Lab Manual - Student Edition

College Physics 2e.

for AP® Courses

College Physics for AP® Courses Lab Manual
Student Version

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This content was originally authored through a collaboration with the Texas Education Agency (TEA). It is presented here with modifications, including updates to align with the 2019 Course and Exam Description for AP Physics. These resources are available to all verified instructors free of charge at the following hyperlink: https://openstax.org/details/books/college-physics-ap-courses?Instructor%20resources.

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 yourself to learn through self-discovery. Instead of simply presenting you with facts to memorize, this manual encourages you to ask questions about the material that you will then answer through your 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 are likely familiar with more physics topics than you realize! The pre-assessment questions are meant to tap into 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 a 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 you 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, which are questions or predictions about what will happen during an 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 will plan how to properly conduct your experiment. 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 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 not supported 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 your findings. Therefore, you will be required to design your 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 definitions 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, before the lab starts, ask your teacher about any concepts of which you are unsure.

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 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 needed to successfully carry out and understand the activities. As with the main introduction, please read these introductions carefully before your lab period. Then, before the lab starts, ask your teacher about any concepts of which you are unsure.

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.

College Board® (CB) Standard Alignment:

College Board® standards are summarized in a table format at the beginning of each lab. The College Board's® AP Physics Course and Exam Description was used to provide this information.
In addition, standards tags are found on the assessments, allowing you to quickly identify which standard is addressed by each question.

Lab 1:
Graphing Motion

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. 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

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

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.

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.

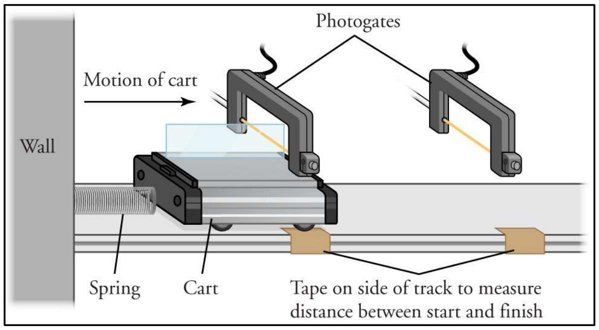


Figure 1.1: The speed of the cart can be measured by using the spring to launch the cart from the wall and then measuring how long the cart takes to travel a fixed distance. This can be done either by having it pass through two photogate timers or by using a stopwatch to measure the time of travel between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

Activity 2: Pre-Assessment

1. What does it mean for an object to travel at constant acceleration? How could you set an object in motion at constant acceleration?
2. 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.

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 1.2 Create a data table in your notebook to record the distance and time for the cart's motion.

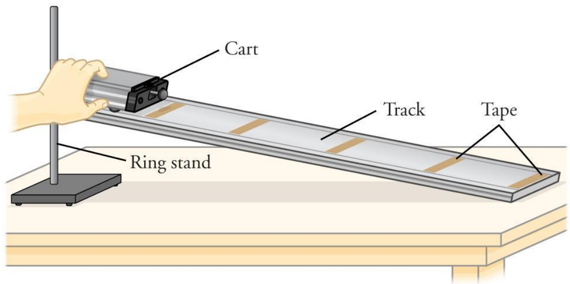


Figure 1.2: A cart that is free to move on an incline will accelerate and will have different velocities at different locations.

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.
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?
   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?

Activity 3: Graph Matching

A position or velocity versus time graph can tell you about the motion of an object. Figure 1.3 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.

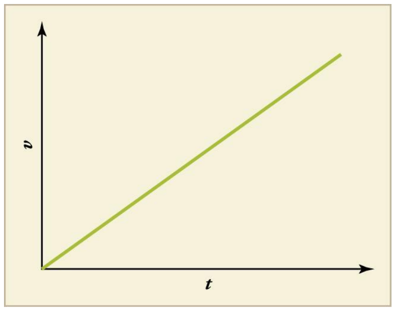


Figure 1.3: An object speeding up with constant acceleration has a straight-line velocity versus time graph.

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.

Structured Inquiry

Step 1: Hypothesize/Predict: Look at the graphs in Figure 1.4. 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?

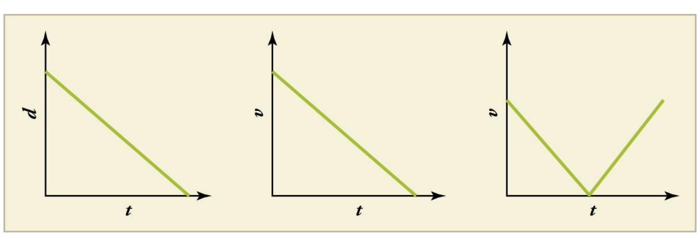


Figure 1.4: Position and velocity versus time graphs describe an object's motion.

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.
   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?
3. Two velocity versus time graphs have the same shape, but their *y*-intercepts are different.
   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?

Lab 2:
Projectile Motion

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. 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. 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*.

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.
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.

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*.

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.
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?
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.

Lab 3:
Newton's 2nd Law

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

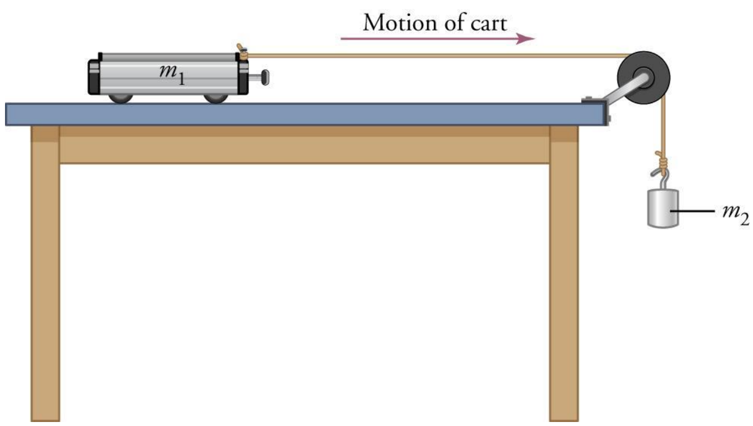


Figure 3.1: The cart of mass m_1 accelerates along the table. Rate of acceleration is directly proportional to mass m^2.

1. 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 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. 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*.

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

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?
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?

Lab 4:
Forces

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. 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. 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*.

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.

Activity 2: Pre-Assessment

1. When you push an object up an inclined plane, what forces seem to be acting on it? Why?
2. 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.

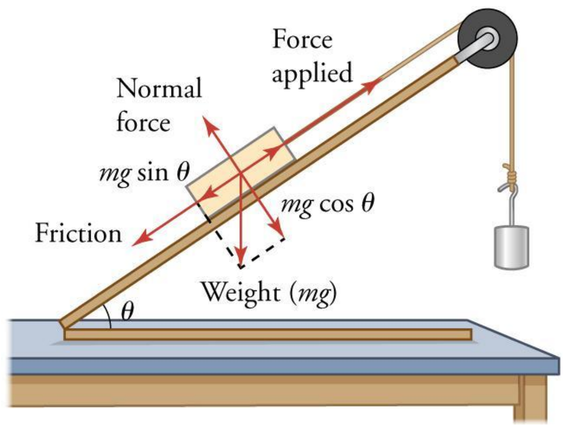


Figure 4.1: Lab model of a cart being pulled up a hill.

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*.

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, $v_f = 2v_{ave}$. 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.
    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.
3. An object is pushed up an inclined plane.
4. Name the forces that are exerted on the object.
5. Calculate each of the forces exerted on your cart that you gave to answer the previous question.

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 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.
    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.
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.
    a. Does the object experience static friction? When?
    b. Does the object experience kinetic friction? When?

Lab 5:
Circular Motion

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. 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. 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*.

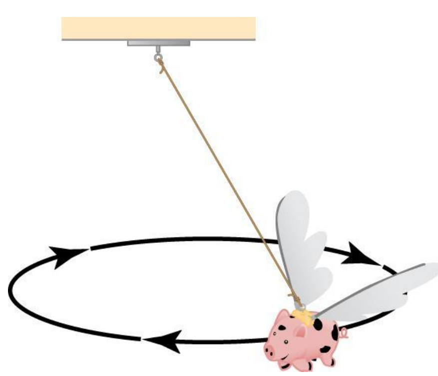


Figure 5.1: The flying pig rotates in a circular path.

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 increased the angular speed (in revolutions per second) of the flying pig? How about if you changed the length of the string but kept 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.
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?
3. (a) Why were you unable to measure centripetal acceleration directly?
4. (b) What measurements enabled you to calculate centripetal acceleration? What intermediate calculations did you have to carry out to calculate centripetal acceleration?

Activity 2 Pre-Assessment

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 5.2 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*.

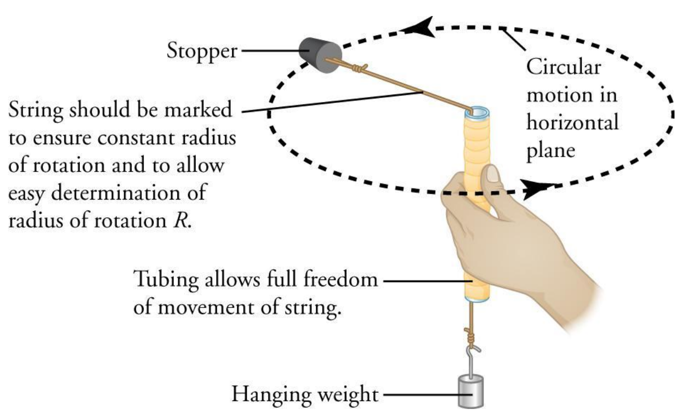


Figure 5.2: The weight hanging from the string provides the centripetal force that causes the motion of the stopper to be circular.

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.

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: In your notebook, 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, and write it in your notebook.

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? Do 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?
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?
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?

Lab 6:
Hooke's Law and Spring Energy

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. 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. 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*.

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 unstrained spring and record that in your notebook. Set up your experiment as shown in the diagram. (Figure 6.1)

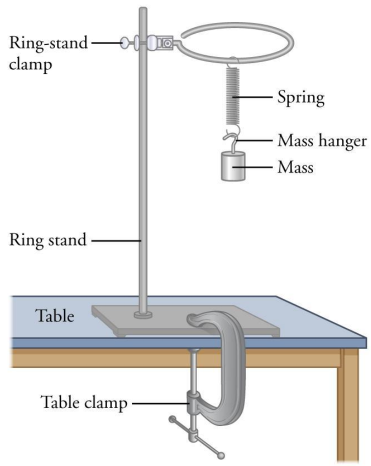


Figure 6.1: An experimental setup to investigate whether the spring obeys Hooke's law.

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.

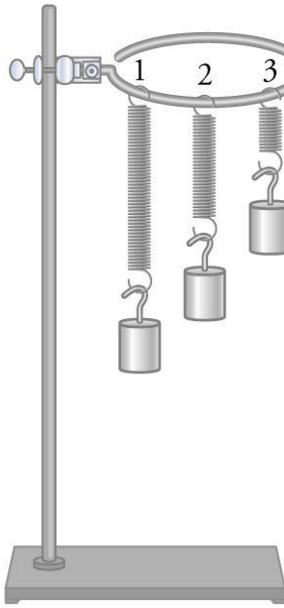
Step 2: Student-Led Planning: How can you alter your procedure to test your hypothesis in step 1? What information will you collect, and how will you display your experimental data? Write your ideas in your notebook.

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.



   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.

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 6.2 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.

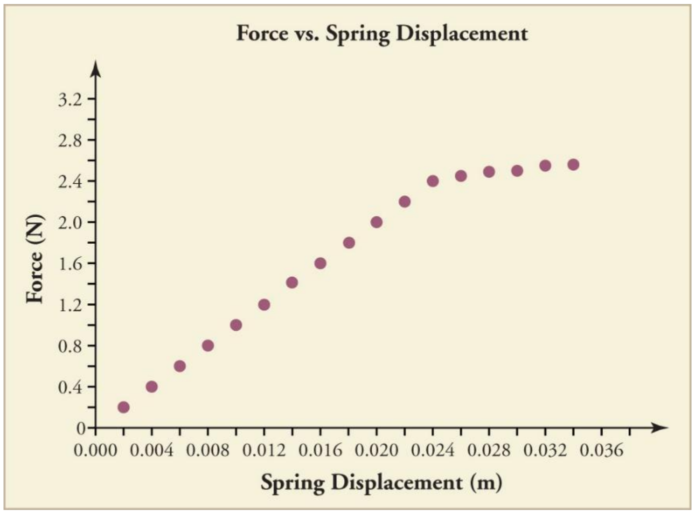


Figure 6.2: Force exerted on a spring as a function of how it is stretched.

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?

Activity 2: Pre-Assessment

1. 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. 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

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.*

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 6.3. For each trial, you should be able to compress and release the spring to propel the cart up the incline.

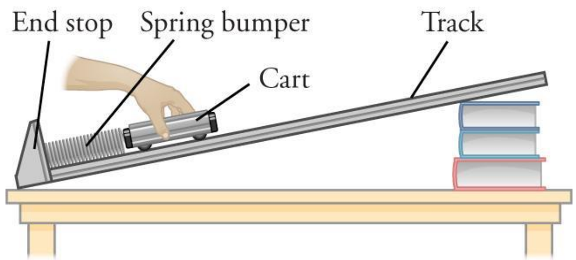


Figure 6.3: The setup for this experiment should allow you to propel the cart up the incline.

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.
   a. In Figure 6.4, draw the cart in its highest position on each ramp.
   b. Provide an explanation for your drawings.

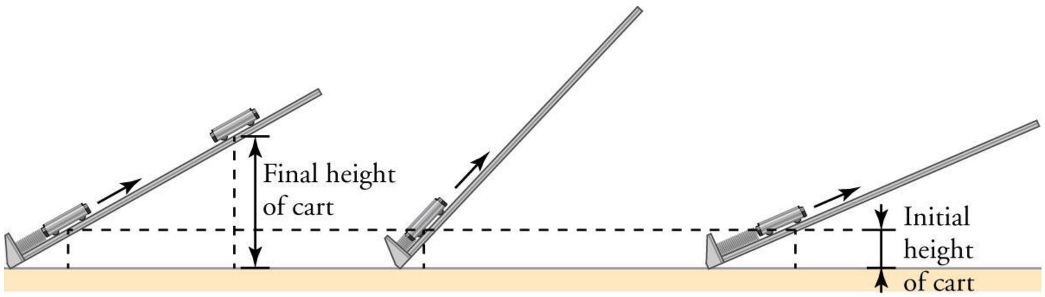


Figure 6.4: Three ramps with different slopes.

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.
   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 6.5.

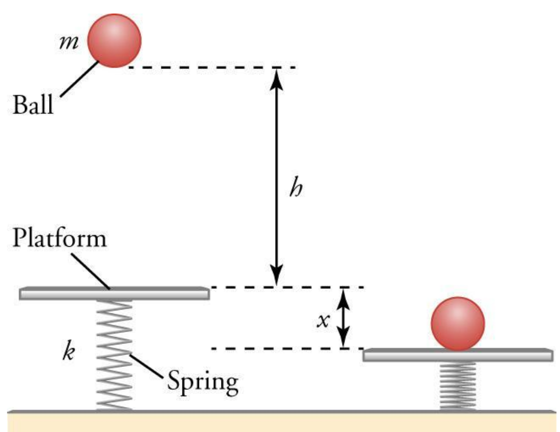


Figure 6.5

   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.

Lab 7:
Impulse and Momentum

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. 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. 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*.

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.

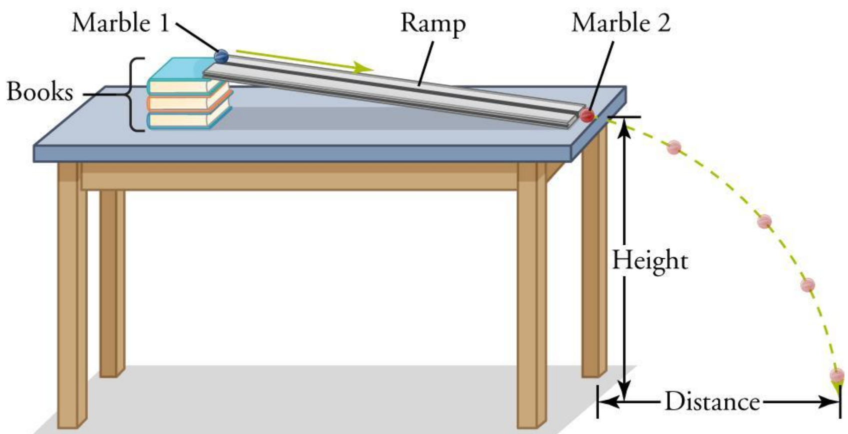


Figure 7.1: The setup shown will allow you to control the side-to-side movement of the marble and the initial energy of the system. Be sure to use more or fewer books to adjust the height in your own setup.

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: $v_{1i} = 10.0 \text{ m/s}, v_{2i} = 0, v_{1f} = 5.0 \text{ m/s}, v_{1f} = 5.0 \text{ m/s}$
   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?
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?

Activity 2: Pre-Assessment

1. 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. 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.

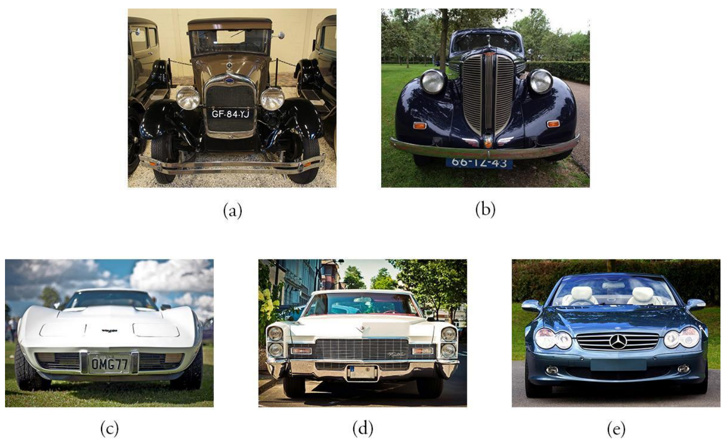


Figure 7.2: Car bumpers have changed over time and come in many shapes, styles, and materials.

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*.

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?
2. What aspect(s) of a collision are modern bumpers designed to change to reduce the impulse felt?
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?

Lab 8:
Conservation of Momentum

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. 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. 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*.

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.

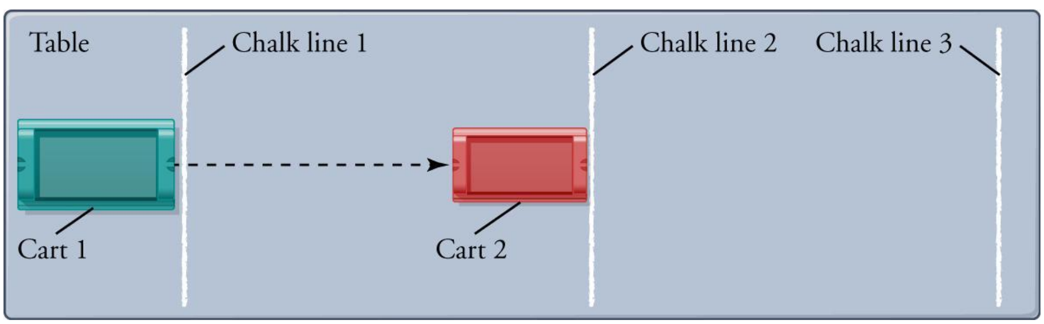


Figure 8.1: Arrangement for using stopwatches to measure the velocities and momenta of a more massive cart colliding elastically with a less massive cart.

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 moment 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:
   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?
3. In an elastic collision, the total momentum of two objects before the collision is $20\ \text{g} \cdot \text{cm/s}$. The mass of the first object is 2.0 g, and its velocity is $5.0\ \text{cm/s}$ after the collision.
   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?

Activity 2: Pre-Assessment

1. 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. 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*.

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.

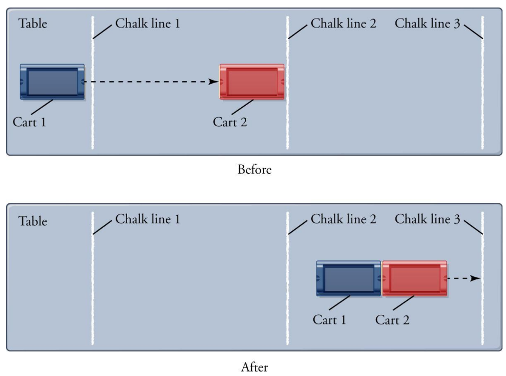


Figure 8.2: Arrangement for using stopwatches to measure the velocities and momenta of two carts undergoing a perfectly inelastic collision.

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 $\boldsymbol{v}_{\mathbf{1i}}$ 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: 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,
    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?
3. In an inelastic collision, where a ball hits a wall, the total momentum of the ball before the collision is $10\ \mathrm{g \cdot cm/s}$.
    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?

Lab 9:
Simple Harmonic Motion

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. What properties of a simple pendulum might possibly determine the period of the pendulum oscillations?
2. 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.*

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.
    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?
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.
    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?

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. How is the value of *g* related to the period of a simple pendulum?
2. 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*.

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.
    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*?
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?

Lab 10:
Rotational Motion

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. Why is the movement of a lever on its fulcrum (in Figure 10.1) 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. 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 10.1. 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.

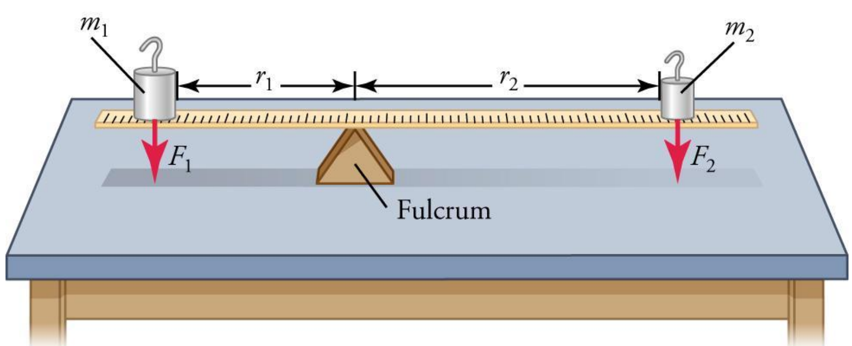


Figure 10.1: The weight of mass produces a torque tending to rotate the lever clockwise. The torque has magnitude $\tau = rF$ and is given a plus sign if it is twisting counterclockwise and a minus sign for twisting clockwise.

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*.

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 $\tau_2 = r_2 F_2$ clockwise and $\tau_1 = r_1 F_1$ 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 10.1. 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 acing 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.
2. Explain how the different masses you investigated in Activity 2 affected the torque that they produced on the lever.
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?
    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?

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*.

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.

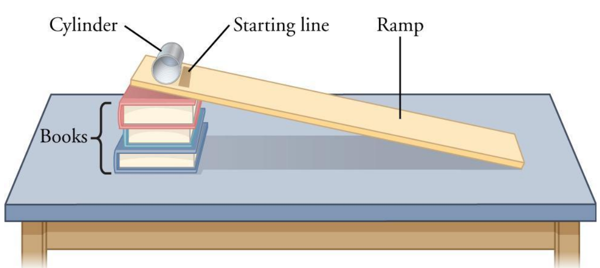


Figure 10.2: Place one end of the plank on a stack of books to create a ramp. Place a cylinder at the top of the ramp and mark a starting line where you will release the cylinder.

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.

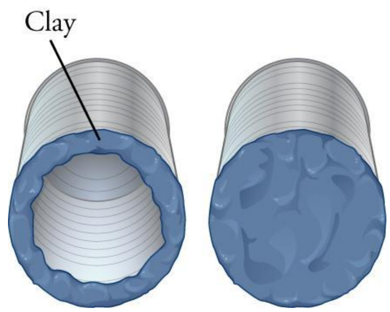


Figure 10.3: Place clay inside the cylinders in a variety of ways to create cylinders with different moments of inertia.

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.
2. Explain how the acceleration of each rotating cylinder was affected by its moment of inertia.
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?

Lab 11:
Mechanical Waves

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. 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. 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*.

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?
2. In what direction do transverse waves oscillate relative to the direction that the wave travels? How about longitudinal waves?

Activity 2: Pre-Assessment

1. How will two or more waves interact with each other?
2. 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

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*.

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?
2. When two waves pass through a region where they overlap, how is the resulting wave related to the two waves?
3. How is the amplitude of the reflected wave related to the amplitude of the incident wave?

Lab 12:
Sound Waves

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. 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. 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.

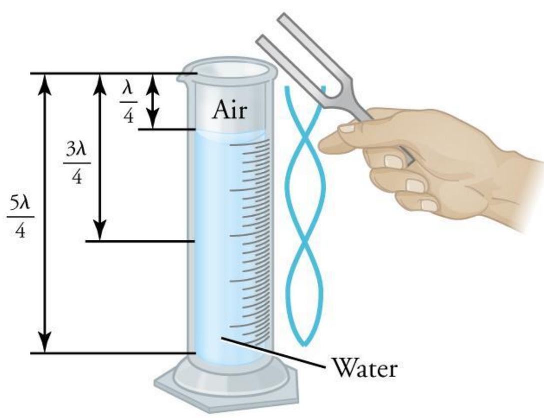


Figure 12.1: Resonances occur when the length of the column of air above the water is the correct multiple of the wavelength.

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*.

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.
   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?
3. Describe why the closed tube resonates at ¼ of the wavelength. Use a diagram to help your explanation.

Lab 13: Electrostatics

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. 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. 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 of 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.

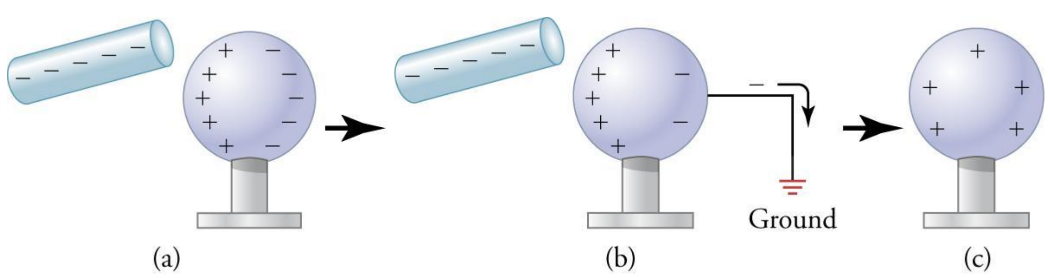


Figure 13.1: Charging by induction. (a) A charged object near the conductor redistributes charge. (b) Grounding allows charge to leave the conductor. (c) Removing the ground leaves an overall excess charge, and removing the charged object allows the excess charge to spread out evenly.

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.

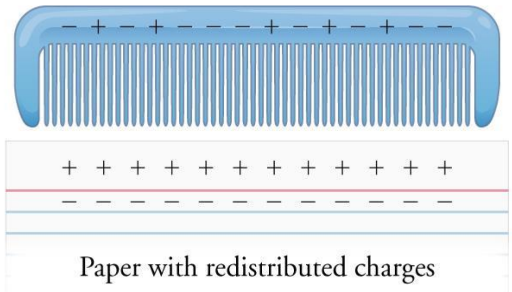


Figure 13.2: The charges in the atoms and molecules of a piece of neutral paper stay slightly closer to the opposite charges on the comb, producing an electric attraction.

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*.

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.

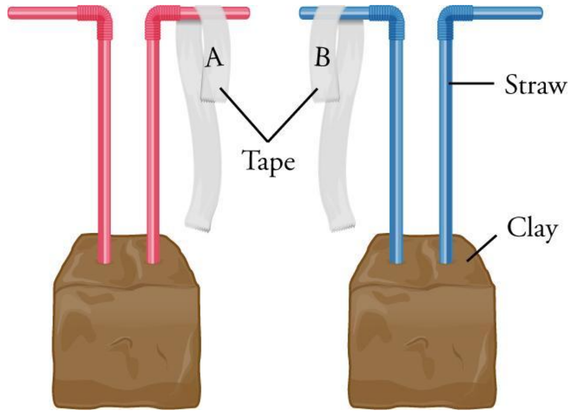


Figure 13.3: The first two charged pieces of tape are placed on the straw arms.

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 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?
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.
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.
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.
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?

Activity 2 Pre-Assessment

1. 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. 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

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

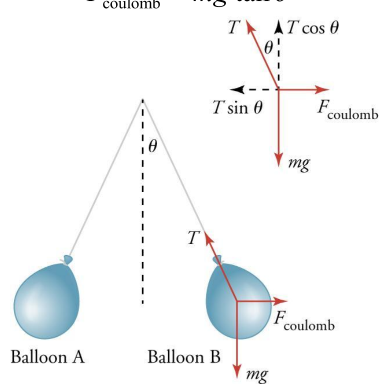


Figure 13.4: The electrostatic force between two charged balloons can be observed and measured.

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.*

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. 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.
    c. How much electrostatic force do the two objects exert on each other after they're moved closer together?
    d. Explain the mathematical reasoning you used to obtain your answer. [

Lab 14:
Ohm’s Law

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. 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. 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.

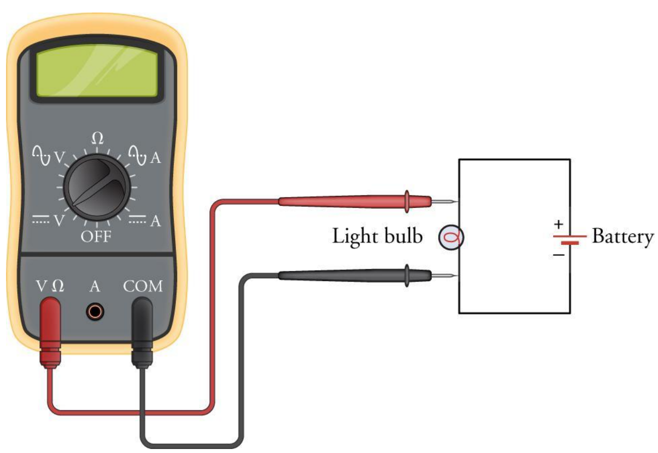


Figure 14.1: A multimeter used as a voltmeter to measure electrical potential through a circuit. This multimeter measures voltage (V) and electrical resistance (Ω) using the same wire port. However, the dial is set to measure voltage.

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.

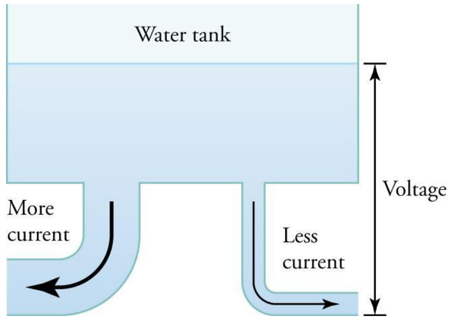


Figure 14.2: The equal water pressure (hydrostatic pressure) at both pipe openings is analogous to the same voltage across two conductors. The pipe width is analogous to the reciprocal of resistance (wider pipes resist less), and the water flow through the pipe is analogous to electric current

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.

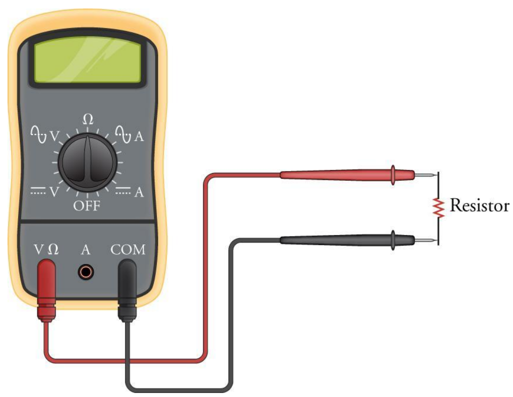


Figure 14.3: Measuring resistance with an ohmmeter

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 light bulb 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*.

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 lightbulb 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 lightbulb? 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.

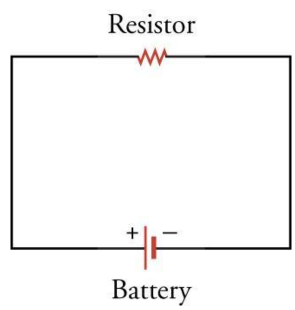


Figure 14.4: A simple circuit consisting of a resistor and a battery

Step 3: Student-Led Planning: Add a lightbulb into the circuit. Then, change the number of batteries in series. Observe the effect on the light bulb, 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.

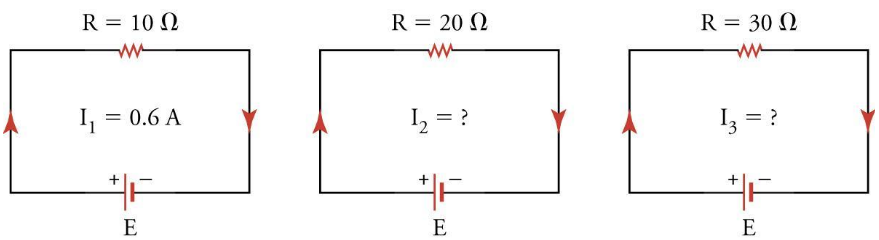
Step 3: Critical Analysis: What mathematical relationship between the current, voltage, and resistance do your findings in Activities 1 and 2 suggest? How can you use your experimental data in this part of the investigation to confirm this relationship? Discuss your answers with your partner, and write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

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.



   a. What is the current in the second circuit?
   b. What is the current in the third circuit?
   c. Explain your reasoning.

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?
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.

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

Activity 2: Pre-Assessment

1. 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. 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.

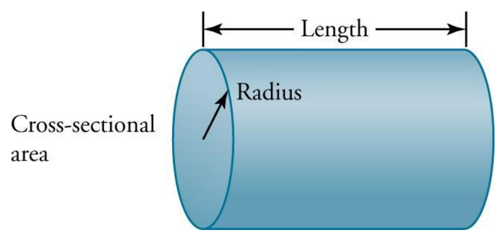


Figure 14.6: The cylinder shown represents the shape of a typical wire.

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*.

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 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 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.
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.
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?

Lab 15:
Resistor Circuits

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 to 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*.

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.

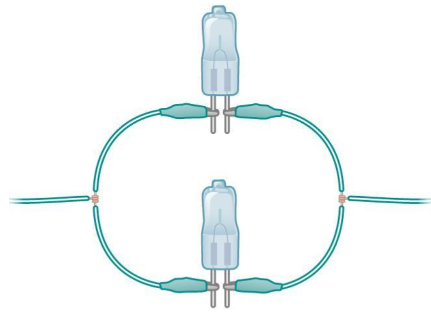


Figure 15.1: This is how to set up two light bulbs in *parallel*. Note that there is an initial wire that splits into two wires. On each of these two wires, there is a light bulb. The wires coming from the light bulb connect at a single wire.

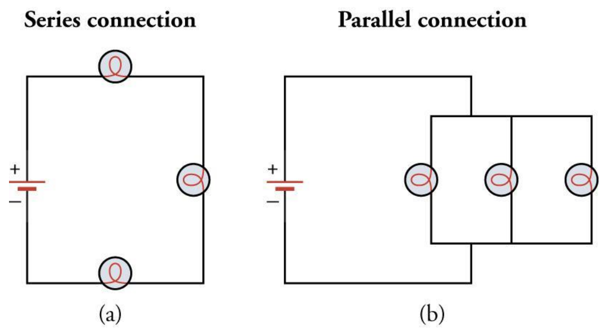


Figure 15.2: (a) A circuit with three light bulbs in a *series* connection. (b) A circuit with three light bulbs in a *parallel* connection.

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?
4. With your circuit diagram from Question 3, list and describe the energy transformations within the electrical circuit.

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?

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*.

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.

Lab 16:
Kinetic Theory of Matter

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. How does temperature relate to the motion or kinetic energy of a collection of particles?
2. 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. 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).

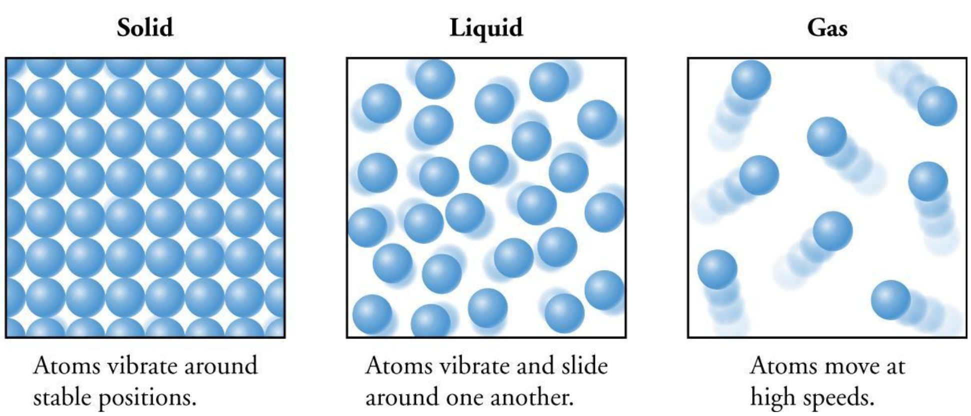


Figure 16.1: As the internal kinetic energy of an object changes, the relative motion of the particles inside the object changes as well.

Kinetic energy depends on two quantities: mass and velocity. The equation we use to calculate an object's kinetic energy is

$$\mathrm{KE} = \tfrac{1}{2}mv^2$$

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 region 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*.

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.

Activity 2: Pre-Assessment

1. If you were to look on 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. 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.**

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 16.1), 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*.

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.
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.

Lab 17:
Gases

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.

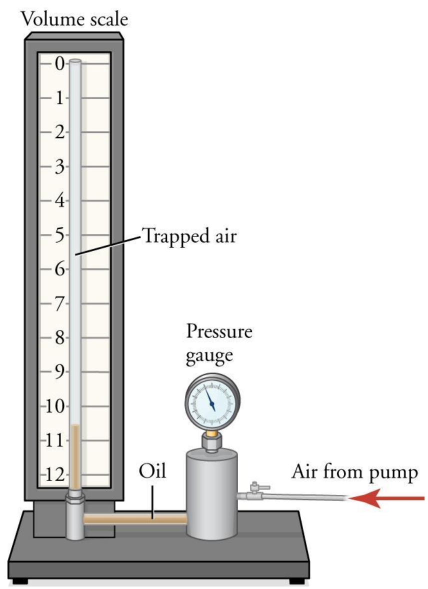


Figure 17.1: Boyle's law apparatus for measuring the pressure and volume of a gas.

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.

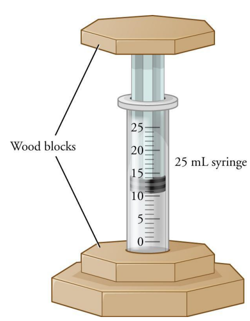


Figure 17.2: Another version of the Boyle's law apparatus. Pressure is applied by adding weight to the top wood block.

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, $g = 9.81 \text{ m/s}^2$.

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 1.01×10^5 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. What do you predict is the relationship between the volume of a sample of gas and its pressure?
2. How could you experimentally determine the relationship between the temperature and pressure of a gas using the 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.*

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 the 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 the Boyle's law apparatus with books. The masses of the books are 520 g, 785 g, and 423 g. Does this scenario describe precise measurements? Why or why not?
   a. 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.
   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 the Boyle's law apparatus. The radius of the syringe is $r = 1.0$ cm. The mass of the weights is *m*= 1.25 kg. The height of the gas sample in the cylinder of the syringe is $h = 10.5$ cm.
   a. What is the volume of the gas (in SI units)?
   b. What is the pressure of the gas (in SI units)?

Activity 2: Finding the Work Done on a Gas Sample

Activity 2: Pre-Assessment

1. 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. How can you measure the volume-pressure relationship required in the question above using the 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 a 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.

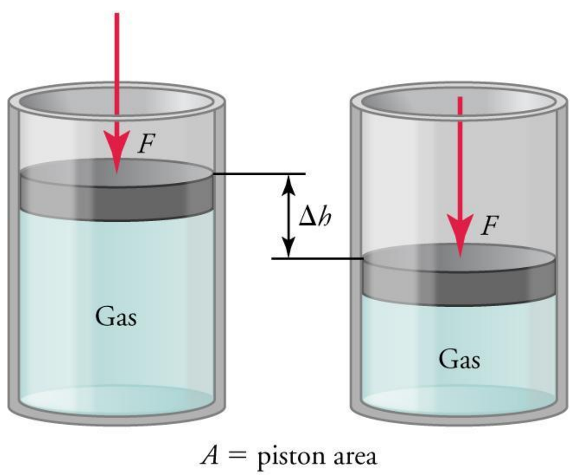


Figure 17.3: The work done on a sample of gas as a result of compression is based on the force (*F*) and displacement (*h*).

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, Δh. 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.

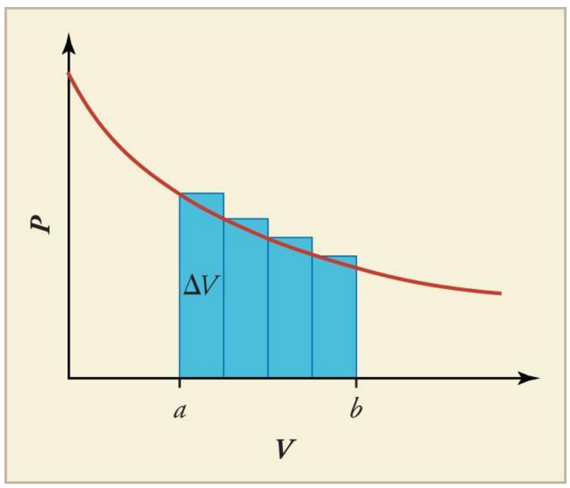


Figure 17.4: The work done on the gas while it is compressed from point *b* to point *a* can be calculated as the area under the *PV* curve between the vertical lines passing through points *a* and *b.*

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 ΔV. 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 ΔV 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*.

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 the 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.
    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.
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 1.6×10^5 Pa as the volume decreases from 3.1×10^{-5} m^3 to 2.8×10^{-5} m^3. Find the work done on the gas by the external pressure (in SI units).
    a. Estimate the change in pressure in this process (in SI units)

Lab 18:
Fluid Dynamics

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. 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. 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*.

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.

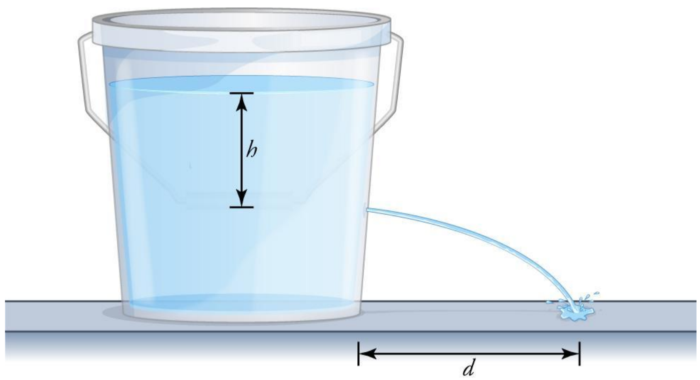


Figure 18.1: The distance the water travels depends on the depth of the hole below the water level.

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?
2. How did the height of the bucket above the ground affect the pressure in the bucket? Why?
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.
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.

Activity 2: Pre-Assessment

1. 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. 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*.

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.

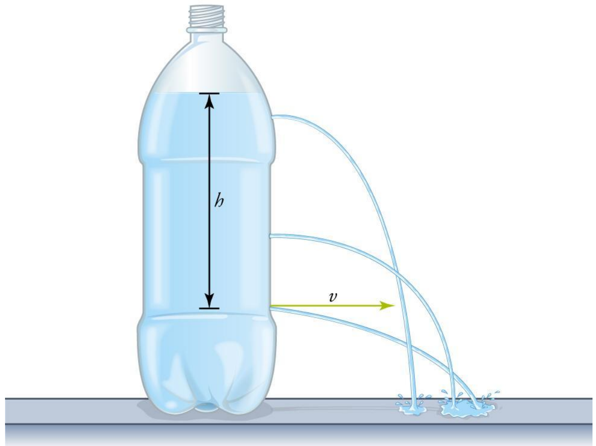


Figure 18.2: The velocity of water leaving the bottle depends on the depth of the hole below the water level.

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.
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.

Activity 3: Pre-Assessment

1. 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. 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.

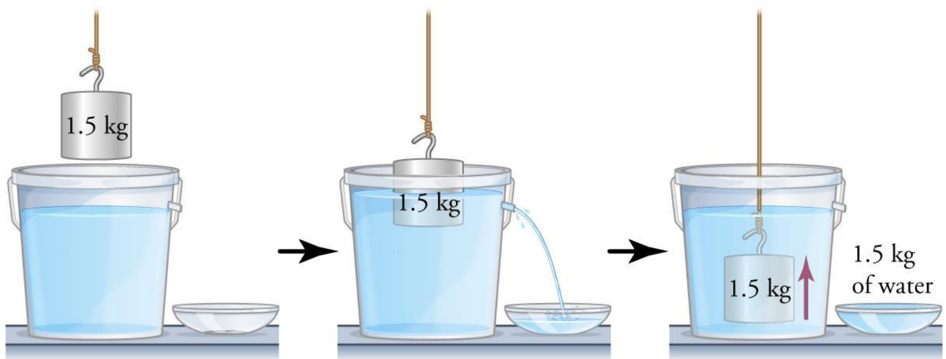


Figure 18.3: According to Archimedes' principle, the buoyant force on an object immersed in a liquid is equal to the weight of the liquid that is displaced by the object.

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*.

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 3 above). Write your results in your notebook.

Step 3: 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.
2. Explain how a steel ship can float.
3. Given your data, determine the density of each of the objects you obtained.
4. Calculate the buoyant force for each object.

Lab 19:
Thermodynamics

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. 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. 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*.

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.

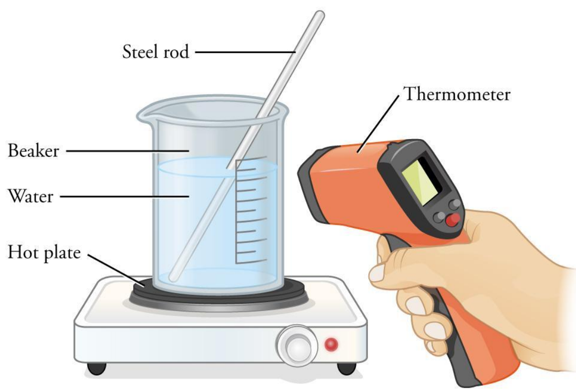


Figure 19.1: Experimental setup for measuring thermal conductivity of a steel rod.

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.
   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 _____.
3. An object is placed in contact with a heat source. The temperature of the object rises. What is the method of thermal transfer being described?
   a. What is the term for the material of the object that increased in temperature when it came into contact with the heat source?

Activity 2: Pre-Assessment

1. 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. 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*.

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
$$Q = (\text{heat of vaporization of water}) \times (\text{mass of water evaporated from T-shirt})$$
$$= 2260\ \text{J/g} \times m$$
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 $e = \dfrac{Q}{E} \times 100\%$

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?

Lab 20:
RC Circuits

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 and
- how the voltage across an RC circuit changes over time

Activity 1: Pre-Assessment

1. 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. 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*.

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 ________.
2. Suppose you have two capacitors of equal magnitude.
    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?

Activity 2: Pre-Assessment

1. Will increasing the voltage across a capacitor change the total charge stored in the capacitor?
2. 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. 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. 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 20.1, current flows through the system until the capacitor becomes fully charged.

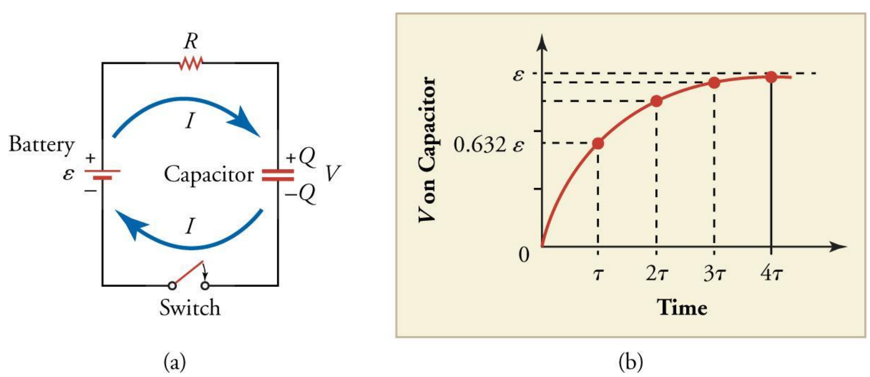


Figure 20.1: (a) A resistor and capacitor connected in series to an external voltage source and (b) the voltage across the capacitor as a function of time.

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 20.2). 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**.

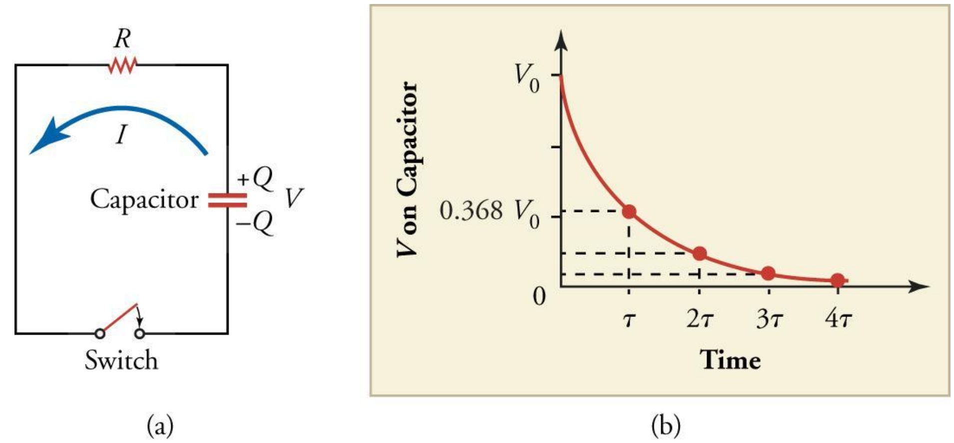


Figure 20.2: (a) A circuit of a capacitor discharging through a resistor and (b) the voltage on the capacitor as a function of time.

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*.

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?
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?
4. Conservation of electric charge leads to conservation of electrical ________ at each point in the circuit.

Lab 21:
Observations of Magnetic FIelds

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. 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. 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*.

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 21.1.

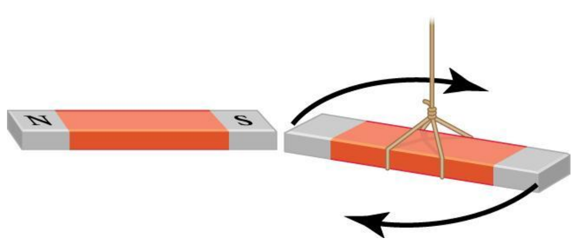


Figure 21.1: Bar magnets interact through their own permanent magnetic fields. The poles of a magnet can be determined based on how it reacts to another magnet.

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]

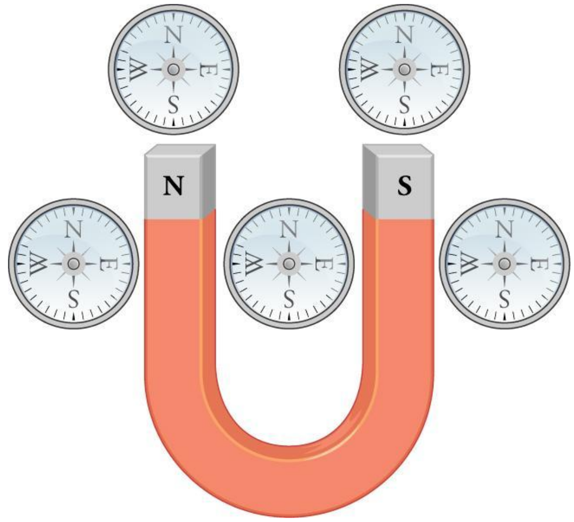


Figure 21.2

Activity 2 Pre-Assessment

1. What is needed to generate a magnetic field? Why do the bar magnets in Activity 1 have magnetic fields around them?
2. 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*.

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 21.3. 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.

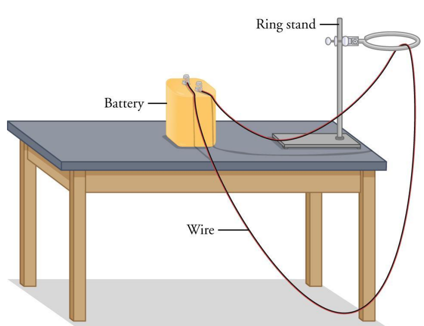


Figure 21.3: Running the wire from the ring stand to the floor leaves a long vertical length of wire away from the rest of the setup. This should give you a better measurement of the magnetic field by reducing interference with other electrical devices.

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?
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?
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.

Lab 22:
Quantitative Magnetism

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. 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. 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*.

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 22.1). 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.

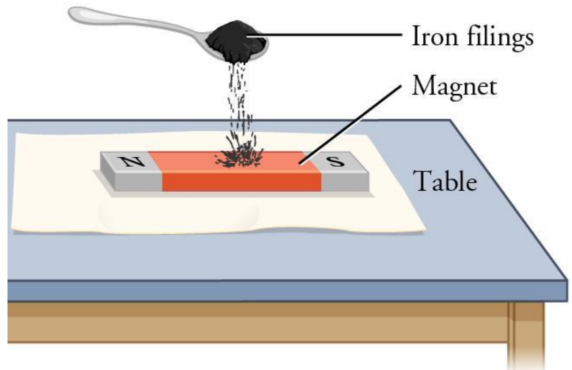


Figure 22.1: Sprinkling iron filings over a bar magnet.

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.
   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 ________.
3. A student finds that when sprinkling iron filings on a bar magnet, the iron filings stay where they are placed.
   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?

Activity 2: Pre-Assessment

1. 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 of the shape of the iron filings and explain your reasoning.
2. 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.

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*.

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 22.2). 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.

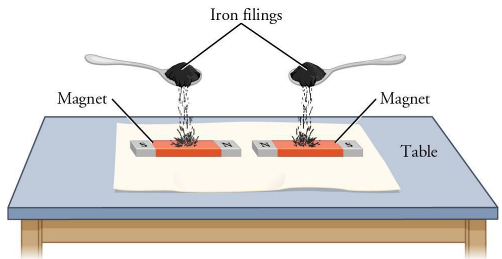


Figure 22.2: Sprinkling iron filings over two bar magnets.

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 place 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.
    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 ________.
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:
    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?

Activity 3: Pre-Assessment

1. What is the connection between electricity and magnetism? Do you think electrical devices have the same magnetic fields as non electrical devices?
2. 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 devices decreases as the distance from the device gets larger.

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*.

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.
    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 ________.
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.
    a. Why is there is 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?

Lab 23:
Electromagnetic Induction

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. What is an electromagnet? What is the advantage of an electromagnet as compared to a regular magnet?
2. 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 23.1. In this drawing, *B* indicates the counterclockwise direction of the magnetic field and *I* represents the flow of conventional current.

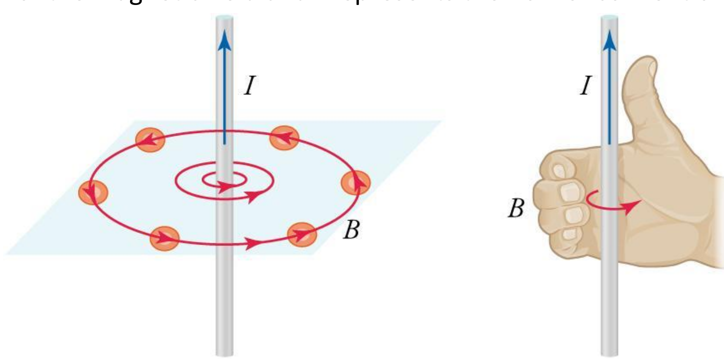


Figure 23.1: Magnetic field around a current-carrying wire. The direction of the field follows a right-hand rule: If you point the thumb of your right hand in the direction of the (positive) current, the fingers curl in the direction of the magnetic field.

Figure 23.2 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.

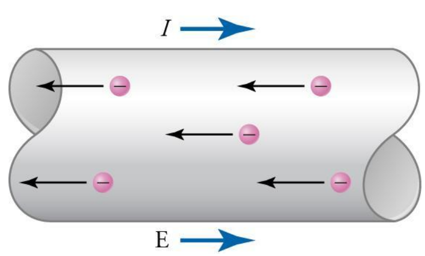


Figure 23.2: The direction of conventional current is the direction that positive charges would follow in an electric field.

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 23.3. In this activity, you will build an electromagnet.

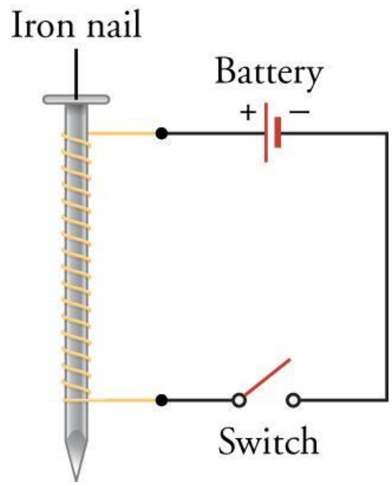


Figure 23.3: You can produce an electromagnet by wrapping circuit wire multiple times around an iron nail and connecting the wire to a battery.

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*.

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 23.4. 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.

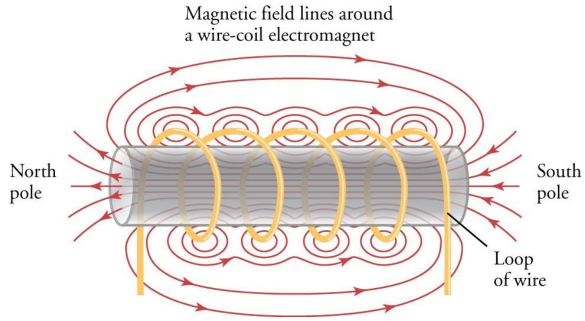


Figure 23.4: The magnetic field around an electromagnet is the sum of the magnetic fields around each loop of wire.

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 23.4 shows a cross-section of the magnetic field around an electromagnet. Apply the right-hand rule described in Figure 23.1 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. What is the orientation of compasses placed near a straight wire that is carrying current?
3. Based on your experimental data, would increasing the current through a straight wire increase the strength of the magnetic field around it? Explain.
4. Why does adding more nails to the electromagnet increase its strength?

Activity 2: Pre-Assessment

1. What is a generator? What are the main parts of a generator? How do the parts work together to generate electricity?
2. 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 23.5 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.

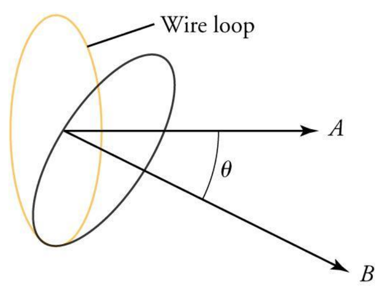


Figure 23.5: Magnetic flux is the product of magnetic field strength *B*, area *A* of a wire loop, and the sine of the angle θ between them.

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*.

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 23.6.

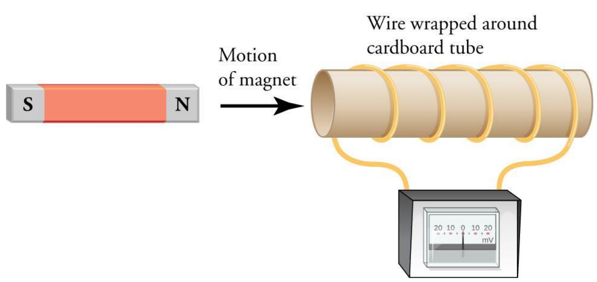


Figure 23.6: A generator made with a magnet and conducting wire wrapped around a cardboard tube.

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?
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. In an early experiment, Faraday wrapped a piece of wire around an electromagnet (Figure 23.7) 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.

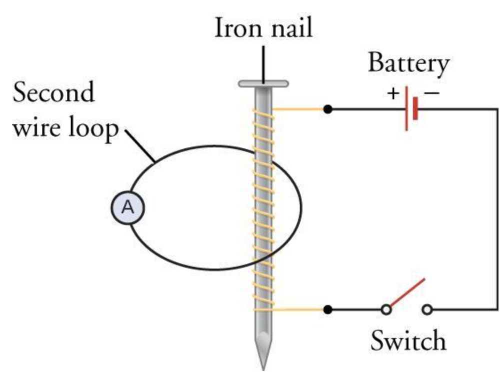


Figure 23.7: This illustration shows an iron nail wrapped in circuit wire that is then connected to a battery and a switch in series. A second wire loop connects an ammeter to the iron nail with the first coiled wire.

Lab 24:
Mirrors

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. 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. 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, card stock, 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*.

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 24.1).
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 24.1.

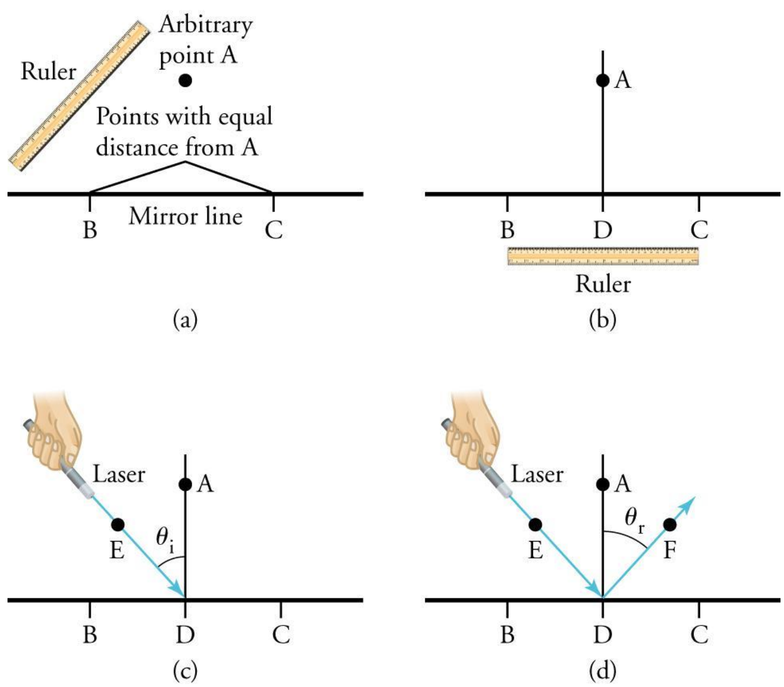


Figure 24.1: Finding the normal line (parts a and b) and the angles of incidence (c) and reflection (d).

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 24.1 (c, d).
   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?
3. What would happen if the student used a flashlight instead of the laser in the above experiments?

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 24.2).

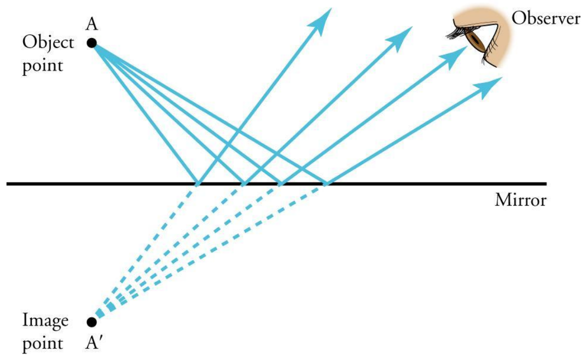


Figure 24.2: Virtual image produced by a plane mirror.

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 24.3.

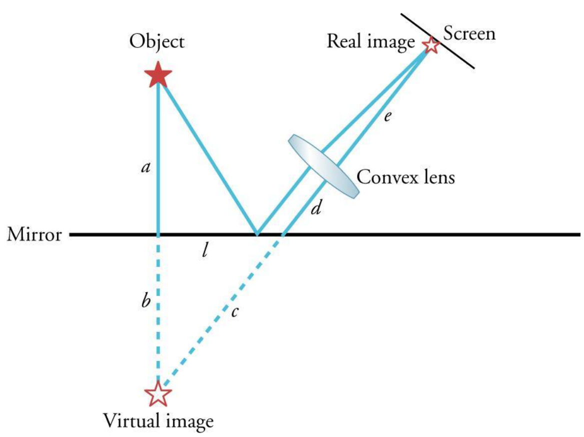


Figure 24.3: Producing a real image from the virtual image behind the mirror.

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 24.4.

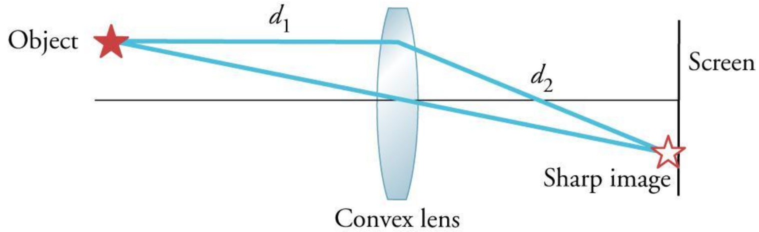


Figure 24.4: Determining the focal length of a convex lens.

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. 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. 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.*

Structured Inquiry

Step 1: Find a way to determine the distances *a* and *b* shown in Figure 24.1 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 24.3 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 24.4. He obtains the following distances from measurements: $d_1 = 10 \text{ cm}, \quad d_2 = 15 \text{ cm}.$

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 24.3. 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*?
3. What can you conclude about the relationship between the mirror-object and mirror-image distances from the results of the previous experiment?

Lab 25:
Geometric Optics

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. 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. 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 25.1 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.

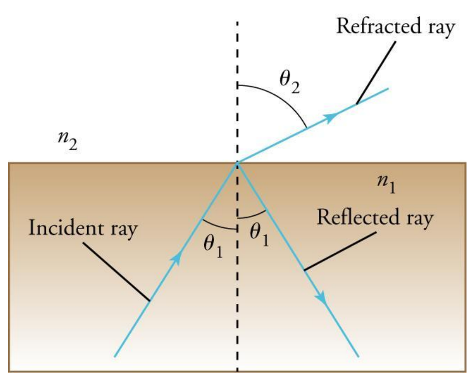


Figure 25.1: An incident ray traveling through a material with an index of reflected n_1 at an angle θ_1 with respect to the normal to the interface. The angle of reflection of the reflected wave equals the incident angle. The refracted wave passes into the second material with an index of refraction 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.*

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.
2. Suppose light is traveling through air into a material with an index of refraction of n = 2, and the angle of incidence is $1°$.
   a. What will the angle of the refracted light be?
   b. What is the speed of light in the material?

Activity 2: Pre-Assessment

1. To focus sunlight to a point, would you use a concave or convex lens?
2. 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 type of lenses, the **focal length** *f* of a lens is the distance from the lens center to the focal point (Figure 25.2).

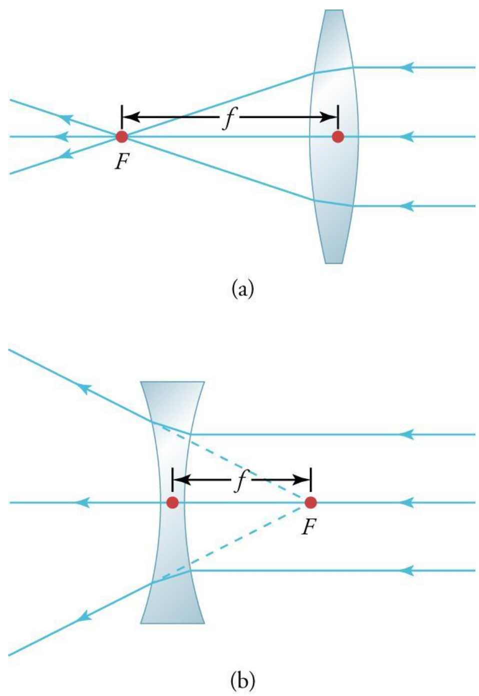


Figure 25.2: Locations of the focal point *F* and focal length *f* for (a) a convex lens and (b) a concave lens.

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**.

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$$

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 25.3. In this activity you will determine the focal length of a convex lens.

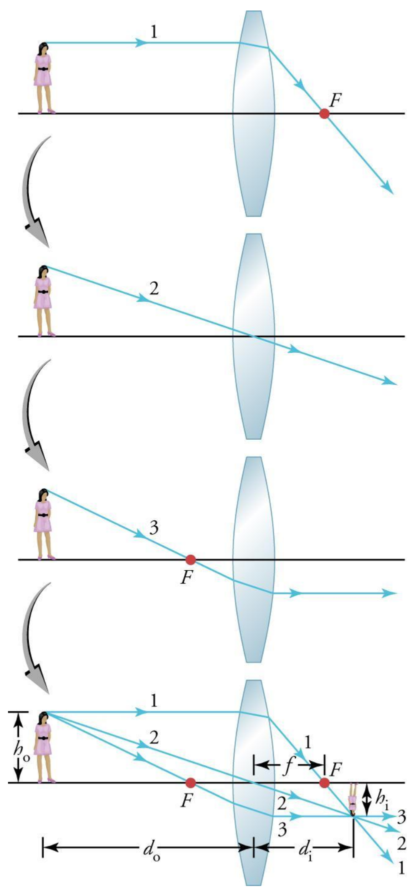


Figure 25.3: A ray diagram showing how to construct an image from an object.

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*.

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?
2. Parallel rays going through a concave lens will ________.
3. What happens when a light ray passes through the center of a thin lens?

Lab 26:
Light as a Particle

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. 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. 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*.

Structured Inquiry

Step 1: Build an electroscope by performing the following steps (refer to Figure 26.1):

- 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 paper clip that you bent in a previous step.
- Place the lid on the jar, being careful not to dislodge the leaf from the clip.

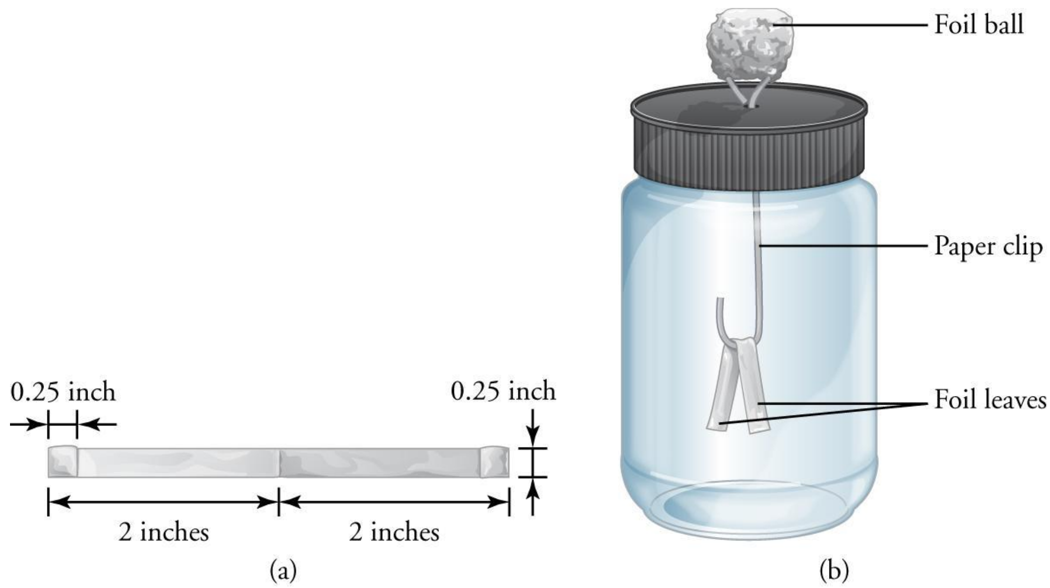


Figure 26.1: (a) The piece of foil that will become the electroscope leaves should be approximately 4 in. (10 cm) long. (b) The aluminum foil leaves of the electroscope hang down straight due to gravity, but push outward in the presence of a charged object.

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?
2. Why does the photoelectric effect require us to think of light as both a particle *and* a wave?
3. What part of the light spectrum will not produce the photoelectric effect? What determines this?

Activity 2: Pre-Assessment

1. 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. 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.

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*.

Structured Inquiry

Step 1: Gather the materials from your instructor to build Circuit 1, as shown in Figure 26.2. With a partner, build the circuit depicted in the diagram. How can you tell if the batteries work?

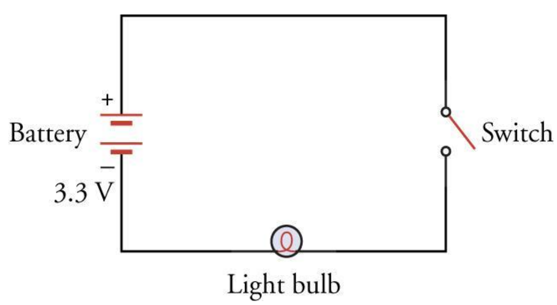


Figure 26.2: Circuit with a battery, switch, and light bulb in series.

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 26.3. Be sure to place the resistor in the circuit and leave the switch open until your teacher checks your circuit.

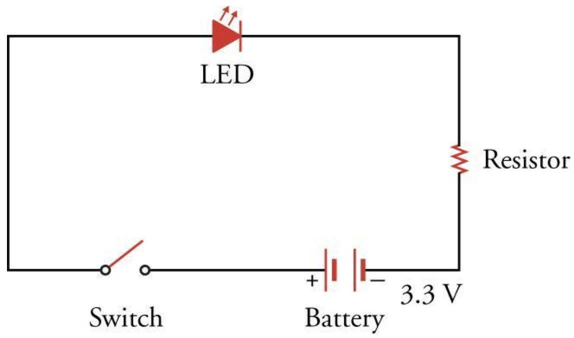


Figure 26.3: Circuit with a battery, switch, resistor, and LED in series.

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 26.4. How can you use this circuit, along with the information in Figure 26.2, 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.

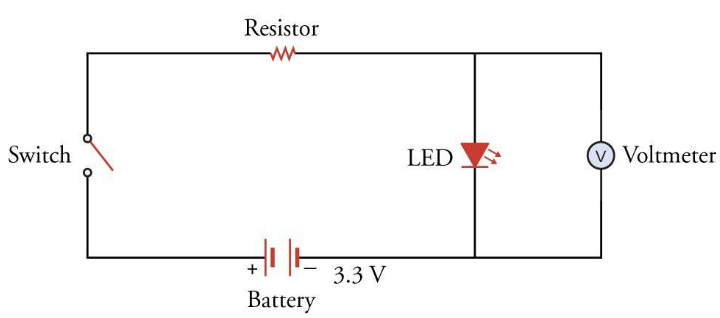


Figure 26.4: Circuit with a battery, switch, resistor, and LED in series.

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 26.5? 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 26.5: 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 $4.5 \times 10^{14}\ \mathrm{s}^{-1}$, 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] Describe how an LED works, in terms of how the LED emits light at the atomic level.

Lab 27:
Double-Slit Interference and Diffraction

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. 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. 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 27.1. 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.

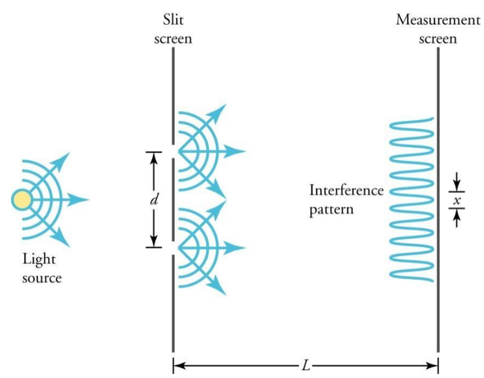


Figure 27.1: When light passes through two small openings, the openings act like point sources of light. The light from these two sources interfere constructively and destructively, depending on location, producing an interference pattern on a screen in front of the openings.

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*.

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 27.2. 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.

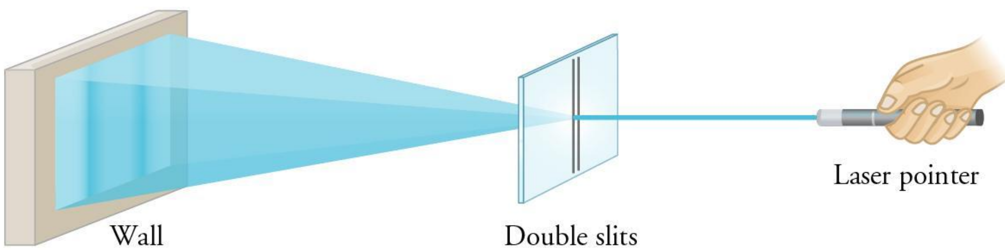


Figure 27.2: Light from a laser pointer directed through a pair of slits forms an interference pattern on a screen directly in front of it.

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?
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?
3. Would you see the same interference pattern if you repeated the double-slit experiment with white light? Why or why not?

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*.

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?

Activity 3: Pre-Assessment

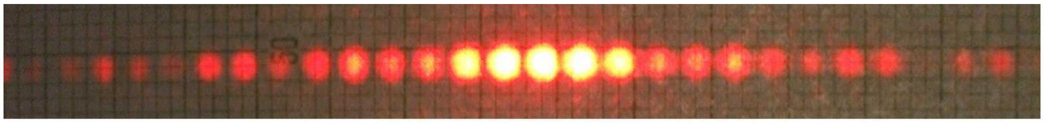
1. Could the double-slit experiment be re-imagined to involve more than two slits? Could you still predict the locations of the bright spots with, say, three slits? Explain.
2. The condition for a bright spot in a two-slit diffraction pattern is that the light from both slits is in phase at that point. 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

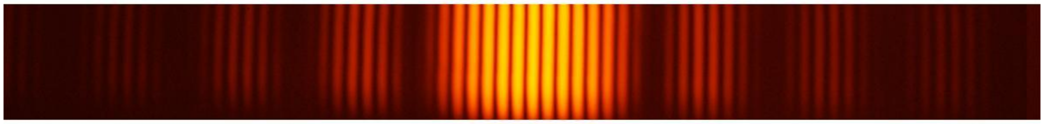
A **diffraction grating** is a set of many closely spaced openings through which you can shine light to form an interference pattern. Instead of being formed by the interference of light from two sources, the pattern is formed by the interference of light from every slit, which can mean hundreds of sources. 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 27.3. 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 27.3: 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*.

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: $\lambda_{\text{red}} = 650\text{ nm}$ $\lambda_{\text{orange}} = 590\text{ nm}$ $\lambda_{\text{yellow}} = 570\text{ nm}$ $\lambda_{\text{green}} = 510\text{ nm}$ $\lambda_{\text{blue}} = 475\text{ nm}$ $\lambda_{\text{violet}} = 400\text{ nm}$
    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.

Lab 28:
Atomic Physics

In this lab you will learn

- how an atom changes when you add or remove subatomic particles to the atom [LO1];
- how to identify an atom through the number of subatomic particles it contains [LO2]; and
- how to determine the percent of isotopes present for various elements [LO3].

Activity 1: Pre-Assessment

1. What happens to an atom when you add an additional proton to it? How about an additional electron? Why is the number of electrons and protons in the atom typically equal?
2. **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 28.1 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.

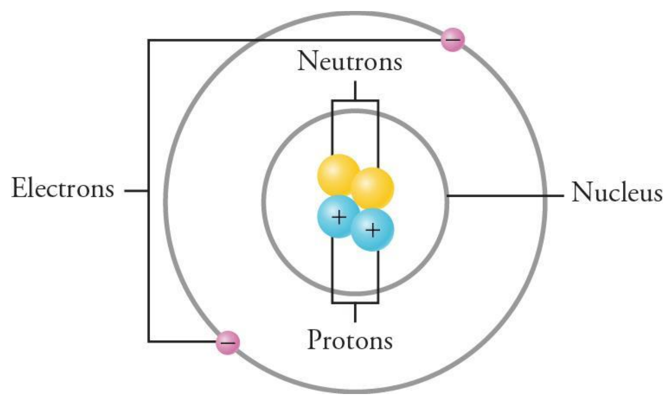


Figure 28.1: A simplified model of an atom (not to scale), showing negatively charged electrons orbiting a nucleus containing positively charged protons and neutral neutrons.

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*.

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.
2. A[n] ________ is an atom that contains a different number of protons than electrons.
3. Suppose an atom contains 10 protons.
   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?

Activity 2: Pre-Assessment

1. How does the number of protons in an atom correspond to different elements?
2. 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 28.2.

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.

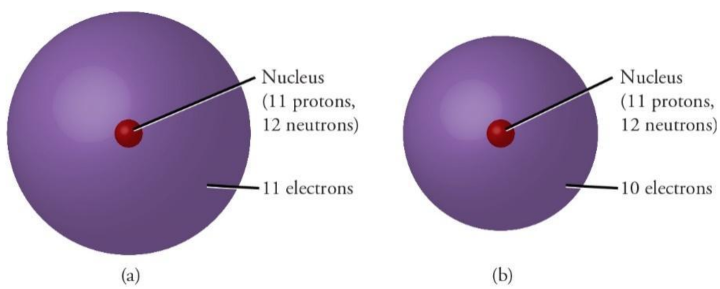


Figure 28.2: A neutral atom (left) and a positively charged ion (right).

For this activity, you will need the following:

- A computer with internet access.

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

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.
2. How many electrons does a neutral carbon atom contain?
3. Elements with different numbers of ________ than protons are called ions.

Activity 3: Pre-Assessment

1. Do different isotopes of the same element have different electric charges?
2. 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*.

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?
2. Do stable or unstable isotopes contribute more to the atomic mass of a given element?

Lab 29:
Models of the Hydrogen Atom

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. 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. 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*.

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.
   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 _________.
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?

Activity 2: Pre-Assessment

1. n 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. 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.

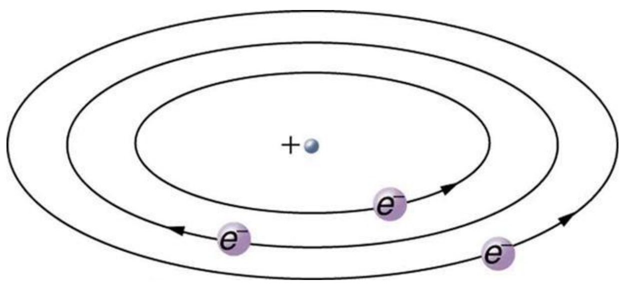


Figure 29.1: Rutherford's planetary model of the atom incorporates the characteristics of the nucleus and electrons, as well as the size of the atom. This model was the first to recognize the structure of atoms, in which low-mass electrons orbit a very small, massive nucleus in orbits much larger than 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*.

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?
2. What is one difference in the behavior of photons between the Plum Pudding and Billiard Ball models?
3. What is interesting about the travel path of electrons in the Solar System model of the hydrogen atom?

Activity 3: Pre-Assessment

1. 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. 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*.

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 in 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?
2. What is one difference in the Experiment mode versus the Billiard Ball model?
3. What is one difference in the Experiment mode versus the Solar System model?