook.

Step 2: Student-Led Planning: Choose materials from those provided by your instructor to create a bumper for your cart. Work in pairs to develop and test your bumper designs using the force sensors. Attempt to keep all variables constant except the design of your bumper. Try to design the bumper so it would minimize the forces encountered in bringing the moving object they are mounted on to a stop. Write your results in your notebook.

Step 3: Critical Analysis: Which bumper designs worked best in their apparent ability to bring a moving object they are mounted on to a stop with the least force? What could have been improved? How could other materials, that you know of that were not provided, have helped you to design a more effective bumper? Discuss your answer with your partner and write it in your notebook.

Assessments

1. The impulse in a collision can be calculated as the average force that acts times the time it acts. What quantities that go into this calculation can be controlled in a collision? [EK 3.D.2; SP 7.2]
2. What aspect(s) of a collision are modern bumpers designed to change to reduce the impulse felt? [EK 3.D.2; SP 6.4]
3. Explain how an airbag works. What concept related to Newton's first law of motion causes the person to hit the airbag when a collision occurs? [SP 7.2]

[Solutions]

1. [EK 3.D.2; SP 7.2] Both the time of impact and the force (determined by mass and acceleration) can be controlled in a collision.
2. [EK 3.D.2; SP 6.4] Modern bumpers reduce the time over which the force acts, so the average force required to reduce the momentum to zero becomes smaller.
3. [EK 5.D.2; SP 7.2] An airbag works by cushioning the body of the passenger, thereby increasing the time required to stop your body from moving forward. The body is moving forward due to inertia under Newton's first law of motion, which says that an object in motion stays in motion, so it tends to continue traveling at the original velocity of the car.

Lab 8: Conservation of Momentum

The **momentum** *p* of an object of mass *m* moving at velocity $\vec{\mathbf{v}}$ is its mass times its velocity, or

$$p = mv \ .$$

Speed is distance traveled along a path divided by the time of travel and has no particular direction. Velocity, in contrast, is the displacement an object undergoes in the direction of motion divided by the time required and is a vector in the direction of the object's motion. The momentum is therefore also a vector in the direction of the object's motion. For motion in one direction along a straight line, we can keep track of directions of vectors by giving the vector quantity a plus sign if it points in one direction and a minus sign for the opposite direction. The SI unit of momentum is $\mathrm{kg \cdot m/s}$, although other units, such as gram-centimeter/second $(\mathrm{g \cdot cm/s})$, may also be used.

The **law of conservation of momentum** states that in a closed system, with no net forces acting from outside the system, the total momentum of the objects within the system remains the same. Therefore, the total momentum after a collision of two objects is the same as it was before the collision.

The kinetic energy of an object is the energy the object has because of its motion. For example, an apple falling from a tree has kinetic energy as long as it is in motion. When it reaches the ground and stops, its kinetic energy is transformed into another form of energy. By having kinetic energy, a moving object has the capacity to do work. For example, if the falling apple strikes another object, it can exert a force and move the second object an additional distance. Therefore, the apple does work on the second object and transfers energy. The kinetic energy of an object of mass *m* moving at speed *v* is

$$\mathrm{KE} = \tfrac{1}{2} m v^2$$

and is proportional to the mass *m* and the square of its speed *v*. The unit of kinetic energy is the joule, which is equal to 1 $\mathrm{kg \cdot m^2/s^2}$. Although the total energy of a closed system is always conserved, the same is not necessarily true for kinetic energy considered alone. Very often, kinetic energy is converted into other forms, such as thermal or potential energy, with the total energy staying the same. In this activity, you will examine the roles of momentum conservation in predicting how objects move after colliding, and how conserving or not conserving kinetic energy affects the outcome of a collision.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- Be sure to emphasize that the conservation of momentum has its own expression that connects the base equation to the concept of conservation. Specifically, when two objects are involved (1 & 2) their total momentums before (B) a collision are added together and set equal to their total momentums after (A) a collision
    - $m_1 * v_{1B} + m_2 * v_{2B} = m_1 * v_{1A} + m_2 * v_{2A}$
- A similar expression can be developed for the conservation of kinetic energy.
- Have a discussion about *where does the energy go* if the KE before is greater than the KE after; but conservation says you cannot destroy the energy you started with.
- Since large objects are being used for the experiments, there should be a discussion about center of mass.
- Reinforce the idea that it is the mass and velocity that are important in momentum calculations NOT mass and acceleration (as used in forces).
- Be careful about the types of lab carts used. Many have both a Velcro bumper and a magnetic bumper. As such, magnet/magnet collisions would presume to be elastic, Velcro/Velcro collisions would be perfectly inelastic (collide and stick) and magnet/Velcro would simply be inelastic.

In this lab you will learn:

- how to determine if momentum is conserved during an elastic collision when a moving object collides into a stationary object of the same mass;
- how to determine if momentum is conserved during an inelastic collision when a moving object collides with another object and comes to a complete stop;
- how to determine if momentum is conserved during an elastic collision when a moving object collides with other moving objects of different masses. Use a velocity-time graph to find out the time of the collision.

Activity 1: Pre-Assessment

1. **Answer the following questions in your notebook**: What do you think might happen to the kinetic energy and momentum of one toy car that collides with another toy car in its path? Does the momentum of the first car change because of the collision? Does the momentum of the second car change because of the collision? Does the kinetic energy of the first car change because of the collision? What about the kinetic energy of the second car?
2. **Answer the following questions in your notebook.** Think of ways to measure the time taken by the car to travel from one end of the table to another. Think of ways to measure the distance traveled by the car before and after the collision.
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 1: Elastic Collision

In most collisions, we assume there are no net forces acting from outside the system, and the total momentum is the same before and after the collision. An **elastic collision** is one in which the total kinetic energy is also unchanged by the collision. Billiard balls provide a good example. When billiard balls collide, the total momentum after the collision is the same as the total momentum before the collision. Even though one of the balls may slow down after the collision, thereby decreasing its own kinetic energy, this is almost entirely because it transfers kinetic energy to the other ball, which then travels with increased kinetic energy and momentum. We can take the total kinetic energy of both billiard balls to be unchanged, making it an example of a **perfect** or **near-perfect elastic collision**.

Safety Precautions

- Inform your teacher immediately of injuries caused by moving objects.
- Clean up and inform your teacher immediately about any broken objects to prevent people from being injured.
- Objects that can roll are hazardous to step on unexpectedly. If the floor is used to roll the carts, immediately remove any cart that rolls out of the temporary test area of the floor.

For this activity you will need the following:

- A rectangular table with a flat surface where the length of the table is longer than the width, or a large, clear floor surface
- Two lab carts of different mass
- One ruler
- Lab scale
- Three chalk pieces of different colors
- Three stopwatches, numbered 1–3, or video camera to record the actions

For this activity you will work *in pairs if using a video camera***,** or *groups of four if using stopwatches*.

Activity 1 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 1:

- Stress that the velocities needed are those immediately before and after the collision, not average velocities. In particular, waiting too long after a collision to take a velocity reading will result in an unusable value, as the object(s) will have slowed down.
- Discuss aspects that could affect the final conservation comparison—that the before momentum is not the same as the after momentum.
- Discuss whether the table or floor being level matters. Bait the students by inferring that since a before and after measurement is taken, that the effect *could* cancel out.
- Are there sports that exhibit examples of momentum?
- As a final follow-up, challenge the students to find two objects at home that collide elastically and bring these objects to the classroom.

The following are recommendations for the Guided Inquiry for Activity 1:

- Start by having the students predict and test the after motion of two carts of identical mass. This information coupled with the previous activity will allow for a more informed prediction for the current activity.
- Are there any situations where the energy after is greater than the energy before?
- Again, caution should be taken based on which types of bumpers are interacting during these activities. Allow the students to try different combinations (if possible) to see if the results change.

Structured Inquiry

Step 1: The idea behind this experiment is to compare the total momentum after a collision with the total momentum before a collision by colliding one moving cart into a second cart at rest. You will determine the initial and final velocities of both carts to calculate the momentum of each cart. You will also use the data you collect to calculate and compare the initial and final kinetic energies.

To measure the velocity of each cart before and after the collision, place chalk marks on the table, one a short distance after the place where the first cart will be released, another where the second cart is at rest, and the third a distance after that. The chalk lines are distance markers for pressing the stopwatch as a cart passes the line. If stopwatches are used, choose one student to be in charge of each stopwatch and one in charge of setting the cart into motion. If a video camera is used, two lab partners can divide the tasks.

Step 2: Hypothesize/Predict: Predict what happens to the velocities and momenta of the two colliding carts when the first cart collides with a second cart of smaller mass in its path. In which direction do you predict each cart will move after the collision? What might happen to the velocity and momentum of the first colliding cart? What might happen to the velocity and momentum of the second colliding cart? What would be the total momentum of the two colliding carts before and after the collision? Will the total momentum be exactly the same or only approximately the same? Add your predictions to the data table you create.

Step 3: Weigh each colliding cart to determine its mass. For this experiment, the first cart should have greater mass than the second. If a video camera is not available, follow the steps below: Draw a chalk line that the first cart will cross after it has been pushed and is rolling on its own. Place the second chalk line where the stationary cart is located, and the third chalk line a distance after that.

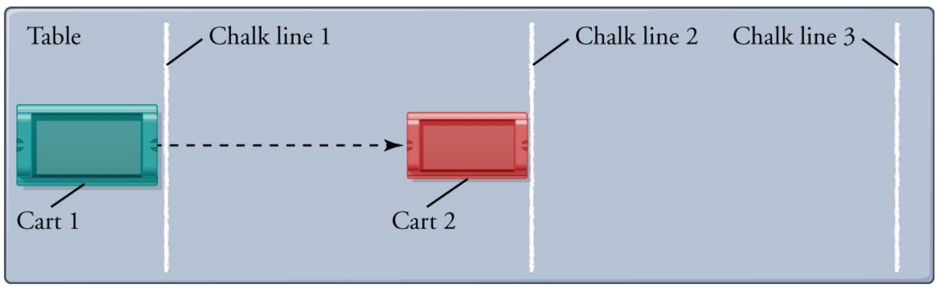


Figure 8.1: Arrangement for using stopwatches to measure the velocities and momenta of a more massive cart colliding elastically with a less massive cart.

Step 4: Student-Led Planning: What data will you need to find the velocity and momentum of each cart? How exactly will you measure the quantities needed, and calculate the intended results from the data collected? Discuss with your lab partner or partners, and describe your proposed method in your notebook. After you have collected your data, you will want to calculate the total kinetic energy of the carts before collision to compare with the total kinetic energy after collision. Describe in your notebook how you will use the data already collected to make that comparison. Decide on the positions of the student timing each part of the motion or operating the video recorder.

Step 5: Use the scale to determine the mass of each cart, and enter the masses into your notebook. Carry out your measurements for the case of a more massive cart colliding into a less massive one at rest. Determine the time and distance of travel for each cart before and after collision to find the velocity and momentum of each cart before the collision and of each cart after the collision. Record your data in the table created in your notebook.

Step 6: Critical Analysis: Based on the observations and calculations in your data table, were the predictions you made in Step 3 supported by your data? Why or why not? How did the total momentum of the two carts before collision compare with the total momentum of the two carts after collision? How accurate were your predictions about the directions in which the carts would move after collision? What methods could you have used to improve your results? Discuss with your partner and then write your answers in your notebook.

Step 7: Critical Analysis: Use your data to calculate the kinetic energy each cart had before collision and the kinetic energy each cart had after collision. How did the kinetic energy of each cart change? Calculate the total kinetic energy of both carts before collision, and the total kinetic energy after collision. Compare how well momentum was conserved with how well kinetic energy was conserved. Discuss with your lab partners and write your answers in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: How do you think the results of the collision would be different if the less massive cart struck the more massive cart at rest? How do you think the directions and relative sizes of the velocities of the two carts after collision would depend on which has the larger mass? Write your ideas in your notebook.

Step 2: Student-Led Planning: How would you design an experiment to measure the total momentum before and after the collision? List the objects and lab equipment that you would need to conduct your experiment. Describe how you would measure important values, and what you would calculate from the collected data. Submit your list and research plan to your teacher. Once your teacher approves, carry out your experiment. Collect your data in your notebook, and determine the velocities, momenta, and total momentum before and after collision. Write your results in your notebook.

Step 3: Critical Analysis: What differences did you notice when the less massive object was moving and struck a more massive stationary object? Did the results confirm your predictions? How well was total momentum conserved? Discuss your answers with your partner and write them in your notebook.

Step 4: Critical Analysis: Determine if your data shows conservation of total kinetic energy. Explain any significant loss or gain of kinetic energy that you found. Discuss your answers with your partner and write them in your notebook.

Assessments

1. A student records the distance traveled by object 1 as 10 cm before and 15 cm after the collision, and the time before and after the collision as 5.0 seconds each. If the 2 objects have a mass of 1.0 g each: [EK 5.D.1; SP 3]
    a. Does this scenario describe a loss in kinetic energy for object 1 after the collision? Why or why not?
    b. Does this scenario describe a loss in momentum for object 1 after the collision? Why or why not?
2. How is the kinetic energy of an object changed if its momentum increases? [EK 5.D.2; SP 3]
3. In an elastic collision, the total momentum of two objects before the collision is $20\ \mathrm{g \cdot cm/s}$. The mass of the first object is 2.0 g, and its velocity is $5.0\ \mathrm{cm/s}$ after the collision. [EK 5.D.3; SP 3]
    a. What should be the total momentum of the two objects after a perfectly elastic collision?
    b. What is the momentum of the first object after the collision?

[Solutions]

1. [EK 5.D.1; SP 3]
    a. No, this scenario does not describe a loss in kinetic energy for object 1 after the collision. Kinetic energy before collision is

    $$\mathrm{KE}_i = \tfrac{1}{2} m v_i^2 = \tfrac{1}{2}(1.0\ \mathrm{g})\left(\frac{10\ \mathrm{cm}}{5.0\ \mathrm{s}}\right)^2 = 2.0\ \mathrm{g \cdot cm^2/s^2}$$

    Kinetic energy after the collision is

    $$\mathrm{KE}_f = \tfrac{1}{2} m v_f^2 = \tfrac{1}{2}(1.0\ \mathrm{g})\left(\frac{15\ \mathrm{cm}}{5.0\ \mathrm{s}}\right)^2 = 4.5\ \mathrm{g \cdot cm^2/s^2}$$

    So the kinetic energy of object 1 after the collision is greater.

    b. No, this scenario does not describe loss in momentum for object 1 after the collision.

    Momentum before the collision = $(1.0\ \mathrm{g})\left(\frac{10\ \mathrm{cm}}{5.0\ \mathrm{s}}\right) = 2.0\ \mathrm{g \cdot cm/s}$

    Momentum after the collision = $(1.0\ \mathrm{g})\left(\frac{15\ \mathrm{cm}}{5.0\ \mathrm{s}}\right) = 3.0\ \mathrm{g \cdot cm/s}$

    So the momentum of object 1 after the collision is greater.

2. [EK 5.D.2; SP 3]
    The kinetic energy increases, because momentum is proportional to velocity while kinetic energy is proportional to velocity squared.

3. [EK 5.D.3; SP 3]
    a. The total momentum of the two objects in a perfectly elastic collision should be $20\ \text{g}\cdot\text{cm/s}$.
    b. The momentum of the first object after the collision is $(2.0\ \text{g})(5.0\ \text{cm/s}) = 10.0\ \text{g}\cdot\text{cm/s}$.

Activity 2: Pre-Assessment

1. **Answer the following questions in your notebook**:
   What do you think might happen to the kinetic energy and momentum of a slowly moving train car when it meets and latches onto another train car that is free to roll but not moving? Do the momentum and velocity of the first car change because of the collision? How? Does the total momentum of both cars change because of the collision? Does the kinetic energy of the first car change because of the collision?
2. **Answer the following questions in your notebook.** Think of how you can measure the kinetic energy and momentum of a small cart as it moves across the floor after it is pushed and released.
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 2: Inelastic Collisions

A perfectly **inelastic collision** occurs when two colliding objects stick together after a collision. One example of an inelastic collision is putty striking a wall. Upon hitting the wall, the putty stops and gets stuck. Both the momentum and kinetic energy it had have been reduced to zero. In this case, neither kinetic energy nor momentum is preserved. Most everyday collisions are inelastic (though not *perfectly* inelastic) because the kinetic energy of the colliding objects are converted into other forms of energy, such as that associated with producing sound.

Safety Precautions

- Inform your teacher immediately of injuries caused by moving objects.
- Clean up and inform your teacher immediately about any broken objects to prevent people from being injured.
- Avoid allowing any objects, especially those capable of rolling, to remain on the floor outside of the area being used for testing, to avoid anyone slipping and falling on them.

For this activity you will need the following:

- A rectangular table with a flat surface where the length of the table is longer than the width, or a large, clear floor surface
- Two lab carts with hook-and-loop fastener tape attached, or a mechanical clip, so that they stick together after collision
- A video camera to record the experiments, or a stopwatch
- One ruler
- Lab scale
- One chalk piece
- Two stopwatches

For this activity you will work *in pairs*.

Activity 2 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 2:

- Is it possible for an object to have more energy than when it started?
- Is a car crash an example of an elastic or inelastic collision?
- Do the two carts have to stick together to be an inelastic collision?
- Could an insect fly fast enough, crash into, and stop a bowling ball moving towards it?
- As a final follow-up, challenge the students to find two objects at home that collide inelastically and bring these objects to the classroom.

The following are recommendations for the Guided Inquiry for Activity 2:

- Have the partners apply conservation of kinetic energy to equate the before and after expressions. Have them predict the relative size of the KE-before vs. the KE-after. Have these values calculated and discussed after the final velocity information has been gathered.
- Would the conservation of momentum/KE work out any differently if the carts have equal mass?
- Would the conservation of momentum/KE work out any differently if both carts were moving before the collision (eg., toward each other)?

Structured Inquiry

Step 1: We will now examine what happens in a perfectly inelastic collision, when one moving cart collides into another at rest with the same mass, and the two stick and move together. To do this, you will need to measure the velocity of the moving cart before colliding and the velocity of the two carts together after colliding.

Step 2: Hypothesize/Predict: When a moving cart collides into another of the same mass at rest, and the two stick together, do you predict that the total momentum will be conserved in the collision? How about the total kinetic energy? How will the velocity of the two carts moving together compare with the velocity the one cart had when it was moving? Discuss your predictions with your partner and write them in your notebook.

Step 3: Weigh each colliding cart to determine its mass in grams. For this experiment, both colliding carts should have the same mass. Assure that patches of hook-and-loop fastener tape, or a mechanical clip mechanism, are in place on the two carts so they will stick together upon collision.

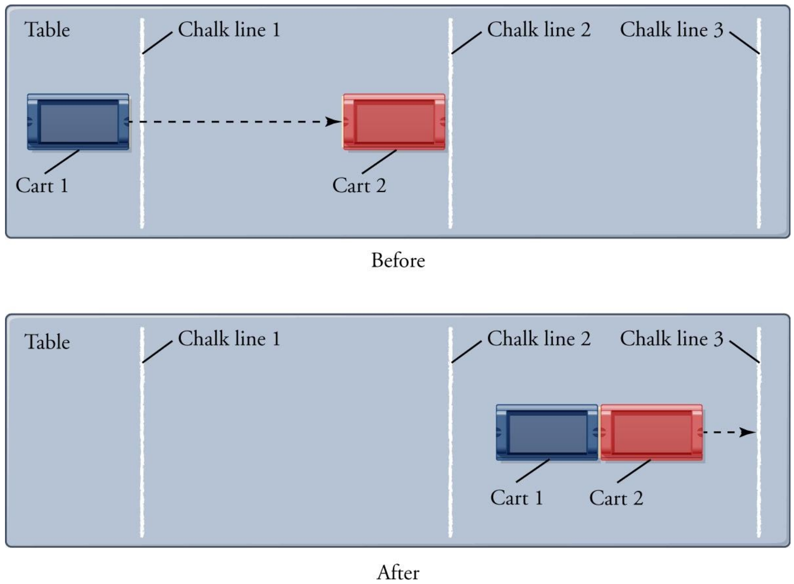


Figure 8.2: Arrangement for using stopwatches to measure the velocities and momenta of two carts undergoing a perfectly inelastic collision.

Step 4: Student-Led Planning: Discuss with your lab partner how you will collect data to determine the velocity of the single moving cart and then of the two carts moving together after collision. Place the second cart in the path of the first cart. Start the video camera and record the entire experiment. If you do not have a video camera, you will use stopwatches to measure the times of travel and the distances between three chalk lines drawn for this purpose. The first chalk line should be at a location where the first cart is moving but no longer being pushed, the second at the collision point, and the third a distance after the collision point. Record your data in your notebook. Calculate the initial velocity of the first cart and the final velocity of the two carts. Then calculate the total momentum before and after the collision.

Step 5: Critical Analysis: Based on the observations and calculations in your data table, were the predictions you made in Step 3 about the initial and final velocity supported by your data? Does your data support the law of conservation of momentum? Explain any causes you can think of for any observed disagreement. What methods could you have used that would improve your results? Discuss with your partner and then write your answers in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: How do you think the results of the inelastic collision experiment would differ if the collision were between carts of unequal mass? Write a mathematical expression for the total momentum of Cart 1 and Cart 2 if Cart 1 has mass m_1 and velocity $\boldsymbol{v}_{1i}$ and Cart 2 has mass m_2 and is not moving. Then write an expression for the total momentum of Cart 1 and 2 stuck to each other and moving together at velocity $\mathbf{v}$. Work with your partner to apply conservation of total momentum to equate the two expressions and to solve the equation that results to predict the final velocity in terms of the initial velocity and the two masses. Write your derivation and prediction in your notebook.

Step 2: Student-Led Planning: Discuss with your partner how to test your prediction by collecting velocity data using methods and equipment from this lab. Carry out the experiment, and enter the masses and measured velocities in a data table in your notebook.

Step 3: Critical Analysis: Use your mass and velocity data in the expression for the final velocity you derived in Step 1 to find a numerical value of the predicted velocity. How well does your prediction compare with your measured final velocity of the two carts moving together? Comment on any reasons you can think of for any substantial disagreement. How could you improve the accuracy of your data? Discuss your answers with your partner and write them in your notebook.

Assessments

1. A student records data about a collision between two objects. Object 1 travels a total of 2 seconds before the collision while object 2 travels 5 seconds before the collision. If both objects have the same mass and object 1 traveled 10 cm and Object 2 traveled 25 cm before the collision, [EK 21.1a; SP 3]
    a. Does this scenario describe object 1 with greater momentum than Object 2 before and after the collision? Why or why not?
    b. Does this scenario describe object 2 with greater kinetic energy than Object 1 before and after the collision? Why or why not?
2. Is it possible for an object to have momentum but not kinetic energy, or kinetic energy without having momentum? [EK 21.1a; SP 3]
3. In an inelastic collision, where a ball hits a wall, the total momentum of the ball before the collision is $10 \text{ g}\cdot\text{cm/s}$. [EK 21.1a; SP 3]
    a. If this collision is inelastic, will the momentum of the ball after the collision be the same, greater, or lesser?
    b. What is the momentum of the wall after the collision?

[Solutions]

1. [EK 21.1a; SP 3]
    a. No, this scenario does not describe object 1 with greater momentum than object 2 before the collision.

       Object 1 momentum before the collision $= mv = \left(\frac{10.0 \text{ cm}}{2.0 \text{ s}}\right)m = (5.0 \text{ cm/s})m$

       Object 2 momentum before the collision $= mv = \left(\frac{25.0 \text{ cm}}{5.0 \text{ s}}\right)m = (5.0 \text{ cm/s})m$

    b. No, this scenario does not describe object 1 with greater kinetic energy than object 2 before the collision.

       Object 1 kinetic energy before the collision = $= \frac{1}{2}mv^2 = \frac{1}{2}\, m\left(\frac{10.0 \text{ cm}}{2.0 \text{ s}}\right)^2 = (2.0 \text{ cm/s})m$

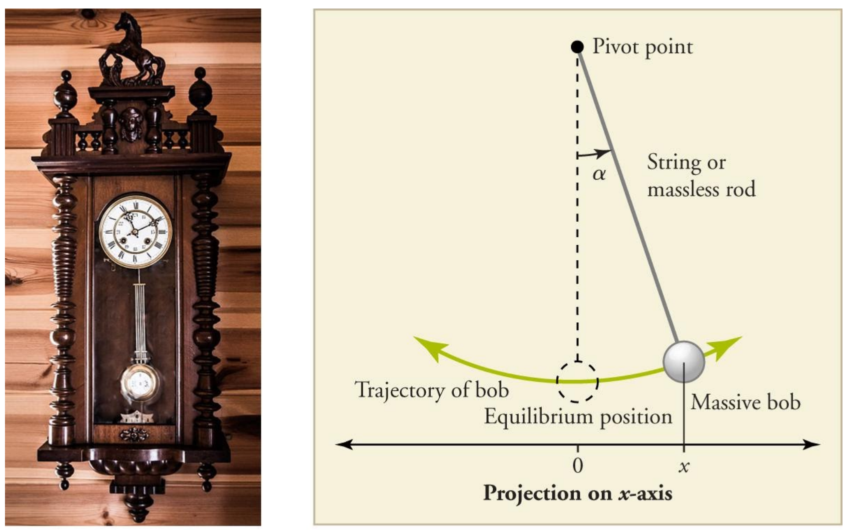
       Object 2 kinetic energy before the collision $= \frac{1}{2}mv^2 = \frac{1}{2}\, m\left(\frac{25.0 \text{ cm}}{5.0 \text{ s}}\right)^2 = (2.0 \text{ cm/s})m$

2. [EK 21.1a; SP 3] No. To have either momentum or kinetic energy, the object must have nonzero velocity, and since the object also has mass, having nonzero velocity means it has both momentum and kinetic energy.

3. [EK 21.1a; SP 3]
    a. In an inelastic collision, the momentum of the ball after the collision will be less than the momentum before the collision.
    b. The momentum of the wall after the collision is 10 $g \cdot cm/s$ because the wall would not move after the collision and so its velocity is zero. Momentum is the product of mass and velocity, so if velocity is zero, momentum is zero also.

Lab 9: Simple Harmonic Motion

An oscillation is a repeating change in the state of a system. For example, it can be a repeating physical motion of a body. We are surrounded by oscillations every day. The back and forth motion of a pendulum is one example. A grandfather clock, a playground swing, an old-fashioned metronome, and many other devices use pendulums. A pendulum consists of a weight (bob) attached to a much lighter string or a rod that can swing back and forth. The bob can be considered a mass point, because its size is much smaller than the length of the string. It is a simple device that can be described mathematically. This mathematical description is the basis for describing more complex oscillating systems, such as the motion of a car on a bumpy road or the beating of a heart. This makes it very useful for us to study a simple pendulum in this lab.



(a) (b)

Figure 9.1: A clock with a pendulum. Each oscillation of the pendulum occurs with the same time period. This allows the clock to keep time.

The motion of a simple pendulum is an example of simple harmonic motion. In a simple harmonic motion, the returning force on the system is directed to move it toward the equilibrium, and the magnitude of this force is proportional to the displacement from equilibrium. The position of the system is following the sine or cosine function. For example, the angle □that the string of a simple pendulum is making with the vertical changes as

$$\alpha(t) = \omega t + \phi \; .$$

(1)

where t is the time, □□ is the angular frequency (the number of full oscillations per unit time times 2π), and □ is the initial phase of the motion (the angle that specifies the position of the bob at time t = 0). The projection of position of the bob on the horizontal x-axis can also be used to describe the motion as

$$x = A \cdot \sin(\omega t + \phi) \quad ,$$

(2)

where A describes the amplitude of the pendulum. If the pendulum is at equilibrium (the position where the restoring force on the system is equal to zero) at time t = 0, then the position of the bob follows a simple sine dependence on time

$$x = A \cdot \sin(\omega t).$$

(3)

The time T for an oscillating system to return to its original position and velocity after a full oscillation cycle is its **period**. If we observe the pendulum at position x at any time t, it will return to the same position and will have the same velocity and acceleration at times $t + T$, $t + 2T$, $t + 3T$, etc. For small amplitudes, the period of a simple pendulum can be found as

$$T = 2\pi \sqrt{\frac{L}{g}} \quad ,$$

(4)

where L is the length of the pendulum string, and g is the acceleration due to gravity (approximately 9.8 m/s^2) at the surface of Earth.

By measuring the value of the period we can calculate the values of the parameters that the period T depends on. The period can be measured using a stopwatch to time how long the pendulum takes for a complete cycle of motion (e.g., from the far right to the far left and back). Averaging over several measurements of T helps to reduce the effect of measurement errors, and measuring the total time over many cycles of motion and dividing by the number of cycles reduces error from judging the time when the swing begins and stops.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- The students should be familiar with a number of background concepts: oscillations, period and frequency of oscillations, angular and trigonometric function and how they relate to periodic mechanical motion. This material should be briefly reviewed on the board, using simple examples, at the beginning of the lab.
- The students should be familiar with using abstract models to describe real physical systems, such as a point mass on a massless string as a model for a real pendulum. The key in building and applying such models is in understanding what influences are

important in describing the system at hand. Simple examples should be presented on the board and briefly discussed.

- It also should be discussed how disregarded, secondary influences can still affect the accuracy of the model and the conclusions.
- The students should be asked questions in the course of this discussion, but the most beneficial way would be to ask the students to introduce the concepts and the equations and to lead the discussion.
- It is important to talk briefly about the significance of making accurate and precise measurements, as well as what the difference is between accuracy and precision. The procedure for finding averages and average deviations should be discussed.

In this lab you will learn:

- how to predict what properties determine the motion of a simple harmonic oscillator and explain the dependence of the motion on these properties;
- how to design, plan, and carry out experiments that let us describe a simple harmonic motion and find its quantitative characteristics;
- how to measure simple harmonic motion and analyze data to find relationships between the properties of simple harmonic motion, as well as, determine unknown properties from the measured data.

Activity 1: Pre-Assessment

1. **Answer the following questions in your notebook:** What properties of a simple pendulum might possibly determine the period of the pendulum oscillations?
2. **Answer the following questions in your notebook:** What experiments can you design to check which of these properties affect the period *T* and which properties do not matter?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 1: Measuring the Period of a Simple Pendulum

The **period** of oscillation is the amount of time for the oscillating system to return to the state (position and velocity direction) that it had at the beginning of the observation. In this activity, we will measure the period of several pendulums using a stopwatch. The pendulums will differ in the mass of the bob and the length of the string. We will need to make several measurements for each pendulum to reduce the uncertainty in the results.

Safety Precautions

- Be careful when swinging weights used in a pendulum so that they do not hit anyone or anything in the classroom.

For this activity you will need the following:

- String
- Set of calibrated masses
- Stopwatch or timer
- Meter stick
- Protractor
- Support rod

For this activity you will work *in pairs.*

Activity 1 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 1:

- This activity is relatively easy to perform. The students should take turns making the practice measurements before they proceed to the runs that will be used to record the results.
- It should be discussed what the precision of the measurements will be and how many significant digits need to be recorded.

The following are recommendations for the Guided Inquiry for Activity 1:

- The students should repeat measurements to obtain acceptable averages. They should present their estimates of the final average error bars to the instructor before concluding this activity.

- The students should be encouraged to recall the background information given in the beginning of the lab session (and at the beginning of this module in the book) as they are analyzing the results.

Structured Inquiry

Step 1: Build a pendulum by attaching the string to the mass and mounting the other end of the string onto a rigid nonmoving support. Then measure and record the length of the string and the mass of the pendulum bob in your notebook.

Step 2: Hypothesize/Predict: What properties of the pendulum created in Step 1 will increase or decrease its period *T*? Record your answers in the notebook.

Step 3: Student-Led Planning: You will now measure the period of the pendulum. Instead of trying to time one swing, time how long the pendulum takes to make at least 10 swings. Then divide the measured time by the number of swings to get the time for one complete swing. A complete swing is one cycle of motion from one side to the other and back. Discuss with your partner the best way to make these measurements. Measure the time at least three times and use the average of the three measurements.

Step 4: Repeat your experiment using at least two other pendulums with two different bob masses and two different lengths of string. Record the length of the string, mass of the period, and the resulting period values for each pendulum.

Step 5: Critical Analysis: In Step 2, did you accurately predict the factors that affected the pendulum period? Why or why not? How did taking multiple trials reduce error in your measurements of the periods? Record your findings in the notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: Do you think the mass of the bob or the length of the string of a simple pendulum determines the period *T* of its oscillations? Does the initial angle have any effect on *T*? What other factors might possibly influence the period? Write your ideas in your notebook.

Step 2: Now, pick five masses to be used as the pendulum bobs. Build a pendulum with each of the masses. Using the stopwatch or timer, determine the period of oscillation for each pendulum as in the structured inquiry above.

Step 3: Student-Led Planning: Now, test the same pendulums you created in Step 2, but change the initial angles of the pendulum. Use values of the initial angle between approximately 10° and 40°. Record the new pendulum periods in a new data table within your notebook.

Step 4: Finally, use the same mass of the bob with five different lengths of string and measure the period *T* for each. Record the new pendulum periods in a new data table within your notebook.

Step 5: Critical Analysis: Which of the tested factors or properties determined the period *T* of the pendulum oscillations? Discuss your answer with your partner and write it in your notebook.

Assessments

1. A student builds a pendulum with a 100 g bob and a 30 cm string. Then the student measures the period of the pendulum oscillations starting from the initial displacement of 10°, 20°, 30°, and 40°. The period values are found to be 1.2 s, 1.2 s, 1.3 s, and 1.3 s. [EK 3.B.3; SP 2.2, SP 5.1]
    a. Does the value of the initial displacement significantly affect the length of the period?
    b. Does this scenario fit the model of a simple pendulum with a point mass and massless string if the mass of the string is 1.0 g and the diameter of the bob is 2.0 cm? Why or why not?
2. What does the accuracy of a measurement indicate about the measurement? [SP 2.2, SP 4.2, SP 5.1]
3. A student builds a pendulum with a 100 g bob and a series of 30 cm, 40 cm, 50 cm and 60 cm strings. Then the student measures the period of oscillation of each pendulum. The period values are found to be 1.2 s, 1.4 s, 1.5 s, and 1.7 s. [EK 3.B.3; SP 2.2, SP 4.2, SP 5.1, SP 6.4]
    a. Does the length of the string significantly affect the period of the pendulum's motion? If so, describe the dependence.
    b. The mass of the bob on the 30 cm pendulum is changed to 50 g. The period is measured to be 1.3 s. Is this data point sufficient to form a conclusion about whether the mass of the bob affects the period of the oscillations? Why or why not?

[Solutions]

1. [EK 3.B.3; SP 2.2, SP 5.1]
    a. No, the change is too small to conclude that there is a significant dependence of *T* on the initial value of □ .
    b. Yes, the ratio of the mass of the string to the mass of the bob is 1/100, and the ratio of the size of the bob to the length of the string is 1/15.
2. [SP 2.2, SP 4.2, SP 5.1] Accuracy refers to how close a measurement is to the actual value of what is being measured.
3. [EK 3.B.3; SP 2.2, SP4.2, SP 5.1, SP 6.4]
    a. Yes. The period increases with increasing string length.
    b. No, the change in the value of the period is in the last significant digit, thus it can be a result of a random error or of the limited precision of the measurements.

Activity 2: Determining the Value of the Free-Fall Acceleration *g* Using a Simple Pendulum

In the next part of the lab, we will determine the acceleration *g* due to gravity by measuring the value of the period of a simple pendulum and applying Equation 4. The value of *g* is usually stated in textbooks to be 9.8 m/s^2. It varies in the third significant figure with elevation and from place to place. There is also a standard value of *g*, defined to be 9.80665 m/s^2, which represents an average value at sea level at 45° latitude.

Activity 2: Pre-Assessment

1. **Answer the following questions in your notebook**: How is the value of *g* related to the period of a simple pendulum?
2. **Answer the following questions in your notebook:** What experiments can you design to determine the value of *g* using a simple pendulum?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 2: Determining the Value of the Acceleration Due to Gravity *g* Using a Simple Pendulum

In order to find a reliable value of *g*, we will need to measure the period of the simple pendulum and its length. The main task is to make these measurements as accurate as possible.

Safety Precautions

- Be careful when swinging weights used in a pendulum so that they do not hit anyone or anything in the classroom.

For this activity you will need the following:

- String
- Meter stick
- A mass
- Stopwatch or timer
- Support rod

For this activity you will work *in pairs*.

Activity 2 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 2:

- This practical execution of this activity builds upon the work that the students carried out in Activity 1. The measurements should be no more difficult. Therefore, it is recommended that the discussion here is dedicated to outlining ways to reduce the error and to improve the accuracy of the final results.

- The students should estimate the resulting error bar and briefly present their conclusions to the instructor before the work on this lab module is concluded.

The following are recommendations for the Guided Inquiry for Activity 2:

- This activity is relatively simple and builds upon the experience the students have gained in working on Activity 1 above. The students should be encouraged to discuss what influences were disregarded as insignificant in the process of performing this activity and the analysis. Also, it would be beneficial to ask the students for suggestions as to how to improve the lab setup to produce even better agreement of the measured data with the theoretical derivations and predictions.

Structured Inquiry

Step 1: Build a simple pendulum. Measure the length of the string as accurately as you can and record it in your notebook.

Step 2: Hypothesize/Predict: How will the value of *g* depend on the period of the pendulum? Record your answers in the notebook.

Step 3: Student-Led Planning: You will now measure the period of the simple pendulum as accurately as possible in order to obtain the value of the acceleration due to gravity *g*. Discuss with your partner the best way to set up this experiment. Discuss possible sources of errors and ways to reduce their impact.

Step 4: Critical Analysis: Record the period of the pendulum in a number of measurements. Discuss the reduction of error achieved by taking appropriate measures planned in the previous step. Record your findings in the notebook making tables for the period and *g* for each measurement. Compare your average results with the textbook value of $g = 9.80\ m/s^2$, and discuss possible sources of disagreement.

Guided Inquiry

Step 1: Hypothesize/Predict: If you had done the experiment to determine *g* with different values of the pendulum length, how would it affect the accuracy of your results? Explain how you think this would happen. For example, what would change if you increased the length and would this make your time measurements more accurate or less accurate? Write your ideas in your notebook.

Step 2: Student-Led Planning: Discuss with your partner how you can test your predictions. Make a table in your notebook for your experiment. Build the pendulums you will test and carry out the measurements.

Step 3: Critical Analysis: What can you do to further reduce the error? Discuss your answer with your partner and write it in your notebook.

Assessments

1. A student builds a pendulum with a 100 g bob and a 30 cm string. Then the student measures the period of the pendulum oscillations in four tries. The period values are found to be 1.0 s, 1.0 s, 1.1 s, and 1.1 [EK 3.B.3; SP 2.2, SP4.2, SP 5.1, SP 6.4]
   a. What is the period of the pendulum based on the data?
   b. What is the experimental value of *g* implied by each value of the period, the average experimental value of *g*, and the average error?
   c. Does the experimentally measured value of *g* agree with the textbook value to within the uncertainty of measurement?
2. What can be the reason for inaccuracy in the textbook value of *g*? [EK 3.B.3; SP 2.2, SP4.2, SP 5.1, SP 6.4]
3. What can be sources of inaccuracy in measuring the period of the simple pendulum that lead to errors in estimating the value of the free-fall acceleration g? [EK 3.B.3; SP 2.2, SP4.2, SP 5.1, SP 6.4]

[Solutions]

1. [EK 3.B.3; SP 2.2, SP4.2, SP 5.1, SP 6.4]
   a. *T* = (1.0 s + 1.0s + 1.1 s + 1.1 s)/4 = 1.05s.
   b. According to the Equation 4, $T = 2\pi\sqrt{\frac{L}{g}}$. Therefore, $g = L\left(\frac{2\pi}{T}\right)^2$. The values of *g* are: 11.8 m/s^2, 11.8 m/s^2, 9.8 m/s^2, 9.8 m/s^2, the average *g* = (11.8 m/s^2 + 11.8 m/s^2 + 9.8 m/s^2 + 9.8 m/s^2)/4 = 10.8m/s^2. The average error is 1.0 m/s^2, *g* = 10.8 m/s^2 ± 1.0 m/s^2.
   c. The textbook value is 9.80 m/s^2. Therefore, yes, the value obtained agrees to within the uncertainty of the measurement.
2. [EK 3.B.3; SP 2.2, SP4.2, SP 5.1, SP 6.4]
   The actual value of g depends on the specific geographical location, it is smaller in places that are closer to the equator and greater in locations closer to the poles of Earth.
3. [EK 3.B.3; SP 2.2, SP4.2, SP 5.1, SP 6.4]
   Sources of inaccuracy include: friction at the point where the string is mounted, timing over too few complete cycles, uncertainty about when a cycle ends or starts, errors in length of string, nonzero size of bob, departure from small-angle approximation, or friction due to air.

Lab 10: Rotational Motion

From electrons to planets, rotating objects are commonplace in our universe and occur on many scales. Rotational motion plays a critical role in our mechanical world as well. Electrical generators, motors, wheels, and axles all function on the basis of rotational motion.

When Newton's second law is applied to rotating bodies, angular momentum, equal to $L = r \times mv$ for each circularly symmetric ring or shell of mass *m* moving at speed *v* by rotating around an axis at distance *r*, plays the role similar to momentum in linear motion. Specifically, the rate of change of the total angular momentum of a rotating object is equal to the torque acting on the object. Torque is calculated as $\tau = rF$ for an applied force that is directly perpendicular to an axis of rotation but a distance *r* away. Essentially, the torque describes how effectively a force twists an object.

Figure 10.1 illustrates the calculation of torque. The applied force is perpendicular to the vector *r* from the axis to the point of application of the force perpendicular to the wrench. The torque from the hand has magnitude $\tau = rF$. The force that the hand exerts for a clockwise torque while the nut resists being turned and exerts a torque in the opposite direction (the nut does not rotate) gives a net torque of zero. Applying the force farther from the nut, by using a longer wrench, increases the torque from the same force, and makes it easier to oppose the torque from the nut in the opposite direction so that it begins to rotate. If the torque was being applied instead to a wheel that is free to rotate without an opposing torque, its rotation would accelerate faster for greater torque.

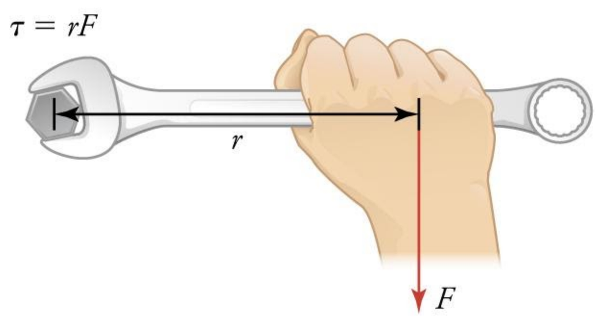


Figure 10.1: The torque is proportional to the applied force causing rotation and proportional to how far the point of application of the force is from the axis of rotation.

Inertia is also involved in the dynamics of rotating bodies. A spinning object will tend to keep spinning unless acted upon by a torque from an external force, such as friction. However, while the linear momentum for a particle is its mass times its velocity, the angular momentum for a shell of mass rotating at distance *R* around an axis is $I\,\omega$, where I is mR^2 and ω is the angular velocity, the rate at which the angle of rotation changes. The quantity *I* is called the moment of inertia. Its value depends on how mass is distributed in the rotating object. It can be made larger for the same total mass merely by having the mass concentrated as far as possible from the axis.

Recall that in order for an object to remain at rest, and therefore not accelerate, the net force acting on it must be zero. In this lab you will be testing experimentally if the lack of rotation of an object corresponds to the net torque acting on it being zero.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- Review the essential features of the rotational motion of an object. Make special note of the right rule for determining the resultant vector for torque. This will assist with the notion of the sign of torque. Also review the notion of moment of inertia and how it relates to inertial mass for motion of an object through space. It will be useful for the student to know the mathematical form for the moment of inertia for several types of objects.
- Discuss with the students the relationship between the forms of the equations of motion for rotational motion of an object versus the equations for motion through space.

In this lab you will learn:

- how to represent the rotational motion of an object descriptively and mathematically;
- how to design an experimental investigation of the motion of a rotating object;
- how to analyze experimental data describing the motion of a rotating object;
- how to calculate the total energy of a system that includes a rotating object.

Activity 1: Pre-Assessment

1. **Answer the following questions in your notebook**: Why is the movement of a lever on its fulcrum (in Figure 10.2) considered rotational motion? Could you move the lever so that one of its outer edges completes a full rotation? How could you measure the radius?
2. **Answer the following questions in your notebook:** If you place a mass on the lever, what factors will affect its motion? How would placing a second mass on the other side of the lever affect its motion? Why? How can you explain the net motion of the lever with masses on either side of the fulcrum in terms of conservation of energy within the system of the lever and the masses?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 1: Torque Lab

To investigate if the net torque on an object needs to be zero in order for it to balance and have zero angular acceleration, we will use the set up shown in Figure 10.2. It consists of a meter stick that can rotate around the point where a fulcrum supports it. Different weights are placed on it and it is positioned to balance. Note that the torque from the mass tends to twist the meter stick clockwise and rotate it counterclockwise. Because the two torques act to cause opposite rotation you will want to give one of them a minus sign relative to the other when performing calculations.

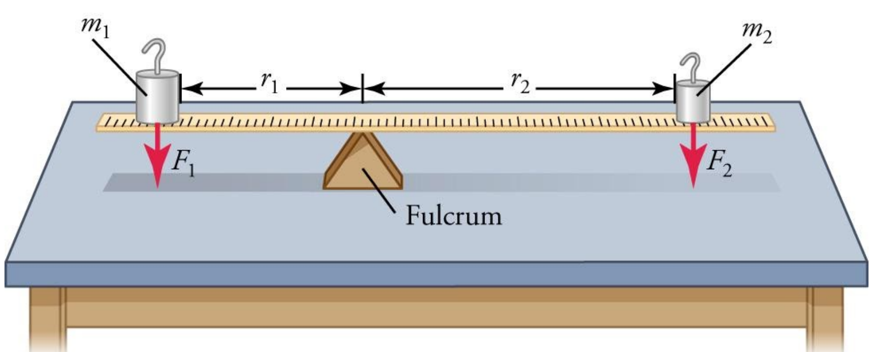


Figure 10.2: The weight of mass produces a torque tending to rotate the lever clockwise. The torque has magnitude $\tau = rF$ and is given a plus sign if it is twisting counterclockwise and a minus sign for twisting clockwise.

Safety Precautions

- Take caution with rotating levers. Be sure they are held far enough away from your face and from other students so that they will not strike anyone when rotated.

For this activity you will need the following:

- Lever (a meter stick or similar object and a fulcrum)

- Set of standard masses or similar solid objects
- Protractor

For this activity you will work *in groups of four*.

Activity 1 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry in Activity 1:

- This lab has a subtle feature in that the meter stick itself can contribute to the overall torque, especially if the balance point is placed at a point other than the midpoint of the meter stick. Review with the students how to formulate the contribution of the meter stick in terms of the differences between the two lengths used on either side of the balance point.
- Review the use of the right-hand rule and how it establishes the sign of the torque.
- Ensure that the students understand that they should do some practice runs so that they understand how to establish that the meter stick and weights have achieved a balance. It is a common misconception that the meter stick will simply stop moving and achieve a horizontal position. It is more common for the stick to act as a slow seesaw with equal slow alternate angular motions on both sides of the balancing point.

The following are recommendations for the Guided Inquiry in Activity 1:

- Discuss with the students the combined role of both the mass and the distance at which it acts to produce a torque. Review with them the method of combining a series of torques, taking special note of the sign of each individual torque. Review the role of the mass distribution of the meter stick and how the choice of the fulcrum point can affect total torque given the situation where the midpoint of the meter stick is not used as the fulcrum.

Structured Inquiry

Your challenge is to measure the necessary information to calculate the torque from each force, to calculate the net torque, and to see if the condition for the meter stick to balance, with no tendency to rotate to the left or right, is for the torques you calculate to add up to zero.

Step 1: Your goal in this lab is to collect data needed to calculate the torque $\tau_2 = r_2F_2$ clockwise and $\tau_1 = r_1F_1$ counterclockwise. You will want to assign torques opposite signs because they twist in the opposite sense of rotation to get the net torque. Create a data table for your measurements.

Step 2: Hypothesize/Predict: Suppose you have already balanced the weights as shown in Figure 10.2. What value would you predict of the net torque, taken as the sum of the two torques, with their sign taken into account? Predict how the torques will change if you move the mass m_2 closer to the end of the meter stick. What effect will that have on the net torque, taken to be the sum of the two torques, with their sign taken into account? What effect do you predict that will have on the orientation of the meter stick?

Step 3: Student-Led Planning: You will measure the weight of the two equal masses, place them on the meter stick and carefully slide the meter stick to a position on the fulcrum where it balances. You will then want to collect all the data needed to calculate the net torque. The position markings on the meter stick will help. Then you will collect the same data when the meter stick is balanced with one mass being twice the other. Note that if your fulcrum is pointy, it may not actually balance, but the balance point can be taken to be where the lever switches from tending to rotate one way to tending to rotate the other. Discuss with your lab partner what data you will collect in order to be able to calculate two torques for both cases. Make a data table in your notebook.

Step 4: Proceed to collect data and enter it into the data table in your notebook. Calculate the net torque for each case, and write it in your notebook.

Step 5: Critical Analysis: Were the predictions you made in Step 2 supported by your data? Did the net torque come out to be close enough to zero when the meter stick was balanced? Why or why not? What methods could you have used that improved your results? Discuss with your partner and then write your answers in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: How do you think the experiment would have differed if you had used three weights, two at different positions on one side and one on the other side? What would the net torque be when the meter stick is balanced? Write your ideas in your notebook.

Step 2: Student-Led Planning: Discuss the details of your experiment to test your predictions with your lab partner. How will you calculate the net torque when the forces are acting at three different positions? Write your answers in your notebook.

Step 3: Critical Analysis: Did your results show the net torque to be zero when the meter stick balanced? Discuss your answer with your partner and write it in your notebook.

Assessments

1. Explain how the torque produced by a weight placed on the meter-stick lever changed if the distance of the weight from the fulcrum was increased, and then decreased. [EK 3A.1b; SP 2]
2. Explain how the different masses you investigated in Activity 2 affected the torque that they produced on the lever. [EK 3A.1b; SP 3]
3. Think about how the weight of the meter stick influences the direction in which it tends to rotate.
    a. Imagine balancing the meter stick on the fulcrum without any additional masses. How would the meter stick move if you placed the fulcrum off center? Why? [EK 3A.1c; SP 3]
    b. How did the weight of the meter stick influence its rotational motion when you were balancing the weights on either side of the fulcrum? [EK 3A.1c; SP 3]

[Solutions]

1. [EK 3A.1b; SP 2] Increasing the distance of the mass from the fulcrum increased the torque, and moving it closer to the fulcrum decreased the torque, because the torque is given by $\tau = rF$ where *r* is the distance of the fulcrum to where the force *F* acts.
2. [EK 3A.1b; SP 3] Using greater mass-produced greater torque, because the force producing the torque is the weight, which is proportional to mass.
3.
    a. [EK 3A.1b; SP 3] The longer arm of the meter stick would rotate downward because that side of the meter stick would have greater weight (*mg*) and therefore would apply greater torque.
    b. [EK 3A.1c; SP 3] The weight of the meter stick between the masses and the fulcrum add to the torque. The side with the greatest total torque from the weight of the mass plus the weight of the meter stick will rotate down.

Activity 2: Rolling Cylinders

For a single rotating point, rotational inertia, also known as **moment of inertia** (*I*) is equal to mr^2, where *m* is mass and *r* is the point's distance to the axis of rotation (which can be thought of as a radius). For a whole rotating object, rotational inertia is the sum of the moment of inertia of each point in the object. We use a capital *R* to distinguish the radius of the entire spinning object from the radius (*r*) of any point in the object. Consult the table of rotational inertias Table 10.12 for simplified rotational inertia formulas for objects of various shapes.
In this lab, you will use a ramp to investigate a rotating cylinder's moment of inertia and energy. You will test how different distributions of mass in the cylinder affect its motion. The energy of a cylinder rolling down an incline (without slipping) can be described by the following equation

$$gh = \frac{1}{2}\left(\frac{I + mR^2}{mR^2}\right)v^2,$$

where *m* is the mass of the cylinder, *R* is its radius, and *v* is the linear speed of the rolling cylinder when its height has decreased by *h*. You can think of I/mR^2 as a geometrical factor reflecting how mass is distributed in the cylinder, since it takes into consideration the moment of inertia as well as the mass and radius of the cylinder. At a given height, if mass is distributed toward the edge of the cylinder, I/mR^2 increases and therefore velocity decreases.

Safety Precautions

- Take caution with rolling cylinders. Do not throw cylinders. Do not allow cylinders to roll onto the floor, as they may cause a tripping hazard.

For this activity you will need the following:

- Plank (a 3' board or similar object)
- Books or similar objects to create a ramp with the plank
- A variety of cylindrical objects cut to 1–3 in. lengths (e.g., cardboard tubes, PVC pipe, small empty tin cans)
- Clay (in sufficient quantity to fill one cylinder)
- Stopwatch
- Tape Measure

For this activity you will work *in groups of 3*.

Activity 2 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry in Activity 2:

- Review with the students the detailed solution to finding the form for the velocity of the rolling object. Discuss with them the role of the mass and moment of inertia in the solution.

- As always with timed events, ensure that the students make practice runs so that consistent times are obtained. This should help reduce the spread in random errors. Discuss with the students what form of systematic errors can be present and how they may be minimized.

The following are recommendations for the Guided Inquiry in Activity 2:

- Discuss with the students the role of mass versus the moment of inertia in determining the acceleration and final velocity of the object. Let them compare this to simple linear motion, such as two objects of different masses falling through the same vertical distance. In this case, the acceleration and final velocity are independent of the mass. Discuss with the students how this relates to what they have observed with the rolling masses.

Structured Inquiry

Step 1: Set up a ramp as shown in the diagram below. Draw a starting line at the top of the ramp and measure the distance from the starting line to the bottom of the ramp. Roll one cylinder down the ramp and record the time it takes to travel from the starting line to the bottom using the stopwatch. Use your data to calculate the acceleration of the cylinder.

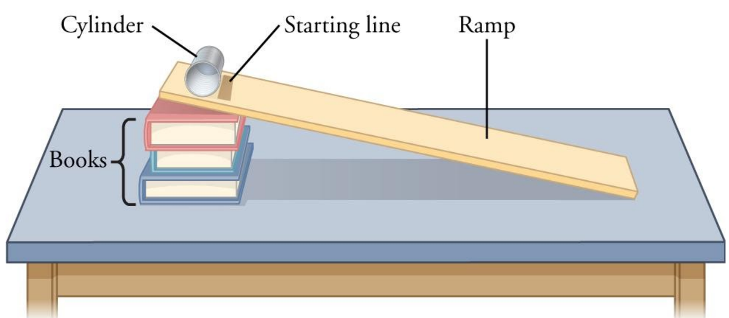


Figure 10.3: Place one end of the plank on a stack of books to create a ramp. Place a cylinder at the top of the ramp and mark a starting line where you will release the cylinder.

Step 2: Hypothesize/Predict: Predict what would happen to the acceleration down the ramp if you filled the cylinder with clay. Discuss your prediction and your reasoning with your lab partner, and record both in your notebook.

Step 3: Student-Led Planning: Discuss with your partner how best to use the materials and your setup to test your prediction. Create an appropriate data table in your notebook.

Step 4: Critical Analysis: Fill your cylinder with clay and use the ramp to test your prediction. Record data in your notebook and discuss your observations. Were the predictions you made in Step 2 supported by your data? What could you have used to improve your results? Discuss with your partner and then write your answers in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: How can you use clay to make cylinders with different moments of inertia? How could you test the effect of moment of inertia on acceleration? Write your ideas in your notebook.

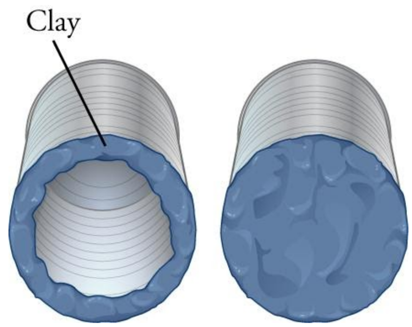


Figure 10.4: Place clay inside the cylinders in a variety of ways to create cylinders with different moments of inertia.

Step 2: Student-Led planning: Make at least two cylinders with different moments of inertia by distributing the clay differently within the cylinders. The figures below show some different ways to distribute clay inside the cylinders to create different moments of inertia, but you may develop some of your own ideas. Sketch your cylinders in your notebook to show the different distributions of mass. Discuss how you will compare the acceleration of the different cylinders.

Step 3: Critical Analysis: How did the distribution of mass and differences in total mass inside each cylinder produce different moments of inertia? How did the different distributions of mass affect each cylinder's center of gravity? How did your experimental design allow you to examine differences in acceleration? Discuss your answers with your partner and write it in your notebook.

Assessments

1. Does the overall mass or radius of a cylinder affect its acceleration down the ramp? Use the conservation of energy to justify your response. [EK 4.C.1; SP 2]
2. Explain how the acceleration of each rotating cylinder was affected by its moment of inertia. [EK 3A.1b; SP 3]
3. Based on your results, if you compared the acceleration of a smooth rubber ball with a hollow cylinder rolling down the ramp, which would be faster? [EK 3A.1c; SP 3]

[Solutions]

1. [EK 4.C.1; SP 2] No, because mass and radius cancel out when we use the conservation of energy to determine a cylinder's overall velocity on the ramp that results from the acceleration due to gravity.

$$\mathrm{PE} = \mathrm{KE}$$
$$mgh = \tfrac{1}{2}mv^2 + \tfrac{1}{2}I\omega^2$$
$$mgh = \tfrac{1}{2}mv^2 + \tfrac{1}{2}\left(\tfrac{1}{2}mR^2\right)\left(\frac{v}{R}\right)^2$$
$$gh = \tfrac{3}{4}v^2$$

2. [EK 3A.1b; SP 3] The solid cylinder had the greatest moment of inertia and accelerated the fastest (reached the bottom of the ramp in the shortest time). Creating a ring of clay inside the cylinder reduced the moment of inertia slightly, causing a small decrease in acceleration (an increase in time it took to reach the bottom of the ramp). [Response based on rotational inertias for annular and solid cylinders. Responses for other distributions will vary, but should be supported by observations of differences in acceleration.]
3. [EK 3A.1c; SP 3] The rubber ball would be faster. The hollow cylinder has all its mass as far as possible from the axis of rotation, while the rubber ball has mass distributed over all possible radii. Hence, inertia would slow down the hollow cylinder more.

Lab 11: Mechanical Waves

Waves are essential to our understanding of the physical world. A **wave** is a disturbance that transfers energy from one location to another. There are two types of waves: those that travel only through matter, such as mechanical waves, and those that can travel through a vacuum, such as electromagnetic waves. The focus of this lab will be mechanical waves. Familiar examples of mechanical waves are waves in water, sound waves, and seismic waves.

Waves carry energy with them as they travel, either through a medium or through empty space. Waves move matter; however, in the case of mechanical waves, matter only moves locally back and forth in oscillations over small distances. Waves are usually characterized by their **frequency, wavelength, speed, amplitude,** and **phase**. The wavelength λ, in Figure 11.1 is the distance between two adjacent identical peaks of the wave. It has units in meters. The period of the wave is the time for a complete wavelength to pass by. Frequency is the number of wavelengths that pass by each second and is the reciprocal of the period. It is in units called hertz (Hz), where 1 Hz means one complete oscillation per second. The speed of the wave is a measure of how fast energy propagates in the wave and has units of meters/second (m/s). The amplitude *X* is the difference between the maximum point of disturbance and the equilibrium position. The phase is the position in time of a particular point on the wave. The frequency *f*, wavelength λ, and the speed *v* are related by the following equation

$$v = f\lambda \ .$$

A typical wave, illustrating the relevant quantities, is shown in Figure 11.1.

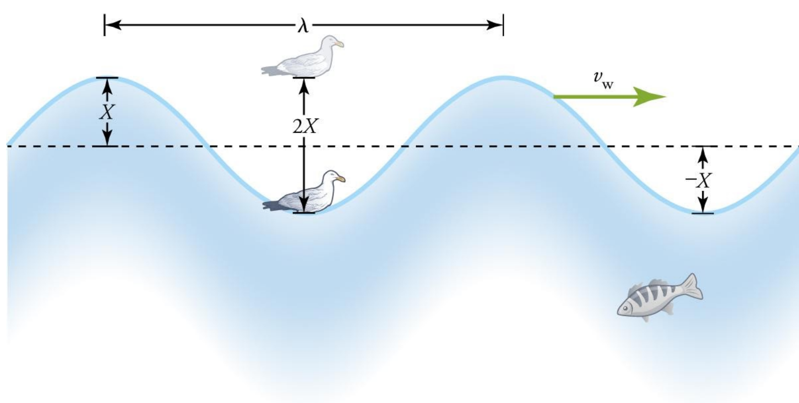


Figure 11.1: A water wave, showing wavelength λ, amplitude *X*, and wave speed v_m.

To understand mechanical waves, think of them as a collection of interacting particles that make up the medium. Waves are able to travel through a medium when a disturbance to one particle leads to a disturbance in the adjacent particles because of interactions between the particles. Therefore, the disturbance will travel from one particle to the next, allowing the wave to travel through the medium. Waves can be differentiated into transverse and longitudinal waves. **Transverse waves**, shown in Figure 11.2, are waves in which the disturbance oscillates perpendicular to the direction that the wave pattern travels. **Longitudinal waves** are waves in which the disturbance oscillates along the direction that the wave travels, as seen in Figure 11.3.

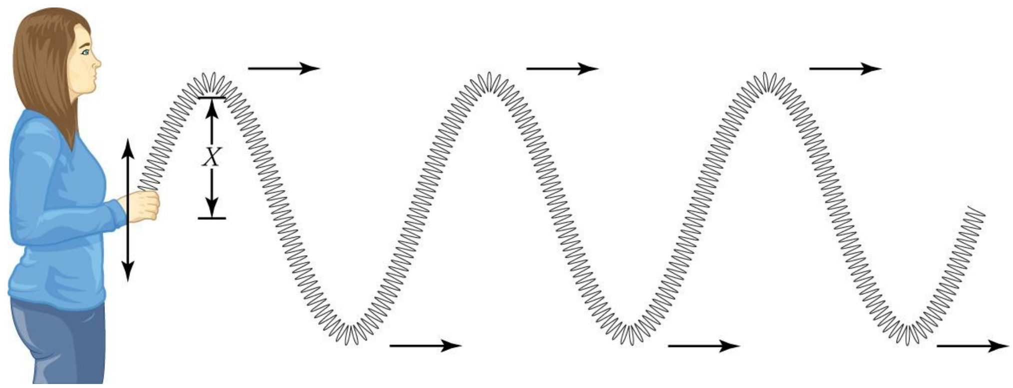


Figure 11.2: A **transverse** wave, showing the amplitude *X* and direction of motion.

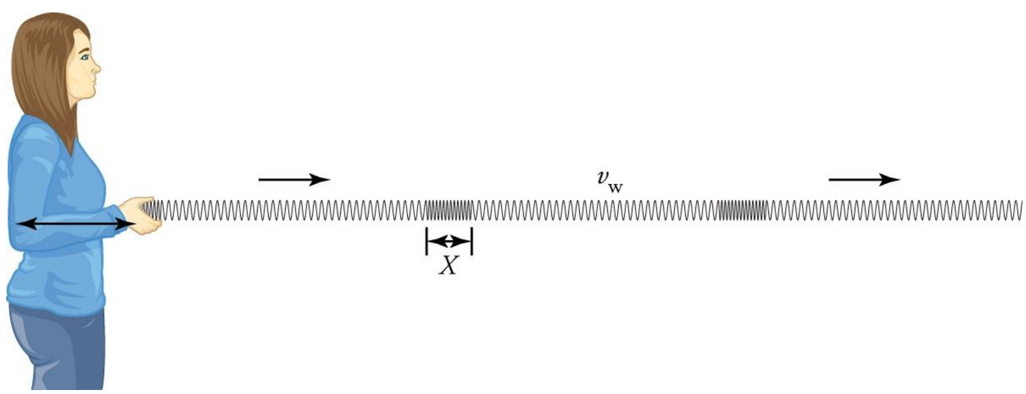


Figure 11.3: A **longitudinal** wave, showing the amplitude *X* and direction of motion.

When two waves interact, the resulting wave will be a **superposition**, or a sum, of the two original waves. To find the resulting wave at each point, you can simply add the disturbance from each wave at that point. Thus, even the complicated motion of multiple ripples in a pond or waves in the ocean can be expressed as a superposition of individual waves.

The end of a medium in which a wave travels, or the location where two different media meet, is referred to as an **interface**. An **incident wave** corresponds to the initial wave impinging a boundary. The part of the wave that returns from the boundary is known as a **reflected wave**. A **transmitted wave** is a wave that travels past the interface into the second medium—the first medium being where the incident wave originated from. The incident wave and the reflected wave travel at the same speed because they are in the same medium. They also have the same wavelength and frequency. However, the reflected wave has a smaller amplitude than the incident wave because some of the energy goes into the transmitted wave. The transmitted wave and incident waves travel at different speeds and have different wavelengths and frequency because they travel through different media.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- If your students have not yet had experience with the mathematical representations of waves, give a brief introduction to sinusoidal functions and their mathematical representations. Be sure to include the necessary information about frequency, wavelength, and amplitude.
- To introduce superposition, build on the mathematical basis of sinusoidal functions by adding together two sinusoidal functions. This is easiest to see if the waves are placed on the same graph using different colors. Examine the addition of these functions by using a few concrete values to help students gain an intuitive understanding. Ask students the circumstances under which superposition might occur.
- Reiterate the differences between transverse and longitudinal waves. Transverse waves have their disturbances oscillating perpendicular to the direction of motion, whereas longitudinal waves have their disturbances oscillating parallel to the direction of motion.

In this lab you will learn:

- how the frequency, wavelength, and speed of a wave are related;
- how waves interact with each other and behave at different types of boundaries.

Activity 1: Pre-Assessment

1. **Answer the following questions in your notebook:** What happens to the speed and the wavelength of the wave when you increase its frequency? How about when you increase the amplitude of the wave?
2. **Answer the following questions in your notebook:** Would a wave travel at the same speed if it was traveling transversally, as opposed to longitudinally? Explain your response.
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 1: Basic Properties of Waves

In this activity, we will investigate the properties of mechanical waves by using a spring toy. We will investigate the relationship between the speed, frequency, and wavelength of a wave.

For this activity you will need the following:

- A spring toy
- A video capture device (such as a smartphone, digital camera, etc.), or a stopwatch
- Meter stick

For this activity you will work *in groups of three*.

Activity 1 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 1:

- Remind students that they should untwist the kinks in the spring toy if any develop, both to maintain the integrity of their data and to avoid damaging the spring toy.
- To make the calculations easier, encourage students to stretch the spring toy to a whole number of meters on the meter stick.
- To ensure that students are creating waves with the same frequency, direct them to move the spring toy to the beat of a popular song, for example, *Stayin' Alive*. A song with a clear beat should help make their wave frequencies more consistent and improve their overall data collection efforts.
- To prepare for Activity 2, ask students to discuss where the energy from the wave goes in this scenario.

The following are recommendations for the Guided Inquiry for Activity 1, guided inquiry:

- To facilitate Step 1, it may be helpful to ask whether a longitudinal wave can ever have the same speed as a transverse wave. Similarly, can a longitudinal wave ever have the same wavelength as a transverse wave?
- To facilitate Step 3, encourage students to consider the various ways they can determine the speed of a wave: measuring how long the wave takes to travel a certain distance, but also by way of the equation wave speed equals frequency times wavelength. For their experiment, given that they already have the frequency, would measuring the wavelength or the speed directly be easier?

Structured Inquiry

Step 1: With you and one of your partners each holding opposite ends of the spring toy, stretch the spring toy on the floor—to about 3 to 4 meters in length. Send a wave to your partner by quickly moving the spring toy back and forth. The third person should record how long the wave takes to travel between you and your partner. Use this result to calculate the wave speed.

Step 2: Hypothesize/Predict: Given that the speed of a wave is a property of the medium through which it travels—for example, the spring toy—use the value obtained for the speed in Step 1 to calculate the wavelength of the waves for a given frequency. Record your predictions in a table.

Step 3: Student-Led Planning: You will now measure the wavelength of waves you send to your partner by using your video capture device. Discuss with your group the best approach to accurately measure the wavelength for different frequencies.

Step 4: Critical Analysis: Record the results of your measurements in a table. How do the measurements compare to your prediction in the previous step? How did the wave speed compare to the speed calculated in Step 1?

Guided Inquiry

Step 1: Hypothesize/Predict: How will the speed of the wave differ if you generate longitudinal waves instead of transverse waves along the spring toy? How will the wavelength differ?

Step 2: Student-Led Planning: With your partner, pick a frequency that you will test that is easy to replicate over several tries. Then, for your chosen frequency, send transverse waves and longitudinal waves to your partner.

Step 3: Determine the speed in each trial, and record your results in a table in your notebook. Do this at least five times.

Step 4: Critical Analysis: Did the speed differ between the transverse and longitudinal waves? Did the frequency differ? Did the wavelength differ? Do you expect the speed of transverse and longitudinal waves to differ? Discuss your results with your partners.

Assessments

1. Imagine a wave traveling in a given material. If the frequency of a wave is doubled, how does that change its wavelength? [EK 16.6b; SP3]
2. In what direction do transverse waves oscillate relative to the direction that the wave travels? How about longitudinal waves? [EK 16.6a; SP3]

[Solutions]

1. [EK 16.6b; SP3] Given that the speed of the wave is constant, increasing the frequency by a factor of two leads to a wave that has half the wavelength of the original.
2. [EK 16.6a; SP3] Transverse waves oscillate perpendicular, whereas longitudinal waves travel parallel to the direction that the wave travels.

Activity 2: Pre-Assessment

1. **Answer the following questions in your notebook:** How will two or more waves interact with each other?
2. **Answer the following questions in your notebook:** Does the behavior of one-dimensional waves differ from that of two-dimensional waves?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 2: Waves and Boundaries [LO2][SP2]

In this activity we will investigate how waves interact with each other and how they behave at different boundaries.

For this activity you will need the following:

- A spring toy
- A video capture device (such as a smartphone, digital camera, etc.), or a stopwatch
- Meter stick
- Water tank
- A card or other flat object

For this activity you will work *in groups of three*.

Activity 2 Instructor Preparation and Teaching Tips

The following are recommendations for Activity 2:

- Remind students that they should untwist the kinks in the spring toy if any develop, both to maintain the integrity of their data and to avoid damaging the spring toy.
- To make the calculations easier, encourage students to stretch the spring toy to a whole number of meters for each of their trials.
- If students have a difficult time seeing what happens in Step 3 of the structured inquiry, remind them that they should only send a single pulse, that is, one wave, instead of the series of waves they had sent in other experiments.
- If students have a difficult time with Step 2 of the guided inquiry, direct them to wait until the water settles between trials, make larger waves, and/or place the card closer to the point of origination for the wave.

The following are recommendations for the Guided Inquiry for Activity 2:

- To facilitate Step 1, it may be useful to demonstrate what happens to a one-dimensional wave in the form of a string attached to a wall. Encourage students to consider where all the energy in the wave goes, especially why the reflected wave is not as large as the initial wave.

- If students are having a difficult time with Step 2 of the guided inquiry, direct them to wait until the water settles between trials, make larger waves, and/or place the card closer to the point of origination for the wave.

Structured Inquiry

Step 1: With you and one of your partners each holding an opposite end of the spring toy, stretch the spring toy along the floor—to about 3 to 4 meters. Send one wave to your partner while your partner simultaneously sends one wave back to you. Have your other partner record what happens to the amplitude as the two waves pass each other and record the time it takes for each wave to travel to your partner and back.

Step 2: Hypothesize/Predict: If you send a wave train, more than one wave, to your partner with a given frequency, and your partner sends a wave train to you with a different frequency, what will happen to each wave train as they pass? Does the speed of each change for different frequencies? Why or why not?

Step 3: Student-Led Planning: Have your partner release one end of the spring toy and send a wave pulse through from the other end. What happens to the wave as it reaches the open end? Lift the spring toy from the floor and stretch it so it doesn't sag too much, while your partner holds one end of the spring toy fixed. Alternatively, fix your partner's end to a position on the wall. Send a single pulse down the spring toy and describe the motion of the pulse before and after it reaches the boundary—that is, your partner or the wall.

Step 4: Critical Analysis: What happens to the pulse when it reaches the boundary? Use Newton's third law of motion to explain the behavior of the wave at the boundary.

Guided Inquiry

Step 1: Hypothesize/Predict: For a two-dimensional wave in a water tank, how will the reflected wave behave at the boundary of the tank?

Step 2: Student-Led Planning: Use a pencil or your finger to create a circular wave in the water tank. Place a barrier, such as a card or other flat object, perpendicular to the outward motion of the wave in the tank. Now, rotate the barrier $45°$. Record your observations both before and after the $45°$ rotation.

Step 3: Critical Analysis: From where does the reflected wave at the boundary seem to originate? How does the angle of reflection of the wave depend on the angle of incidence?

Assessments

1. Two waves travel toward each other in a given medium, one with amplitude A_1, the other with a smaller amplitude A_2. If the waves have the same frequency and phase, what equation would represent the maximum possible amplitude of the resulting wave? [EK 16.6c; SP3]
2. When two waves pass through a region where they overlap, how is the resulting wave related to the two waves? [EK 16.6c; SP3]
3. How is the amplitude of the reflected wave related to the amplitude of the incident wave? [EK 16.6c; SP3]

[Solutions]

1. [EK 16.6c; SP3] The amplitude will be $A = A_1 + A_2$, where the waves meet with the same phase, and $A = A_1 - A_2$, where they meet with the opposite phase.
2. [EK 16.6c; SP3] The disturbance at each point is the sum of the disturbances from each wave.
3. [EK 16.6c; SP3] It is inverted, or $180°$ out of phase, and travels in the opposite direction.

Lab 12: Sound Waves

Sound travels through air and other materials as a compression wave. These waves are alternating areas of higher and lower pressure. As with all waves, the frequency and wavelength are related by the equation

$$v = \lambda f \ .$$

Therefore, if you can measure the wavelength (λ) for a specific frequency (f), you can obtain the speed of the sound wave.

The speed of sound depends on the medium, or material, it travels through. In addition, the speed of sound in air changes slightly if the pressure or temperature of the medium changes. In this lab, you will measure the speed of sound in your classroom and check how your measured speed compares with the speed under standard temperature and pressure, or STP. You will measure the speed of sound indirectly using the wave properties of sound.

To measure the wavelength of sound you will use the ability of sound waves to interfere with each other. Consider a cylinder of air closed at both ends, possibly with a small hole for inputting sound waves. Sound waves traveling along the cylinder will be reflected at each end. The original wave and reflected wave then interfere, amplifying each other when they reach a location with the same phase and cancelling each other when they arrive with the opposite phase. For most wavelengths, the waves that are being bounced back and forth repeatedly from the ends of the tube involve many different relative phases and interfere to weaken and mute one another on average. But, if the length of the tube is an exact multiple of half the wavelength, then each reflected wave can have peaks and dips in phase with the wave that caused the reflection. Relatively large amounts of energy can be pumped into these waves so they produce a strong response, or a **resonance**. The closed tube vibrates loudly at the frequencies that correspond to these specific resonance wavelengths, but not others. If the tube is open at one end and closed at the other, the same phenomenon occurs, but the condition the wavelengths satisfy for a resonance is slightly different.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- If your students have not yet had experience with the mathematical representations of waves, give a brief introduction to sinusoidal functions and their mathematical representations. Be sure to include the necessary information about frequency, wavelength, and amplitude.

- To introduce resonance, build on the mathematical basis of sinusoidal functions by adding together two sinusoidal functions. This is easiest to see if the waves are placed on the same graph using different colors. Examine the addition of these functions by using a few concrete values to help students gain an intuitive understanding. Ask students the circumstances under which resonance might occur.
- To develop the background information for this lab, you may direct students to investigate the history of the discovery of the speed of sound. Have them examine the discoveries about sound that preceded this, and how they contributed to Mersenne's discovery. It may be helpful to note that Leonardo Da Vinci discovered that sound was a wave around 1500.

In this lab you will learn:

- to use graphs of waveforms to see how waves can constructively and destructively interfere based on how they overlap;
- to design a suitable experiment and analyze data illustrating the superposition of mechanical waves—only for pulses or standing waves;
- to design a plan for collecting data to determine the exact means of interference of two waves.

Activity 1: Pre-Assessment

1. **Answer the following questions in your notebook**: How are frequency, velocity, and wavelength related? What are harmonics and how do they relate to a specified frequency? Do you think the temperature of the medium impacts the results?
2. **Answer the following questions in your notebook:** Using what you know of harmonics, how could you use a tuning fork (or several) and a cylinder partially filled with an adjustable amount of water to determine the speed of sound? What data would you need to collect? Design a data table and draw it in your notebook.
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 1: Speed of Sound

Sound traveling through a cylinder closed at one or both ends will resonate at specific wavelengths related to the frequency of the sound produced. A tube partially filled with water is an example of a closed cylinder because the water surface reflects the sound wave. Closed tubes have a fundamental resonance at a length that is ¼ of the wavelength, with additional resonances each at ½ wavelength intervals. See Figure 12.1.

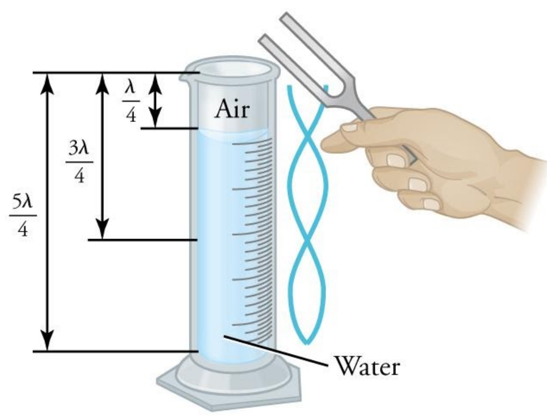


Figure 12.1: Resonances occur when the length of the column of air above the water is the correct multiple of the wavelength.

Resonant frequencies can be identified by listening to the sound coming from the top of the graduated cylinder while setting the air inside into vibration at a specific frequency. Each frequency corresponds to a specific wavelength because of the relationship

$$\lambda = \frac{l}{f}.$$

When the length of the air column does not match a resonant wavelength, you will have interference breaking down the wave and the sound will be muted. When the length of the air column matches the correct multiple of the wavelength for the specified frequency, you will hear a greatly increased sound volume.

Safety Precautions

- Inform your teacher immediately of any broken glassware, as it could cause injuries.
- Clean up any spilled water or other fluids to prevent slips and falls.

For this activity you will need the following:

- Graduated cylinder
- Water
- Tuning forks of various frequencies
- Ruler in cm
- Thermometer

For this activity, you will work *in pairs*.

Activity 1 Instructor Preparation and Teaching Tips

The following are recommendations for Activity 1:

- Remind students that they should not allow the tuning forks to touch the glass. Doing so could break the graduated cylinder.
- Students may think that the water in the bottle is vibrating. To discourage them from this thinking, show them a slow-motion video of a tuning fork entering water. At first, the sound is heard and the water is still. As the tuning fork enters the water, the water vibrates, and the sound stops.
- Students should obtain the lengths $\lambda/4$, $3\lambda/4$, and so on. You should direct them to see if their column lengths follow the progression x, $3x$, $5x$, and so on. It is possible that they have missed a resonance or counted something that was not really a resonance.
- To further build on Step 4 in the structured inquiry, direct students who finish early to determine in what direction higher or lower temperature and pressure biases the speed of sound.

The following are recommendations for Activity 1, guided inquiry:

- To facilitate Step 1, encourage students to pick notes that will be easy to work with. Note that, in the equal-tempered scale where A_4 = 440 Hz, A_2 = 110 Hz, whereas G_8 = 6271.93 Hz.
- To facilitate Steps 2 and 3, encourage students to start their investigations with roughly $\lambda/4$ as the height of their air column. This will make finding the specific note significantly easier than trying to find the notes by trial and error.

Structured Inquiry

Step 1: Determine the frequencies of the tuning forks available to you. Knowing the various frequencies, find the first three harmonics. Add these values to the data table for your measurements and show your calculations in your notebook.

Step 2: Hypothesize/Predict: Knowing the frequency of the tuning fork and that the speed of sound is roughly 300 m/s, hypothesize ¼ of the wavelength to be used as the height of the air column. Add your predictions to the data table you created in Step 1.

Step 3: Student-led Planning: You will now find the air column height, and resultant water level, for the first three harmonics of each tuning fork using Figure 12.1 as a reference. Discuss with your partner how best to set up your graduated cylinder to find the resonant frequencies.

Step 4: Critical Analysis: Record the air column height and related wavelength for each tuning fork and harmonic. Calculate the speed of sound from your data to the nearest tenth of a m/s. Are the predictions you made in Step 2 supported by your data? Why or why not? Is the speed of sound you measured close to the speed of sound for the temperature and air pressure in your classroom? (This information can be found online if you know the temperature of your classroom.) Calculate the percent error. How could you improve your results? Discuss your answers with your partner and write them in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: Now that you know the speed of sound for the air of your classroom, find a song that has 3 – 4 simple notes and print out the notes for your reference. If you need help with this task, ask your instructor for assistance. Write your song or part of your song in your notebook. You should have at least five measures of notes.

Step 2: Student-led Planning: Submit your chosen song to your teacher. Once your teacher approves, determine which frequencies create those notes. Your teacher may allow you access to an online music synthesizer or other instrument. Once you have determined the frequencies of the three notes, find their related wavelengths in a closed column. Write all your results in your notebook.

Step 3: Using your calculated values, create your 3 – 4 notes by filling water bottles with water to the correct levels. Test your notes by blowing across the tops of the partially-filled water bottles. If possible, make a recording of your song on a cell phone or other device and use it to adjust the notes until they are as close as possible to your chosen song. Then, play your song and see if your classmates can guess it. See Figure 12.2 to identify how your setup might look.

Step 4: Critical Analysis: Were you successful at creating all of your notes and playing your song? Could your classmates identify the song? Which notes were easier to create and why do you think this was the case? Would a different size bottle have made this easier? Discuss your answers with your partner and write them in your notebook.

Figure 12.2: Bottles filled to different heights with liquid can be used to play music by producing sounds of specific frequencies.

Assessments

1. Assuming a student is using a graduated cylinder, find the first three resonant frequencies of each tuning fork in a and b below. Also, what are the related air column lengths that the student should adjust to find these resonant frequencies? Assume that the speed of sound is 343. m/s. [EK 6.B.4; SP 1.4]
    a. Assume the tuning fork has a frequency of 400. Hz.
    b. Assume the tuning fork has a frequency of 700. Hz.
2. What limits how many harmonics you can create using the setup in this lab? [EK 6.D.4; SP 5.2]
3. Describe why the closed tube resonates at ¼ of the wavelength. Use a diagram to help your explanation. [EK 6.D.3; SP 5.3]

[Solutions]

1. [EK 6.B.4; SP 1.4]
    a. f_1 = 400 Hz, L = 21.6 cm, f_2 =133.3 Hz, L = 64.7 cm, f_3 = 80 Hz, L = 107cm
    b. f_1 = 700 Hz, L = 12.3 cm, f_2 = 233.3 Hz, L = 37.0cm, f_3 = 140 Hz, L = 61.6 cm
2. [EK 6.D.4; SP 5.2] The length of the graduated cylinder and the frequency of the tuning fork limit how many harmonics may be created.
3. [EK 6.D.3; SP 5.3] The smallest piece of a waveform that does not destructively interfere when reflected back on itself is one-quarter of a wavelength.

Lab 13: Electrostatics

Electrostatics is the study of phenomena associated with the buildup of **electric charge** on objects and surfaces. Examples of electrostatic phenomena are lightning and the small shock a person sometimes gets when touching a doorknob after walking across a rug.

Electric charge is a part of all matter because it is a property of the subatomic particles that make up matter. Electric charge cannot be created or destroyed. The basic unit of charge is represented by *e*, where $e = 1.6022 \times 10^{-19}\ \mathrm{C}$. **Electrons** are subatomic particles that each have a negative charge of –*e*. **Protons** are subatomic particles that each have a positive charge of +*e*.

Most of the time, objects have equal numbers of protons and electrons and are **neutral,** which means they have no overall electric charge. However, certain events cause electrons to move from one object to another or from one area to another within an object. As a result, the object (or part of the object) is **charged.** An excess of electrons results in a negative net charge. Conversely, a loss of electrons results in a positive net charge because more protons than electrons remain.

The behavior of charges is affected by properties of materials. Some materials, called **conductors,** allow charges to flow easily through them. In contrast, other materials, called **insulators,** do not allow the flow of charge. Common conductors are steel, copper, and aluminum, all metals. At the atomic level, some of the electrons can move throughout the metal rather than each being held around a specific nucleus. These loosely held particles form a sea of electrons that can flow through the metal, conducting an electric charge. In contrast, the atoms of insulators hold onto their electrons tightly.

A common application of conductors is grounding, which is the use of a conductor to protect homes from lightning and to help prevent different kinds of electrical accidents. In grounding, a charged object is discharged by providing a conducting path for the charge. Of course, creating any electrical circuit requires electrical conductors.

In this lab, you will study how charged objects interact with each other and the kinds of events that cause objects to become charged.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- The students should be familiar with the concepts of electrostatic charge, interaction of charges, the basis for charges (disbalance of electrons and protons).

- The above means that the students need to be familiar with the concept of atoms and the subatomic particles (electrons, protons, neutrons).
- The students should be asked questions regarding these physical concepts at the beginning of the lab, but the most beneficial way of proceeding is to ask the students themselves to make a brief presentation and to lead the discussion. If this is done, the students should be assigned the task of preparing for the presentation and discussion one or two weeks in advance.
- This lab is light on quantitative analysis; it is highly qualitative in the nature of observations that can be made. At the same time, the success of executing the assignments depends on careful work and favorable conditions. For example, it is desirable to schedule the lab for a day when the humidity is expected to be low.
- It is highly recommended that the instructor and any assistants carry out the lab themselves in advance, before the actual lab session with the students.

In this lab you will learn:

- the direction of the electrostatic force between two charged objects;
- the three ways objects can become charged;
- how to identify insulators and conductors;
- the factors that affect the magnitude of the electrostatic force between two charged objects.

Activity 1 Pre-Assessment

1. **Answer the following questions in your notebook:** Sometimes you get a shock after walking on a rug and touching a metal doorknob. What causes the shock? Does the kind of shoes you wear affect whether you get a shock? Why do you feel the shock only when you touch a doorknob, as opposed to the wooden part of a door?
2. **Answer the following questions in your notebook:** When clothes are taken out of a dryer, sometimes two pieces of clothing stick together, and sometimes they fly away from each other. Could charge differences cause each of these interactions to occur?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 1: Static Electricity Interactions

Charged objects exert electrostatic forces on each other. In these interactions, charges of the same sign repel each other, and charges of opposite sign attract each other. Charging occurs in three distinct ways. In **charging by friction,** surfaces that move against each other are charged. The motion provides energy to separate electrons from atoms and move the electrons from one surface to another. The direction of electron transfer is determined by the ability of each material's surface to hold or give up electrons.

When an object is charged, it can charge a neutral conducting object by the process of **induction** if the neutral object is **grounded.** During charging by induction, the two objects are not touching. For example, when the negatively charged rod shown in Figure 13.1 is brought near the neutral metal sphere, electrons inside the sphere move in response. As a result, negative charge and positive charge accumulate in different parts of the sphere (Figure 13.1a). Adding a grounding wire to the sphere results in movement of negative charge away from the sphere (Figure 13.1b). Breaking the connection to the grounding wire before the charged rod is removed leaves the sphere with excess positive charge. Finally, removing the negatively charged rod creates an even distribution of positive charge in the sphere (Figure 13.1c). Therefore, in induction, the charged object induces an opposite charge in a neutral conductor without, itself losing any of its excess charge.

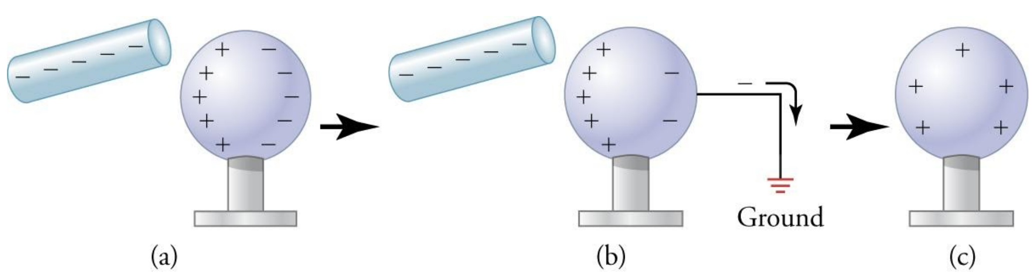


Figure 13.1: Charging by induction. (a) A charged object near the conductor redistributes charge. (b) Grounding allows charge to leave the conductor. (c) Removing the ground leaves an overall excess charge, and removing the charged object allows the excess charge to spread out evenly.

A charged object can also attract a neutral, non-conducting object, such as a small scrap of paper, because of **polarization.** If the comb shown in Figure 13.2 has a net negative charge, its electrostatic force makes electrons stay more on the far sides of the atoms in the paper and less on the near sides, polarizing the paper. The force of attraction between nearby unlike charges becomes greater than the force of repulsion between slightly farther like charges, and the scrap of paper is attracted to the comb. Note that no charge is removed during polarization.

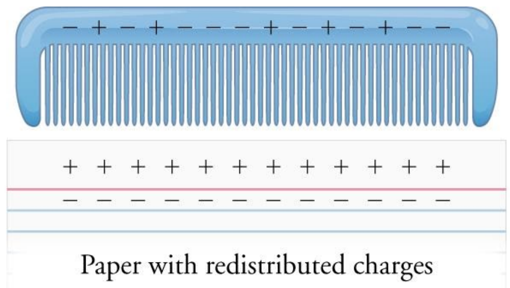


Figure 13.2: The charges in the atoms and molecules of a piece of neutral paper stay slightly closer to the opposite charges on the comb, producing an electric attraction.

Safety Precautions

- Be careful not to cut yourself on the sharp edge of the tape dispenser.

For this activity you will need the following:

- Clay
- Straws with flexible necks
- Frosted transparent tape
- Plastic rod or comb
- Wool or fur cloth
- Small piece of foil
- Small piece of plastic
- Small strips of paper

For this activity you will work *in pairs*.

Activity 1 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 1:

- The students should be reminded that the quality of the results of this activity depends on the patience and care exercised during the work. They should be reminded to keep their hands clean and to touch the pieces of tape as little as possible.
- It is possible that, in spite of the efforts, this activity will not yield acceptable results the first time it is attempted by the students. In this case, the instructor should encourage the students and direct them to repeat the experiments from scratch.

The following are recommendations for the Guided Inquiry for Activity 1:

- The students should be encouraged to relate their analysis of the results of this activity to the background information provided at the beginning of the lab session and at the beginning of this lab module. If the students cannot come up with specific connections, they should be asked direct questions, such as, "What law does this particular observation illustrate?"
- It is beneficial to encourage the students to come up with suggestions for improving the agreement between the measurements and the presented theory. This is a lab module that can take patience and care to execute, so it should be relatively easy for the students to come up with a list of influences that can reduce the accuracy and then to provide ideas as to how to improve the lab setup. If the students have difficulties with this, the instructor can ask helping questions, such as, "What do you see as the reason why the first try of this or that particular measurement failed?"

Structured Inquiry

Step 1: Charging Pieces of Tape: You can prepare charged pieces of tape and suspend them from straws to observe their interactions. To do this, follow these steps:

1. Create two cubes of clay, each about 1 inch (2.5 cm) on each side.
2. Place two straws in each cube at the same height, as shown in Figure 13.3.
3. Bend each straw so that it has a horizontal arm as shown. The four arms will each hold a charged piece of tape.
4. Press two pieces of tape, each about 6 inches (15 cm) in length, flat on your tabletop, sticky side down. These base pieces of tape will stay on the table.
5. Place a second piece of tape, sticky side down, on top of each base tape, and press firmly. Fold one end to act as a handle, and write "A" on it.
6. Now add a third piece of tape on top of the A pieces of tape, sticky side down, and press firmly. Fold one end to act as a handle, and write "B" on it.

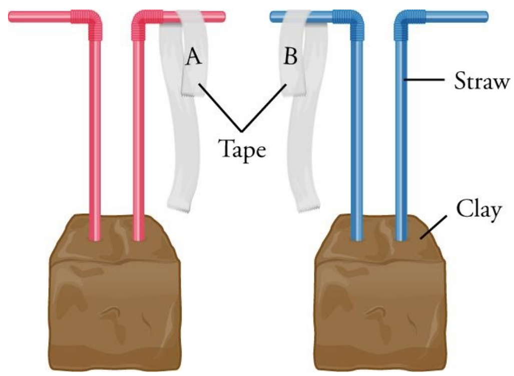


Figure 13.3: The first two charged pieces of tape are placed on the straw arms.

Step 2: Hypothesize/Predict: If your group prepares the four pieces of tape as described in Step 1, predict whether the pieces of tape will become charged and if they will have different or similar charges. Which pieces of tape might have a similar charge? What will be the direction of electrostatic force when each combination of two pieces of tape—AA, BB, and AB—interact? Record your predictions in a table in your notebook.

Step 3: Student-Led Planning: Quickly tear the A and B pieces, still sticking together, from the base tape. Then pull A and B apart quickly, and hang each piece of tape on the straw arms. Figure 13.3 shows the setup. Observe and record the interactions between the pieces of tape in your notebook.

Step 4: Critical Analysis: Did the pieces of tape become charged? Were the predictions you made in Step 2 supported by your data? Why or why not? Does tape have one or two kinds of surfaces, and how does this affect charging? If the tape became charged, what kind of charging occurred? Discuss your answers with your partner, and record the information in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: When a comb is rubbed with wool, the comb becomes negatively charged, and the wool becomes positively charged. How will charged objects like these interact with the charged pieces of tape (A and B)? How will a neutral metal object affect the charged piece of tape after they come into brief contact? How will a neutral plastic object affect the charged piece of tape after they come into brief contact? How will a neutral paper object interact with a charged piece of tape if there isn't any contact but it's held close by? Record your predictions for each of these scenarios in a table in your notebook.

Step 2: Student-Led Planning: Choose at least two charged and two uncharged objects to create the scenarios described in Step 1. Review the list with your teacher, and then carry out each scenario. Observe and record the interactions in the data table in your notebook.

Step 3: Critical Analysis: Were you able to determine the charges on the A and B pieces of tape? If yes, what are their charges? Which scenario included conduction? What happened in this scenario? Which scenario included charging by polarization? What happened in this scenario? How did touching the tape to the foil and/or plastic affect the charge on the tape? How were you able to determine this? Discuss your answers with your partner, and record the information in your notebook.

Assessments

1. Wood attracts electrons more strongly than nylon does. A wooden dowel is rubbed with nylon cloth, and electrons move as a result.
   a. Draw *before* and *after* pictures and describe the change in charge distribution on the dowel and cloth before and after the electrons move. In the *before* picture, draw 10 negative charges and 10 positive charges on the dowel and 10 negative charges and 10 positive charges on the cloth. Then show the change that occurs in the *after* picture.
   b. What kind of charging is described in part a? [EK 5.C.2; SP 1.1, 6.4]
2. In a science museum, a person touches a positively charged Van de Graaff sphere, and electrons move as a result. The person's strands of hair fly up upon becoming charged.
   a. Draw *before* and *after* pictures and describe the change in a charge distribution on the positive sphere and the person before and after the electrons move. In the *before* picture, draw five negative charges and 10 positive charges on the sphere, and 10 negative charges and 10 positive charges on the person. Then show the change that occurs in the *after* picture.
   b. Explain why the person's strands of hair flew up. [EK 5.C.2; SP 1.1, 6.4]
3. A negatively charged comb attracts a neutral piece of paper suspended from a string.
   a. Draw *before* and *after* pictures and describe the change in charge distribution in a piece of neutral paper when the negatively charged comb is brought nearby. In the *before* picture, draw 10 negative charges and five positive charges on the comb and five negative charges and five positive charges on the paper, evenly distributed. Then show the change that occurs in the *after* picture.
   b. Why is the charged comb able to attract the neutral piece of paper in this scenario?
   c. When the comb is removed, the charges in the paper move until they again become evenly distributed. Explain why this occurs. [EK 5.C.2; SP 1.1, 6.4]
4. You charge a comb and place it halfway between two pieces of sticky tape. You observe that both pieces of sticky tape are attracted to the comb. However, the first piece of tape is attracted more strongly to the comb than the second piece of tape is. Propose *two* possible explanations for this observation. [EK 5.C.2, SP 1.1, 6.4]
5. A student holds a neutral metal ball with an attached glass rod. The student brings the ball near a negatively charged rubber rod and then touches the ball to a nearby metal faucet.
   a. Create a drawing to show the charges on the rubber rod and metal ball when the two objects are held near each other.
   b. What happens when the metal ball touches the faucet?
   c. What is the final charge of the metal ball, and what kind of charging occurred? [EK 5.C.2; SP 1.1, 6.4]

[Solutions]

1. [EK 5.C.2; SP 1.1, 6.4]
    a. The drawing must show the following: some or all the electrons on the nylon have moved to the wood, the charge is conserved, and the positive charges do not move.
    b. Charging by friction
2. [EK 5.C.2; SP 1.1, 6.4]
    a. The drawing must show the following: five of the electrons have moved from the person to the sphere, the charge is conserved, and the positive charges do not move.
    b. The strands of hair become positively charged and repel each other.
3. [EK 5.C.2; SP 1.1, 6.4]
    a. Because the electrons in the paper move away from the comb, the part of paper near the comb is positively charged. Different charges attract each other. The drawing must show the following: The charges in the paper become distributed, with positive charges near the comb and negative charges farther away from the comb; no charges are transferred; and the charge is conserved.
    b. Polarization of the paper by the charged comb
    c. When the charged comb is moved away, the only forces on the charges in the comb are attraction between unlike charges and repulsion between like charges. These forces cause the charges to move so that they are evenly distributed in the paper.
4. [EK 5.C.2, SP 1.1, 6.4] One possible scenario is that both pieces of tape have the same kind of charge, but the first piece of tape has more charge. Another possible scenario is the first piece of tape is charged and the second piece of tape is neutral and moves because of polarization.
5. [EK 5.C.2; SP 1.1, 6.4]
    a. The drawing must show the following: the rubber rod has excess negative charge, and the metal ball has equal number of positive and negative charges that are unevenly distributed. The positive charges are located on the side of the ball near the rubber rod.
    b. The faucet provides a path to ground. Negative charges move away from the metal ball.
    c. The metal ball is positive due to induction by the charged rod.

Activity 2 Pre-Assessment

1. **Answer the following questions in your notebook:** When you charged pieces of tape, you observed that they exerted electrostatic force on each other. What variables affect the strength of electrostatic force? What variables are directly and inversely proportional to the strength of electrostatic force? What might an equation for the strength of electrostatic force look like?
2. **Answer the following questions in your notebook:** When electrostatic force is used on a charged balloon suspended on a string to move it upward and sideways, what forces oppose the electrostatic force? How could you use your knowledge of these opposing forces to measure the strength of the electrostatic force?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 2: Coulomb's Law

Electrons respond to other electrons because charged objects exert electrostatic forces on each other. The force acts over a distance and has both direction and magnitude. Like charges repel, and unlike charges attract.

The electrostatic force acts between pairs of charged objects. The variables that affect the strength of the electrostatic force are the magnitude of each charge, measured in coulombs, and the distance between the charges. If the amount (magnitude) of charge is increased, the electrostatic force is stronger. If the distance between charges is increased, the electrostatic force is weaker.

Coulomb's law states the electrostatic force is proportional to the product of the charges and inversely proportional to the square of the distance between them. In equation form, the force F between two charges q_1 and q_2 is equal to

$$F = k\frac{q_1 q_2}{r^2},$$

where F is the electrostatic force in newtons (N); q_1 and q_2 are the amounts of charge on two charged objects, in coulombs (C); r is the distance between the objects in meters (m); and k is a constant, 9.0×10^9 N•m^2/C^2. When the charges have the same sign, the force calculated with this equation is positive; this corresponds to repulsion. If the charges are opposite, the force is negative, which signifies attraction (the direction of the force is toward reducing the distance between the charges).

The electrostatic force between two charged objects can be measured in a laboratory experiment. If two balloons are charged and suspended with threads from a common attachment point, they will repel each other. The vertical and horizontal components of the forces on the balloons are balanced, as shown in Figure 13.4. The absolute values of the vertical components in the diagram are equal to the gravitational forces on the balloons. Gravitational force, or weight, is equal to the mass of the balloon times the gravitational acceleration, *g,* 9.8 m/s^2. The absolute values of the horizontal components in the diagram are equal to the electrostatic forces on the balloons. This quantity is unknown, but it can be calculated using trigonometry. The absolute value of electrostatic force is related to the absolute value of gravity and the angle θ by the tangent function

$$F_{\text{coulomb}} = mg \tan\theta \; .$$

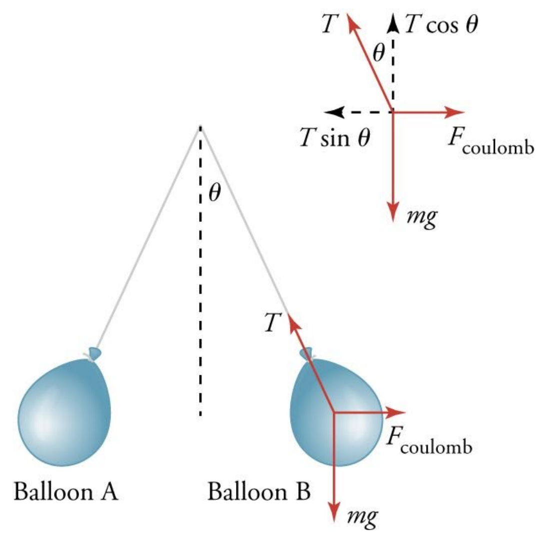


Figure 13.4: The electrostatic force between two charged balloons can be observed and measured.

Safety Precautions

- Do not place charged objects near electronic devices.

For this activity you will need the following:

- Two balloons
- Marking pen
- Two pieces of thread, each 3 feet (1 m) in length
- Stand to suspend the balloons (a yardstick or meter stick with a thumbtack, laid across a space between two lab desks can be used if a stand is not available)
- Balance that can measure the mass of the balloons
- Wool or fur cloth
- String with an attached weight that can serve as a plumb line
- Protractor

For this activity, you will work *in pairs.*

Activity 2 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 2:

- The general advice about execution of this activity is the same as for Activity 1. However, it is to be expected that the students will acquire some experience by the time they proceed to Activity 2, and so this section of the lab should carry out more smoothly.
- It is crucial that the instructor rehearses this activity in advance to confirm that the balloons are capable of producing acceptable charges.

The following are recommendations for the Guided Inquiry for Activity 2:

- Because this activity does involve more quantitative analysis, the students should be briefly reminded about the concepts of accuracy, precision, and employing repeated measurements to obtain acceptable averages of the measurements and the resulting physical properties. The students should roughly assess the error bars of their results and present their estimates to the instructor before concluding the activity.
- Similar to the suggestion for Activity 1, the students should be encouraged to produce recommendations for improving the experimental setup and making the agreement between theory and the measurements become closer.

Structured Inquiry

Step 1: Setting Up the Balloons: Begin by setting up the balloons using the following method:

1. Label two balloons “A” and “B.”
2. Find the mass of each empty balloon and record it in Table 13.1.
3. Blow up the balloons (assume the mass of air is negligible), tie their ends, and tie each balloon to a 1 yard (1 m) length of string.
4. Suspend each balloon from the stand. Measure the distance from the support (or plumb line) to the center of each balloon and record it in Table 13.1. (Note that the setup data is measured now but not used until the subsequent activity.)

Step 2: Hypothesize/Predict: Predict the motion of the balloons when they are first charged. Predict how the motion of the balloons will change when one balloon is rubbed more times. Predict how the motion of the balloons will change when they are placed closer and farther away from each other.

Step 3: Student-Led Planning: Discuss with your partner how you will be able to determine if your predictions are correct and what quantities you will measure. Review your method with your teacher before you begin. Then, rub each balloon with fur or wool cloth to charge it, and measure the distance between the balloons. Record your trials and findings in your notebook.

Step 4: Critical Analysis: Were the predictions about the electrostatic force you made in Step 2 supported by your data? Why or why not? Did your data support Coulomb's law? Explain your reasoning in detail. What methods could you have used that would have improved your results? Discuss your answers with your partner, and record them in your notebook.

Table 13.1: Data for Setup

	Mass (*m*, in g)	Distance from Support to Center of Balloon (*l*, in m)
Balloon A		
Balloon B		

Guided Inquiry

Step 1: Hypothesize/Predict: Predict an approximate magnitude of force that you think the two charged balloons exert on each other. Explain your reasoning for your prediction.

Step 2: Student-Led Planning: With your partner, determine a way to measure the force between the two charged balloons and the amount of excess charge on each balloon. Review the introduction and consider other forces on the balloons as you work on a method. Review your method with your teacher, and record it in your notebook before you begin. Create a data table in your notebook to record your findings, and then carry out your experiment.

Step 3: Critical Analysis: Was the prediction you made in Step 1 supported by your data? Assuming both balloons have the same amount of charge, what is the charge in coulombs on each balloon? How would you determine this? Given that an individual electron has a charge of -1.602×10^{-19} C and a proton has a charge of 1.602×10^{-19} C , how many excess individual charges are found on each balloon? Discuss your answers with your partner, and record your calculations in your notebook.

Assessments

1. An electronic equipment company had some components fail because electric charge built up on employees and discharged when they touched the equipment. The company has changed the flooring material and issued special shoes to the employees to prevent the buildup of charge.
   a. Describe what kind of material (conductor or insulators) the floor and shoes should be made of, and explain why that material will prevent a buildup of charge on employees.
   b. Describe what data you would collect to decide if a new material prevents a buildup of electric charge. [EK 5C.2, SP 1.1, 6.4]
2. Two charged objects exert an electrostatic force of 0.08 N on each other. The objects are moved so that the distance between them is halved.
   a. How much electrostatic force do the two objects exert on each other after they're moved closer together?
   b. Explain the mathematical reasoning you used to obtain your answer. [SP 1.1, 6.4]

[Solutions]

1. [EK 5C.2, SP 1.1, 6.4]
   a. Conducting materials should be used. This is because charges will flow from the person to the floor and spread out.
   b. You would collect data about how much excess charge is found on a person after working with each material.
2. [SP 1.1, 6.4]
   a. The electrostatic force is 0.32 N after the move.
   b. The distance is halved, so the new distance is $\frac{r}{2}$. The change in force exerted on one charged object by another is proportional to the reciprocal of change in distance squared. The distance was halved, so the force increases by a factor of four (2^2).

Lab 14: Ohm's Law

All electrical devices require electrical energy to operate. For example, a battery provides the electrical energy to run a flashlight in Figure 14.0. The battery uses stored chemical energy to produce a flow of electric charge in a complete closed path, namely from the battery, along the wire, through the lightbulb filament, and along a wire back through the battery. A closed pathway of this kind for the flow of charge is an **electric circuit**. The flow of charge carries energy from the battery to the filament.

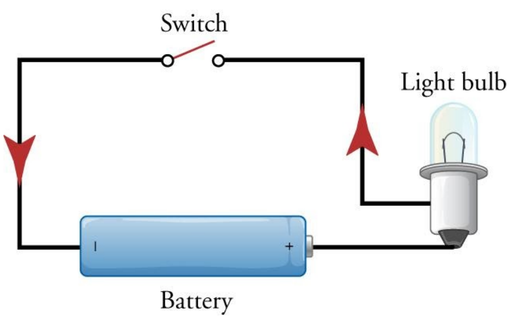


Figure 14.0: Electric circuit of a flashlight, with charge flowing from the battery (when the switch is closed), through the bulb, and back through the battery.

The flashlight battery acts as an energy source in the electric circuit. Chemical processes inside the battery can do work by moving charge from one battery terminal to the other, creating an electric potential difference between the two terminals (also known as **voltage**). Chemical energy within the battery is transformed into electric potential energy, and the voltage (V) can be found by dividing the difference in potential energy the charge would have at the two terminals by the amount of charge. As a result of charge separation inside the battery, an electric field is established between the two terminals of the battery, directed from the positive terminal toward the negative terminal. When conducting wire is connected to the battery terminals, this electric field pushes free electrons through the wire. The resulting flow of electric charge through an external circuit is called an **electric current.**

In a metallic wire, negatively charged electrons carry the electric current. Historically, however, we have described electric current in terms of the conventional current, which is the flow of hypothetical positive charges that would have the same effect as the flow of electrons. However, as electrons travel through the circuit, they collide multiple times with the atoms within the wire or other conducting material. These collisions randomize the motion of individual electrons, impeding the current and causing energy to be lost as heat. This phenomenon is called electrical **resistance** and explains why some conducting materials carry current more efficiently than others.

Ohm's law describes the relationship between the voltage applied across a material, the resistance of this material, and the resulting current through a piece of material. It was discovered by German physicist Georg Simon Ohm (1787–1854), based purely on the experimental evidence that he had collected.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- If the students are not familiar with circuits, an exercise such as connecting a bulb, battery, and wire to light the bulb should be completed to introduce circuits.
    - Provide a single piece of wire, a battery, and a lightbulb. Challenge the students to make the bulb light up. You'll find that it's more difficult than you imagine for most. Be sure to have *not* handed out the lab yet, as the illustrations might lead them to a conclusion without having actually learned why they did what they did.
- Remind students that Ohm's law is a direct relationship between the voltage, current, and resistance. Namely that $V = I \times R$.
- You will want to review the symbols associated with a battery, lightbulb, and resistor vs. a pictorial-type representation.
- Discuss that the physical layout of the circuit is not what makes it operate properly but the electrical connections themselves. For example, the battery can be shown on the opposite side of the lightbulb from what is illustrated in Figure 14.0, and the bulb would remain lit.
- For an object to be a resistor, it has a length between where the voltage is connected that the current will travel along, it has a cross-sectional area (an opening) that the current will pass through, and it is made of a material that allows electrical current to flow through it. That being said, have the students understand that the lightbulb itself is also a resistor.
    - This will be investigated further in Activity 2.

In this lab you will learn:

- the relationship between current, voltage, and resistance in a simple circuit;
- how to calculate resistance, current and voltage using Ohm's law, as well as how to measure these variables in an actual circuit using a multimeter;
- what factors affect resistance of various materials.

Activity 1: Pre-Assessment

1. **Answer the following questions in your notebook:** What is an electric circuit? What is needed for electric charge to flow from one end of a conducting wire to another? Does voltage produce current, or does current produce voltage?
2. **Answer the following questions in your notebook:** What simple experimental demonstration would illustrate the cause-and-effect relationship between resistance and current in an electric circuit? What materials would you use for your demonstration? Draw a circuit diagram to show how you connect your materials. Explain what observations you will be making.
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 1 Resistance and Current

We can create a simple electric circuit using a source of electrical energy (battery), a conductor of the electrical energy (wire) connected to the energy source, and a device that uses and transforms the electrical energy (lightbulb).

Current can be measured with an **ammeter** and voltage with a **voltmeter.** You may also use a multimeter that combines these functions, and often some others, into a single instrument as illustrated in Figure 14.1. The current is measured in amperes (A). One ampere is the rate of flow of one coulomb (C) of charge per second. To measure the current, the ammeter must be inserted in the circuit so that the current passes directly through it.

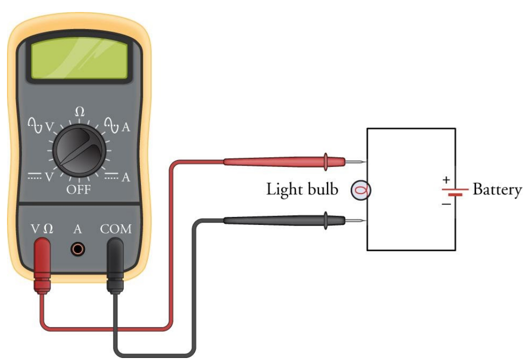


Figure 14.1: A multimeter used as a voltmeter to measure electrical potential through a circuit. This multimeter measures voltage (V) and electrical resistance (Ω) using the same wire port. However, the dial is set to measure voltage.

Described earlier was electrical resistance on a microscopic level, how it results from obstacles to the flow of electrons in the conducting material. We now use a very common analogy that compares the flow of charge through a conductor to the flow of water through pipes. In this analogy, the voltage is represented by the hydrostatic pressure of water, and current is represented by the water flow. Consider a water tank with two pipes, one narrow and one wide, as shown in Figure 14.2. Water flows through the narrow pipe at a slower rate than through the wider pipe under the same pressure. We can regard the narrow pipe to have greater resistance to water flow. Think of this analogy as you explore the relationship between current and resistance in a simple circuit with constant voltage.

The unit of voltage is volt (V). One volt is an energy of one joule per coulomb of electric charge. A voltage of one volt between two points means that electric charge has one joule per coulomb more energy at one point than at the other. A voltmeter measures the voltage (electric potential difference) between two points in a circuit. Therefore, the voltmeter must be connected across the points and is not inserted into the circuit.

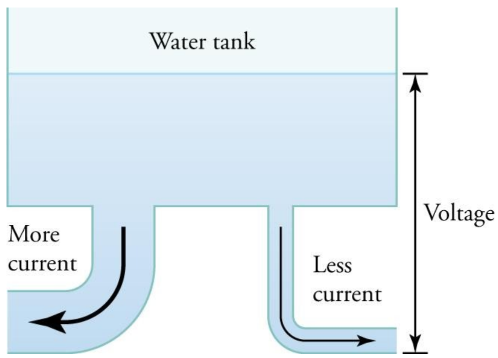


Figure 14.2: The equal water pressure (hydrostatic pressure) at both pipe openings is analogous to the same voltage across two conductors. The pipe width is analogous to the reciprocal of resistance (wider pipes resist less), and the water flow through the pipe is analogous to electric current.

Electrical resistance is measured in ohms (Ω). One ohm is the resistance for which a 1 V difference in electric potential produces 1 A of current. You can use an **ohmmeter** or multimeter to measure resistance. Disconnect the resistor from the battery before measuring resistance. Then connect the leads of the ohmmeter across the resistor as shown in Figure 14.3.

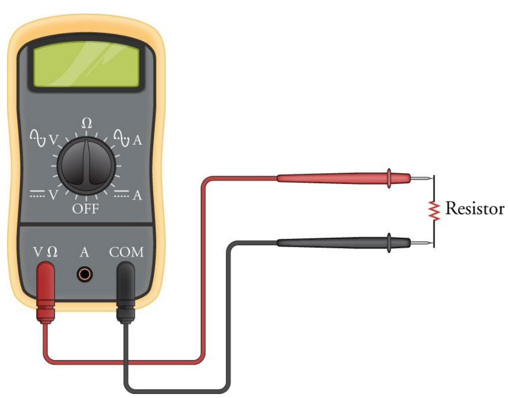


Figure 14.3: Measuring resistance with an ohmmeter.

Safety Precautions

- If you choose to use a power supply rather than a battery pack, set the voltage to a fixed maximum around 5 V.
- Emphasize proper meter usage.

For this activity you will need the following:

- Battery holder(s) that can hold up to four batteries
- Four batteries
- Wire leads with alligator clip
- One miniature light bulb with corresponding bulb holder (check maximum voltage for lightbulb to avoid burnout)
- Four to six different resistors
- Basic multimeters or single-value meters (ammeter and ohmmeter)

For this activity you will work *in pairs*.

Activity 1 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 1:

- The voltage (1.5–6.0 V) and current involved in the experiments are of no immediate safety concerns to students. Nonetheless, they should learn precautions with how to deal with electricity safely to form good habits (e.g. not touching conducting parts, except with insulated forceps, gloves, etc.)
- All resistors operate within a tolerance range (usually plus or minus 5 to 10 percent). As such, you will want to discuss the students' resistor value findings with the expected value of the resistor provided (from a printed label or its color code).
- If the probes of the multimeter are connected correctly in the circuit for the current and/or voltage measurements, the display will indicate a positive number. A negative result means that the probes are backward, not that the magnitude of the value shown is incorrect.
- Be mindful that the resistance of a resistor increases with temperature. Therefore, circuits that are connected for a long period will show the lightbulb getting dimmer and dimmer because of the current flow heating the resistor.
    - An extension would be to place an ice cube on a hot resistor and observe the effect on the brightness of the lightbulb.
- Additional extensions could involve the use of resistor combinations in the lightbulb circuit. Have the students predict the relative brightness for a series and a parallel circuit that contain the same resistors.

The following are recommendations for the Guided Inquiry for Activity 1:

- Graphical analysis of this data is useful in seeing trends. In particular, a plot of voltage vs. current.

- Students should find the resistance of any single resistor to be relatively constant within the allowed tolerance for that resistor.
  - However, measurements for extremely small resistors might have the adverse effect of resistance from the wiring interfering with the measurements. A discussion about wires and the minimization of extra resistance should be completed.
  - Additionally, the use of extremely large currents may cause undue resistor heating, which in turn can skew a resistor's value.

Structured Inquiry

Step 1: Hypothesize/Predict: Put together a simple circuit to light the light bulb using batteries. Suppose you inserted different resistors into the circuit without changing the light bulb or batteries? How do you predict this would affect the current and the brightness of the light bulb? How do you predict changing the voltage by changing the number of batteries in series would affect the current through the light bulb? Write your predictions in your notebook.

Step 2: Measure resistance of all resistors, and record these values in your notebook. Construct the simple circuit shown in Figure 14.4 with one resistor.

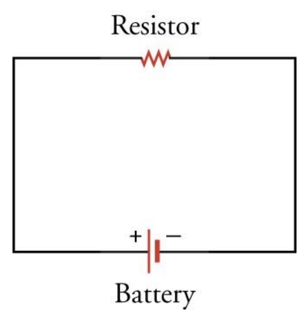


Figure 14.4: A simple circuit consisting of a resistor and a battery.

Step 3: Student-Led Planning: Add a lightbulb into the circuit. Then, change the number of batteries in series. Observe the effect on the lightbulb, and record your observations. Discuss with your partner how best to measure the current. Create a data table for the measurements of current and resistance in your notebook. Include correct units in all measured values. Test the predictions you made in Step 1.

Step 4: Critical Analysis: Does your data support the predictions you made in Step 1? Does it support your statement with calculations? Why or why not? Describe the relationship you found between the voltages across the resistor, and express it mathematically. Discuss your answers with your partner, and then write them in your notebook. Discuss the results of the experiment with your partner, and then write your conclusion in your notebook. Formulate the relationship you found between the current through the resistor and the resistance both descriptively and mathematically.

Guided Inquiry

Step 1: Hypothesize/Predict: What is the mathematical relationship between voltage, current, and resistance? Write your prediction in your notebook.

Step 2: Student-Led Planning: Decide with your partner how you can confirm your prediction experimentally. Think of conducting several experiments. For each experiment, identify which variable(s) you will control and which variable(s) you will vary. Design the data table for each experiment, and complete the experiments.

Step 3: Critical Analysis: What mathematical relationship between the current, voltage, and resistance do your findings in Activities 1 and 2 suggest? How can you use your experimental data in this part of the investigation to confirm this relationship? Discuss your answers with your partner, and write them in your notebook.

Assessments

1. From their recent trip to Russia, your parents/guardians brought home an electrical samovar for making tea, as done in traditional Russian tea ceremonies (Figure 14.5). The samovar is designed for a 220 V electric outlet. Your family invited guests to a ceremony and plugged the samovar into the wall outlet (110 V), but water did not boil. Why? [EK 4.E.5; SP 6]

Figure 14.5: Traditional Russian samovar for boiling water.

2. Each of the three simple circuits have the same battery. The voltages of batteries for each circuit and the current through the first circuit are shown in Figure 14.6.

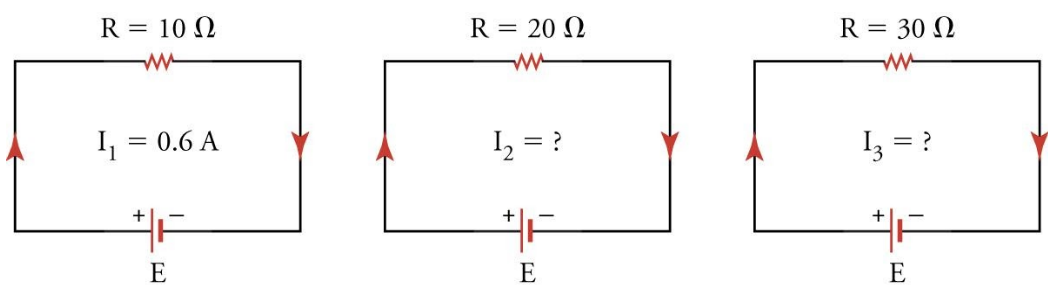


Figure 14.6

   a. What is the current in the second circuit?
   b. What is the current in the third circuit?
   c. Explain your reasoning. [EK 1.B.1; EK 4.E.5; SP 6]

3. A light bulb filament has a resistance of 580 Ω. A voltage of 120 V is connected across the filament. How much current is in the filament? [EK 1.B.1; EK 4.E.5; SP 2]

4. A variable resistor is connected to a battery. Each value of the resistance and the corresponding current is listed in Table 14.1 Question 3. Use the data to determine the voltage of the battery. Explain your reasoning and calculations. [EK 4.E.5; SP 5]

Table 14.1 Question 3

Resistance (kΩ)	Current (mA)
0.01	300
0.10	30
0.33	9.1
0.56	5.4
1.0	3.0
10.0	0.3

[Solutions]

1. [EK 4.E.5; SP 6] The samovar works like an electric kettle. When you plug the kettle into an electrical outlet, a large electric current flows into the heating element. The element's resistance turns the electrical energy into thermal energy. The samovar is designed to boil water with an input of 220 V. When it is plugged into a 110 V electrical outlet, the current through the heating element is lower. The samovar, therefore, does not release sufficient heat to boil the water.
2. [EK 1.B.1; EK 4.E.5; SP 6]
   a. In the second circuit the resistance is two times the resistance in the first circuit, so the current is one-half that in the first circuit, i.e.,

   $$I_2 = \frac{10}{20} \times (0.6\ \text{A}) = 0.3\ \text{A}.$$

   b. In the third circuit the voltage is three times the voltage in the first circuit, so the current is one-third of that in the first circuit, i.e.,

   $$I_2 = \frac{10}{30} \times (0.6\ \text{A}) = 0.2\ \text{A}.$$

   c. According to Ohm's law, the current through the resistor is inversely proportional to its resistance. Therefore, $I_1 R_1 = I_n R_n$,
3. [EK 1.B.1; EK 4.E.5; SP 2] According to Ohm's law, $I = \frac{V}{R} = \frac{120\ \text{V}}{580\ \Omega} = 0.2\ \text{A}$.
4. [EK 4.E.5; SP 5] According to Ohm's law, the current through the resistor is inversely proportional to the resistance, so the product of current and resistance remain the same. This means that the circuit satisfies Ohm's law and voltage of the battery can be found as $V = IR$. Calculations shown in the table confirm that Ohm's law can be applied and that the battery voltage is 3.0 V.

Table 14.2

Resistance, kΩ	Current, mA	$V = I \cdot R$
0.01	300	3.0
0.10	30	3.0
0.33	9.1	3.0
0.56	5.4	3.0
1.0	3.0	3.0
10.0	0.3	3.0

Activity 2: Pre-Assessment

1. **Answer the following questions in your notebook:** What is the resistance of an electric skillet that draws 12 A of current when connected to 120 V circuit? Metals are electrical conductors, so why do they have resistance to the electric current?
2. **Answer the following questions in your notebook:** What do we mean by an "intrinsic property of a material"? Give an example of an intrinsic property. Give an example of a property of a material that is not intrinsic. Can you make two wires from the same material that have different resistance? Can you make two wires from different materials that have the same resistance?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 2 Resistance and Resistivity

Based on Ohm's law, the electrical resistance of a conducting object (e.g., a wire) is defined as the ratio of the voltage across the object to the electric current through it. Recall the analogy between the flow of charge through a conductor and the flow of water through a pipe. The narrow pipe resists water flow more than the wide pipe. By analogy, a thin wire has more resistance to electric current than a thick wire. The longer pipe resists water flow more than a short pipe. By analogy, a longer wire has more resistance than a short wire. Recall that electrical resistance results from obstacles to the flow of electrons in the conducting material. Therefore, the electrical resistance also depends on the material composing the conductor. Electrical resistivity is an intrinsic property that quantitatively describes how strongly a given material will oppose electric current.

In this activity you will compare resistance of wires made from different materials that have different length and/or cross-sectional areas, and you will determine a mathematical relationship between resistance, resistivity, length, and cross-sectional area of a resistor. We will assume that all wires have cylindrical shape. The cross-sectional area of a cylinder is the area of a circle formed at its base. If the radius of the cylinder is *r*, then cross-sectional area is πr^2. The length of the cylinder is also the height of the cylinder defined as the perpendicular distance between the bases.

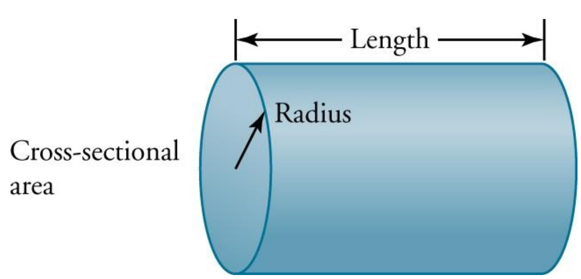


Figure 14.6: The cylinder shown represents the shape of a typical wire.

Safety Precautions

- Emphasize proper meter usage.
- Note that the wire may become hot when connected to the voltage source for long periods of time.

For this activity you will need the following:

- Wires of different diameter and length (at least three different diameters per length per material, three different lengths per diameter per material, and three different materials per length per diameter)
- An ohmmeter or multimeter
- Ruler for length measurements
- Caliper for diameter measurements
- Table of values of electrical resistivity for common metals that includes metals used in this activity

For this activity you will work *in pairs*.

Activity 2 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 2:

- The class as a whole can compare observations of the three properties (length, cross-sectional area, and resistivity) for the various objects. You can then point out what the explanations have in common and how they are different.
- Graphical analysis of this type of data collection can enhance the students' ability to see the patterns involved.
- An extension could involve the use of combinations of the wires. Have the students predict the resistance/voltage/current for a series and a parallel combination that contain the same wire segments.
- Have the students find (at school or at home) three items they feel have a range of resistance (high, medium, and low). Have a class discussion about each of the items, and have the students justify their selections. Following, have the students test the resistances to see if they were correct.

The following are recommendations for the Guided Inquiry for Activity 2:

- Stress that diameter is not the same as cross-sectional area. Although related, neither the numerical values nor the units work out correctly if diameter is used in place of area.
- Discuss the units for resistivity and why they are important.
- As before, the use of extremely large currents may cause undue heating of the wire samples, which in turn can skew their resistance/resistivity values.

Structured Inquiry

Step 1: Hypothesize/Predict: What is the relationship between the resistance of a wire and its length? What is the relationship between the resistance of a wire and its cross-sectional area?

Step 2: Student-Led Planning: Discuss with your partner how best to take the measurements to find each relationship you predicted in Step 1. Think of conducting one experiment for each relationship. For each experiment, identify which variable(s) you will control and which variable(s) you will vary. For example, to find the relationship between the resistance of a wire and its length, you should use wires of the same diameter made from the same material but in different lengths. Design the data table for each experiment and complete the experiments.

Step 3: Critical Analysis: Discuss the results of each experiment with your partner. For each experiment, describe how the resistance of a wire depends on the specific properties of the wire, and express this relationship mathematically. Explain how you arrived at the mathematical formula describing each relationship.

Guided Inquiry

Step 1: Hypothesize/Predict: Which material has higher resistivity? How does the resistance of a wire depend on the resistivity of the material from which it is made? What is the mathematical relationship between resistance and resistivity?

Step 2: Student-Led Planning: Discuss with your partner which variable(s) you will control and which variable(s) you will vary to test the relationship between resistance and resistivity. For resistivity values, use the reference table provided by your teacher. How will you organize your data? Display your data in the best way to test your predictions. Carry out necessary measurements of controlled and varied variables.

Step 3: Critical Analysis: Were the predictions you made in Step 1 supported by your data? Discuss the results of the experiment with your partner, and then write your conclusions in your notebook. Using your data, develop a mathematical relationship between resistance and resistivity of a wire. What role does length and cross-sectional area of a wire play in this relationship? Use your findings from previous activities to develop a formula that can be used to calculate resistance of a wire based on resistivity of the material, length, and cross-sectional area of the wire. Confirm your formula for wires that you have available to you.

Assessments

1. Does the resistance of a copper wire increase or decrease when both the length and the diameter of the wire are doubled? Justify your answers. [EK 4.E.4; SP 6]
2. Two wires have the same length and the same resistance; one is made from aluminum, and the other one is made from copper.
    a. Explain how that is possible.
    b. Provide calculations to support your explanation. [EK 1.E.2; EK 4.E.4; SP 6]
3. The resistance of a particular wire is 21 Ω. It is melted down, and a new wire is made from all of the melted material. The new wire is twice as long as the original wire. What is the resistance of the new wire? [EK 4.E.4; SP 2]

[Solutions]

1. [EK 4.E.4; SP 6] When the length of the wire is doubled, the resistance is doubled because resistance is proportional to the length. When the diameter is doubled, the cross-sectional area is quadrupled, because the resistance is inversely proportional to the cross-sectional area. Therefore, if both the length and the diameter of the wire are doubled, the resistance decreases by half.
2. [EK 1.E.2; EK 4.E.4; SP 6]
    a. If two wires have the same length and the same resistance but are made from different materials, then they must have different diameter.
    b. In order for resistance to be the same for the same length, $\frac{\rho_1}{\rho_2} = \frac{A_1}{A_2}$, where ϱ is resistivity and *A* is cross-sectional area.
3. [EK 4.E.4; SP 2].

    Given $R = \rho \frac{L_1}{A_1} = 21\ \Omega$, so $\rho = \frac{21 A_1}{L_1}$, the volume of the wire, can be found as a product of cross-sectional area and length. If the new wire is two times longer, then the cross-sectional area is two times smaller in order to keep the same volume. The new resistance can then be calculated as follows:

$$R = \rho \frac{L_2}{A_2} = \rho \frac{(2L_1)}{\left(\frac{A_1}{2}\right)} = \frac{(21\ \Omega) A_1}{L_1} \frac{(2L_1)}{\left(\frac{A_1}{2}\right)} = 84\ \Omega$$

.

Lab 15: Resistor Circuits

Most of the electronic devices that you use and enjoy every day contain many smaller circuits. Despite the complexity of these devices, there are only a few ways to wire the components. However, there are effectively an infinite number of ways to combine simple circuit patterns. This lab will explore basic circuit patterns that combine to form complex circuits. Within each circuit, a handful of simple rules apply. First, electric charge is conserved. This means that if some quantity of current flows into a point, then an equal quantity of charge must flow out of that point. This is especially useful when calculating how current flows at junctions where multiple wires meet. The second simple rule is that the sum of all the voltage changes around a circuit loop must always equal zero. This is based on conservation of energy. Voltage is defined as the energy per unit charge, so given that the charge is conserved by the previous rule and given that energy is conserved, we know that the voltage change must be zero.

In the first activity, you will set up circuits with bulbs in series and in parallel. Then, you will observe the circuits and summarize your observations. In the second activity, you will again set up circuits with bulbs in series and in parallel. Next, you will measure the voltage and current at various places within the circuit.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- In order for students to understand that energy cannot be created or destroyed, explain the principle of *conservation of energy*.
- For students to understand the concept of a *series* circuit, explain, with the help of a diagram, how in a series circuit, the electric current has only one path to take, and so the total resistance or voltage of the circuit will be equal to the sum of the resistances or voltages of the individual resistors.
- For students to understand the concept of a *parallel* circuit, explain, with the help of a diagram, how in a parallel circuit, the electric current has multiple parallel paths to travel, and so the resistance of voltage of each of the individual resistors will be the same as the resistance or voltage of the entire circuit.

In this lab you will learn:

- to construct or interpret a graph of the energy changes within an electric circuit;
- to apply conservation of energy concepts to the design of an experiment;
- to apply conservation of energy in calculations involving the total electric potential difference for complete circuit loops;
- to apply conservation of electric charge to the comparison of electric current in various segments of an electrical circuit.

Activity 1: Brightness of Bulbs

The basic tool for analysing electronics is a circuit. **Circuits** are closed paths around which electrons flow. The current of electrons is driven by a power source, such as a battery. In addition to a power source, a circuit includes a resistance. You will be investigating two types of circuits. **A series circuit** is a circuit in which the resistors (e.g., light bulbs) are placed in a series, so that there is only a single path for the electrons that passes through all the resistors. A **parallel circuit** is a circuit in which the resistors are placed in parallel, so each resistor provides a different path for the electrons to flow. You will construct a few examples of each circuit and record your observations. How do you think the number of bulbs and circuit types determine how the bulbs will light up? How would more complicated circuit types affect your investigation? While observing each type of circuit, consider practical situations where that type of circuit would be useful.

Safety Precautions

- Be careful with the fragile light bulbs so you do not injure yourself with broken glass.
- Do not break or pierce batteries, as they contain poisonous chemicals.

For this activity you will need the following:

- Several lengths of wire
- Three light bulbs
- One power source, most likely a battery

For this activity, you will work *in pairs or small groups*.

Activity 1 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 1:

- In advance of the lab, show students all the different items that will be used for this activity. If students need to bring any of the items, provide them with a list and instructions about where to get the items. Provide specific details about the type of wire, light bulbs, as well as type and voltage and kind of battery for the power source.
- Since the students are to work in pairs or small groups, explain what each student needs to do so that all students equally contribute to the activity. Decide in advance which students will help build the circuit and which students will record observations. Students can take turns recording the observations, so that no students are left out.
- To understand how the electric current is distributed in a series circuit, repeat the experiment with a larger number of light bulbs and a longer wire, and observe at what distance from the battery source the bulb fails to light up.

The following are recommendations for the Guided Inquiry for Activity 1:

- Create a series circuit with bulbs of different wattages. Make a table of the results of how the wattage of the bulb affects the brightness of the bulb and the distance from the circuit.
- When designing the mixed series circuit, find the configurations that make the bulbs stay the brightest and the configurations that make the bulbs the dimmest. Draw diagrams of both in your notebook.
- Build a circuit to demonstrate how the number of bulbs of the same wattage affects the brightness for both parallel and series circuits.

Structured Inquiry

Step 1: Create a simple circuit with one light bulb and one battery. Observe how bright the bulb is. Record your observations. Discuss with your partner how best to judge the brightness of bulbs qualitatively. Create data tables as needed in your notebook to list different arrangements of light bulbs and the brightness observed or predicted.

Step 2: Hypothesize/Predict: Knowing what you know about series and parallel circuits, predict how the brightness of the bulbs in the circuits depicted in Figure 15.1 and Figure 15.2 will differ. Write your prediction in the table you created in Step 1.

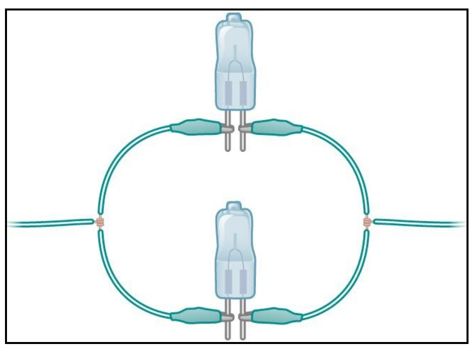


Figure 15.1: This is how to set up two light bulbs in *parallel*. Note that there is an initial wire that splits into two wires. On each of these two wires, there is a light bulb. The wires coming from the light bulb connect at a single wire.

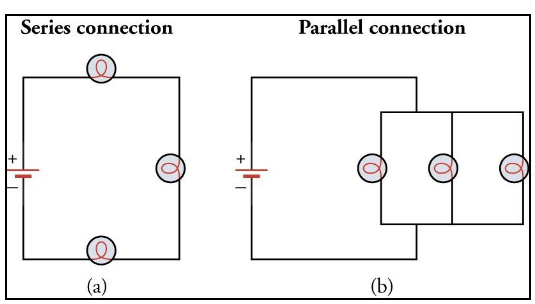


Figure 15.2: (a) A circuit with three light bulbs in a *series* connection. (b) A circuit with three light bulbs in a *parallel* connection.

Record your observations and your experimental setup, including the number of bulbs and whether they are in series or in parallel.

Step 3: Student-Led Planning: Construct the four circuits—two parallel circuits and two series circuits—using Figure 15.1 and Figure 15.2 as a guide. For each circuit, record your observations of bulb brightness.

Step 4: Critical Analysis: Were the predictions you made in Step 2 supported by your data? Why or why not? What methods could you have used that would have improved your results? Discuss your answers with your partner and then write the analysis in your notebook.

Guided Inquiry

Step 1: Student-Led Planning: Now, design four circuits with a range of arrangements, including a few mixed circuit types. Diagram each of your circuits in your notebook and show them to your teacher.

Step 2: Hypothesize/Predict: Upon approval, rank the circuits in order of how bright the bulb will shine in each. Do you think that all the bulbs in a circuit will shine with the same brightness? Is it possible that none of your bulbs will light up at all? Write your rankings and answers in your notebook. Then, create data tables that you could use to test your hypotheses.

Step 3: Construct the circuits you designed in Step 1. Observe and record your findings in your notebook.

Step 4: Critical Analysis: Which circuits had all the lights remain at the same level of brightness? Which circuits had no lights come on? How did the circuit type and number of bulbs influence which bulbs stayed lit and which ones dimmed? Discuss your answer with your partner and write the analysis in your notebook.

Assessments

1. Explain how the number of bulbs in a series circuit affected the brightness of the bulbs.
2. Explain how the number of bulbs in a parallel circuit affected the brightness of the bulbs.
3. Diagram one of the electric circuits that you made. Are the bulbs in series or in parallel? [EK 5.B.9.1]
4. With your circuit diagram from Question 3, list and describe the energy transformations within the electrical circuit. [EK 5.B.9.1]

[Solutions]

1. The brightness in each bulb gradually decreased the further they were placed from the circuit. This was more pronounced when there were three bulbs than two, because the third bulb was especially dim.
2. The brightness in each bulb was the same for each of the bulbs in parallel and brighter than the bulbs in series. Unless the current available from the batteries is limited, the bulbs in parallel should be similarly bright. In fact, when we went from two bulbs to three bulbs, we found that the bulbs in each case had the same brightness.
3. [EK 5.B.9.1] Answers will vary based on the circuit the student chooses to diagram.
4. [EK 5.B.9.1] Answers will vary. In a simple circuit with a single bulb attached to one battery, the energy will change from chemical energy within the battery to the energy carried by a flow of electrons. In the wire, some electrical energy may be transformed to thermal energy from the resistance of the wire. At the bulb, electrical energy is transformed into the energy of light and of heat.

Activity 2: Series and Parallel Circuits

For this next activity, we explore circuits quantitatively. You will use a multimeter to collect data at various points on each circuit. Then, you will develop equations that describe your observations. If you need to make additional observations, you may conduct your experiment with additional light bulbs. How do you think the number of bulbs and type of circuit determine the voltage and current? How would more complicated circuit types affect your investigation?

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- In order for students to understand how to measure electric current on a circuit, explain how a multimeter works and demonstrate how to take measurements using a multimeter.
- In order for students to understand how a circuit can contain a combination of series and parallel circuits, demonstrate with a number of resistors and a wire. Measure the voltage at both the parallel and series circuit using a voltmeter.

When you explain your results, it will be helpful to think about the results from Activity 1.

For this activity you will need the following:

- Several lengths of wire
- At least three light bulbs
- One power source, most easily a battery
- One multimeter

For this activity, you will work *in pairs or small groups*.

Activity 2 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 2:

- In advance of the lab, show students all the different items that will be used for this activity. If students need to bring any of the items, provide them with a list and instructions about where to get the items. Provide specific details about the type of wire, light bulbs, as well as type and voltage and kind of battery for the power source.
- Since the students are to work in pairs or small groups, explain what each student needs to do so that all students equally contribute to the activity. Decide in advance which students will help build the circuit and which students will record observations. Students can take turns recording the observations, so that no students are left out.

- To show how resistors work, repeat the experiment for series and parallel circuits using a resistor and record the voltage measurements using a multimeter. Demonstrate how to use a multimeter.

The following are recommendations for the Guided Inquiry for Activity 2:

- Build a circuit and tabulate the results to explain the differences in how the current and voltage change between series and parallel circuits.
- Build a circuit to find out how the current through a parallel circuit compares to the current through a series circuit if the voltage supplied by the power source is the same.
- Build an electric circuit that would allow you to collect evidence for the conservation of electric charge.

Structured Inquiry

Step 1: Create a simple circuit with one light bulb and one battery. Measure the voltage and current at various points throughout your circuit. Create a data table for your observations. Discuss with your partner where in the circuit to apply the multimeter probes to measure these quantities.

Step 2: Hypothesize/Predict: Based on what you know about series and parallel circuits, predict how the voltage and current in the circuits will change for each of the circuits you intend to investigate. Add your predictions to the data table that you created in Step 1.

Step 3: Student-Led Planning: You will now construct four circuits—two parallel circuits and two series circuits—using Figure 15.1 and Figure 15.2 as a guide. Copy the table below into your notebook. Then, decide with your partner where best to take all of the measurements listed in the table.

Data and Observations

Table 15.1

Location of Measurement	Voltage (V)	Current (A)
Series circuit with two bulbs		
Between battery and first bulb		
Between first bulb and second bulb		
Between second bulb and battery		

Series circuit with three bulbs		
Between battery and first bulb		
Between first bulb and second bulb		
Between second bulb and third bulb		
Between third bulb and battery		
Parallel series circuit with two bulbs		
Between battery and first junction		
Between first junction and first bulb		
Between first junction and second bulb		
Between first bulb and second junction		
Between second bulb and second junction		
Between second junction and battery		
Parallel series circuit with three bulbs		
Between battery and first junction		
Between first junction and first bulb		
Between first junction and second bulb		
Between first junction and third bulb		
Between first bulb and second junction		

Between second bulb and second junction		
Between third bulb and second junction		
Between second junction and battery		

Step 4: To collect these data, you will use a multimeter. Suppose that you want to obtain the voltage between two light bulbs. First, make sure the multimeter is set to measure DC voltage. Then, place one multimeter probe in contact with one conducting end of the wire between the bulbs, and the other multimeter probe to the other conducting end of the wire between the bulbs, as shown in Figure 15.3.

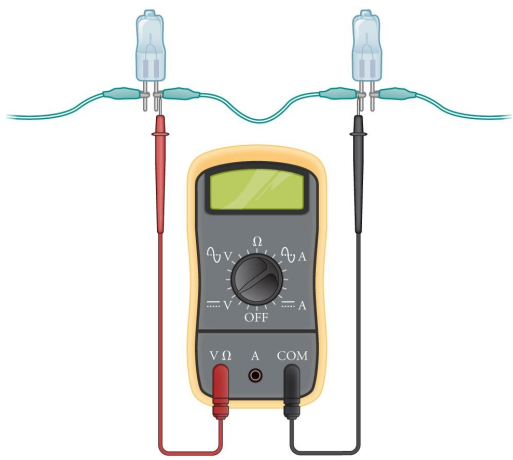


Figure 15.3: Illustration of how to measure the voltage between two light bulbs.

Make all measurements in the table above, recording voltages in volts and current in amperes.

Step 5: Critical Analysis: Were the predictions you made in Step 2 supported by your data? Why or why not? How could you have improved your results? Discuss your answers with your partner and then write them in your notebook.

Guided Inquiry

Step 1: Student-Led Planning: Now, design four circuits with a variety of arrangements, including a few mixed circuit types. Diagram each of your circuits in your notebook and show them to your teacher.

Step 2: Hypothesize/Predict: Upon approval, rank the circuits in order of the voltage and current drop that you predict they will have. Explain how you think the circuit type and number bulbs will influence how the voltage and current change. Write your ranking and answers in your notebook. Then create data tables that you could use to test your hypotheses.

Step 3: Construct the circuits you designed in Step 1. Observe and record your findings—as in Step 3 above—at each of the relevant junctions. Write your results in your science notebook.

Step 4: Critical Analysis: Which light bulbs in each circuit had the largest voltage drop across them? Which circuits had the largest current through them? How did the circuit type and number of bulbs influence how the voltage and current changed? Discuss your answers with your partner and write the analysis in your notebook.

Assessments

1. Explain the differences in how the current and voltage change between series and parallel circuits.
2.
    a. How does the current through a parallel circuit compare to the current through a series circuit, if the voltage supplied by the power source is the same?
    b. How do these differences between series and parallel circuits relate to your observations from Activity 1?
3. [EK 5.C.3.1]
    a. Based on your data, does the current through each light bulb or the voltage across each light bulb add when they are connected in series? Explain.
    b. How about for a parallel circuit?
4. Design an experiment of an electric circuit that would allow you to collect evidence for the conservation of electric charge. Include a description of your experimental setup, a list of what you would measure, and a description of how this would help you collect evidence for the conservation of electric charge. [EK 5.C.3.2]

[Solutions]

1. In series circuits, the current is the same everywhere. In parallel circuits, the current is divided according to how many paths it has available; the current outside the parallel branches is equal to the sum of the current in each parallel branch. For voltage in a series circuit, the sum of the *voltage drops* equals the voltage of the battery. In a parallel circuit, the voltage drop is the same across each parallel branch.
2.
    a. The current is greater for the parallel circuit. It seems to imply that the parallel circuit draws more current from the battery than the series circuit.
    b. This meshes well with the observations from Activity 1, because the bulbs in the parallel circuits remained bright as an additional bulb was added, whereas the bulbs in the series circuits dimmed as an additional bulb was added.
3. [EK 5.C.3.1]
    a. For a series circuit, the current is the same everywhere and the voltage throughout the circuit is equal to the sum of the individual voltage drops.
    b. For a parallel circuit, the voltage is the same everywhere and the current is the sum of the current through each bulb.
4. [EK 5.C.3.2] Answers will vary based on the student's experimental design. A sample design might read as follows: We will use a normal battery in a parallel circuit with three light bulbs. We will measure the current at the battery, at the junctions, and between the two wires leading to the bulbs. This would help us collect evidence for the conservation of electric charge because we should see that the current remains the same from the battery to the junction, then splits into equal parts over the parallel branches—the sum of the current in each branch being equal to the total current measured initially—and then returns to its initial value from the junction back to the battery.

Lab 16: Kinetic Theory of Matter

In your studies of kinematics, you learned that when objects possessed certain qualities such as velocity or **kinetic energy** $(\mathrm{KE} = \frac{1}{2}mv^2)$ and then collided with other objects, momentum was conserved. During the discussion of these topics, we dealt with objects that were macroscopic, like a tennis ball. However, these principles can also be applied to objects that are **microscopic**. For this experiment we are going to assume that **atoms** and **molecules** behave like little tennis balls that have velocity and kinetic energy. When they collide with one another, they can transfer momentum.

In this lab you will relate **temperature** to the kinetic energy of atoms or molecules, using a simulation that will allow you to study the motion of microscopic objects by modeling them macroscopically. You will begin to understand why a balloon holds its shape when it is filled with a gas. You will also relate **pressure** to the collisions of atoms or molecules against the sides of its container. The goal is to be able to turn the things you learned about a tennis ball's velocity, kinetic energy, and momentum and translate them into a particle's temperature and pressure.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- For students to have an understanding of kinetic energy and microscopic objects, explain the basic assumptions that support the kinetic theory: (1) matter consists of small particles, (2) there is a separation between the particles, and (3) the particles are in constant motion.
- For students to better understand kinetic energy and the three states of matter—solids, liquids, and gases—demonstrate with a tennis ball, liquid in a container, and a helium balloon. Explain how solids have the least amount of energy, so they don't change shape; liquids have more kinetic energy, so the particles move more and take the shape of the container they are in; and gases have the most energy, so they can take the entire space of the container.
- For students to understand how matter can change from one form to another when energy is increased, demonstrate how a solid ice cube melts and becomes liquid when heated and how a pot of water becomes water vapor when heated.

In this lab you will learn:

- how pressure of a gas is related to the collisions of molecules and the wall of a container and how pressure changes affect temperature;
- how to qualitatively analyze the collision between a molecule and the container wall by calculating the pressure, force, or area;
- how the average kinetic energy of the molecules in a container is related to the temperature inside that container;
- how to connect the distribution of kinetic energies possessed by all of the molecules in a container to the temperature inside of the container.

Activity 1: Pre-Assessment

1. **Answer the following question in your notebook:** How does temperature relate to the motion or kinetic energy of a collection of particles?
2. **Answer the following questions in your notebook:** If Object A has a higher velocity than Object B, can we safely say that Object A is moving faster than Object B? Why or why not? What else might you need to know to compare the speeds of the two objects?
3. **Answer the following questions in your notebook:** What makes the air in winter feel cold and the air in summer feel warm? What about the molecules of air is changing to make you feel these two different sensations?
4. **Discuss the answers to questions 1, 2, and 3 with the class.**

Activity 1: Kinetic Theory of Matter

Recall that kinetic energy is defined as energy due to the motion of a body. If an object is moving, it is doing so because it has kinetic energy. The atoms of any object have some amount of motion, whether vibrational, translational, or rotational (Figure 16.1).

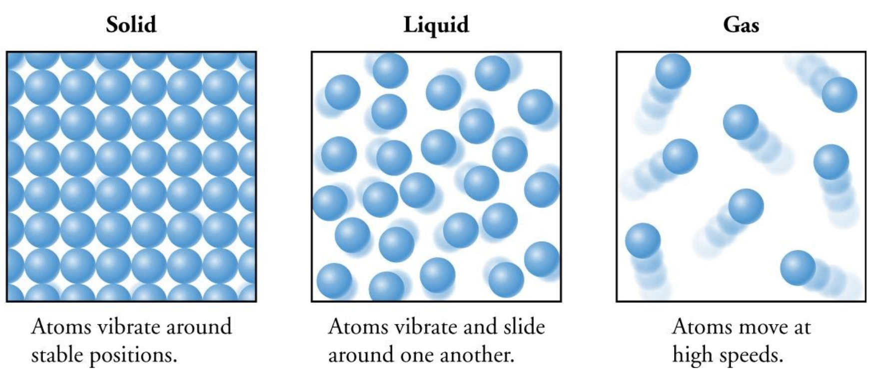


Figure 16.1: As the internal kinetic energy of an object changes, the relative motion of the particles inside the object changes as well.

Kinetic energy depends on two quantities: mass and velocity. The equation we use to calculate an object's kinetic energy is

$$KE = \tfrac{1}{2}mv^2,$$

where KE is kinetic energy, *m* is mass, and *v* is velocity. Joules (J) are often used as units for energy. In this section we are going to apply the concept of kinetic energy and relate it to the temperature of a **system**. A system is the group of objects or regions of space that you are selecting to study, such as corn kernels in a popcorn popper or gas molecules in a closed box. Using a PhET simulation, you will be able to describe how kinetic energy and temperature are related.

Safety Precautions

- Please handle computers responsibly.

For this activity you will need the following:

- A computer with an internet connection with the appropriate software for running PhET simulations.
- The following website: https://phet.colorado.edu/en/simulation/legacy/states-of-matter

For this activity you will *work alone*.

Activity 1 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 1:

- In advance of the lab, conduct a demonstration of how to conduct a PhET simulation and how to change settings and record observations.
- Explain to the students what software is required to run the PhET simulations, and help the students to install the software if they don't have it.
- Explain to the students how to take the required measurements from the PhET simulations.
- Repeat the experiment with oxygen and argon to understand the relation between kinetic energy and temperature for different gases.

The following are recommendations for the Guided Inquiry for Activity 1:

- Repeat the experiment with atoms and molecules in the simulation: argon, oxygen, water to understand the relation between kinetic energy and temperature for different gases.
- Tabulate the results and compare the results for all the atoms and molecules.

Structured Inquiry

Step 1: Sign on to a computer and visit the following website: https://phet.colorado.edu/en/simulation/legacy/states-of-matter. When you get to the website, press the big play button on the image to start running the simulation.

Step 2: Hypothesize/Predict: When the simulation starts up, notice the motion of the spheres representing the different elements and the temperature displayed on the thermometer at the top of the simulation. Predict what you think will happen to the kinetic energy of the spheres when heat is applied by moving the slider up. Also predict what would happen if you were to move the slider down to remove heat. Write your predictions in your notebook.

Step 3: Student-led Planning: In your notebook, create a table that will allow you to relate the temperature of the system and the kinetic energy of the system. Start by adding heat to increase the temperature of the spheres. As the temperature rises from 40 K to 100 K in 10 K increments, take several screenshots of the simulation at each temperature, and count, in each screenshot, how many atoms are in the top inch (2 cm) of the container. Calculate the average at each temperature.

Step 4: Critical Analysis: After completing Step 3, were the predictions in Step 2 supported by your data? Why or why not? Describe the relationship between temperature and kinetic energy. How would that relationship change if you were to use different elements? Write your answers in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: Sign on to a computer and visit the following website: https://phet.colorado.edu/en/simulation/legacy/states-of-matter. Without making any changes to the simulation, predict what would happen to the particles if you were to add or remove heat. Would adding a little heat or a lot of heat make any difference? Write your ideas in your notebook.

Step 2: Student-led Planning: When you are ready to begin this step, press the big play button on the image to start running the simulation. In your notebook, draw a data table that will allow you to collect data for the temperature and kinetic energy of neon as heat is added or removed. Determine how you will know when the neon atoms have high kinetic energy or low kinetic energy, and pick seven different temperatures to investigate. Rank the kinetic energy of each temperature from 1–7 with 7 being the highest kinetic energy. Complete the data table in your notebook.

Step 3: Critical Analysis: After completing Step 2, describe the relationship between temperature and kinetic energy. Does it change if you use different elements? Were the predictions in Step 1 supported by your data? Why or why not? Write your answers in your notebook.

Assessments

1. Draw a graph that shows the relationship between kinetic energy and temperature. Which variable is the independent variable? After you draw and label your graph, briefly explain why you chose to draw your graph in this fashion.
2. Notice that not every sphere was moving at the same speed in the simulation. Why do you think that is?
3. If you were given two containers with no thermometer, each filled with moving spheres, how could you use data on the kinetic energy of the particles in the two containers to determine which container had the higher temperature? Explain.

[Solutions]

1. [EK 7.A.2; SP 7] Students should label the *x*-axis of the graph as temperature (independent variable) and the *y*-axis as kinetic energy. There should be some sort of line that shows a direct relationship between the two so that as temperature increases, kinetic energy increases as well. They should explain after drawing the graph that as the temperature increased, the spheres in the simulation moved faster, suggesting that kinetic energy is increasing as well.
2. [EK 7.A.2; SP 7] Students should mention that not every sphere is moving the same because they are colliding with other spheres or the sides of the container, causing the momentum of the spheres to constantly change.
3. [EK 7.A.2; SP 7] Students should say that they could tell which container was hotter by determining an average kinetic energy for all of the moving spheres and picking the container with the highest average kinetic energy as having the highest temperature.

Activity 2: Pre-Assessment

1. **Answer the following questions in your notebook:** If you were to look at the driver-side door frame of a car, it tells you to what pressure the car's tires should be inflated. It also states that this is what the *cold* pressure should be. Why does it mention temperature? What does temperature do to a tire?
2. **Answer the following questions in your notebook:** How does pressure (force per unit area) translate into characteristics that affect the behavior of microscopic objects? How can the motion of particles tell you if there is a high pressure or a low pressure? Can you think of a real-world example?
3. **Discuss the answers to questions 1 and 2 with the class.**

Instructor Introduction Notes

The following are recommendations for introducing this activity's background content to your students:

- For students to understand that when temperature goes up, pressure goes up, demonstrate an experiment where an empty tin can with a lid is heated on a Bunsen burner on a tripod. As the temperature increases, the air pressure inside the tin can increases, and the lid pops off.
- For students to understand that when temperature goes down, pressure goes down, demonstrate with a hard-boiled egg that just fits in the mouth of a glass jar. Put a burning piece of paper inside the jar, then the egg in the mouth. When the paper has finished burning, the temperature inside the bottle falls. When the temperature falls, the pressure inside the bottle falls also. Because the outside pressure is now greater than the inside pressure, the egg gets sucked inside the bottle.

Activity 2: Kinetic Energy and Pressure

When a balloon is not filled with air, it has no real shape. When air is added to the balloon, what does it do to the inside? From the first activity we know that the molecules inside of a balloon have **kinetic energy** and are constantly moving and bumping into other air molecules as well as the sides of the container. **Pressure** is created when these molecules bump into the walls of the balloon. In (Figure 16.2), you can see the motion of the particles and how they interact with the sides of a container. Each particle applies a force per unit area on the side of the container that allows the walls of the balloon to hold a shape. It's a little like people standing underneath a sheet while punching it upward. In this activity we are going to relate the kinetic energy of particles with the pressure inside of a container.

Safety Precautions

- Please handle computers responsibly.

For this activity you will need the following:

- A computer with internet connection that can run the software necessary for PhET simulations,
- The following website: https://phet.colorado.edu/en/simulation/legacy/states-of-matter.

For this activity you will work *alone*.

Activity 2 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 2:

- In advance of the lab, conduct a demonstration of how to conduct a PhET simulation and how to change settings and record observations.
- Explain to the students what software is required to run the PhET simulations, and help the students to install the software if they don't have it.
- Explain to the students how to take the required measurements from the PhET simulations.

The following are recommendations for the Guided Inquiry for Activity 2:

- Let the students repeat the experiment atoms and molecules in the simulation: argon, oxygen, water
- Let the students tabulate the results and compare the results for all the atoms and molecules

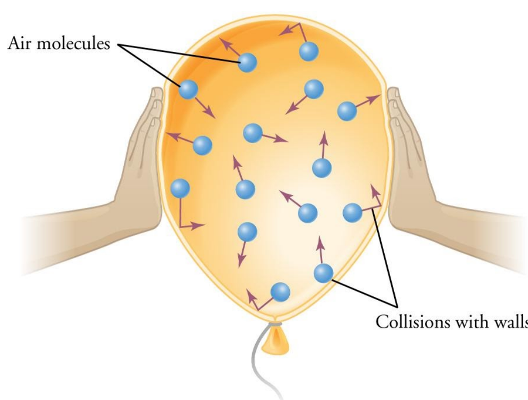


Figure 16.2: Air molecules bump into the sides of the container, creating pressure.

Structured Inquiry

Step 1: Sign on to a computer and visit the following website: https://phet.colorado.edu/en/simulation/legacy/states-of-matter. When you get to the website, press the big play button on the image to start running the simulation.

Step 2: Hypothesize/Predict: When the simulation starts up, click on the *Phase Changes* tab and notice the motion of the spheres representing the different elements and the pressure displayed on the scale at the top of the simulation. Predict what you think will happen to the kinetic energy of the spheres *and* pressure when heat is applied by moving the slider up. Also predict what would happen if you were to move the slider down to remove heat. Write your predictions in your notebook.

Step 3: Student-led Planning: In your notebook, create a table that will allow you to compare temperature, pressure, and kinetic energy. Start by adding heat to increase the temperature of the spheres to four temperatures of you choosing between 40 K and 100 K. From 40 K to 100 K in 10 K increments, take several screenshots of the simulation and count, in each screenshot, how many atoms are in the top 2 cm of the container. Calculate the average at each temperature. The reading on the scale will fluctuate, so press the pause button to get a value to put in the table. Write the temperatures, pressures, and kinetic energy rankings in your notebook.

Step 4: Critical Analysis: After completing Step 3, describe the relationship between pressure and kinetic energy. Does it change if you were to use different elements? Were the predictions in Step 2 supported by your data? Why or why not? Write your answers in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: Sign on to a computer and visit the following website: https://phet.colorado.edu/en/simulation/legacy/states-of-matter. Without making any changes to the simulation, predict what would happen to the particles if you were to add or remove heat. How is the temperature and pressure of the system going to change when heat is added or taken away? Write your ideas in your notebook.

Step 2: Student-led Planning: When you are ready to begin this step, press the big play button on the image to start running the simulation and click on the *Phase Changes* tab. In your notebook, draw a data table that will allow you to collect data on the temperature, pressure, and kinetic energy of neon as heat is added or removed. Determine how you will know when the neon has high kinetic energy or low kinetic energy, and pick seven different temperatures to investigate. Rank the kinetic energy of each temperature from 1–7, with 7 being the highest kinetic energy. Also take note of the pressure at each temperature. The reading on the scale will fluctuate, so press the pause button to get a value to put in your data table. Write the temperatures, pressures, and kinetic energy rankings in your notebook.

Step 3: Critical Analysis: After completing Step 2, describe the relationship between pressure and kinetic energy. Does it change if you were to use different elements? Were the predictions in Step 1 supported by your data? Why or why not? Write your answers in your notebook.

Assessments

1. Why did the pressure scale constantly fluctuate in the phase change simulation? How is kinetic energy related to the collisions of particles and the collision of particles against the walls of the container? Explain how the change in temperature affected the pressure readings based on the activity. [EK 7.A.1; SP 3]
2. In the simulation, how did the particles hitting the side of the container affect the pressure? Qualitatively explain how, by measuring pressure, you would determine the magnitude of the force exerted by the particles when they collide with the sides of a container. [EK 7.A.1; SP 2]

[Solutions]

1. [EK 7.A.1; SP 3] Students should mention that the readings fluctuated because the particles weren't hitting the side of the containers in a regular fashion. They should also mention that the kinetic energy is directly related to the collisions of particles with one another and with the sides of the container. Finally, they should say that as temperature increased, the pressure increased as well.
2. [EK 7.A.1; SP 2] Students should mention that the speed and direction of impact is important to determining pressure. The higher the speed and the more directly the particles hit the walls, the higher the pressure. They should also mention that knowing the equation for pressure is force/area $(P = F / A)$, they can determine the force exerted by the particles hitting the sides of a container by finding the area of one of the container's sides and multiplying it by the pressure reading.

Lab 17: Gases

Gases are a form of matter that can easily change both volume and shape. **Volume** is the most easily measurable physical property because it is closely related to the size of the container with the gas. Changes in volume can be caused by changes in **pressure**. Pressure is the force acting on the gas per unit area of the surface at which the force is applied. If gas is contained in a syringe, the force applied to the piston of the syringe divided by the area of the piston is equal to the applied pressure, $P = F / A$. Because the particles of the gas constantly move, they hit the walls of the container, and in this way the gas itself exerts pressure on the walls. If the pressure of the gas is equal to the external pressure (such as the pressure applied to the syringe or atmospheric pressure), then the state of **equilibrium** is achieved, and the volume of the gas does not change. In SI units, the pressure is measured in pascals (*Pa*) or kilopascals (*kPa*) and the volume is determined in cubic meters. The empirically determined relationship between volume and pressure of an ideal gas is known as **Boyle's law**.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- If your students have not covered factors affecting pressure, discuss how temperature and pressure are related.
- Remind students that that energy is conserved, and predictions can be made about work done on a system based on heat transfer.
- Use energy charts to show the transfer of energy and the work done on the system. Discuss with the students how the energy of a system changes when an outside force acts on it.
- Discuss that work is found by taking the product of force and displacement.
- Explain how, in a pressure versus volume graph, the area under the curve is equal to the work done on the system. This value should be equal to the work done on the system.

In this lab you will learn:

- how to determine the amount of work done on a system from the force and displacement values;
- how to use the principle of conservation of energy qualitatively to predict changes in energy of the system due to heat transferred to the system or work done on the system ;
- how to create a plot of pressure versus volume using measured or given data.

In this lab, you will experimentally obtain the relationship between the volume (V) of a sample of gas and its pressure (P). We need to know how volume changes with changing pressure in many real-life situations. Pumping air into a bicycle or car tire includes compression and expansion of the gas in accordance with increased and decreased pressure (for example, in the cylinder of the pump). A car engine compresses an air-gas mixture in its cylinders before igniting the mixture. A balloon can change its volume as the external pressure changes.

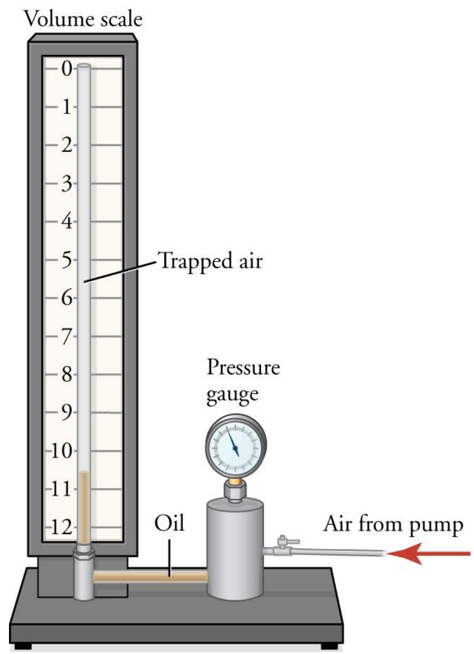


Figure 17.1: Boyle's law apparatus for measuring the pressure and volume of a gas.

It is convenient to measure the relationship between gas pressure and volume using a Boyle's law apparatus, such as the one shown schematically in Figure 17.1. Air is pumped to create pressure in the oil, which conveys this pressure to the trapped volume of gas. The gas volume can be measured with the volume scale. The pressure is measured with the pressure gauge. Therefore, by pumping the air at various pressures, we can measure different volumes of the trapped gas. We can then produce a pressure-volume table or graph from these data. Other versions of the apparatus can be used. In each of them, we can measure the value of equilibrium pressure of a trapped volume of gas.

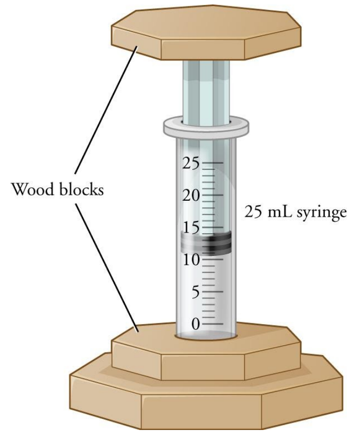


Figure 17.2: Another version of Boyle's law apparatus. Pressure is applied by adding weight to the top wood block.

For example, Figure 17.2 shows a simple system in which objects of known mass (books, small bricks, etc.) can be placed on top of the upper wood block. The volume of the gas in the syringe is recorded, and then you can measure the total weight on top of the syringe. The pressure is the gravitational force *mg* divided by the area of the syringe piston ($A = \pi r^2$), where *r* is the radius of the piston. Here *g* is the acceleration due to gravity, $g = 9.81\ \mathrm{m/s^2}$.

You should always remember that if you use a system in which the pressure is varied by adding weights on top of a piston, the gravitational part of the pressure should be added to the atmospheric pressure that is already present. The atmospheric pressure value is approximately $1.01 \times 10^5\ \mathrm{Pa}$, and the additional gravitational pressure should not be much less than this value. If the gravitational pressure is too small, you will not observe any appreciable change in the volume, and accurate measurements of the pressure-volume dependence will not be possible.

Finally, if it is completely impossible to obtain a Boyle's law apparatus, you can carry out this lab by using an online simulator at http://phet.colorado.edu/en/simulation/gas-properties .

Activity 1: Pre-Assessment

1. **Answer the following question in your notebook:** What do you predict is the relationship between the volume of a sample of gas and its pressure?
2. **Answer the following question in your notebook:** How could you experimentally determine the relationship between the temperature and pressure of a gas using Boyle's law apparatus?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 1: Determining the Relationship Between the Volume and the Pressure of a Gas Sample

You will use a Boyle’s law apparatus to determine the relationship between the volume of a gas sample and its pressure. Assume that the atmospheric pressure is equal to 1.01×10^5 Pa, unless your teacher provides a more accurate number for your location.

Safety Precautions

- Be careful when stacking objects on top of the upper wooden block of the Boyle’s law apparatus, because they can fall.
- Excessive pressure buildup can lead to explosive breaking of the apparatus. You shouldn’t have to use excessive force to compress the air.

For this activity you will need the following:

- Boyle’s law apparatus
- Mass scales
- Solid objects
- Rulers
- Graph paper or graphing calculator
- Objects that are heavy enough to compress gas in the cylinder of the Boyle’s law apparatus (books, small bricks, etc.)

For this activity you will work *in pairs.*

Activity 1 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 1:

- This lab is best done in pairs so that each student can interact with the apparatus.
- As mentioned in the introduction, if it is not possible to use a Boyle’s law apparatus, you can use the online simulator at http://phet.colorado.edu/en/simulation/gas-properties . It is beneficial for students to interact with the actual apparatus rather than the simulation, however.

- The online simulation can be used to demonstrate to students what they should see during their experiment. This would also be good to use for discussion after the lab.
- Check that students are using the proper amounts of weights as they are working on their lab. Remind them throughout the lab that their gravitational pressure should be close to the atmospheric pressure in order to observe accurate changes in pressure.

The following are recommendations for the Guided Inquiry for Activity 1:
- This lab is best done in pairs so each student can interact with the apparatus.
- This portion of the lab is very similar to the Structured Inquiry. Students should follow the same guidelines when performing this portion.
- When checking students' designs, make sure that the objects have sufficient mass to give accurate measurements and that they can easily be stacked on the apparatus.

Structured Inquiry

Step 1: Hypothesize/Predict: How do you think the volume of a sample of gas changes as the pressure changes? Does the volume increase or decrease with increasing pressure? What is the mathematical relationship between the pressure and volume of a gas? Write a hypothetical equation in your notebook.

Step 2: Student-led Planning: You will now measure the physical quantities necessary to determine how the volume of the gas and its pressure are related. Determine what values (length, mass, area, etc.) have to be measured to find the relationship between a gas's volume and its pressure. Also discuss with your partner how best to set up Boyle's law apparatus, what values have to be recorded, and how many series of measurements are needed.

The general procedure for using the apparatus is as follows:
1. Insert the piston into the cylinder.
2. Make sure the top and bottom wooden blocks are firmly attached.
3. Read the volume of gas inside the cylinder on the apparatus scale.
4. Calculate the pressure as the sum of the atmospheric pressure (use the value provided by the teacher or 1.01×10^5 Pa) and the total weight of the upper part of the apparatus (the mass of the upper part plus any additional weights times the free-fall acceleration *g*) divided by the area of the cylinder cross-section.

Step 3: Critical Analysis: Create a data table and record the necessary physical values and the resulting pressure and volume values. Are the predictions you made in Step 2 supported by your data? Why or why not? What methods could you have used that would improve your results? Discuss with your partner, and then write your answers in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: How does the volume of a gas sample depend on the pressure of the gas? What is the dependence of the pressure on the mass of the additional objects placed on the upper part of the Boyle's apparatus? What shape of gas container would facilitate measuring the volume accurately and efficiently? Write your ideas in your notebook.

Step 2: Student-led Planning: Pick several objects that can be used to create pressure in the Boyle's law apparatus. Submit your chosen objects to your teacher. After your teacher approves, measure the volume of the gas in the apparatus as you place various combinations of the objects on top of the upper wooden block. Measure the mass of each combination of the objects that you use this way. Write your results in your science notebook. Create a table of weights and the corresponding positions of the piston.

Step 3: Critical Analysis: What is the dependence of the gas volume on the mass of the objects used to create pressure? Calculate the pressure and the gas volume for each of the measurements, and find the mathematical relationship between them. Draw a graph of the pressure versus volume to assist yourself in this task. Discuss your answers with your partner, and write them in your notebook.

Assessments

1. A student uses Boyle's law apparatus with books. The masses of the books are 520 g, 785 g, and 423 g. [EK 1.1, EK 1.4, EK 2.2, EK 4.2, EK 5.1, EK 6.4]
    a. Does this scenario describe precise measurements? Why or why not?
    b. Was this set of weights well chosen for the task of determining the volume-pressure relationship for the gas sample? Why or why not? Assume that the additional pressure due to the gravitational force is comparable with the atmospheric pressure.
2. A student uses the Boyle's law apparatus and takes several measurements of the resulting volume for each set of weights. [SP 1.1, SP 1.4, SP 2.2, SP 4.2, SP 6.4]
    a. Does this procedure increase the accuracy of the measurements?
    b. What other ways can you suggest for increasing the accuracy of determining the relationship between the volume and pressure?
3. A student is using Boyle's law apparatus. The radius of the syringe is $r = 1.0\ \text{cm}$. The mass of the weights is $m = 1.25\ \text{kg}$. The height of the gas sample in the cylinder of the syringe is $h = 10.5\ \text{cm}$. [SP 1.1, SP 1.4, SP 2.2, SP 5.1]
    a. What is the volume of the gas (in SI units)?
    b. What is the pressure of the gas (in SI units)?

[Solutions]

1. [SP 1.1, SP 1.4, SP 2.2, SP 4.2, SP 5.1, SP 6.4]
    a. The measurements are precise to the third significant digit. It is not possible to assess their accuracy from the data given.
    b. Yes, the masses can vary by up to 10 percentage points. Since volume is inversely proportional to pressure (as long as the temperature is constant), we can expect a significant amount of variation in the gas volume.
2. [SP 1.1, SP 1.4, SP 2.2, SP 4.2, SP 6.4]
    a. Yes, this procedure should reduce the random error in measuring the volume of the gas sample.
    b. The students can also take several measurements of the mass of each of the sets of the weights used in this experiment in order to improve the accuracy of determining the gas pressure.
3. [SP 1.1, SP 1.4, SP 2.2, SP 5.1]
    a. The volume is equal to

       $$V = \pi r^2 h = \pi (0.010\ \text{m})^2 (0.105\ \text{m}) = 3.30 \times 10^{-5}\ \text{m}^3.$$

    b. The additional pressure is equal to

       $$P = \frac{F}{A} = \frac{mg}{\pi r^2} = \frac{(1.25\ \text{kg})(9.81\ \text{m/s}^2)}{\pi (0.010\ \text{m})^2} = 3.90 \times 10^4\ \text{Pa}.$$

    The total pressure includes the pressure of the atmosphere,

    $$P = 1.01 \times 10^5\ \text{Pa} + 3.90 \times 10^4\ \text{Pa} = 1.40 \times 10^5\ \text{Pa}$$

Activity 2: Finding the Work Done on a Gas Sample

Activity 2: Pre-Assessment

1. **Answer the following question in your notebook:** A student is using a constant pressure to pump air into a bicycle tire. How would you calculate the amount of work done on the air if you know the force the student is applying to the pump and the dimensions of the pump chamber?
2. **Answer the following question in your notebook.** How can you measure the volume-pressure relationship required in the question above using Boyle's law apparatus?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 2: Finding the Work Done on a Gas Sample

In the previous part of the lab, we determined the dependence of gas volume on pressure, or Boyle's law. **Boyle's law** is an experimentally determined relation between the volume and the equilibrium pressure of a gas at constant temperature. It states that if a certain constant amount of gas is kept at a constant temperature, then the product of the gas volume by its pressure is a constant: $PV = \text{const}.$ Or, if we compare pressure and volume values at two different moments, 1 and 2, then $P_1V_1 = P_2V_2$. The units of *P* and *V* are not important as long as they are kept the same. If the temperature is not constant, then the behavior of gas can be approximately described by the **ideal gas law**

$$PV = nRT \, .$$

Here *n* is the number of moles of the gas sample (the mass of the gas sample divided by the molar mass of the gas), *R* is the universal gas constant, and *T* is the temperature in degrees Kelvin. In SI units, the pressure is measured in pascal, the volume is determined in cubic meters, and the value of the gas constant is $R = 8.314 \text{ J/(mol} \cdot \text{K)}.$

You will use Boyle's law apparatus to determine the work done on a sample of gas by changing external force (and thus changing pressure). Assume that the atmospheric pressure is equal to $1.01 \times 10^5 \text{ Pa},$ unless your teacher provides a more accurate number for your location.

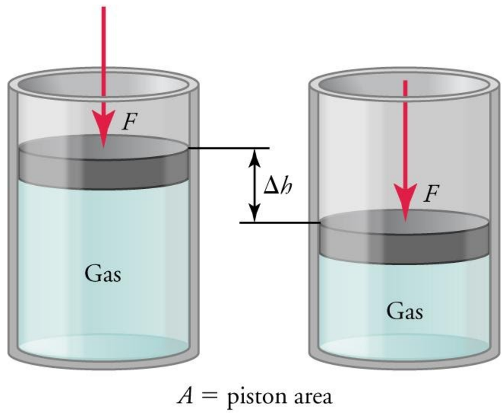


Figure 17.3: The work done on a sample of gas as a result of compression is based on the force (*F*) and displacement (*h*).

Let us consider the process shown in Figure 17.3. A sample of gas is compressed by an external force, *F*, and the piston moves a distance, h. We can calculate the work done as the product of force and displacement, so the amount of work done in this compression is

$$\Delta W = F\Delta h.$$

In the case of a gas sample, this equation can be rewritten as

$$\Delta W = P\Delta V.$$

If the pressure is created by the gravitational force, it can be found as this force divided by the area of the piston, or

$$P = \frac{mg}{A}.$$

The atmospheric pressure has to be added to this value to find the total pressure on the gas.

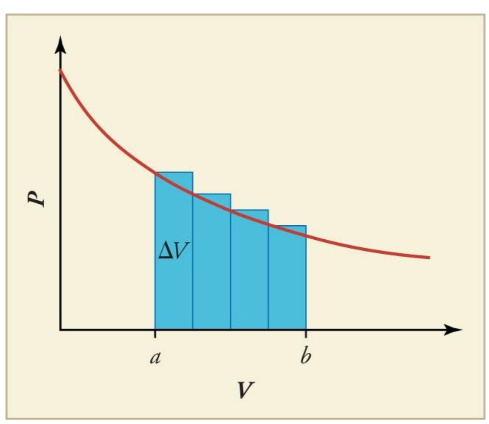


Figure 17.4: The work done on the gas while it is compressed from point *b* to point *a* can be calculated as the area under the *PV* curve between the vertical lines passing through points *a* and *b.*

Suppose that we need to obtain the amount of work done on the gas, and we know the pressure of the gas as a function of volume. Then the work done in each of these small parts of the path is equal to the product of the pressure at that part and the change of volume □ *V*. Overall, the work done is equal to the area under the *PV* curve between the vertical lines passing through points *a* and *b* (Figure 17.4).

However, the pressure that is included in the equation for the work done on the gas is the external pressure. It can be approximated by the pressure of the gas itself only if the external pressure and the pressure of the gas are equal. This happens when the compression of the gas occurs very slowly. In this case, the width of the elements □ *V* in Figure 17.4 becomes very small, and the amount of work done on the gas becomes very close to the area under the *PV* graph. Such a process is said to be reversible.

We must remember that the total pressure on the gas is the sum of the pressure of any weights on top of the Boyle's law apparatus and the atmospheric pressure.

Safety Precautions

- Be careful when stacking objects on top of the upper wooden block of the Boyle's law apparatus, because they can fall.
- Also, excessive pressure buildup can lead to explosive breaking of the apparatus. You shouldn't have to provide excessive force to compress the air.

For this activity you will need the following:

- Boyle's law apparatus
- Mass scales
- Solid objects
- Rulers
- Graph paper or graphing calculator
- Objects that are heavy enough to compress gas in the cylinder of the Boyle's law apparatus (books, small bricks, etc.)

For this activity you will work *in pairs*.

Activity 2 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 2:

- This lab is best done in pairs so that each student can interact with the apparatus.
- As mentioned in the introduction, if it is not possible to use a Boyle's Law apparatus, you can use the online simulator at http://phet.colorado.edu/en/simulation/gas-properties. It is beneficial for students to interact with the actual apparatus rather than the simulation, however.

- The online simulation can be used to demonstrate to students what they should see during their experiment. This would also be good to use for discussion after the lab.
- After Step 1, check that students have the proper quantities listed. Students will need: radius, change in height, masses added to apparatus.
- During the Hypothesize/Predict step, check students' relationship between the physical quantities.
- Check that students are using the proper amounts of weights as they are working on their lab. Remind them throughout the lab that their gravitational pressure should be close to the atmospheric pressure to observe accurate changes in pressure.

The following are recommendations for the Guided Inquiry for Activity 2:

- This portion of the lab is very similar to the Structured Inquiry. Students should follow the same guidelines when performing this portion.
- When checking students' designs, make sure that the objects have sufficient mass to give accurate measurements and that they can easily be stacked on the apparatus.
- After the lab, discuss with students why a graph is better at calculating work than using individual data points.

Structured Inquiry

Step 1: Determine what physical quantities (length, mass, area, etc.) you need to measure to find the amount of work done on a sample of gas by compression.

Step: Hypothesize/Predict: Relate the physical quantities determined in Step 1 to the work done on the gas. What other influences affect the amount of work done on the gas in the process of compression?

Step 3: Student-led Planning: You will now measure the physical quantities necessary to determine the compression work done on the gas. Discuss with your partner how best to set up the Boyle's law apparatus, what values have to be recorded, how many series of measurements are needed, and how to minimize experimental error. Discuss ways to find the area under the *PV* graph.

Step 4: Critical Analysis: Create a data table, and record the necessary physical values and the resulting pressure and volume. Are the predictions you made in Step 2 supported by your data? Why or why not? What methods could you have used that would improve your results? Discuss with your partner and then write your answers in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: Since the amount of work can be calculated from the *PV* graph, do you need to measure any more parameters than you did in the previous activity in this lab? What amount of work will be done when weights of various masses are used? What condition has to be observed in choosing the weights in order to obtain accurate readings for the work calculations? Write your ideas in your notebook.

Step 2: Student-led Planning: Pick several objects that can be used to create pressure in the Boyle's law apparatus. Make sure that the masses satisfy the conditions for the compression to be slow enough to permit accurate calculation of work. Submit your chosen objects to your teacher. After your teacher approves, measure the volume of the gas in the apparatus as you place various combinations of the objects on top of the upper wooden block. Measure the mass of each combination of objects that you use this way. Write your results in your science notebook. Create a table of weights and the corresponding positions of the piston. Carry out this part for both compression (increasing the amount of weight on top of the apparatus) and expansion (removing objects from the top block).

Step 3: Critical Analysis: How can the amount of work be calculated from the collected data? Calculate the pressure and the gas volume for each of the measurements. Draw the *PV* graph (the graph of pressure as a function of volume). Produce a separate graph for each measurement series. Find the area under the curve, the total amount of work on the gas during the process of compression, and the work done by the gas in the process of the following expansion. Are these amounts approximately equal? If not, which one is greater and why? Do the amounts of work you have calculated agree with your hypothesis in Step 1? Discuss your answers with your partner and write them in your notebook.

Assessments

1. A student uses Boyle's law apparatus with small bricks. The masses of the bricks are 1,520 g, 3,785 g, and 5,423 g. The diameter of the piston is 2.0 cm. [EK 7.A.1, SP 1.1, SP 1.4, SP 2.2, SP 4.2, SP 5.1, SP 6.4]
    a. What is the additional pressure provided by the bricks and the total pressure for the smallest weight in the set?
    b. Was this set of bricks well chosen for the task of determining the amount of work done on the gas in the process of compression of the bricks are simply placed on top of the apparatus one by one? Why or why not?
    c. Is the range of the masses sufficient to obtain an accurate value of the compression work? Why or why not?
2. Give two factors that do not allow us to state that all the work done on the gas is transferred into the increase of the internal energy of the gas. [SP 1.1, SP 1.4, SP 4.2, SP 5.1]
3. A student is using the Boyle's law apparatus to find the amount of the compression work done on the gas. The average pressure of the gas is $1.6\times10^{5}\ \text{Pa}$ as the volume decreases from $3.1\times10^{-5}\ \text{m}^3$ to $2.8\times10^{-5}\ \text{m}^3$. [EK 7.A.3, SP 1.1, SP 1.4, SP 2.2, SP 4.2, SP 5.1]
    a. Find the work done on the gas by the external pressure (in SI units).
    b. Estimate the change in pressure in this process (in SI units)

[Solutions]

1. [EK 7.A.1, SP 1.1, SP 1.4, SP 2.2, SP 4.2, SP 5.1, SP 6.4]
    a. The additional pressure is equal to

    $$P=\frac{F}{A}=\frac{mg}{\pi r^2}=\frac{(1.520\ \text{kg})(9.81\ \text{m/s}^2)}{\pi(0.010\ \text{m})^2}=4.75\times10^{4}\ \text{Pa}.$$

    The total pressure is (assuming the atmospheric pressure is $1.01\times10^{5}\ \text{Pa}$)

    $$P=1.01\times10^{5}\ \text{Pa}+0.48\times10^{5}\ \text{Pa}=1.49\times10^{5}\ \text{Pa}.$$

    b. First of all, the value of the additional pressure is comparable with the atmospheric pressure. Therefore, a significant change in the volume of the gas sample will occur. But the answer to the overall question is negative. The difference in the masses of the bricks is too great (percentage-wise). The pressure of the gas and the external pressure will differ by too much, so the ideal curve such as the one shown in Figure 17.4 will not be followed.
    c. Yes. The masses of the bricks can differ by up to ten percent. This will permit a significant overall change in the volume of the gas. If the change of the volume is too small, it cannot be measured accurately, and thus the overall accuracy of determining the compression work will be diminished.

2. [SP 1.1, SP 1.4, SP 4.2, SP 5.1]
   The factors are the friction between the piston and the walls of the cylinder of the Boyle's law apparatus and the transfer of heat between the gas and the environment. Both these factors consume some of the energy resulting from the compression work.
3. [EK 7.A.3, SP 1.1, SP 1.4, SP 2.2, SP 4.2, SP 5.1]
   a. The work is $\Delta W = P\Delta V = (1.6 \times 10^5 \text{ Pa})(2.8 \times 10^{-5} \text{ m}^3 - 3.1 \times 10^{-5} \text{ m}^3) = -0.48 \text{ J}.$
   b. The volume changes by approximately 10 percent. Because Boyle's law states that the pressure of gas is inversely proportional to its volume at constant temperature, we can assume that the pressure is also changing by approximately 10 percent or $\Delta W = P\Delta V = (1.6 \times 10^5 \text{ Pa})(2.8 \times 10^{-5} \text{ m}^3 - 3.1 \times 10^{-5} \text{ m}^3) = -0.48 \text{ J}$

Lab 18: Fluid Dynamics

Fluid dynamics is the study of how fluids flow. Note that the term *fluids* does not mean only liquids like water, but also includes gases such as air. Thus, fluid dynamics is used to calculate how air flows for studies in aerodynamics and optimizing aircraft designs. The equations that govern fluid dynamics are also used to understand and predict a wide variety of other object movements, including traffic patterns, weather movement, and the movement of interstellar dust clouds in space (nebulae). In this lab, you will explore some of the basic principles of fluid dynamics.

In the first activity, you will set up a bucket with a hole in it and then fill the bucket with water. Then, you will measure how far the water travels and document your results. In the second activity, you will examine a more complex version of the first activity. Specifically, you will investigate the behavior of water in a bucket that has multiple holes at different levels. In the third activity, you will use Archimedes' principle to measure the density of a few solids and a liquid.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- Students should have already covered two-dimensional kinematics before attempting this lab. It would also be helpful to review kinematic calculations before Activity 1.
- While it is not necessary to have completed the energy unit, it is helpful for students to understand the basic tenets of gravitational potential energy and kinetic energy before beginning this lab.
- It is helpful for students to have a basic understanding of density as it relates to mass and volume before starting this lab. Ideally, students should work as a class to remember the formula for density before beginning. They should have had this formula in previous science classes.
- After this lab, work with the students as a class to derive Bernoulli's equation. Encourage them to use the data and relationships they discovered during the lab to help them.

In this lab you will learn:

- how to use Bernoulli's equation and/or the relationship between force and pressure to make calculations related to a moving fluid;
- how the properties of a system are determined by the interactions of its constituent substructures;
- to predict density, differences in densities among different substances, or how density will change under different conditions for natural phenomena, and design an investigation to verify the prediction;
- to select from experimental data the information necessary to determine the density of an object and/or compare densities of several objects.

Activity 1: Pre-Assessment

1. **Answer the following questions in your notebook**: What happens when an object goes deeper underwater? Does the density of an object change as it goes deeper underwater? What about the pressure exerted on the object?
2. **Answer the following questions in your notebook:** Can you measure the water pressure exerted on an object solely by measuring the depth of the object in the water? Why or why not?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 1: Water Pressure and Depth

Consider all the water above a submarine. This water exerts pressure on the submarine because the water is pulled downward by gravity. If a deeply submerged submarine springs a leak, this pressure causes water to jet into the submarine very quickly. We can examine this principle on a smaller scale by considering a container full of water with a hole in the side.

In the next activity, you will need to use the equations for projectile motion. Recall that the equation for horizontal distance traveled by a projectile is given by

$$d = v_i t + \frac{1}{2}at^2 ,$$

where *d* is the distance traveled, v_i is the initial velocity, *t* is the time, and ***a*** is the acceleration.

Here you'll be investigating water pressure and depth. You'll put water into a bucket with a hole in it, and then record your observations of how far the water travels. While you're conducting your experiment, consider the situations that would increase the pressure.

Safety Precautions

- Be sure to clean up any water spills to avoid slipping on a wet floor.

For this activity you will need the following:

- Plastic bucket with a hole in the side near the bottom
- Meter stick
- Water

For this activity you will work *in pairs or small groups*.

Activity 1 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 1:

- Smaller groups will allow for students to have more direct input to the activity. However, it may be advisable to have pairs discuss ideas with other pairs to reduce the time needed for this lab.
- Larger containers will have a more marked change when students make changes to the setup. With this in mind, larger containers also make a bigger mess.
- Straight-sided buckets will make for easier measuring for the students. It may also be helpful to permanently mark levels on the inside of the bucket.
- Students often confuse velocity (v) and volume (V). Be sure to point out that volume is generally capitalized to help alleviate this confusion.

The following are recommendations for the Guided Inquiry for Activity 1:

- It might be helpful to have the students determine variables they can control as a class and make a list for all groups to use in their notebooks.
- This is also a good time to check progress on the structured inquiry section of the lab before they start the guided inquiry section.

Structured Inquiry

Step 1: Hypothesize/Predict: How could a plastic bucket with a hole near the bottom be used to study the effects of water pressure? Given what you have learned about water pressure and projectile motion, predict how the horizontal distance that the leaking water travels will change with the depth of the water in the bucket (Figure 18.1). What level of water would likely be needed to double and triple the horizontal distance that the water travels? Write your hypothesis in your notebook.

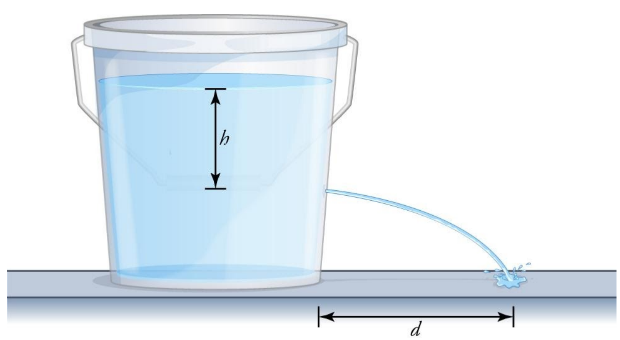


Figure 18.1: The distance the water travels depends on the depth of the hole below the water level.

Step 2: Student-led Planning: Discuss with your partner how you will test your hypotheses from Step 1. Then create a data table for your observations in your notebook.

Step 3: Now conduct at least four trials to measure the horizontal distance that the water travels for each depth of water in the bucket. Record your observations in your notebook.

Step 4: Critical Analysis: Were the predictions you made in Step 1 supported by your data? Why or why not? What methods could you have used that would have improved your results? Discuss with your partner and then write your answers in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: How do you think the size of the bucket, depth of the water, and size of the hole affect how far the water travels? How would a larger bucket affect your investigation? Write your hypothesis in your notebook.

Step 2: Student-led Planning: Conduct four trials with two or three combinations of variables, including different water levels but possibly larger buckets or buckets placed slightly higher. For example, conduct one series of trials with a water level that is 10 cm higher in which the bucket is placed 20 cm higher, using a few textbooks or blocks. Describe each setup. Observe and record your findings (as in Step 2 above). Write your results in your notebook.

Step 3: Critical Analysis: Which combination of variables caused the water to travel the farthest? Which arrangement had the water travel the shortest distance? How did the bucket size and water level affect how far the water traveled? Discuss your answer with your partner and write it in your notebook.

Assessments

1. How did the depth of the water in the bucket affect the pressure in the bucket? [5.B.10.2]
2. How did the height of the bucket above the ground affect the pressure in the bucket? Why? [5.B.10.2]
3. Pressure is defined as force divided by area. Consider your experimental setup, and describe how you would calculate the pressure the water is under as it leaves the bucket. [5.B.10.2]
4. With your procedure from Question 3, calculate the pressure of the water as it leaves the bucket at three different times during your experiment. Perform these calculations. [5.B.10.2]

[Solutions]

1. As the depth of water in the bucket decreased, so did the distance that the water traveled.
2. As the height of the bucket increased, so too did the distance that the water traveled. However, this was not due to changes in pressure, but because the water takes longer to reach the ground from a greater height. At some point of raising the bucket, the momentum in the horizontal direction would have stopped through air resistance and any further increases in bucket height would have not affected the distance the water traveled.
3. [5.B.10.2]
   Answers will vary based on the experimental setup, but the rough answer should describe that the pressure will be the atmospheric pressure plus the pressure exerted by the liquid, which is calculated as the density of the liquid times the acceleration due to gravity times its height.
4. [5.B.10.2]
   Answers will vary based on the experimental setup, but supposing a height of 0.5 m, acceleration due to gravity of 9.8 m/s^2, and that the liquid is water so it has a density of 1 g/mL, we obtain the pressure as 101.3 kPa plus 4.9 kPa, or 106.2 kPa.

Activity 2: Pre-Assessment

1. **Answer the following questions in your notebook:** What factors affect the velocity of water streaming out of a bucket with a hole in it? How can we isolate the effects of each of these variables?
2. **Answer the following questions in your notebook:** If a bucket were to have multiple holes in it, would this relieve some of the pressure on the holes situated lower? Why or why not?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 2: Torricelli's Theorem

For this next activity, you are going to investigate water pressure and depth in more detail. As noted in Activity 1, water pressure affects the velocity of the water that exits the holes. In this instance, you will punch multiple holes in a two-liter bottle at different heights and observe how the velocity of water exiting is affected by depth. When you are explaining your results, it will be helpful to think about the results from Activity 1.

Safety Precautions

- Be sure to clean up any water spills to avoid slipping on the wet floor.
- Be careful with the awl: it is sharp. When punching holes in your bottle, be aware of where your hands are so that you do not hurt yourself.

For this activity you will need the following:

- Two-liter bottle
- Meter stick
- Awl or other means of punching a consistent hole in the bottle
- Water

For this activity you will work *in pairs or small groups*.

Activity 2 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 2:

- Again, small groups will allow students to have more interaction during the lab, increasing learning.
- It will be helpful to have extra 2 L bottles on hand in case students cause accidental damage one during the hole-making process.
- When students are punching holes with the awl, caution them to not punch the hole through the other side of the bottle as this will affect their measurements.

- It may be helpful to have students place the lid on to keep the water inside the bottle if they need to move the filled bottle or make adjustments. Encourage creativity when students are trying to fill the bottles that have holes in them.
- Check in with students after Step 1 to see what method they have decided to use to measure velocity. They should not need additional materials.

The following are recommendations for the Guided Inquiry for Activity 2:

- Encourage students to graph their results to compare and make a determination when answering the analysis questions.

Structured Inquiry

Step 1: Puncture a series of holes in the 2-L bottle at various heights. Fill the bottle with water and allow the water to drain out. Fill the bottle with water to various depths and measure the velocity at which the streaming water exits from each hole. Create a data table for your observations. Discuss with your partner how best to measure the velocity.

Step 2: Hypothesize/Predict: Given what you have learned about water pressure and projectile motion, predict how the velocity at which the water exits changes with the depth of the water in the bucket and at the different heights of the holes. Add your predictions to the data table you created in Step 1.

Step 3: Student-led Planning: Conduct at least three trials for each depth of water. Record your observations of the horizontal distance that the water travels and the accompanying depth of water in the bucket.

Step 4: Critical Analysis: Were the predictions you made in Step 2 supported by your data? Why or why not? What methods could you have used that would have improved your results? Discuss with your partner and then write your answers in your notebook.

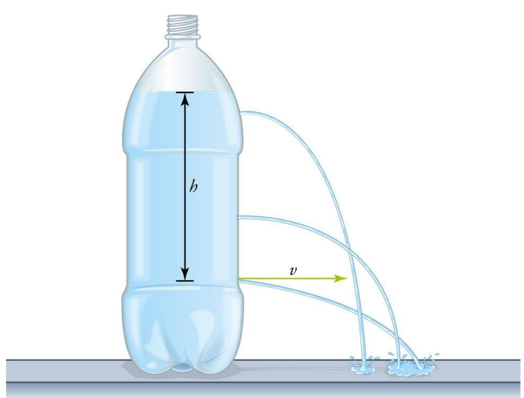


Figure 18.2: The velocity of water leaving the bottle depends on the depth of the hole below the water level.

Guided Inquiry

Step 1: Hypothesize/Predict: How do you think the velocity of the water, the depth of the water above the hole, and the force of gravity are related? How would different values of the depth affect your investigation? Write your ideas in your notebook.

Step 2: Student-led Planning: Conduct four trials with different water levels. Describe each of your setups. Observe and record your findings (as in Step 2 above). Write your results in your notebook.

Step 3: Critical Analysis: Which arrangement led to the water exiting the hole with the greatest velocity? How did the water level above the hole affect the velocity with which the water traveled? How would you mathematically represent these relationships? Discuss your answers with your partner and write them in your notebook.

Assessments

1. How did the depth of the water in the bottle affect how far the water traveled?
2. How did the height of the holes affect how far the water traveled? Why?
3. A student uses Bernoulli's equation and/or the relationship between force and pressure to make calculations related to a moving fluid. Consider your experimental results and give a mathematical relationship that determines the velocity of water as it leaves the bucket in terms of the force of gravity and the height of the water above the bucket. [5.B.10.2]
4. A student uses Bernoulli's equation and/or the relationship between force and pressure to make calculations related to a moving fluid. With your procedure from Question 3, calculate the velocity of the water as it leaves the bucket at three different times during your experiment. [5.B.10.2]

[Solutions]

1. As the depth of water in the bucket decreased, so did the distance that the water traveled.
2. As the height of the holes increased, the distance that the water traveled decreased.
3. [5.B.10.2]
   Answers will vary based on the experimental setup, but the rough answer should be Toricelli's theorem, namely, $v^2 = 2gh$.
4. [5.B.10.2]
   Answers will vary based on the experimental setup, but supposing that gravity is its normal 9.8 m/s^2 and that the height is 0.25 m, the velocity should be the square root of 4.9 m/s, or 2.21 m/s.

Activity 3: Pre-Assessment

1. **Answer the following questions in your notebook**: Consider a graduated cylinder of water. What happens when you place a solid object in this graduated cylinder? What information does this give you about the solid object?
2. **Answer the following questions in your notebook.** Can you measure the density of an object solely by using Archimedes' principle? Why or why not?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 3: Archimedes' Principle

For this next activity, you are going to explore Archimedes' principle. It involves the relationship between the weight of water displaced by an object and the buoyant force on an object. Specifically, consider an object that is denser than water. When you place it in water, it will sink; that is, it will be submerged below the water. However, not all objects that are heavier than water sink all the way to the bottom. That is determined by the balance between the weight of the object and the buoyant force on the object.

When you enter a bathtub or put ice into a cup of water, some volume of the water is displaced. According to Archimedes' principle, the buoyant force on an object immersed in a liquid is equal to the weight of the liquid that is displaced by the object.

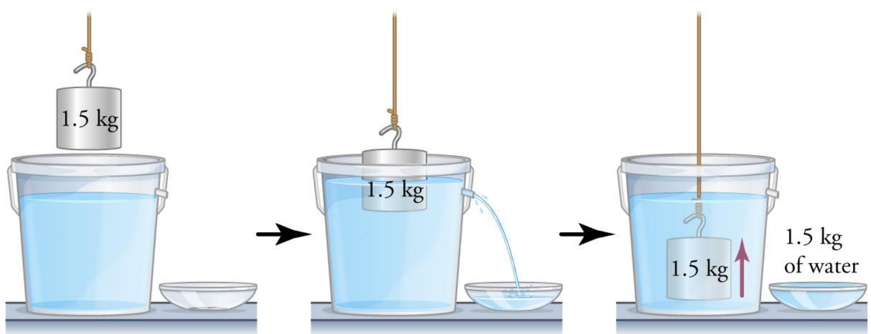


Figure 18.3: According to Archimedes' principle, the buoyant force on an object immersed in a liquid is equal to the weight of the liquid that is displaced by the object.

Safety Precautions

- Be sure to clean up any water spills to avoid slipping on the wet floor.

For this activity you will need the following:

- Scale
- Two objects: one that you think will float, one that you think will sink
- Water and three other unknown liquids of different density

- Graduated cylinder
- At least four objects of irregular shape

For this activity you will work *in pairs or small groups*.

Activity 3 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 3:

- Again, small groups will allow students to have more interaction during the lab, increasing learning. This activity could also be done individually.
- An easy way to make liquids of various densities is to make different concentrations of saline (salt water) and syrup (sugar water). You can also use other common liquids like oil, vinegar, etc. Be sure to wash objects at the end of the lab so they do not corrode.

The following are recommendations for the Guided Inquiry for Activity 3:

- Be sure to pick objects that could not have their volume calculated easily using measurements. Things like toy soldiers, Lego, oddly shaped rocks, etc. work well for this activity.

Structured Inquiry

Step 1: Hypothesize/Predict: How could you compare the density of the two objects using Archimedes' principle? Predict how much displacement will result for the two objects provided by your teacher when placed in the same liquid. Could you use Archimedes' principle to compare the density of two liquids using a single object? Predict how much displacement will result if you used two liquids of different density provided by your teacher.

Step 2: Student-led Planning: Determine how best to test your hypotheses using the two liquids, two objects and a graduated cylinder to measure the displacement of the liquids. Determine the best starting volume for your liquids. Then create a data table to record your results in your notebook.

Step 3: Conduct your trials on your objects. Use the scale to measure the mass of each object. Record your measurements of the volume and whether the object sank or floated.

Step 4: Critical Analysis: Were the predictions you made in Step 1 supported by your data? Why or why not? What methods could you have used that would have improved your results? Discuss with your partner and then write your answers in your notebook

Guided Inquiry

Step 1: Hypothesize/Predict: How might the objects with more complicated shapes supplied in your lab affect your investigation? Pick four additional objects. Write your ideas in your notebook.

Step 2: Student-led Planning: What liquids should you use to test your new shapes? Discuss your plans with your teacher and create a data table in your notebook.

Step 3: Observe and record your findings (as in Step 2 above). Write your results in your notebook.

Step 4: Critical Analysis: Which objects had the largest displacement? Which objects had the greatest density? How did the buoyant force keep some objects from sinking all the way to the bottom of your vessel? Discuss your answers with your partner and write them in your notebook.

Assessments

1. Describe how to determine the density of an object with a scale and the overflow apparatus. [1.A.5.2]
2. Explain how a steel ship can float. [1.A.5.2]
3. Given your data, determine the density of each of the objects you obtained. [1.E.1.2]
4. Calculate the buoyant force for each object. [1.E.1.2]

[Solutions]

1. 1[1.A.5.2]
   To determine the density of an object you need two things: its mass and its volume. You can determine the mass with a scale and you can determine the volume by the amount of liquid it displaces. Then simply divide the mass by the volume to obtain the density.
2. [1.A.5.2]
   Even though the boat is made of steel, which is denser than water, because it is hollow on the inside, it displaces a large enough quantity of water to generate enough of a buoyant force to keep it afloat.
3. [1.E.1.2]
   Answers will vary based on student data, but supposing that the object had a mass of 100 grams and a volume of 50 cubic centimeters as measured by Archimedes' principle, we can calculate that the density is 100 grams divided by 50 cubic centimeters or 2 g/cm^3.
4. [1.E.1.2]
   Answers will vary based on student data, but supposing that the object had a volume of 10 cubic centimeters and is placed in water, the buoyant force will be 0.1 N.

Lab 19: Thermodynamics

Thermodynamics is the branch of physics that studies heat and temperature, as well as the transformation of heat to other forms of energy. Heat is transferred from one object to another by three methods: conduction, convection and radiation. In simple terms, conduction is the transfer of heat by direct contact, convection is the transfer of heat by the movement of heated particles, and radiation is the transfer of heat in the form of electromagnetic waves.

Thermal conductivity is the property of a material that governs the rate of heat transfer. Heat transfers at a high rate through materials with a high thermal conductivity and at a lower rate through materials with low thermal conductivity. The thermal conductivity coefficient is a numerical value indicating the rate at which a material can conduct heat. If the coefficient of thermal conductivity is positive, it indicates transfer of heat occurs in the direction of increasing temperature. A negative coefficient indicates transfer of heat occurs in the direction of decreasing temperature.

The formula to calculate the coefficient of thermal conductivity is

$$k = \frac{QL}{A\Delta T},$$

where *k* is the thermal conductivity, *Q* is the rate of heat transfer in watts, *L* is the length of the material through which heat is transferred, *A* is the surface area of the material through which heat is transferred, and ΔT is the temperature difference of the object to which heat is transferred. The unit of measurement for thermal conductivity is $[k] = \mathrm{W/m \cdot K},$ where W is watts, m is meters and K is temperature in kelvins.

Some materials are very good conductors of heat. These materials are known as **thermal conductors.** For example, if you stir fry food in a frying pan using a steel spoon with a steel handle, you will find that eventually the handle of the spoon becomes too hot to hold directly. In general, metals are good thermal conductors.

Not all materials are good conductors of heat. Materials that are poor conductors of heat are known as thermal insulators, or simply **insulators**. If the spoon that you use to stir fry food has a wooden handle, you can hold the spoon for a much longer time without the handle getting hot. Materials such as plastic, wood, and silicon are examples of insulators.

One method for measuring thermal conductivity is to compare the temperature of an object as it comes into contact with another object at a higher temperature. If the objects have high thermal conductivity, there is a noticeable difference in the temperature of the objects at the point of contact for a short period of time. On the other hand, if the objects have a low thermal conductivity, there is no noticeable difference in the temperature of the objects at the point of contact.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- It will be helpful for students to understand how to measure the volume of various shapes used in this lab such as cylinders and rectangular prisms. Have students derive some of the formulas as a class (or remember them from previous classes).
- Using the thermal conductivity factors above, have students determine which factors are directly proportional vs inversely proportional to thermal conductivity. Provide students with the divisor bar, and as a class, see if they can derive the equation by placing each factor in the numerator or denominator.
- Remind students that any knowledge they can recall from chemistry classes may be helpful in this unit and laboratory. Encourage them to apply knowledge from other disciplines in this lab.

In this lab you will learn:

- how to measure the thermal conductivity of different materials;
- how to measure the thermal conductivity of objects during collisions by observing the difference in temperature at the point of collision;
- how to compare thermal conductivity of different materials by observing the difference in the rate at which heat is transferred by different objects;
- how to calculate the efficiency of a hair dryer by drying a wet t-shirt and calculating the energy used.

Activity 1: Pre-Assessment

1. **Answer the following questions in your notebook:** What happens to a steel spoon when it is immersed in boiling water? What are the factors that determine the measure of thermal conductivity of the steel spoon? If the surface area of the spoon is larger, will the thermal conductivity be higher or lower? Why did you choose your answer? If the length of the spoon is longer, will the thermal conductivity be higher or lower? Why or why not?
2. **Answer the following questions in your notebook:** How would you devise an experiment to calculate the thermal conductivity of a steel rod? What apparatus would you need? What measurements would you need?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 1: How to Measure Rate at Which Heat is Conducted by an Object

Safety Precautions

- Place objects gently to avoid breakage.
- Be careful when handling hot objects.
- Inform your teacher immediately of any broken glassware as it could cause injuries.
- Clean up any spilled water or other fluids to prevent people from slipping.

For this activity you will need the following:

- Hot plate
- Two rods of different lengths and different diameters, one made of steel and one made of copper
- Two rods for the guided inquiry
- Water
- Safety goggles
- Paper towels (to clean up any spilled water)
- Infrared digital thermometer (to measure the temperature of the rod)
- Heat-resistant beaker (in which water can be boiled safely)
- Gloves
- Stopwatch

For this activity, you will work *in pairs*.

Activity 1 Instructor Preparation and Teaching Tip

The following are recommendations for the Structured Inquiry for Activity 1:

- Smaller groups will allow for students to have more direct input to the activity.

- The metal rod will get very hot and needs to be handled with caution. Advise students with what to do with the hot rod when it is removed from the water to prevent injury and damage to countertops.
- Students may need assistance using the infrared thermometer if they have not used one before. This may be a good thing to go over as a class before the lab starts.

The following are recommendations for the Guided Inquiry for Activity 1:

- Check with students after they have planned the data collection steps to ensure they will be successful. If the students are missing information they need to collect, give them hints if it is something they need to take during the lab. If it is dimensions or other information that can be taken any time, let them figure it out when they get to their calculations.

Structured Inquiry

Step 1: Measure the length and diameter of the rod and write them in your notebook.

Step 2: Hypothesize/Predict: What would happen if the steel rod is placed into water and the water is heated? What would happen when the water gets hotter? What part of the rod will change temperature first? What can you say about the time it would take to heat a rod of longer length versus a rod of shorter length?

Step 3: Student-led Planning: Place water in the beaker and heat the beaker on the hot plate. Take the following measurements: (1) initial temperature of the rod, (2) initial temperature of water. Now place one end of the longer rod in water and heat the water (Figure 19.1). Wait for the water to boil. Start the stopwatch. Every five seconds, record (3) the temperature of the rod outside the water, and (4) the length of the rod. Take a total of six readings. Create a data table and record the length of rod, initial temperature of water, initial temperature of rod, final temperature of rod, and time at which final temperature was taken. See sample data table below. Graph the data with temperature on the *y*-axis and time on the *x*-axis.

Step 4: Repeat Step 3 with the copper rod.

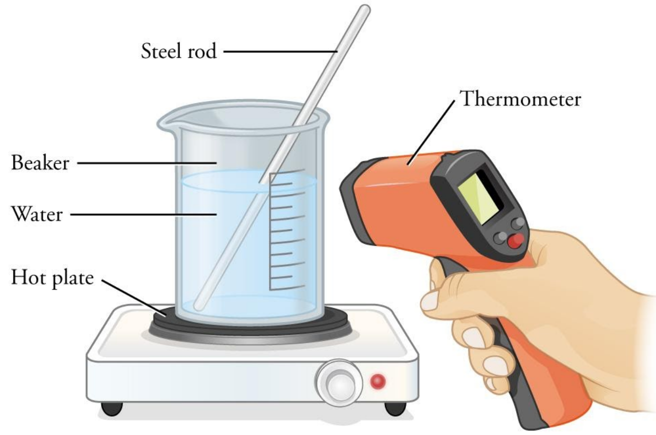


Figure 19.1: Experimental setup for measuring thermal conductivity of a steel rod.

Step 5: Critical Analysis: Analyze the data recorded in your data table. From the graph, determine which rod transferred heat at a faster rate: the steel or the copper rod. What will happen if a steel rod of a larger diameter or surface area is used? What will happen if a longer copper rod is used?

Guided Inquiry

Step 1: Hypothesize/Predict: Of the two materials aluminum and brass, which material do you think would be a better conductor of heat?

Step 2: Student-led Planning: You will now design an experiment using (1) a heat source and (2) two thermal conducting objects of your choice, of the same material and different thicknesses to measure how heat is conducted through a thermal conductor. Discuss with your partner how you will set up your experiment. Then have your teacher approve your plan before starting to collect data. Create appropriate data tables for your investigations.

Step 3: Conduct your experiment and record your data. Plot a graph of time versus temperature to compare the transfer of heat for the different objects. Analyze how the length of the objects and the surface area affects the transfer of heat.

Step 4: Critical Analysis: What difficulties did you encounter when implementing the experiment based on your initial design? What did you learn about the time it takes for heat to be conducted through the thermal conductor? What did you learn about how the thickness of an object affects the transfer of heat?

Assessments

1. A student finds that the time to heat a thermal conducting rod of length 10 cm to $40°C$ is 2 minutes and the time to heat another thermal conducting rod of the same thickness and length of 5 cm to the same temperature is 3 minutes. [EK 5.B.5.5; SP 4.1, 4.2, 5.1]
   a. Does this scenario accurately reflect the time it takes for heat to travel through a thermal conductor? Why or why not?
   b. Do you think the time needed by the two rods to heat would be accurate if the rods were of the same length and thickness? Why or why not?
2. Thermal conductivity refers to the ability of an object to conduct _____. [EK 5.B.5.5; SP 4.1, 4.2, 5.1]
3. An object is placed in contact with a heat source. The temperature of the object rises. [EK 5.B.5.5; SP 4.1, 4.2, 5.1]
   a. What is the method of thermal transfer being described?
   b. What is the term for the material of the object that increased in temperature when it came into contact with the heat source?

[Solutions]

1. [EK 5.B.5.5; S.P 4.1, 4.2, 5.1]
   a. No, the scenario does not accurately reflect the time it takes for heat to travel through a thermal conductor. Both rods are of the same material and same thickness, so the shorter rod should take less time to heat.
   b. No, if the rods were of the same material and same length and thickness, the time it takes for both rods to get heated to the same temperature should be the same.
2. [EK 5.B.5.5; S.P 4.1, 4.2, 5.1] heat
3. [EK 5.B.5.5; S.P 4.1, 4.2, 5.1]
   a. Thermal conduction is the method described.
   b. Thermal conductor

Activity 2: Pre-Assessment

1. **Answer the following questions in your notebook:** What would likely affect how quickly an air dryer dries a wet piece of clothing? What would determine how much energy the hair dryer uses to dry the same piece of clothing?
2. **Answer the following questions in your notebook:** What is the heat of vaporization of water and why is it important in determining how quickly a wet object dries?
3. **Discuss the answers to questions 1 and 2 with the class**

Activity 2: How to Compare Thermal Conductivity of Different Materials

Safety Precautions

- Be careful handling electric devices.
- Be careful when handling hot objects.
- Inform your teacher immediately of any broken glassware, as it could cause injuries.
- Clean up any spilled water or other fluids to prevent people from slipping.

For this activity you will need the following:

- Hair dryer
- Wet T-shirt
- Electric outlet
- Weighing machine
- Paper towel (to clean up any spilled water)

For this activity you will work *in pairs*.

Activity 2 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 2:

- Smaller groups will allow for students to have more direct input to the activity, however, this activity could be done with groups of three or four as well as individually.
- When students wring out the shirts, advise them to ensure the shirt is not dripping wet so that water mass lost will be from the hair dryer, not from water falling off the shirt.
- Encourage students to work on drying the whole shirt, not just one area so the shirt does not get overheated.

The following are recommendations for the Guided Inquiry for Activity 2:

- Check on students after they have designed their experiment. When students propose their ideas, check to be sure they have not created a fire hazard with the proposed design.

- As an alternative, have students determine the efficiency of a clothes dryer at home or at a laundromat.

Structured Inquiry

Step 1: Find the initial weight of the T-shirt. Next, wet the T-shirt and wring it dry. Then, weigh the T-shirt again and record both values in your notebook. From the final and initial weight of the T-shirt, calculate the mass of water, in grams, that was added to the T-shirt. Also record the power of the hair dryer. This is typically given in watts and will be provided by your teacher.

Step 2: Hypothesize/Predict: If you use the hair dryer to dry the T-shirt, how can you calculate the amount of energy used to evaporate the water? What is the relationship between the amount of energy used and the area of the dry T-shirt? What factors can cause the efficiency of the hair dryer to be reduced when drying the T-shirt?

Step 3: Student-led planning:
Your teacher has provided a clothesline or other device on which to hang your T-shirt. Place the wet T-shirt on a hanger and hang it on the clothes line. Then, dry the wet T-shirt for five minutes using the hair dryer (Figure 19.2). After drying the T-shirt, find the mass of water that evaporated from the T-shirt. Tabulate the results in your notebook.

Figure 19.2: Experimental setup for finding the efficiency of a hair dryer.

Step 4: Perform the following calculations:
1. Mass of water *m* evaporated from the T-shirt
2. Amount of energy *Q* used to evaporate the water, using the formula

$$\begin{aligned} Q &= (\text{heat of vaporization of water}) \times (\text{mass of water evaporated from T-shirt}) \\ &= 2260 \text{ J/g} \times m \end{aligned}$$

3. Input energy E, using the formula

$$E = (\text{power of hair dryer}) \times (\text{heating time in seconds})$$

4. Efficiency percentage e, using the formula

$$e = \frac{Q}{E} \times 100\%$$

Step 5: Critical Analysis: Analyze the data recorded in your data table. What are the factors that would affect the efficiency of the hair dryer? Will the efficiency increase or decrease if the input energy is greater? Will the efficiency increase or decrease if the output energy is greater? Discuss with your partner and then write your answers in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: Think of ways in which you can measure the efficiency of a fan, hair dryer, or heater. Discuss your methods with your teacher and your class.
Step 2: Student-led Planning: Design an experiment using a fan or heater to measure how efficiently a fan dries a wet object. Calculate the efficiency percentage of the fan.
Step 3: Critical Analysis: What difficulties did you encounter when implementing the experiment based on your initial design? What did you learn about the efficiency of different devices used to dry a wet object?

Assessments

1. The mass of a T-shirt when dry is 200 g. The mass after adding water is 700 g. The mass after drying with a hair dryer is 600 g. [5.B.5.5; SP B.7.1]
    a. What is the mass of water evaporated from the shirt?
    b. What is the amount of energy used to evaporate the water?
2. If the power of a hair dryer is 2000 W and the T-shirt was dried for 10 minutes, what is the Input Energy? [5.B.5.5; SP B.7.1]
3. If the efficiency of a hair dryer is 0.2578, what is the percentage of efficiency? [5.B.5.5; SP. B.7.1]

[Solutions]

1. [5.B.5.5; SP B.7.1]
    a. The mass of water evaporated from the shirt is 700 g – 600 g = 100 g.
    b. The amount of energy used to evaporate the water is

    $$2260\ \text{J/g} \cdot 100\ \text{g} = 226{,}000\ \text{J} = 2.26\ \text{MJ}$$

2. [5.B.5.5; SP. B.7.1] Input energy is $E = 2000\ \text{W} \cdot 600\ \text{s} = 1{,}200{,}000\ \text{J} = 1.2\ \text{MJ}$
3. [5.B.5.5; SP. B.7.1] 25.78 percent

Lab 20: RC Circuits

An understanding of electronics is an essential part of developing today's modern technologies. Although many modern electronic systems employ sophisticated components, such as transistors, most if not all electrical systems rely on a basic knowledge of resistors and capacitors. Electrical **resistance** is a measure of how easily electric current can pass through a given object. Electric current can pass through objects with a small resistance much more readily than through objects with a large resistance. The **capacitance** of an object measures how well the object can store electric charge. Objects with large capacitance can store more charge than objects with small capacitance.

An **RC circuit**, the focus of this lab, contains resistors and capacitors. The components of such a circuit can be connected in a variety of ways. Components connected in **series** form a single path so that the current flowing through each component is the same. When components are arranged such that the same voltage is applied across each component, the arrangement is known as **parallel**. An example of four resistors connected in series and in parallel is shown in Figure 21.1.

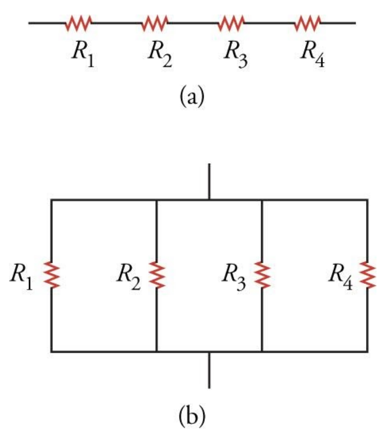


Figure 21.1: Example of a circuit of resistors connected (a) in series and (b) in parallel.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- The students should know the difference between series and parallel circuits; draw a diagram for basic series and parallel circuits on the board if needed.
- Students should know the basics of resistors and capacitors.
- Review how to use a multimeter to measure current and voltage in a circuit and across a resistor or capacitor.

In this lab you will learn:

- how capacitors work when connected in series and in parallel;
- how resistors and capacitors behave when in a circuit together;
- how the voltage across an RC circuit changes over time.

Activity 1: Pre-Assessment

1. **Answer the following questions in your notebook:** What happens to the capacitance of a circuit when adding two capacitors in series? Will the overall capacitance be larger or smaller than the individual components?
2. **Answer the following question in your notebook:** What happens to the capacitance of a system when you connect two capacitors in parallel?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 1: Capacitors in Series and Parallel

In this activity, you will investigate the properties of capacitors when connected in series or in parallel with each other. The most common type of capacitor is a parallel-plate capacitor, consisting of two parallel conductive plates that are insulated from each other. When a voltage or electric potential *V* is applied between the two plates, a charge *+Q* will accumulate on one plate and *–Q* will accumulate on the other. The charge on either plate is related to the voltage between the two by the capacitance *C*, according to the relation

$$C = Q / V \, .$$

The standard unit of charge is the *coulomb* (C), and the units of capacitance are coulomb/volt. This unit of capacitance is known as a *farad*, named after the physicist Michael Faraday. Electric current enters or leaves a capacitor only when the voltage applied across it varies with time. The current-voltage relationship of a capacitor is given as

$$I = C\frac{\Delta V}{\Delta t} \, ,$$

where *I* is the current in units of *amperes*, *C* is the capacitance, and $\Delta V / \Delta t$ is the change in the applied voltage *V* over a time difference *t*. Thus, in a static situation that does not change over time, no current flows through a capacitor. This relation can be used to determine the time it takes for a capacitor to become fully charged. For a given current, larger capacitors take longer to fully charge than smaller ones.

Two capacitors C_1 and C_2 connected in series produce an overall capacitance *C* given by

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} \, .$$

The same two capacitors connected in parallel have an overall capacitance given by

$$C = C_1 + C_2 \, .$$

For this activity you will need the following:

- Three D-cell batteries
- 8–10 connecting wires

- Four miniature screw lamps (size #40 or #50, with holders)
- At least two nonpolar 100-F (or 25-F) capacitors
- Stopwatch

For this activity, you will work *in groups of 3 to 4 students*.

Activity 1 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 1:

- It is best to do this activity in groups of three or four, so students can interact with the equipment. Often, equipment availability limits group sizes.
- Remind students how current behaves in a series circuit and how to calculate voltage and current in a series circuit and across a capacitor.
- Check students' plans at Step 3 to verify they are on the right track to finding the capacitance in both configurations.

The following are recommendations for the Guided Inquiry for Activity 1:

- It is best to do this in groups of three or four, so students can interact with the equipment. Often, equipment availability limits group sizes.
- Remind students how changing the voltage in a circuit changes the current in the whole circuit. Review how to calculate voltage and current in a series circuit and across a capacitor.
- Check students' plans at Step 2 to verify they are on the right track to finding the capacitance in both configurations.

Structured Inquiry

Step 1: Working with your group, connect a battery to a capacitor and lamp in series. The lamp in this example behaves as a resistor, so this would be an example of a simple RC circuit. Notice how long it takes for the lamp to go from fully lit to completely off.
Step 2: Hypothesize/Predict: Given that the time it takes to charge or discharge a capacitor is proportional to its capacitance, how will the time change when adding an additional capacitor in series to your first? How about when adding an additional one in parallel? Record your predictions in a table.
Step 3: Student-Led Planning: Connect an additional capacitor in series with your original capacitor, and then in parallel. Discuss with your group the best way to accurately measure the overall capacitance of the two configurations.
Step 4: Critical Analysis: Record the results of your measurements in a table. How do the measurements compare to your prediction in Step 2?

Guided Inquiry

Step 1: Hypothesize/Predict: How will the charging time change when doubling the applied voltage (i.e., connecting another battery in series)? What about when tripling the applied voltage? Write your hypotheses in your notebook.
Step 2: Student-Led Planning: Plan how you will test your hypotheses from part 1. Create appropriate data tables.
Step 3: Carry out the experimental plan you created in Step 2. Be sure that your teacher checks your voltages before turning on the circuit. Record your results in your tables.
Step 4: Critical Analysis: Was there a change in the time to charge the capacitor? Did the overall capacitance change? Discuss your results with your group.

Assessments

1. Capacitors are able to store electric ________. [21.4e; SP 3]
2. Suppose you have two capacitors of equal magnitude. [21.4e; SP 3]
    a. What is the overall capacitance when you connect them in series?
    b. What is the charge stored in the system for a given voltage?

[Solutions]

1. [21.4e; SP 3] charge
2. [21.4e; SP 3]
    a. The total capacitance is $C_{\text{tot}} = \dfrac{1}{\dfrac{1}{C} + \dfrac{1}{C}} = \dfrac{C}{2}$.
    b. The charge of the system is $Q = C_{\text{tot}} \times V = \dfrac{C}{2} \times V$.

Activity 2: Pre-Assessment

1. **Answer the following questions in your notebook:** Will increasing the voltage across a capacitor change the total charge stored in the capacitor?
2. **Answer the following question in your notebook:** For a given current, will the voltage drop be larger or smaller for two resistors connected in series compared with a single resistor? How about if the resistors are connected in parallel?
3. **Answer the following question in your notebook:** How will the total resistance change when connecting two resistors in parallel? Will the overall resistance be larger or smaller than that of the individual components? How will the total resistance change when connecting two resistors in series?
4. **Answer the following question in your notebook:** Does the presence of a resistor in a circuit that contains a capacitor affect the charge on the capacitor?
5. **Discuss the answers to questions 1–5 with the class.**

Activity 2: Potential Difference and Resistors in RC Circuits

In this activity, you will investigate how resistors affect the charge on a capacitor in a circuit. The resistance of an object behaves differently from the capacitance. Conceptually, resistance parallels the idea of mechanical friction. Given a voltage difference *V* across a resistor with value *R*, the current *I* flowing through the resistor is obtained through Ohm's law,

$$R = V / I \,,$$

where *R* is in units of volts/ampere, which is known as an *ohm* (Ω).

Combining resistors works in the opposite way as combining capacitors. The overall resistance *R* of two resistors R_1 and R_2 in series is given by the sum of the two,

$$R = R_1 + R_2 \,.$$

If they are connected in parallel, the overall resistance is given by

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} \,.$$

You will also investigate how potential differences change across various circuit elements when changing the capacitance. When a voltage source, such as a battery, is connected to a capacitor and resistor in series, as seen in Figure 21.2, current flows through the system until the capacitor becomes fully charged.

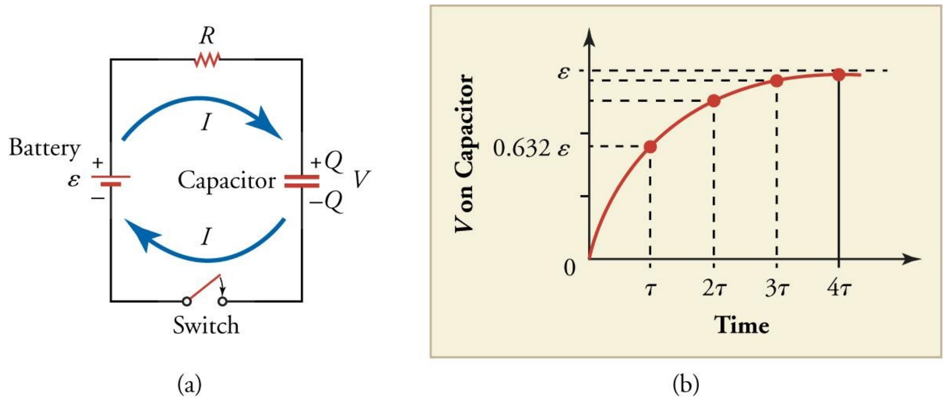


Figure 21.2: (a) A resistor and capacitor connected in series to an external voltage source and (b) the voltage across the capacitor as a function of time.

When the capacitor becomes fully charged, the current decreases to zero, and the voltage drop across the capacitor is equal to that of the battery. Furthermore, since no current flows through such a system at this point, the voltage drop across the resistor is zero. If the battery is disconnected from the circuit, the charge on the capacitor discharges in the form of current through the resistor until no more charge is left on the capacitor (Figure 21.3). The overall time needed to charge or discharge the capacitor is given by the time constant

$$\tau = RC \ ,$$

which is known as the RC **time constant**.

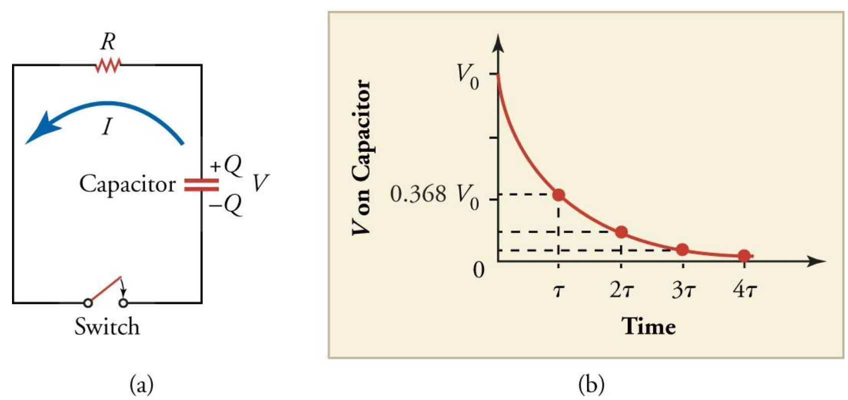


Figure 21.3: (a) A circuit of a capacitor discharging through a resistor and (b) the voltage on the capacitor as a function of time.

The current and potential difference in an electrical circuit can be found from two equalities, known as **Kirchhoff's circuit rules**. The first rule, **Kirchhoff's current rule**, is derived from the conservation of electric charge and states that at any junction of components, or node, of an electrical circuit, the current flowing into the node is equal to the current flowing out of the node. The second rule follows from conservation of energy and states that the sum of any potential difference around a closed network (loop) is zero.

For this activity you will need the following:

- Three D-cell batteries
- 8–10 connecting wires
- Four miniature screw lamps (size #40 or #50, with holders)
- At least two nonpolar 100-F (or 25-F) capacitors
- Stopwatch
- Several resistors ranging from 10–50 ohms rated to at least 1 watt and resistors ranging from 200–500 ohms rated to at least 0.5 watt or a resistor decade box with variable resistance
- Voltmeter or multimeter
- Single pole switch

For this activity, you will work *in groups of three to four students*.

Activity 2 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 2:

- It is best to do this in groups of three to four, so each student can interact with the circuit.
- Draw a circuit diagram on the board, showing students how to make a connection that bypasses the battery correctly in Step 1.
- At Step 3, verify that the circuits students have designed will work to test their predictions.

The following are recommendations for the Guided Inquiry for Activity 2:

- It is best to do this in groups of three to four, so each student can interact with the circuit.
- Review how to use a multimeter to measure current and voltage in a circuit and across a resistor or capacitor.
- Check students' planned circuits in Step 2 to verify they are parallel. Have students show you how they plan to connect the circuit to bypass the battery to allow the capacitor to discharge.

Structured Inquiry

Step 1: Working with your group, connect a resistor, capacitor, and lamp in series to a battery. Then, create a connection that bypasses the battery and observe how long it takes to discharge the capacitor by looking at how much light is emitted from the lamp.
Step 2: Hypothesize/Predict: If you double the resistance of the resistor, what happens to the total charge on the capacitor? What happens to the time needed to discharge the capacitor? Record your prediction in a table for a few different resistance values. Discuss with your teacher which resistance values you should test.

Step 3: Student-Led Planning: Working with your group, design circuits that can test the different resistance values your teacher approved in Step 2. Add columns to the tables you created to test the total charge on the capacitor at each resistance value.
Step 4: Test the total charge on the capacitor at your different resistance values, using the circuits you created in Step 3. Record your results and compare them to your predictions from Step 2.
Step 5: Critical Analysis: Does changing the resistance and capacitance of the system change the time constant of the circuit? If the capacitance is halved, how will the resistance need to be changed to maintain the same time constant?

Guided Inquiry

Step 1: Hypothesize/Predict: How will the potential or voltage drop across a resistor vary over time when connected to a capacitor in series? How will it change if the capacitor is connected in parallel to the resistor instead?
Step 2: Student-Led Planning: Create several different circuits, each containing a battery, a switch, and at least one capacitor and one resistor. For each circuit, observe the potential difference across the resistor, the capacitor, and the battery as a function of time after closing the switch. Use the multimeter to measure the potential difference. Discuss with your group how best to record the potential drop across the various components as a function of time.
Step 3: Critical Analysis: Was there a change in the time to charge the capacitor between connecting the resistors and capacitors in series and parallel? Did your results from Step 2 match your expectations from Step 1? Discuss your results with your group.

Assessments

1. A resistor R_1 is connected in parallel to a combination of a capacitor *C* and resistor R_2 connected in series. How will the potential drop across R_1 change as the capacitor is being charged? [EK 21.5c; SP 3]
2. In the previous question, a current *I* is flowing through the circuit and the capacitor *C* is fully charged. [EK 21.4e, 21.5c; SP 3]
   a. What is the potential drop across each of R_1, R_2, and *C*?
   b. What is the current flowing through R_1?
3. A 5-ohm resistor and 2-F capacitor are connected in series to a 5-volt source.
   a. What is the RC time constant of the system?
   b. How much charge is stored on the capacitor when it is fully charged?
   c. How will the charge stored on the capacitor change if a 10-ohm resistor is used instead? [EK 21.5b; SP 3]
4. Conservation of electric charge leads to conservation of electrical ________ at each point in the circuit. [EK 21.5c; SP 3]

[Solutions]

1. [EK 21.5b; SP 3] The potential drop of the resistor R_1 is unaffected by the charging of *C* and remains constant with time because the voltage across R_1 is constant.
2. [EK 21.4e, 21.5c; SP 3] First, we must note that the capacitor is fully charged, and so no current is flowing through it or the resistor R_2.
   a. The potential drop across R_1 is $V_1 = I \times R_1$. Since no current flows through R_2, the potential drop is zero, and the potential drop across *C* is $V = V_1$.
   b. Again, no current is flowing through R_2 or *C*, so the current flowing through R_1 equals the total current *I*.
3. [EK 21.5b; SP 3]
   a. The RC time constant is $\tau = R \times C = 5\,\Omega \times 2\text{ F} = 10\text{ s}$.
   b. The total charge on the capacitor is $Q = C \times V = 2\text{ F} \times 5\text{ V} = 10\text{ C}$.
   c. The overall charge of the capacitor will remain the same due to conservation of electric charge, but the time needed to fully charge will increase by a factor of two.
4. [EK 21.5c; SP 3] current

Lab 21: Observations of Magnetic Fields

As with other fields that you have studied, magnetic fields cannot be directly observed. Instead, to identify the characteristics of a magnetic field, you have to look at how objects respond to the field. You have probably observed in the past that two magnets attract when their opposite poles are together and repel when their like poles are together. This behavior demonstrates that a second magnet is a good probe of a magnetic field. However, some metal objects that are not themselves magnets also respond to magnetic fields. For example, magnets stick to a refrigerator door, even though the door itself is not a magnet. Metal objects, like a refrigerator door, can act as induced magnets—meaning they form a dipole in response to the presence of an external magnetic field.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- Review with students the concepts of both electric and magnetic fields. Discuss the similarities and differences, especially the fact that magnetic field lines do not go from a source to a sink as with electric field lines, where the lines go between electric charges. Discuss the meaning of *north* and *south* magnetic poles, and make a point of saying that this is not the equivalent of a magnetic charge, as with electric fields and charges.

In this lab you will learn:

- how permanent magnets interact through their magnetic fields;
- how to use a compass to observe magnetic fields;
- how to produce a magnetic field using a current-carrying wire.

Activity 1 Pre-Assessment

1. **Answer the following questions in your notebook:** How do you know that a permanent magnet, such as a refrigerator magnet, has its own magnetic field? How is a permanent magnet different from another piece of metal, such as a paper clip, that also interacts with magnets?
2. **Answer the following questions in your notebook:** What would happen if you broke a bar magnet in half? Would you get two smaller magnets, each with a north pole and a south pole, or would you get a north magnet and a south magnet? Explain.
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 1: Qualitative Magnetic Observation

A bar magnet is a permanent magnet, which means it generates its own magnetic field. As a result, bar magnets can interact with other external magnetic fields. In particular, two bar magnets interact with each other because each is a magnet. However, the field at the north pole of a magnet is not the same as the field at the south pole of the magnet, so the interaction between two bar magnets depends on their relative orientations.

The needle of a magnetic compass is a small permanent magnet that is free to rotate around an axis. The needle aligns itself with whatever external magnetic field it is placed within. Earth's magnetic field is the strongest magnetic field in most locations, so a magnetic compass can be used for navigation because it aligns with Earth's magnetic field. However, if it is placed in a stronger field, such as that of a bar magnet, it will align with that field.

For this activity you will need the following:

- Two bar magnets
- A piece of string
- A compass
- A blank piece of paper

For this activity, you will work *in pairs*.

Activity 1 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry in Activity 1:

- Ensure that students make practice runs with the bar magnets. It is easy for the behavior of the test magnet to be seemingly erratic if the students are not careful in how they approach the test magnet with the reference magnet.

The following are recommendations for the Guided Inquiry in Activity 1:

- Review with students the idea that the magnetic field lines—as with electric field lines—show the direction of the force at that point in space. This should aid them in conceptualizing the layout of the field lines. The students should review if the field lines they draw make sense in terms of the direction of the force observed between the reference and test magnets.

Structured Inquiry

Step 1: Your teacher will give you two bar magnets. The poles of one of the magnets will be labeled, but the labels for the poles of the other magnet will be covered. Using the piece of string, hang the magnet with its labels covered from the ceiling—or from your desk or another convenient location—so that the magnet is free to move, as shown in Figure 22.1.

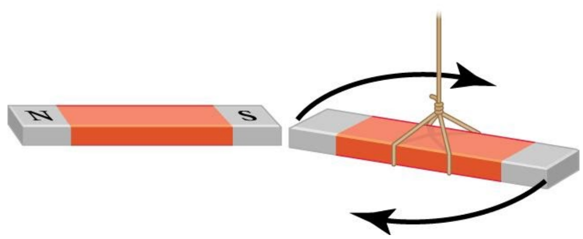


Figure 22.1: Bar magnets interact through their own permanent magnetic fields. The poles of a magnet can be determined based on how it reacts to another magnet.

Step 2: Hypothesize/Predict: Based on what you know about how bar magnets interact, predict what the hanging bar magnet will do when you bring the other bar magnet close to it. What will you be able to learn about the poles of the hanging magnet by observing this behavior? Record your predictions in your notebook.

Step 3: Student-Led Planning: Use the second bar magnet to observe the reaction of the hanging magnet to the free magnet in all different orientations. Consider all the possible orientations that should be tested and determine how you will keep track of them to make sure that you have observed all possible orientations. Create a data table in your notebook and record your observations of how the magnets interact in various orientations. Once you have done that, lay one of the magnets in the middle of a sheet of paper and trace the magnet's perimeter so its position will be shown after the magnet is removed. You will then use the compass to map the magnetic field of this magnet on a blank piece of paper.

Step 4: Place the compass at various locations around the magnet on the paper, starting at one pole and working your way around to the other, noting on the paper the direction of the compass needle at each location.

Step 5: Critical Analysis: Use your observations of the interactions of the magnets to identify the north and south poles of the hanging magnet. Then, uncover the labels and check whether they agree with your determination. Next, place your magnet in the middle of your blank sheet of paper and move the compass around the paper, recording the orientation of the needle at each point. Does the needle point in the direction you would expect? What could account for any discrepancies? Is there anything you could do to improve your technique? Discuss these questions with your partner and then write your answers in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: Based on your observed compass readings, what will the magnetic field of your bar magnet look like? Draw your prediction of the magnetic field for the bar magnet in your notebook.

Step 2: Student-Led Planning: Discuss with your partner what the orientation of the compass tells you about the direction of the magnetic field around the bar magnet. Can you use your recordings of the compass orientations to map the magnetic field lines around the bar magnet? With your partner, create a plan for how you can map the magnetic field lines around the bar magnet.

Step 3: Carry out the plan you designed in Step 2.

Step 4: Critical Analysis: Did the magnets interact as you expected in each orientation? If not, what could account for that discrepancy? Did the magnetic field lines you mapped for the bar magnet look like the field you would expect for a bar magnet? If there are any differences, what could have caused them? How could you have improved your mapping to make it look more like what you expected? Discuss these questions with your partner and then write your answers in your notebook.

Assessments

1. Imagine repeating the first part of this experiment, but with the labels covered on both magnets. Would you still be able to determine the poles of the hanging magnet? If so, how? If not, what information would you be able to determine? [EK 2.D.3; SP 3,4]
2. Suppose that you took a paper clip and brought one end of it near the north pole of a magnet and it stuck to the magnet. [EK 2.D.3,4; SP 6]
    a. Why is the paper clip attracted to the magnet?
    b. Would the same end of the same paper clip attract or repel the south pole of the magnet? Why?
    c. Is there an orientation in which the paper clip will repel the magnet?
3. Based on what you know about how a compass behaves in a magnetic field, draw which direction the needle would point on each compass surrounding the horseshoe magnet below. [EK 2.D.3; SP 1]

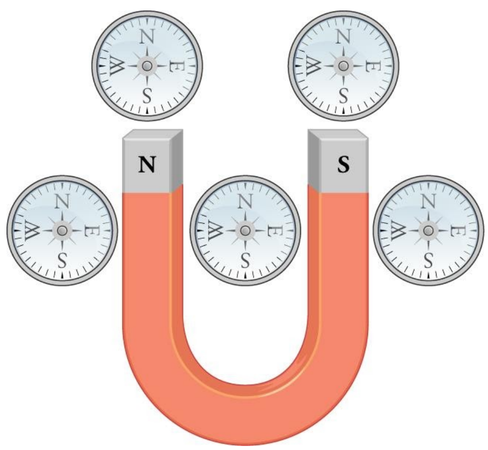


Figure 22.2

[Solutions]

1. [EK 2.D.3; SP 3,4] No, you wouldn't be able to determine the poles of the magnets. You would only be able to determine which poles were like and which were opposite when comparing the two magnets.
2. [EK 2.D; SP 3, 4, 6]
    a. The paper clip is attracted to the magnet because it is made of a material that can have an induced magnetic dipole in an external magnetic field.
    b. The paper clip would also be attracted to the south end of the magnet because its dipole is induced by the field in which it is located. So, the dipole will reverse when it is put near the opposite magnetic pole.
    c. The paper clip cannot repel the magnet because its dipole is due to the external field; it is always oriented so that it attracts.

4. [EK 2.D.3; SP 1]

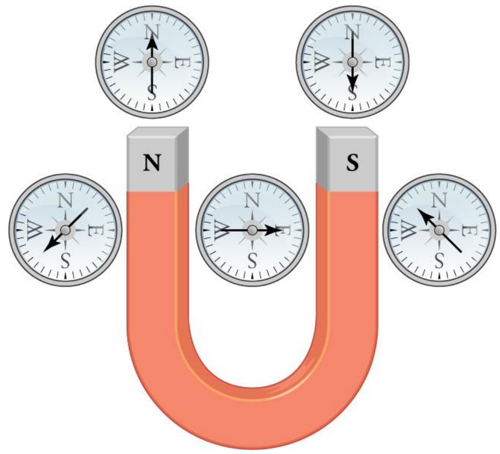


Figure 22.3

Activity 2 Pre-Assessment

1. **Answer the following questions in your notebook:** What is needed to generate a magnetic field? Why do the bar magnets in Activity 1 have magnetic fields around them?
2. **Answer the following question in your notebook:** Why do magnetic field lines always have to be loops, unlike electric field lines, which can have one end at a charge but then go off to infinity? How does this relate to your answer to question 2 in the Pre-Assessment for Activity 1?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 2: Magnetism and Current

Magnetic fields are generated by moving charges. As a result, any wire carrying current has a magnetic field around it. The field lines form closed loops, with the wire running through the center of the loop and perpendicular to the plane of the loop. The strength of the field is affected by the current in the wire and the distance from the wire where the field is measured.

Safety Precautions

- Do not connect the wires to the battery without first connecting the switch. The battery will short circuit and could start on fire.

For this activity you will need the following:

- Batteries of various sizes and voltages
- Two pieces of wire, one short and one long, each with ends that can connect to the switch or battery
- One circuit switch
- A magnetic compass
- A ring stand, or other support

For this activity, you will work *in pairs*.

Activity 2 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry in Activity 2:

- Discuss with the students the conceptual aspects of magnetic field lines around a current-carrying wire. Ensure that they realize the importance of having a relatively long length of straight wire to use for their measurements. Otherwise, it could be very difficult to accurately map the circular field lines about the wire.

The following are recommendations for the Guided Inquiry in Activity 2:

- Review with students the role of voltage and current in the strength of the magnetic field. It is common for students not to realize just how large a current is needed to create a strong magnetic field. The students should come to an understanding of the limitations of strength of a magnetic field made from connecting a wire to a battery.
- As an additional activity, it may be useful to discuss designs of actual electromagnets, such as those used at particle and medical accelerators. Students could research the basic working designs of such electromagnets.

Structured Inquiry

Step 1: Using the ring stand, hang the wire so that there is a long vertical length of wire from the top of the ring stand almost to the floor, as shown in Figure 22.4. This leaves you with a long length of wire around which to observe the magnetic field. Place the switch on the table and adjust the wire length so that you can easily connect the hanging wire to one end of the switch. Then, connect the short wire to the opposite end of the switch.

Note—*Do not* connect the wires to the battery without first connecting the switch. The battery will short-circuit and could start a fire.

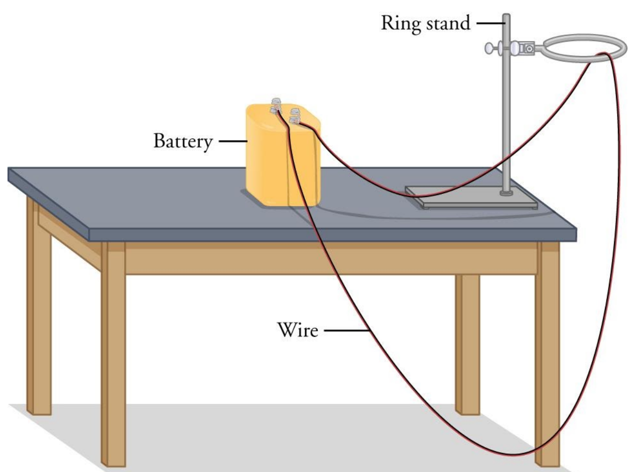


Figure 22.4: Running the wire from the ring stand to the floor leaves a long vertical length of wire away from the rest of the setup. This should give you a better measurement of the magnetic field by reducing interference with other electrical devices.

Step 2: Hypothesize/Predict: Compass readings will be used to map the magnetic field around the wire. If you move the compass around with one end of the wire disconnected from the battery, what should you observe? How do you expect this to change when you connect both wires to the battery? How will the current you apply affect the compass readings? Write a hypothesis for how the voltage applied to the wire will affect the behavior of the compass needle.

Step 3: Student-Led Planning: Discuss with your partner how and where the compass readings should be taken and create an appropriate data table in your notebook. Then, connect both wires to the battery and throw the switch. Use your compass to observe the magnetic field around the wire.

Step 4: Critical Analysis: Vary the current in the wire by replacing the battery with others available in the lab that have different voltages. Record the compass readings around the length of wire for each battery, as well as the battery's voltage. Then, disconnect each end of the wire and reconnect it to the opposite terminal. In what direction did the compass needle point in each situation? Did changing the battery or switching the terminals affect your readings? If so, was it in the way(s) that you expected? Discuss these questions with your partner and then write your answers in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: How do you expect the magnetic field lines from the current-carrying wire to be similar to those from the bar magnet? How do you expect them to be different? How do you expect varying the voltage to affect the magnetic field lines? Make a drawing of the field you expect to find around the current-carrying wire.

Step 2: Student-Led Planning: Discuss with your partner what the orientation of the compass needle tells you about the direction of the magnetic field around the wire. Use your recordings of the compass needle orientations to map the magnetic field lines around the wire for the various experimental parameters that you tested.

Step 3: Critical Analysis: Do the magnetic field lines appear as you would expect for the field around a current-carrying wire? Did changing the experimental parameters change your results in the ways that you expected? Discuss your answers with your partner and record them in your notebook.

Assessments

1. Imagine that you repeated one of your measurements of the field around a current-carrying wire, but this time you added a 100-Ω resistor to the wire. Would this change your measurement? If so, how? [EK 2.D.2; SP 6,7]
2. Would you expect two current-carrying wires to be able to attract or repel each other, like two bar magnets? Why or why not? [EK 2.D.2; SP 6]
3. When you use a compass to observe the magnetic field around a wire, what two fields is the compass needle being affected by? Use this answer to explain why you need a fairly high current to make this experiment work well. [EK 2.D.2,3; SP 6]

[Solutions]

1. [EK 2.D.2; SP 6,7] This shouldn't change the shape or direction of the magnetic field. But it will make the field weaker, so you will have to hold the compass closer to the wire in order to measure the magnetic field.
2. [EK 2.D.2; SP 6] Two current-carrying wires should attract or repel each other, like two bar magnets, because they both have magnetic fields. Objects with magnetic fields interact with each other due to those fields.
3. [EK 2.D.2; SP 6] The compass needle is affected by Earth's magnetic field and the field from the wire. In order to observe the field from the wire, that field needs to be significantly larger than Earth's field. A larger current produces a larger field, so it will also improve the results of this experiment.

Lab 22: Quantitative Magnetism

A magnet has a north pole and a south pole. Like poles repel and unlike poles attract, which means that two north poles or two south poles repel, but a north pole and a south pole attract. If you have two bar magnets and place them with their north poles close to each other, the magnets will move away from each other. If you place the magnets so that the north pole of one magnet is close to the south pole of the other magnet, the magnets will move closer to each other.

Earth is also like a large magnet with a North Pole and a South Pole. If you are lost in the woods, for instance, you can use a magnetic compass to find your direction. The needle in the compass is magnetized, so the north end of the needle is attracted toward the magnetic South Pole of Earth (which is located at the geographic North Pole) and the south end of the needle is attracted toward the magnetic North Pole of Earth.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- In order for students to understand the magnetic field of the earth demonstrate how a compass works. Move the compass across the room and have the students learn the location of the direction of the north pole of the earth.
- In order for students to understand the concept magnetism, explain the key terms: (1) *magnetic field*—area around which an object exhibits a magnetic property, and (2) *magnetic force*—the force or energy in a magnetic field.
- In order for students to understand how opposite poles in a magnet attract demonstrate to the students using two bar magnets. Explain how the attraction is due to the magnetic field around the magnets.
- In order for students to understand the magnetic field of Earth, demonstrate how the magnetic field is influenced by the distance from the magnet, demonstrate with iron filings and a bar magnet how filings further away from the magnet are attracted less.
- In order for students to understand the concept of magnetic field around a magnet, demonstrate using a horseshoe magnet and iron filings.
- In order for students to understand why iron filings are attracted to a magnet, explain to the students how the magnetic field of the magnet makes each iron particle (which is a magnetic material) to become a tiny magnet with a north and south pole, the opposite poles then attract making the iron filings to cling to each other and to the magnet.
- In order for students to understand how a gauss meter works, bring a gauss meter to class and demonstrate how it can be used to measure magnetic fields around objects.

- In order for students to understand the concept of electromagnetic fields or EMFs provide examples of power lines and electrical appliances where the electric and magnetic fields are caused by electromagnetic radiation.

In this lab you will learn:

- how to observe and draw a diagram of the magnetic field of magnets of different shapes and sizes;
- how to observe and draw a diagram of the magnetic field of two bar magnets of the same size when placed in different positions;
- how to observe and record the magnetic field from electrical devices in your surroundings.

Activity 1: Pre-Assessment

1. **Answer the following questions in your notebook:** What happens when you place a magnet on a refrigerator? Why does the magnet not fall off? What happens when you bring two bar magnets close to each other? Do they always attract? Why or why not?
2. **Answer the following question in your notebook:** What is magnetism and what do you think causes magnetism?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 1: Observe the Magnetic Field Lines of a Magnet

Even though magnetic fields are invisible, they can still be observed by investigating how metal objects react to a magnet. Iron filings are tiny flakes of iron that can be used to reveal the structure of a magnetic field. Iron filings and other techniques used for visualizing magnetism reveal how the structure of magnetic fields is organized and predictable.

Safety Precautions

- Place objects gently to avoid injury
- Be careful when handling magnets and iron filings
- Iron filings are very fine particles and can stick to clothing, so use a lab coat or gloves as needed

For this activity you will need the following:

- Different shaped magnets (e.g. bar magnet, horseshoe magnet)
- Different sizes of magnets
- Breakable magnets (optional)
- Thick paper on which to place the magnets and sprinkle the iron filings
- Container to collect the iron filings
- Lab spoon to help sprinkle the iron filings
- Lab coat and gloves as needed

For this activity you will work *in pairs*.

Activity 1 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 1:

- Before proceeding with the lab, show the students all the different items that will be used for this activity. If students need to bring any of the items, provide them with a list and instructions from where to get them. Provide specific details about the type of bar magnet, horseshoe magnet, breakable magnets, iron filings, and lab spoon required.
- Since the students are working in pairs, explain what each student needs to do so that both students can equally contribute to the activity. Students can take turns conducting the experiments and recording the observations.

- Repeat the experiment using the broken pieces of magnet and observe and record how the shape of the iron filings change depending on the shapes of the broken pieces.

The following are recommendations for the Guided Inquiry for Activity 1:

- Sprinkle iron filings on the center of a bar magnet. Record in your notebook through a drawing how the iron filings behave. Do they stay where they are placed? Do they move to one of the poles? Do you have to do anything to make the filings move?
- Using a compass and a bar magnet, identify which pole of the magnet is north pole and which pole is south pole. Record and draw the observations in your notebook.

Structured Inquiry

Step 1: Hypothesize/Predict: What would happen to the shape of the filings if the shape of the magnet is a horseshoe magnet?

Step 2: Student-Led Planning: Place the paper on a flat surface on the table. Place a bar magnet on the paper (Figure 23.1). Draw the outline of the magnet and mark the north and south poles of the magnet on the paper. Take a spoonful of iron filings and sprinkle them over the bar magnet. Watch as the filings stick to the magnet. Repeat with 2–3 more spoons of the iron filings. Using a pencil, gently trace 2–3 lines on each side of the magnet from the north to the South Pole along the path of the iron filings on the paper. Mark tracings along the outermost and innermost paths of the filings on both sides of the magnet. How would you design experiments to get the best patterns of iron filings around magnets of different shapes?

Step 3: Now empty the filings into a container. Notice the shape of the iron filings. Make a note of the shape and save the tracings that you made in your notebook.

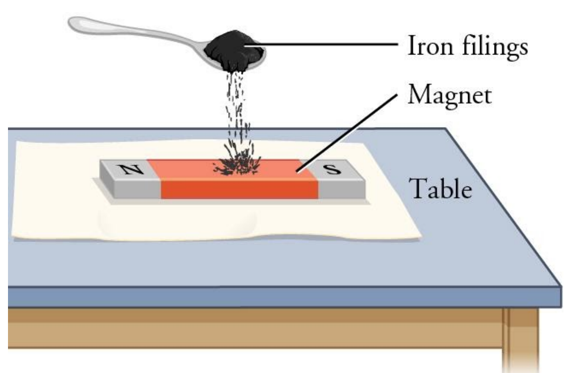


Figure 23.1: Sprinkling iron filings over a bar magnet.

Step 4: Critical Analysis: Analyze the shapes from the two different magnets. Were the predictions you made in Step 1 supported by your data? Why or why not? What did you notice about the distance of the filings in relation to the length of the magnet? What other methods can you use to visualize the magnetic fields around a magnet?

Guided Inquiry

Step 1: Hypothesize/Predict: How would the shape of the magnetic field likely appear for differently shaped magnets? Pick two additional magnets of different shapes and predict the shapes of their magnetic field by drawing a hypothetical field in your notebook. Your teacher may also have you analyze how the magnetic field of a magnet changes after it is broken.

Step 2: Student-Led Planning: Create a data table in your notebook with the following information: (1) shape of magnet, (2) longest length of magnet, and (3) maximum distance of iron filings from the center of the magnet. Determine the shape of the magnetic field of each magnet using the iron filings. Repeat the experiment with magnets of different sizes and shapes. Draw the pattern of the shape of the filings for each case.

Step 3: Critical Analysis: Were the predictions you made in Step 1 supported by your data? How did the actual magnetic fields compare with those you drew in your notebook? Why do you think any differences occurred? What determines the shape of a magnetic field?

Assessments

1. A student finds that when two bar magnets are brought close to each other, they tend to move apart. [EK 2.D.3.1, SP 1.2]
    a. What can you tell about the poles of the magnets?
    b. What would happen if you reposition the first magnet so that the other end of the magnet is now close to the second magnet?
2. The area around a magnet that can attract or repel iron or other magnets is known as ________. [EK 2.D.3.1, SP 1.2]
3. A student finds that when sprinkling iron filings on a bar magnet, the iron filings stay where they are placed. [EK 2.D.3.1, SP 1.2]
    a. Is this a correct observation?
    b. What may be happening if the iron filings are simply staying where they are placed on a bar magnet?

[Solutions]

1. [EK 2.D.3.1, SP 1.2]
    a. Since the magnets are moving apart, the two poles of the magnets have to be the same. Both magnets have their north poles or their south poles close to each other.
    b. If the magnets are repositioned, they should attract, because now the opposite poles are close to each other.
2. [EK 2.D.3.1, SP 1.2] magnetic field
3. [EK 2.D.3.1, SP 1.21]
    a. No, iron filings should arrange themselves around a bar magnet in a particular shape.
    b. If the iron filings are simply staying where they are placed, it is possible that the magnet is not magnetized, or does not have magnetic properties.

Activity 2: Pre-Assessment

1. **Answer the following questions in your notebook:** What do you think would be the shape of the iron filings when two bar magnets are placed close, but not touching, and with their north poles facing each other? What would happen to the shape of the filings if the magnets are placed close to each other but not touching, so that the north pole of one magnet faces the south pole of the other? Make a prediction by drawing the shape of the iron filings and explain your reasoning.
2. **Answer the following questions in your notebook.** How would the magnetic field of one magnet affect the magnetic field of another magnet? Would it matter which poles were facing each other? Explain.
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 2: Observing the magnetic field of two bar magnets

All magnets have a region around them where they can attract or repel other magnets. This region is known as the magnetic field. Since Earth also acts like a magnet, it has a magnetic field around it as well. Only magnetic objects have a magnetic field. The magnetic field surrounding a magnet is larger if the magnet size is larger or if more than one magnet is placed in close proximity to another magnet. The magnetic field decreases as the distance from the magnet gets larger.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- In order for students to understand the magnetic field of the earth, demonstrate how the magnetic field is influenced by the distance from the magnet. Show how iron filings and a bar magnet filings that are further away from the magnet and have less attraction.
- In order for students to understand the concept of magnetic field around a magnet, demonstrate using a horseshoe magnet and iron filings.
- In order for students to understand why iron filings are attracted to a magnet, explain to the students how the magnetic field of the magnet makes each iron particle (which is a magnetic material) to become a tiny magnet with a north and south pole, the opposite poles then attract making the iron filings to cling to each other and to the magnet.

Safety Precautions

- Place objects gently to avoid injury
- Be careful when handling magnets and iron filings
- Iron filings are very fine particles and can stick to clothing, so use a lab coat or gloves as needed.

For this activity you will need the following:

- Two bar magnets of the same size
- Thick paper on which to place the magnets and sprinkle the iron filings
- Container to collect the iron filings
- Lab spoon to help sprinkle the iron filings
- Lab coat and gloves as needed

For this activity you will work *in pairs*.

Activity 2 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 2:

- Before proceeding with the lab, show the students all the different items that will be used for this activity. If students need to bring any of the items, provide them with a list and instructions from where to get them. Provide specific details about the type of bar magnet, iron filings and lab spoon needed.
- Since the students are working in pairs, explain what each student needs to do so that both students equally contribute to the activity. Students can take turns conducting the experiments and recording the observations.
- Repeat the experiment using different shapes of magnet and observe and record how the shape of the iron filings change depending on the shapes of the broken pieces.

The following are recommendations for the Guided Inquiry for Activity 2:

- Experiment to identify the distance of the magnetic field from the north and south poles: Find the area of the magnetic field around a bar magnet by sprinkle iron filings around it. At what distance from the north and south poles do the iron filing stop getting attracted to the bar magnet? Repeat the experiment with different size bar magnets and tabulate the results.
- Experiment to indicate the changing shape of the magnetic fields: Place two bar magnets with the same poles facing each other. Sprinkle iron filings on the magnet. Slowly move one of the magnets. See what happens. Record the pattern of iron filings in your notebook. Repeat the experiments with different distances between the magnets.

Structured Inquiry

Step 1: Hypothesize/Predict: How do you think the shape of the magnetic field of a magnet would change if:

a. Another magnet is placed nearby so that the like poles of the two magnets face each other, but do not touch
b. Another magnet is placed nearby so that the opposite poles of the two magnets face each other, but do not touch.

Draw predicted magnetic fields for these two situations in your notebook.

Step 2: Student-Led Planning: Select bar magnets of different sizes and determine how you would place the magnets so that you can observe how the poles of the magnets affect the behavior of the iron filings.

Step 3: Procedural Directions: Place the paper sheet on a flat surface on the table. Place two bar magnets on the paper with their like north poles facing each other, but not touching (Figure 23.2). Draw the outlines of the magnets and mark the north and south poles of the magnets on the paper. Take a spoonful of iron filings and sprinkle them over the two bar magnets. Watch as the filings stick to the magnets. Repeat with 2–3 more spoons of the iron filings. Using a pencil, gently trace 2–3 lines on each side of the magnet from the north to the South Pole along the path of the iron filings on the paper. Trace the outline of the filings closest to the magnets and farthest away from the magnet. Now empty the filings into a container. Save the tracings that you made in your notebook.

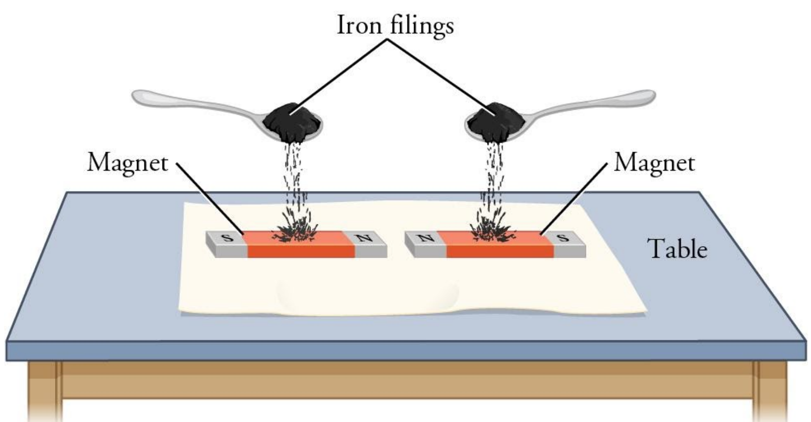


Figure 23.2: Sprinkling iron filings over two bar magnets.

Step 4: Repeat Step 3 with the following four positions for the two bar magnets:

- North pole of first magnet facing south pole of second magnet but not touching
- South poles of the two magnets facing each other but not touching
- The two bar magnets with their longer sides parallel to each other but not touching, and the north poles of both magnets facing away from you
- The two bar magnets with their longer sides parallel to each other but not touching, and the first magnet with the north pole facing away from you and the second magnet with the south pole facing away from you.
- Save the tracings from all five drawings.

Step 5: Critical Analysis: Analyze the shapes from all five positions of the bar magnets. Were your predictions supported by the results? Why or why not? Think of other ways you can extend this experiment with different positions for two or more bar magnets.

Guided Inquiry

Step 1: Hypothesize/Predict: Can you think of ways to visualize the magnetic fields of two bar magnets? Do you think there might be a difference in the magnetic fields depending on the position in which the magnets are placed? What materials and methods would you use? Write your ideas in your notebook.

Step 2: Student-Led Planning: Design an experiment using two bar magnets of the same size to help see the magnetic field around an object. Discuss the experiment with your teacher to find out how you can safely conduct the experiment and record the results. Conduct the experiment and create diagrams to record the magnetic field around different magnetic objects. Now repeat the experiment using magnets of different shapes. What happens if you have more than two magnets? What happens if you combine placing one bar magnet side-by-side with a horseshoe magnet?

Step 3: Critical Analysis: What difficulties did you encounter when implementing the experiment based on your initial design? What did you learn about how the placement of the magnets affects the shape of the magnetic field around the magnets?

Assessments

1. A student finds that when iron filings are sprinkled over two bar magnets of the same shape and size, with the south poles facing each other but not touching, the filings move toward each other. [EK 2.D.4.1, SP 1.4]
    a. Do you think this is an accurate observation? Why or why not?
    b. What would happen to the shape of the iron filings if you reposition the first magnet so that the two bar magnets have their north and south poles facing each other, but not touching?
2. Iron filings were sprinkled around two bar magnets that were tested to have magnetic properties, but some of the filings that were farther away from the magnets were not attracted or repelled by the magnets. This is because ________. [EK 2.D.4.1, SP 1.4]
3. Two bar magnets of the same shape and size with their North poles facing each other, but not touching, have iron files sprinkled over them. What happens to the iron filings when: [EK 2.D.4.1, SP 1.4]
    a. the magnets are slowly moved so that the north pole of one magnet faces the south pole of the other magnet?
    b. the filings are carefully sprinkled over only the first magnet alone from its north to south poles, making sure no iron filings are sprinkled over the second magnet?

[Solutions]

1. [EK 2.D.4.1, SP 1.4]
    a. This is not an accurate observation. Since the south poles of the magnets are facing each other, the iron filings will repel or move away from each other.
    b. If the magnets are repositioned, the iron filings will move toward each other, since opposite poles attract.
2. [EK 2.D.4.1, SP 1.4] the iron filings were outside of the magnetic field of the magnets.
3. [EK 2.D.4.1, SP 1.4]
    a. The iron filings will also change shape and move toward each other.
    b. The iron filings will take shape around the magnetic field of the first magnet alone from its north to south poles.

Activity 3: Pre-Assessment

1. **Answer the following question in your notebook:** What is the connection between electricity and magnetism? Do you think electrical devices have the same magnetic fields as nonelectrical devices?
2. **Answer the following question in your notebook.** What objects in your surroundings do you think will have stronger magnetic fields and which will have weaker magnetic fields?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 3: Record the magnetic field from electrical devices

Electrical devices in our surroundings emit magnetic energy. A magnetic field is caused by an electrical device that is plugged into an electrical outlet and is powered on and working. A simple device such as a gauss meter can help measure the level of magnetic field from kitchen appliances, computers, and electric bulbs. The unit of measure for magnetic fields on the gauss meter is the Tesla. As with magnets, the magnetic field from an electrical device decreases as the distance from the device gets larger.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- In order for students to understand how a gauss meter works, bring a gauss meter to class and demonstrate how it can be used to measure magnetic field around objects.
- In order for students to understand the concept of electromagnetic fields or EMFs, provide examples of power lines and electrical appliances where the electric and magnetic fields are caused by electromagnetic radiation.

Safety Precautions

- Be careful around electrical devices
- Be careful when handling magnetic sensor devices

For this activity you will need the following:

- A device such as a gauss meter to measure magnetic fields from electrical devices
- Electrical devices in your surroundings—electric bulbs, smart phones, and computers

For this activity you will work *in pairs*.

Activity 3 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 3:

- Before proceeding with the lab, show the students all the different items that will be used for this activity. If students need to bring any of the items, provide them with a list

and instructions from where to get them. Provide specific details about how the gauss meter works, and how to handle electronic devices with care.
- Since the students are working in pairs, explain what each student needs to do so that both students equally contribute to the activity. Students can take turns conducting the experiments and recording the observations.
- Repeat the experiment using different items both indoors and outdoors.

The following are recommendations for the Guided Inquiry for Activity 3:
- Take a laptop computer, power it on using the power adapter and measure the magnetic field using a gauss meter. Repeat the experiment using (1) a battery, (2) different distances and (3) laptop powered off. Record the results. Explain in your own words why the results are what they are.

Structured Inquiry

Step 1: Listen closely as your teacher explains how to use the gauss meter to measure magnetic fields.

Step 2: Hypothesize/Predict: Do you think there is a magnetic field from electrical objects in your surroundings? Will the magnetic field be affected by the kind of electrical device? Why or why not? Do you think an electric device that is not powered on and running will have the same magnetic field as an electric device that is powered off and not running? Why or why not?

Step 3: Student-Led Planning: Take the gauss meter close to various electrical devices around you that can be powered on and off: for example, an electric bulb, computer or smartphone. Record the readings for the various devices when the device is powered on and running and when the device is not running. Create a data table for your observations.

Step 4: Critical Analysis: Analyze the data recorded in your data table. Were the predictions you made in Step 2 supported by your data? Why or why not? What other electrical devices can you test in your surroundings? Discuss with your partner and then write your answers in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: What electrical objects in your surroundings do you think will have a magnetic field? How do you think you can measure the magnetic field around objects? Do you think the distance from the object will affect the measured strength of the magnetic field? Why or why not? Do you think the distance from an object emitting a magnetic field would affect the measured strength of the magnetic field? Why or why not? Write your ideas in your notebook.

Step 2: Student-Led Planning: Design an experiment using an instrument, such as a gauss meter, to record and measure the magnetic fields around a few electrical objects in your surroundings. Discuss the experiment with your teacher to find out how you can safely conduct the experiment and record the results. Record the readings from different distances by taking the gauss meter close to and farther away from the electrical source when it is powered on and running. Create a data table and record the following information: (1) type of electrical device, (2) reading from the gauss meter, (3) distance from the device and (4) device powered on and running? (Y/N). Rank the devices on the strength of their magnetic field for the same distance.

Step 3: Critical Analysis: What difficulties did you encounter when implementing the experiment based on your initial design? What did you learn about the magnetic field when the electrical device is powered on and running or not powered on? What did you learn about the magnetic field when you move closer and farther away from the electrical device emitting the magnetic field?

Assessments

1. A student finds that an electrical device emits the same amount of magnetic field when it is powered on and running, or powered off. [EK 4.E.1.1; SP 1.1, 1.4, 2.2]
    a. Does this scenario accurately reflect the magnetic field emitted by an electrical device? Why or why not?
    b. Do you think the measurements could be accurate for a different device? Why or why not?
2. When an electrical device emits a magnetic field, the field is known as ________. [EK4.E.1.1; SP 1.1, 1.4, 2.2]
3. A student measures the magnetic field around a TV in the living room. The gauss meter shows a reading for a magnetic field, and this reading changes as the student approaches the TV and walks away from the TV. [EK 4.E.1.1; SP 1.1, 1.4, 2.2]
    a. Why is there a difference in the readings closer to and away from the TV?
    b. Is the magnetic field of all electrical devices affected by the distance from the device? Why or why not?

[Solutions]

1. [EK 4.E.1.1; SP 1.1, 1.4, 2.2]
    a. No, the scenario does not accurately reflect the magnetic field emitted by an electrical device. This is because electrical devices typically emit a greater magnetic field when they are powered on and running.
    b. No, for all electrical devices that are powered on and running, the magnetic field should be greater than when the electrical devices are powered off and not working.
2. [EK 4.E.1.1; SP 1.1, 1.4, 2.2] an electromagnetic field
3. [EK 4.E.1.1; SP 1.1, 1.4, 2.2]
    a. As you move away from the source of the electrical device, the strength of the magnetic field decreases.
    b. Yes, just as for magnets where the strength of the field is greatest in the area around the magnet, for electrical devices also the strength of the field is greater as you get closer to the device and decrease as you get farther away from the device.

Lab 23: Electromagnetic Induction

Electric and magnetic forces are exerted over a distance by fields. In the late nineteenth century, a series of discoveries and inventions led to the concept of **electromagnetism**, which explains that electric force and magnetic force can be thought of as different aspects of a single electromagnetic force. One of these inventions is the **electromagnet**, which is a device that uses current to create a magnetic force field. A second invention is the **generator**, which is a device that uses electromagnetic induction to induce current in a wire. The generator, which works on the principle of electromagnetic induction, was incorporated into electric power plants, a technology that has transformed society. **Electromagnetic induction** is the process by which a voltage or electric force is created within an electric conductor when interacting with a changing magnetic flux (or field). In this lab, you will explore firsthand how electric force and magnetic force are connected.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- In order for students to better understand the key terms, explain the terms: electromagnetism, electromagnet, generator and electromagnetic induction.
- In order for students to understand the concept of an electromagnet, demonstrate how to create one using a conductive wire wrapped around a piece of metal and charged by battery. Explain how when current flows through the wire it creates a magnetic field around the wire and magnetizes the metal.
- In order for students to understand the uses of electromagnets, provide examples from daily life including MRI machines and doorbells.
- In order for students to better understand the key terms, explain the terms: Magnetic Flux, Induced EMF, Faraday's Law and Lenz's law.
- In order for students to understand the concept of Faraday's law demonstrate using a diagram how electromagnetic induction is the process in which electric current is produced due to changes in magnetic field.
- In order for students to understand the concept of Lenz's law, demonstrate through a simple experiment using a pipe, a magnet and a steel ball how the magnet falls through the pipe much slower than the steel ball.

In this lab you will learn:

- how to build an electromagnet;
- what changes to the design of an electromagnet can change its magnetic strength and the location of its poles;
- how to build a generator;
- what changes to the design and operation of a generator can change its induced current;
- how to calculate magnetic flux;
- about the relationship between induced voltage, change in magnetic flux and change in time in a generator.

Activity 1: Pre-Assessment

1. **Answer the following questions in your notebook**: What is an electromagnet? What is the advantage of an electromagnet as compared to a regular magnet?
2. **Answer the following questions in your notebook.** How can the strength of an electromagnet be changed? How can the location of the magnetic poles of an electromagnet be changed?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 1: Electromagnets

One concept of electromagnetism is that a stationary electric charge exerts an electric force, whereas a moving electric charge exerts both an electric force and a magnetic force. Both forces are part of a single electromagnetic force exerted by the electric charge. Note that the motion of the charge, and which force it exerts, depends on the frame of reference of the observer. This fact demonstrates that electric and magnetic fields are two aspects of the same underlying phenomenon.

The magnetic field around a current-carrying wire is shown in Figure 24.1. In this drawing, *B* indicates the counterclockwise direction of the magnetic field and *I* represents the flow of conventional current.

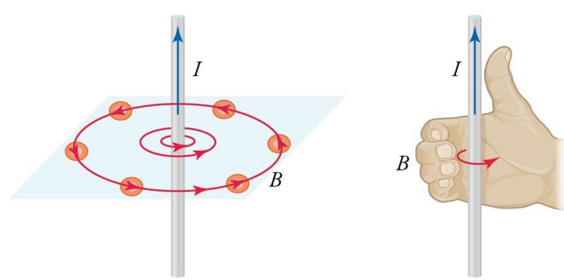


Figure 24.1: Magnetic field around a current-carrying wire. The direction of the field follows a right-hand rule: If you point the thumb of your right hand in the direction of the (positive) current, the fingers curl in the direction of the magnetic field.

Figure 24.2 shows the flow of conventional current. Note that the direction of conventional current is opposite to the direction of electron flow. The drawing also shows how to use your right hand to determine the direction of conventional current.

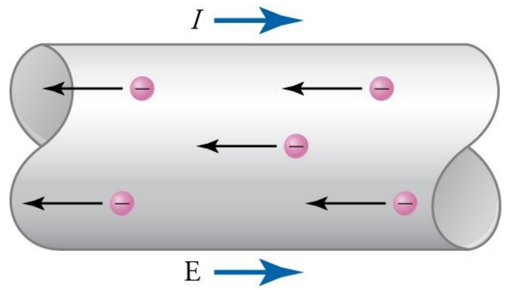


Figure 24.2: The direction of conventional current is the direction that positive charges would follow in an electric field.

Further experimentation with current-carrying wires led to the discovery that creating a coil with multiple loops of wire strengthened the magnetic field. This discovery led to the invention of the electromagnet. A simple electromagnet is shown in Figure 24.3. In this activity, you will build an electromagnet.

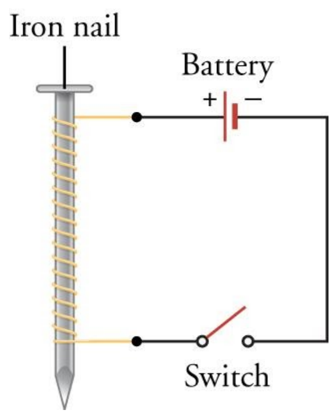


Figure 24.3: You can produce an electromagnet by wrapping circuit wire multiple times around an iron nail and connecting the wire to a battery.

Safety Precautions

- Wear proper eye protection.
- Be careful when handling sharp objects.
- Disconnect a clip lead immediately if the circuit smokes or gets hot.
- Make sure magnets are not placed near any electronic device.

For this activity you will need the following:

- 3 feet of fine-gauge magnetic wire (copper or aluminum wire covered with thin insulation)
- Sandpaper or wire stripper
- Two D batteries and battery holders
- Two clip leads
- switch

- One magnet with poles labeled
- Three galvanized iron nails
- 30 small metal paper clips
- balance
- Tape

For this activity, you will work *in pairs*.

Activity 1 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 1:

- In advance of the lab show the students all the different items that will be used for this activity. If students need to bring any of the items, provide them with a list, and instructions from where to get these. Provide specific details about the type of magnetic wire, wire stripper, magnet, galvanized iron nails and balance needed.
- Since the students are to be working in pairs, explain what each student needs to do so that both students equally contribute to the activity. For example, to begin with both students can help set up the apparatus. Both students can make the drawing in their notebooks.

The following are recommendations for the Guided Inquiry for Activity 1:

- Compare the similarities and differences of the electric field between an electromagnet and regular bar magnet. Record the observations in your notebook.
- Build an electromagnet. Change the strength of the charge using batteries of different voltages. Observe and tabulate how iron filings behave for the different voltages.

Structured Inquiry

Step 1: Create an electromagnet by doing the following actions: Remove the insulation from the two ends of the wire, using sandpaper or a wire stripper. Remove enough insulation so that the clip leads can be attached to bare wire. Wrap the wire around one galvanized nail, placing the coils close together, but not overlapping. Leave about 8 inches of straight wire on each end. Use clip leads to attach the ends of the coil to one of the D batteries and a switch.

Step 2: Hypothesize/Predict: Review Figure 24.4. If the wire is bent into a wire coil, where would you predict the magnetic poles are located, and why? Include a drawing to support your explanation for your prediction. (*Hint*—Two things to consider in your prediction: Recall that the magnetic field is strongest at the poles, and that magnetic field strength increases when more fields align in the same direction.) Write your ideas in your notebook.

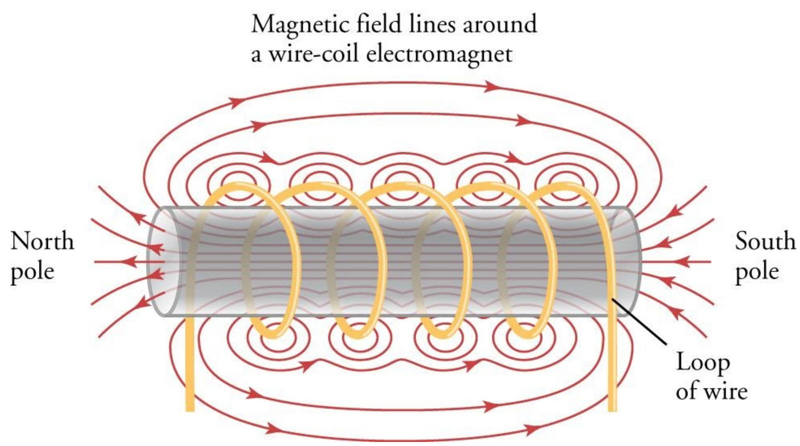


Figure 24.4: The magnetic field around an electromagnet is the sum of the magnetic fields around each loop of wire.

Step 3: Student-led Planning: Test the location of the poles of your electromagnet and its strength at different locations. Make a drawing of your electromagnet that shows the direction of conventional current and the location of the north and south poles.

Step 4: Critical Analysis: Was the prediction you made in Step 2 supported by your testing? If not, what errors did you make in your reasoning? Figure 24.4 shows a cross-section of the magnetic field around an electromagnet. Apply the right-hand rule described in Figure 24.1 to determine the direction of conventional current in this electromagnet. Discuss each question with your partner and write your answers in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: How could you change the strength of your electromagnet? How could you change which pole is North versus South? Write your ideas in your notebook.

Step 2: Student-led Planning: Come up with changes to the design of the electromagnet that might affect its strength and the location of its poles. Begin by increasing the number of loops in the wire coil without increasing its length. You may now overlap the coils to achieve this. Record each design in your notebook and then test its strength by measuring the number of paper clips the electromagnet can pick up. Also, test the location of its poles. Be careful to change only one variable at a time. Create a data table to record your results

Step 3: Critical Analysis: How did increasing the number of loops in the wire coil affect the electromagnet? Why did the change have this effect? How did the other changes you made affect the electromagnet? Explain why each change had the effect that it did.

Assessments

1. What are the advantages of an electromagnet as compared to a regular magnet? [2.D.2.1, 2.D.3]
2. What is the orientation of compasses placed near a straight wire that is carrying current? [2.D.2.1, 2.D.3.1]
3. Based on your experimental data, would increasing the current through a straight wire increase the strength of the magnetic field around it? Explain. [2.D.2.1]
4. Why does adding more nails to the electromagnet increase its strength? [2.D.4.1]

[Solutions]

1. [2.D.2.1, 2.D.3.] The strength and location of the poles can be easily changed.
2. [2.D.2.1, 2.D.3.1] The magnetic field vectors around a straight wire that carries electric current are tangent to concentric circles centered on that wire. The compass needle's north pole would point in the direction of one of those vectors. The direction of the vectors can be determined by using a right-hand rule, where the vectors point in the same direction as the fingers of your right hand when wrapped around the wire with the thumb pointing in the same direction as the positive current.
3. [2.D.2.1] Yes, because increasing current in the electromagnet increased its strength. In both cases, the magnetic field vectors that encircle the wire increase in magnitude.
4. [2.D.4.1] The magnetic domains in the iron align with and add to the strength of the magnetic field of the electromagnet.

Activity 2: Pre-Assessment

1. **Answer the following questions in your notebook**: What is a generator? What are the main parts of a generator? How do the parts work together to generate electricity?
2. **Answer the following question in your notebook.** When a magnet is moved back and forth inside a loop of wire, how would you represent the magnetic field inside the area of the wire loop at each instant in time?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 2: Simple Coils and Emf

In a generator, a magnet and a loop of wire are in relative varying motion. The varying motion of the magnet creates a varying magnetic field. In turn, the varying magnetic field gives rise to a varying electric field, which then induces current in the wire. This phenomenon is electromagnetic induction.

The total magnetic field that passes through the loop of wire at any given time is called **magnetic flux**. Specifically, it is the total number of magnetic lines of force passing at right angles through a specified area in a magnetic field. The equation for calculating magnetic flux through a surface that contains a loop of wire of area *A* is:

$$\Phi = BA\cos\theta \,.$$

The SI unit of magnetic flux is the weber (Wb), which is the same as a volt-second. Area *A* is measured in meters squared (m^2) and *B* is measured in teslas (T). A flux density of 1 Wb/ m^2 is 1 T.

Figure 24.5 shows the variables in the equation for magnetic flux. The strength of the magnetic field is measured through the area that is at right angles to the magnetic field, not necessarily the area of the wire loop itself. For example, if the wire loop were parallel to the lines of force, then the magnetic field wouldn't be moving through the loop.

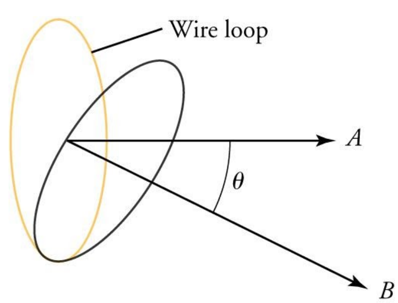


Figure 24.5: Magnetic flux is the product of magnetic field strength *B*, area *A* of a wire loop, and the sine of the angle θ between them.

When a varying magnetic field passes through a loop of wire and induces current, an induced voltage also arises, called the **induced emf**. The induced emf in a single loop of wire can be calculated by measuring how magnetic flux changes over time. This relationship is called **Faraday's law**. We write the equation for Faraday's law for a single loop of wire; to modify the equation for a wire coil, just multiply the right side by *N*, the number of loops in the coil.

$$\varepsilon = -\frac{\Delta\Phi}{\Delta t}$$

Why is there a negative sign in Faraday's law? Note that there are two magnetic fields when emf and current are induced. The first magnetic field is the field that moves through the loop of wire. The direction of this field and the magnetic flux is the same. The second magnetic field is the field created by the current induced in the wire. The direction of this second field and the induced emf is the same, but both are opposite to the direction of the magnetic flux. This is the meaning of the minus sign in Faraday's Law, and this concept is called **Lenz's law**. In this activity, you will build a generator.

Safety Precautions

- Wear proper eye protection.
- Be careful when handling sharp objects.
- Disconnect a clip lead immediately if the circuit smokes or gets hot.
- Make sure magnets are not placed near any electronic device.

For this activity you will need the following:

- 4 feet of fine-gauge magnetic wire (copper or aluminum wire covered with thin insulation)
- Sandpaper or wire stripper
- Two hollow cardboard tubes, about 10 cm in length and of different diameters, but both large enough to fit the magnet
- Several different strong bar magnets with labeled poles
- One voltmeter or multimeter

For this activity, you will work *in pairs*.

Activity 2 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 2:

- In advance of the lab show the students all the different items that will be used for this activity. If students need to bring any of the items, provide them with a list and instructions from where to get these. Provide specific details about the type of magnetic wire, wire stripper, bar magnets, voltmeter and multimeter needed.
- Since the students are to be working in pairs, explain what each student needs to do so that both students equally contribute to the activity. For example, to begin with both students can help set up the apparatus and take turns recording the observations.

- Repeat the experiment with the cardboard tube where the wires are wound closely together. Compare the observations, differences, and similarities between the two experiments.

The following are recommendations for the Guided Inquiry for Activity 2:
- Repeat Faraday's experiment from Figure 24.2 and observe and record the results in your notebook.

Structured Inquiry

Step 1: Create a generator by doing the following actions: Remove the insulation from the two ends of the wire, using sandpaper or a wire stripper. Remove enough insulation so that the clip leads can be attached to bare wire. Wrap the wire around the cardboard tube, placing the coils as close together as possible without overlapping them. Leave about 8 inches of straight wire on each end and attach the ends to the voltmeter or multimeter (set to measure millivolts). The generator is operated by moving a magnet into and out of the tube. Figure 24.6.

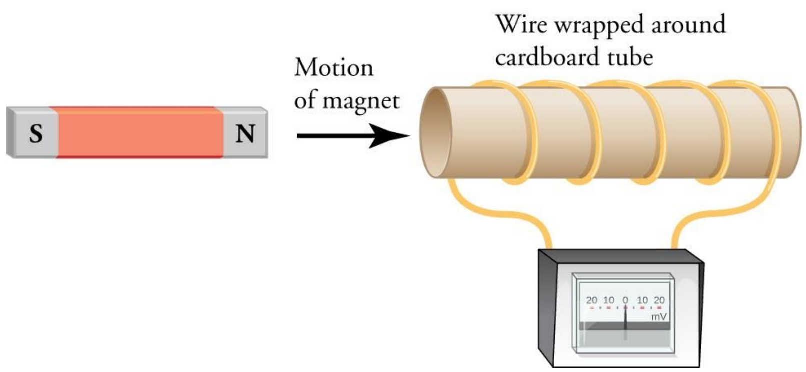


Figure 24.6: A generator made with a magnet and conducting wire wrapped around a cardboard tube.

Step 2: Hypothesize/Predict: What action will induce current in the wire? How will the voltage change when current is induced in the wire? Would moving the tube and keeping the magnet still also result in electromagnetic induction? Give a reason for each prediction. Write your ideas in your notebook.

Step 3: Student-led planning: Test your predictions from Step 2 and record your observations in your notebook.

Step 4: Critical Analysis: Were the predictions you made in Step 2 supported by your testing? If not, revise the reasons you gave for each prediction. If you flipped the magnet so that the opposite pole is moving into the wire coil, what would change? Discuss each question with your partner and write your answers in your notebook.

Guided Inquiry

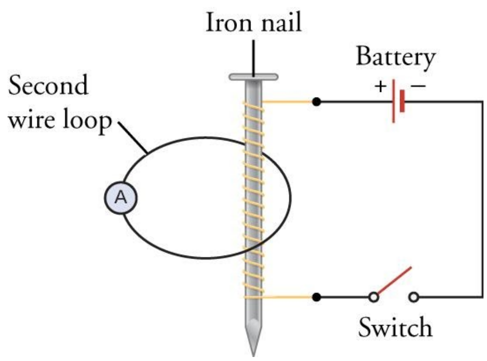
Step 1: Hypothesize/Predict: How could you change the amount of induced emf? Write your ideas in your notebook.

Step 2: Student-led planning: Come up with changes to the design or operation of the generator that might affect the amount of induced emf. Record each idea in your notebook and then test it by recording the amount of induced emf. Be careful to change only one variable at a time. Create a data table to record your results.

Step 3: Critical Analysis: How did each change you made affect the generator? Explain why each change had the effect that it did. Apply Faraday's law in your explanations. Discuss with your partner and write your answers in your notebook.

Assessments

1. A magnet is moved in and out of a wire coil. What are three factors that affect the induced emf? [4.E.2.1]
2. A generator has a magnet moving at a right angle through a wire coil. The coil has 100 turns and a radius of 1.5 m. Over each 2.0-s interval a maximum voltage of 120 V is induced. What is the strength of the magnetic field in T? [3.A.1.3, 4.E.2.1]
3. In an early experiment, Faraday wrapped a piece of wire around an electromagnet (Figure 24.2) because he thought its magnetic field would induce current in the wire. However, he only observed current in the wire during the brief moments when he turned the switch on and off. When the electromagnet was fully on or off, no current was induced in the wire. Explain the reason for Faraday's observations. [4.E.2.1]



[Solutions]

1. [4.E.2.1]The factors are the area of the wire coil that is at right angles to the magnetic field; the number of turns in the wire coil; and the change in magnetic flux per unit of time.
2. [2.D.2.a, 3.A.1.3, 4.E.2.1]

$$\varepsilon = -N\frac{\Delta\Phi}{\Delta t} = -N\frac{\Delta(BA)}{\Delta t}$$

Rearrange to find ΔB :

$$\Delta B = -\frac{\varepsilon(\Delta t)}{NA} = -\frac{120\text{ V}\cdot 2.0\text{ s}}{100\cdot 7.1\text{ m}^2} = 0.34\text{ T}$$

3. [4.E.2.1] Current is only induced if the magnetic field is varying. The only time the magnetic field of the electromagnet varied was when the switch was turned on or off.

Lab 24: Mirrors

When light strikes almost any surface, some of the light bounces away from it. This behavior is called **reflection**. However, if we can see an image from the reflected light, the surface is called a **mirror**. We use mirrors to see our own image and when we drive, to see images of cars behind us. A dentist can use a mirror to see an image of our teeth from an angle that cannot be viewed easily. Thus, mirrors are used to produce **images**, or virtual likenesses of an object that cannot be touched but can be seen or photographed. These images are useful to us because of the way mirrors form.

Figure 25.1 shows the key elements related to reflection of light in a flat, or plane mirror. The **normal line** is perpendicular to the surface of the mirror at the point where the reflection occurs. A **light ray** is a line representing the propagation of light. The **ray of incidence** is the ray approaching the mirror surface. It forms the **angle of incidence** θ_i with the normal line. The **ray of reflection** is the ray reflected from the mirror surface. It forms the **angle of reflection** θ_r with the normal line. The basic law of reflection states that the magnitudes of the incidence and reflected angles are equal, $\theta_i = \theta_r$.

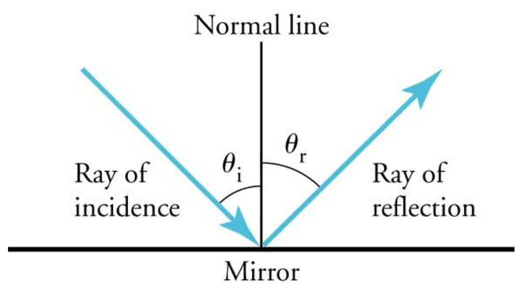


Figure 25.1: In reflection from a plane mirror, the angle of incidence equals the angle of reflection. The angles are measured from a line drawn perpendicular (or normal) to the mirror surface.

In this part of the lab you will study the relationship between the values of the angles of incidence and reflection. You will use a laser as a source of light because lasers produce highly focused and directional rays of light, unlike regular light bulbs that emit light in all directions. A piece of white paper or cardstock can be placed across the ray of laser light to find the precise position through which the ray of light produced by the laser is passing. After you note the position of the laser beam on the card, you can project this position on a horizontal plane (for example, on a sheet of paper covering the table). By following the beam this way, you can plot its path on the sheet.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- The students should be familiar with the basics of line optics. They should know about rays, mirrors, lenses and the basic governing laws.
- This opportunity should also be used to briefly talk about lasers and the coherent induced light beams and their use.
- This lab module involves quantitative analysis. Therefore, the concepts of accuracy and precision, error bars and use of repeated measurements as a way to improve accuracy of the results should be discussed.
- It is beneficial to charge the students with leading the presentation and discussion during these pre-lab activities. At the very least, they should be asked a great number of questions.
- It is recommended that the instructor and any assistants rehearse this lab in advance, at least in an abbreviated way.

In this lab you will learn:

- how to relate the behavior of incident and reflected light rays;
- to solve problems related to formation of a reflected image;
- solve problems related to formation of an image produced by a lens.

Activity 1: Pre-Assessment

1. **Answer the following questions in your notebook:** What happens to a ray of light when it strikes a plane mirror? Does a ray (a line) provide a good representation of the propagating and reflected light? Does the answer to the last question change depending on whether the light is produced by a laser or by an incandescent or LED light bulb? Explain your reasoning.
2. **Answer the following questions in your notebook.** What is the relationship between the angle of incidence and the angle of reflection? What experiments would you use to determine this relationship?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 1: Determining Relationship Between the Angles of Incidence and Reflection

You will use a piece of paper, cardstock, or an index card that can serve as a screen; a laser; and a mirror to determine the relationship between angles that the incident and reflected rays make with the line that is normal to the mirror.

Safety Precautions

- Always ensure that the light from the laser cannot shine into anyone's eyes.

*Note—Do not use lasers powerful enough to damage the eye.

For this activity you will need the following:

- Mirror with a stand
- Laser
- Piece of paper or an index card
- Larger sheet of paper on which the whole experimental setup can be placed
- Pen or pencil
- Ruler

For this activity, you will work *in pairs*.

Activity 1 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 1:

- This activity is conceptually simple, but tracing the laser light rays can be somewhat tricky the first time the students attempt it. The students should practice tracing the beam first, before making the actual experiment.
- If the students still have difficulties tracing the light, the group should experiment with making the room darker, if at all possible.
- The students should be reminded of the safety rules before working with the laser.

The following are recommendations for the Guided Inquiry for Activity 1:

- It is beneficial to briefly discuss the law of cosines before the students carry out this guided inquiry.
- The students should make initial estimates of the error bars of their results before concluding the activity. The estimates should be briefly presented to the instructor.

Structured Inquiry

Step 1: Find a way to determine the angles using the pen or pencil, the ruler and the paper on which the experiment was set up.

Step 2: Hypothesize/Predict: What do you expect the relationship between the angles of incidence and reflection will be? Will they be the same, or will one of them be greater?

Step 3: Student-led Planning: Design an experiment that will enable you to measure reflection angles for several incident angles. You will need to use the laser as the source of light. By changing the angle of the laser's position with respect to the mirror, you can change the value of the incident angle. Then you can also find the direction of the reflected beam by using a piece of white paper or cardstock as described previously. Record the necessary measurements and make a table that lists angles of incidence and reflection for several measurements.

Step 4: Critical Analysis: What can you conclude about the relationship of these angles? Justify your uncertainty for your angle measurements. How could you have obtained more decimal places for each measurement? What methods could you use to improve the accuracy of your results? Discuss with your partner, and then write your answers in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: Do you think the angles of incidence and reflection will be the same? Write your ideas in your notebook.

Step 2: Student-led Planning: You can use the supplies that you need to measure the angles of incidence and reflection in the following way. The specific steps to follow are:

1. First, draw a line on the large sheet of paper. You will later align the mirror with this line. Pick a point that is several centimeters away from the line, and label it A.
2. Using the ruler, find two points on the line that lie at the same distance from this point, and label them B and C. Choose this distance. (Figure 25.2).
3. Then use the ruler to find the point that is located exactly in the middle of the (BC) interval and label it D.
4. Draw a line through points A and D. This is the normal line to the plane of the mirror. This procedure is described graphically in Figure 25.2.

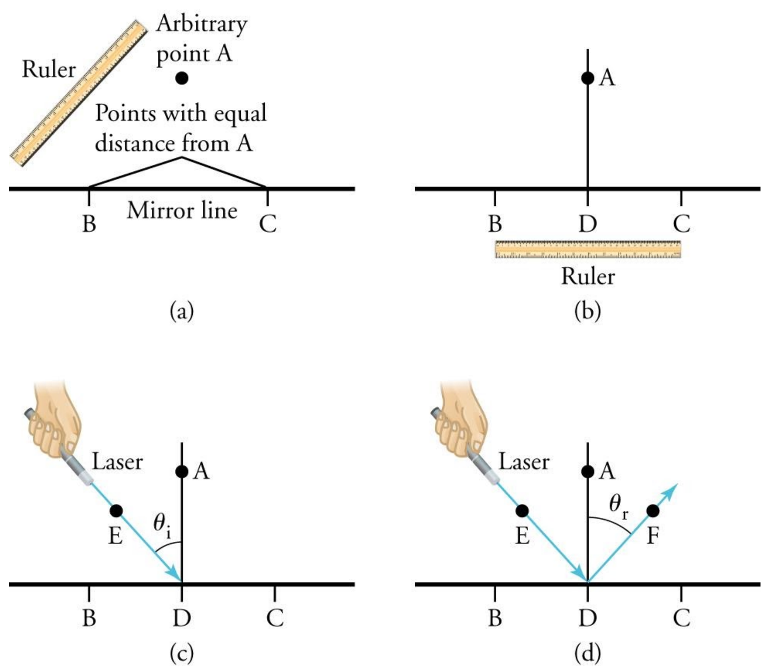


Figure 25.2: Finding the normal line (parts a and b) and the angles of incidence (c) and reflection (d).

You can calculate the angle of incidence θ_i (part [c] of the figure) by picking an arbitrary point E on the incident ray and measuring the sides of the resulting triangle ADE. Per the law of cosines, you have

$$\cos\theta_i = \frac{DE^2 + DA^2 - EA^2}{2DE \cdot DA}.$$

Therefore, you can find the angle by measuring the distances between these three points. You can find the reflection angle θ_r in the same way (part [d]). Use the screen/index card to trace the position of the rays and mark them on the sheet of paper on which you set up the experiment. Make measurements of the lengths, calculate the angles of incidence and reflection and record all these results in your science notebook.

Step 3: Critical Analysis: What can you conclude about the relationship between the incident and reflected angles? Justify your uncertainty for your angle measurements. How could you have obtained more decimal places for each measurement?

Assessments

1. Use one set of values of the lengths ED, EA, AD, DF and AF that you have obtained with the experimental setup shown in Figure 25.2 (c, d). [EK 6.E.1, EK 6.E.2, SP 1.1, SP 1.4, SP 2.2, SP 4.2, SP 5.1, SP 6.4]
    a. What are the values for the angles of incidence and reflection?
    b. What is the relationship between the angles of incidence and reflection?
2. A student repeats measurements for two more angles of incidence. The results are □= 62.2°, □= 63.4° and □= 84.5°, □= 88.0°. What can he or she conclude about the relationship between the angles of incidence and reflection? [EK 6.E.1, EK 6.E.2, SP 1.1, SP 1.4, SP 2.2, SP 4.2, SP 5.1, SP 6.4]
3. What would happen if the student used a flashlight instead of the laser in the above experiments? [EK 6.E.1, EK 6.E.2, SP 1.1, SP 1.4, SP 2.2, SP 4.2, SP 5.1, SP 6.4]

[Solutions]

1. [EK 6.E.1, EK 6.E.2, SP 1.1, SP 1.4, SP 2.2, SP 4.2, SP 5.1, SP 6.4]
   Answers will vary. Assume sample values of ED = 12 cm, EA = 11 cm, AD = 13 cm, DF = 10 cm, AF = 10 cm.

   Using the law of cosines, we can see that the two angles are roughly equal (disregarding rounding error).

$$\cos\theta_{\mathrm{i}} = \frac{12^2 + 13^2 - 11^2}{2\cdot 12\cdot 13} = 0.6154, \quad \theta_{\mathrm{i}} = 52.0°$$

$$\cos\theta_{\mathrm{r}} = \frac{13^2 + 10^2 - 10^2}{2\cdot 13\cdot 10} = 0.6500, \quad \theta_{\mathrm{r}} = 49.5°$$

2. [EK 6.E.1, EK 6.E.2, SP 1.1, SP 1.4, SP 2.2, SP 4.2, SP 5.1, SP 6.4] These values are approximately the same for each measurement.
3. [EK 6.E.1, EK 6.E.2, SP 1.1, SP 1.4, SP 2.2, SP 4.2, SP 5.1, SP 6.4] The incident and the reflected rays would not be rays (straight lines) but rather a broad cone of light. No accurate measurements of the angles would be possible.

Activity 2: Virtual Images in Plane Mirrors

Rays of light reflecting from a mirror create an image of the object from which they originate or reflect. This image is called a **virtual image** because its apparent location is behind the mirror, so it cannot be accessed directly. However, the reflected rays of light act as if they are coming from an object behind the mirror (Figure 25.3).

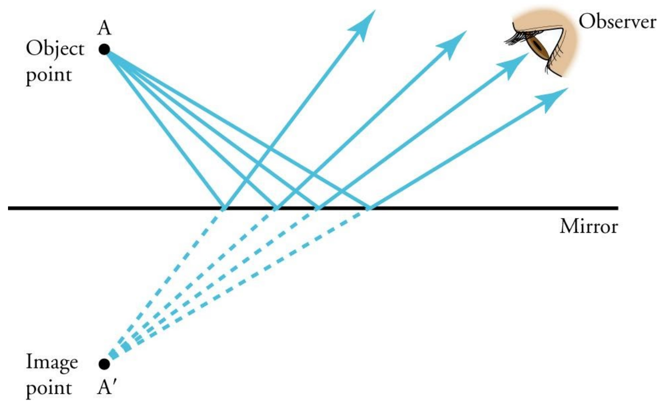


Figure 25.3: Virtual image produced by a plane mirror.

A convex lens and a piece of paper/index card (used as a screen) can focus a real image of the original object, as shown in Figure 25.4.

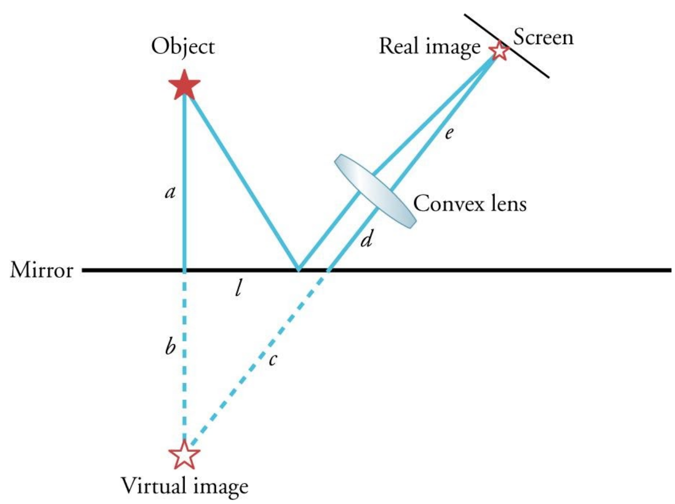


Figure 25.4: Producing a real image from the virtual image behind the mirror.

The distance from the object to the plane mirror *a* is equal to the distance from the mirror to the virtual image *b*. The overall distance from the virtual image to the lens is $c+d$. The distance from the lens to the position of the screen that yields a sharp real image is *e*. Per the equation of the convex lens,

$$\frac{1}{f}=\frac{1}{c+d}+\frac{1}{e},$$

where *f* is the focal length of the lens. This focal length can be determined as shown in Figure 25.5.

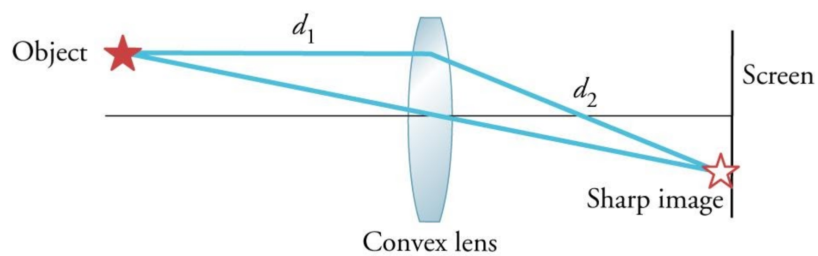


Figure 25.5: Determining the focal length of a convex lens.

An object (such as a candle) is positioned at a fixed distance d_1 from the lens. The screen (a piece of paper, an index card, etc.) is moved on the other side of the lens until a sharp image of the candle is formed on it. The distance d_2 from the lens to the screen is measured at this point. The focal length of the lens *f* can then be found from the equation

$$\frac{1}{f}=\frac{1}{d_1}+\frac{1}{d_2}.$$

In this part of the lab you will measure the distance from an object (candle) to the plane mirror and from the mirror to the virtual image using a candle, a convex lens and a ruler. You will then make conclusions about the relationship between the distance from the mirror to the object and from the mirror to the virtual image.

Activity 2: Pre-Assessment

1. **Answer the following questions in your notebook:** What kind of an image is formed when rays of light from an object interact with a mirror? How can we obtain an image of the original object that can be seen on a screen?
2. **Answer the following questions in your notebook:** What is the relationship between the distance from the object to the mirror and the distance from the mirror to the image of the object? What experiments would you use to determine this relationship?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 2: Virtual Images in Plane Mirrors

You will use a piece of paper, card stock, or an index card that can serve as a screen, a candle, a mirror, a convex lens, and a ruler to determine the relationship between the distances from an object to the mirror and from the mirror to the image of the object.

Safety Precautions

- Always make sure that hair, clothing, or other items do not catch fire when using lit candles. Exercise caution to make sure that the candle is not accidentally tipped over.

For this activity you will need the following:

- Mirror with a stand
- Candle and matches or a lighter
- Piece of paper or an index card
- Convex lens with a stand
- Larger sheet of paper on which the whole experimental setup can be placed
- Pen or pencil
- Ruler

For this activity. you will work *in pairs.*

Activity 2 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 2:

- Extreme care should be used while working with the open flames in this lab activity. It is highly recommended that the students are closely supervised, but they should still carry out the work on their own.
- It is recommended that the students would derive the equations resulting from the setup shown in Figure 25.3 and Figure 25.4 on their own — or at least that they would briefly present and discuss these derivations before proceeding with the lab. The instructor can choose a different simple setup that would illustrate derivations in optics.
- It is important that the instructor rehearses this activity before the actual lab session. This is even more crucial for Activity 2 than for Activity 1.

The following are recommendations for the Guided Inquiry for Activity 2:

- The instructor should briefly discuss with the students the relevant formulas of optics.
- The students should make initial estimates of the error bars of their results before concluding the activity. The estimates should be briefly presented to the instructor.

Structured Inquiry

Step 1: Find a way to determine the distances *a* and *b* shown in Figure 25.2 from the object (candle) to the mirror and from the mirror to the virtual image. Set up the experiment on a large sheet of paper and use it for marking and measuring the required distances. You will also need the pen or pencil, and the ruler.

Step 2: Hypothesize/Predict: How do you expect the distances between the candle and the mirror relate to the virtual image of the candle? Write your predictions in your notebook.

Step 3: Student-led Planning: Design an experiment to determine the focal length of the lens. Design an experiment that will enable you to measure the distances from the mirror to the candle and from the mirror to the image. Record the necessary measurements to find the value of the focal distance of the lens. Determine the value of the focal length, and record it in your notebook. Record the necessary measurements, and make a table that will list the mirror-object and mirror-image distances for several trials.

Step 4: Critical Analysis: What can you conclude about the relationship between the distances from the object to the mirror and from the mirror to the virtual image of the object? What do you estimate to be the average error of the measurements? What methods could you use to improve the accuracy of your results? Discuss with your partner, and then write your answers in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: Do you think the distance from the mirror to the object and the distance from the mirror to the virtual image of that object will be the same? Write your ideas in your notebook.

Step 2: Student-led Planning: Make the necessary length measurements to obtain the focal length of the lens. The procedure has been described in the introductory text for this part of the lab.

1. You can use the supplies that you need to measure the distances from the mirror to the object and to the image in the following way. Refer to Figure 25.4 and make use of the sheet of paper, on which the experimental setup is built, in the same way as in the first part of the lab. You can measure distances *d*, *e*, *f*, and *a* directly. Then the distance *c* can be found from the lens equation

$$\frac{1}{f} = \frac{1}{c+d} + \frac{1}{e}.$$

2. After this you can use the Pythagorean theorem to find the distance *b* from the mirror to the virtual image, as $b^2 + l^2 = c^2$.
3. Make the length measurements that are necessary to obtain the distances from the object to the mirror and from the mirror to the virtual image of the object for several relative positions of the candle, mirror and the lens. Calculate the corresponding mirror-object and mirror-image distances, and record all these results in your science notebook (make tables for the distances).

Step 3: Critical Analysis: What can you conclude about the relationship between the distances from the mirror to the object and from the mirror to the virtual image? What is your estimation of the error bars for these distances?

Assessments

1. A student builds the experimental setup shown in Figure 25.5. He obtains the following distances from measurements: $d_1 = 10$ cm, $d_2 = 15$ cm. [EK 6.E.5.1, EK 6.E.5.2, SP 1.1, SP 1.4, SP 2.2, SP 4.2, SP 5.1, SP 6.4]
   a. What is the focal length of the lens?
   b. The student repeats an experiment for a shorter d_1 and cannot find a position of the screen that would yield a sharp image. What is the reason? What should the student do?
2. A student sets up the experiment shown in Figure 25.4. He measures the following values of the lengths: $a = 6.8\text{ cm},\quad d = 3.0\text{ cm},\quad e = 12\text{ cm},\quad l = 3.0\text{ cm}.$
   The focal length of the lens is 4.5 cm. What is the value of the distance from the mirror to the image *b*? [EK 6.E.4.1, EK 6.E.4.2, EK 6.E.5.1, EK 6.E.5.2, SP 1.1, SP 1.4, SP 2.2, SP 4.2, SP 5.1, SP 6.4]
3. What can you conclude about the relationship between the mirror-object and mirror-image distances from the results of the previous experiment? [EK 6.E.4.1, EK 6.E.4.2, EK 6.E.5.1, EK 6.E.5.2, SP 1.1, SP 1.4, SP 2.2, SP 4.2, SP 5.1, SP 6.4]

[Solutions]

1. [EK 6.E.5.1, EK 6.E.5.2, SP 1.1, SP 1.4, SP 2.2, SP 4.2, SP 5.1, SP 6.4]
   a. Using the lens equation,

$$\frac{1}{f} = \frac{1}{10\text{ cm}} + \frac{1}{15\text{ cm}} = 0.16666(6)\text{ cm}^{-1},\ f = \frac{1}{0.16666(6)\text{ cm}^{-1}} = 6.0\text{ cm}.$$

   b. If d_1 is too small, d_2 will be negative. This means that the image will be virtual, and it will be impossible to project it on the screen. The student should move the candle farther away from the lens.
2. [EK 6.E.4.1, EK 6.E.4.2, EK 6.E.5.1, EK 6.E.5.2, SP 1.1, SP 1.4, SP 2.2, SP 4.2, SP 5.1, SP 6.4]

$$\frac{1}{c+d} = \frac{1}{f} - \frac{1}{e} = \frac{1}{4.5\text{ cm}} - \frac{1}{12\text{ cm}} = \frac{1}{7.2\text{ cm}},$$

$$c = 7.2\text{ cm} - 3.0\text{ cm} = 4.2\text{ cm},\quad b^2 = c^2 - l^2 = (4.2\text{ cm})^2 - (3.0\text{ cm})^2, b = 2.9\text{ cm}$$

3. [EK 6.E.4.1, EK 6.E.4.2, EK 6.E.5.1, EK 6.E.5.2, SP 1.1, SP 1.4, SP 2.2, SP 4.2, SP 5.1, SP 6.4]
   The distances appear to be the same, but you cannot form the conclusion until you run more experiments with different relative positions of the candle, mirror and lens.

Lab 25: Geometric Optics

Optics concerns the study of light and its interactions with matter. Because light is an electromagnetic wave, most phenomena in optics can be described using classical electrodynamics. However, some phenomena are better described using **geometrical optics**, which is a simplified model that treats light as rays that travel in straight lines.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- Stress that the normal line is not merely a line perpendicular to the interface, but it *must* be located where the incident beam meets the interface.
- If available, a small glass rod (such as a stirring rod) can be used to enhance the laser beam. With the rod lying on its side, project the laser beam perpendicularly to the rod's surface. The beam will spread out into a line that will be much easier to observe and measure.
- You may wish to dim the room lights or provide a cardboard box shield for the experiments, as a laser beam is sometimes difficult to see in the presence of overhead lighting.
- Reinforce the idea that in geometrical optics, light is assumed to move only in straight lines, except where it meets barriers.

In this lab you will learn:

- how to use Snell's law to determine the index of refraction of a given material;
- how to determine the focal length of a converging lens.

Activity 1: Pre-Assessment

1. **Answer the following question in your notebook:** When looking at an object on the bottom of a pool, the object appears to be in a different location than where it actually is. Why is this?
2. **Answer the following question in your notebook:** Why does the sun appear larger and redder during sunrise and sunset?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 1: Snell's Law

A **light ray** is a simplified model of light where each ray is a line drawn perpendicular to the wave front of the actual light and pointing in the direction of propagation of the light. The speed of a light ray through a given material or medium is given by the **index of refraction** of that material, defined as

$$n = \frac{c}{v},$$

where *n* is the index of refraction, *c* is the speed of light in a vacuum, and *v* is the speed of light through that material. Light rays can change direction when traveling through different media. Consider a light ray traveling from one medium to another. The incoming ray in the first medium is known as an **incident ray**. When the incident ray strikes the interface (or boundary) between the two media, the ray splits into a **reflected ray** that corresponds to the ray reflected back from the interface via the original medium, and a **refracted ray** that corresponds to the light that gets transmitted through the interface into the second medium. Suppose the incident ray makes an angle θ_1 with respect to the **normal to the interface**, which is the line perpendicular to the interface surface. The reflected ray reflects off the surface with the same angle θ_1, while the refracted ray passes through the second material with an angle θ_2 with respect to the normal. The relationship between θ_1 and θ_2 is given by **Snell's law**

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1},$$

where n_1 and n_2 are the indices of refraction of the two materials. Figure 26.1 illustrates the refraction of a light ray when traveling between two different materials.

In this activity you will investigate how light is reflected and refracted through different materials.

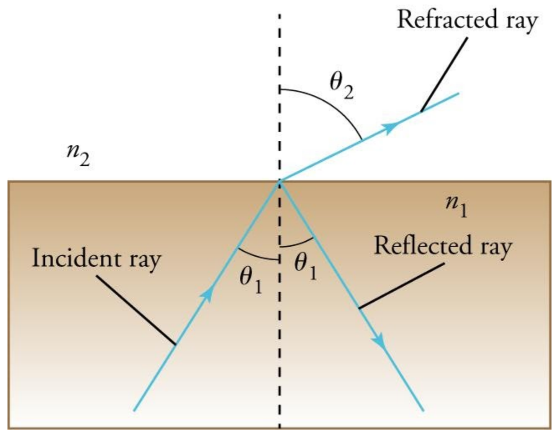


Figure 26.1: An incident ray traveling through a material with an index of reflected n_1 at an angle θ_1 with respect to the normal to the interface. The angle of reflection of the reflected wave equals the incident angle. The refracted wave passes into the second material with an index of refraction n_2 at an angle θ_2 with respect to the interface.

For this activity you will need the following:

- Laser source (such as a laser pointer)
- Piece of glass in the shape of a half-cylinder
- Protractor
- Paper
- Pencil to sketch the outline of the glass

Safety Precautions

- Take care to avoid shining the laser in anyone's eyes, as this can cause permanent damage to the retina.
- Be careful with the edge of the glass half-cylinder, as it can cause cuts.
- Notify your teacher immediately if any of the glass breaks.

For this activity, you will work *in groups of four students.*

Activity 1 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 1:

- This lab should NOT involve lasers with enough power to cause eye damage. Most laser pointers do not have sufficient power to damage the retina in this way as long as they <1 mW.
- You should expect the value for the index of refraction for the glass to be approximately 1.5.

- Tracing the beam on the paper using a pencil can be easiest to do by making dots in the center of the beam where the incident beam strikes the glass and along the exit path and then later connecting these dots with a ruler.
- Unlike a mathematical/theoretical ray, the beam from the laser is not infinitely thin. As such, you will want to discuss what errors this might introduce and how the students can minimize them.

The following are recommendations for the Guided Inquiry for Activity 1:

- This lab should NOT involve lasers with enough power to cause eye damage. Most laser pointers do not have sufficient power to damage the retina in this way as long as they <1 mW.
- The students can have the incident beam strike either the curved or the flat side of the block. Entering the curved side and allowing the internal reflection to take place along the flat side will likely provide more information than attempting to use the curved side for internal reflection.
- Discuss applications, such as fiber optic cables, that utilize total internal reflection.
- Have the students note the intensity of the incident beam vs. the internally reflected beam(s). They should note a drop in the intensity. Discuss the utilization of a beam amplifier at intervals along long internal reflections runs.

Structured Inquiry

Step 1: First draw the outline of the half-cylinder piece of glass on your paper. The outline should resemble a semicircle. Next, use the protractor to label several angles with respect to the flat end of the half circle.

Step 2: Hypothesize/Predict: Given that light travels faster through air than through glass, will the incident angle be larger or smaller than the refracted angle? Write your hypothesis in your notebook.

Step 3: Student-Led Planning: Shine your laser light through the non-curved sides of the glass and record the angle at which the light exits the glass from the other side. Do this for several incident angles.

Step 4: Critical Analysis: Use the measurement of the incident and refracted angles to determine the index of refraction of the glass, given that the index of refraction of air is $n_{\text{air}} \approx 1.$ Is this consistent with your hypothesis in Step 2?

Guided Inquiry

Step 1: Hypothesize/Predict: Given the index of refraction for the glass, what incident angle will correspond to an angle of refraction of $90°$ (the critical angle)? Write your hypothesis in your notebook.

Step 2: Student-Led Planning: How would you position the laser so that total internal reflection is achieved? Discuss with your group, and then keep experimenting until total internal reflection is achieved. Describe each of your trials in your notebook as you complete each one.

Step 3: Critical Analysis: Is there any refracted light at the angle calculated in Step 1? How would this angle change if the index of refraction of the glass were doubled? Discuss your results with your group.

Assessments

1. The ________ of a material determines how fast light propagates through that material. [25.6e.3; SP 3]
2. Suppose light is traveling through air into a material with an index of refraction of n = 2, and the angle of incidence is $1°$. [25.6e.3; SP 3]
   a. What will the angle of the refracted light be?
   b. What is the speed of light in the material?

[Solutions]

1. index of refraction [25.6e.3; SP 3]
2.
   a. We can use Snell's law to write

$$\sin\theta = \left(\frac{n}{n_{\text{air}}}\right)\sin 1°.\quad \sin\theta = \frac{n_{\text{air}}}{n}\sin 1°.$$

Given that $n_{\text{air}} \approx 1,$ we can use the small-angle approximation $\sin\theta \approx \theta$ to write

$\theta = 2\times 1° = 2°$. [26.6e; SP 3]

   b. According to the data, $n/n_{\text{air}} = 2,$ so that $v = \frac{1}{2}c.$ [25.6e.3; SP 3]

Activity 2: Pre-Assessment

1. **Answer the following question in your notebook:.** To focus sunlight to a point, would you use a concave or convex lens?
2. **Answer the following question in your notebook:** Do nearsighted people (those who can only focus on nearby things) need to wear glasses with concave or convex lenses?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 2: Lenses and Images

A device that leads to a convergence or divergence of light rays is known as a **lens.** A lens that leads to a convergence of parallel light rays is known as a **convex lens**, whereas a lens that diverges parallel light rays is known as a **concave lens**. For a convex lens, parallel light rays entering the lens converge to a point, known as the **focal point**, on the other side of the lens. Similarly, light diverging from a concave lens appears as if it is originating from a single point on the other side of the lens, also known as the focal point. For both types of lenses, the **focal length** *f* of a lens is the distance from the lens center to the focal point (Figure 26.2).

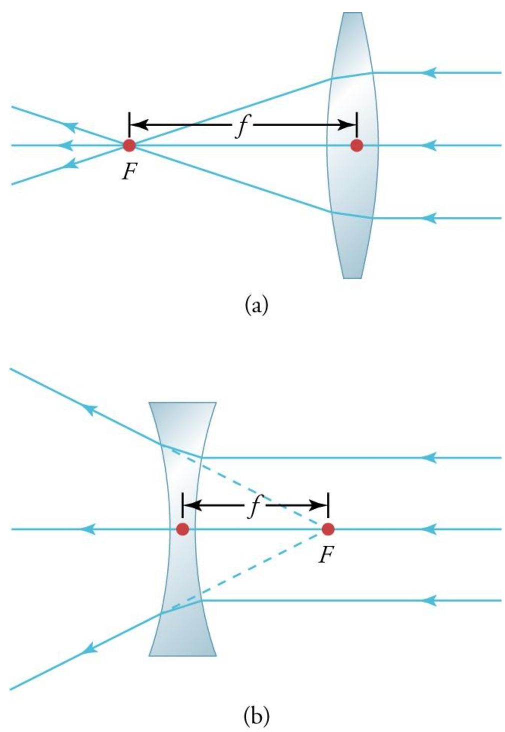


Figure 26.2: Locations of the focal point *F* and focal length *f* for (a) a convex lens and (b) a concave lens.

The focal length for a lens in air can be determined from the **lens maker's equation**

$$\frac{1}{f}=(n-1)\left[\frac{1}{R_1}-\frac{1}{R_2}+(n-1)\frac{d}{nR_1R_2}\right],$$

where *n* is the index of refraction of the lens, R_1 is the radius of curvature of the lens surface that is nearest to the source of light, R_2 is the radius of curvature of the lens surface farthest away from the light source, and *d* is the thickness of the lens along the lens axis between the two surfaces. For a very small value of *d*, the lens maker's equation reduces to an equation known as the **thin lens approximation.**

$$\frac{1}{f}=(n-1)\left(\frac{1}{R_1}-\frac{1}{R_2}\right)$$

Note that the signs of R_1 and R_2 usually follow the following sign convention: The value is positive if the vertex (peak) lies to the left of the center of curvature, and it is negative if the vertex lies to the right of the center of curvature.

If an object of height h_o is placed at a distance d_o from the lens, then an **image** is formed at a distance d_i from the lens. The distance of the image can be related to the distance of the object and the focal length by the **thin lens equation**.

$$\frac{1}{f}=\frac{1}{d_\mathrm{o}}+\frac{1}{d_\mathrm{i}}$$

A **ray diagram** is a diagram that is used to locate the point on an image formed by a lens by tracing the path that light takes from the object. To draw an image from a given object

1. draw a ray from the top of the object parallel to the axis of the lens; this ray changes direction at the lens and passes through the focal point;
2. draw a ray from the top of the object through the center of the lens; this ray passes through the lens in a straight line; and
3. draw a ray from the top of the object through the focal point *on the same side of the lens as the object*; this ray changes direction at the lens and travels parallel to the axis of the lens.

Find the intersection point of the three rays. The image is located where the three rays intersect at a distance d_i from the lens and at a height h_i from the axis of the lens. In this case, the image will appear inverted from the original object. The entire process is illustrated for a convex lens in Figure 26.3. In this activity you will determine the focal length of a convex lens.

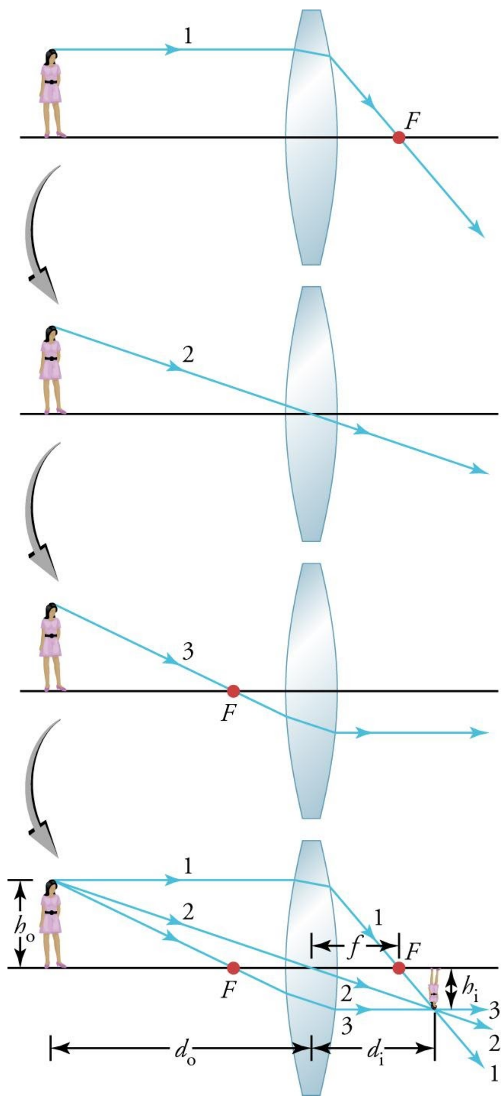


Figure 26.3: A ray diagram showing how to construct an image from an object.

For this activity, you will need the following:

- Light source, such as a clear lamp or candle
- Converging lenses with focal lengths between 15 and 25 cm
- Lens holders
- Yard or Meter stick
- Index card for a screen (5 × 7 inches or larger)

Safety Precautions

- Be careful with the flame from the candle to avoid burns.
- Notify your teacher immediately if any of the glass breaks.

For this activity, you will work *in groups of four students*.

Activity 2 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 2:

- If using a clear lamp, be sure the students understand that it is the image of the filament they are trying to focus on, not the physical bulb itself.
- If a clear bulb is not available and you do not prefer to use a candle, a frosted bulb with an object drawn on its face with a permanent marker (such as an arrow) will work just as well. In this case, be sure that the students know to focus the image of the drawn object, not the physical bulb itself.
- At times, the image is right-side up, and, at other times, it is upside-down. Discuss the nature of these images with the students.
- Sometimes the image is enlarged, and sometimes it is minimized. Discuss the nature of these images with the students.
- Have a class-wide discussion about why a concave lens is not also being tested during this laboratory.
    - This is a good time to discuss real and virtual images.
- Did all three of the rays meet at the same point? If not, discuss why this might have occurred and what could be done to minimize this issue.
- The calculation of the focal length in the experiment relies on the measured object and image distances. Ask the students to predict the image distance for an object very far away (such as infinity). How does this relate to the focal length of the lens? Challenge the students to perform an experiment to justify their prediction.

Structured Inquiry

Step 1: Working with your group, place a lens in the lens holder. Now, place your light source at a given distance (no more than 1 meter) from your lens. On the other side of the lens, use your index card to find the distance where you see a clear image. Record your results.

Step 2: Hypothesize/Predict: If you increase the distance of the light source from the lens, how does the distance of the image change? What about if you decrease the distance between the light source and the lens? Make predictions on the distance of the image from the lens based on the results in Step 1. Create an appropriate table in your notebook to record your data.

Step 3: Student-Led Planning: Working with your group, you will now test your hypothesis from Step 2 by placing the light source at various distances from the lens. What distances would make the most sense to test?

Step 4: On graph paper, plot the inverse of the image distance vs. light source distance and draw a straight line through the data points. The intersection of the line with the *y*-axis should be equal to the focal length. Repeat Steps 1–3 for lenses of different focal lengths.

Step 5: Critical Analysis: Was your hypothesis supported by your results? How does the measured focal length compare to the known focal length of the lens? Does the focal length of a given lens change as the distance between the light source and lens changes? Can the image ever be farther away from the lens than the light source? Why or why not? Write all of your answers in your notebook.

Assessments

1. The focal length of a given lens is f = 5 cm. If an object is located $d_o = 20\text{ cm}$ away from the lens, where will the image be located? [EK 25.6E.5; SP 3]
2. Parallel rays going through a concave lens will ________. [EK 25.6E.5; SP 3]
3. What happens when a light ray passes through the center of a thin lens? [EK 25.6E.5; SP 3]

[Solutions]

1. We can write the distance of the image as

$$d_i = \frac{1}{\frac{1}{f} - \frac{1}{d_o}} = \frac{1}{\frac{1}{5\text{ cm}} - \frac{1}{20\text{ cm}}} = 20/3\text{ cm} = 6.67\text{ cm}.$$

   [EK 25.6E.5; SP 3]
2. diverge [EK 25.6E.5; SP 3]
3. The light will pass through the lens without any deviation of its trajectory. [EK 25.6E.5; SP 3]

Lab 26: Light as a Particle

When we think of light as a wave, we can understand how it travels through various media and passes through transparent materials. On the other hand, when we think of light as a particle, we find that each particle cannot be broken into smaller pieces and has a discrete energy value that we can measure. These particles are known as **quanta** (the singular form is quantum) and govern the interaction of light with solid materials. Keep this in mind as you begin Activity 1.

Quantization of light is also key to understanding how **light-emitting diodes (LEDs)** work. If we do not think of light as existing in discrete packets, then operating LEDs, which work at specific frequencies, would be impossible. A wave-based description cannot explain what we see when LEDs function. Since LEDs convert electrical energy into photon energy, we need an equation that lets us convert between the two. We use the equation

$$E = hf ,$$

where *E* is energy, *f* is wave frequency, and *h* is Planck's constant.

$$h = 6.626070040(81) \times 10^{-34}\ \mathrm{J \cdot s}$$

This equation lets us calculate the energy needed to release a photon associated with a specific frequency. You will use this equation when you make your calculations in the second activity.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- In order for students to better understand the concept of dual property of light—light as a wave and light as a particle—demonstrate Young's double-slit experiment using a laser light wire and electrical tape (https://www.youtube.com/watch?v=kKdaRJ3vAmAv). With a single slit, light behaves as a particle, but with a double slit, the light behaves as both a particle and a wave.
- In order for students to understand the concept of light particles or quanta, explain the concept of a photon (the basic unit of electromagnetic energy that cannot be broken into smaller parts).
- In order for students to understand the concept of charge buildup, demonstrate static electricity and explain how it is caused by an imbalance of positive and negative charges on an object.
- In order for students to understand the photoelectric effect, provide an explanation of the key terms: (1) Photoelectric Effect: Light can push electrons free from the surface of a solid; this process is known as the photoelectric effect or photoelectric emission. (2) Photoelectrons: The electrons ejected from the surface of the object by the light.

In this lab you will learn:

- how to describe absorption and emission spectra associated with electronic transitions as transitions between allowed energy states of the atom;
- how to support the photon model of radiant energy with evidence provided by the photoelectric effect;
- how to choose a model of radiant energy appropriate to the scale of the interaction with matter.

Activity 1: Pre-Assessment

1. **Answer the following questions in your notebook:** How does a charge build up on a surface? What is actually building up to create a negative charge? What is building up to create a positive charge?
2. **Answer the following questions in your notebook:** How can we dissipate a buildup of negative charge on an object besides touching it? Think about the buildup of static electricity on yourself or another object. Does the object remain charged forever if it remains untouched? Could light be used to dissipate this charge?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 1: The Photoelectric Effect

Albert Einstein won his Nobel Prize in 1921 for explaining a phenomenon known as the **photoelectric effect**, the process in which electrons are ejected from a material after being struck by electromagnetic waves or light. Scientists had performed the exact experiment you will be doing in Activity 1. However, they struggled to explain why the photoelectric effect happened until Einstein published his paper in 1905. The key to understanding the photoelectric effect is realizing that light has properties of both a particle and a wave.

Safety Precautions

- Do not shine the lights in students' eyes.

For this activity, you will need the following:

- Tin foil (or gold foil)
- Plastic peanut butter jar or similar
- Two paper clips
- Pushpin
- Zinc plate
- Plastic rod with wool or rabbit fur (or another combination to give negative charge)
- Steel wool
- UV light
- Visible-spectrum light (desk lamp)

For this activity, you will work *in pairs*.

Activity 1 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 1:

- In advance of the lab, show the students all the different items that will be used for this activity. If students need to bring any of the items, provide them with a list and instructions from where to get these. Provide specific details about the type of tin foil, zinc plate, plastic rod, rabbit fur, steel wool, and UV light that will be used for this experiment.

- Since the students are to be working in pairs, explain what each student needs to do so that both students equally contribute to the activity. Divide the activity of building the electroscope so that both students get the opportunity to equally contribute.
- Ask the students to provide an explanation in their own words and write in their individual notebooks about what happens to the charge of the object following the photoelectric effect.

Structured Inquiry

Step 1: Build an electroscope by performing the following steps (refer to Figure 27.1):

- Unbend one paper clip so that you have a 4-in. (10-cm) length of straight metal.
- Starting with a $10 \text{ in.} \times 10 \text{ in.}$ $(25 \text{ cm} \times 25 \text{ cm})$ piece of aluminum foil, mash the foil into a ball around a second paper clip that is not unbent. Flatten the top side of the ball. Then connect the ball to the straight metal.
- Using a pushpin, carefully poke a hole in the top of the jar large enough to insert the unbent paper clip.
- Push the paper clip through the hole so the ball is on the outside of the lid. Bend the bottom 0.5 in. of the paper clip so it is 90° from the vertical portion.
- Starting with a 10-in. (25-cm) piece of foil, bend the foil so that the final dimensions are 0.5 in. by 4.5 in. (1.25 cm by 11.5 cm). Bend the ends in by 0.25 in. twice, so the overall length is now 4 in. (10 cm). Make a crease in the center, 2 in. (5 cm) from each end.
- Place the foil piece you just made (the leaves) on the 0.5 in. of a paperclip that you bent in a previous step.
- Place the lid on the jar, being careful not to dislodge the leaf from the clip.

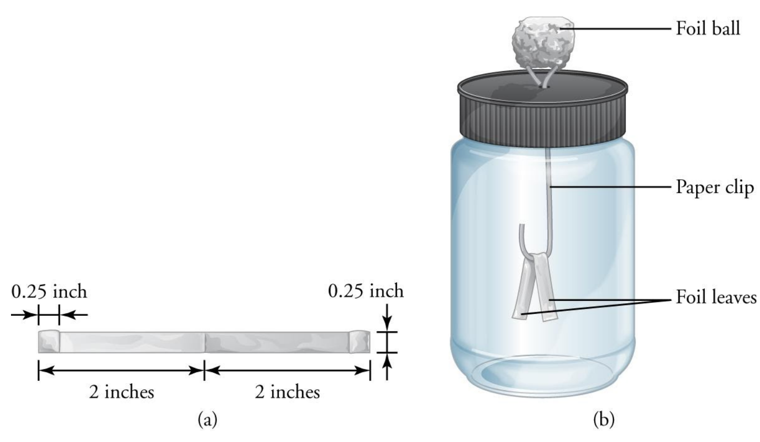


Figure 27.1: (a) The piece of foil that will become the electroscope leaves should be approximately 4 in. (10 cm) long. (b) The aluminum foil leaves of the electroscope hang down straight due to gravity, but push outward in the presence of a charged object.

Step 2: Place the zinc plate on top of the ball. Using the plastic rod and wool, create a charge on the rod. Using induction, bring the rod near the foil and touch the foil ball with your finger to induce a charge on the foil leaves. Use the steel wool to clean the sides of the zinc plate, which may have a thin layer of oxidation on both sides that could interfere with the experiment.

Step 3: Hypothesize/Predict: Using what you know about how light behaves, think about what might happen if you shine a regular visible light or a UV light at the zinc plate. Write your thoughts and ideas in your notebook.

Step 4: Student-Led Planning: You will now shine the visible light and UV light on the zinc plate, one at a time. With your partner, observe what happens and hypothesize why it is happening. Repeat the process several times at various distances to help you make sense of what is happening.

Step 5: Critical Analysis: What would have to be true about the behavior of light to explain the results you see in this experiment? What is the difference between UV light and visible light? If the UV light releases the electrons through the photoelectric effect, is the light acting as a wave or a particle? Discuss with your partner and then write your answers in your notebook.

Assessments

1. What do we mean when we say that energy in light interacting with matter is *quantized*? What determines the size of the quanta? [EK 6.F.3]
2. Why does the photoelectric effect require us to think of light as both a particle *and* a wave? [EK 5.B.8]
3. What part of the light spectrum will not produce the photoelectric effect? What determines this? [EK 5.B.8]

[Solutions]

1. When light interacts with matter, it exists only in discrete pieces, or quanta, not an analog range of sizes. The sizes of quanta are determined by the frequency of the light. [6.f.3]
2. The photoelectric (PE) effect requires us to think of light as a particle because only very specific-*sized* particles cause the effect. The PE effect requires us to think of the light as a wave; because there is no time delay, the effect is practically instantaneous. [5.b.8]
3. The red end of the electromagnetic spectrum will not produce the PE effect, regardless of the intensity of the light. This is because the frequency of this light is too low to drive an electron from the metal's surface. The frequency (and some specific values related to the material) determines whether the PE effect will happen or not. [5.b.8]

Activity 2: Pre-Assessment

1. **Answer the following questions in your notebook:** Why shouldn't you connect the positive side of a battery directly to the negative side? (Note—*Do not* actually do this, you are only to think about what happens!) What would happen to the battery if you do this?
2. **Answer the following questions in your notebook:** Since you cannot connect the two ends of a battery to each other directly, what do you put in a circuit to adjust the amount of current for a given battery voltage? Recalling Ohm's law, how are these variables related to each other?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 2: LEDs and the Photoelectric Effect

Light-emitting diodes, or LEDs, are examples of a newer type of bulb that function differently than traditional incandescent bulbs. In a traditional incandescent light bulb, the current flowing through the bulb is linearly related to the voltage and resistance of the bulb. This is because an incandescent bulb has resistance due to the wire used in the filament. On the other hand, an LED is a special kind of semiconductor called a diode (that is the D in LED), which exponentially increases the current for a specific voltage. LEDs do not have resistance, so when you use them in a circuit, certain safety precautions must be observed. This means you need to be sure to use a resistor in series with the LEDs *every* time you connect them to a power source.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- In order for students to better understand the difference between LED, incandescent, and fluorescent bulbs, demonstrate the difference between the bulbs to the students using the actual bulbs.
- In order for students to understand the concept of an LED, provide an explanation of the key terms: (1) LED: A light-emitting-diode that converts electrical energy into electromagnetic radiation and emits light. (2) Diode: An electronic component that acts as a one-way valve that has low resistance when current flows through it in one direction and high resistance when current flows through it in the other direction.
- In order for students to understand the relation between the energy of a quantum to its frequency, provide an explanation of Planck's constant indicated by the symbol h.

Safety Precautions

- *Do not* place LEDs in a circuit without a resistor.

For this activity, you will need the following:

- Switch
- Incandescent bulb for circuit
- LEDs (possibly of different colors)
- Circuit board with variable resistor
- Battery or other power source

For this activity, you will work *in pairs*.

Activity 2 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 2:

- In advance of the lab, show the students all the different items that will be used for this activity. If students need to bring any of the items, provide them with a list and instructions from where to get these. Provide specific details about different color LEDs, circuit board, variable resistor, and the kind of battery or power source used.
- Since the students are to be working in pairs, explain what each student needs to do so that both students equally contribute to the activity. Both students can participate in the building of the circuit board. The students can take turns recording the observations.
- Repeat the experiment for all colors of the LED listed in Figure 27.2 below.

The following are recommendations for the Guided Inquiry for Activity 2:

- Build the circuit from Figure 27.4 use LED lights of different colors and wattage and tabulate the results. What do you observe when the colors and wattage are different?

Structured Inquiry

Step 1: Gather the materials from your instructor to build Circuit 1, as shown in Figure 27.2. With a partner, build the circuit depicted in the diagram. How can you tell if the batteries work?

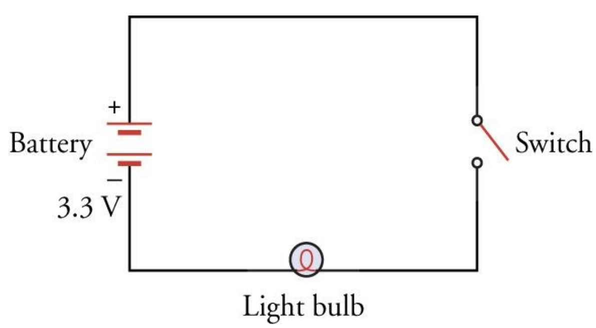


Figure 27.2: Circuit with a battery, switch, and light bulb in series.

Step 2: Hypothesize/Predict: With the switch closed, does the light bulb light? Will current flow regardless of where you place your battery in the circuit? Are both ends of the battery the same or different? Write your predictions in your notebook.

Step 3: Now build circuit 2, as depicted in Figure 27.3. Be sure to place the resistor in the circuit and leave the switch open until your teacher checks your circuit.

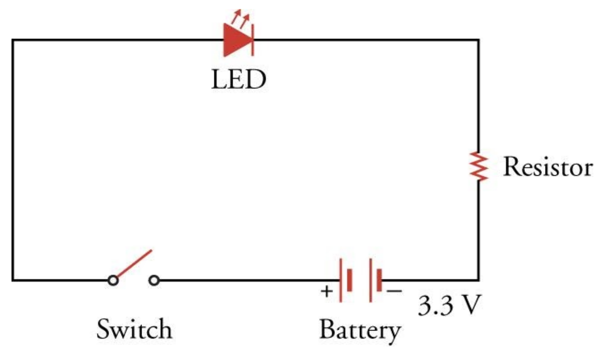


Figure 27.3: Circuit with a battery, switch, resistor, and LED in series.

Step 4: Student-Led Planning: Did your LED light up? If not, what could be the cause? Try turning the LED around and see if the LED lights up. Is the battery sufficiently charged? What does this tell you about the LED? Write the results of all your trials in your notebook.

Step 5: Critical Analysis: Do you think the size of the resistor has an effect on the circuit? Can you use any size resistor? Try a different-sized resistor from your teacher's supply. How will that change the various measured values in the circuit? Discuss your answers with your partner and write them in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: Use the information about the behavior of light learned in the first activity and your experience with LEDs to hypothesize whether LEDs will work at any voltage, or only specific voltages (or quanta). Write and explain your hypothesis in your notebook.

Step 2: Student-Led Planning: Construct the circuit depicted in Figure 27.4. How can you use this circuit, along with the information in Figure 27.2, to measure the minimum voltage needed to turn on the LED? Discuss with your partner and then have your teacher approve your plan. Create all data tables you will need for your experiment. Note—The voltmeter MUST be placed in parallel with the LED to measure the voltage drop across the LED, as shown in the circuit diagram. Take the voltage measurement as soon as you see light from the LED and continue until the LED turns off.

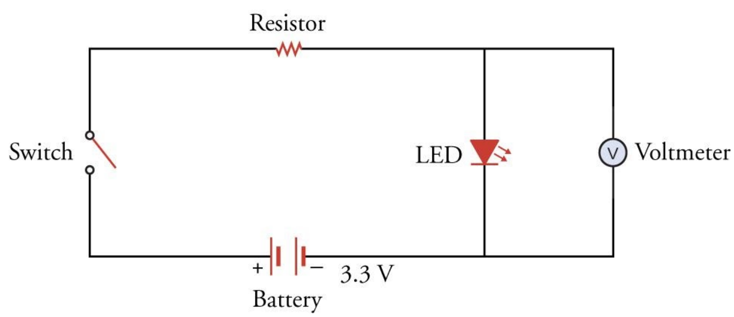


Figure 27.4: Circuit with a battery, switch, resistor, and LED in series.

Step 3: Perform the experimental procedure you designed in Step 2 three times. Then, if possible, switch out your LED for one of another color and repeat this step. Write your results in your notebook.

Step 4: Critical Analysis: What do you think is the relationship between photon energy and frequency? Looking at the voltage needed to light the LED, what frequency photon do you think was emitted? Does this line up with the visible light spectrum shown in Figure 27.5? If you were able to test more than one type of LED, what did you notice about each LED operating band? Discuss your answers with your partner and write them in your notebook.

Color	Frequency
Violet	668–789 THz
Blue	630–668 THz
Cyan	606–630 THz
Green	526–606 THz
Yellow	508–526 THz
Orange	484–508 THz
Red	400–484 THz

Figure 27.5: LEDs produce color by operating at the listed frequencies.

Assessments

1. If a red LED converts most of its approximately 0.03 W (or J/s) of power into light and has a frequency of $4.5 \times 10^{14}\ \text{s}^{-1}$, estimate the number of photons per second produced by the red LED. [EK 5.B.8]
2. Is the voltage drop across the diode directly or inversely proportional to the energy of the photons emitted by the LED? [EK 5.B.8]
3. Describe how an LED works, in terms of how the LED emits light at the atomic level. [EK 5.B.8]

[Solutions]

1. $E = hf = (6.62 \times 10^{-34}\ \text{J} \cdot \text{s})(4.5 \times 10^{14}\ \text{s}^{-1}) = 3.0 \times 10^{-19}\ \text{J}$, $0.03 \dfrac{\text{J}}{\text{s}} \times \dfrac{1\ \text{photon}}{3.0 \times 10^{-19}\ \text{J}} = 10^{17}\ \text{photons}$ [5.B.8]
2. The voltage drop across the LED is directly proportional to the energy emitted by the LED. The voltage drop is directly proportional to the power used by the LED and the power is directly proportional to the energy of the photons of light emitted, as seen in the equation $E = hf$. [EK 5.B.8]
3. As the current passes through the LED, its electrons are added to the atoms of the LED material. This allows the atoms to fill their valence shells. They then release excess energy as photons of light. [EK 5.B.8]

Lab 27: Double-Slit Interference and Diffraction

From previous labs, we know that light is an electromagnetic wave. The color of the light that we see is determined by the frequency and wavelength of the wave, which are related by

$$c = \lambda f \ ,$$

where c is the speed of light, λ is the wavelength, and f is the frequency. **Huygens's principle** tells us that each point on a wave front acts as a point source from which waves can spread. This spreading out process is called **diffraction**. If light passes through an opening comparable to the size of its wavelength, the opening acts as a source from which the light can spread. If light passes through two openings, each opening acts as a point source, and the light from the two openings forms an **interference pattern**, which is the intensity pattern resulting from adding together the waves from the two sources. If the two waves are **in phase**, meaning that their crests and troughs are aligned, then you get **constructive interference** at that point where the two waves add, producing a wave with a higher amplitude. If the two waves are **out of phase**, meaning that the crests of one wave are aligned with the troughs of the other wave, then you get **destructive interference** at that point where the two waves add, so they cancel each other and you see no light.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- If you students have not yet learned about light behavior and waves, it may be helpful to review how frequency and wavelength are related.
- Review with students constructive and destructive interference. It may be helpful to draw wave diagrams that reflect the two types of interference.
- Discuss with students how light spreads through a slit and through a diffraction grating. Have students draw this and display it during the lab.
- *Do not* use lasers with enough power to cause damage to the retina. Most laser pointers do not have sufficient power to damage the retina as long as they are less than 1 mW.

In this lab you will learn:

- how to form an interference pattern using a double slit and a diffraction grating;
- how to measure the wavelength of a laser using an interference pattern;
- how varying experimental parameters affects an interference pattern.

Activity 1: Pre-Assessment

1. **Answer the following questions in your notebook:** Why don't you see any diffraction when you shine a flashlight through an open door? How could you change that experiment so you would get diffraction?
2. **Answer the following question in your notebook.** Light is both a particle and a wave, so it has some properties that are particle-like, and other properties that are wave-like. Is diffraction a particle-like or wave-like property? Explain.
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 1: Green Laser Wavelength

The double-slit experiment is performed by passing light of a particular wavelength through two openings that have a similar width and spacing as the wavelength of the light. The light that passes through the openings is observed on a screen some distance in front of the slits, as shown in Figure 28.1. If you look at a particular point on the screen, light will arrive at that point from both slits, but the light from one slit will have traveled a slightly greater distance than light from the other slit. If the difference in those distances is equal to the wavelength (or an integer multiple of the wavelength), then the light from the two slits is in phase, so it will interfere constructively and produce a bright spot on the screen. If instead the difference in those distances is equal to a half wavelength (or an odd-integer multiple of a half wavelength), then the light from the two slits will be out of phase, so it will interfere destructively and produce a dark spot on the screen. Based on the geometry of your setup, the wavelength of the light can be determined from the locations of the bright spots in the diffraction pattern by using the equation

$$\lambda = \frac{x \cdot d}{L},$$

where λ is the wavelength of the light, x is the distance between the bright spots on the screen, d is the spacing between the two slits, and L is the distance from the double slit to the screen.

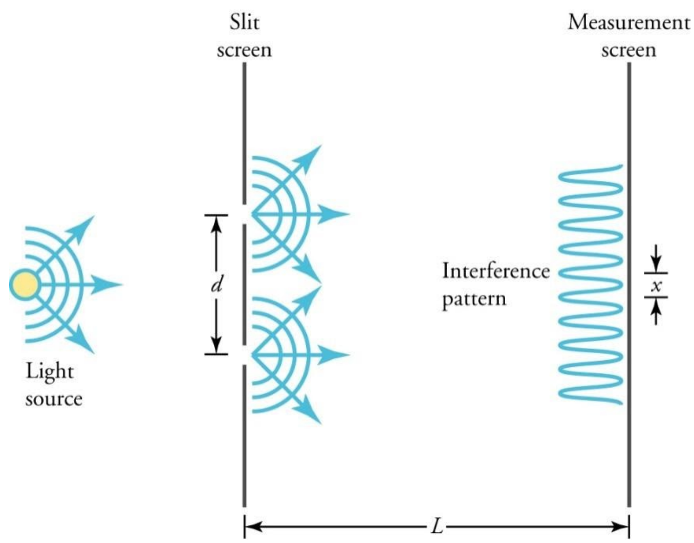


Figure 28.1: When light passes through two small openings, the openings act like point sources of light. The light from these two sources interfere constructively and destructively, depending on location, producing an interference pattern on a screen in front of the openings.

Safety Precautions

- Be careful not to direct your laser pointer into your own or anyone else's eyes. While they are not very powerful, they can still cause permanent eye damage.

For this activity you will need the following:

- A green laser pointer
- A double-slit plate for diffraction*
- A mount for the double-slit plate
- A ruler or meter stick
- A blank piece of paper
- Tape

*Note—This activity can also be done with a diffraction grating; however, the pattern and relevant equations would be different.

For this activity, you will work *in pairs*.

Activity 1 Instructor Preparation and Teaching Notes

The following are recommendations for the Structured Inquiry for Activity 1:

- This activity should be done in pairs, so students can interact with the laser and easily view the results of the interference. If there is a shortage of lasers, students can work in larger groups, but it would be better to have them share the lasers and trace their results so they can then do the analysis without the laser.

- Do not use lasers with enough power to cause damage to the retina. Most laser pointers do not have sufficient power to damage the retina as long as they are less than 1 mW.
- As students are shining the laser through the slit, make sure they are pointing it as perpendicular to the wall as possible to achieve the best results.
- As students are working, check that they are recording all necessary measurements at Step 3. They should have distance between the bright spots on the screen, spacing between the two slits, and the distance from the double slit to the wall.

The following are recommendations for the Guided Inquiry for Activity 1:
- Students should remain in the same groups as the structured activity.
- The basic procedure of this activity is the same as the structured activity, but students change the variables and observe the effect of that change.
- Remind students that they should change one variable at a time. You may want to assign groups which variable to change: the distance between the slits or the distance to the screen.

Structured Inquiry

Step 1: Mount your double slit plate on a table about 1–2 meters from a wall. Make sure that the double slits are vertical, and that light passing through the slits is directed at the wall, as shown in Figure 28.2. Tape your blank piece of paper on the wall across from the double slits so that the light that passes through them will strike the paper.

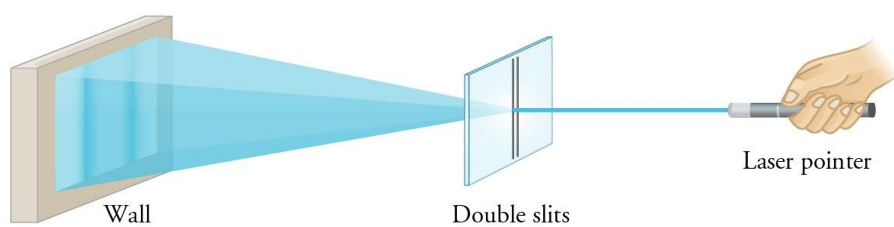


Figure 28.2: Light from a laser pointer directed through a pair of slits forms an interference pattern on a screen directly in front of it.

Step 2: Hypothesize/Predict: Based on what you know about double-slit interference, predict what you will see on the sheet of paper when you shine the laser through the double slits. What should the interference pattern look like? What parameters about your setup will affect the pattern that you see? Record your hypothesis in your notebook.

Step 3: Student-Led Planning: Use your double-slit setup to measure the wavelength of your green laser pointer. Discuss with your partner what measurements you will need to determine the wavelength of the laser. Use the blank piece of paper to record the diffraction pattern that you see, so you don't have to take measurements from the laser light.

Step 4: Critical Analysis: Determine the wavelength of the green laser. Does the number you calculated based on your measurements agree with your observation that this is green light? Does it agree with the wavelength claimed by the laser pointer documentation? How could you improve your measurement technique to get a more accurate measurement of the wavelength? Discuss with your partner and then write your answers in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: What would be an acceptable range for a measurement of the wavelength of green light? If you measure something outside this range, is it more likely because the wavelength of the light is not in this range or because of errors in your measurements? Record your hypothesis in your notebook.

Step 2: Student-Led Planning: Discuss with your partner how the distances between objects in your setup and the double-slit experiment in general allow you to measure the wavelength of light. Consider any modifications to the geometry of your setup and the effects they would have on the observed diffraction pattern.

Step 3: Critical Analysis: Change the distance between the slits and the screen in your experiment and repeat your measurement of the diffraction pattern. Use this to calculate the wavelength of the laser. Did the diffraction pattern change from the previous measurement? If so, how? Does this agree with what you hypothesized in Step 1? Did your calculated wavelength agree with your previously calculated value and the expected value for the laser pointer? If not, can you think of any explanation for the discrepancies?

Assessments

1. Imagine that you are color blind. You know the spacing of the bright spots in the double-slit experiment for the green laser from your measurement. You then repeat the experiment without changing anything except the color of the laser. The bright spots are now closer together than they were for the green laser. What can you say about the wavelength of the light from the new laser? [EK 6.C.2.3; SP 2]
2. If you shine a laser pointer at two slits that are each 10 cm wide and 5 cm apart, you wouldn't expect to see diffraction. What type of electromagnetic radiation would be appropriate for doing a double slit experiment with this setup? [EK 6.C.2.3; SP 6]
3. Would you see the same interference pattern if you repeated the double-slit experiment with white light? Why or why not? [EK 6.C.1; SP 6]

[Solutions]

1. [EK 6.C.2.3; SP 2] Based on the formula $\lambda = \frac{x \cdot d}{L}$, if the bright spot spacing decreased, then the wavelength must have also decreased, because they're directly proportional. This might be blue or violet light.
2. [EK 6.C.2.3; SP 6] The size of the openings in the double-slit experiment should be around the same size as the wavelength of the light used. If the slits are 10 cm wide, microwaves would be the most appropriate type of light to use, because an EM wave with a 10-cm wavelength would be classified as a microwave.
3. [EK 6.C.1.2; SP 6] No, because we assumed that we have only one wavelength of light. This is how we could say where the light would interfere constructively and destructively. White light has all of the wavelengths of visible light, so you would get some constructive and some destructive interference at every point by every wavelength.

Activity 2: Pre-Assessment

1. **Answer the following questions in your notebook:** Draw the double slit and screen setup in your notebook, as shown in Figure 28.1. Draw two rays of light, one coming from each slit, that meet at a point on the screen. The two lines should have different lengths. Can you write an expression in terms of the experimental parameters x, d, and L for the difference in the lengths of the two rays?
2. **Answer the following questions in your notebook:** If the difference in the path lengths of the light from the two slits is just determined by the geometry of the setup, would changing the wavelength of the light change the interference pattern? Why or why not?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 2: Red Laser and Double-Slit Interference

In Activity 1, you used a double-slit setup to determine the wavelength of light from a laser pointer. However, the pattern that you observed was determined not only by the wavelength, but also by the double slit itself and the relative positions of the slits and the screen. Every combination of laser light and experimental setup produces a unique diffraction pattern.

Safety Precautions

- Be careful not to direct your laser pointer into your own or anyone else's eyes. While they are not very powerful, they can still cause permanent eye damage.

For this activity you will need the following:

- A red laser pointer
- A green laser pointer
- A double-slit plate for diffraction*
- A mount for the double-slit plate
- A ruler or meter stick
- Four blank pieces of paper
- Tape

*Note—This activity can also be done with a diffraction grating; however, the pattern and relevant equations would differ than those below.

For this activity, you will work *in pairs*.

Activity 2 Instructor Preparation and Teaching Notes

The following are recommendations for the Structured Inquiry for Activity 2:

- This activity should be done in pairs, so students can interact with the laser and easily view the results of the interference. If there is a shortage of lasers, students can work in larger groups, but it would be better to have them share the lasers and trace their results so they can then do the analysis without the laser.
- *Do not* use lasers with enough power to cause damage to the retina. Most laser pointers do not have sufficient power to damage the retina as long as they are less than 1 mW.
- When students are making their prediction, instruct them to be exact. They should measure out and mark the distance between the bright spots on the screen.
- As students are shining the laser through the slit, make sure they are pointing it as perpendicular to the wall as possible to achieve the best results.
- As students are working, check that they are recording all necessary measurements at Step 3. They should have distance between the bright spots on the screen, spacing between the two slits, and the distance from the double slit to the wall.

The following are recommendations for the Guided Inquiry for Activity 2:

- Students should remain in the same groups as the structured activity.
- The basic procedure of this activity is the same as the structured activity, but students change the variables and observe the effect of that change.
- Remind students that they should change one variable at a time. You may want to assign groups which variable to change: the distance between the slits or the distance to the screen.

Structured Inquiry

Step 1: For this section, you can use the same setup as in Activity 1.

Step 2: Hypothesize/Predict: How will the diffraction pattern for the red laser be similar to and different from the pattern you observed for the green laser in Activity 1? Record your hypothesis in your notebook. On a blank piece of paper, draw your prediction for the diffraction pattern of the red laser pointer.

Step 3: Student-Led Planning: Switch from the green laser pointer to the red laser pointer to determine the effect of wavelength on the double-slit diffraction pattern.

Step 4: Place your predicted diffraction pattern on the screen across from the double slits and shine the red laser through the slits. Record the actual diffraction pattern on the same paper that shows your prediction.

Step 5: Critical Analysis: Do the results line up with the drawings of your predictions? If not, what could you improve about your predictions or measurements to get better agreement? Discuss with your partner and then write your answers in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: Other than wavelength, what experimental parameter could you vary to change your diffraction pattern? Refer to the equation for double-slit diffraction to determine which parameters affect the diffraction pattern. In what way will changing this parameter affect the diffraction pattern? Record your hypothesis in your notebook. Then predict two new values for your chosen experimental parameter. How will the diffraction patterns for the red and green lasers change? Draw the predicted patterns on separate blank sheets of paper.

Step 2: Student-Led Planning: How will you change your chosen parameter from Step 1? Discuss with your partner, then get approval from your teacher before proceeding.

Step 3: Carry out the experiment approved by your teacher in Step 2.

Step 4: Critical Analysis: Compare the two green laser diffraction patterns. How are their diffraction patterns different? What does that tell you about the effect of your varied parameter from Step 1 on the spacing between bright spots in the diffraction pattern? Does this agree with what you expect from the equation for double-slit diffraction? Next, compare the red and green laser diffraction patterns for the same experimental setup. How are the diffraction patterns different? What does that tell you about the effect of wavelength on the spacing between bright spots in the diffraction pattern? Does this agree with what you expect from the equation for double-slit diffraction? Discuss with your partner and record your answers in your notebook.

Assessments

1. In your experiment, you were limited in which experimental parameters you could change because the double-slit spacing was fixed. Would varying the spacing have changed your pattern, and if so, how? [EK 6.C.2.3; SP 6]
2. A student finds a double-slit plate and does not know the spacing between the slits. She sets up the slits 1 m from a wall and shines a laser pointer with a wavelength of 517 nm through the slits. She observes that the bright spots in the pattern are 2 cm apart. What is the slit spacing for the double-slit plate she found? [EK 6.C.2.3; SP 2]
3. Could you use your experimental setup from this activity, without changing any of the parameters, to look at diffraction patterns of X-rays ($\lambda \approx 10^{-10}\,\mathrm{m}$)? What about for radio waves ($\lambda \approx 10^{1}\,\mathrm{m}$)? Why or why not? [EK 6.C.2.3; SP 6]

[Solutions]

1. [EK 6.C.2.3; SP 6] Varying the spacing between the slits would change the diffraction pattern. We know that $\lambda = \frac{x \cdot d}{L}$, so increasing the slit spacing would decrease the spacing between the bright spots, and vice versa, because *x* and *d* are inversely proportional.
2. [EK 6.C.2.3; SP 2] $d = \frac{\lambda \cdot L}{x} = \frac{(517\ \mathrm{nm})(1\ \mathrm{m})}{(2\ \mathrm{cm})} = 25.8\ \mu\mathrm{m}$
3. [EK 6.C.2.3; SP 6] No, this wouldn't work because the spacing of the bright spots is proportional to the wavelength of the light. If the wavelength is much smaller, the spots will be too close together to tell them apart. If the wavelength is much larger, the spots will be too far apart for you to see on the screen.

Activity 3: Pre-Assessment

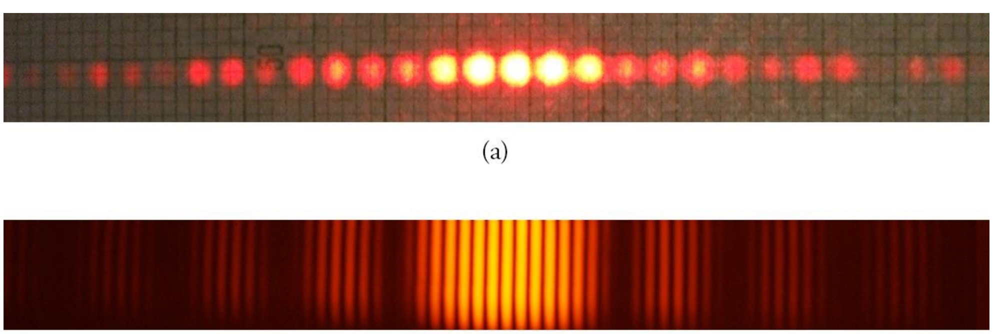
1. **Answer the following questions in your notebook:** Could the double-slit experiment be re-imagined to involve more than two slits? Could you still predict the locations of the bright spots with, say, three slits? Explain.
2. **Answer the following question in your notebook:** The condition for a bright spot in a two-slit diffraction pattern is that the light from both slits is in phase at that point. If you have more than two slits, would you expect the bright spots to occur more often or less often? Why?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 3: Red Laser and Diffraction Gratings

A **diffraction grating** is a set of many closely spaced openings through which you can shine light to form an interference pattern. Instead of being formed by the interference of light from two sources, the pattern is formed by the interference of light from every slit, which can mean hundreds of sources. As a result, the requirement for a bright spot—that most or all of the light is interfering constructively—becomes harder to meet, resulting in sharper, more spaced out bright spots, as shown in Figure 28.3. The interference pattern for a diffraction grating can be described by

$$m\lambda = \frac{x \cdot d}{L},$$

where λ is the wavelength, *d* is the slit spacing, *L* is the distance from the grating to the screen, and *m* is the index of the bright spot ($m = 1$ being the bright spot closest to the point directly across from the grating, and increasing as you get farther away). Note—Diffraction gratings are usually described by the density of slits—for example, 100 slits per cm. The slit spacing is the inverse of this number, in cm per line.



(a)

(b)

Figure 28.3: Shining a laser pointer through a diffraction grating produces an interference pattern consisting of bright, spread-out points where the light from all of the slits is interfering constructively.

Safety Precautions

- Be careful not to direct your laser pointer into your own or anyone else's eyes. While they are not very powerful, they can still cause permanent eye damage.

For this activity you will need the following:

- A red laser pointer
- A green laser pointer
- A diffraction grating
- A mount for the diffraction grating
- A ruler or meter stick
- Two blank pieces of paper
- Tape

For this activity, you will work *in pairs*.

Activity 3 Instructor Preparation and Teaching Notes

The following are recommendations for the Structured Inquiry for Activity 3:

- This activity should be done in pairs, so students can interact with the laser and easily view the results of the interference. If there is a shortage of lasers, students can work in larger groups, but it would be better to have them share the lasers and trace their results so they can then do the analysis without the laser.
- Do not use lasers with enough power to cause damage to the retina. Most laser pointers do not have sufficient power to damage the retina as long as they are less than 1 mW.
- As students are shining the laser through the slit, make sure they are pointing it as perpendicular to the wall as possible to achieve the best results.
- As students are working, check that they are recording all necessary measurements at Step 3. They should have the slit spacing (inverse of the density of slits), the distance from the grating to the screen, the index of the bright spot, and the distance of the spot matching that index.
- Students are only observing the diffraction in the structured inquiry, they will be calculating the wavelength in the guided inquiry portion.

The following are recommendations for the Guided Inquiry for Activity 3:

- Students should remain in the same groups as the structured activity.
- The basic procedure of this activity is the same as the structured activity, but students change the variables and observe the effect of that change.
- Discuss with students what types of errors could happen with each type of diffraction and how this could lead to more or less accurate results.

- In determining which method is better to determine wavelength, remind students to not only think of their results but how accurate their measurements could be in each procedure. The fact that their results were accurate or not should not be the only consideration when determining the best method.

Structured Inquiry

Step 1: On your setup from Activities 1 and 2, replace the double slit with a diffraction grating.

Step 2: Hypothesize/Predict: What will the diffraction pattern look like if you shine the red laser through the diffraction grating? How would it be similar and different for the green laser? Record your answers in your notebook.

Step 3: Student-Led Planning: Use the diffraction grating to measure the wavelengths of your laser pointers. Discuss with your partner what quantities need to be measured to determine the wavelength using the diffraction grating. Decide where you will need to tape your piece of blank paper in order to make your measurements.

Step 4: Critical Analysis: Observe and record the diffraction patterns from the green and red laser pointers. Did they appear as you expected? How were they similar and different from each other? How were they similar and different from the patterns in the double-slit experiments? Discuss with your partner and then write your answers in your notebook.

Guided Inquiry

Step 1: Hypothesize/Predict: What do you expect to calculate for the wavelengths of the red and green lasers? How should this compare to your previous measurements with the double slit? Record your answers in your notebook.

Step 2: Student-Led Planning: Discuss with your partner how you will use the diffraction patterns to determine the wavelengths of the lasers. Make sure you understand what each variable in the appropriate formula is and how you will measure it.

Step 3: Critical Analysis: Based on your observed diffraction patterns, calculate the wavelengths of your laser pointers. Do these numbers agree with those from Activities 1 and 2? If not, why do you think there is a discrepancy? What could you have done differently to get better agreement? Which do you think is a better method for measuring wavelength: the double slit or the diffraction grating? Why? Discuss your answers with your partner and record them in your notebook.

Assessments

1. A reflection grating is like a diffraction grating, but with closely spaced reflective lines instead of slits (a CD is an example of this). If you shine a laser at a reflection grating, will it form a pattern similar to the diffraction grating? Explain. [EK 6.C.1.2, 6.C.1.3; SP 6, SP 7]
2. The peak wavelengths for the colors in the rainbow are as follows: $\lambda_{\text{red}} = 650 \text{ nm}$, $\lambda_{\text{orange}} = 590 \text{ nm}$, $\lambda_{\text{yellow}} = 570 \text{ nm}$, $\lambda_{\text{green}} = 510 \text{ nm}$, $\lambda_{\text{blue}} = 475 \text{ nm}$, and $\lambda_{\text{violet}} = 400 \text{ nm}$. [EK 6.C.2.3; SP 2]
    a. Calculate the locations of the *m* = 1 spot for each color on a screen 1 m away through a grating with 100 slits per cm.
    b. Calculate the location of the *m* = 2 spot for violet. Does it overlap any of the *m* = 1 spots or is it past all of them?
    c. Use this to explain why white light passing through a diffraction grating forms a series of rainbows.

[Solutions]

1. [EK 6.C.1.2, 6.C.1.3; SP 6,7] The reflection grating does form a pattern like the diffraction grating. Each reflective line acts like a source of light, just like each slit did in the grating, and the reflected light from the lines interferes to give you an interference pattern.
2. [EK 6.C.1.2, 6.C.1.3; SP 6]
    a. Red: 6.5 mm; Orange: 5.9 mm; Yellow: 5.7 mm; Green: 5.1 mm; Blue: 4.75 mm; Violet: 4 mm
    b. The *m* = 2 spot for violet is at 8 mm, which is beyond all of the *m* = 1 spots.
    c. All of the *m* = 1 spots are gathered together and separated from the *m* = 2 spots, and the peaks for the colors are close together but separated in the correct order to form a rainbow.

Lab 28: Atomic Physics

The history of atomic physics dates back to approximately 430 B.C., when the Greek philosopher Democritus proposed that all substances are made up of indestructible, invisible particles called *atomos*. Over the ages, the idea has waxed and waned in popularity, and it wasn't until more than two millennia later that experimental evidence hinted at the atomic nature of matter. John Dalton carried out experiments on chemical reactions in the early nineteenth century and postulated that each element consists of a unique type of atom that cannot be altered or destroyed. He also went further and showed how atoms of different elements can combine to create composite particles called *molecules*. Amedeo Avogadro's work on gases expanded on this idea and allowed for accurate estimation of atomic masses. In 1905, Albert Einstein was able to explain the erratic motion of pollen in water, known as *Brownian motion*, by proposing that the observed motion was a result of the pollen interacting with individual water molecules. Scattering experiments in 1909 led Ernest Rutherford to deduce that the majority of the mass of an atom was concentrated in a very small fraction of the total volume. The development of quantum theory in the early twentieth century led to the first full theory of the structure of atoms.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- Some students may not believe that simulations provide accurate information about the real world, but note that simulations are increasingly becoming a major source of scientific knowledge beyond theory and observation. To illustrate this, give examples of climate change models and astrophysical models.
- Although atoms are generally indivisible particles, they still consist of other subatomic particles. Students should know the constituent parts of the atom; reviewing the properties of protons, neutrons, and electrons will help students throughout this lab.
- To develop the background information for this lab, you may want to discuss with your students how people have inferred the existence of atoms—they are so small that we can only see them indirectly. What is the smallest thing that your students have seen? How small is that compared to the size of an atom? And how did Einstein's description of Brownian motion contribute to our understanding of the existence of atoms?

In this lab you will learn:

- how an atom changes when you add or remove subatomic particles to the atom;
- how to identify an atom through the number of subatomic particles it contains;
- how to determine the percent of isotopes present for various elements.

Activity 1: Pre-Assessment

1. **Answer the following questions in your notebook:** What happens to an atom when you add an additional proton to it? How about an additional electron?
2. **Answer the following question in your notebook:** Why is the number of electrons and protons in the atom typically equal?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 1: Subatomic Particles

Today, we know that atoms are not themselves fundamental particles, but consist of **electrons** bound to a nucleus containing **protons** and **neutrons**. Electrons and protons carry electric charge of equal magnitude but opposite signs. Figure 29.1 shows, in a simplified way, how the protons, neutrons, and electrons are arranged in an atom. Electrons are thought to be fundamental particles, but protons and neutrons are composite, consisting of smaller particles called *quarks* and force-carrier particles known as *gluons* that bind the quarks together. Nevertheless, we will treat protons and neutrons as fundamental particles during the course of this lab.

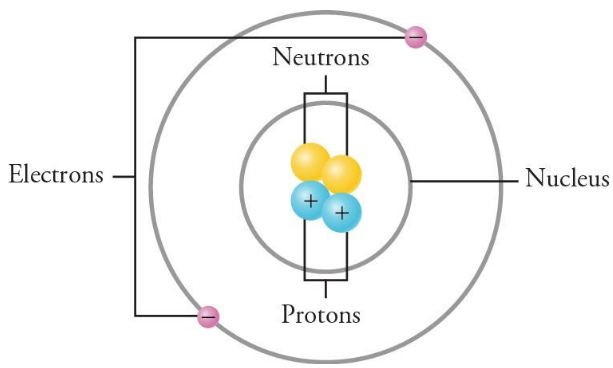


Figure 29.1: A simplified model of an atom (not to scale), showing negatively charged electrons orbiting a nucleus containing positively charged protons and neutral neutrons.

The masses of the proton and neutron are 1.673×10^{-27} kg and 1.675×10^{-27} kg, respectively, which are much larger than the electron mass of 9.110×10^{-31} kg. Atoms are usually measured in **atomic mass units (u)** instead of kilograms. One atomic mass unit (u) is approximately 1.66×10^{-27} kg, which gives the neutron and proton a mass of about 1 u each. In this activity, you will use a PhET simulation to investigate what happens to an atom when you add or take away subatomic particles.

For this activity you will need the following:

- A computer with internet access.

For this activity, you will work *individually or in pairs*.

Activity 1 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 1:

- Note that the atomic mass unit (u) is based on the mass of a carbon-12 atom, which is set as being equal to 12 atomic mass units. Provide students with a table of the ratio of the atomic mass to the mass number (i.e., the nucleon number, which measures the number of protons and neutrons in a nucleus). How do the atomic mass and the mass number relate?
- Note that there are only three particles that are relevant for this simulation: electrons, protons, and neutrons. Some students may be confused about where photons, gluons, or other particles come into play; either say that these other particles are irrelevant, or explain what roles these other particles have and how they do not contribute to charge or mass here (if you think this explanation will not cause additional confusion).
- For students who finish early, have them write a draft of a computer program that would tell you some set of properties about an atom (or ion) based on the number of protons, neutrons, and electrons it has. Ask students to detail the list of properties that they could provide and how these properties would be resolved.

The following are recommendations for the Guided Inquiry for Activity 1:

- To facilitate Step 1, you may need to note that electrons have a negative charge, protons a positive charge, and neutrons a neutral or no charge.
- To facilitate Step 2, you may find it helpful to demonstrate a specific atom, say, carbon-12. That is, a molecule with six protons, six neutrons, and six electrons. Demonstrate why this has a neutral charge by adding up the charges of its constituent parts.

Structured Inquiry

Step 1: Go to the PhET home page (https://phet.colorado.edu/en/simulations/category/physics) and click on the *Build an Atom* simulation.

Step 2: Hypothesize/Predict: What will happen if you add one electron to one atom? How would the mass of an atom change if you added an additional neutron? Create a table with your predictions of the total mass of the atom in atomic mass units and of the overall electric charge in units of the electron charge for the three different configurations above.

Step 3: Student-Led Planning: Use the *Build an Atom* simulation to build the different configurations mentioned in Step 2.

Step 4: Critical Analysis: Create a data table and record your results in it. Then compare your data to the predictions. How does the simulation compare to your predictions?

Guided Inquiry

Step 1: Hypothesize/Predict: How would the charge of the atom change if you added an additional electron? How about if you added a proton or a neutron?

Step 2: Student-Led Planning: Create atoms with varying numbers of electrons, protons, and neutrons. Determine the total charge in each case.

Step 3: Critical Analysis: What is the relationship among the number of protons, electrons, and neutrons in the atom to the total charge? Discuss your results with your group.

Assessments

1. The atomic number is determined by the number of ________ in the atom. [EK 1.A.4; SP 3]
2. A[n] ________ is an atom that contains a different number of protons than electrons.
3. Suppose an atom contains 10 protons. [EK 1.A.4; SP 3]
    a. How many electrons does this atom have for it to be electrically neutral?
    b. How many electrons does this atom have if the charge is equal to that of three protons?

[Solutions]

1. protons [EK 1.A.4; SP 3]
2. ion
3. [EK 1.A.4; SP 3]
    a. Protons have an electric charge that is equal in magnitude but of opposite sign as electrons, so there must be 10 electrons to cancel the positive charge of the 10 protons.
    b. If the overall charge is that of three protons, that means there are three more protons in the atom than electrons, so the total number of electrons is seven.

Activity 2: Pre-Assessment

1. **Answer the following question in your notebook:** How does the number of protons in an atom correspond to different elements?
2. **Answer the following question in your notebook:** How is the mass of a chemical element related to the mass of the protons and neutrons in the nucleus?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 2: Identifying Elements

Chemical elements are determined by the number of protons in a given atom, known as the **atomic number**. For example, hydrogen contains only one proton, whereas carbon contains six. To maintain charge neutrality, atoms usually contain the same number of electrons and protons. **Ions** are atoms that have a different number of electrons compared to protons. An illustration of a neutral atom and an ion are shown in Figure 29.2.

In this activity, you will use a PhET simulation to determine how to build an atom and identify that atom knowing only the number of subatomic particles.

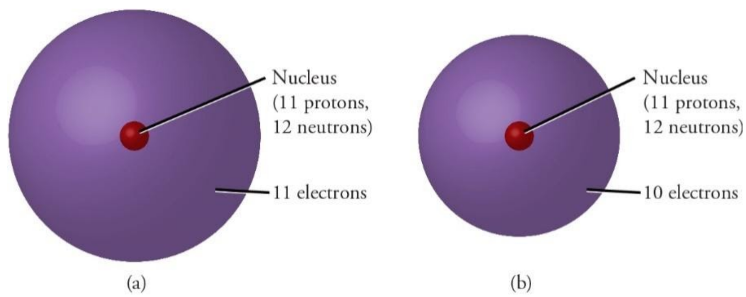


Figure 29.2: A neutral atom (left) and a positively charged ion (right).

For this activity, you will need the following:

- A computer with internet access.

For this activity, you will work *individually or in pairs*.

Activity 2 Instructor Preparation and Teaching Tips

The following are recommendations for Activity 2:

- Ions are often a confusing concept for students. Whenever you show examples, be sure to include examples that are positively charged and examples that are negatively charged, so that students do not think ions can only be positive or only negative.

- Students may be confused by how to identify atoms by their atomic number, that is, the number of protons they contain. The term *atomic mass units* often seems similar to *atomic number*, even though these are quite different concepts. Be sure to spend extra time demonstrating to students that the type of element for an atom or ion is determined by the number of protons it contains.
- To further build on Step 4 in this structured inquiry, ask students to consider a situation in which an ion has an extra electron. What would happen to the ion if it reacted with a bare proton (i.e., H^+)? Why does the ion not become a different element? If necessary, give the example of a negatively charged chlorine ion.

Structured Inquiry

Step 1: Go to the PhET home page (https://phet.colorado.edu/en/simulations/category/physics) and click on the *Build an Atom* simulation.
Step 2: Hypothesize/Predict: How will the number of protons, neutrons, and electrons in an atom change the chemical element? Which element contains two protons? How about five protons? What is the atomic mass of the first isotope of hydrogen? Consider a carbon atom (atomic number six) that contains eight electrons—what is the resulting charge? Record your predictions in a table.
Step 3: Student-Led Planning: Use the *Build an Atom* simulation to check your answers from Step 2.
Step 4: Critical Analysis: Does adding additional electrons while keeping the same number of protons and neutrons change the chemical element? How about adding additional neutrons?

Assessments

1. Chemical elements are defined by the number of ________ in the atom. [EK 1.A; SP 3]
2. How many electrons does a neutral carbon atom contain? [EK 1.A; SP 3]
3. Elements with different numbers of ________ than protons are called ions. [EK 1.A; SP 3]

[Solutions]

1. protons [EK 1.A; SP 3]
2. The atomic number of carbon is six because it contains six protons. To maintain charge neutrality, the number of protons and electrons must be equal, so there are six electrons in this atom. [EK 1.A; SP 3]
3. electrons [EK 1.A; SP 3]

Activity 3: Pre-Assessment

1. **Answer the following question in your notebook:** Do different isotopes of the same element have different electric charges?
2. **Answer the following question in your notebook:** What are the different types of radiation that come from unstable isotopes?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 3: Isotopes

Atoms of a given chemical species with different numbers of neutrons are known as **isotopes**. Each element can have several different isotopes. The atomic mass of a given element with *N* number of isotopes is determined by

$$\bar{m} = x_1 m_1 + x_2 m_2 + \cdots + x_N m_N,$$

where x_i corresponds to the relative abundance of the *i*th isotope of mass m_i. This is an example of a **weighted average**. Different isotopes can either be **stable**, meaning they do not undergo radioactive decay, or **unstable**, meaning they will transform into other elements or isotopes through radioactive decay. The radiation from such isotopes is in the form of *alpha particles* (helium nuclei), *beta particles* (high-energy electrons), or *gamma rays* (high-energy photons). As an isotope radiates, the number of the original isotope decreases. The **half-life** of an isotope is defined as the time it takes for half of the atoms to radioactively decay to another substance.

In this activity, you will use a PhET simulation to determine the percent of isotopes present for various elements.

For this activity you will need the following:

- A computer with internet access.

For this activity, you will work *individually or in pairs*.

Activity 3 Instructor Preparation and Teaching Tips

The following are recommendations for Activity 3:

- The notation for calculating a weighted average may be confusing, so an example might be helpful. Show students how to calculate the weighted average density for a ship's cargo if it is 10% iron and 90% wood, where iron's density is 7.87 g/cm^3 and wood's density is 0.75 g/cm^3.

- Students may think that adding more neutrons to an isotope will make it more stable, because more mass would lead to more gravitational force. However, you may need to inform students that the atomic nucleus is not held together by gravity but by the *strong force*. Note that the strong force is incredibly powerful over very short distances, but becomes weak as that distance increases.
- To further build on Assessment 2, have students research how we know the relative abundances for different isotopes. Ask them about whether isotopic ratios vary based on location and how this could be used.
- If students finish this lab early, ask them to explain why the periodic table is not defined in terms of the number of neutrons. Would there be advantages to having a periodic table based on neutrons? What would the disadvantages be?

Structured Inquiry

Step 1: Go to the PhET home page (https://phet.colorado.edu/en/simulations/category/chemistry) and click on the *Isotopes and Atomic Mass* simulation.

Step 2: Hypothesize/Predict: How will adding more neutrons to a stable isotope change it? Write your hypothesis in your notebook.

Step 3: Student-Led Planning: Use the *Isotopes and Atomic Mass* simulation to verify your prediction in Step 2.

Step 4: Critical Analysis: Determine the atomic masses of hydrogen, carbon, and oxygen using weighted averages.

Assessments

1. An isotope has a half-life of one year. How long will it take before the initial number of atoms is reduced by one quarter? [EK 1.A; SP 3]
2. Do stable or unstable isotopes contribute more to the atomic mass of a given element? [EK 1.A; SP 3]

[Solutions]

1. Two years. After one year, the initial concentration will be half of the original. After another year, it will be halved again, so that we end up with one quarter of the initial number. [EK 21.5b; SP 3]
2. Stable isotopes are more abundant, and thus contribute more in the weighted average to determine the atomic mass.

Lab 29: Models of the Hydrogen Atom

The Greek philosopher Democritus proposed the theory that if you keep dividing an object into smaller and smaller pieces, it will eventually become invisible. The smallest invisible piece that cannot be divided any more would be known as the *atom*, which means *indivisible*. By the nineteenth century, scientists had to devise methods to figure out the structure of the atom without being able to see one.

When a beam of light is passed through a transparent object (such as glass), the light can be seen on the other side of the object at almost the same level of brightness. If the object is translucent (such as a sheet of paper), only some of the light passes through, and the light on the other side of the object may not be as bright. When light is passed through atoms, the atoms behave like objects in some ways. When particles of light, called **photons**, strike an atom, they can pass through the atom, get absorbed by the atom, or bounce off the atom.

Instructor Introduction Notes

The following are recommendations for introducing this lab's background content to your students:

- Some students may not believe that simulations provide accurate information about the real world, but note that simulations are increasingly becoming a major source of scientific knowledge beyond theory and observation. To illustrate this, give examples of climate change models and astrophysical models.
- Students may recall some similarities to Rutherford's gold foil experiment. How does their simulation differ from Rutherford's gold foil experiment? How is it similar? You may want to have students compare and contrast the material being struck, the material being shot, the results, and the meanings of those results.
- To develop the background information for this lab, you may want to discuss with your students how they think atoms are structured. By now, they know the subatomic particles, but they likely do not know how these subatomic particles are structured or relate to each other within the atom. As students make descriptions of atomic structure, try to guide the discussion into the consequences of that model for this simulation.

In this lab you will learn:

- to use the PhET simulation model in Experiment mode to observe and record the behavior of the photons as they pass through the invisible hydrogen atom;
- to use the PhET simulation model in Prediction mode to observe and compare the behavior of photons for each of the different models as they pass through a visible hydrogen atom;
- to use the PhET simulation model to compare the ways that the results of the experiment were similar to or different from the prediction models.

Activity 1: Pre-Assessment

1. **Answer the following questions in your notebook:** What do you think will happen to a piece of cheese if you keep cutting it into smaller and smaller pieces? When the tiny pieces become smaller and smaller, and are so small that you can no longer see them with your own eye, what methods can you use to see the tiny pieces?
2. **Answer the following questions in your notebook:** What do you know about atoms? What are atoms made of? What are the components of a hydrogen atom?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 1: Observing and Recording the Behavior of Photons

In this lab, you will use a PhET simulation model developed by the University of Colorado to visualize the different models of the hydrogen atom that have been developed, based on what happens to the photons as they hit the atom. To be able to access the simulations, you need a computer with an internet connection. You will need to register and log in to the *Models of the Hydrogen Atom* simulation at this website: https://phet.colorado.edu/en/simulation/hydrogen-atom.

Safety Precautions

- Get help to register for an account and log in to the PhET simulation site.
- Be careful when handling electronic devices such as a computer, keyboard, and computer mouse.

For this activity you will need the following:

- Access to a computer with internet connection
- Access to the PhET simulation lab for models of the hydrogen atom (https://phet.colorado.edu/en/simulation/hydrogen-atom)
- A stopwatch or clock to time the simulations

For this activity, you will work either *individually or in pairs*.

Activity 1 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 1:

- After Step 1 of the Structured Inquiry, it may be helpful to revisit students' thoughts on what happens in each of the situations listed. Lead a discussion about what happens to the individual photons as they pass through a solid piece of wood, glass, and thin sheets of paper. Be sure that someone mentions that the photons are absorbed and then re-emitted in some cases.
- The color of a photon is related to its wavelength, the amount of energy it carries, and its frequency. Ask students to consider how these properties might affect what happens when the photon strikes the invisible hydrogen atom in the box.

- To build on Assessment 3, have students describe what is happening between the photon and the atom for each behavior they listed. Note that it is okay if they do not know, and explain that this is merely for them to develop some working hypotheses.

The following are recommendations for Guided Inquiry for Activity 1:

- To facilitate Step 1, you may need to have students draw the paths that photons take in each step, and compare these to the possibilities for photons interacting with a hydrogen atom.
- To facilitate Step 2, remind students that the color of a photon is related to its wavelength, the amount of energy it carries, and its frequency. Ask students to consider how these properties might affect what happens when the photon strikes the invisible hydrogen atom in the box.

Structured Inquiry

Step 1: Hypothesize/Predict: What happens to a beam of light as it passes through different materials? For example, what would happen when a beam of light is passed through a solid piece of wood? What if the wood is replaced with glass or thin sheets of paper? Write down your predictions in your notebook.

Step 2: Student-Led Planning: Download the PhET simulation applet on your computer and learn how the applet works. In Experiment mode, learn how to (1) start and stop the experiment, (2) slow down and speed up the experiment, and (3) use the spectrometer to count the number and color of photons that are deflected.

Step 3: Conduct the experiment in two phases, as described below.

Phase 1: Run the experiment in slow mode. Make the following observations in your notebook:

- What happens to most of the photons as they hit the invisible hydrogen atom in the box?
- Do all of the photons come out of the box containing the invisible hydrogen atom, or do some of the photons go missing?
- What do you notice, if anything, about the color of the photons that hit the invisible hydrogen atom?
- Do all of the photons that come out of the box behave the same way? If not, what differences do you observe in the way they emerge from the box containing the invisible hydrogen atom?

Phase 2: Run the experiment in slow mode. Activate the spectrometer to record the number and color of the photons that are deflected. Run the experiment for one minute and record the results in your notebook. Repeat the experiment to complete three trials. Create a data table similar to the one below and record your results.

Behavior of Photons	Observations
Number bouncing off	
Number passing through	
Number missing	
Number changing color	
Number passing through with change in direction	
Other observations	

Step 4: Critical Analysis: Analyze the results from your data table. Why do you think the photons were deflected or bounced back? Were the predictions you made in Step 2 supported by your data? Why or why not? What did you notice about the behavior of the photons that you had not considered earlier?

Guided Inquiry

Step 1: Hypothesize/Predict: What do you know about transparent, translucent, and opaque objects? What happens when a beam of light is passed through (1) wood, (2) glass, and (3) a sheet of white paper? Given that a hydrogen atom behaves like an object and that atoms only absorb photons that have the right amount of energy, what are all the different ways in which a photon can behave when it strikes a hydrogen atom?

Step 2: Student-Led Planning: Download and run the PhET simulation lab for *Models of the Hydrogen Atom* at https://phet.colorado.edu/en/simulation/hydrogen-atom. Run the simulation in Experiment mode to study the behavior of the photons as they hit the invisible hydrogen atom inside the box. Run the simulation at different speeds and for different times, and record the results. Decide the speeds and the times at which to run the simulation. Use the spectrometer to record the number and color of the photons, and their behavior. Tabulate the results and analyze what the differences are when the speed and times are different.

Step 3: Critical Analysis: What did you learn about the behavior of the photons as they encountered the hydrogen atom in their path? What percentage of the photons bounced off the atom? What percentage changed direction? What did you learn about how different speeds affected the behavior of the photons? What did you learn about how the different times affected the behavior of the photons?

Assessments

1. A student finds that in the PhET simulation of the hydrogen atom, in Experiment mode, all the photons passed through. [1.A.4.1; SP 1.1, 7.1]
    a. Is this a correct observation? Why or why not?
    b. What do most of the photons do as they hit the hydrogen atom?
2. An atom will absorb a photon only if ________. [1.A.4.1; SP 1.1, 7.1]
3. In the PhET simulation of the hydrogen atom in Experiment mode, what are the different behaviors exhibited by the photons as they hit the invisible hydrogen atom inside the box? [1.A.4.1; SP 1.1, 7.1]

[Solutions]

1. [1.A.4.1; SP 1.1, 7.1]
    a. No, this is not a correct observation. When photons hit the hydrogen atom, at least some of them do not pass through.
    b. As the photons hit the hydrogen atom, most of the photons appear to pass through the hydrogen atom without any change in behavior.
2. [1.A.4.1; SP 1.1, 7.1] It has the right amount of energy.
3. [1.A.4.1; SP 1.1, 7.1] The different behaviors exhibited by the photons are that they (1) pass through with no change in direction, (2) pass through with a change in direction, (3) bounce back, (4) disappear, and (5) change color.

Activity 2: Pre-Assessment

1. **Answer the following question in your notebook:** In the PhET simulation of the hydrogen atom, what can you say about the structure of the hydrogen atom based on the behavior of the photons?
2. **Answer the following question in your notebook:** What do you know about the different models of the hydrogen atom?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 2: Observing the Behavior of Photons As They Pass Through a Visible Hydrogen Atom

Over the years, various scientists developed different models for the hydrogen atom by passing light through the invisible atom and studying the resulting patterns. Indeed, a model or mental picture is needed to explain the atom, which is too small to be directly observed with visible light. For example, in the late 1800s, Lord Ernest Rutherford discovered, through experimentation, the size and mass of the atomic nucleus, as well as the mass of electrons. His results led him to propose the planetary model of the atom, where low-mass electrons orbit a high-mass nucleus. This model is analogous to how low-mass planets in our solar system orbit the large-mass Sun at large distances. In the atom, the attractive **Coulomb force** is analogous to the gravitational force in the planetary system.

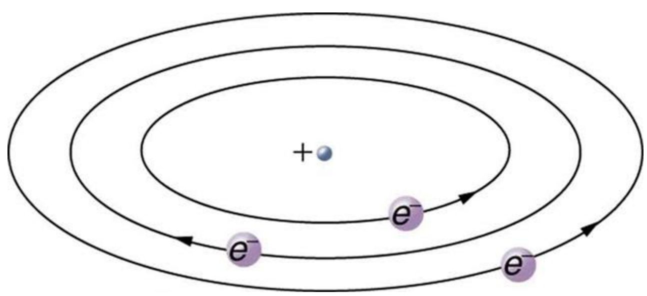


Figure 30.1: Rutherford's planetary model of the atom incorporates the characteristics of the nucleus and electrons, as well as the size of the atom. This model was the first to recognize the structure of atoms, in which low-mass electrons orbit a very small, massive nucleus in orbits much larger than the nucleus. The atom is mostly empty and is analogous to our planetary system.

Throughout history, there have been many models of the atom, each evolving as more details about the atom were discovered. As a result, different models of the atoms have different assumptions about how the atom is structured and works. In this activity, you will explore how the various assumptions of six different atomic models change the results of the *Models of the Hydrogen Atom* PhET simulation.

Safety Precautions

- Get help to register for an account and log in to the PhET simulation site.
- Be careful when handling electronic devices such as a computer, keyboard, and computer mouse.

For this activity you will need the following:

- Access to a computer with an internet connection
- Access to the PhET simulation lab for models of the hydrogen atom https://phet.colorado.edu/en/simulation/hydrogen-atom
- Stopwatch or clock to time the simulations

For this activity, you will work either *individually or in pairs*.

Activity 2 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 2:

- To introduce this activity, introduce students to the different models of the hydrogen atom. It will be helpful to provide a historical perspective along with the experiments that led to the updated understanding, and thus, the new model.
- To introduce de Broglie and Schrödinger's models, you may end up getting bogged down explaining quantum theories that are difficult concepts for students. To simplify matters, it may be best to note that de Broglie's model explains the *why* of Bohr's orbits (in terms of standing waves) and that the electrons occupy these orbits statistically, instead of being in a particular location in an orbit, and Schrödinger's model describes the probability that an electron will be at a particular location, which defines more of a set of clouds than a set of possible orbits.

The following are recommendations for the Guided Inquiry for Activity 2:

- To introduce this activity, introduce students to the different models of the hydrogen atom. It will be helpful to provide a historical perspective along with the experiments that led to the updated understanding and thereby the new model.
- To introduce de Broglie and Schrodinger's models, you may end up getting bogged down in quantum concepts that are difficult for students. To simplify matters, it may be best to note that de Broglie's model explains the why of Bohr's orbits (in terms of standing waves) and that the electrons occupy these orbits statistically instead of being in a particular location in an orbit, and Schrodinger's model describes the probability that an electron will be in a particular location, which defines more of a set of clouds than a set of possible orbits.

- To build on Step 3 of the guided inquiry, you could ask students to classify each model based on certain observed properties. Specifically, have students answer the following questions. Which properties are relevant for classifying models? Which models are roughly similar? Which models should be in a class by themselves? This should help students to better differentiate between the models and improve their observation skills.

Structured Inquiry

Step 1: Hypothesize/Predict: Download the PhET simulation applet on your computer and learn how the applet works. What are the different models of the hydrogen atom used in the simulation? How do you think the photons will behave in each of the different models?

Step 2: Student-Led Planning: In Prediction mode, learn how to run the simulations for the different models of the hydrogen atom.

Conduct the experiment in two phases, as described below. For each phase, run all six models in the simulation: (1) Billiard Ball, (2) Plum Pudding, (3) Solar System, (4) Bohr, (5) de Broglie, and (6) Schrödinger.

Phase 1: Run the experiment in slow mode. Make the following observations in your notebook:

- What happens to most of the photons as they hit the hydrogen atom in the model?
- Do all of the photons come out of the hydrogen model, or do some of the photons go missing?
- What do you notice, if anything, about the color of the photons that strike the hydrogen atom?
- Do all of the photons that come out of the box behave the same way? If not, what differences did you observe in the way they emerge after hitting the hydrogen atom?

Phase 2: Run the experiment in slow mode. Activate the spectrometer to record the number and color of the photons that are deflected. Run the experiment for one minute, and record the results in your notebook. Repeat the experiment to complete three trials. Create a data table similar to the one below, for all six models in the simulation, and record your results.

Billiard Ball Model	**Observations**
Number bouncing off	
Number passing through	
Number missing	
Number changing color	
Number passing through with change in direction	
Other observations	

Step 3: Critical Analysis: Analyze the results from your data table. What did you notice about the behavior of the photons in the different models? Were the predictions you made in Step 2 supported by your data? Why or why not? What did you notice about the differences or similarities between the Plum Pudding model and the Bohr model?

Guided Inquiry

Step 1: Hypothesize/Predict: What do you know about the different hydrogen models? What do you think will be the similarities or differences in the behavior of the photons between the different models in the PhET simulation?

Step 2: Student-Led Planning: Download and run the PhET simulation lab for *Models of the Hydrogen Atom* at https://phet.colorado.edu/en/simulation/hydrogen-atom. Run the simulation in Prediction mode for all six models in the simulation to study the behavior of the photons as they strike the hydrogen atom. Run the simulation at different speeds and for different times, and record the results. Do you notice any difference between the hydrogen models based on speed? Do you notice any difference between the hydrogen models based on time? Use the spectrometer to record the number and color of the photons and their behavior.

Step 3: Critical Analysis: What did you learn about the different models as the photons hit the hydrogen atom? What were the biggest differences between the models? What were the similarities? What other unexpected behavior did you notice?

Assessments

1. In the Bohr model, what happens to an electron when it is hit by a photon of the right energy? [7.C.1.1; SP 1.4]
2. What is one difference in the behavior of photons between the Plum Pudding and Billiard Ball models? [7.C.1.1; SP 1.4]
3. What is interesting about the travel path of electrons in the Solar System model of the hydrogen atom? [7.C.1.1; SP 1.4]

[Solutions]

1. [7.C.1.1; SP 1.4] In the Bohr model, the electron orbits the nucleus and can be bumped to a higher level when hit with a photon of the right energy.
2. [7.C.1.1; SP 1.4] In the Plum Pudding model, some of the photons go through the hydrogen atom. In the Billiard Ball model, no photons go through the hydrogen atom.
3. [7.C.1.1; SP 1.4] In the Solar System model, the electron orbits a nucleus, but it loses energy and spirals inward, collapsing into the nucleus.

Activity 3: Pre-Assessment

1. **Answer the following question in your notebook:** In the PhET simulation of the *Models of the Hydrogen Atom*, what can you say about the differences in the behavior of the photons in Experiment mode versus Prediction mode?
2. **Answer the following question in your notebook:** Why do you think the results from the Experiment mode may or may not be different from the results from the Prediction mode for the different models of the hydrogen atom?
3. **Discuss the answers to questions 1 and 2 with the class.**

Activity 3: Using the PhET Simulation Model to Compare Results

The PhET simulation model works by modeling the passage of photons through the hydrogen atom. The simulation has two modes: the Experiment mode and the Prediction mode. In the Experiment mode, the hydrogen atom is invisible, and you can observe how the photons behave as each photon hits the hydrogen atom. In the Prediction mode, the hydrogen atom is visible, and you can compare each model of the hydrogen atom to your results from the Experiment mode to understand the similarities and the differences between the models. In this activity, you will observe the differences between the Experiment and Prediction modes of the hydrogen atom in the PhET simulation.

Safety Precautions

- Get help to register for an account and log in to the PhET simulation site.
- Be careful when handling electronic devices such as a computer, keyboards, and computer mouse.

For this activity you will need the following:

- Access to a computer with an internet connection
- Access to the PhET simulation lab for *Models of the Hydrogen Atom* (https://phet.colorado.edu/en/simulation/hydrogen-atom).
- Stopwatch or clock to time the simulations

For this activity, you will work either *individually or in pairs*.

Activity 3 Instructor Preparation and Teaching Tips

The following are recommendations for the Structured Inquiry for Activity 3:

- You will likely find it helpful to demonstrate the difference between the Experiment and Prediction modes. Explain that the Experiment mode provides data as if the model was a real situation, whereas the Prediction mode only provides data as if the model was reality.

- You may want to note that as students use more recent models, they should find that the observations match better to the experimental results, but that the improvements from one model to the next are noticeably smaller. Ask students to consider why this might be the case.
- For students who finish early, have them describe the model that best matches the Experiment mode results. Have them describe what improvements can/should be made to that model, if any.

The following are recommendations for the Guided Inquiry for Activity 3:

- To facilitate Step 1, it may be helpful to describe the difference between the Experiment and Prediction modes. Explain that the Experiment mode provides data as if it were a real situation, whereas the Prediction mode only provides data as if the model were reality.
- To further facilitate Step 1, review each model and have the class make predictions about what each model will do. Specifically, have them hypothesize exactly how the photons will interact with that model. As they consider each model, encourage them to note their expected differences between each model.

Structured Inquiry

Step 1: Hypothesize/Predict: In the PhET simulation, what are the differences between the Experiment mode and the Prediction mode for each of the different hydrogen atom models?

Step 2: Student-Led Planning: Download the PhET simulation applet on your computer and learn how the applet works. First, run the simulations at slow speed in Experiment mode. Then run the simulations in slow speed in Prediction mode for each of the six hydrogen atom models. For each model, record the differences in the behavior of the photons between the Experiment mode and the Prediction mode. Create a data table similar to the sample below, and record your results.

Model 1—Billiard Ball Model

	Experiment Mode Observations	**Prediction Mode Observations**
Number bouncing off		
Number passing through		
Number missing		
Number changing color		
Number passing through with change in direction		
Other observations		

Step 3: Critical Analysis: Analyze the results from your data table. What did you notice about the behavior of the photons in the different models in the Experiment mode versus the Prediction mode? Were the predictions you made in Step 1 supported by your data? Why or why not?

Guided Inquiry

Step 1: Hypothesize/Predict: In the PhET simulation, do you think there will be a difference between the behavior of the photons in the Experimental mode versus the Prediction mode for each of the different hydrogen atom models? Why or why not?

Step 2: Student-led Planning: Download and run the PhET simulation lab for *Models of the Hydrogen Atom* at https://phet.colorado.edu/en/simulation/hydrogen-atom. First, run the simulation in Experiment mode and record the results. Then run the simulation in Prediction mode (for the same speed and times) for all six models in the simulation, and record the results for each of the six different hydrogen atom models. Use the spectrometer to record the number and color of the photons, and their behavior.

Step 3: Critical Analysis: What did you learn about the differences in the Prediction mode for the different models as the photons hit the hydrogen atom as compared with the Experiment mode? What were the biggest differences between the models? What were the similarities? What other unexpected behavior did you notice?

Assessments

1. What do you notice about most of the red photons in the Experiment mode versus the Billiard Ball model? [1.A.4.1; 7.C.1.1; SP 1.1, 7.1; SP 1.4]
2. What is one difference in the Experiment mode versus the Billiard Ball model? [1.A.4.1; 7.C.1.1; SP 1.1, 7.1; SP 1.4]
3. What is one difference in the Experiment mode versus the Solar System model? [1.A.4.1; 7.C.1.1; SP 1.1, 7.1; SP 1.4]

[Solutions]

1. [1.A.4.1; 7.C.1.1; SP 1.1, 7.1; SP 1.4] In the Experiment mode, most of the red photons go through. In the Billiard Ball model, many more of the red photons bounce back.
2. [1.A.4.1; 7.C.1.1; SP 1.1, 7.1; SP 1.4] In the Billiard Ball model, there are more deflections in the gray photons.
3. [1.A.4.1; 7.C.1.1; SP 1.1, 7.1; SP 1.4] In the Solar System model, all photons appear to pass through with none bouncing back.