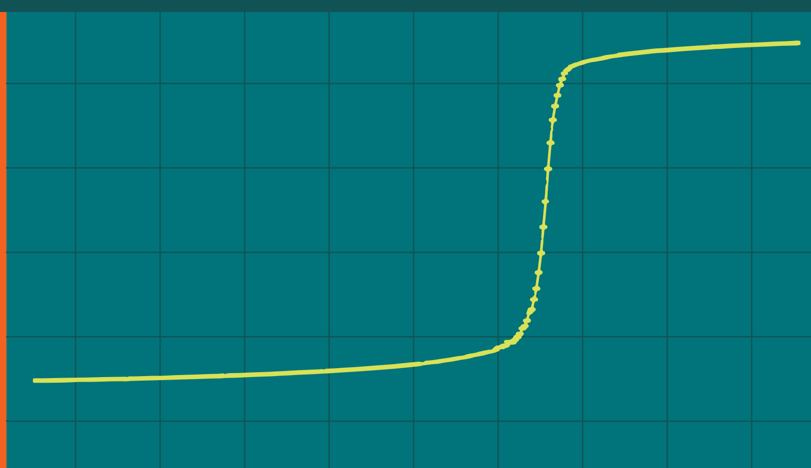
Vernier Experiment Sampler



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Vernier Experiment Sampler

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Published by Vernier Science Education
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ISBN: 978-1-948008-45-7
Edition: 1.1

Preface

The *Vernier Experiment Sampler* includes four experiments each in biology, chemistry, engineering, middle school science, and physics, as well as an Introduction to Data Collection experiment to help get started. The experiments for biology, chemistry, middle school science, and physics utilize **Vernier Go Direct wireless sensors** and the free **Vernier Graphical Analysis app**. The engineering experiments utilize a variety of sensors and software because of the breadth and range of our engineering topics. See the Instructor Information files in this download for specific details and instructions for each unique experiment.

These experiments are complete samples from the following Vernier lab books. For more information and to learn more about the available experiments, click the links below.

Subject	Lab Book	Appropriate For
Biology	***Biology with Vernier***	High School, College
Chemistry	***Chemistry with Vernier***	High School, College
Engineering	***Materials Testing: Beams to Bridges with Go Direct® Structures & Materials Tester*** ***Renewable Energy with Vernier*** ***Vernier Coding Activities with Arduino®: Analog Sensors***	High School, College
Middle School Science	***Middle School Science with Vernier***	Middle School
Physics	***Physics with Vernier*** ***Vernier Video Analysis: Motion and Sports***	High School, College

Student Information

Student experiment information and instructions files are provided in PDF format within the Student Experiments folder in this download, so you can print them and have your students follow the procedures as they are written. PDF format is also ideal for viewing experiments on mobile devices or other platforms.

Instructor Information

The PDF Instructor Information file for each experiment has sample results, answers to questions, and other helpful hints regarding the planning and implementation of the experiment.

Proper safety precautions must be taken to protect teachers and students during experiments described herein. Neither the authors nor the publisher assumes responsibility or liability for the use of material described in this publication. It cannot be assumed that all safety warnings and precautions are included.

Contents

Sensors for
Vernier Experiment Sampler

		Sensors																	Accessories		
		Temperature	Light and Color	3-Axis Magnetic Field	Force and Acceleration	Gas Pressure	Colorimeter	Optical Dissolved Oxygen	Oxygen Gas	Carbon Dioxide Gas	pH	Drop Counter	Conductivity	Motion	Photogate	Accelerometer	Structures and Materials Tester	Energy Sensor	Picket Fence	Vernier Variable Load	KidWind Advanced Wind Experiment Kit
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* This activity can also be performed with the Go Direct Force and Acceleration Sensor (order code GDX-FOR).

** This activity requires a Vernier Gas Pressure Sensor (order code GPS-BTA). It does not support the Go DIrect Gas Pressure Sensor (order code GDX-GP).

^ Optional

Chemical Safety Information

For all chemicals used in this book, refer to the Safety Data Sheet (SDS) that came with the chemical for proper handling, storage, and disposal information. These can also be found online from the manufacturer.

The signal words DANGER and WARNING, as used in the Globally Harmonized System of Classification and Labeling of Chemicals (GHS), are included throughout this book to help identify hazardous chemicals. However, they are not meant to replace safety training, guidance, and monitoring by the instructor.

The *Science Catalog Reference Manual*, published yearly by Flinn Scientific, Inc., is an outstanding reference that can be used as you order chemicals, store chemicals, mix solutions, use chemicals in your classroom, and dispose of chemicals. We strongly urge you to obtain and use a current copy of the *Science Catalog Reference Manual* by contacting Flinn Scientific at 800-452-1261 or through their website, **www.flinnsci.com**

Introduction to Data Collection

Data collection is a very important part of science. Meteorologists collect weather data over time to keep an historical record and to help make forecasts. Oceanographers collect data on the salinity (saltiness) of seawater to study changing trends in our Earth's oceans. While data have been collected by hand for thousands of years, the technology to collect data electronically was developed in the 1950s. Only since the 1980s has this technology been available and accessible to schools.

This experiment was designed to introduce you to two of the most common modes of data collection that will be used in this class. Part I will guide you through collecting and analyzing data over time. A temperature probe will be used to record the temperature of water for 60 seconds at a rate of one sample per second. In Part II, you will collect data using a mode called Events with Entry. This style of data collection allows you to collect one point of data, and then enter in a corresponding value. In this part, the data collected will be the temperature of your hand and the value you enter will be your assigned group member number.

OBJECTIVES

- Become familiar with Graphical Analysis data-collection app.
- Use Graphical Analysis and a temperature probe to make measurements.
- Analyze a graph of the data.
- Use this graph to make conclusions about the experiment.
- Determine the response time of a temperature probe.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis app
Go Direct Temperature
two 250 mL beakers
cold tap water
hot tap water
ice
paper towels

Figure 1

PROCEDURE

Part I Time Graph

1. Place about 100 mL of tap water into a 250 mL beaker. Add two or three ice cubes.
2. Launch Graphical Analysis. Connect the Go Direct Temperature Probe to your Chromebook, computer, or mobile device.
3. Set up the data-collection mode.
   a. Click or tap Mode to open Data Collection Settings.
   b. Change Rate to 0.5 samples/s and End Collection to 60 s. Click or tap Done.
4. Place the temperature probe into the cold water and stir briefly. Then position the probe in the cold-water beaker as shown in Figure 1. **Note**: Make sure the beaker will not tip over from the weight of the probe.
5. Place about 150 mL of hot water into a second 250 mL beaker.
6. When everything is ready, click or tap Collect to start data collection. Do not stir or move the water.
7. When exactly 10 seconds have gone by, quickly move the probe to the beaker containing hot water and allow data collection to continue. Do not stir the water or move the probe during the remainder of the data collection period.
8. Data collection will stop automatically after 60 seconds.
9. Remove the probe from the beaker and dry it with a paper towel.
10. Determine the elapsed time when the highest temperature was reached.
    a. When data collection is complete, a graph of temperature *vs*. time is displayed. Click or tap the graph to examine the data. **Note**: You can also adjust the Examine line by dragging the line.
    b. Find the highest temperature.
    c. Record this temperature (round to the nearest 0.1°C) and the time when it was first reached in the data table.
11. Sketch or export an image of your graph according to your teacher's instructions.
12. You can confirm the time when the highest temperature was reached by viewing the data table.
    a. Click or tap View, ⊞, and turn on the Data Table.
    b. Find the time when the highest temperature was first reached. Did you get the same time both ways?

Part II Events with Entry

13. Click or tap File, 🗋, and choose New Experiment. Click or tap Sensor Data Collection.

14. Set up the data-collection mode.
    a. Click or tap Mode to open Data Collection Settings. Change Mode to Event Based.
    b. Enter **Member** as the Event Name and leave the Units field blank. Click or tap Done.

15. Assign numbers to the members of your group by age with the oldest being number one. Record the names in the data table for Part II. Add more lines if needed.

16. Click or tap Collect to start data collection.

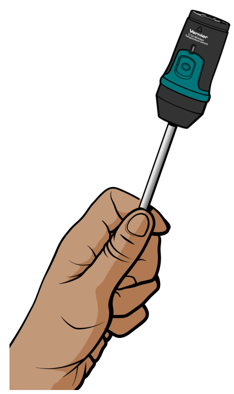


Figure 2

17. Measure the hand temperature of the first group member.
    a. Group member number one should pick up the probe and hold its tip in the palm of his or her hand as shown in Figure 2.
    b. Watch the live temperature readout. When the temperature stops rising, click or tap Keep.
    c. You will be prompted to enter a number. Enter **1** as the student's group member number, then click or tap Keep Point. The temperature and group member number have been saved.

18. Cool the probe down by placing it in the cold water from Part I. Monitor the temperature on the screen and remove it from the water when the temperature reaches 25°C.

19. Pass the probe to the next group member.

20. Repeat Steps 17–19 until every group member has his or her hand temperature recorded, entering the correct group member number for each person.

21. Click or tap Stop to stop data collection.

22. Determine each person's hand temperature by using one of the methods described in Steps 10 and 12. Record the values in the data table.

23. Sketch or export an image of your graph according to your teacher's instructions.

DATA

Part I Time Graph

Maximum temperature (°C)	Elapsed time (s)

Part II Events with Entry

Group member number	Group member name	Maximum temperature (°C)
1		
2		
3		
4		
5		
6		
Group average		

PROCESSING THE DATA

Part I Time Graph

1. Describe the appearance of your graph from Part I.
2. Why is time plotted on the horizontal axis in this experiment?
3. Why is temperature plotted on the vertical axis?
4. Determine the temperature probe's response time. To do this, use your data to find how long it took for the temperature probe to reach the maximum temperature after moving it from the cold water to the hot water.
5. Explain how you determined your answer to Question 4.

Part II Events with Entry

6. Calculate your group's average for the maximum temperatures. Record the result in the data table.
7. Who had the hottest hand?
8. Who had the coldest hand?

Introduction to Data Collection

1. The experiments in this book were selected to provide a sampling of Vernier experiments that cover several subjects and key scientific concepts. The downloaded zip file contains PDF files of the student experiments. You can print the PDF, distribute it to students electronically, or post the file to a password-protected class web page or learning management system.

2. This experiment was adapted from *Earth Science with Vernier*, Experiment 01. Learn more at **vernier.com/esv**

3. If you do not have hot tap water available in your classroom for Part I, water can be heated on a hot plate. A temperature of about 60°C works well.

4. As it is written, this experiment gives the students the option to export, sketch, or print graphs of their data. If you prefer to have your students graph "by hand," instruct them to record data from the table at two-second intervals for this purpose.

5. For additional information about the Vernier probeware used in this experiment, including tips and product specifications, visit **www.vernier.com/manuals** and download the appropriate user manual.

6. See **www.vernier.com/start/go-direct** for information about how to connect to your Go Direct sensors in Graphical Analysis.

ESTIMATED TIME

We estimate that this experiment can be completed in one 45–55 minute class period.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Crosscutting Concepts
Analyzing and interpreting data	Cause and effect

SAMPLE DATA

Part I Time Graph

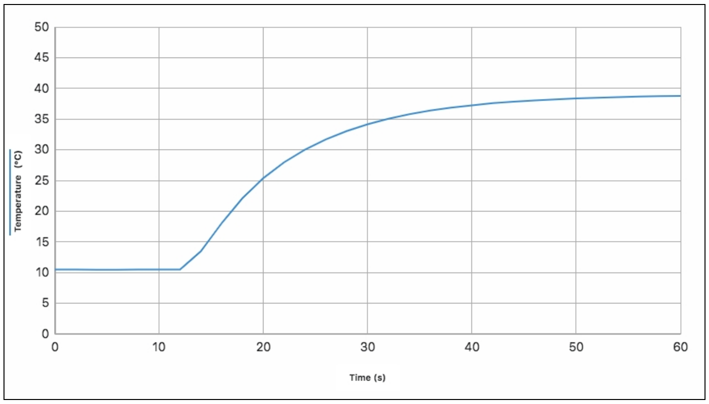


Figure 1

Maximum temperature (°C)	Elapsed time (s)
38.8	60

Part II Events with Entry

Group member number	Group member name	Maximum temperature (°C)
1	Starr C.	35.0
2	Kaden W.	32.5
3	Jeremy N.	33.4
4	Roberto G.	33.7
5	Patrice S.	32.1
6	Tonie L.	31.9
Group Average		33.1

ANSWERS TO QUESTIONS

Part I Time Graph

1. The curve is flat until the point at 12 s, then it curves up rapidly. It slowly levels off at the maximum temperature.

2. Time is plotted on the horizontal axis because it is the independent variable. (The independent variable is plotted on the horizontal axis.)

3. Temperature is plotted on the vertical axis because it is the dependent variable in this experiment. (The dependent variable is plotted on the vertical axis.)
4. Answers will vary. In the example above, the response time is 48 seconds.
5. The response time was calculated by taking the time elapsed when the probe first reached the maximum temperature and subtracting 12 seconds.

Part II Events with Entry

6. See data table.
7. Answers will vary.
8. Answers will vary.

ACKNOWLEDGMENT

We wish to thank Don Volz and Sandy Sapatka for their help in developing and testing this experiment.

Reflectivity of Light

Light is reflected differently from various surfaces and colors. In this experiment, you will be measuring the percent reflectivity of various colors. You will measure reflection values from paper of the various colors using a Light Sensor and then compare these values to the reflection value of aluminum foil. You will then calculate percent reflectivity using the relationship

$$\%\ \text{reflectivity} = \frac{\text{value for paper}}{\text{value for aluminum}} \times 100$$

OBJECTIVES

- Use a Light Sensor to measure reflected light.
- Calculate percent reflectivity of various colors.
- Make conclusions using the results of the experiment.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis app
Go Direct Light and Color
white paper
black paper
aluminum foil
2 other pieces of colored paper
ring stand
utility clamp

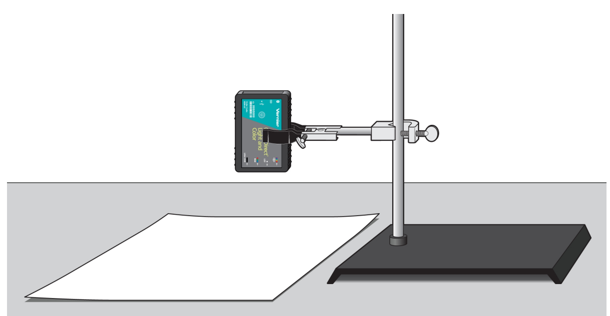


Figure 1

PROCEDURE

1. Launch Graphical Analysis. Connect the Light Sensor to your Chromebook, computer, or mobile device.

2. Click or tap View, ⊞, turn on Meters, and turn off Graph. Then, dismiss the View menu.

3. Use a utility clamp and ring stand to fasten a Light Sensor 5 cm from and perpendicular to the surface of the table (see Figure 1). The classroom lights should be on.
4. Position a piece of aluminum foil under the Light Sensor.
5. When the reading stabilizes, record the reflected light value (in lux). Lux is the SI unit for brightness of light (which is called illuminance).
6. Obtain pieces of white paper and black paper. Repeat Steps 4–5.
7. Obtain two other pieces of paper of other colors. Repeat Steps 4–5. When you record light values, record the color of the paper as well.
8. Before closing Graphical Analysis, continue to the Processing the Data section.

DATA

Color	Reflection value	Percent reflectivity
Aluminum		100%
Black		
White		
____________		
____________		

PROCESSING THE DATA

1. Calculate the percent reflectivity of each color using the formula given in the introduction. Show your work in the data table.
2. Which color, other than aluminum, has the highest reflectivity?
3. Which color has the lowest reflectivity?
4. What surfaces might give a planet a high reflectivity? Explain.
5. Does the planet Earth have high reflectivity? Why or why not?

EXTENSIONS

1. Design an experiment to test the reflectivity of sand, soil, water, and other materials. Perform the experiment you designed.
2. Design an experiment to determine if there is a relationship between reflected light and heat absorbed by various colors or materials. Perform the experiment you designed.

Reflectivity of Light

1. The experiments in this book were selected to provide a sampling of Vernier experiments that cover several subjects and key scientific concepts. The downloaded zip file contains PDF files of the student experiments. You can print the PDF, distribute it to students electronically, or post the file to a password-protected class web page or learning management system.
2. This experiment was adapted from *Middle School Science with Vernier*, Experiment 07. Learn more at **vernier.com/msv**
3. Equal-size pieces of construction paper and aluminum foil can be used and saved for reuse.
4. The range of the Vernier Go Direct Light and Color Sensor automatically adjusts; there is no switch to set. Light is the default channel that is active when you connect this sensor.
5. You may want students to turn on the white LED on the Go Direct Light and Color Sensor to provide a consistent light source. You can also see **www.vernier.com/start/go-direct** for information about how to connect your sensor.
6. For additional information about the Vernier probeware used in this experiment, including tips and product specifications, visit **www.vernier.com/manuals** and download the appropriate user manual.

ESTIMATED TIME

We estimate that this experiment can be completed in one 45–60 minute class period.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Developing and using models Planning and carrying out investigations Analyzing and interpreting data Using mathematics and computational thinking Constructing explanations and designing solutions	PS3.B Conservation of Energy and Energy Transfer PS4.B Electromagnetic Radiation ESS2.D Weather and Climate ESS3.D Global Climate Change	Patterns Cause and effect Scale, proportion, and quantity Systems and system models Energy and matter Structure and function

SAMPLE RESULTS

Note: The sample data were collected with a Vernier Light Sensor.

Color	Reflection value	Percent reflectivity
Aluminum	737.7 lux	100%
Black	231.2 lux	31.3%
White	582.2 lux	78.9%
Purple	326.9 lux	44.3%
Green	425.1 lux	57.6%

ANSWERS TO QUESTIONS

1. See the Sample Results.
2. White has the highest reflectivity.
3. Black has the lowest reflectivity.
4. Snow, ice, sand, clouds, and water would be expected to give a planet high reflectivity.
5. Planet Earth has high reflectivity because much of it is covered by snow, ice, sand, clouds, and water. The results of this experiment suggest that dark-colored parts of the earth, such as forests and green cropland, would have lower reflectivity.

Freezing Temperature of Water

Freezing temperature is the temperature at which a substance turns from a liquid to a solid. In this experiment, you will study the freezing of water and find its freezing temperature.

OBJECTIVES

- Observe the freezing of water.
- Measure temperature.
- Analyze data.
- Use your data and graph to make conclusions about freezing.
- Determine the freezing temperature of water.
- Apply the concepts studied in a new situation.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis app
Go Direct Temperature
ring stand
utility clamp
test tube
400 mL beaker
10 mL graduated cylinder
distilled water
tap water
ice
salt
spoon

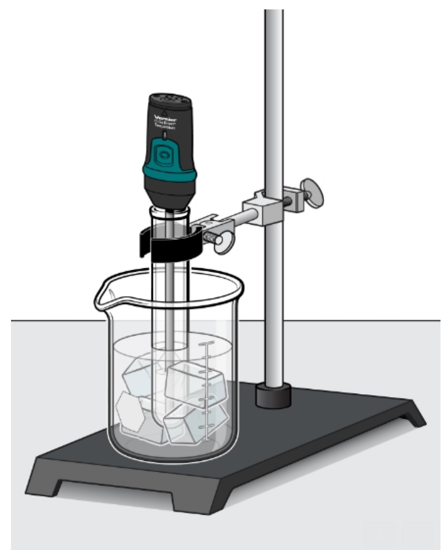


Figure 1

PROCEDURE

1. Fill a 400 mL beaker 2/3 full with ice, then add 100 mL of tap water as shown in Figure 1.

2. Put enough distilled water into a test tube so that about 2 cm of the tip of the Temperature Probe will be submerged. Use a utility clamp to fasten the test tube to a ring stand. The test tube should be clamped above the water bath. Place the Temperature Probe into the water inside the test tube.

3. Launch Graphical Analysis. Connect the Temperature Probe to your Chromebook, computer, or mobile device.

4. Click or tap Mode to open Data Collection Settings. Change the Time Units to min. Change Rate to 10 samples/min and End Collection to 15 minutes. Click or tap Done.

5. When everything is ready, click or tap Collect to start data collection. Then lower the test tube into the ice-water bath.

6. After lowering the test tube, add 5 spoons of salt to the beaker and stir with a spoon. Continue to stir the ice-water bath.

7. Slightly, but continuously, move the probe during the first 10 minutes of data collection. Be careful to keep the probe in, and not above, the ice as it forms. When 10 minutes have gone by, stop moving the probe and allow it to freeze into the ice. Continue to stir the ice-water bath. Add more ice cubes as the original ice cubes get smaller.

8. Make and record observations as the water freezes.

9. When 15 minutes have passed, data collection will stop.

10. Determine and record the freezing temperature of water.
    a. Identify and select the flat portion of the graph that represents freezing.
    b. Click or tap Graph Tools, , and choose View Statistics.
    c. Record the mean (average) temperature (to the nearest 0.1°C) in your data table. This is your value for the freezing temperature of water.
    d. Dismiss the Statistics box.

11. Sketch, export, download, or print the graph as directed by your teacher. Label the freezing temperature on your graph.

12. Do not attempt to remove the Temperature Probe from the ice! Place the test tube into a beaker of warm water to melt the ice, then remove the Temperature Probe.

OBSERVATIONS

DATA

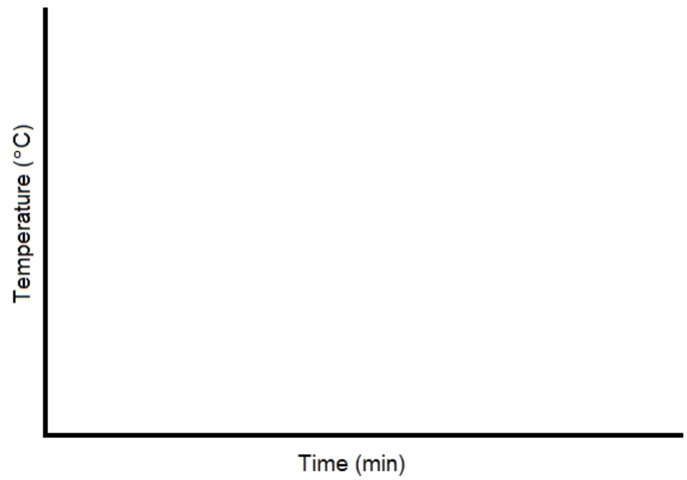
Freezing temperature of water: ___________°C

PROCESSING THE DATA

1. Describe your temperature *vs*. time graph.

2. What happened to the temperature of the water during freezing?

3. Phenyl salicylate has a freezing temperature of 41.5°C. In the space to the right, sketch and label a freezing curve for phenyl salicylate. Be sure to indicate the freezing temperature on the graph.



EXTENSION

Modify the procedure to study the freezing of another substance suggested by your teacher.

Freezing Temperature of Water

1. The experiments in this book were selected to provide a sampling of Vernier experiments that cover several subjects and key scientific concepts. The downloaded zip file contains PDF files of the student experiments. You can print the PDF, distribute it to students electronically, or post the file to a password-protected class web page or learning management system.

2. This experiment was adapted from *Middle School Science with Vernier*, Experiment 14. Learn more at **vernier.com/msv**

3. Size 18 × 150 mm test tubes work well for this experiment. Sizes 20 × 150 mm and 25 × 150 mm work as well.

4. A water sample size of 5 mL works well. Larger samples will take more time than is provided in this procedure.

5. If you want your students to also determine the melting temperature of water, have them monitor temperature after removing the test tube from the cold-water bath. For best results, the probe should not be moved during melting.

6. Moving the temperature probe during freezing gives more constant freezing temperature readings and delays the drop of temperature below freezing temperature. No probe movement, in contrast, gives more constant temperature readings during melting.

7. Some possible substances for use in a modified version of this experiment are:
   - Palmitic acid (Hexadecanoic acid) (m.p. = 63°C)
   - Lauric acid (Dodecanoic acid) (m.p. = 44°C)
   - tert-Butanol (2-Methyl-2-Propanol) (m.p. = 25.5°C)

   Note: Treat all laboratory chemicals with caution. Prudent laboratory practices should be observed.

8. See **www.vernier.com/start/go-direct** for information about how to connect to your Go Direct sensors in Graphical Analysis.

9. For additional information about the Vernier probeware used in this experiment, including tips and product specifications, visit **www.vernier.com/manuals** and download the appropriate user manual.

ESTIMATED TIME

We estimate that this experiment can be completed in one 45–60 minute class period.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Developing and using models Planning and carrying out investigations Analyzing and interpreting data Using mathematics and computational thinking Constructing explanations and designing solutions	PS1.A Structure and Properties of Matter PS3.A Definitions of Energy	Cause and effect Systems and system models Energy and matter Structure and function Stability and change

SAMPLE RESULTS

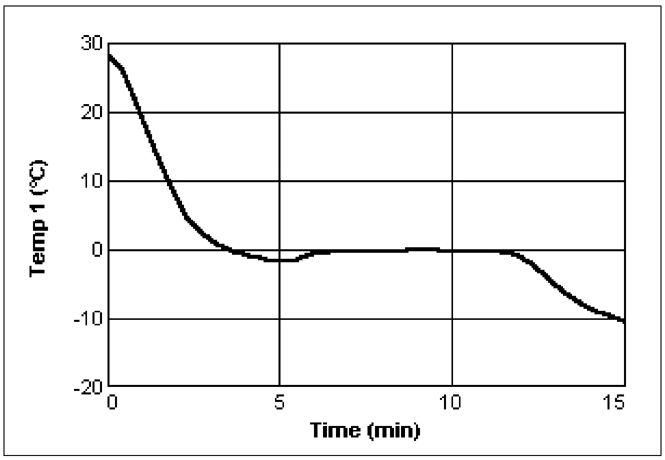


Figure 1 Freezing of water

ANSWERS TO QUESTIONS

1. Answers will vary.
2. The temperature stays relatively constant at about 0°C during freezing.
3. The graph should have the same shape as the water-freezing curve. The plateau should be at 41.5°C, phenyl salicylate's freezing temperature, instead of 0°C.

Mapping a Magnetic Field

The region around a magnet where magnetic force acts is called a *magnetic field*. In this experiment, you will map the magnetic field at one-centimeter intervals along a bar magnet.

OBJECTIVES

- Measure and graph magnetic field strength at points along a bar magnet.
- Analyze data.
- Make conclusions about the magnetic field at various points on a bar magnet.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis app
Go Direct 3-Axis Magnetic Field
bar magnet
tape
ruler

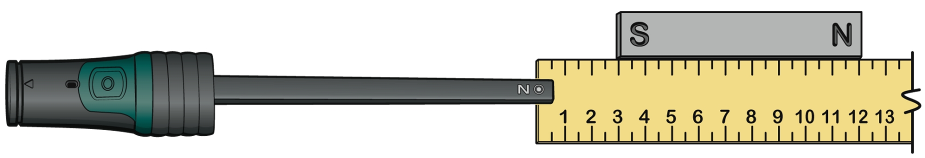


Figure 1

PROCEDURE

1. Tape a meter stick to the table top with pieces of tape at about 50 cm and 95 cm.

2. Launch Graphical Analysis. Connect the Magnetic Field Sensor to your Chromebook, computer, or mobile device.

3. Set up the data collection mode.
   a. Click or tap Mode to open Data Collection Settings. Change Mode to Event Based.
   b. Enter **Position** as the Event Name and **cm** as the Units. Click or tap Done.

4. Click or tap Collect to start data collection.

5. Collect data at the 0 cm distance.
   a. Ensure the Magnetic Field Sensor is positioned so the Sensor Location dot is at the 0 cm mark (see Figure 1).
   b. Position the bar magnet beside the ruler with the S-pole end of the magnet at the 3 cm mark. Tape the magnet to the table top. If the poles are not marked, orient the magnet so that you get positive magnetic field readings.
   c. When the reading has stabilized, click or tap Keep.
   d. Enter **0** (for 0 cm) and click or tap Keep Point to save this data pair.

6. Move the sensor and repeat the Step 5 procedure at 1 cm intervals until you have reached a point 3 cm beyond the N-pole end of the bar magnet. **Important**: Keep the probe parallel to the magnet throughout data collection (see Figure 2).

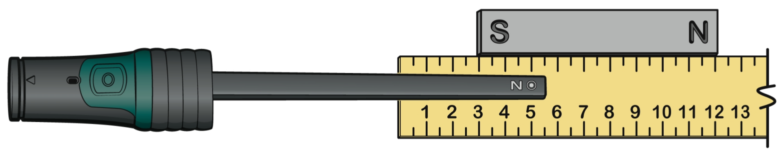


Figure 2

7. When you have finished, click or tap Stop to stop data collection.

8. To examine the data pairs on the displayed graph, click or tap any data point. As you tap each data point, the magnetic field strength and position values of each data point are displayed. Record the magnetic field strength values. **Note**: You can also adjust the Examine line by dragging the line.

9. Sketch, export, download, or print the graph as directed by your teacher.

DATA

Position (cm)	Magnetic field (mT)	Position (cm)	Magnetic field (mT)	Position (cm)	Magnetic field (mT)
0		6		12	
1		7		13	
2		8		14	
3		9		15	
4		10		16	
5		11		17	

PROCESSING THE DATA

1. At what position beside the bar magnet was the largest positive magnetic field strength reading observed?
2. At what position beside the bar magnet was the most negative magnetic field strength reading observed?
3. At what position does your graph have a zero value magnetic field strength value? At what location is this on the bar magnet?
4. Why does the graph have both positive and negative magnetic field strength values?

EXTENSION

Test the strengths of different magnet types at the same distance from the sensor. Which magnet types are strongest? Weakest?

Mapping a Magnetic Field

1. The experiments in this book were selected to provide a sampling of Vernier experiments that cover several subjects and key scientific concepts. The downloaded zip file contains PDF files of the student experiments. You can print the PDF, distribute it to students electronically, or post the file to a password-protected class web page or learning management system.

2. This experiment was adapted from *Middle School Science with Vernier*, Experiment 27. Learn more at **vernier.com/msv**

3. When collecting data, it is important to be aware of the location of the sensor within the housing of the probe. It may be helpful to discuss this with students before they start collecting data.

   The end of Go Direct 3-Axis Magnetic Field has three dots: one at the tip and two on the sides labeled Y and Z. The location of these dots marks the position of the sensor within the wand and the Y and Z labels show the directions in which positive values are measured. The tip is the x-direction and measures positive values when the field has a component in the same direction that the tip of the wand is pointing.

4. One way to think of how our Magnetic Field Sensors work is that they measure the quantity and direction of the magnetic field lines that cut through the end of the probe (see Figure 1).

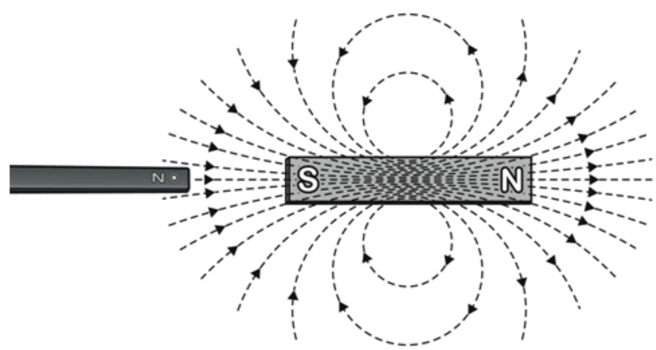


Figure 1 The x-direction measurement is positive when the wand points toward the south pole of the magnet.

5. Bear in mind that magnets are sometimes mislabeled. All of our Magnetic Field Sensors will read a positive value when pointed directly toward the S pole of the magnet, and a negative value when pointed directly toward the N pole of the magnet, regardless of how the ends of the magnet are labeled.

6. You may find it necessary to position the sensor farther to the side of stronger bar magnets. Positions too close to the sensor may have a magnetic field that is too strong for the sensor to measure. We have found that 2–3 cm to the side of the magnet generally works well. On

the Go Direct 3-Axis Magnetic Field sensor, a reading of exactly 5.0 mT indicates the field is too strong to be measured at a given distance.

7. The Go Direct 3-Axis Magnetic Field Sensor has two ranges for measurement. The lower (and more precise) range of ±5 mT generally works well for this experiment. The ±5 mT range is the default for this sensor. However, if you would like to use the higher (and less precise) range of ±130 mT, instruct students to select the Magnetic Field X-Axis 130 mT sensor after starting Graphical Analysis and connecting the sensor.

8. See **www.vernier.com/start/go-direct** for information about how to connect to your Go Direct sensors in Graphical Analysis.

9. For additional information about the Vernier probeware used in this experiment, including tips and product specifications, visit **www.vernier.com/manuals** and download the appropriate user manual.

ESTIMATED TIME

We estimate that this experiment can be completed in one 45–60 minute class period.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Developing and using models Planning and carrying out investigations Analyzing and interpreting data Using mathematics and computational thinking Constructing explanations and designing solutions	PS2.B Types of Interactions	Patterns Cause and effect Scale, proportion, and quantity Systems and system models Energy and matter Structure and function

SAMPLE RESULTS

Position (cm)	Magnetic field (mT)	Position (cm)	Magnetic field (mT)	Position (cm)	Magnetic field (mT)
0	1.093	6	–3.201	12	0.813
1	1.230	7	–3.762	13	1.099
2	1.126	8	–3.861	14	1.130
3	0.710	9	–2.978	15	0.959
4	–0.485	10	–1.615	16	0.762
5	–2.010	11	–0.249	17	

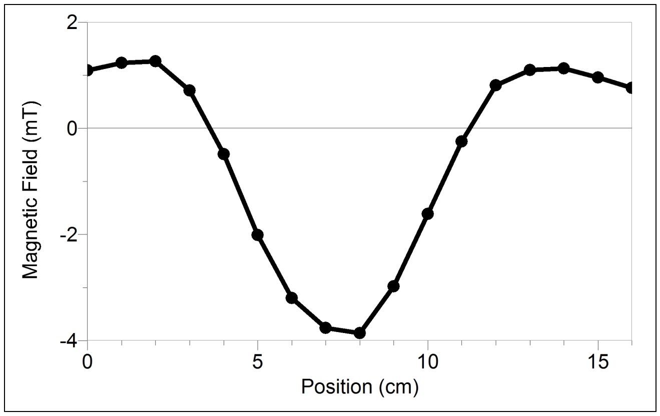


Figure 2

ANSWERS TO QUESTIONS

1. The largest positive magnetic field strength reading is obtained at one of the poles (at the S pole in the Sample Results).

2. The most negative magnetic field strength reading is obtained in the center portion of the magnet.

3. The graph has a zero magnetic field strength value at two points towards the ends of the magnet.

4. The magnetic field strength values with opposite signs are caused by opposite magnetic field directions. (As this experiment is designed, the positive values correspond to the field being directed toward the right, and the negative values correspond to the field being directed toward the left.)

Friction

(Force Sensor)

Friction is a force that resists motion. It involves objects in contact with each other, and it can be either useful or harmful. Friction helps when you want to slow or stop a bicycle, but it is harmful when it causes wear on the parts of a machine. In this activity, you will study the effects of surface smoothness and the nature of materials in contact on sliding friction. You will use a Force Sensor to measure frictional force, in Newtons (N), as you pull a block across different surfaces.

OBJECTIVES

- Measure sliding friction.
- Measure friction between a wooden block and smooth-surface wood.
- Measure friction between a wooden block and rough-surface wood.
- Make predictions about other surfaces.
- Test your predictions.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis app
Go Direct Force and Acceleration
wooden block (with a hook)
paper clip
wood with smooth surface
wood with rough surface
sandpaper

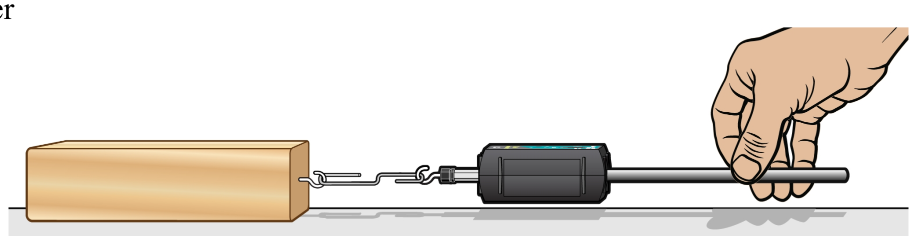


Figure 1

PROCEDURE

Part I Smooth and Rough Surfaces

1. Launch Graphical Analysis. Connect the Force Sensor to your Chromebook, computer, or mobile device.

2. Click or tap Mode to open Data Collection Settings. Change End Collection to 3 s. Click or tap Done.

3. Zero the Force Sensor.
   a. Lay the Force Sensor on the tabletop in the position shown in Figure 1.
   b. When the readings on the screen stabilize, click or tap the Force meter and choose Zero. When the process is complete, the readings for the sensor should be close to zero.

4. Get a wooden block (with a hook on one end). Partly straighten a paper clip—leaving a hook at each end. Use the paper clip to attach the wooden block to the Force Sensor.

5. Slowly pull the wooden block across a piece of wood with a smooth surface. Hold the Force Sensor by its handle and pull it toward you, as demonstrated by your teacher. The Force Sensor should be held parallel to and about 1 cm above the surface. Once the wooden block is moving at a steady rate, click or tap Collect to start data collection.

6. Determine and record the force used to pull the block.
   a. After data collection stops, click or tap Graph Tools, , and choose View Statistics.
   b. Record the mean (average) force (in N).

7. Repeat Steps 5–6 as you pull the block over a piece of wood with a rough surface.

Part II Predicting Friction

8. You will measure friction as the block is pulled across your desktop, the floor, and sandpaper. In the space provided in the data table below, predict the order of friction for these surfaces—from lowest to highest.

9. Repeat Steps 5–6 for each of the surfaces.

DATA

Part I Smooth and rough surfaces		
Surface	Smooth wood	Rough wood
Force (N)		

Part II Predicting friction		
Predicted order of values for desktop, floor, and sandpaper		
(Lowest)		(Highest)

Surface	Desktop	Floor	Sandpaper
Force (N)			

PROCESSING THE DATA

1. What is the effect of surface roughness on friction?
2. How did you decide the order of your predictions in Part II?
3. How good were your predictions? Explain.
4. Give two examples of situations where friction is helpful.
5. Give two examples of situations where it is best to reduce friction.
6. Summarize the results of this experiment.

EXTENSIONS

1. Test the friction of other surfaces, such as glass, metals, rubber, and different fabrics.
2. Investigate how frictional force varies with contact area and mass.
3. Design an experiment to test methods of reducing friction.

Friction

1. The experiments in this book were selected to provide a sampling of Vernier experiments that cover several subjects and key scientific concepts. The downloaded zip file contains PDF files of the student experiments. You can print the PDF, distribute it to students electronically, or post the file to a password-protected class web page or learning management system.
2. This experiment was adapted from *Middle School Science with Vernier*, Experiment 29. Learn more at **vernier.com/msv**
3. A 15 cm (6 in) long wooden block cut from a 5 cm × 10 cm (2 in by 4 in) piece of wood works well. Insert a hook in the center of one end. Use a paper clip or a piece of string to attach it to the force sensor or sensor cart. Other flat-surface objects can be substituted.
4. Scrap pieces of wood obtained at a wood shop, building materials store, or a lumberyard can be used as surfaces for Part I.
5. Illustrate proper technique for pulling a wooden block across a surface with the force sensor or sensor cart before the experiment.
6. Remind your students not to pull the block too fast.
7. Your students should get better results using the force sensor/sensor cart and average force values than they would with spring scales.
8. For additional information about the Vernier probeware used in this experiment, including tips and product specifications, visit **www.vernier.com/manuals** and download the appropriate user manual.
9. See **www.vernier.com/start/go-direct** for information about how to connect to your Go Direct sensors in Graphical Analysis.

ESTIMATED TIME

We estimate that this experiment can be completed in one 45–60 minute class period.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Developing and using models Planning and carrying out investigations Analyzing and interpreting data Using mathematics and computational thinking Constructing explanations and designing solutions	PS2.A Forces and Motion	Patterns Cause and effect Scale, proportion, and quantity Systems and system models Energy and matter Stability and change

SAMPLE RESULTS

Surface	Smooth wood	Rough wood	Desktop	Floor	Sandpaper
Force (N)	0.62	0.98	0.67	0.92	2.21

ANSWERS TO QUESTIONS

1. Surface roughness increases friction.
2. Answers will vary.
3. Answers will vary.
4. Some examples of where friction is helpful are when it keeps you from slipping and sliding, between the brake lining and brake pads of a car, between a car's tires and the road during acceleration, snow tires, and a baseball player's use of rosin.
5. Some examples of where it is best to reduce friction are the bottoms of racing skis, between wheels and axles, between internal parts of a lock, between the cylinder walls and pistons of a car, and on a bicycle chain.
6. Friction depends on the nature of the materials in contact and the smoothness of their surfaces. Rough surfaces cause more friction than smooth surfaces.

Enzyme Action: Testing Catalase Activity

(Gas Pressure Sensor)

Many organisms can decompose hydrogen peroxide (H_2O_2) enzymatically. Enzymes are globular proteins, responsible for most of the chemical activities of living organisms. They act as catalysts, as substances that speed up chemical reactions without being destroyed or altered during the process. Enzymes are extremely efficient and may be used over and over again. One enzyme may catalyze thousands of reactions every second. Both the temperature and the pH at which enzymes function are extremely important. Most organisms have a preferred temperature range in which they survive, and their enzymes typically function best within that temperature range. If the environment of the enzyme is too acidic or too basic, the enzyme may irreversibly denature, or unravel, until it no longer has the shape necessary for proper functioning.

H_2O_2 is toxic to most living organisms. Many organisms are capable of enzymatically breaking down the H_2O_2 before it can do much damage. H_2O_2 can be converted to oxygen and water, as follows:

$$2\ H_2O_2 \rightarrow 2\ H_2O + O_2$$

Although this reaction occurs spontaneously, the enzyme catalase increases the rate considerably. Catalase is found in most living organisms.

A great deal can be learned about enzymes by studying the rates of enzyme-catalyzed reactions. The rate of a chemical reaction may be studied in a number of ways including:

- Measuring the pressure of the product as it appears
- Measuring the rate of disappearance of substrate
- Measuring the rate of appearance of a product

In this experiment, you will measure the rate of enzyme activity under various conditions, such as different enzyme concentrations, pH values, and temperatures. It is possible to measure the pressure of oxygen gas formed as H_2O_2 is destroyed.

OBJECTIVES

- Measure the production of oxygen gas as hydrogen peroxide is broken down by the enzyme catalase or peroxidase at various enzyme concentrations.
- Measure and compare the initial rates of reaction for this enzyme when different concentrations of enzyme react with H_2O_2.
- Measure the production of oxygen gas as hydrogen peroxide is broken down by the enzyme catalase or peroxidase at various temperatures.
- Measure and compare the initial rates of reaction for the enzyme at each temperature.
- Measure the production of oxygen gas as hydrogen peroxide is broken down by the enzyme catalase or peroxidase at various pH values.
- Measure and compare the initial rates of reaction for the enzyme at each pH value.

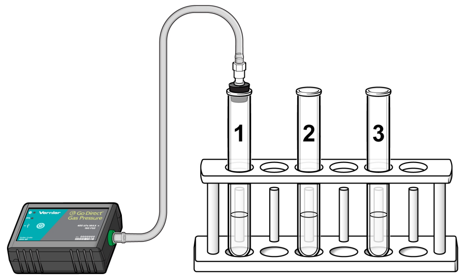


Figure 1

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis app
Go Direct Gas Pressure
1-hole rubber stopper assembly
plastic tubing with Luer-lock fitting
10 mL graduated cylinder
250 mL beaker of water
three Beral pipettes
3% H_2O_2
600 mL beaker
enzyme suspension
three 18 × 150 mm test tubes
ice
pH buffers
test tube rack
thermometer
goggles

PROCEDURE

1. Obtain and wear goggles.
2. Connect the plastic tubing to the valve on the Gas Pressure Sensor.
3. Launch Graphical Analysis. Connect the Gas Pressure Sensor to your Chromebook, computer, or mobile device.
4. Set up the data-collection mode
   a. Click or tap Mode to open Data Collection Settings.
   b. Change Rate to 0.5 samples/s and End Collection to 180 s.
   c. Click or tap Done.

Part I Effect of enzyme concentration

5. Place three test tubes in a rack and label them 1, 2, and 3.
6. Add 3 mL of 3.0% H_2O_2 and 3 mL of water to each test tube.

7. Initiate the enzyme catalyzed reaction. **Note**: The next steps should be completed as rapidly as possible.
   a. Using a clean dropper pipette, add 1 drop of enzyme suspension to test tube 1. **Note**: Be sure to not let the enzyme fall against the side of the test tube.
   b. Stopper the test tube and gently swirl to mix the contents. The reaction should begin immediately.
   c. Connect the free-end of the plastic tubing to the connector in the robber stopper as shown in Figure 2.
   d. Click or tap Collect to start data collection. Data collection will end after 180 s. **Note**: Monitor the pressure readings displayed on the screen. If the pressure exceeds 130 kPa, the pressure inside the tube will be too great and the rubber stopper is likely to pop off. Disconnect the plastic tubing from the Gas Pressure Sensor if the pressure exceeds 130 kPa.

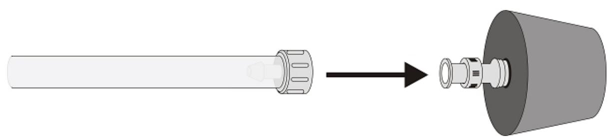


Figure 2

8. When data collection has finished, disconnect the plastic tubing connector from the rubber stopper. Remove the rubber stopper from the test tube and discard the contents in a waste beaker.

9. Determine the rate of enzyme activity:
   a. Select the data in the most linear region of the graph.
   b. Click or tap Graph Tools, , and choose Apply Curve Fit.
   c. Select Linear as the curve fit. Click or tap Apply.
   d. Record the slope, *m*, as the reaction rate in Table 2.
   e. Dismiss the Curve Fit box.

10. Find the rate of enzyme activity for test tubes 2, and 3:
   a. Add 2 drops of the enzyme solution to test tube 2. Repeat Steps 7–9. **Note**: The previous data set is automatically saved.
   b. Add 3 drops of the enzyme solution to test tube 3. Repeat Steps 7–9.

11. Display all three runs of data on a single graph.
   a. To display multiple data sets on a single graph, click or tap the y-axis label and select only the data sets you want to display. Dismiss the box to view the graph.
   b. Use the displayed graph and the data in Table 2 to answer the questions for Part I.

Part II Effect of temperature

Your teacher will assign a temperature range for your lab group to test. Depending on your assigned temperature range, set up your water bath as described below. Place a thermometer in your water bath to assist in maintaining the proper temperature.

- 0–5°C: 400 mL beaker filled with ice and water
- 20–25°C: No water bath needed to maintain room temperature

- 30–35°C: 400 mL beaker filled with warm water
- 50–55°C: 400 mL beaker filled with hot water

12. Rinse the three numbered test tubes used for Part I. Fill each test tube with 3 mL of 3.0% H_2O_2 and 3 mL of water then place the test tubes in the water bath. The test tubes should be in the water bath for 3 minutes before proceeding to Step 13. Record the temperature of the water bath, as indicated on the thermometer, in the space provided in Table 3.

13. Find the rate of enzyme activity for test tubes 1, 2, and 3:
    - Add 2 drops of enzyme suspension to test tube 1. Repeat Steps 7–9. Record the reaction rate in Table 3.
    - Add 2 drops of enzyme suspension to test tube 2. Repeat Steps 7–9. Record the reaction rate in Table 3.
    - Add 2 drops of enzyme suspension to test tube 3. Repeat Steps 7–9. Record the reaction rate in Table 3.

14. Calculate the average rate for the three trials you tested. Record the average in Table 3.

15. Record the average rate and the temperature of your water bath from Table 3 on the class data table. When the entire class has reported their data, record the class data in Table 4.

Part III Effect of pH

16. Place three clean test tubes in a rack and label them pH 4, pH 7, and pH 10.

17. Add 3 mL of 3% H_2O_2 and 3 mL of each pH buffer to each test tube, as in Table 1.

Table 1		
pH of buffer	Volume of 3% H_2O_2 (mL)	Volume of buffer (mL)
pH 4	3	3
pH 7	3	3
pH 10	3	3

18. Find the rate of enzyme activity for test tubes labeled pH 4, pH 7, and pH 10:
    - Add 2 drops of enzyme suspension in test tube pH 4. Repeat Steps 7–9. Record the reaction rate in Table 5.
    - Add 2 drops of enzyme suspension in test tube pH 7. Repeat Steps 7–9. Record the reaction rate in Table 5.
    - Add 2 drops of enzyme suspension in test tube pH 10. Repeat Steps 7–9. Record the reaction rate in Table 5.

19. Display all three runs of data on a single graph. Use the displayed graph and the data in Table 5 to answer the questions for Part III.

DATA

Part I Effect of enzyme concentration

Table 2	
Sample	Reaction rate (kPa/min)
1 drops	
2 drops	
3 drops	

Part II Effect of temperature

Table 3	
Sample	Reaction rate (kPa/min)
Trial 1	
Trial 2	
Trial 3	
Average	
Temperature range: ________ °C	

Table 4: Class Data	
Temperature tested (°C)	Average rate (kPa/min)

Part III Effect of pH

Table 5	
Sample	Reaction rate (kPa/min)
pH 4	
pH 7	
pH 10	

PROCESSING THE DATA

1. Multiply your rate by 60 s/min to convert to kPa/min. Record the rates in Table 3.
2. For Part I of this experiment, make a graph of the rate of enzyme activity *vs*. enzyme concentration. Plot the rate values from Table 3 on the y-axis and the number of drops of enzyme on the x-axis.
3. For Part II of this experiment, make a graph of the rate of enzyme activity *vs*. temperature. Plot the rate values from Table 3 on the y-axis and the temperature on the x-axis.
4. For Part III of this experiment, make a graph of the rate of enzyme activity *vs*. pH. Plot the rate values from Table 3 on the y-axis and the pH on the x-axis.

QUESTIONS

Part I Effect of enzyme concentration

1. How does changing the concentration of enzyme affect the rate of decomposition of H_2O_2?
2. What do you think will happen to the rate of reaction if the concentration of enzyme is increased to 5 drops? Predict what the rate would be for 5 drops.

Part II Effect of temperature

3. At what temperature is the rate of enzyme activity the highest? Lowest? Explain.
4. How does changing the temperature affect the rate of enzyme activity? Does this follow a pattern you anticipated?
5. Why might the enzyme activity decrease at very high temperatures?

Part III Effect of pH

6. At what pH is the rate of enzyme activity the highest? Lowest?
7. How does changing the pH affect the rate of enzyme activity? Does this follow a pattern you anticipated?

EXTENSIONS

1. Determine the reaction rates of trials in Part I for each 30 second interval. What patterns do you see? What could explain the different rates you determined?
2. Different organisms often live in very different habitats. Design a series of experiments to investigate how different types of organisms might affect the rate of enzyme activity. Consider testing a plant, an animal, and a protist.
3. Presumably, at higher concentrations of H_2O_2, there is a greater chance that an enzyme molecule might collide with H_2O_2. If so, the concentration of H_2O_2 might alter the rate of oxygen production. Design a series of experiments to investigate how differing concentrations of the substrate hydrogen peroxide might affect the rate of enzyme activity.

4. Design an experiment to determine the effect of boiling the catalase on the reaction rate.
5. Explain how environmental factors affect the rate of enzyme-catalyzed reactions.

Enzyme Action: Testing Catalase Activity

1. The experiments in this book were selected to provide a sampling of Vernier experiments that cover several subjects and key scientific concepts. The downloaded zip file contains PDF files of the student experiments. You can print the PDF, distribute it to students electronically, or post the file to a password-protected class web page or learning management system.

2. This experiment was adapted from *Biology with Vernier*, Experiment 06. Learn more at **vernier.com/bwv**

3. Test the experiment before the students begin. Depending on the type of enzyme you use, the activity will vary greatly, you may need to dilute the enzyme solution or make a new solution to get the ideal reaction rate.

4. This experiment may take a single group several lab periods to complete. A good breaking point is after the completion of Part I, when students have tested the effect of different enzyme concentrations. Alternatively, if time is limited, different groups can be assigned one of the three tests and the data can be shared.

5. Your hot tap water may be in the range of 50–55°C for the hot-water bath. If not, you may want to supply pre-warmed temperature baths for Part II, where students need to maintain very warm water. Warn students not to touch the hot water.

6. Many different organisms may be used as a source of catalase in this experiment. Beef liver, potato, or living yeast can be used for this experiment. If enzymes from an animal, a protist, and a plant are used by different teams in the same class, it will be possible to compare the similarities and differences among those organisms.

7. We recommend purchasing purified catalase enzyme from Flinn Scientific, Ward's Natural Science, or Sigma-Aldrich. The concentration of enzyme varies from 2000–5000 units/mg and depends on the bottle. Store the catalase powder as instructed. Enzyme activity may decrease from year to year, but will remain viable for up to three years.

8. Follow the instructions below to prepare an enzyme solution:
   a. Purified catalase
      i. Make a stock solution of 1000 units/mL.
      ii. Dilute the stock solution to 200 units/mL for use by the students.

   b. Yeast suspension
      i. Dissolve 1 package (7 g) of dried yeast per 100 mL of 2% sugar solution. To prepare a 2% sugar solution, add 20 grams of sugar to make one liter of solution.
      ii. Incubate the suspension in 37–40°C water for at least 10 minutes to activate the yeast.

   iii. To ensure a uniform yeast concentration, make the suspension available on a magnetic stirrer and instruct your students to withdraw their samples from the center as the suspension is being stirred.
   iv. The yeast may need to be diluted if the reaction occurs too rapidly.

   c. Liver suspension
   i. Homogenize 0.5 to 1.5 g of beef liver in 100 mL of cold water.
   ii. Keep the suspension on ice until it is to be used.
   iii. Dilute the suspension as needed based on reaction rate.

9. You can purchase 3% H_2O_2 at any supermarket. If refrigerated, bring it to room temperature before starting the experiment.

10. Vernier sells a pH buffer package for preparing buffer solutions with pH values of 4, 7, and 10 (order code: PH-BUFCAP). Simply add the capsule contents to 100 mL of distilled water.

11. You can also prepare pH buffers using the following recipes:
    - pH 4: Add 2.0 mL of 0.1 M HCl to 1000 mL of 0.1 M potassium hydrogen phthalate.
    - pH 7: Add 582 mL of 0.1 M NaOH to 1000 mL of 0.1 M potassium dihydrogen phosphate.
    - pH 10: Add 214 mL of 0.1 M NaOH to 1000 mL of 0.05 M sodium bicarbonate.

12. You may need to let students know that at pH values above 10 enzymes will become denatured and the rate of activity will drop. If you have pH buffers higher than 10, have students perform an experimental run using them.

13. The accessory items used in this experiment are the #1 single hole stopper fitted with a tapered valve connector and the section of plastic tubing fitted with Luer-lock connectors. Remind your students that a 1/2 to 3/4 turn of the Luer lock is sufficient to tighten the connection. Tightening down the Luer lock too much can damage the fitting.

14. See **www.vernier.com/start/go-direct** for information about how to connect to your Go Direct sensors in Graphical Analysis.

15. For additional information about the Vernier probeware used in this experiment, including tips and product specifications, visit **www.vernier.com/manuals** and download the appropriate user manual.

ESTIMATED TIME

We estimate that setup and data collection can be completed in two 45-minute class periods.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Analyzing and Interpreting Data Developing and Using Models	LS1.A: Structure and Function	Cause and Effect Structure and Function

SAMPLE RESULTS

Test tube	Slope (or rate) (kPa/min)
1 drop	10.23
2 drops	44.98
3 drops	59.36
4 drops	98.26
0–5°C range: 4°C	41.43
20–25°C range: 21°C	48.02
30–35°C range: 34°C	73.85
50–55°C range: 51°C	27.55
pH 4	36.57
pH 7	66.86
pH 10	75.27

ANSWERS TO QUESTIONS

1. The rate should be highest when the concentration of enzyme is highest. With higher concentration of enzyme, there is a greater chance of an effective collision between the enzyme and H_2O_2 molecule.

2. Roughly, the rate doubles when the concentration of enzyme doubles. Since the data are somewhat linear, the rate is proportional to the concentration. At a concentration of 5 drops, the rate in the above experiment should be about 111 kPa/min.

3. The temperature at which the rate of enzyme activity is the highest should be close to 30°C. The lowest rate of enzyme activity should be at 60°C.

4. The rate increases as the temperature increases, until the temperature reaches about 50°C. Above this temperature, the rate decreases.

5. At high temperatures, enzymes lose activity as they are denatured.

6. Student answers may vary. Activity is usually highest at pH 10 and lowest at pH 4.

7. Student answers may vary. Usually, the enzyme activity increases from pH 4 to 10. At low pH values, the protein may denature or change its structure. This may affect the enzyme's ability to recognize a substrate or it may alter its polarity within a cell.

Biological Membranes

The primary objective of this experiment is to determine the stress that various factors, such as osmotic balance, detergents, and pH, have on biological membranes. Membranes within cells are composed mainly of lipids and proteins. They often serve to help maintain order within a cell by containing cellular materials.

In plants, there is a membrane-bound vacuole that is quite large and usually contains water. In beet plants, this vacuole also contains a water soluble red pigment, *betacyanin*, that gives the beet its characteristic color. Since the pigment is water soluble and not lipid soluble, it is contained in the vacuole when the cells are healthy. However, if the integrity of a membrane is disrupted, the contents of the vacuole will spill out into the surrounding environment and color it red. This usually means the cell is dead. The intensity of color in the environment should be proportional to the amount of cellular damage.

In this experiment, you will test the effect of osmotic balance, detergents, and pH changes on biological membranes and their integrity. The presence of certain salts is essential for most cellular functions, but too much salt can kill cells. Even salts that are not transported across cell membranes can affect cells—by altering the osmotic balance. Osmosis is the movement of water across a semipermeable membrane from a region of low solute concentration to a region of higher solute concentration. It can greatly affect a cell's water content when the amount of water inside the cell is different than the amount outside the cell.

Detergents are designed to make lipids soluble in water. Since biological membranes are made of both lipids and water soluble materials, they can be disrupted by detergents.

The pH of an environment is critical for living things. If the environment is too acidic or too basic, organisms cannot survive because it can alter proteins that are found in their biological membranes.

You will be using a Colorimeter. The solutions used in this experiment are clear. If the beet pigment leaks into the solution, it will color the solution red. A higher concentration of colored solution absorbs more light and transmits less light than a solution of lower concentration. The Colorimeter monitors the light received by the photocell as either an *absorbance* or a *percentage transmittance* value. The *absorbance* of light will be used to monitor the extent of cellular membrane damage.

OBJECTIVES

- Use a Colorimeter to measure color changes due to disrupted cell membranes.
- Determine the effect of osmotic balance on biological membranes.
- Determine the effect of detergents on biological membranes.
- Determine the effect of pH on biological membranes.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis app
Go Direct Colorimeter
100 mL beaker
three 18 × 150 mm test tubes
test tube rack
Beral pipets
forceps
knife
microplate, 24-well
beet
15% salt solution
detergent solution
pH buffer solutions
lab apron
gloves
ruler
tap water
timer or stopwatch
tissues (preferably lint free)
toothpicks

PROCEDURE

1. Obtain and wear goggles, an apron, and gloves.

Part I Testing for the effect of osmotic stress

2. Obtain a piece of beet from your instructor. Cut six squares, each 0.5 cm × 0.5 cm × 0.5 cm in size. Each square should fit into a microwell easily, without being wedged in. Be sure that:
   - there are no ragged edges.
   - no piece has any of the outer skin on it.
   - all of the pieces are the same size.
   - the pieces do not dry out.

3. Rinse the beet pieces twice using a small amount of water. Immediately drain off the water. This will wash off any pigment released during the cutting process.

4. Obtain 10 mL of 15% salt solution and about 10 mL of tap water. Place each into a labeled test tube. **Caution**: *Treat all laboratory chemicals with caution. Prudent laboratory practices should be observed.*

5. Prepare six salt solutions: 0%, 3%, 6%, 9%, 12%, and 15%.
   a. Using a pipet, add the number of drops of water specified in Table 1 to five of the six wells in the microwell plate.
   b. Using a different pipet, add the number of drops of 15% salt solution specified in Table 1 to five of the six wells in the microwell plate.

Table 1			
Well number	H_2O (drops)	15% salt (drops)	Concentration of salt (%)
1	60	0	0
2	48	12	3
3	32	24	6
4	24	32	9
5	12	48	12
6	0	60	15

6. Set the timer to 10 minutes and begin timing. Using forceps, add a piece of beet to each of the six well plates as shown in Figure 1.

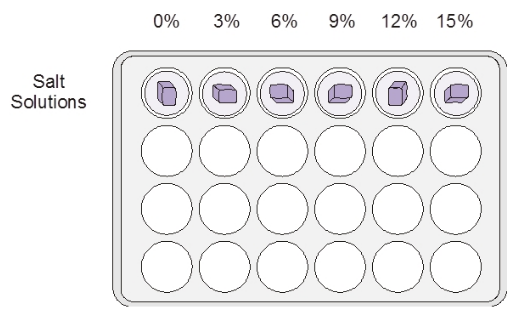


Figure 1

7. Stir the beet in the salt solution once every minute with a toothpick. While one person is performing this step, another team member should proceed to Step 8. **Note**: Be careful not to puncture or damage the beet with the toothpick.

8. Prepare a blank by filling an empty cuvette 3/4 full with distilled water. Seal the cuvette with a lid. To correctly use a cuvette, remember:
   - Wipe the outside of each cuvette with a lint-free tissue.
   - Handle cuvettes only by the top edge of the ribbed sides.
   - Dislodge any bubbles by gently tapping the cuvette on a hard surface.
   - Always position the cuvette so the light passes through the clear sides.

9. Launch Graphical Analysis. Connect the Colorimeter to your Chromebook, computer, or mobile device.

10. Calibrate the Colorimeter.
    a. Place the blank in the cuvette slot of the Colorimeter and close the lid.
    b. Press the < or > button on the Colorimeter to select a wavelength of 470 nm (Blue).
    c. Press the CAL button until the red LED begins to flash, then release. When the LED stops flashing, calibration is complete.

11. Set up the data-collection mode.
    a. Click or tap Mode to open Data Collection Settings. Change Mode to Event Based.
    b. Enter **Concentration** as the Event Name and **%** as the Units.
    c. Click or tap Done.

12. Prepare the solutions and cuvette for use.
    a. When the timer ends, remove the beet pieces from the wells. Remove them in the same order in which they were placed in the well. Discard the beet pieces and retain the colored solutions.
    b. Empty the blank. Transfer all of the 0% salt solution from Well 1 into the cuvette using a pipet. Wipe the outside with a tissue and place it in the Colorimeter. Close the lid.

13. Click or tap Collect to start data collection.

14. You are now ready to collect absorbance data for the salt solutions.
    a. Wait for the absorbance value displayed on the screen to stabilize and click or tap Keep.
    b. Enter the concentration of salt from Well 1.
    c. Click or tap Keep Point. The absorbance and concentration values have now been saved.

15. Collect the next data point.
    a. Discard the cuvette contents into your waste beaker. Remove all of the solution from the cuvette.
    b. Transfer all of the salt solution from Well 2 into the cuvette using a pipet. Wipe the outside with a tissue and place it in the device. Close the lid of the Colorimeter.
    c. Wait for the absorbance value to stabilize and click or tap Keep.
    d. Enter the concentration of salt from Well 2.
    e. Click or tap Keep Point. The absorbance and concentration values have now been saved.

16. Repeat Step 15, using the solutions in Wells 3, 4, 5, and 6.

17. Click or tap Stop to stop data collection. Click or tap the graph to examine the data.

18. Click or tap on each point to examine the data and record the absorbance values in Table 2. **Note**: you can also adjust the Examine line by dragging the line.

Part II Testing for the effect of detergents

19. Predict what results you expect when cells are immersed in detergent.

20. Design an experiment with six trials that test the effect of detergent on cell membranes.

21. In your lab book, describe in detail how you would test the effect of detergent on cell membranes. Think about the equipment you will need in your experiment and make a materials list. You may want to use some of the materials list that were used in Part I.

22. Have your instructor check the procedure you wrote. If it is approved, carry out the experiment. Make a data table that contains the data and describe the results and conclusions of your experiment. **WARNING**: *Sodium lauryl sulfate (a component in detergent)*, $CH_3(CH_2)_{11}OSO_3Na$: *Causes skin and serious eye irritation.*

Part III Testing for the effect of pH changes

23. Predict the results when the pH of the cells change from acidic to basic conditions.

24. Design an experiment with six trials that test the effect of pH changes on cell membranes.

25. In your lab book, describe in detail how you would test the effect of pH changes on cell membranes. Think about the equipment you will need in your experiment and make a materials list. You may want to use some of the materials list that were used in Part I.

26. Have your instructor check your procedure. If it is approved, carry out the experiment. Put your results in a data table and describe the results and conclusions of your experiment. **WARNING**: *Buffer: May be harmful if swallowed, inhaled, or in contact with skin. Causes skin and eye irritation.* **Note**: Although the 470 nm wavelength (Blue) was used in the Colorimeter as a light source, use the 565 m wavelength (Green) setting when you measure pH effects. At some pH values, the betacyanin pigment turns blue, so blue light is not absorbed by the pigment and will not give a useful reading. **Important**: You must recalibrate the Colorimeter as in Step 11, using the 565 nm setting in place of the 470 nm setting.

DATA

Table 2	
Concentration of salt (%)	Absorbance
0	
3	
6	
9	
12	
15	

QUESTIONS

Part I Testing for the effect of osmotic stress

1. Which concentration of salt produced the most intensely red solution? The least intensely red solution?

2. Which salt concentration(s) had the least effect on the beet membrane? How did you arrive at this conclusion?

3. Did more damage occur at high or low salt concentrations? Explain why this might be so.

4. An effective way to kill a plant is to pour salt onto the ground where it grows. How might the salt prevent the plant's growth? Is this consistent with your data?

Part II Testing for the effect of detergents

5. What effect did detergents have on cell membranes?

6. How did your answer in Question 5 compare to your prediction?

7. What assumptions did you make while designing your experiment that tested for the effect of detergents? How do you know they are valid assumptions to make?

8. How would you modify your experiment to either improve your results or to explore the validity of your assumptions?

Part III Testing for the effect of pH changes

9. What effect did changing the pH of the cell's environment have on cell membranes?

10. How did your answer in Question 9 compare to your prediction?

11. What assumptions did you make while designing your experiment that tested for the effect of pH changes? How do you know they were valid assumptions to make?

Biological Membranes

1. The experiments in this book were selected to provide a sampling of Vernier experiments that cover several subjects and key scientific concepts. The downloaded zip file contains PDF files of the student experiments. You can print the PDF, distribute it to students electronically, or post the file to a password-protected class web page or learning management system.

2. This experiment was adapted from *Biology with Vernier*, Experiment 09. Learn more at **vernier.com/bwv**

3. In this series of experiments, students test the effect of salt, detergent, and pH changes on biological membranes. The first of these experiments, testing salt, is presented as a model for students. The second and third experiments are designed by the students. It often works well to have students work independently on the initial design and then collaboratively to finalize their procedures. You may want to allow sufficient class time for small group and class discussions of the various experimental designs. Emphasize that there is no one right way to do the lab.

4. Obtain large, red beets from a local store. Carefully cut a 0.5 × 0.5 × 10 cm piece of beet just before use. Do not let the cut surfaces dry out.

5. Beets will stain hands and clothing. Lab aprons and gloves should be worn to prevent staining.

6. The cuvette must have at least 2 mL of solution in order to get a valid absorbance reading. If students fill the cuvette as described in the procedure, they should be within this range.

7. The use of a single cuvette in the procedure is to eliminate errors introduced by slight variations in the absorbance of different plastic cuvettes. If one cuvette is used throughout the experiment by a student group, this variable is eliminated.

8. If desired, students can use cotton swabs to dry a cuvette after water or a solution has been emptied from it. The cotton swabs will remove any remaining droplets in the cuvette.

9. To prepare a 15% salt solution, measure 15 g of NaCl (GHS Signal Word: **WARNING**) into sufficient water to make 100 mL of solution. Each group needs approximately 10 mL.

10. In the student Procedure, students are directed to use Beral pipets to measure volumes of 15% salt solution and water in drops. Students can use 2 mL graduated pipets instead of Beral pipets, but you will need to provide them with volumes in milliliters:

Table 1

Well number	H_2O (mL)	15% salt (mL)	Concentration of salt (%)
1	2.4	0.0	0
2	1.9	0.5	3
3	1.4	1.0	6
4	1.0	1.4	9
5	0.5	1.9	12
6	0.0	2.4	15

11. Tips for determining the effects of detergents on cell membranes:
    - To prepare a 0.5% detergent solution, measure 0.5 grams of sodium lauryl sulfate (abbreviated SDS, and also called sodium dodecyl sulfate) into sufficient water to make 100 mL of solution. Approximately 10 mL will be needed per group. (GHS Signal Word: **WARNING**)
    - You may want to have different groups try a variety of different detergents.
    - Sodium lauryl sulfate (SLS), also known as sodium dodecyl sulfate (SDS), is the active ingredient in many shampoos.

12. Tips for determining the effects of pH on cell membranes:
    - Solutions of these pH values should be available for students: 2, 4, 6, 8, 10, and 12.
    - To prepare the buffered solutions:
        a. Make 500 mL of 0.4 M H_3PO_4 (90 mL concentrated phosphoric acid (GHS Signal Word: **DANGER**) to 410 mL water)
        b. Make 500 mL of 0.4 M Na_3PO_4 (76 g sodium phosphate tribasic (GHS Signal Word: **DANGER**) to sufficient water to make 500 mL).
        c. Combine the two buffer solutions until the correct pH's are obtained. Each team will require about 10 mL of each buffer.
    - Betacyanin solution color shifts slightly as pH changes. Students should change the wavelength from 470 nm (Blue) to 565 nm (Green).

13. This experiment gives you a good opportunity to discuss the relationship between percent transmittance and absorbance. At the end of the experiment, students can click the vertical-axis label of the graph (Absorbance), and choose Transmittance. The graph will then be transmittance *vs*. concentration. You can also discuss the mathematical relationship between absorbance and percent transmittance, as represented by either of these formulas:

$$A = \log(100 / \%T) \quad \text{or} \quad A = 2 - \log\%T$$

14. See **www.vernier.com/start/go-direct** for information about how to connect to your Go Direct sensors in Graphical Analysis.

15. For additional information about the Vernier probeware used in this experiment, including tips and product specifications, visit **www.vernier.com/manuals** and download the appropriate user manual.

ESTIMATED TIME

We estimate that setup and data collection can be completed in two 45-minute class periods.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Analyzing and Interpreting Data Developing and Using Models	LS1.A: Structure and Function	Cause and Effect Structure and Function Systems and System Models

HAZARD ALERTS

The chemical safety signal words used in this experiment (DANGER and WARNING) are part of the Globally Harmonized System of Classification and labeling of Chemicals (GHS). Refer to the Safety Data Sheet (SDS) that came with the chemical for proper handling, storage, and disposal information. These can also be found online from the manufacturer. See the Chemical Safety Information in the introduction for more information.

o-phosphoric acid, H_3PO_4: **DANGER**: Do not eat or drink when using this product—harmful if swallowed. Causes severe skin burns and eye damage. Fatal if inhaled. Industrial exposure to vapors and mists is listed as a known human carcinogen by International Agency for Research on Cancer (IARC).

Sodium chloride, solid, NaCl: **WARNING**: May be harmful if swallowed. Treat as a non-food-grade chemical. Prudent laboratory practices should be observed.

Sodium chloride, 15%, NaCl: This chemical is considered nonhazardous according to GHS classifications. Treat all laboratory chemicals with caution. Prudent laboratory practices should be observed.

Sodium lauryl sulfate, solid, $CH_3(CH_2)_{11}OSO_3Na$: **DANGER**: Keep away from heat, sparks, open flames, and hot surfaces—flammable solid. Do not eat or drink when using this product—harmful if swallowed. Toxic in contact with skin. Causes skin and serious eye irritation. Avoid breathing dust and fumes—may cause respiratory irritation.

Sodium lauryl sulfate, 0.5%, $CH_3(CH_2)_{11}OSO_3Na$: **WARNING**: Causes skin and serious eye irritation.

Sodium phosphate, tribasic, solid, Na_3PO_4: **DANGER**: Causes severe skin burns and eye damage. Do not breathe dust or fumes.

SAMPLE RESULTS

Part I Testing Osmotic Stress

Table 2	
Salt (%)	Absorbance
0	0.302
3	0.190
6	0.201
9	0.193
12	0.199
15	0.380

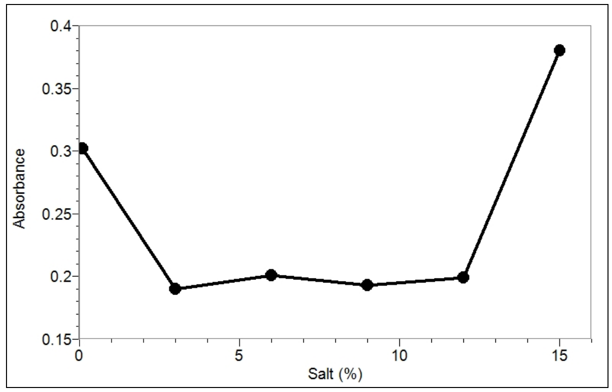


Figure 1

Part II Testing the Effect of Detergents

Table 3	
SDS (%)	Absorbance
0	0.056
0.1	0.490
0.2	0.806
0.3	0.833
0.4	0.840
0.5	0.800

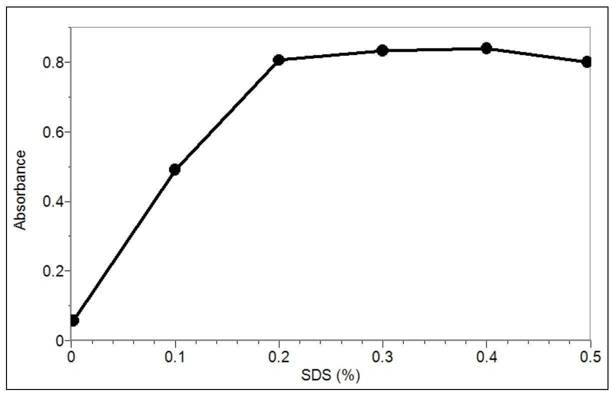


Figure 2

Part III Testing the Effect of pH Changes

Table 4	
pH	Absorbance
2	0.791
4	0.346
6	0.077
8	0.065
10	0.115
12	0.266

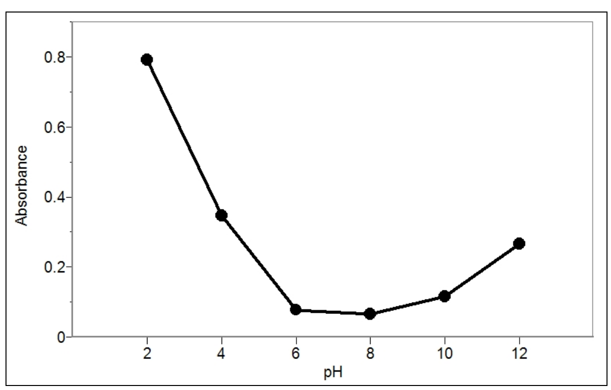


Figure 3

ANSWERS TO QUESTIONS

1. Answers may vary. In the above experiment, 15% salt caused the most intensely red solution, while the 3% solution was least intense.
2. Salt concentrations between 3% and 12% caused the least damage. Those solutions were only faintly red. Cellular damage was minimal.
3. More damage occurred at very high salt concentrations. This was due to osmotic stress. So much water was drawn out of the cells that they were destroyed. Plasmolysis occurred.
4. Salt on the ground might cause cellular damage due to plasmolysis, the loss of water in the cell, in plant tissues. This is supported by the evidence in Question 3.
5. Detergents had a drastic effect at even very low concentrations. The damage increased up to 0.2% SDS, and stabilized at higher concentrations. Detergents are designed to make lipids soluble in water. Since membranes have lipids and other non-polar molecules in them, membrane disruption and cellular damage are expected.
6. Answers may vary. Their responses should be consistent with their predictions.
7. Answers may vary.
8. Answers may vary.
9. Cell membranes were least damaged in a pH range of 6–10. In acidic conditions, the damage was extensive.
10. Answers may vary. Their responses should be consistent with their predictions.
11. Answers may vary.

Dissolved Oxygen in Water

(Optical Dissolved Oxygen Probe)

Aquatic life depends upon oxygen dissolved in water, just as organisms on land rely upon oxygen in the atmosphere. Molecular oxygen is used by organisms in aerobic respiration where energy is released during the combustion of sugar in the mitochondria. Without sufficient oxygen, they suffocate. Some organisms, such as salmon, mayflies, and trout, require high concentrations of oxygen in the water. Other organisms, such as catfish, midge fly larvae, and carp can survive with much less oxygen.

Oxygen dissolves at the interface between the water and the air or when aquatic autotrophs release oxygen as a byproduct of photosynthesis. Abiotic factors including temperature and pressure influence the maximum amount of oxygen that can be dissolved in pure water. Biotic life also influences the amount of oxygen that is dissolved.

The quality of the water can be assessed with fair accuracy by observing the aquatic animal populations in a stream. Table 1 indicates the oxygen and temperature tolerance levels of selected animals based on known dissolved oxygen tolerances. If a stream has only species that can survive at low oxygen levels, it is expected to have low oxygen levels.

Table 1

Animal	Temperature range (°C)	Minimum dissolved oxygen (mg/L)
Trout	5–20	6.5
Smallmouth bass	5–28	6.5
Caddisfly larvae	10–25	4.0
Mayfly larvae	10–25	4.0
Stonefly larvae	10–25	4.0
Catfish	20–25	2.5
Carp	10–25	2.0
Water boatmen	10–25	2.0
Mosquito	10–25	1.0

OBJECTIVES

- Measure the concentration of dissolved oxygen in water using an Optical DO Probe.
- Determine the effect of temperature on the amount of dissolved oxygen in water.
- Apply the results to predict the effect of water temperature on aquatic life.

MATERIALS CHECKLIST

Chromebook, computer, **or** mobile device
Graphical Analysis app
Go Direct Optical Dissolved Oxygen
two 250 mL beakers
100 mL beaker
polystyrene foam cup
1-gallon plastic milk container
hot and cold water
ice
goggles

PROCEDURE

1. Set up the Optical Dissolved Oxygen Probe to collect DO and temperature data.
   a. Launch Graphical Analysis.
   b. Connect the Optical Dissolved Oxygen Probe to your Chromebook, computer, or mobile device.
   c. Click or tap Sensor Channels. Select Temperature. **Note**: Leave DO Concentration selected.
   d. Click or tap Done.
2. Set up the data-collection mode.
   a. Click or tap Mode to open Data Collection Settings.
   b. Change Mode to Event Based.
   c. Change Event Mode to Selected Events.
   d. Select Average sensor reading over 10 seconds.
   e. Click or tap Done.
3. Click or tap Collect to start data collection.
4. Obtain two 250 mL beakers. Fill one beaker with ice and cold water. Place the polystyrene foam cup into the second, empty beaker.
5. Place approximately 100 mL of cold water and a couple small pieces of ice, from the beaker filled with ice water, into a clean plastic one-gallon milk container.
6. Seal the container and vigorously shake the water for a period of 2 minutes. This will allow the air inside the container to dissolve into the water sample.

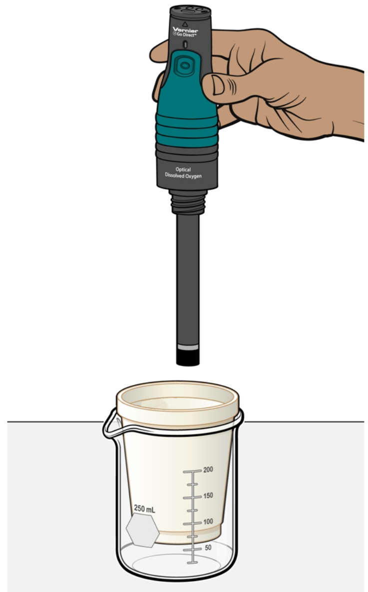


Figure 1

7. Pour the water from the milk container into the polystyrene foam cup.
8. Place the shaft of the Optical DO Probe into the water.
9. Monitor the dissolved oxygen readings displayed on the screen. Give the dissolved oxygen readings ample time to stabilize (90–120 seconds).
10. When the readings have stabilized, click or tap Keep. **Important**: Do not remove the probe until the 10-second averaging period is complete.
11. Remove the probe from the water sample.
12. Pour the water from the polystyrene foam cup back into the milk container. Seal the container and shake the water vigorously for 1 minute. Pour the water back into the polystyrene foam cup.
13. Repeat Steps 8–12 until the water sample reaches room temperature.
14. Fill a second beaker with very warm water about 40–50°C. When the water in the polystyrene foam cup reaches room temperature, add about 25 mL of the very warm water prior to shaking the water sample.
15. Repeat Steps 8–12 until the water temperature reaches 35°C.
16. When all samples have been taken, click or tap Stop to stop data collection.
17. Record the dissolved oxygen and temperature readings in Table 2.

18. Create a single graph of dissolved oxygen *vs*. temperature to help you answer the questions.
    a. Click or tap View, ⊞, and choose 1 Graph.
    b. Plot dissolved oxygen concentration on the y-axis and temperature on the x-axis. To change what is plotted on each axis, click or tap the axis label and select the correct column.

DATA

Table 2

Temperature (°C)	Dissolved oxygen (mg/L)

QUESTIONS

1. At what temperature was the dissolved oxygen concentration the highest? Lowest?
2. Does your data indicate how the amount of dissolved oxygen in the water is affected by the temperature of water? Explain.
3. If you analyzed the invertebrates in a stream and found an abundant supply of caddisflies, mayflies, dragonfly larvae, and trout, what minimum concentration of dissolved oxygen would be present in the stream? What maximum temperature would you expect the stream to sustain?
4. Mosquito larvae can tolerate extremely low dissolved oxygen concentrations, yet cannot survive at temperatures above approximately 25°C. How might you account for dissolved oxygen concentrations of such a low value at a temperature of 25°C? Explain.
5. Why might trout be found in pools of water shaded by trees and shrubs more commonly than in water where the trees have been cleared?

Dissolved Oxygen in Water

1. The experiments in this book were selected to provide a sampling of Vernier experiments that cover several subjects and key scientific concepts. The downloaded zip file contains PDF files of the student experiments. You can print the PDF, distribute it to students electronically, or post the file to a password-protected class web page or learning management system.
2. This experiment was adapted from *Biology with Vernier*, Experiment 19. Learn more at **vernier.com/bwv**
3. Temperatures of 5, 10, 15, 20, 25, and 30°C are typical.
4. When students are adding ice into their milk container, warn them to not add more than will melt while they are shaking the container.
5. See **www.vernier.com/start/go-direct** for information about how to connect to your Go Direct sensors in Graphical Analysis.
6. For additional information about the Vernier probeware used in this experiment, including tips and product specifications, visit **www.vernier.com/manuals** and download the appropriate user manual.

ESTIMATED TIME

We estimate that setup and data collection can be completed in one 45-minute class period.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Analyzing and Interpreting Data Developing and Using Models	LS2.A: Interdependent Relationships in Ecosystems LS4.D: Biodiversity and Humans	Cause and Effect

SAMPLE RESULTS

Temperature (°C)	Dissolved oxygen (mg/L)
8.96	11.19
14.89	9.66
18.74	8.81
22.71	7.99
33.65	5.71

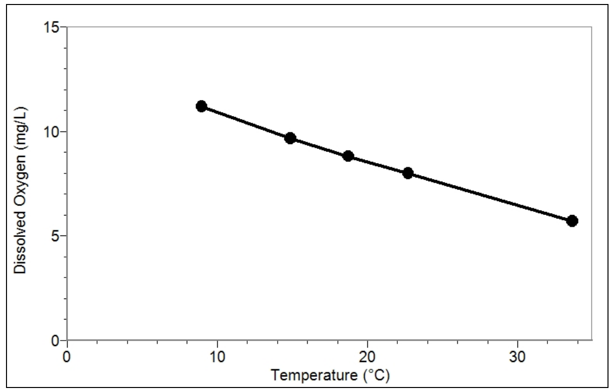


Figure 1

ANSWERS TO QUESTIONS

1. The amount of dissolved oxygen will be highest at the coldest temperature and lowest at the warmest temperature.
2. As the temperature increases, the amount of dissolved oxygen decreases. The relationship does not appear to be linear.
3. Since trout were present, the minimum amount of dissolved oxygen would be 6.5 mg/L. According to these data, fast-moving water could not be warmer than 30–32°C. This temperature is much higher than trout generally live in, however.
4. Other factors must have caused the low dissolved oxygen levels. Bacteria and other organisms can lower the dissolved oxygen of water when they respire aerobically.
5. Trout require high dissolved oxygen levels. Since trees shade the water from the sun, they help keep it cool. Cool water has a higher dissolved oxygen level than warm water and is preferred by trout.

Photosynthesis and Respiration

(CO_2 and O_2 Gas Sensors)

Plants make sugar, storing the energy of the sun into chemical energy, by the process of photosynthesis. When they require energy, they can tap the stored energy in sugar by a process called cellular respiration.

The process of photosynthesis involves the use of light energy to convert carbon dioxide and water into sugar, oxygen, and other organic compounds. This process is often summarized by the following reaction:

$$6\ H_2O + 6\ CO_2 + \text{light energy} \rightarrow C_6H_{12}O_6 + 6\ O_2$$

Cellular respiration refers to the process of converting the chemical energy of organic molecules into a form immediately usable by organisms. Glucose may be oxidized completely if sufficient oxygen is available by the following equation:

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ H_2O + 6\ CO_2 + \text{energy}$$

All organisms, including plants and animals, oxidize glucose for energy. Often, this energy is used to convert ADP and phosphate into ATP.

OBJECTIVES

- Use an O_2 Gas Sensor to measure the amount of oxygen gas consumed or produced by a plant during respiration and photosynthesis.
- Use a CO_2 Gas Sensor to measure the amount of carbon dioxide consumed or produced by a plant during respiration and photosynthesis.
- Determine the rate of respiration and photosynthesis of a plant.

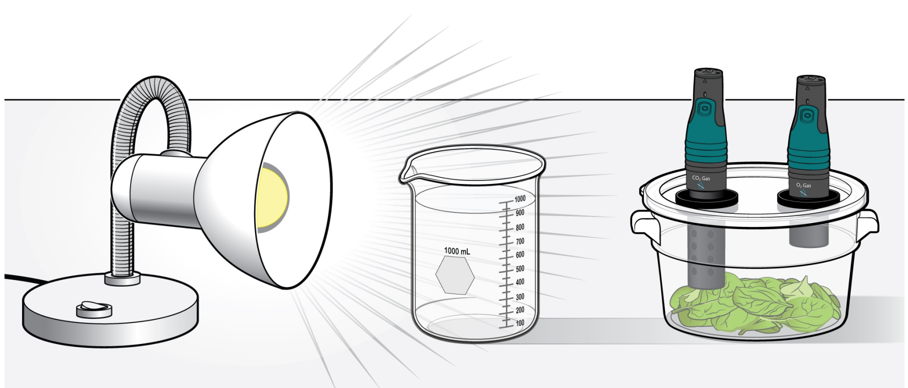


Figure 1

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis app
Go Direct O_2 Gas
Go Direct CO_2 Gas
BioChamber 2000
600 mL beaker
aluminum foil
spinach leaves
goggles

PROCEDURE

1. Wrap the BioChamber with aluminum foil so that no light will reach the leaves.
   a. Wrap the outside of the chamber with foil.
   b. Cover the lid with foil, poking the holes open to insert the sensors.
2. Cover the bottom of the chamber with a one centimeter layer of fresh, turgid spinach leaves.
3. Launch Graphical Analysis. Connect the CO_2 Gas Sensor and the O_2 Gas Sensor to your Chromebook, computer, or mobile device.
4. Set up the data-collection mode.
   a. Click or tap Mode to open Data Collection Settings.
   b. Change Rate to 15 samples/min and End Collection to 15 min. Click or tap Done.
5. Change the unit to ppt by clicking or tapping the CO_2 meter and choosing ppt from the Units menu. Repeat the process with the Oxygen Gas meter to select ppt as the units for the O_2 Gas Sensor.
6. Secure the lid on the chamber and insert the sensors into the holes.
7. Wait 5 minutes for the sensors to equilibrate, then click or tap Collect to start data collection.
8. When data collection is complete, determine the rate of respiration/photosynthesis.
   a. Click or tap Graph Tools, , for the CO_2 graph and choose Apply Curve Fit.
   b. Select Linear as the curve fit. Click or tap Apply.
   c. Record the slope of the line, m, as the rate of respiration/photosynthesis for CO_2 in Table 1.
   d. Repeat this process for the O_2 data.
9. Make a heat sink by filling a 600 mL beaker with water.
10. Set up the lamp and heat sink as shown in Figure 1. **Important**: Do not turn the lamp on until instructed to do so.
11. Remove the aluminum foil from the respiration chamber.
12. Turn on the lamp.

13. Repeat Steps 7–8 to collect and analyze data for photosynthesis. **Note**: Data from the previous run will automatically be stored.

14. Graph both runs of data on a single graph.
    a. To display multiple data sets on a single graph, click or tap the y-axis label and select the data sets you want to display. Dismiss the box to view the graph.
    b. Use the displayed graph and Table 1 to answer the questions below.

15. Clean and dry the respiration chamber.

DATA

Table 1		
Leaves	CO_2 Rate of respiration/photosynthesis (ppt/min)	O_2 Rate of respiration/photosynthesis (ppt/min)
In the dark		
In the light		

QUESTIONS

1. Was either of the rate values for CO_2 a positive number? If so, what is the biological significance of this?

2. Was either of the rate values for O_2 a negative number? If so, what is the biological significance of this?

3. Do you have evidence that cellular respiration occurred in leaves? Explain.

4. Do you have evidence that photosynthesis occurred in leaves? Explain.

5. List five factors that might influence the rate of oxygen production or consumption in leaves. Explain how you think each will affect the rate.

EXTENSIONS

1. Design and perform an experiment to test one of the factors that might influence the rate of oxygen production or consumption in Question 5.

2. Compare the rates of photosynthesis and respiration among various types of plants.

Photosynthesis and Respiration

1. The experiments in this book were selected to provide a sampling of Vernier experiments that cover several subjects and key scientific concepts. The downloaded zip file contains PDF files of the student experiments. You can print the PDF, distribute it to students electronically, or post the file to a password-protected class web page or learning management system.

2. This experiment was adapted from *Biology with Vernier*, Experiment 31. Learn more at **vernier.com/bwv**

3. Plant material used must be fresh, moist, and turgid. Spinach leaves purchased from a grocery store work very well and are readily available any time of the year.

4. For best results, the spinach should be stored in a refrigerator or in a cooler. If kept cold, the spinach should produce good results for several days.

5. Each class period should use fresh spinach leaves directly from the refrigerator or cooler so the leaves stay as fresh as possible.

6. Before placing the spinach in the BioChamber, the leaves should be gently dried off with paper towels. Excess moisture on the leaves can cause condensation in the chamber, affecting the results.

7. The type of light bulb is very important for this experiment.
   - We recommend 12 W LED grow lights; they give the best results because they provide the correct wavelengths for photosynthesis and produce minimal heat energy.
   - 35 W halogen, flood-beam bulbs or standard 100 W incandescent bulbs can work. However, both bulbs radiate a lot of heat energy, which can affect the results.
   - 12-inch, fluorescent ring lamps work well because they fit nicely around the BioChamber 2000, bathe the leaves in light from all sides, and give off little heat energy. However, they can be difficult to obtain. Note that this type of bulb requires a ballast that screws into a plug-in socket adapter.

   For more information see **www.vernier.com/til/1519**

8. A heat sink is recommended to protect the spinach leaves no matter what type of light source you use. A 600 mL beaker can be used but a tissue culture flask filled with water makes a good heat sink because it is thinner, and will allow the leaves to receive much more light from the same lamp than a beaker.

9. The waiting time before starting data collection may need to be lengthened depending on the rate of gas production. You may wish to monitor the gas concentrations and start collecting data when the levels of gas begin to move in the correct direction. It may take up to 15 minutes under some conditions.

10. See **www.vernier.com/start/go-direct** for information about how to connect to your Go Direct sensors in Graphical Analysis.

11. For additional information about the Vernier probeware used in this experiment, including tips and product specifications, visit **www.vernier.com/manuals** and download the appropriate user manual.

ESTIMATED TIME

We estimate that setup and data collection can be completed in one 45-minute class period.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Analyzing and Interpreting Data Developing and Using Models	LS1.A: Structure and Function LS1.C: Organization for Matter and Energy Flow in Organisms LS2.B: Cycles of Matter and Energy Transfer in Ecosystems	Cause and Effect Structure and Function Energy and Matter Systems and System Models

SAMPLE RESULTS

Leaves	Rate of respiration/photosynthesis (ppt/min)
In the dark	0.0177
In the light	–0.0202

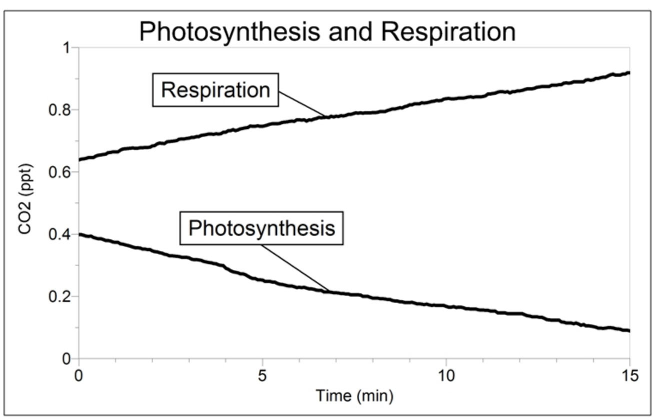


Figure 1

ANSWERS TO QUESTIONS

1. The CO_2 rate value for leaves in the dark was a positive number. The biological significance of this is that CO_2 is produced during respiration. This causes the concentration of CO_2 to increase, as sugar is oxidized and broken into CO_2, water, and energy.

2. The rate value for leaves in the light was a negative number. The biological significance of this is that CO_2 is consumed during photosynthesis. This causes the concentration of CO_2 to decrease, as the CO_2 is converted into glucose.

3. Yes, cellular respiration occurred in leaves, since CO_2 increased when leaves were in the dark and photosynthesis was not possible.

4. Yes, photosynthesis occurred in leaves, since CO_2 decreased when leaves were exposed to light.

5. Answers may vary. They might include:
   a. A greater number of leaves should increase the rate, since there are more chloroplasts to undergo photosynthesis and more cells to require energy through cellular respiration.
   b. A greater light intensity will increase the rate of photosynthesis. It may not affect the rate of cellular respiration, however.
   c. A cooler room may decrease both rates, as cellular metabolism decreases in cooler weather.
   d. Facing the top of the leaves toward the light should increase the rate of photosynthesis, since the chloroplasts are closer to the light source.
   e. If the plants overheat due to the heat from the lamp, they may wilt and stop functioning. This will decrease all rates.
   f. If there are too many leaves, diffusion may be restricted and prevent accurate readings. This may apparently decrease both rates.

Freezing and Melting of Water

Freezing temperature, the temperature at which a substance turns from liquid to solid, and melting temperature, the temperature at which a substance turns from a solid to a liquid, are characteristic physical properties. In this experiment, the cooling and warming behavior of a familiar substance, water, will be investigated. By examining graphs of the data, the freezing and melting temperatures of water will be determined and compared.

OBJECTIVES

- Collect temperature data during the freezing and melting of water.
- Analyze graphs to determine the freezing and melting temperatures of water.
- Determine the relationship between the freezing and melting temperatures of water.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis app
Go Direct Temperature
ring stand
utility clamp
10 mL graduated cylinder
400 mL beaker
test tube
stirring rod
salt
ice
distilled water
tap water

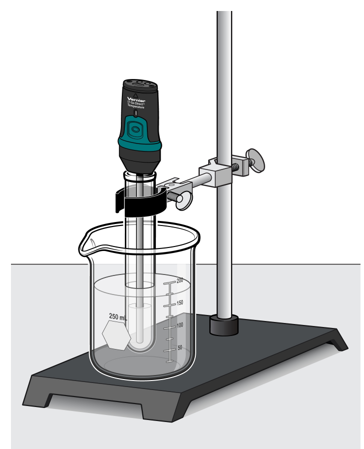


Figure 1

PROCEDURE

Part I Freezing

1. Fill a 400 mL beaker 1/3 full with ice, then add 100 mL of tap water.

2. Put 5 mL of distilled water into a test tube and use a utility clamp to fasten the test tube to a ring stand. The test tube should be situated above the water bath. Place the Temperature Probe into the water inside the test tube.

3. Launch Graphical Analysis. Connect the Temperature Probe to your Chromebook, computer, or mobile device.

4. Click or tap Mode to open Data Collection Settings. Change Rate to 0.2 samples/s and End Collection to 900 s. Click or tap Done.

5. When everything is ready, click or tap Collect to start data collection. Lower the test tube into the ice-water bath.

6. Soon after lowering the test tube, add 5 spoons of salt to the beaker. Continue to stir the ice-water bath throughout the remainder of Part I.

7. Slightly, but continuously, move the Temperature Probe during the first 10 minutes of Part I. Be careful to keep the probe in, and not above, the ice as it forms. When 10 minutes have gone by, stop moving the probe and allow it to freeze into the ice. Add more ice cubes to the beaker as the original ice cubes get smaller.

8. Data collection will stop after 15 minutes. Keep the test tube submerged in the ice-water bath until Step 10.

9. Analyze the flat part of the graph to determine the freezing temperature of water.
   a. Select the flat region of the graph that represents freezing.
   b. Click or tap Graph Tools, , and choose View Statistics.
   c. Record the mean (average) temperature. This is your value for the freezing temperature of water.

Part II Melting

10. Click or tap Collect to start data collection, then raise the test tube and fasten it in a position above the ice-water bath. Do not move the Temperature Probe during Part II. **Note**: The previous data set is automatically saved.

11. Dispose of the ice water as directed by your teacher. Obtain 250 mL of warm tap water in the beaker. When 12 minutes have passed, lower the test tube and its contents into this warm-water bath.

12. Data collection will stop after 15 minutes. Analyze the flat part of the graph to determine the melting temperature of water.
    a. Select the flat portion of the graph that represents melting.
    b. Click or tap Graph Tools, , and choose View Statistics.
    c. Record the mean (average) temperature. This is your value for the melting temperature of water.

13. A good way to compare the freezing and melting curves is to view both sets of data on one graph. To do this, click or tap the y-axis label and select the data sets you want to display. Dismiss the box to view the graph.

14. (optional) To annotate your graph, click or tap Graph Tools, , and choose Add Annotation. Export, download, or print a graph of temperature *vs*. time (with two curves displayed).

DATA TABLE

Freezing temperature of water (°C)	
Melting temperature of water (°C)	

PROCESSING THE DATA

1. What happened to the water temperature during freezing? During melting?

2. According to your data and graph, what is the freezing temperature of water? The melting temperature? Express your answers to the nearest 0.1°C.

3. How does the freezing temperature of water compare to its melting temperature?

4. Tell if the *kinetic energy* of the water in the test tube increases, decreases, or remains the same in each of these time segments during the experiment when:
   a. the temperature is changing at the beginning and end of Part I.
   b. the temperature remains constant in Part I.
   c. the temperature is changing at the beginning and end of Part II.
   d. the temperature remains constant in Part II.

5. In those parts of Question 4 in which there was no kinetic energy change, tell if *potential energy* increased or decreased.

Freezing and Melting of Water

1. The experiments in this book were selected to provide a sampling of Vernier experiments that cover several subjects and key scientific concepts. The downloaded zip file contains PDF files of the student experiments. You can print the PDF, distribute it to students electronically, or post the file to a password-protected class web page or learning management system.
2. This experiment was adapted from *Chemistry with Vernier*, Experiment 02. Learn more at **vernier.com/cwv**
3. This entire experiment requires a full 45–50 minute period. We recommend that students perform Experiment 1 before this one because it was designed to give students familiarity with the data-collection equipment. As the Sample Data show, this procedure can give excellent results.
4. The stored calibration for all Vernier temperature probes works well for this experiment—the freezing and melting temperatures of water should be within ±0.2°C of 0°C using these calibrations. For additional information about the Vernier probeware used in this experiment, including tips and product specifications, visit **www.vernier.com/manuals** and download the appropriate user manual.
5. We recommend 12 × 120 mm test tubes for this experiment.
6. A water sample size of 5 mL works well. Larger samples will take more time than is recommended in this procedure. Before performing the experiment with your students, we suggest testing to find the volume that works best for your temperature probes and test tubes.
7. As shown in the first graph in the Sample Results, many of the samples will supercool. Stirring will bring the super-cooled water to the melting temperature plateau.
8. For additional information about the Vernier probeware used in this experiment, including tips and product specifications, visit **www.vernier.com/manuals** and download the appropriate user manual.
9. See **www.vernier.com/start/go-direct** for information about how to connect to your Go Direct sensors in Graphical Analysis.

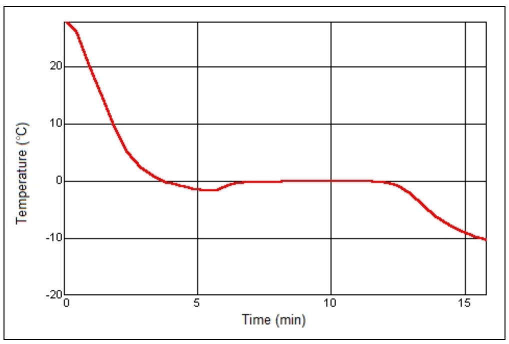
ANSWERS TO QUESTIONS

1. The water temperature stayed constant near 0°C during freezing and melting.
2. The expected value is 0°C for both the freezing and melting temperatures, but answers will vary slightly.
3. The freezing and melting temperatures of water are the same.

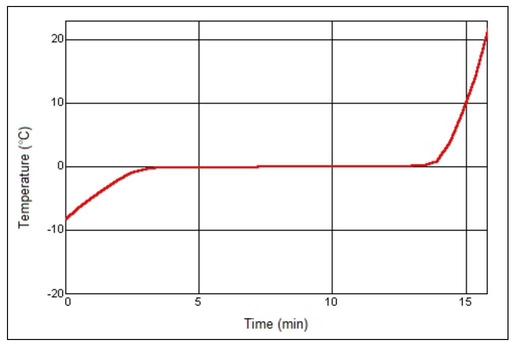
4. Student answers:
   a. Average kinetic energy decreases with the temperature decrease at the beginning and end of Part I
   b. Since there is no temperature change during freezing, average kinetic energy remains constant.
   c. Average kinetic energy increases with the temperature increase at the beginning and end of Part II.
   d. Since there is no temperature change during melting, average kinetic energy is constant.

5. Student answers:
   b. Potential energy decreased during freezing
   d. Potential energy increased during melting.

SAMPLE DATA



Part I: Freezing water



Part II: Melting water

Boyle's Law: Pressure-Volume Relationship in Gases

The primary objective of this experiment is to determine the relationship between the pressure and volume of a confined gas. The gas we use will be air, and it will be confined in a syringe connected to a gas pressure sensor (see Figure 1). When the volume of the syringe is changed by moving the piston, a change occurs in the pressure exerted by the confined gas. This pressure change will be monitored using a gas pressure sensor. It is assumed that temperature will be constant throughout the experiment. Pressure and volume data pairs will be collected during this experiment and then analyzed. From the data and graph, you should be able to determine what kind of mathematical relationship exists between the pressure and volume of the confined gas. Historically, this relationship was first established by Robert Boyle in 1662 and has since been known as Boyle's law.

OBJECTIVES

- Use a gas pressure sensor and a gas syringe to measure the pressure of an air sample at several different volumes.
- Determine the relationship between pressure and volume of the gas.
- Describe the relationship between gas pressure and volume in a mathematical equation.
- Use the results to predict the pressure at other volumes.

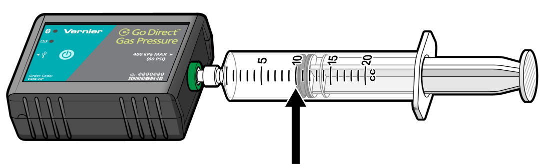


Figure 1

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis app
Go Direct Gas Pressure
20 mL gas syringe

PROCEDURE

1. Prepare the data-collection equipment and an air sample for data collection.
   a. Launch Graphical Analysis. Connect the Gas Pressure Sensor to your Chromebook, computer, or mobile device.

b. With the 20 mL syringe disconnected from the Gas Pressure Sensor, move the piston of the syringe until the front edge of the inside black ring (indicated by the arrow in Figure 1) is positioned at the 10.0 mL mark.

c. Attach the 20 mL syringe to the valve of the Gas Pressure Sensor.

2. Set up the data-collection mode.
   a. Click or tap Mode to open Data Collection Settings. Change Mode to Event Based.
   b. Enter **Volume** as the Event Name and **mL** as the Units. Click or tap Done.

3. To obtain the best data possible, you will need to correct the volume readings from the syringe. Look at the syringe; its scale reports its own internal volume. However, that volume is not the total volume of trapped air in your system since there is a little bit of space inside the pressure sensor.

   To account for the extra volume in the system, you will need to add 0.8 mL to your syringe readings. For example, with a 5.0 mL syringe volume, the total volume would be 5.8 mL. It is this total volume that you will need for the analysis.

4. You are now ready to collect pressure and volume data. It is easiest if one person takes care of the gas syringe and another enters volumes.
   a. Click or tap Collect to start data collection.
   b. Move the piston so the front edge of the inside black ring (see Figure 2) is positioned at the 5.0 mL line on the syringe. Hold the piston firmly in this position until the pressure value displayed on the screen stabilizes.
   c. Click or tap Keep and enter **5.8**, the gas volume (in mL). Remember, you are adding 0.8 mL to the volume of the syringe for the total volume. Click or tap Keep Point to store this pressure-volume data pair.

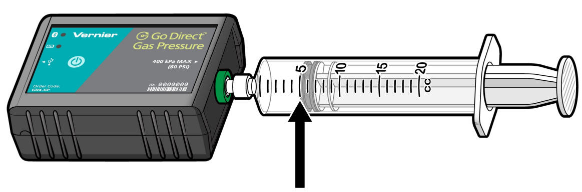


Figure 2

   d. Continue this procedure using syringe volumes of 10.0, 12.5, 15.0, 17.5, and 20.0 mL.
   e. Click or tap Stop to stop data collection.

5. When data collection is complete, a graph of pressure *vs*. volume will be displayed. To examine the data pairs on the displayed graph, tap any data point. As you tap each data point, the pressure and volume values are displayed to the right of the graph. Record the pressure and volume data values in your data table.

6. Based on the graph of pressure *vs*. volume, decide what kind of mathematical relationship exists between these two variables, direct or inverse. To see if you made the right choice:
   a. Click or tap Graph Tools, , and choose Apply Curve Fit.
   b. Select Power as the curve fit and Dismiss the Curve Fit box. The curve fit statistics are displayed for the equation in the form

   $$y = ax^b$$

   where x is volume, y is pressure, a is a proportionality constant, and b is the exponent of x (volume) in this equation. **Note**: The relationship between pressure and volume can be determined from the value and sign of the exponent, b.
   c. If you have correctly determined the mathematical relationship, the regression line should very nearly fit the points on the graph (that is, pass through or near the plotted points).
   d. Rescale the axes on your graph by clicking or tapping Graph Tools, . Choose Edit Graph Options and set the x-axis to display 0 to 25 mL and the y-axis to display 0 to 300 kPa. Dismiss the Graph Options box.
   e. (optional) Export, download, or print the graph with the curve fit displayed.
7. With the best-fit curve still displayed, proceed directly to the Processing the Data section.

DATA AND CALCULATIONS

Volume (mL)	Pressure (kPa)	Constant, *k* (P / V or P • V)

PROCESSING THE DATA

1. With the best-fit curve still displayed, click or tap Graph Tools, , and turn on Interpolate. Dismiss the Graph Tools box and click the graph to interpolate. Move along the regression line until the volume value is 5.0 mL. Note the corresponding pressure value. Now move to the point where the volume value is doubled (10.0 mL). What does your data show happens to the pressure when the volume is *doubled*? Show the pressure values in your answer.

2. Using the same technique as in Question 1, what does your data show happens to the pressure if the volume is *halved* from 20.0 mL to 10.0 mL? Show the pressure values in your answer.

3. Using the same technique as in Question 1, what does your data show happens to the pressure if the volume is *tripled* from 5.0 mL to 15.0 mL? Show the pressure values in your answer.

4. From your answers to the first three questions *and* the shape of the curve in the plot of pressure *vs*. volume, do you think the relationship between the pressure and volume of a confined gas is direct or inverse? Explain your answer.

5. Based on your data, what would you expect the pressure to be if the volume of the syringe was increased to 40.0 mL? Explain or show work to support your answer.

6. Based on your data, what would you expect the pressure to be if the volume of the syringe was decreased to 2.5 mL? Explain or show work to support your answer.

7. What experimental factors are assumed to be constant in this experiment?

8. One way to determine if a relationship is inverse or direct is to find a proportionality constant, k, from the data. If this relationship is direct, $k = P/V$. If it is inverse, $k = P \bullet V$. Based on your answer to Question 4, choose one of these formulas and calculate k for the seven ordered pairs in your data table (divide or multiply the P and V values). Show the answers in the third column of the Data and Calculations table.

9. How *constant* were the values for k you obtained in Question 8? Good data may show some minor variation, but the values for k should be relatively constant.

10. Using P, V, and k, write an equation representing Boyle's law. Write a verbal statement that correctly expresses Boyle's law.

EXTENSION

1. To confirm that an inverse relationship exists between pressure and volume, a graph of pressure *vs*. *reciprocal of volume* (1/volume) may also be plotted. To do this, it is necessary to create a new column of data, reciprocal of volume, based on your original volume data:
   a. Click or tap More Options, , in the Volume column header in the table. Choose Add Calculated Column.
   b. Enter **1/volume** as the Name and **1/mL** as the Units.
   c. Click or tap Insert Expression and choose A/X as the expression.
   d. Enter **1** as Parameter A and select Volume as the Column.
   e. Click or tap Apply.

2. Plot a best-fit regression line on your graph of pressure *vs*. 1/volume:
   a. Click or tap Graph Tools, , and choose Edit Graph Options.
   b. Enter **0** as the value for both the Left value for the x-axis and the Bottom value for the y-axis.
   c. Dismiss the Graph Options box. Your graph should now include the origin (0,0).
   d. Click or tap Graph Tools, , and choose Apply Curve Fit.

e. Select Linear as the curve fit and Dismiss the Curve Fit box. The linear-regression statistics are displayed in the form:

$$y = mx + b$$

where x is 1/volume, y is pressure, m is a proportionality constant, and b is the y-intercept.

f. If the relationship between P and V is an inverse relationship, the graph of pressure *vs.* 1/volume should be direct; that is, the curve should be linear and pass through (or near) the origin. Examine your graph to see if this is true for your data.

Boyle's Law: Pressure-Volume Relationship in Gases

1. The experiments in this book were selected to provide a sampling of Vernier experiments that cover several subjects and key scientific concepts. The downloaded zip file contains PDF files of the student experiments. You can print the PDF, distribute it to students electronically, or post the file to a password-protected class web page or learning management system.

2. This experiment was adapted from *Chemistry with Vernier*, Experiment 06. Learn more at **vernier.com/cwv**

3. This experiment is written for the Gas Pressure Sensor and the Go Direct Gas Pressure Sensor. The default calibration for this experiment has units of kPa (kilopascals). You can use other units (mmHg, atm, or psi) by changing them in the data-collection software.

4. In order to save time, you may prefer to do Step 1 of the student Procedure prior to the start of class.

5. As explained in the student procedures, this experiment is written to compensate for the small inside volume of the white stem that leads to the inside of the Gas Pressure Sensor. The volume of this space is about 0.8 mL. This means that when students enter a volume of 5.0 mL (as read on the syringe), the volume is really about 5.8 mL. To compensate for this error, the students are instructed add 0.8 mL to each of the volumes they enter. By doing this, they will get better results for the value of the exponent, *b*, in Step 7.

6. You should never have to perform a new calibration when using the Gas Pressure Sensor in pressure experiments. Simply use the stored calibration. For additional information about the Vernier probeware used in this experiment, including tips and product specifications, visit **www.vernier.com/manuals** and download the appropriate user manual.

7. Question 8 in the Processing the Data section asks the students to calculate a proportionality constant, *k*, using the equation, $k = P \bullet V$. Your students can do this manually, or you could have them create a calculated column in Graphical Analysis using the following directions:
   a. In the data table, click or tap More Options, ⋯, in the column header of one of the columns. Then, choose Add Calculated Column.
   b. Enter a Name and units for your new column of data.
   c. Click or tap Insert Expression and choose the function to perform on your data.
   d. Adjust the variables and/or columns that match your function and data. Click or tap Apply.
   e. Click Done.
   f. To change what is displayed on the graph, click or tap the x- or y-axis label and select only the columns you want to display. Dismiss the box and then rescale the graph axes if necessary.

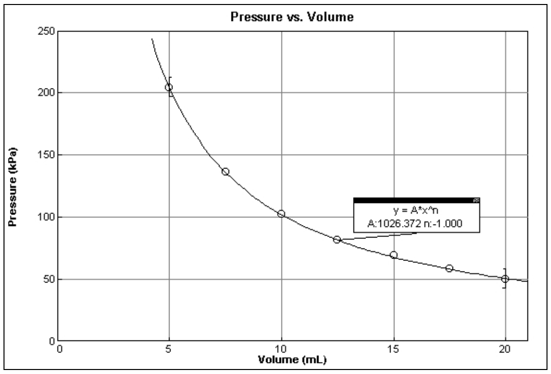
8. See **www.vernier.com/start/go-direct** for information about how to connect to your Go Direct sensors in Graphical Analysis.

ANSWERS TO QUESTIONS

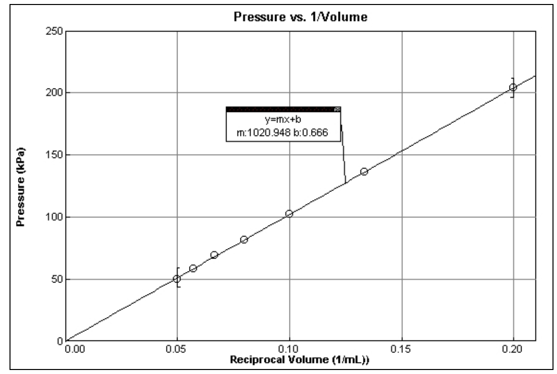
1. When the volume was doubled, the pressure was halved (pressure went from 204.6 kPa to 103.3 kPa).
2. When the volume was halved, the pressure doubled (pressure went from 50.7 kPa to 103.3 kPa).
3. The pressure is reduced by a factor of 1/3 (pressure went from 204.6 kPa to 69.9 kPa).
4. From the data, the relationship appears to be inverse. When pressure data increases, volume data seems to decrease proportionally. The shape of the pressure-volume plot appears to be a simple inverse relationship.
5. If the volume is increased to 40.0 mL, one would expect the pressure to be 1/2 of what it was at 20.0 mL. This would be a pressure of approximately 25 kPa.
6. If the volume were reduced to 2.5 mL, one would expect the pressure to be double what it was at 5.0 mL. This would be a pressure of approximately 400 kPa.
7. The temperature and the number of molecules in the gas sample are assumed to be constant.
8. The correct formula for an inverse relationship is: $k = P \bullet V$. For k values, see the third column of the sample results on this page (1027 kPa•mL is the average value for the constant, k).
9. Values were quite constant, with a very small deviation.
10. The equation representing Boyle's law is: $k = P \bullet V$. The pressure of a confined gas varies inversely with the volume of the gas if the temperature of the sample remains constant.

SAMPLE RESULTS

Volume (mL)	Pressure (kPa)	Constant, *k* (kPa•mL)
5.8	175.9	1020
7.8	131.4	1025
9.8	105.1	1030
11.8	87.0	1027
13.8	74.4	1027
15.8	65.1	1029
17.8	57.6	1025
19.8	52.0	1030



Pressure vs. *volume*



Pressure vs. *reciprocal of volume*

Acid-Base Titration

A titration is a process used to determine the volume of a solution needed to react with a given amount of another substance. In this experiment, you will titrate hydrochloric acid solution, HCl, with a basic sodium hydroxide solution, NaOH. The concentration of the NaOH solution is given and you will determine the unknown concentration of the HCl. Hydrogen ions from the HCl react with hydroxide ions from the NaOH in a one-to-one ratio to produce water in the overall reaction:

$$H^+(aq) + Cl^-(aq) + Na^+(aq) + OH^-(aq) \rightarrow H_2O(l) + Na^+(aq) + Cl^-(aq)$$

When an HCl solution is titrated with an NaOH solution, the pH of the acidic solution is initially low. As base is added, the change in pH is quite gradual until close to the equivalence point, when equimolar amounts of acid and base have been mixed. Near the equivalence point, the pH increases very rapidly, as shown in Figure 1. The change in pH then becomes more gradual again, before leveling off with the addition of excess base.

In this experiment, you will use a pH Sensor to monitor pH as you titrate. The region of most rapid pH change will then be used to determine the equivalence point. The volume of NaOH titrant used at the equivalence point will be used to determine the molarity of the HCl.

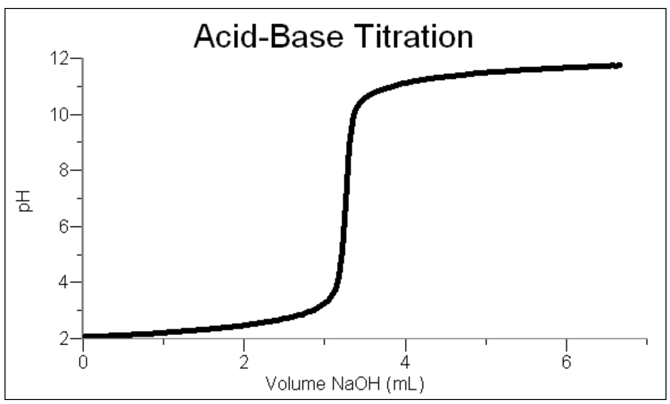


Figure 1

OBJECTIVES

- Use a pH Sensor to monitor changes in pH as sodium hydroxide solution is added to a hydrochloric acid solution.
- Plot a graph of pH *vs*. volume of sodium hydroxide solution added.
- Use the graph to determine the equivalence point of the titration.
- Use the results to calculate the concentration of the hydrochloric acid solution.

MATERIALS

Materials for both Method 1 (buret) and Method 2 (Drop Counter)

Chromebook, computer, **or** mobile device	HCl solution, unknown concentration
Graphical Analysis app	~0.1 M NaOH solution
Go Direct pH	pipet bulb or pump
Stir Station	250 mL beaker
magnetic stirring bar	wash bottle
(optional) Phenolphthalein	distilled water

Materials required only for Method 1 (buret)

Electrode Support	buret clamp or utility clamp
50 mL buret	2nd 250 mL beaker
10 mL pipet	

Materials required only for Method 2 (Drop Counter)

Go Direct Drop Counter	100 mL beaker
60 mL reagent reservoir	10 mL graduated cylinder
5 mL pipet or graduated 10 mL pipet	utility clamp

CHOOSE A METHOD

Method 1: Deliver volumes of NaOH titrant from a buret. After titrant is added, and pH values have stabilized, the student is prompted to enter the buret reading manually and a pH-volume data pair is stored.

Method 2: Use a Vernier Drop Counter to take volume readings. NaOH titrant is delivered drop by drop from the reagent reservoir through the Drop Counter slot. After the drop reacts with the reagent in the beaker, the volume of the drop is calculated, and a pH-volume data pair is stored.

METHOD 1: Measuring Volume Using a Buret

1. Obtain and wear goggles.

2. Use a pipet bulb (or pipet pump) to pipet 10 mL of the HCl solution into a 250 mL beaker. Add 50 mL of distilled water. **DANGER**: *Hydrochloric acid solution,* HCl: *Causes severe skin and eye damage. Do not breathe mist, vapors, or spray. May cause respiratory irritation. May be harmful if swallowed*.

3. Place the beaker on a Stir Station and add a stirring bar.

4. Launch Graphical Analysis. Connect the pH Sensor to your Chromebook, computer, or mobile device.

5. Set up the data-collection mode.
   a. Click or tap Mode to open Data Collection Settings. Change Mode to Event Based.
   b. Enter **Volume** as the Event Name and **mL** as the Units. Click or tap Done.

6. Use an Electrode Support to suspend a pH Sensor on a Stir Station (see Figure 2). Position the pH Sensor in the HCl solution and adjust its position so it will not be struck by the stirring bar. Turn on the Stir Station, and adjust it to a medium stirring rate (with no splashing of solution). Check to see that the pH value is between 1.5 and 2.5.

Figure 2

7. Obtain a 50 mL buret and rinse the buret with a few mL of the ~0.1 M NaOH solution. Dispose of the rinse solution as directed by your teacher. **WARNING**: *Sodium hydroxide solution,* NaOH: *Causes skin and eye irritation.*

   Use a buret clamp or a utility clamp to attach the buret to the Stir Station as shown in Figure 2. Fill the buret a little above the 0.00 mL level of the buret with ~0.1 M NaOH solution. Drain a small amount of NaOH solution so it fills the buret tip *and* leaves the NaOH at the 0.00 mL level of the buret. Record the precise concentration of the NaOH solution in your data table.

8. You are now ready to perform the titration. This process is faster if one person manipulates and reads the buret while another person enters volumes.
   a. Click or tap Collect to start data collection.
   b. Before you have added any drops of NaOH solution, click or tap Keep and enter **0** as the buret volume in mL. Click or tap Keep Point to store the first data pair for this experiment.
   c. Add the next increment of NaOH titrant (enough to raise the pH about 0.15 units). When the pH stabilizes, click or tap Keep, enter the current buret reading (to the nearest 0.01 mL), and then click or tap Keep Point.
   d. Continue adding NaOH solution in increments that raise the pH by about 0.15 units and enter the buret reading after each increment. When a pH value of approximately 3.5 is reached, change to a one-drop increment. Enter a new buret reading after each increment. **Note**: It is important that all increment volumes in this part of the titration be equal; that is, one-drop increments.

e. After a pH value of approximately 10 is reached, again add larger increments that raise the pH by about 0.15 pH units, and enter the buret level after each increment.
f. Continue adding NaOH solution until the pH value remains constant.

9. Click or tap Stop to stop data collection.

10. Examine the data on the graph of pH *vs*. volume to find the *equivalence point*—that is the largest increase in pH upon the addition of 1 drop of NaOH solution. Move to the region of the graph with the largest increase in pH (you can adjust the Examine line by dragging the flag). Find the NaOH volume just *before* this jump. Record this value in the data table. Then record the NaOH volume *after* the drop producing the largest pH increase was added. **Note**: Another method for determining the equivalence-point volume is described in the Alternate Equivalence Point Method of this experiment.

11. (optional) Export, download, or print a copy of the graph of pH *vs*. volume.

12. Dispose of the beaker contents as directed by your teacher. Rinse the pH Sensor and return it to the pH storage solution.

METHOD 2: Measuring Volume with a Drop Counter

1. Obtain and wear goggles.

2. Add 40 mL of distilled water to a 100 mL beaker. Use a pipet bulb (or pipet pump) to pipet 5.00 mL of the HCl solution into the 100 mL beaker with distilled water.
   DANGER: *Hydrochloric acid solution,* HCl: *Causes severe skin and eye damage. Do not breathe mist, vapors, or spray. May cause respiratory irritation. May be harmful if swallowed*.

3. Obtain approximately 40 mL of ~0.1 M NaOH solution in a 250 mL beaker. Record the precise NaOH concentration in your data table. **WARNING**: *Sodium hydroxide solution,* NaOH: *Causes skin and eye irritation.*

4. Obtain the plastic 60 mL reagent reservoir. **Note**: The bottom valve will be used to open or close the reservoir, while the top valve will be used to finely adjust the flow rate. For now, close both valves by turning the handles to a horizontal position.

   Rinse the reagent reservoir with a few mL of the ~0.1 M NaOH solution. Attach the reagent reservoir to the Stir Station. Add the remainder of the NaOH solution to the reagent reservoir.

   Drain a small amount of NaOH solution into the 250 mL beaker so it fills the reservoir's tip. To do this, turn both valve handles to the vertical position for a moment, then turn them both back to horizontal.

5. Launch Graphical Analysis. Connect the pH Sensor and the Drop Counter to your Chromebook, computer, or mobile device.

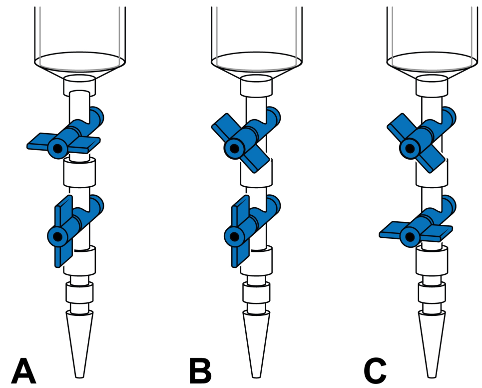


Figure 3

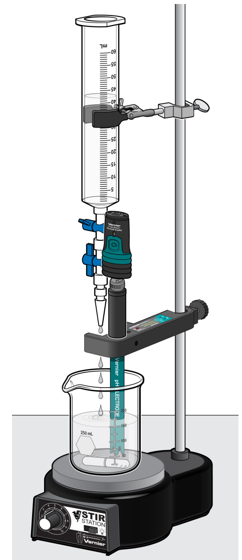


Figure 4

6. Calibrate the Drop Counter so that a precise volume of titrant is recorded in units of milliliters.
   a. Attach the Drop Counter to the Stir Station.
   b. Adjust the handles on the reagent reservoir so the top valve is closed (horizontal) and the bottom valve is open (vertical) (see Figure 3A).
   c. Place a 10 mL graduated cylinder directly below the slot on the Drop Counter, lining it up with the tip of the reagent reservoir.
   d. Click or tap the Volume meter and choose Calibrate.
   e. Follow the on-screen prompts to calibrate the Drop Counter. To adjust the drop flow, slowly open the top valve of the reagent reservoir (see Figure 3B) so that drops are released at a slow rate (~1 drop every two seconds). When the volume of solution in the graduated cylinder is between 9 and 10 mL close the bottom valve (see Figure 3C).
   f. Discard the solution in the graduated cylinder as indicated by your instructor and set the graduated cylinder aside.

7. Assemble the apparatus.
   a. Insert the pH Sensor through the large hole in the Drop Counter.
   b. Adjust the positions of the Drop Counter and reagent reservoir so they are both lined up with the center of the Stir Station.
   c. Lift up the pH Sensor, and slide the beaker containing the HCl solution onto the Stir Station. Lower the pH Sensor into the beaker. Check to see that the pH value is between 1.5 and 2.5.
   d. Place the stirring bar in the beaker and adjust the position of the pH Sensor so that it will not be struck by the stirring bar.
   e. Adjust the reagent reservoir so its tip is just above the Drop Counter slot.

8. Turn on and adjust the Stir Station so it is stirring at a fast rate.

9. You are now ready to begin collecting data. Click or tap Collect to start data collection. No data will be collected until the first drop goes through the Drop Counter slot. Fully open the **bottom valve**—the top valve should still be adjusted so drops are released at a rate of about 1 drop every 2 seconds. When the first drop passes through the Drop Counter slot, check the graph to see that the first data pair was recorded.

10. Continue watching your graph to see when a large increase in pH takes place—this will be the equivalence point of the reaction. When this jump in pH occurs, let the titration proceed for several more milliliters of titrant, then click or tap Stop to stop data collection. Turn the bottom valve of the reagent reservoir to a closed (horizontal) position.

11. Dispose of the beaker contents as directed by your teacher.

12. Examine the data on the graph of pH *vs*. volume to find the *equivalence point*. Move to the region of the graph with the largest increase in pH. Find the NaOH volume just *before* this jump. Record this value in the data table. Then record the NaOH volume *after* the drop producing the largest pH increase was added. **Note**: Another method for determining the equivalence-point volume is described in the Alternate Equivalence Point Method of this experiment.

13. (optional) Export, download, or print the graph.

14. If time permits, repeat the procedure.

ALTERNATE EQUIVALENCE POINT METHOD

An alternate way of determining the precise equivalence point of the titration is to take the first and second derivatives of the pH-volume data.

1. Determine the peak value on the first derivative *vs*. volume plot.
   a. Click or tap Column Options, ⋯, in the pH column header in the table. Then, choose Add Calculated Column.
   b. Enter **d1** as the Name and leave the Units field blank.
   c. Click or tap Insert Expression and choose 1st Derivative(Y,X) as the expression.
   d. Select pH as Column Y and Volume as Column X. Click or tap Apply.
   e. To display a graph of d1 *vs*. volume, click or tap the y-axis label, select only d1, and dismiss the box.
   f. On the graph of d1 *vs*. volume, examine the data to determine the volume at the peak value of the first derivative.
2. Determine the zero value on the second derivative *vs*. volume plot.
   a. Click or tap More Options, ⋯, in the Volume column header in the table. Then, choose Add Calculated Column.
   b. Enter **d2** as the Name and leave the Units field blank.
   c. Click or tap Insert Expression and choose 2nd Derivative(Y,X) as the expression.
   d. Select pH as Column Y and Volume as Column X. Click or tap Apply.

e. Click or tap the y-axis label, select only d2 to display a graph of d1 *vs*. volume, and dismiss the box.

f. Click or tap the y-axis label, select only the d2 column, and dismiss the box. On the displayed graph of d2 *vs*. volume, examine the data to determine the volume when the 2nd derivative equals approximately zero.

DATA TABLE

Concentration of NaOH	M	M
NaOH volume added before largest pH increase	mL	mL
NaOH volume added after largest pH increase	mL	mL

Volume of NaOH added at equivalence point	mL	mL
Moles NaOH	mol	mol
Moles HCl	mol	mol
Concentration of HCl	mol/L	mol/L
Average [HCl]	M	

Acid-Base Titration

1. The experiments in this book were selected to provide a sampling of Vernier experiments that cover several subjects and key scientific concepts. The downloaded zip file contains PDF files of the student experiments. You can print the PDF, distribute it to students electronically, or post the file to a password-protected class web page or learning management system.

2. This experiment was adapted from *Chemistry with Vernier*, Experiment 24. Learn more at **vernier.com/cwv**

3. Experiment 23, "Titration Curves of Strong and Weak Acids and Bases," from *Chemistry with Vernier*, serves as a good introduction to this experiment.

4. There are two methods in the student pages. Method 1 has the student deliver volumes of NaOH titrant from a buret, so buret volumes must be read (and entered) manually. Method 2 uses a Vernier Drop Counter to take volume readings. Method 1 has students titrate 10 mL of HCl solution. Method 2 has students titrate 5 mL of HCl solution. The reason we use less HCl volume in Method 2 is to decrease the time required for each data collection. Sample Results were collected using Method 1.

5. The preparation of 0.1 M NaOH requires 4.0 g of NaOH (GHS Signal Word: **DANGER**) per liter of solution.
   - Consider it to be 0.1000 M NaOH (the volume can also be read to four significant figures).
   - Standardize the solution with a standard acid solution and indicate its concentration to three or four significant figures (using a centigram or milligram balance to weigh out the acid).

6. Unknown samples with HCl concentrations in the 0.075 to 0.15 M range work well. The preparation of 0.075 M HCl requires 6.2 mL of concentrated HCl (GHS Signal Word: **DANGER**) per liter of solution. HCl that is 0.15 M requires 12.5 mL of concentrated reagent per liter.

7. To help determine the equivalence-point volume, students can create calculated columns and display graphs of first derivative *vs*. volume (ΔpH/Δvol) or second derivative *vs*. volume (Δ^2pH/Δvol^2). See Figures 1 and 2 for example first- and second-derivative plots.

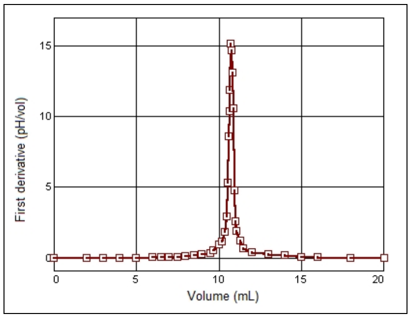


Figure 1 First derivative

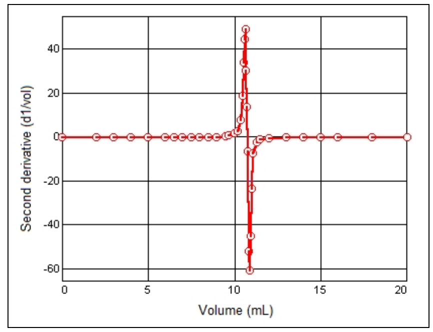


Figure 2 Second derivative

8. Consider having your students add two or three drops of phenolphthalein indicator at the beginning of each titration. They can then observe the phenolphthalein equivalence point and compare it with their pH equivalence point for each titration.

9. The stored pH calibration works well for this experiment. For more accurate pH readings, you (or your students) can do a 2-point calibration for each pH Sensor using pH-4 and pH-7 buffers. For additional information about the Vernier probeware used in this experiment, including tips and product specifications, visit **www.vernier.com/manuals** and download the appropriate user manual.

10. A magnetic stirring plate or a stirring rod can be used instead of the Stir Station (order code: STIR) included in the student Materials list. The Microstirrer that came with the Stir Station or the Drop Counter can be used instead of a magnetic stirring bar (additional Microstirrers are available—order code: MSTIR). If using Method 1 (buret), a utility clamp can be used in place of the Electrode Support.

11. See **www.vernier.com/start/go-direct** for information about how to connect to your Go Direct sensors in Graphical Analysis.

HAZARD ALERTS

The chemical safety signal words used in this experiment (DANGER, WARNING, and N/A) are part of the Globally Harmonized System of Classification and labeling of Chemicals (GHS). Refer to the Safety Data Sheet (SDS) that came with the chemical for proper handling, storage, and disposal information. These can also be found online from the manufacturer. See the Chemical Safety Information at the beginning of this book for more information.

Hydrochloric acid, 0.075–<0.1 M, HCl: **WARNING**: May be harmful if swallowed, inhaled, or in contact with skin. Causes skin and eye irritation. Industrial exposure to vapors and mists is listed as a known human carcinogen by International Agency for Research on Cancer (IARC).

Hydrochloric acid, 0.1–0.15 M, HCl: **DANGER**: Causes severe skin and eye damage. Do not breathe mist, vapors, or spray. May cause respiratory irritation. May be harmful if swallowed. Industrial exposure to vapors and mists is listed as a known human carcinogen by International Agency for Research on Cancer (IARC).

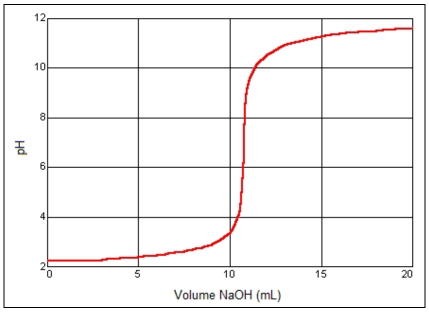
Hydrochloric acid, 12 M, HCl: **DANGER**: Causes severe skin and eye burns and damage. Harmful if swallowed or inhaled. Do not eat or drink when using this product. Do not breathe mist, vapors, or spray. May be corrosive to metals. Industrial exposure to vapors and mists is listed as a known human carcinogen by International Agency for Research on Cancer (IARC).

Sodium hydroxide, 0.1 M, NaOH: **WARNING**: Causes skin and eye irritation.

Sodium hydroxide, solid, NaOH: **DANGER**: Causes severe skin burns and eye damage. Do not breathe mist, vapors, or spray. May be corrosive to metals.

SAMPLE RESULTS

pH	Volume (mL)	pH	Volume (mL)
2.25	0.00	4.79	10.60
2.28	2.00	5.31	10.65
2.32	3.00	5.91	10.70
2.37	4.00	6.49	10.75
2.43	5.00	7.17	10.80
2.49	6.00	8.36	10.85
2.54	6.50	8.86	10.90
2.59	7.00	9.12	10.95
2.65	7.50	9.30	11.00
2.72	8.00	9.56	11.10
2.81	8.50	9.91	11.30
2.93	9.00	10.19	11.50
3.10	9.50	10.53	12.00
3.20	9.70	10.95	13.00
3.36	10.00	11.15	14.00
3.60	10.20	11.29	15.00
3.98	10.40	11.40	16.00
4.17	10.50	11.52	18.00
4.40	10.55	11.61	20.00



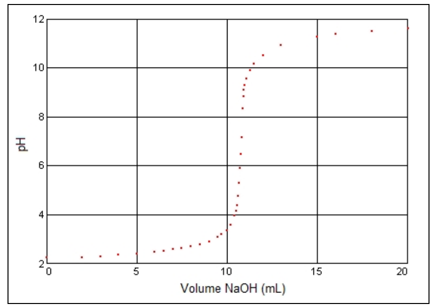


Figure 3 Acid-base titration for sodium hydroxide and hydrochloric acid

	Trial 1	Trial 2
Concentration of NaOH	0.1000 M	0.1000 M
NaOH volume added before largest pH increase	10.80 mL	10.90 mL
NaOH volume added after largest pH increase	10.85 mL	10.95 mL

Volume of NaOH added at equivalence point	$\frac{10.80+10.85}{2} = 10.825\text{ mL}$ 10.83 mL	$\frac{10.90+10.95}{2} = 10.925\text{ mL}$ 10.93 mL
Moles NaOH	(0.100 mol/L)(0.01083 L) = 0.00108 mol	(0.100 mol/L)(0.01093 L) = 0.00109 mol
Moles HCl	$\frac{1\text{ mol HCl}}{1\text{ mol NaOH}} \times 0.00108\text{ mol} =$ 0.00108 mol	$\frac{1\text{ mol HCl}}{1\text{ mol NaOH}} \times 0.00109\text{ mol} =$ 0.00109 mol
Concentration of HCl	$\frac{0.00108\text{ mol}}{0.0100\text{ L}} =$ 0.108 mol/L	$\frac{0.00109\text{ mol}}{0.0100\text{ L}} =$ 0.109 mol/L
Average [HCl]	$\frac{0.108+0.109}{2} = 0.1085\text{ L}$ 0.109 M	

Properties of Solutions: Electrolytes and Non-Electrolytes

In this experiment, you will discover some properties of strong electrolytes, weak electrolytes, and non-electrolytes by observing the behavior of these substances in aqueous solutions. You will determine these properties using a Conductivity Probe. When the probe is placed in a solution that contains ions, and thus has the ability to conduct electricity, an electrical circuit is completed across the electrodes that are located on either side of the hole near the bottom of the probe body (see Figure 1). This results in a conductivity value that can be read by data-collection software. The unit of conductivity used in this experiment is the microsiemens per centimeter, or µS/cm.

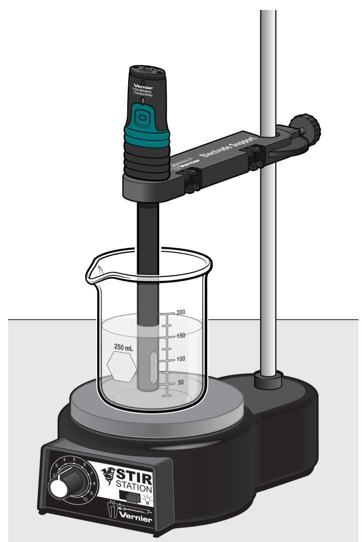


Figure 1

The size of the conductivity value depends on the ability of the aqueous solution to conduct electricity. Strong electrolytes produce large numbers of ions, which results in high conductivity values. Weak electrolytes result in low conductivity, and non-electrolytes should result in no conductivity. In this experiment, you will observe several factors that determine whether or not a solution conducts, and if so, the relative magnitude of the conductivity. Thus, this simple experiment allows you to learn a great deal about different compounds and their resulting solutions.

In each part of the experiment, you will observe a different property of electrolytes. Keep in mind that you will be encountering three types of compounds and aqueous solutions:

Ionic Compounds

These are usually strong electrolytes and can be expected to 100% dissociate in aqueous solution.

Example: $NaNO_3(s) \rightarrow Na^+(aq) + NO_3^-(aq)$

Molecular Compounds

These are usually non-electrolytes. They do not dissociate to form ions. Resulting solutions do not conduct electricity.

Example: $CH_3OH(l) \rightarrow CH_3OH(aq)$

Molecular Acids

These are molecules that can partially or wholly dissociate, depending on their strength.

Example (strong electrolyte): $H_2SO_4 \rightarrow H^+(aq) + HSO_4^-(aq)$ (100% dissociation)

Example (weak electrolyte): $HF \leftrightarrow H^+(aq) + F^-(aq)$ (<100% dissociation)

OBJECTIVES

- Write equations for the dissociation of compounds in water.
- Use a Conductivity Probe to measure the conductivity of solutions.
- Determine which molecules or ions are responsible for conductivity of solutions.
- Investigate the conductivity of solutions resulting from compounds that dissociate to produce different numbers of ions.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis app
Go Direct Conductivity
Stir Station and magnetic stir bar
Electrode Support
250 mL beaker
wash bottle and distilled water
tissues
H_2O (tap)
H_2O (distilled)
0.05 M NaCl
0.05 M $CaCl_2$
0.05 M $AlCl_3$
0.05 M $HC_2H_3O_2$
0.05 M H_3PO_4
0.05 M H_3BO_3
0.05 M HCl
0.05 M CH_3OH (methanol)

PROCEDURE

1. Obtain and wear goggles! **DANGER**: *Handle all the solutions in this experiment with care. They may be harmful if swallowed or in contact with the skin or eyes. Do not handle until all safety precautions have been understood Notify your teacher in the event of an accident.*

2. Assemble the Conductivity Probe, Electrode Support, and Stir Station as shown in Figure 1. Be sure the probe is clean and dry before beginning the experiment.

3. Launch Graphical Analysis. Connect the Conductivity Probe to your Chromebook, computer, or mobile device.

4. Obtain the Group A solution containers. The solutions are: 0.05 M $CaCl_2$, 0.05 M NaCl, and 0.05 M $AlCl_3$.

5. Measure the conductivity of each of the solutions.
   a. Carefully raise each vial and its contents up around the Conductivity Probe until the hole near the probe end is completely submerged in the solution being tested. **Important**: Since the two electrodes are positioned on either side of the hole, this part of the probe must be completely submerged.
   b. Briefly swirl the vial contents. Monitor the conductivity reading displayed on the screen for 6–8 seconds, then record the value in your data table.
   c. Before testing the next solution, clean the electrodes by surrounding them with a 250 mL beaker and rinse them with distilled water from a wash bottle. Blot the outside of the probe end dry using a tissue. It is *not* necessary to dry the *inside* of the hole near the probe end.

6. Obtain the four Group B solution containers. These include 0.05 M $HC_2H_3O_2$, 0.05 M HCl, 0.05 M H_3PO_4, and 0.05 M H_3BO_3. Repeat the Step 5 procedure.

7. Obtain the five Group C solutions or liquids. These include distilled H_2O, tap H_2O, 0.05 M CH_3OH, and 0.05 M $C_2H_6O_2$. Repeat the Step 5 procedure.

DATA TABLE

Solution	Conductivity (μS/cm)
A - $CaCl_2$	
A - $AlCl_3$	
A - NaCl	
B - $HC_2H_3O_2$	
B - HCl	
B - H_3PO_4	
B - H_3BO_3	
C - $H_2O_{distilled}$	
C - H_2O_{tap}	
C - CH_3OH	

PROCESSING THE DATA

1. Based on your conductivity values, do the Group A compounds appear to be molecular, ionic, or molecular acids? Would you expect them to partially dissociate, completely dissociate, or not dissociate at all?

2. Why do the Group A compounds, each with the same concentration (0.05 M), have such large differences in conductivity values? **Hint**: Write an equation for the dissociation of each. Explain.

3. In Group B, do all four compounds appear to be molecular, ionic, or molecular acids? Classify each as a strong or weak electrolyte, and arrange them from the strongest to the weakest, based on conductivity values.

4. Write an equation for the dissociation of each of the compounds in Group B. Use → for strong; ↔ for weak.

5. For H_3PO_4 and H_3BO_3, does the subscript "3" of hydrogen in these two formulas seem to result in additional ions in solution as it did in Group A? Explain.

6. In Group C, do all four compounds appear to be molecular, ionic, or molecular acids? Based on this answer, would you expect them to dissociate?

7. How do you explain the relatively high conductivity of tap water compared to a low or zero conductivity for distilled water?

Properties of Solutions: Electrolytes and Non-Electrolytes

1. The experiments in this book were selected to provide a sampling of Vernier experiments that cover several subjects and key scientific concepts. The downloaded zip file contains PDF files of the student experiments. You can print the PDF, distribute it to students electronically, or post the file to a password-protected class web page or learning management system.

2. This experiment was adapted from *Chemistry with Vernier*, Experiment 13. Learn more at **vernier.com/cwv**

3. We suggest that you set up the Conductivity Probes before the experiment. If your sensors have a switch, set the switch to the 0–20000 µS/cm range.

4. Fewer sets of Groups A, B, and C can be prepared if students are advised that they need not start with Group A. Add solutions to 100 mL beakers or small vials to a depth that easily allows the hole near the Conductivity Probe tip to be completely submerged (the graphite electrodes of the probe are located on either side of this hole).

5. Preparation of solutions (prepare all solutions in distilled water):

   0.050 M $CaCl_2$: 5.55 g of solid calcium chloride, $CaCl_2$ (GHS Signal Word: **WARNING**), per 1 L solution.

   0.050 M NaCl: 2.93 g of solid sodium chloride, NaCl (GHS Signal Word: **WARNING**), per 1 L solution.

   0.050 M $AlCl_3$: 12.05 g of solid aluminum chloride, $AlCl_3 \cdot 6H_2O$ (GHS Signal Word: **WARNING**), per 1 L solution—preferred. Alternatively, 6.67 g anhydrous $AlCl_3$ (GHS Signal Word: **DANGER**) per liter of solution.

   0.050 M HCl: 4.2 mL of concentrated hydrochloric acid, HCl (GHS Signal Word: **DANGER**), per 1 L solution.

   0.050 M $HC_2H_3O_2$: 2.9 mL of glacial acetic acid, $HC_2H_3O_2$ (GHS Signal Word: **DANGER**), per 1 L solution.

   0.050 M H_3PO_4: 3.4 mL of o-phosphoric acid, H_3PO_4 (GHS Signal Word: **DANGER**), per 1 L solution.

   0.050 M H_3BO_3: 3.09 g of solid boric acid, H_3BO_3 (GHS Signal Word: **DANGER**), per 1 L solution.

   0.050 M CH_3OH: 1.60 g (2.1 mL) methanol (GHS Signal Word: **DANGER**) per 1 L solution.

6. Conductivity readings are normally reported in microsiemens per centimeter, or µS/cm. This SI derived unit has replaced the conductivity unit, micromho/cm.

7. Students are instructed to rinse the probe with distilled water between samples. They are told to blot the probe tip dry—however, the directions also remind them that they do *not* need to blot dry the inside of the hole containing the graphite electrodes. It is cumbersome to do so, and leaving a drop or two of distilled water does not significantly dilute the next sample.

8. Using the stored calibration, measured conductivity values for H_3BO_3, CH_3OH, or distilled water will be in the range of 0 to 30 µS/cm. If a two-point calibration is performed, students will get readings closer to 0 µS/cm. We encourage you to try this as a teacher demonstration or have students do it as an extension to the experiment. These four samples will usually have a small conductivity value due to dissolved carbon dioxide, which forms aqueous ions according to the equation:

$$CO_2(g) + H_2O(l) \leftrightarrow H^+(aq) + HCO_3^-(aq)$$

   The resulting conductivity is usually about 1–3 µS/cm. Students will notice that the conductivity of boric acid is higher than distilled water or 0.05 M methanol. This way, they can see that boric acid is a weak acid that ionizes to a very small extent. For example, we get a reading of 3.2 µS/cm for 0.05 M boric acid, but only 1.0 µS/cm for distilled water, and 1.0 µS/cm for 0.05 M methanol. **Note**: If your sensors have a switch, set the switch to the narrower 0–200 µS/cm setting if you choose to do this activity.

9. The student Materials list includes a Stir Station (order code: STIR) and an Electrode Support (order code: ESUP). A magnetic stirring plate or a stirring rod can be used in instead of Stir Station and a utility clamp can be used if no Electrode Support is available.

10. If you wish to calibrate the Conductivity Probe to improve conductivity readings at low concentrations (as discussed in item 8 above), follow these directions:

   First Calibration Point

   a. If your Conductivity Probe has a switch, set it to the 0–20000 µS/cm position.
   b. Start the calibration mode in your data-collection software.
   c. For the first calibration point, the Conductivity Probe should simply be in the air (out of any liquid or solution).
   d. Type **0** in the edit box as the conductivity value (in µS/cm).
   e. Wait until the voltage stabilizes, then Keep the point.

   Second Calibration Point

   f. Place the Conductivity Probe into a standard solution that is equivalent to 10,000 µS/cm. **Note**: This standard can be prepared by dissolving 5.566 g of solid sodium chloride, NaCl, in enough distilled water for 1 liter of solution.
   g. Type **10000** in the edit box as the conductivity value for the second calibration point (in µS/cm).
   h. Wait until the voltage stabilizes, then Keep the point. Then select either OK or Done depending on the software. This completes the calibration.

11. For additional information about the Vernier probeware used in this experiment, including tips and product specifications, visit **www.vernier.com/manuals** and download the appropriate user manual.

12. See **www.vernier.com/start/go-direct** for information about how to connect to your Go Direct sensors in Graphical Analysis.

HAZARD ALERTS

The chemical safety signal words used in this experiment (DANGER, WARNING, and N/A) are part of the Globally Harmonized System of Classification and labeling of Chemicals (GHS). Refer to the Safety Data Sheet (SDS) that came with the chemical for proper handling, storage, and disposal information. These can also be found online from the manufacturer. See the Chemical Safety Information at the beginning of this book for more information.

Acetic acid, 0.05 M, CH_3OOH: N/A: This chemical is considered nonhazardous according to GHS classifications. Treat all laboratory chemicals with caution. Prudent laboratory practices should be observed.

Acetic acid, glacial, CH_3OOH: **DANGER**: Keep away from heat, sparks, open flames, and hot surfaces—flammable liquid and vapor. May be harmful if swallowed. Causes severe skin burns and eye damage. Avoid breathing mist, vapors, or spray—toxic if inhaled.

Aluminum chloride, 0.05 M, $AlCl_3$: N/A: This chemical is considered nonhazardous according to GHS classifications. Treat all laboratory chemicals with caution. Prudent laboratory practices should be observed.

Aluminum chloride, anhydrous, solid, $AlCl_3$: **DANGER**: May be harmful if swallowed. Causes severe skin burns and eye damage.

Aluminum chloride hexahydrate, solid, $AlCl_3•6H_2O$: **WARNING**: May be harmful if swallowed. Causes skin and serious eye irritation. May cause respiratory irritation. Avoid breathing dust or fumes.

Boric acid, 0.05 M, H_3BO_3: **DANGER**: May be harmful if swallowed. May damage fertility or the unborn child. Do not handle until all safety precautions have been understood. Use personal protective equipment as required.

Boric acid, solid, H_3BO_3: **DANGER**: May be harmful if swallowed. May damage fertility or the unborn child. Do not handle until all safety precautions have been understood. Use personal protective equipment as required.

Calcium chloride, 0.05 M, $CaCl_2$: N/A: This chemical is considered nonhazardous according to GHS classifications. Treat all laboratory chemicals with caution. Prudent laboratory practices should be observed.

Calcium chloride, solid, $CaCl_2$: **WARNING**: Do not eat or drink when using this product—harmful if swallowed. Causes serious eye irritation.

Hydrochloric acid, 0.05 M, HCl: **WARNING**: May be harmful if swallowed, inhaled, or in contact with skin. Causes skin and eye irritation. Industrial exposure to vapors and mists is listed as a known human carcinogen by International Agency for Research on Cancer (IARC).

Hydrochloric acid, 12 M, HCl: **DANGER**: Causes severe skin and eye burns and damage. Harmful if swallowed or inhaled. Do not eat or drink when using this product. Do not breathe mist, vapors, or spray. May be corrosive to metals. Industrial exposure to vapors and mists is listed as a known human carcinogen by International Agency for Research on Cancer (IARC).

Methanol, CH_3OH: **DANGER**: Keep away from heat, sparks, open flames, and hot surfaces—highly flammable liquid and vapor. Toxic if swallowed, in contact with skin, or if inhaled. Do not eat or drink when using this product. Do not breath mist, vapors, or spray. Causes skin and serious eye irritation. Causes damage to organs.

o-phosphoric acid, 0.05 M, H_3PO_4: **WARNING**: May be harmful if swallowed, inhaled, or in contact with skin. Causes skin and eye irritation. Industrial exposure to vapors and mists is listed as a known human carcinogen by International Agency for Research on Cancer (IARC).

o-phosphoric acid, H_3PO_4: **DANGER**: Do not eat or drink when using this product—harmful if swallowed. Causes severe skin burns and eye damage. Fatal if inhaled. Industrial exposure to vapors and mists is listed as a known human carcinogen by International Agency for Research on Cancer (IARC).

Sodium chloride, solid, NaCl: **WARNING**: May be harmful if swallowed. Treat as a non-food-grade chemical. Prudent laboratory practices should be observed.

ANSWERS TO QUESTIONS

1. All three are ionic. They completely dissociate in water.

2. $AlCl_3 \rightarrow Al^{3+} + 3\ Cl^-$ (4 moles of ions per mole)

   $CaCl_2 \rightarrow Ca^{2+} + 2\ Cl^-$ (3 moles of ions per mole)

   $NaCl \rightarrow Na^+ + Cl^-$ (2 moles of ions per mole)

   Even though all three solutions have the same initial concentration, 0.05 M, $AlCl_3$ dissociates to yield the largest number of moles of ions per mole, and as a result exhibits the highest conductivity in this series. $CaCl_2$ is next, and NaCl yields the fewest moles of ions per mole.

3. All three are molecular acids. HCl is a strong acid. H_3PO_4 is borderline between strong and weak, but is usually classified as a weak acid. Acetic acid, $HC_2H_3O_2$ is the next weakest acid and H_3BO_3 is the weakest.

4. $HCl \rightarrow H^+ + Cl^-$ $H_3PO_4 \leftrightarrow H^+ + H_2PO_4^-$

   $HC_2H_3O_2 \leftrightarrow H^+ + C_2H_3O_2^-$ $H_3BO_3 \leftrightarrow H^+ + H_2BO_3^-$

5. Since H_3PO_4 and H_3BO_3 are two of the weak acids in this series, one would conclude that the subscript "3" contributes little to their strengths. The equations for their dissociations indicate that only one H^+ dissociates to any appreciable extent from either of these weak acids. The dissociations of the second and third H^+ ions are insignificant by comparison.

6. All four compounds in Group C are molecular. None of them dissociates significantly.

7. Even though the water itself is molecular, it contains ionic impurities, such as Ca^{2+}, Mg^{2+}, HCO_3^-, and Cl^-. The ionic impurities contribute significantly to the conductivity of the solution. These ionic impurities have been removed from distilled water.

SAMPLE RESULTS

Solution	Conductivity (μS/cm)
A - $CaCl_2$	9362
A - NaCl	5214
A - $AlCl_3$	11707
B - $HC_2H_3O_2$	461
B - HCl	17330
B - H_3PO_4	6661
B - H_3BO_3	0
C - H_2O (distilled)	0
C - H_2O (tap)	(varies) 20 – 1000
C - CH_3OH	0

Graph Matching

One of the most effective methods of describing motion is to plot graphs of position, velocity, and acceleration *vs.* time. From such a graphical representation, it is possible to determine in what direction an object is going, how fast it is moving, how far it traveled, and whether it is speeding up or slowing down. In this experiment, you will use a motion detector to determine this information by plotting a real-time graph of *your* motion as you move across the classroom.

The motion detector measures the time it takes for a high-frequency sound pulse to travel from the detector to an object and back. Using this round-trip time and the speed of sound, the distance to the object is calculated. This is the position of the object relative to the sensor. The change in position is then used to calculate the object's velocity and acceleration. All of this information can be displayed in a graph. A qualitative analysis of the graphs of your motion will help you develop an understanding of the concepts of kinematics.

OBJECTIVES

- Analyze the motion of a student walking across the room.
- Predict, sketch, and test position *vs.* time kinematics graphs.
- Predict, sketch, and test velocity *vs.* time kinematics graphs.

CHOOSE A METHOD

Method 1: Bluetooth Connection–Use Method 1 if you are using a mobile device, such as a tablet or a phone, and connecting to a Go Direct Motion via Bluetooth. You will hold the motion detector and measure your position and velocity relative to a wall.

Method 2: USB Connection–Use Method 2 if you are using a computer or Chromebook, and are connecting the motion detector via USB. You will measure your position and velocity relative to a stationary motion detector.

MATERIALS

Required for *both* Method 1 (Bluetooth connection) and Method 2 (USB connection)

Graphical Analysis app
Go Direct Motion
meter stick
masking tape

Required for Method 1 *only* (Bluetooth connection)

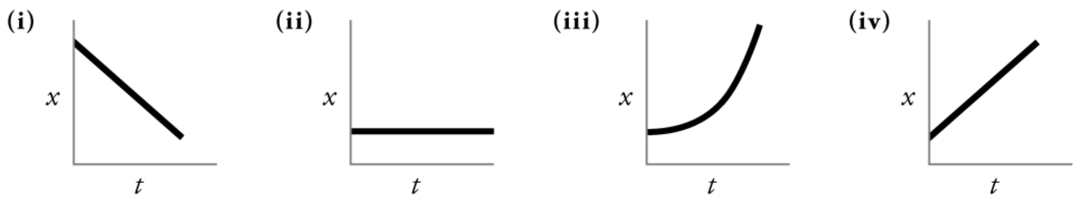
mobile device

Required for Method 2 *only* (USB Connection)

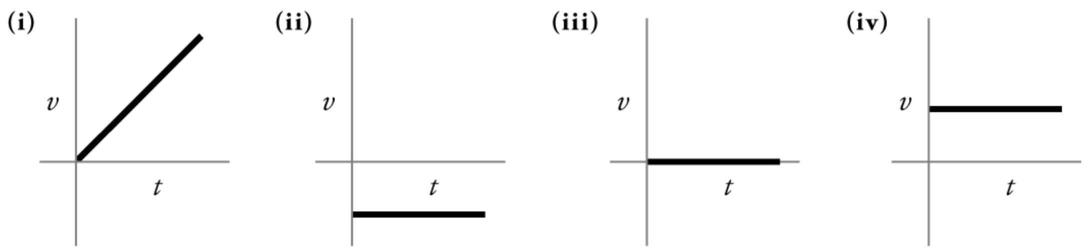
computer or Chromebook

PRELIMINARY QUESTIONS

1. Below are four position *vs.* time graphs labeled (i) through (iv). Identify which graph corresponds to each of the following situations and explain why you chose that graph.
   a. An object at rest
   b. An object moving in the positive direction with a constant speed
   c. An object moving in the negative direction with a constant speed
   d. An object that is accelerating in the positive direction, starting from rest



2. Below are four velocity *vs.* time graphs labeled (i) through (iv). Identify which graph corresponds to each of the following situations. Explain why you chose that graph.
   a. An object at rest
   b. An object moving in the positive direction with a constant speed
   c. An object moving in the negative direction with a constant speed
   d. An object that is accelerating in the positive direction, starting from rest



PROCEDURE

Method 1 Bluetooth Connection

Part I Preliminary Experiments

1. Find an open area at least 2 m long in front of a wall. Use short strips of masking tape on the floor to mark distances of 0.5 m, 1 m, 1.5 m, and 2 m from the wall. You will be measuring your position from the motion detector in your hands to the wall.

2. Launch Graphical Analysis. Connect the motion detector to your mobile device.

3. Click or tap Mode to open Data Collection Settings. Change End Collection to 5 s. Click or tap Done.

4. Monitor the position readings and practice walking toward the wall holding the motion detector and mobile device. During data collection, the sensor portion of the motion detector should always point directly at the wall as shown in Figure 1. Sometimes you will have to walk backwards. Confirm that the position values make sense as you move back and forth.

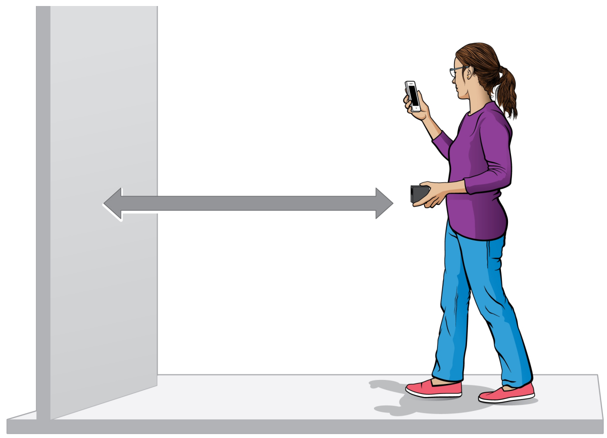


Figure 1

5. Make a graph of your motion while you walk away from the wall with constant velocity. To do this, stand about 0.5 m from the wall and click or tap Collect to start data collection. Slowly walk backward away from the wall after data collection begins.

6. Examine the graph. Sketch a prediction of what the position *vs.* time graph will look like if you walk faster. Check your prediction with the motion detector. Start data collection when you are ready to begin walking. **Note**: The previous data set is automatically saved.

Part II Position *vs.* Time Graph Matching

7. Click or tap Graph Tools, , and choose Add Graph Match. Choose Position. A position target graph is displayed for you to match.

8. Describe how you would walk to reproduce the target graph.

9. To test your prediction, choose a starting position. Start data collection, then walk in such a way that the graph of your motion matches the target graph on the screen.

10. If you were not successful, start data collection again when you are ready to begin walking. Repeat this process until your motion closely matches the graph on the screen. Export, print, or sketch the graph with your best attempt showing both the target graph and your motion data.

11. To perform a second position graph match, click or tap Graph Tools, , choose Add Graph Match, and then Position. Repeat Steps 8–10.

12. Answer the Analysis questions for Part II before proceeding to Part III.

Part III Velocity *vs.* Time Graph Matching

13. Graphical Analysis can also generate random target velocity graphs for you to match. Click or tap Graph Tools, , and choose Add Graph Match. Choose Velocity to view a velocity target graph.

14. Describe how you would walk to produce this target graph. Sketch or print a copy of the graph.

15. To test your prediction, choose a starting position and stand at that point. Start data collection, then walk in such a way that the graph of your motion matches the target graph. It is more difficult to match the velocity graph than the position graph.

16. If you were not successful, start data collection again when you are ready to start walking. Repeat this process until your motion closely matches the graph on the screen. Export, print, or sketch the graph with your best attempt showing both the target graph and your motion data.

17. To perform a second velocity graph match, click or tap Graph Tools, , choose Add Graph Match, and then Velocity. Repeat Steps 14–16.

18. Remove the masking tape from the floor.

19. Proceed to the Analysis questions for Part III.

Method 2 USB Connection with Computers or Chromebooks

Part I Preliminary Experiments

1. Place the motion detector so that it points toward an open space at least 2 m long. Use short strips of masking tape on the floor to mark distances of 0.5 m, 1 m, 1.5 m, and 2 m from the motion detector.

2. Launch Graphical Analysis. Connect the motion detector to your Chromebook or computer.

3. Click or tap Mode to open Data Collection Settings. Change End Collection to 5 s. Click or tap Done.

4. Monitor the position readings and practice walking toward the motion detector. Sometimes you will have to walk backwards. Confirm that the position values make sense as you move back and forth.

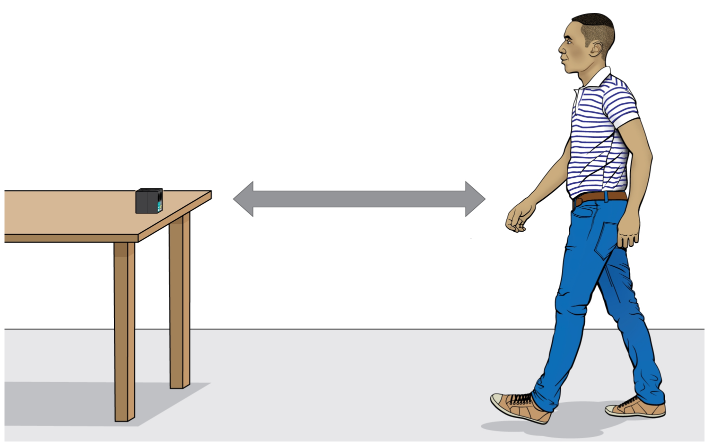


Figure 2

5. Make a graph of your motion while you walk away from the motion detector with constant velocity. To do this, stand about 0.5 m from the motion detector and click or tap Collect to start data collection. Slowly walk backward away from the motion detector after data collection begins.

6. Examine the graph. Sketch a prediction of what the position *vs.* time graph will look like if you walk faster. Check your prediction with the motion detector. Start data collection when you are ready to begin walking. **Note**: The previous data set is automatically saved.

Part II Position *vs.* Time Graph Matching

7. Click or tap Graph Tools, , and choose Add Graph Match. Choose Position. A position target graph is displayed for you to match.
8. Describe how you would walk to reproduce the target graph.
9. To test your prediction, choose a starting position. Start data collection, then walk in such a way that the graph of your motion matches the target graph on the screen.
10. If you were not successful, start data collection again when you are ready to begin walking. Repeat this process until your motion closely matches the graph on the screen. Export, print, or sketch the graph with your best attempt showing both the target graph and your motion data.
11. To perform a second position graph match, click or tap Graph Tools, , choose Add Graph Match, and then Position. Repeat Steps 8–10.
12. Answer the Analysis questions for Part II before proceeding to Part III.

Part III Velocity *vs.* Time Graph Matching

13. Graphical Analysis can also generate random target velocity graphs for you to match. Click or tap Graph Tools, , and choose Add Graph Match. Choose Velocity to view a velocity target graph.
14. Describe how you would walk to produce this target graph. Sketch or print the graph.
15. To test your prediction, choose a starting position and stand at that point. Start data collection, then walk in such a way that the graph of your motion matches the target graph. It is more difficult to match the velocity graph than the position graph.
16. If you were not successful, start data collection when you are ready to start walking again. Repeat the process until your motion closely matches the graph. Export, print, or sketch the graph with your best attempt showing both the target graph and your motion data.
17. To perform a second velocity graph match, click or tap Graph Tools, , choose Add Graph Match, and then Velocity. Repeat Steps 14–16.
18. Remove the masking tape from the floor.
19. Proceed to the Analysis questions for Part III.

ANALYSIS

Part II Position *vs.* Time Graph Matching

1. Describe how you walked for each of the graphs that you matched.
2. Explain the significance of the slope of a position *vs.* time graph. Include a discussion of positive and negative slope.
3. What type of motion is occurring when the slope of a position *vs.* time graph is zero?
4. What type of motion is occurring when the slope of a position *vs.* time graph is constant?
5. What type of motion is occurring when the slope of a position *vs.* time graph is changing? Test your answer to this question using the motion detector.

Part III Velocity *vs.* Time Graph Matching

6. Describe how you walked for each of the graphs that you matched.
7. What type of motion is occurring when the slope of a velocity *vs.* time graph is zero?
8. What type of motion is occurring when the slope of a velocity *vs.* time graph is not zero? Test your answer using the motion detector.

EXTENSIONS

1. Create a graph-match challenge. Click or tap File, , and choose New Experiment. Click or tap Sensor Data Collection. Set up data-collection to end after 5 seconds. Click or tap View, , and choose 1 Graph. Click or tap Graph Tools, , and choose Add Prediction. Use the Prediction tool to sketch a position *vs.* time graph. Click or tap Save. Challenge another student to match your graph. Have the other student challenge you in the same way.
2. Create a velocity *vs.* time challenge in a similar manner.

Graph Matching

1. The experiments in this book were selected to provide a sampling of Vernier experiments that cover several subjects and key scientific concepts. The downloaded zip file contains PDF files of the student experiments. You can print the PDF, distribute it to students electronically, or post the file to a password-protected class web page or learning management system.
2. This experiment was adapted from *Physics with Vernier*, Experiment 01. Learn more at **vernier.com/pwv**
3. For additional information about the Vernier probeware used in this experiment, including tips and product specifications, visit **www.vernier.com/manuals** and download the appropriate user manual.
4. See **www.vernier.com/start/go-direct** for information about how to connect to your Go Direct sensors in Graphical Analysis.

RELATED SKILLS

- Change-data collection setup

ESTIMATED TIME

We estimate that data collection for this experiment can be completed in two 45-minute class periods. The time needed can vary depending on class size and available equipment.

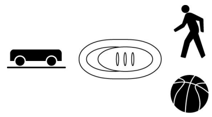
NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Analyzing and Interpreting Data	PS2.A Forces and Motion	Patterns Cause and Effect

EQUIPMENT TIPS

Tips for obtaining useful data with a Motion Detector.

- Motion detectors have a range over which they can detect an object. Ideally, the experiment is set up so that the target gets close to, but not closer than, the minimum distance at which the motion detector can detect an object. Motion detectors *with* a sensitivity switch (shown below) will detect objects as close as 0.15 m. Go Direct Motion will detect objects as close as 0.25 m on the default Motion channel and as close as 0.15 m on the Motion (cart) channel. Older motion detector models *without* a sensitivity setting will detect objects starting about 0.5 m from the sensor. Edit the student notes to match the closest measurable distance of your motion detectors.



- Ultrasound is emitted from a motion detector in a cone about 15° off the axis (30° wide); this includes downward. Anything within the ultrasound cone can cause a reflection and possibly an accidental measurement. A common problem is getting unintentional reflections from a desk, chair, or computer. Unintended reflections can be minimized by tilting the motion detector slightly upward.
- The maximum range for Go Direct Motion is about 3.5 m. Stray objects in the detection cone can be problematic at greater distances and therefore, typical maximum practical range is 2 to 2.5 m.
- If the velocity and acceleration graphs are noisy, increase the strength of the ultrasonic reflection from the target by increasing the target's area and ensuring the target creates a strong reflection of the ultrasound. For example, if the target is a person wearing a bulky sweater, the resulting graph may be inconsistent. Try having your students hold a large book out in front of them as they walk in front of the motion detector.
- If you begin with a velocity or acceleration graph and obtain a confusing display, switch back to the position graph for troubleshooting.

DATA COLLECTION AND ANALYSIS TIPS

1. It is very helpful to use masking tape and place marks on the floor for position reference. The student instructions ask students to place the tape on the floor. If this is not practical in your classroom, remove those instructions, but the exercise will be more difficult for your students.

2. Students, at first, may find it difficult to match a position *vs.* time graph. Encourage them to repeat data collection until they get acceptable results. This may take some practice. If using a computer, place the computer monitor so that the walking student can easily see the screen. If using a phone or tablet, students can hold the device while walking in order to see the graph.

3. Students find that matching the velocity graphs is more difficult than matching the position graphs. The biggest problem will be to generate a smooth graph since the trunk of the body undergoes accelerations during each step. The best results occur with small, shuffling steps.

4. If an object gets in the way, causing an unintentional reflection, it will affect the graph. In the example in Figure 1, a student was trying to match the dark line. She stood in the same location for 1 second and then moved away from the motion detector. At Point A, she was still moving away, but the motion detector started to measure the distance to a chair that was closer to the detector, rather than tracking the student. Before Point B, the student had started to walk toward the motion detector. At Point B, she walked past the chair, and the motion detector started to measure the position of the student rather than the chair.

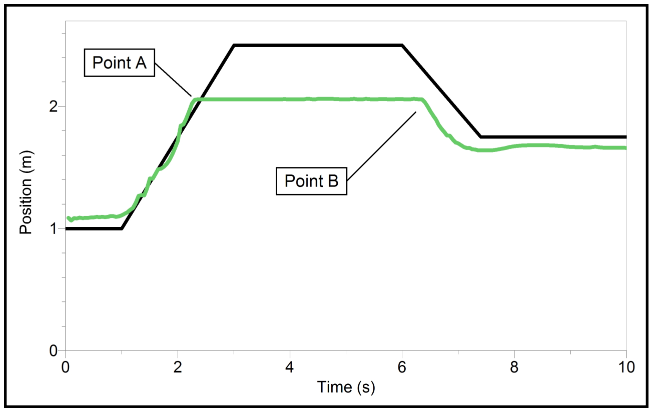


Figure 1 Position vs. *time graph showing an unintentional reflection when a student walked behind a chair (Point A).*

ANSWERS TO PRELIMINARY QUESTIONS

1. Answers follow:
   a. Graph (ii). The flat line indicates that the position of the object does not change.
   b. Graph (iv). The slope is positive (positive direction) and the shape is linear (constant speed).
   c. Graph (i). The slope is negative and the shape is linear, indicating constant speed and movement in the negative direction.
   d. Graph (iii). The curved shape indicates an acceleration. The upward direction indicates movement in a positive direction.

2. Answers follow:
   a. Graph (iii). The velocity is zero and constant for an object at rest.
   b. Graph (iv). A flat line with a positive y-value indicates constant positive velocity.
   c. Graph (ii). A flat line with a negative y-value indicates constant negative velocity.
   d. Graph (i). Linear velocity with a positive slope indicates a constant, positive acceleration.

SAMPLE RESULTS

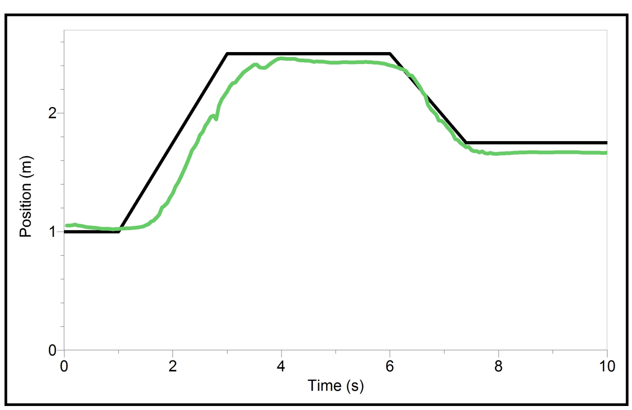


Figure 2 Graph match for a position vs. *time graph*

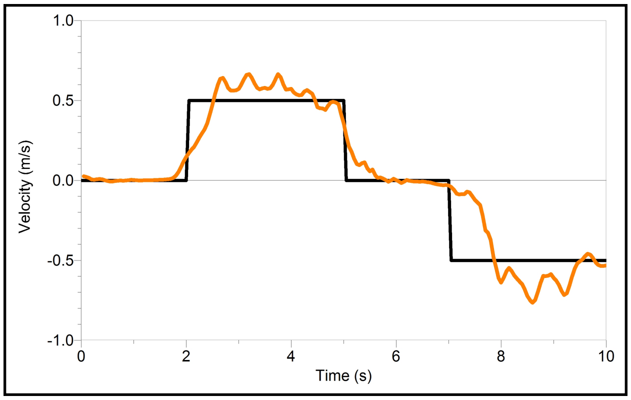


Figure 3 Graph match for a velocity vs. *time graph*

ANSWERS TO PROCEDURE QUESTIONS

Part I Preliminary Experiments

7. The sketch will have a larger positive slope than the trial graph obtained in Step 6. The sketch will have a larger positive slope than the trial graph obtained in Step 6.

ANSWERS TO ANALYSIS QUESTIONS

Part II Position *vs.* Time Graph Matching

1. Answers will vary.
2. A positive slope on a position *vs.* time graph corresponds to moving *away* from the motion detector and positive velocity. A negative slope corresponds to motion toward the detector and negative velocity.
3. A zero slope for a position *vs.* time graph corresponds to zero velocity.
4. A constant slope for a position *vs.* time graph corresponds to a constant velocity.
5. A changing slope in a position *vs.* time graph corresponds to a changing velocity; that is, either speeding up or slowing down.

Part III Velocity *vs.* Time Graph Matching

6. Answers will vary.
7. A zero slope on a velocity *vs.* time graph represents zero acceleration; that is, constant speed.
8. A non-zero slope on a velocity *vs.* time graph represents a non-zero acceleration; that is, speeding up or slowing down.

Picket Fence Free Fall

We say an object is in *free fall* when the only force acting on it is the Earth's gravitational force. No other forces can be acting; in particular, air resistance must be either absent or so small as to be ignored. When the object in free fall is near the surface of the Earth, the gravitational force on it is essentially constant. As a result, an object in free fall accelerates downward at a constant rate. This acceleration is usually represented with the symbol, g.

Physics students measure the acceleration due to gravity using a wide variety of timing methods. In this experiment, you will have the advantage of using a very precise timer and a photogate. The photogate has a beam of infrared light that travels from one side to the other. It can detect whenever this beam is blocked. You will drop a piece of clear plastic with evenly spaced black bars on it, called a Picket Fence. As the Picket Fence passes through the photogate, the photogate measures the time from the leading edge of one bar blocking the beam until the leading edge of the next bar blocks the beam. This timing continues as all eight bars pass through the photogate. From these measured times, the software calculates and plots the velocities and accelerations for this motion.

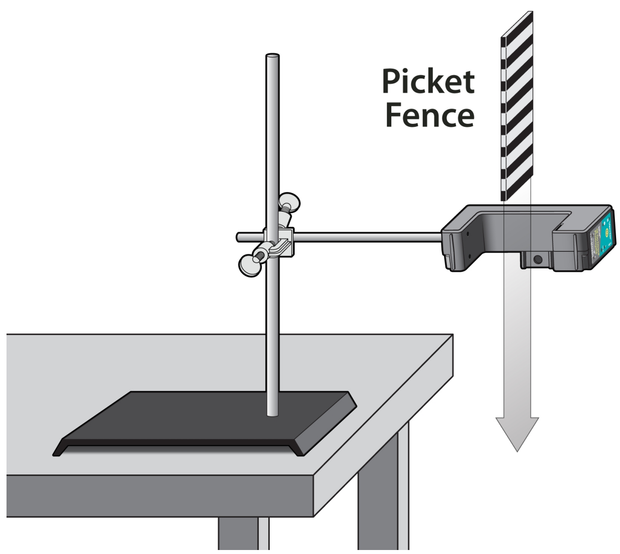


Figure 1

OBJECTIVE

Measure the acceleration of a freely falling body, g, to better than 0.5% precision using a Picket Fence and a Photogate.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis app
Go Direct Photogate
Picket Fence
clamp and ring stand to secure Photogate

PRELIMINARY QUESTIONS

1. Inspect your Picket Fence. You will be dropping it through a photogate to measure *g*. The distance, measured from one edge of a black band to the same edge of the next band, is 5.0 cm. What additional information is needed to determine the average speed of the Picket Fence as it moves through the photogate?
2. If an object is moving with constant acceleration, what is the shape of its velocity *vs.* time graph?
3. Does the initial velocity of an object have anything to do with its acceleration? For example, compared to dropping an object, if you throw it downward would the acceleration be different after you released it?

PROCEDURE

1. Fasten the Photogate rigidly to a ring stand so the arms extend horizontally, as shown in Figure 1. The entire length of the Picket Fence must be able to fall freely through the Photogate. To avoid damaging the Picket Fence, provide a soft landing surface (such as a carpet).
2. Set up the Photogate.
   a. Launch Graphical Analysis.
   b. Connect the Photogate to your computer, Chromebook, or mobile device.
   c. Click or tap Sensor Channels.
   d. Enable the Gate 1 - Gate State channel and disable the Object Velocity channel.
   e. Click or tap Done.
3. Click or tap View, ⊞, and choose 2 Graphs. If the second graph is not a graph of velocity *vs*. time, click or tap the y-axis label on the second graph and select Velocity. Dismiss the box to view the graph.
4. Observe the live Gate State readings in Graphical Analysis. Block the Photogate with your hand; note that the Gate State changes to **1**, indicating the gate is blocked. Remove your hand and the display should change to **0** (unblocked).
5. Click or tap Collect to start data collection. **Note**: Data will be displayed on the graph when the gate is blocked for the first time after data collection is started.
6. Hold the top of the Picket Fence between two fingers, allowing the Picket Fence to hang freely just above the center of the Photogate, without blocking the gate. Release the

Picket Fence so it leaves your grasp completely before it enters the Photogate. The Picket Fence must remain vertical and should not touch the Photogate as it falls.

7. When the Picket Fence has completely passed through the Photogate, a graph of position *vs.* time and velocity *vs.* time appears on the screen. Sketch the graphs on paper for later use.

8. Examine your velocity *vs.* time graph. The slope of a velocity *vs.* time graph is a measure of acceleration. If the velocity graph is approximately a straight line of constant slope, the acceleration is constant. If the acceleration of your Picket Fence appears constant, fit a straight line to your data.
   a. Click or tap Graph Tools, , and choose Apply Curve Fit.
   b. Select Linear as the curve fit. Click or tap Apply.
   c. Record the slope of the linear curve fit in the data table.
   d. Dismiss the Linear curve fit box.

9. To establish the reliability of your slope measurement, repeat Steps 5–8 five more times. Do not use drops in which the Picket Fence hits or misses the Photogate. Record the slope values in the data table.

DATA TABLE

Trial	1	2	3	4	5	6
Slope (m/s^2)						

	Minimum	Maximum	Average
Acceleration (m/s^2)			

Acceleration due to gravity, *g*	±	m/s^2
Precision		%

ANALYSIS

1. From your six trials, determine the minimum, maximum, and average values for the acceleration of the Picket Fence. Record them in the data table.

2. Describe in words the shape of the position *vs.* time graph for the free fall.

3. Describe in words the shape of the velocity *vs.* time graph. How is this related to the shape of the position *vs.* time graph?

4. The average acceleration you determined represents a single best value, derived from all your measurements. The minimum and maximum values give an indication of how much the measurements can vary from trial to trial; that is, they indicate the precision of your measurement. One way of stating the precision is to take half of the difference between the minimum and maximum values and use the result as the uncertainty of the measurement.

Express your final experimental result as the average value, ± the uncertainty. Round the uncertainty to just one digit and round the average value to the same decimal place.

For example, if your minimum, average, and maximum values are 9.12, 9.93, and 10.84 m/s^2, express your result as g = 9.9 ± 0.9 m/s^2. Record your values in the data table.

5. Express the uncertainty as a percentage of the acceleration. This is the precision of your experiment. Enter the value in your data table. Using the example numbers from the last step, the precision would be

$$\frac{0.9}{9.9} \times 100\% = 9\%$$

6. Compare your measurement to the generally accepted value of g (from a textbook or other source). Does the accepted value fall within the range of your values? If so, your experiment agrees with the accepted value.
7. Inspect your velocity graph. How would the associated acceleration *vs.* time graph look? Sketch your prediction on paper. Change the y-axis to acceleration. Comment on any differences between the acceleration graph and your prediction. To examine the data pairs on the displayed graph, tap any data point. As you tap each data point, the acceleration and time values are displayed. Note that the vertical scale of the graph does not include zero. Is the variation as large as it appears?
8. Use the Statistics tool and the acceleration graph to find the average acceleration. How does this compare with the acceleration value for the same drop, determined from the slope of the velocity graph?

EXTENSIONS

1. Use the position *vs.* time data and a quadratic fit to determine g.
2. Would dropping the Picket Fence from higher above the Photogate change any of the parameters you measured? Try it.
3. Would throwing the Picket Fence downward, but letting go before it enters the Photogate, change any of your measurements? How about throwing the Picket Fence upward? Try performing these experiments.
4. How would adding air resistance change the results? Try adding a loop of clear tape to the upper end of the Picket Fence. Drop the modified Picket Fence through the Photogate and compare the results with your original free-fall results.
5. Investigate how the value of g varies around the world. For example, how does latitude affect the value of g? What other factors cause this acceleration to vary at different locations? For example, is g different at high latitudes such as Svalbard, an archipelago north of Norway?
6. Collect g measurements for your entire class, and plot the values in a histogram. Is there a most common value? Are the measurements consistent with one another?

Picket Fence Free Fall

1. The experiments in this book were selected to provide a sampling of Vernier experiments that cover several subjects and key scientific concepts. The downloaded zip file contains PDF files of the student experiments. You can print the PDF, distribute it to students electronically, or post the file to a password-protected class web page or learning management system.
2. This experiment was adapted from *Physics with Vernier*, Experiment 05. Learn more at **vernier.com/pwv**
3. For additional information about the Vernier probeware used in this experiment, including tips and product specifications, visit **www.vernier.com/manuals** and download the appropriate user manual.
4. See **www.vernier.com/start/go-direct** for information about how to connect to your Go Direct sensors in Graphical Analysis.

RELATED SKILLS

- View different graphs
- Add curve fits to data
- Use the Statistics tool to calculate statistics

ESTIMATED TIME

We estimate that data collection and analysis for this experiment can be completed in one 45-minute class period.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Using mathematics and computational thinking Obtaining, evaluating, and communicating information	PS2.A Forces and Motion PS2.B Types of Interactions	Cause and Effect

EQUIPMENT TIPS

1. Picket Fences are available from Vernier (order code: PF). You can make your own picket fences using clear plastic and black tape, but the tape tends to stretch and it is difficult to achieve precise results with a handmade fence. The separation of the leading edge of the bars must be 5.0 cm. If they are not, the velocity values calculated by the data-collection software will be incorrect.

2. New Picket Fences from Vernier come with a blue plastic coating to protect them during shipping. Remove and discard the films from both sides before use to reveal a clear, hard plastic with black bars spaced every 5.0 cm.

3. Dirty or scratched Picket Fences may give erratic results.

4. Have the students drop the Picket Fence onto a rug or other soft surface so that it does not get scratched or damaged.

5. The Photogate must be rigidly fixed to avoid systematic error. In particular, do not hold the Photogate in your hand.

DATA COLLECTION AND ANALYSIS TIPS

1. It is important that the Picket Fence remains vertical during the fall. If not, the vertical distance between bars gets smaller and the results are incorrect.

2. For best results, hold the Picket Fence above the Photogate between two fingers, allowing the Picket Fence to hang freely at the center of, but slightly above, the Photogate. Position the Picket Fence as closely as possible to the Photogate opening without blocking the opening. Start data collection; data will not be collected until the Photogate is blocked for the first time after data collection has been started. Then, drop the Picket Fence by releasing it from your fingers as cleanly as possible.

3. There is a good discussion of variation in the acceleration due to gravity on the Earth's surface in the chapter on gravitation in *Fundamentals of Physics* by Halliday, Resnick, and Walker.

4. Another alternative to the extension in which students put a piece of tape on the end of the Picket Fence to add air resistance is to tape a coffee filter, parachute style, to the top of the picket fence and proceed as instructed.

5. Parker Moreland did an excellent analysis about measuring the acceleration due to gravity, *g*, with a Photogate and suggests a procedure for minimizing error.[1] The article also includes a formula and chart for calculating a local value of gravitation acceleration. You can get a theoretical local value for *g* from WolframAlpha, **www.wolframalpha.com**. Use the query: "gravitational acceleration" and add your location name; for example, "gravitational acceleration Beaverton, OR."

6. When finding the average acceleration due to gravity, the students are asked to round the uncertainty to one digit, recognizing that uncertainty values are usually not well-determined. Anything more than one digit is usually statistically unjustified for typical uncertainties.

ANSWERS TO PRELIMINARY QUESTIONS

1. Because we know that the distance from one edge of a bar to the corresponding edge of the next bar is 5.0 cm, we need to know the time interval (Δt) it took for the Picket Fence to

[1] Moreland, P. "Improving precision and accuracy in the g lab." *The Physics Teacher* 38, no. 6 (September 2000): 367. http://dx.doi.org/10.1119/1.1321823

move this far to determine the speed. Then, we can use the ratio 5.0 cm/Δ*t* to calculate the speed.

2. An object in constant acceleration has a linear velocity *vs.* time graph; that is, the slope of the graph is constant.

3. Initial velocity is independent of the slope of the graph; that is, the acceleration. An object thrown downward still accelerates after release at the same rate as an object that is dropped.

SAMPLE RESULTS

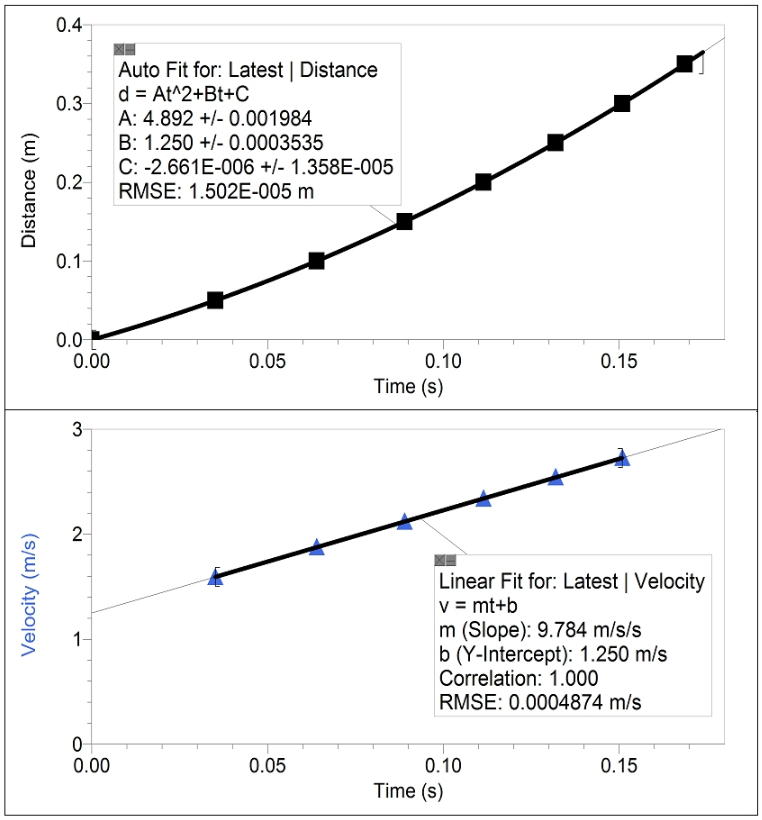


Figure 1 Distance and velocity of Picket Fence in free fall

Trial	1	2	3	4	5	6
Slope (m/s^2)	9.784	9.797	9.791	9.810	9.810	9.819

	Minimum	Maximum	Average
Acceleration (m/s^2)	9.784	9.819	9.802

Acceleration due to gravity, *g*	9.80 ± 0.02 m/s^2
Precision	0.2 %

ANSWERS TO ANALYSIS QUESTIONS

1. Values entered in data table.
2. The position *vs.* time graph is a parabola.
3. The velocity *vs.* time graph is a straight line. The slope of the position *vs.* time graph at a point is equal to the velocity.
4. Using the example values, the uncertainty is ½ (9.819 – 9.784) = 0.0175, which is approximately ± 0.02 m/s^2. In the last step, the uncertainty has been rounded to two decimal places. **Note**: This is a simple measure of the precision of the acceleration measurements. More advanced physics students should use the standard deviation of the measurements for a more rigorous measure.
5. 0.02/9.80 = 0.2%
6. Many physics textbooks use the value of 9.80 m/s^2 for *g*. Since this value is within the range of the 9.80 ± 0.02 m/s^2, the experimental result agrees with the textbook value. It is coincidental that the average value, rounded to two decimal places, is the same as the textbook value.
7. Because the velocity graph is linear with a constant slope, the acceleration graph would be a constant function—a horizontal line above the time axis. Note that the data may appear irregular. This is due to small variations in the timing measurement.
8. When the acceleration *vs.* time graph is selected, it is autoscaled, magnifying these variations. When the origin is included on the vertical axis, the data appear very consistent, as in the graph in Figure 2.

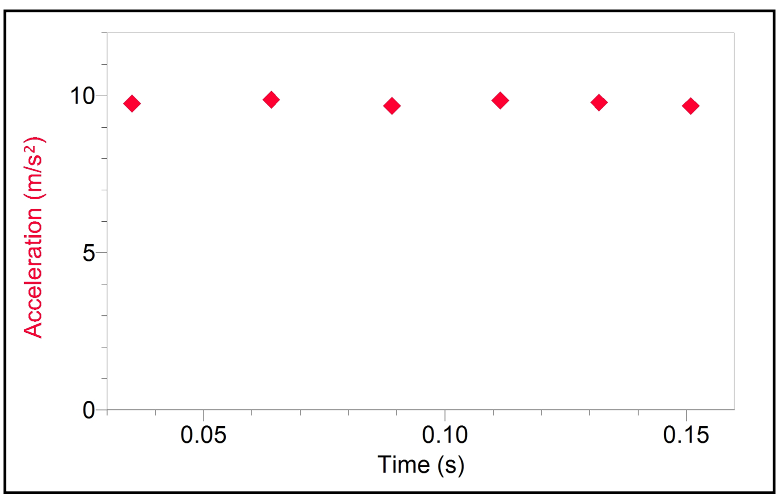


Figure 2 Graph of sample data scaled to include the origin

Accelerations in the Real World

The portability of the data-collection equipment makes it ideal for studying accelerations that occur outside the physics laboratory. Some interesting situations are the automobile and amusement park rides, as well as high-speed elevators, motorcycles, and go-carts.

An accelerometer measures the acceleration in a specific direction. You will need to choose an appropriate time scale and the direction in which to hold the accelerometer to obtain meaningful information. Obtaining acceleration data from independent kinematics measurements can transform an informal study into an empirical evaluation of a mathematical model.

This experiment highlights several situations where you can collect real-world acceleration data. A general procedure is given that you will modify depending on which study is performed. After the general procedure, you will find several suggestions for acceleration investigations. You will need to plan an experiment around the motion to be studied, adjusting data-collection parameters as needed.

OBJECTIVES

- Measure acceleration in a real-world setting.
- Compare the acceleration measured to the value calculated from other data.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis app
Go Direct Acceleration **or** Go Direct Force and Acceleration

SET UP PROCEDURE

The following steps will guide you through configuring Graphical Analysis to collect acceleration data with an acceleration sensor. You will probably need to modify either the time between samples or the number of points collected for your particular circumstances. Adjust these values as you design your experiment.

1. Launch Graphical Analysis. Connect the Go Direct Force and Acceleration Sensor or the Go Direct Acceleration Sensor to your Chromebook, computer, or mobile device. Click or tap Sensor Channels, and select the appropriate channels for your experiment.

2. Set up the data-collection mode.
   a. Click or tap Mode to open Data-Collection Settings.
   b. Change Rate to 10 samples/s and End Collection to 20 s. You may want to use different values according to your experimental conditions. Click or tap Done.

3. Zero the acceleration sensor in the orientation you plan to collect data. For example, if the acceleration sensor is to be oriented horizontally during data collection, place the sensor on a horizontal surface while zeroing. Or, if you will be collecting data with the sensor oriented vertically, then place the sensor against a vertical surface.
   a. Orient your sensor as appropriate for your experiment. **Note**: If you are collecting data along multiple axes, you will zero the sensor multiple times. Orient the sensor for one of the axes you will use.
   b. Click or tap the appropriate Acceleration meter and choose Zero. When the process is complete, the acceleration values are close to zero.
   c. If collecting data for multiple axes, repeat this process for each axis along which you will collect data.
4. Click or tap Collect to start data collection when you are ready to collect data.
5. When data collection is complete, a graph of acceleration *vs.* time is displayed. Click or tap the graph to examine the data. **Note**: You can also adjust the Examine line by dragging the line.

AUTOMOBILES AND MOTORCYCLES

Part I Linear Acceleration on a Straight Road

The accelerometer can record the acceleration of a motor vehicle. A good motion to study is speeding up from rest, followed by slowing to a stop. Initially, set up data collection for a duration of 30 seconds, although you may find that this time should be shortened or extended. Zero the accelerometer with the relevant arrow held horizontally.

Secure the accelerometer in a horizontal direction with the relevant arrow of the accelerometer aligned with the direction of the motion. Start data collection just before starting the vehicle. Accelerate to a safe speed, and then slow to a stop. Keep the vehicle moving in a straight line and keep it on a level section of roadway for this experiment.

Ask the driver to maintain a constant acceleration while speeding up, as well as a constant acceleration when slowing down. Compare different vehicles; compare acceleration patterns with automatic and manual transmissions. For an independent acceleration measurement, collect velocity *vs.* time data during the trial, either by calling out times and recording the instantaneous velocities, or perhaps by collecting video of the speedometer. Compare the accelerations you obtain with the accelerations that are recorded by the interface.

Part II Centripetal Acceleration in Corners

When a vehicle turns a corner, a centripetal acceleration is present. By securing the relevant axis of the accelerometer horizontally and perpendicular to the forward direction, you can record the accelerations in curvilinear motion. Initially set up data collection for a duration of 30 seconds, although you may find that this time should be shortened or extended. Set up a path that has several curves of measured radii as well as straight sections. A parking lot not used on weekends would be best. Practice until the driver can maneuver through the course while maintaining a steady speed. Orient the relevant arrow of the accelerometer in the horizontal direction so it is stable relative to the vehicle and perpendicular to the vehicle's motion (the relevant arrow should be pointing to the inside of curve). Accelerate to the planned speed and keep the vehicle moving at a constant speed. Start data collection just before entering the test section containing the curves.

For an independent acceleration measurement from kinematics, you will need to know both the radii of the turns and the speed of the vehicle.

ELEVATORS

Investigate a high-speed elevator in a building with six stories or more. Zero the accelerometer with the relevant arrow held vertically. Initially set up data collection for a duration of 90 seconds. You will want to adjust this time depending on the transit time of your elevator.

Enter the elevator and place the accelerometer against the elevator wall or floor with the relevant arrow pointing upward. Do not hold it in your extended hand because the motion of your arm will change the acceleration measurement.

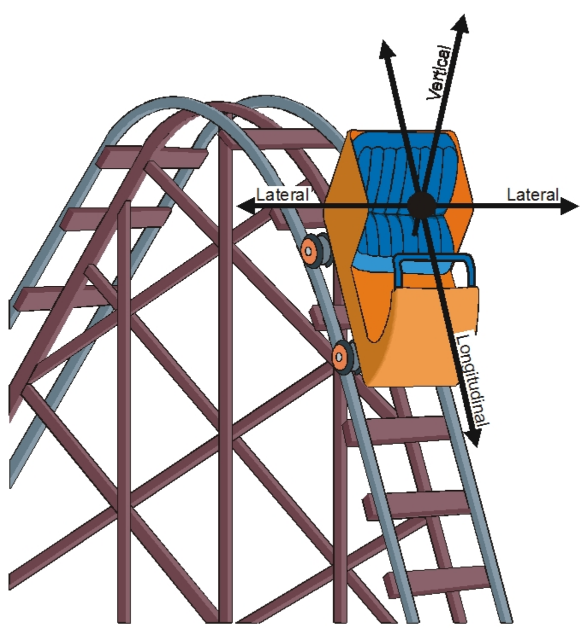
Program the elevator to stop at two floors on the way up, then program it to stop at two floors on the way back down. Start data collection when the doors close on the elevator.

Optional: If you can determine the height of a single story, you can collect data on floor-number *vs.* time to obtain velocities while the elevator is ascending or descending. You can use a video recording to measure this. Compare the velocity you obtain this way with the area under the acceleration *vs.* time graph.

AMUSEMENT PARKS

Many amusement parks feature a Physics Day where students take instruments on the rides and perform calculations. Sensor-based data collection can extend data collection so that the ride characteristics can be studied in more detail than is possible with traditional methods. Several categories of study are suggested below.

For any ride it is essential that you plan your data collection carefully. It is best to concentrate on a single portion of a ride, such as a particular loop or corner of a roller coaster. Decide which part of the ride you want to study, and estimate the length of time you will need to collect data. You may want to measure the time interval while watching others on the ride. The time between samples can then be calculated by dividing the desired time interval by the number of points you want to collect.



Along with planning the data-collection parameters, you must plan the orientation of the accelerometer during the ride. Which axis of the acceleration do you want to record?

Hold or fasten the accelerometer so the arrow is parallel to this axis. The direction of the arrow will correspond to positive acceleration.

When describing the directions of accelerations on an amusement park ride, it is convenient to have a common vocabulary. The diagram defines the terms vertical, lateral and longitudinal. These designations are from the frame of reference of the rider.

Note: Depending on the ride, you may need to begin data collection before the ride begins. Extend the suggested data collection duration accordingly. A duration of 60–80 seconds is usually needed to record a complete ride. A decision on which axis to record should be made before getting on the ride.

Part I Dips

Most roller coasters feature a dip following the first major climb, as well as several others during the course of the ride. If you know the speed of the train at the top of the hill and the vertical distance to the bottom, expected speed of the train at the bottom can be calculated using conservation of energy. Knowing the radius of the curve at the bottom, the expected acceleration due to circular motion can be calculated using kinematics.

The acceleration during such a dip can be measured as the train descends into the dip, and the maximum acceleration can be determined by tracing along the graph.

To record a single dip, first zero the accelerometer with the relevant arrow upward. On the ride, secure the accelerometer vertically with the arrow upward relative to the rider. Set the data-collection duration to 15 seconds. Start data collection just before the car starts over the edge of the first drop. Compare the readings obtained at the front of the train as compared to those at the center or at the back of the train. Explain any differences.

Part II Vertical Loops

Many modern roller coasters feature vertical loops. To record acceleration data during loops, first zero the accelerometer with the relevant arrow upward. On the ride, secure the accelerometer with the arrow upward relative to the rider. Set the data collection time to approximately 15 seconds and start data collection just before the car enters the loop.

Part III Corners

Many roller coasters have the cars riding on rails, and so the corners can be nearly horizontal. If the axis of the accelerometer is secured so that it is level and perpendicular to the direction of the motion, the *lateral* acceleration will be recorded. Zero the accelerometer while the relevant axis is horizontal.

Set the data-collection duration for 15–30 seconds, as determined by your study of the ride in advance. Start data collection just before the train enters the horizontal curve.

Part IV Barrels

Some rides at amusement parks and carnivals feature a barrel in which the riders appear to be held to the inside surface by an outward force. In fact, there is no outward force. Instead, the inward normal force from the wall keeps the riders moving in a circular path. To take data in a barrel ride, first zero the accelerometer with the relevant arrow held horizontally. Secure the accelerometer such that the relevant arrow is pointing inward radially toward the center of the circular motion.

Part V Starts and Stops

Many rides feature large accelerations. If the direction is forward or back, the reference is to *longitudinal* acceleration, while if it is up or down, it is *vertical*.

Rapid starts and stops are usually short lived. A data-collection duration of 10–15 seconds is usually enough to capture the entire acceleration, allowing you to start data collection just before the ride begins. If you wish to record the stopping of the car, again a short duration is needed; possibly as short as 10 seconds. Study the ride in advance to choose an appropriate data collection time.

Some parks feature rides that have vertical rises and falls. Recording data on such a ride consists of choosing an appropriate time and holding the relevant arrow of the accelerometer in a vertical direction throughout the ride. Zero the accelerometer while the arrow is vertical.

Part VI Scrambler

Some parks have rides known as scramblers. In the scrambler, the rider's seat rotates about a pivot point with a small radius while that point is being carried around in a larger radius by the overall ride. The axis of the accelerometer directed to the side of the rider will record the lateral acceleration throughout the ride. The axis of the accelerometer that is pointed forward or backward relative to the rider will record the longitudinal acceleration. For these rides, zero the accelerometer twice, while the relevant arrow is held horizontally. Some scramblers may even have vertical accelerations, in which case use all three axes of the accelerometer.

ANALYSIS

Automobiles and Motorcycles

1. For the motion along a straight line, is the acceleration of a motorized vehicle constant? If not, why do you suspect the rate is larger during part of the run than another part? How does the acceleration while speeding up compare to the acceleration while stopping? Why do you suppose this pattern is true? Characterize the ability of your driver to accelerate the vehicle at a constant rate.

2. For the cornering motions, how do the calculated accelerations from kinematics equations compare to the accelerations measured with the interface? How do the measured accelerations compare to the acceleration due to gravity, or *g*?

Elevators

3. How large is the acceleration when the elevator begins to move? How large is the acceleration when the elevator has been underway for a few seconds? How large is the acceleration when the elevator is slowing to a stop? What does the sign of the acceleration indicate?

4. Use the integral tool to analyze a graph of acceleration *vs.* time. How does the area under the acceleration graph while speeding up compare to the area under the graph while it is slowing down? Why should these two areas be equal magnitude but of opposite signs?

5. Can you determine which direction the elevator is moving (upwards or downwards) by the size or direction of the accelerations? Explain your answer.

6. If you collect data while holding the accelerometer in your hand (arm in front of your body), how does the resulting acceleration compare to that recorded while the accelerometer is held rigidly against the elevator itself?

Amusement Parks

Part II Vertical Loops

7. How does the acceleration at the bottom of the loop compare to the value at the top of the loop? How does the value at the top compare to the acceleration due to gravity? What does the reading you get at the top mean? Is the loop circular in shape? If not, why not?

Part III Corners

8. By measuring the speed of the ride, and estimating the radius of curvature, you can calculate an independent value for the centripetal acceleration using kinematics. Compare this value with the measured value. What aspect of the ride could lead to the two accelerations being different?

Part IV Barrels

9. Because this type of ride is rotating at a constant angular velocity, the physics is that of uniform circular motion. The acceleration is radially inward and should be equal to $4\pi^2 R/T^2$. Calculate an acceleration from measurements of the radius R and the period T for comparison to the acceleration measured while on the ride. The changes in this value while the ride is starting up and also while slowing down can be studied using the interface.

Part V Starts and Stops

10. Which is larger, the starting or the stopping acceleration? Why might one be larger than the other? Is the vertical acceleration experienced during the ride ever that of free fall?

Part VI Scrambler

11. How close are the radial accelerations of the scrambler to that of the acceleration of an object in free fall?

EXTENSIONS

1. For any of the applications discussed in this activity, you can use all three axes of the Go Direct Force and Acceleration Sensor or the Go Direct Acceleration Sensor. The vector sum of the three acceleration components can be calculated to give the acceleration magnitude.

2. Collect acceleration data while snow skiing or snowboarding. Make several turns while recording the lateral acceleration. A procedure similar to the one described above could be employed to study the turning accelerations as the rider makes sharp and gradual turns.

3. Have a skier, skateboarder, or a bicyclist go over a vertical jump and record the acceleration in the vertical direction during the jump. Video analysis measurements could be used to compare to the interface measurements.

4. Have a rider on a skateboard, ice skates, or roller blades execute a series of turns while collecting acceleration data. Video analysis measurements could be used to compare to the interface measurements.
5. Other carnival and amusement park rides can be studied using techniques similar to the ones described in this experiment. Most have a preferred direction of acceleration that can be ascertained by studying the motion of the ride.
6. Use the altitude channel of a Go Direct Acceleration to measure changes in elevation during the motion of an elevator or roller coaster ride.

Accelerations in the Real World

1. As indicated in the title, this experiment features measurements made in the real world rather than in the typical physics laboratory. Taking the measurement tools outside the walls of the classroom helps to make physics real for students. This experiment is unlike any other in the book in that detailed instructions are not given, nor is it possible to give them. The varying conditions outside the laboratory require varying data-collection durations, rates, and analysis.
2. The experiment suggestions offer an opportunity for students to observe a variety of interesting phenomena and then to make measurements on them. Your students will often have to decide what constitutes useful or interesting data. A limited number of questions are offered for most of the suggested experiments. You may want to add your own questions tailored to your local situation, or you may want to have students pose their own questions to be answered.
3. The experiments in this book were selected to provide a sampling of Vernier experiments that cover several subjects and key scientific concepts. The downloaded zip file contains PDF files of the student experiments. You can print the PDF, distribute it to students electronically, or post the file to a password-protected class web page or learning management system.
4. This experiment was adapted from *Physics with Vernier*, Experiment 21. Learn more at **vernier.com/pwv**
5. For additional information about the Vernier probeware used in this experiment, including tips and product specifications, visit **www.vernier.com/manuals** and download the appropriate user manual.
6. See **www.vernier.com/start/go-direct** for information about how to connect to your Go Direct sensors in Graphical Analysis.

RELATED SKILLS

- Zero sensors
- Set up data-collection parameters based on experimental conditions

ESTIMATED TIME

The time needed for this experiment depends on the experimental setup and what you decide to investigate.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Obtaining, evaluating, and communicating information	PS2.A Forces and Motion	Cause and Effect

EQUIPMENT TIPS

1. It is important to choose an appropriate data-collection duration and rate prior to beginning data collection. The orientation of the sensor during the measurements must also be planned in advance

   Data-collection duration should be based on the event being measured. For a continuing event such as a rotating barrel ride, the total time is not as important. For an amusement park ride, focusing on a small portion has an advantage over trying to take data over the entire ride. The resulting data is more descriptive and students have an easier time ascertaining important details. This is, however, not always possible.

   The time between samples can be calculated by dividing the data-collection duration by the number of samples to be taken. For example, to take 200 points of data for 100 seconds would require a time between samples of 100/200 or 0.5 s/sample.

2. Practice is required to get good results. Have the students take data in a controlled situation inside the classroom if possible. When they have the routine under control, they will be ready for the real experiment.

3. Whenever possible, the accelerations measured using the interface and accelerometer should be compared to accelerations inferred from kinematics or energy considerations. The comparison functions as both a consistency check and a means of reviewing the multiple descriptions of nature possible in physics.

4. Additional ideas for amusement park physics can be found in the following sources:
   - "Acceleration measurement in the Amusement Park," by Charles Reno and Robert R. Speers, *The Physics Teacher*, Sept., 1995, p. 382.
   - *Amusement Park Physics* by Clarence Bakken (available from the American Association of Physics Teachers)

5. LabQuest 2 and Graphical Analysis users have the option of using the Go Direct Acceleration Sensor (order code: GDX-ACC) or Go Direct Force and Acceleration Sensor (order code: GDX-FOR). Both can connect wirelessly with your LabQuest 2, computer, Chromebook, or mobile device via Bluetooth® wireless technology, and both include a 3-axis accelerometer and 3-axis gyroscope. Go Direct Acceleration also includes an altimeter.

DATA COLLECTION AND ANALYSIS TIPS

Automobiles and Motorcycles

Consider all safety issues when using automobiles, motorcycles, and go-carts. We have included two possible experiments using these real-world events, but suggest the following:

- A responsible adult driver should be the driver.
- The physics instructor should supervise the actual experimentation.
- A plan should be submitted by the students detailing the steps they propose to take during their experimentation prior to starting data collection. The instructor and another school official should approve this plan.
- The students' parents or guardians should formally approve of the use of motorized vehicles before allowing the students to continue with their lab work. The teacher and a school administrator can work out a permission form.
- For curvilinear motion, drivers should carefully lay out a track with the radii of the curves large enough to keep the centripetal acceleration less than $0.2g$, or $1.2\ m/s^2$. This will keep the vehicle within the limits of normal static friction.
- A constant speed is important in the curvilinear experiment in order to be able to calculate values for the acceleration from kinematics.

Elevators

Some towns may not have high-speed elevators or tall buildings available. One substitution that could have similar effects would be to use a string going over a pulley mounted as high as possible. The students could then treat the movement of the sensor on the end of the string much like a motor operating an elevator.

If students are going to be performing experiments on a public elevator, obtain permission from the building owner or operator. It would also be wise to conduct their experiments during off hours rather than at busy times

A video camera could be used in an outside or glass elevator to record the position as a function of time. If recording the position of the elevator for video analysis, note that the plane of motion may not be sufficiently perpendicular unless the camera is far away.

Amusement Parks

These activities are designed to be used when the school's physics students are attending a Physics Day event at the local amusement park. They can also be carried out at other times when the park is in operation. If there is any doubt about permission to take a data-collection interface onto a ride, contact the park in advance.

The most difficult part of recording accelerations on a ride is deciding what portion of the ride to focus upon. Recording the acceleration during a whole ride may make the interpretation of the data challenging—simply too many things are happening. Although the rides may feel smooth, in fact they are fairly bumpy and the data collected can look quite random. Students will find it difficult to interpret the complex data. Focusing on select portions of rides where the accelerations are unusual or large yields better results.

The orientation of the Accelerometer is key to gathering meaningful data. For example, if the ride has a large initial acceleration in the forward direction, the axis of the accelerometer should be directed longitudinally in order to obtain that value. If the point in question is the top of a bump, the bottom of a dip or the top of a vertical loop, the acceleration of interest is likely vertical. Hold the accelerometer with its axis oriented so the arrow will be vertical at that point in the ride. Finally, if the ride has a large acceleration due to circular motion, holding the accelerometer with its axis radial to the circle and pointing inward will give this acceleration. Students should plan their data collection carefully in order to get meaningful data.

On an amusement park ride, you will need to secure the sensor and interface or phone so they do not fall. Using a belt pack/bum bag or clothing with zippered pockets is recommended.

SAMPLE RESULTS

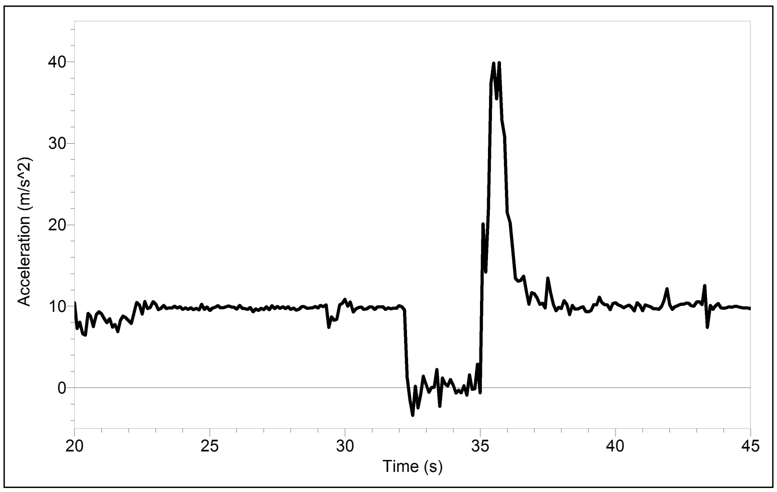


Figure 1 Acceleration data[1] from the Drop Zone at Great America in Santa Clara, CA

The ride is initially at rest, then it is in free fall for about 5 seconds, and then braking causes a large upward acceleration.

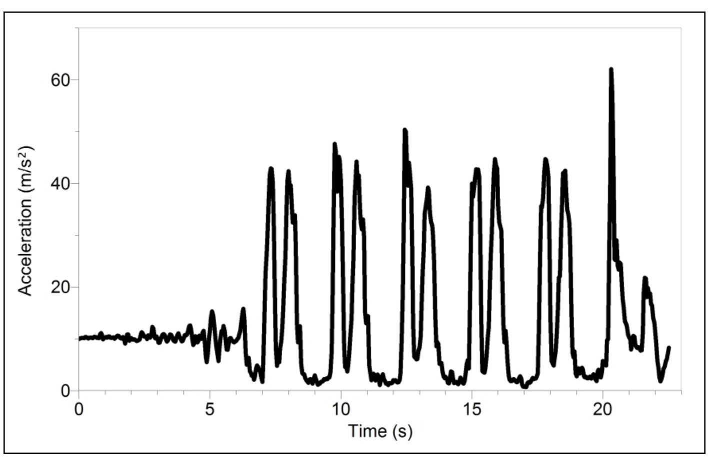


Figure 2 Acceleration data from a BMX bike on a half-pipe

[1]The data were collected and provided by Clarence Bakken.

The rider is in free fall after the vert, then acceleration peaks in the transition from the vert to the flat region, where the rider experiences only the acceleration due to gravity. On the last vert, the rider incorporates an air trick, flair, wherein both the rider and bike do a backflip combined with a 180, to land facing back down the ramp. The rider reaches his maximum acceleration on this landing.

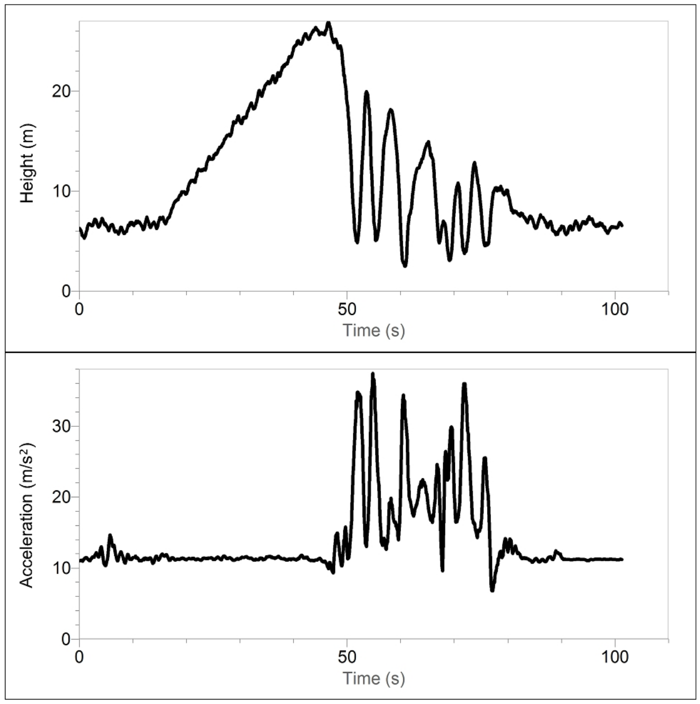


Figure 3 Acceleration data[2] from the Vortex, a stand-up roller coaster

Note the accelerations experienced at different heights during the ride.

ANSWERS TO ANALYSIS QUESTIONS

Automobiles and Motorcycles

1. The magnitude of the acceleration of a vehicle depends upon factors such as gear ratio, torque, and engine speed. Do not expect the acceleration to be constant. In general, vehicles can create larger accelerations from braking than they can by speeding up or turning.

2. The measured acceleration using the Accelerometer and the acceleration inferred from kinematics should be within 10%. If speed varies, the agreement will be worse. Typical accelerations are smaller than g.

Elevators

3. The magnitudes will vary, depending on the elevator used. The sign of the acceleration while starting to move upward will be positive, while stopping on the way up will be negative indicating that the acceleration is directed downward.

[2]The data were collected and provided by Clarence Bakken.

4. The two areas should be equal, but the second is negative while the former is positive. The area indicates the change in velocity, which is equal but opposite for starting versus stopping. This is true because the elevator begins and ends at rest.

5. The elevator can experience positive acceleration while moving in either direction. The sign of the acceleration alone does not give definitive information. However, the sign of the acceleration coupled with the knowledge that a given data series started with the elevator at rest will show the direction of motion. For example, if the elevator starts from rest and the initial acceleration is negative, then the elevator has started to descend. We assume that the arrow on the accelerometer was oriented straight upward and that the default calibration was used.

6. If the Accelerometer is held in the hand, the acceleration is extended over a longer time and is less reliable as a measure of the elevator's true acceleration. Essentially, you measure the hand's acceleration, which is different from the elevator's acceleration.

Amusement Parks

Part II Vertical Loops

7. The acceleration at the top of the loop is smaller than the acceleration at the bottom. The acceleration measured by the sensor is always in the inward-directed centripetal acceleration, since the Accelerometer axis is held perpendicular to the direction of travel. The cart is usually moving much more slowly at the top, so that the centripetal acceleration is smaller. The loop is often not round, but has smaller radius of curvature at the top compared to the bottom. This will compensate for the slowing of the train as it rises higher in the loop, maintaining a sufficiently large centripetal acceleration throughout the loop so that the cart does not leave the track.

Part III Corners

8. If the corner is banked at all, the measured acceleration will be changed, since the Accelerometer will not be horizontal.

Part IV Barrels

9. Answers will vary by ride.

Part V Starts And Stops

10. The stopping acceleration can be much larger, reflecting the fact that it is easier to take energy away from an object (braking through friction) than it is to add energy to an object. Some rides do approach or exceed free-fall acceleration magnitudes.

Part VI Scrambler

11. Answers will vary by ride.

FREQUENT QUESTIONS ON ACCELEROMETER MEASUREMENTS

Since accelerometers are sensitive to both acceleration and the Earth's gravitational field, interpreting accelerometer measurements is complex. A useful model for understanding accelerometer measurements is a spring-based scale with a reference mass (or object) attached to the scale. If the scale is pointing upward (the usual orientation for such a device), the weight of the mass causes the spring to compress, and you get a non-zero reading. If you were to turn the scale upside down, the spring will be extended, instead of compressed, and we get a reading of the opposite sign. If you turn the scale so it points sideways, and keep it motionless, then the spring will just be at its relaxed length, and the reading will be zero. If you accelerate the scale toward the mass, then the spring would compress. If you accelerate the scale away from the mass, the spring would stretch. In each case, the scale is reading a value corresponding to the normal force on the mass. This reading can be made relative by dividing out the mass, giving units of N/kg, which is the same as m/s^2.

Q: What does an accelerometer measure?

A: Normal force per unit mass. Note that it's not the net force per unit mass (which would be acceleration), but it is the normal force per unit mass. This somewhat unusual quantity corresponds with what a rider on a roller coaster feels during the turns. This interpretation is useful even for the scalar total acceleration value, which is 9.8 N/kg for an Accelerometer at rest, zero for one in free fall, and greater than 9.8 for one making a corner.

This normal force interpretation works even for a one-axis accelerometer being accelerated in a horizontal direction. The reading is non-zero as the test mass inside the device has to have a force applied to accelerate it. That is just a normal force that happens to be horizontal.

When discussing the accelerometer reading, we can call it the Normal Force per Unit Mass, with units of N/kg.

Q: I thought the Accelerometer measured acceleration!

A: Here, we are being very careful to not call something an acceleration when it is not a kinematic acceleration. For example, an "acceleration" of 9.8 m/s^2 for an object that remains at rest is clearly a problematic interpretation, yet that is what the accelerometer reads.

You can correct the accelerometer reading to get a true acceleration by adding the component of the gravitational acceleration field along the direction of the sensor arrow. For example, if the axis of the accelerometer is pointing upward, then the gravitational component is –9.8 m/s^2. The accelerometer reads 9.8 m/s^2 when the arrow is upward and the device is at rest. By adding –9.8 m/s^2, we get zero, which is the correct acceleration. If the arrow is horizontal, then the reading is zero, but the gravitational component is zero, and we still have zero for the true acceleration.

Q: What about *g*-force measurements?

A: We avoid the term *g*-force because the quantity does not have units of force. Instead, *g*-factor can be used as a simplified label for Normal Force per Unit Mass in axis labels and discussions.

You can see that the *g*-factor is then 1 for an object sitting at rest on a table, zero in free fall, etc. The *g*-factor is dimensionless. If the Normal Force is a vector, then so is the *g*-factor. The *g*-factor is completely optional—it is just a shortcut to avoid a long name.

Activity **17**

Projectile Motion

Introduction

Up to this point it is likely that you have examined the motion of an object in one dimension only—either falling vertically under the influence of Earth's gravity or on a horizontal or inclined surface.

In this experiment, you will examine the behavior of a projectile—an object moving in space due to some initial launching force. Such an object can undergo motion in two dimensions simultaneously. Using the Vernier Video Analysis app, you will compare features of the position *vs*. time and velocity *vs*. time graphs with those of one-dimensional motion.

Objectives

In this experiment, you will

- Use video analysis techniques to obtain position, velocity, and time data for a projectile.
- Analyze the position *vs*. time and velocity *vs*. time graphs for both the horizontal and vertical components of the projectile's motion.
- Create and analyze your own video of an object undergoing projectile motion.

Materials

Vernier Video Analysis app in a web browser on a computer, Chromebook, **or** mobile device
camera capable of recording digital video (e.g., the camera on a phone or tablet)
tripod or other equipment to support the device used to record the video
meter stick or some other object to provide scale
projectile: a brightly-colored ball works well
video editing software (optional)

Pre-Lab Investigation

Your instructor will launch a projectile. Observe its motion carefully, then discuss its position *vs*. time and velocity *vs*. time behavior. Sketch a graph of the projectile's horizontal velocity *vs*. time, and sketch another graph of vertical velocity *vs*. time. Share your sketched graphs with your group or with the class.

Analysis

Part 1 Analysis of an existing video

1. Examine the graph of *x* position *vs*. time. If it appears to be linear, fit a straight line to your data. If the slope of the graph appears to change abruptly, select each segment, one at a time, and fit separate straight lines to each portion of the graph that appears to be linear.
   a. Click-and-drag or touch-and-drag across the graph to select the portion of the graph that appears linear.
   b. Click or tap Graph Tools, , choose Apply Curve Fit, and apply a linear curve fit.
   c. Repeat Steps a and b for additional linear regions of the graph, if desired.
2. Write the equation that describes the *x* position *vs*. time behavior of the ball in each segment; be sure to include units.
3. Based on what you have learned in previous experiments, write a description of the horizontal component of the motion of the projectile. Note when any change in the horizontal component of the motion occurs.
4. Now, examine the graph of *y* position (Y) *vs*. time.
   a. Click or tap the vertical axis label to open the Plot Manager. Turn on the *y* position and turn off *x* position.
   b. Fit an appropriate curve to this graph (or to each portion of the graph). To do this, click or tap Graph Tools, , choose Apply Curve Fit. Select the curve fit model that best fits your data, and apply the curve fit.
   c. Write the equation that describes the *y* position *vs*. time behavior of the ball in the first segment; be sure to include units.
5. Based on what you have learned in previous experiments, write a description of the vertical component of the position of the projectile.
6. Now, to test your analysis in Step 5, examine the graph of *y* velocity *vs*. time.
   a. Click or tap the vertical axis label to open the Plot Manager. Turn on *y* velocity (Y Velocity) and turn off *y* position.
   b. Click-and-drag or touch-and-drag across the graph to select the portion of the graph that appears linear.
   c. Click or tap Graph Tools, , choose Apply Curve Fit, and apply a linear curve fit. Fit a straight line to the first portion of the graph only, if there are multiple linear regions.
   d. Repeat Steps b and c for additional regions of the graph, if desired.
7. What can you say about the rate of change of the *y* velocity as a function of time? How does the value of the slope of the linear fit compare to the acceleration of a freely falling object? Summarize in a sentence or two.
8. Compare the a and b parameters (including values and units) of the curve fits you performed in Step 4 to the slope and intercept of the linear fit you performed in Step 6.
9. Explain the differences in the horizontal and vertical components of the velocity of the projectile in terms of the force(s) acting on the projectile after it was launched.

10. Display the velocity vectors for the motion of the projectile, and then explain how the vectors correspond to the motion of the projectile in the vertical and horizontal directions. To display the velocity vectors, follow these steps:
    a. Use View, ⊞, to display the video if it is hidden.
    b. Click or tap Vectors, ↗, to add a vector display. (Click or tap Add, ⌖, if the Vectors option is not visible.)
    c. Enable the velocity vectors only. To do this, click or tap the visibility toggle next to Velocity until Components, ⮡, is displayed.
    d. Adjust the Scale Factor and Vector Frequency so you can clearly see the vectors.
    e. Explain how the displayed vectors correspond to the motion of the projectile in the vertical and horizontal directions that you have also described with graphs and equations.

Part 2 Production and analysis of your own video

11. Perform the analysis of your movie as you did with the video provided to you in Part 1.

Extensions

1. Suppose that, in the shooting of your video, you placed the meter stick used for scaling against the wall you used for your background. However, the plane of the ball's motion was 0.50 m in front of the wall. The distance between the camera and the wall was 5.0 m. Would this error result in a value for the acceleration of gravity in your analysis of the *y* velocity *vs*. time graph that was smaller or larger than the accepted value? By what factor would this value differ from the expected value? Explain using a diagram.

2. Repeat the production and video analysis of a projectile, but this time use an extended body (i.e., an object that cannot be readily modeled by a point-particle). Consider carefully how best to mark the position of such an object during its motion. Interpret your position *vs*. time and velocity *vs*. time graphs as you did for Part 1.

3. Using either the analysis of the basketball shot sample video or the analysis of the video you created, model the vertical motion based on ideal conditions. Create a new calculated column and use the initial upward velocity of the object and the acceleration of gravity to calculate the ideal vertical velocity. Use the graph to compare the video-based velocities with the model-based velocities. Suggest reasons for any discrepancies.

   Note: Instructions for creating a calculated column are found in the Vernier Video Analysis User Manual, **http://www2.vernier.com/manuals/video-analysis-manual.pdf**

Projectile Motion

Projectile motion is an ideal candidate for analysis using video. This experiment should be performed only after students have had the opportunity to explore the behavior of an object moving with constant velocity as well as one that undergoes uniform acceleration.

Note that Part 2 of this activity requires students to create their own video. There are suggestions in the instructions for capturing video that are useful for analysis. Additional tips for collecting, editing, and analyzing video are available in Appendices A, B, and C.

If you need to alter this activity for time, you may omit Part 2 (in which students create and analyze their own video) of this activity by editing it out of the word-processing file of the instructions.

If this is your students' first time using Vernier Video Analysis, we recommend giving them the Guided version of the instructions. If your students are already familiar with using Vernier Video Analysis, consider giving them the Abridged version of the instructions.

This experiment was adapted from *Vernier Video Analysis: Motion and Sports*, Experiment 04. Learn more at **vernier.com/hsb-vvams-e**

Objectives

In this experiment, the student objectives include

- Use video analysis techniques to obtain position, velocity, and time data for a projectile.
- Analyze the position *vs*. time and velocity *vs*. time graphs for both the horizontal and vertical components of the projectile's motion.
- Create and analyze your own video of an object undergoing projectile motion.

During this experiment, you will help the students

- Recognize that the horizontal component of a projectile's motion is best described as an object moving with constant velocity.
- Recognize that the vertical component of a projectile's motion is best described as an object undergoing uniform acceleration.
- Recognize that, neglecting air resistance, the acceleration of the object very nearly equals a_g.
- Capture and edit a video for analysis in the Vernier Video Analysis app.

Equipment Tips

Students have the opportunity to create and analyze their own projectile video in this activity. To do this, students will need either a phone or digital camera, a tripod or other supporting device, and some object they can use for scaling. For most students, the first object they should use for a projectile should be a small ball that is massive enough not to experience significant slowing from air resistance. A ball that bounces will provide an opportunity to examine how the horizontal component of the motion changes after the ball bounces. Students are likely to want to examine the behavior of more "interesting" objects. While more advanced students may be able to handle this well, encourage most students to save those objects for the Extension activity and remind them to be safe.

Pre-Lab Discussion

This experiment should be performed only after students have had the opportunity to explore the behavior of an object moving with constant velocity as well as one that undergoes uniform acceleration. Demonstrate tossing a ball, then ask the students to describe the position-time behavior and velocity-time behavior of the ball. They are likely to describe the ball's path as parabolic but may have more difficulty describing how its velocity changes with time. Suggest that separate analyses of the horizontal and vertical components of the ball's motion could be revealing. Ask students to predict and sketch *x* velocity *vs*. time and *y* velocity *vs*. time graphs for the projectile.

Lab Performance Notes

We recommend that students first learn how to do video analysis on the provided "Basketball Shot" movie. Analysis of this movie is likely to yield results that are easier to interpret as other movies may suffer from poor scaling, perspective problems, or blurred images.

The basketball in the provided movie bounces on the pavement, and has a different horizontal velocity before and after the bounce. Consider whether to instruct students to graph all the motion or only the motion prior to the bounce. Edit the student instructions accordingly.

Sample Results and Analysis

Steps 1–3

Depending on how you instruct students to do this activity, they may have either one or two linear segments of the graph. In the sample graph Figure 1, the first slope is from data collected before the basketball hit the ground and the second slope is from after the basketball hit the ground (showing that the ball slowed down).

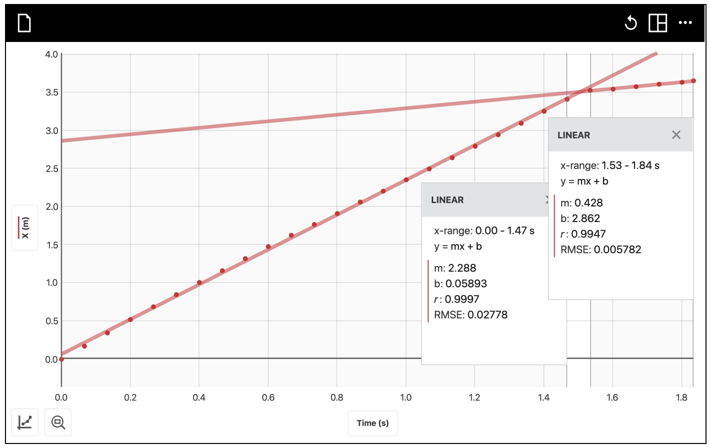


Figure 1 Graph of x *position* vs. *time with two linear curve fits*

The equations for the graph in Figure 1 are $x = (2.288 \text{ m/s})t + 0.05893$ m and $x = (0.428 \text{ m/s})t + 2.862$ m.

Steps 4–5

Students should recognize that a quadratic fit is appropriate for the *y* position *vs*. time graph. They may perform a quadratic fit to just the motion before the ball bounces (see Figure 2), or they may add the quadratic fit for each parabolic segment.

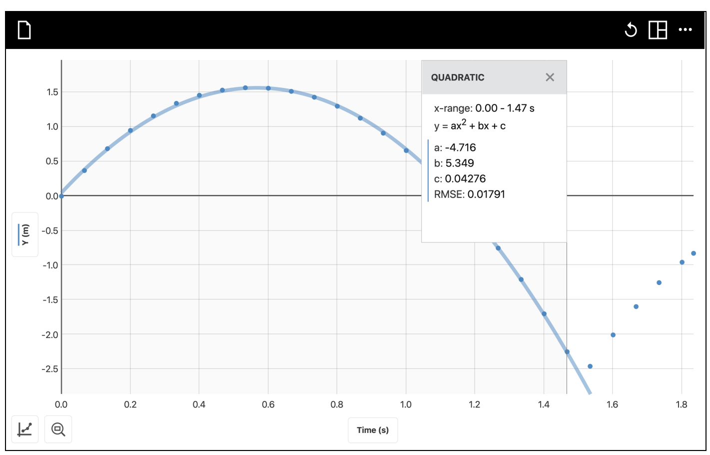


Figure 2 Graph of y *position* vs. *time with one quadratic curve fit*

The equation for the first segment is $y = (-4.716 \text{ m/s}^2)t^2 + (5.349 \text{ m/s})t + 0.04276$ m. The fact that a quadratic fits the *y* position *vs*. time graph so nicely indicates that the ball is undergoing acceleration.

The *a* coefficient for the quadratic is close to the expected value. However, it is obviously lower than the expected value. It is useful to have a class discussion about why the value is lower than expected. You may bring up the difficulty of scaling to the meter stick, since the ends are difficult to discern in the video. In addition, the basketball may not be moving in the same plane as the meter stick (the meter stick may be farther from the camera). Finally, depending on the lens of the camera, there is a certain amount of distortion in the video image the farther away you get from the center of the frame. The apparent location of the ball may be affected by this distortion. Errors such as these can be reduced by doing the following:

- Use a longer scale object with good contrast against the background and ensure that it is in the plane of the motion.
- Ensure that the camera is "square" to the plane of the motion and aimed at the center of the motion.
- Change the camera lens or the lens setting to a "narrow focus" or telephoto.
- Move the camera farther away from the motion.

Steps 6–7

The interval used for performing the linear fit should not include the first few and last few points.[1] The *y* velocity *vs*. time graph shows that the vertical component of the ball's velocity changed at a constant rate (see Figure 3). Students should recognize the rate of change of the velocity as the acceleration of the ball. If the object used for scaling and the plane of the ball's path coincide, the value of the acceleration should be nearly –9.8 m/s^2, a_g.

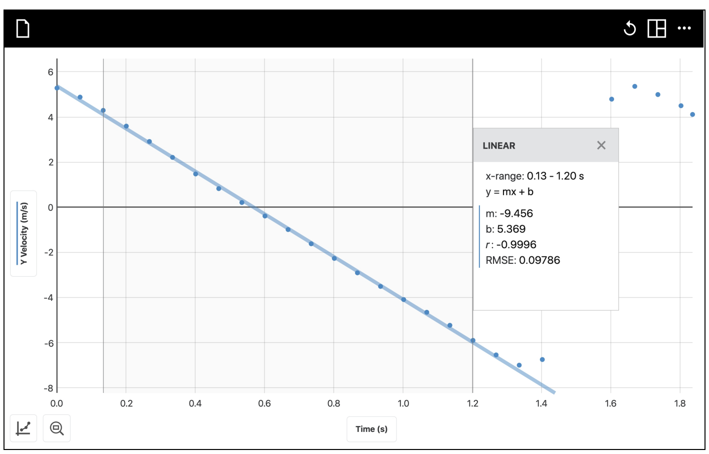


Figure 3 Graph of y *velocity* vs. *time*

Step 8

By comparing the value of a in the quadratic fit of the *y* position *vs*. time graph to the slope of the linear fit of the *y* velocity *vs*. time graph, students should be able to conclude that a is half of the acceleration. Furthermore, note that for the parabola before the bounce, the b parameter is the same as the intercept of the line of best fit to the corresponding *y* velocity *vs*. time graph.

[1]This is due to the way that Vernier Video Analysis calculates the velocity of the object at each clock reading. See **www.vernier.com/til/1011** or the Instructor Notes for Activity 2, Accelerated Motion in this book.

This intercept is the y velocity for the first frame used in the analysis. Once these connections have been made, students should recognize that the general equation for the position of an object moving with constant acceleration, $y = \frac{1}{2}at^2 + v_0 t + y_0$, describes the vertical component of the motion of the projectile.

Step 9

From their understanding of the relationship between motion and forces, students should conclude that no net force acts on the projectile in the horizontal direction, except when it makes contact with the ground. Note that the x velocity decreases after the bounce. The projectile accelerates in the vertical direction because of the force exerted on it by the earth. The sign of the acceleration is consistent with the direction of gravitational force.

Step 10

Students add horizontal and vertical velocity vector components to the video view. Note that the horizontal velocity vectors show that the x velocity is constant (but with different values before and after the basketball bounces). The vertical velocity vectors are consistent with an object that is undergoing acceleration in the (negative) y direction.

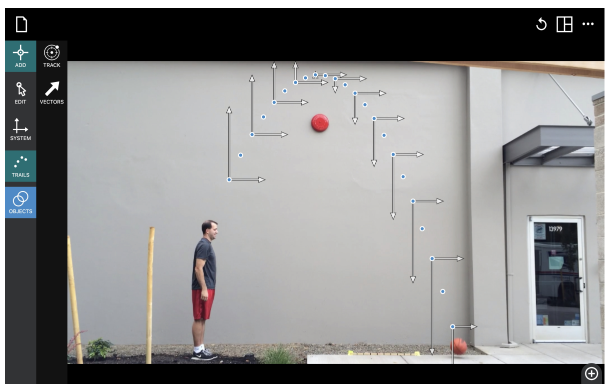


Figure 4 Vectors representing the velocity components of the projectile

Step 11

Student results will vary depending on the student video. Results should be similar to those found in Part 1.

Extensions

1. If the object used for scaling were farther from the camera than the plane of the motion, the video analysis will report values of position and velocity that are larger than they actually are. This will result in a value of the slope of the y velocity *vs*. time graph that is 5.0/4.5 = 1.1 times larger than the accepted value (a_g would appear to be –10.9 m/s^2).

2. For the analysis of the motion of an extended body that undergoes rotation during the motion, students should mark the center of gravity (a piece of contrasting tape works well) before recording the video so they can mark the position of its center of mass. Analysis of

the motion of the center of mass of the extended body should yield results much like those of a point particle.

3. Modeling the ideal motion can be done using the expression A*X+B found in the calculated column expressions. A is the acceleration of gravity, –9.8 m/s^2, and B is the initial upward velocity. For the purpose of this activity, the student may use either the initial velocity from the Y Velocity column or the *y* intercept of the linear fit for the *y* velocity *vs*. time graph (see Figure 5). If some students or groups use the Y Velocity column and others use the *y* intercept, students can discuss the differences between the models and the reasons for them. **Note**: Instructions for creating a calculated column are found in the Vernier Video Analysis User Manual, **http://www2.vernier.com/manuals/video-analysis-manual.pdf**

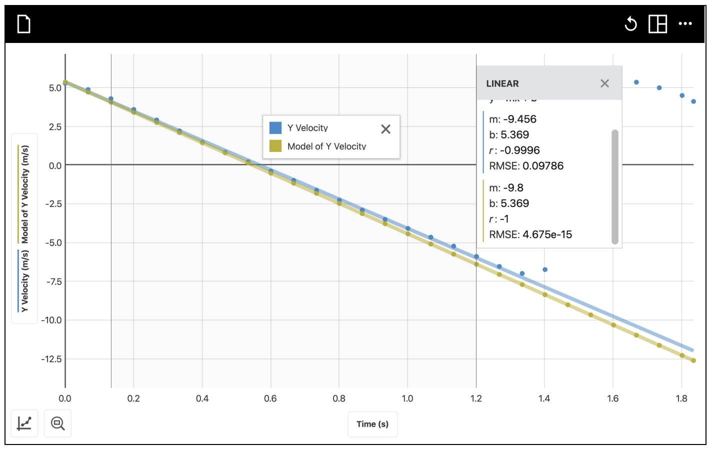


Figure 5 Two linear models, one based on the original curve fit (blue) and one based on the y intercept of the original curve fit (light green), are displayed.

Deflection of a Center-Loaded Rectangular Beam

Imagine you are walking across a simple plank that spans a creek and you stop in the middle of the plank to enjoy the scenery. Consider the plank you are standing on. You will notice it is bowing a bit downward where you stand. If you were to change the dimensions, could you make the beam less flexible (more rigid)?

PRELIMINARY OBSERVATIONS

1. Find a small uniform beam, such as a Popsicle stick or a pencil. Place your fingers on the ends and gently push up on the center with your thumbs. What do you observe?

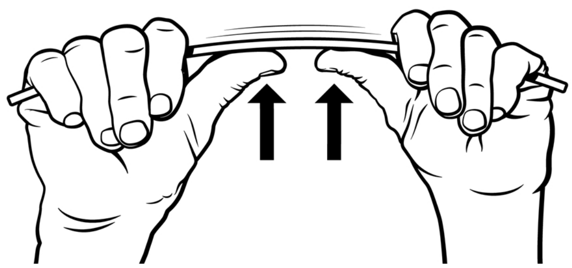


Figure 1 Use one or both thumbs to apply a force in the middle of the beam

2. Discuss your observations with your group or class. Consider the following questions:
   - How many beam characteristics can you identify that may affect the beam's flexibility?
   - What dimensions of the beam could you change to make the beam more stiff?
   - Which dimension will have the greatest effect on the stiffness of the beam?
   - Can you identify any changes that will not affect the stiffness of the beam?
   - Draw a qualitative graph that represents the relationship between force and deflection at the center of the beam. Label the axes and explain your reasoning.

3. Observe as your instructor places a beam on the Structures & Materials Tester and applies a load to the center of the beam. Notice that the beam is centered over the force sensor and the cross-bars are equal-distance from the center of the apparatus. Also note when and how to zero the force and displacement sensors so that when you are using the equipment on your own, you will be able to set it up correctly.

INVESTIGATION

You will investigate one or more elements that affect the flexibility of the beam:

1. Develop a procedure for your investigation.
   - Include the question you will investigate.
   - Articulate your hypothesis, and, if appropriate, propose a relationship between variables.
   - List the measurement equipment you will use.
   - Decide how much data to take in order to have enough information to satisfy your purpose and stand up to questioning by your peers.
   - Remember to change only one independent variable at a time.
2. Discuss and decide which factors you will measure to develop your model of the flexibility.
3. Carry out the investigation.

ANALYSIS

For each part of the procedure consider the following questions: Is the graph of variables you measured a linear graph? If not, you may need to perform one or more mathematical operations to linearize your data or use the curve fit tool to determine the mathematical relationship. Develop a mathematical model for your data and discuss with your group how your variables fit into the model. When you discuss the results with your class, be sure to share your model and ideas. You may also wish to do some research to support your experimental data.

EXTENSION

Do you think there is a difference between using a plank that is 2"×4" on edge and using two 2"×2" planks stacked (but not secured together). Test this idea by creating samples appropriate for the Structures & Materials Tester.

Deflection of a Center-Loaded Rectangular Beam

INTRODUCTION

This investigation begins with Preliminary Observations, which are designed to engage the student physically and mentally with the phenomena. After facilitating a class discussion about students' observations, you will pose a question to the students that frames the intended investigation. Following this structure allows you to assess students' pre-existing knowledge and assumptions as well as offers a way to engage the students in the process of designing their investigation

This investigation was adapted from *Materials Testing: Beams to Bridges with Go Direct® Structures & Materials Tester*, Experiment 01. Learn more at **vernier.com/gdx-vsmt-bb-e**

OVERVIEW OF INVESTIGATION 1

Students should finish this activity with a clear model of the factors affecting the deflection of a beam. In the Preliminary Observations, students observe a beam bending under a load and brainstorm what physical characteristics affect the amount of bending (aka deflection) that occurs. Students should ultimately use their model to predict the deflection of a beam, given specific beam parameters and a known applied force.

WHAT SHOULD STUDENTS KNOW BEFORE DOING THIS ACTIVITY?

Students should have an intuitive grasp of the individual factors that affect the flexibility of a beam. A class discussion should reveal the general nature of the individual relationship. For example, the greater the span between the supports, the greater the beam deflects with a given load. Students need not be familiar with the modulus of elasticity (E), but will recognize that the type of material will also affect the deflection.

INSTRUCTOR INFORMATION

This activity offers students the opportunity to explore the factors affecting the flexibility of a center-loaded beam that is supported at both ends. The student handout directs students to push up on a beam that is supported on both ends and observe the resulting deflection.

The equation that models the deflection behavior is

$$\Delta S = \frac{FL^3}{48EI}$$

where Δs is the beam's elastic, vertical displacement at mid-span, F is the load, L is the span length, E is the modulus of elasticity, and I is the area moment of inertia. If we consider a solid rectangular beam of base *b* and height *h*, then the area moment of inertia, *I*, is $bh^3/12$, and the model becomes

$$\Delta S = \frac{FL^3}{4Ebh^3}$$

If students express uncertainty relating to the general nature (direct or inverse) of the factors, a discussion of extremes may help. For example, compare the amount of bending that occurs when you stand on a 2×4 that spans a short length versus one that spans 10 times the length. This should allow them to derive the relative relationships as shown in this (incorrect) proportionality:

$$\Delta \propto FL/bh$$

This is a good starting point for students to use as a prediction of what they might expect from their investigation. When this preliminary model breaks down, it will be important to encourage students to stop and evaluate the system and hypothesize why the data show what they do.

LEARNING OUTCOMES

- Students will engage in an inquiry activity to develop a mathematical model based on observations (of their own devising) of the physical world.
- Students will understand the factors that affect the deflection of a center-loaded rectangular beam, supported on both ends, including width, thickness, and length.
- Students will construct a model representing the relationship of factors affecting the deflection of center-loaded rectangular beams.

NEXT GENERATION SCIENCE STANDARDS

Disciplinary Core Ideas	Crosscutting Concepts	Science and Engineering Practices
ETS1.A. Defining and Delimiting Engineering Problems ETS1.B. Developing Possible Solutions ETS1.C. Optimizing the Design Solution	Patterns Cause and effect Scale, proportion, and quantity Systems and system models	Asking questions and defining problems Developing and using models Planning and carrying out investigations Analyzing and interpreting data Using mathematics and computational thinking Constructing explanations and designing solutions Engaging in argument from evidence

ESTIMATED TIME

The project is designed to be completed in two 45-minute periods, or less if you break the activity into individual assignments for investigation and then bring the parts together in a class discussion. In the latter approach, plan on a single 45-minute period, with the potential need for an additional 20 minutes on a following day to integrate all the components into your students' models.

MATERIALS

Make the following materials available for student use. Items in bold are needed for the Preliminary Observations.

computer, Chromebook, or mobile device
Graphical Analysis app
Go Direct Structures & Materials Tester (GDX-VSMT)
rectangular beam
rulers or Popsicle sticks
rectangular beams of adequate number (5 different widths and thicknesses; see Tips for materials recommendations)

PRELIMINARY OBSERVATIONS

In the Preliminary Observations, students are instructed to take a simple rectangular beam, such as a ruler or Popsicle stick, and test it for bending while thinking about the characteristics that may affect its flexibility.

Question the students to help them think about how changing a characteristic of the beam will affect the flexibility. For example, "If you increase the height of the beam, will it bend more or less or perhaps not change at all?" is an appropriate initial probe. You may follow up by asking them, "If you double the height, how will the deflection be affected?"

IMPLEMENTATION

After the Preliminary Observations and discussion, frame the investigation. Challenge students to identify beam characteristics that affect the flexibility of the beam. You can decide to have each lab group choose one characteristic to investigate, or have all lab groups evaluate all characteristics. If you choose the former approach, we recommend bringing the students back together as a class to share their results and build a more comprehensive model.

Demonstrate the general approach to using the Structures & Materials Tester by attaching appropriate tackle (e.g., eye-bolt, U-bolt, and quick link, if needed) and placing a beam on the cross bars. Demonstrate how the equipment can be used to gather force and displacement data. Show students how to zero the sensors in Graphical Analysis before starting data collection. This is especially important for the displacement sensor, as the zero point changes with samples of different heights.

Provide students with the materials for the investigation. We recommend the use of basswood dimensioned samples, which can be purchased from several online sources or local hobby shops. You can purchase longer lengths and cut to an appropriate length (~30 cm works well).

ANALYSIS

Students should notice a direct relationship between span and displacement, meaning that as the span increases the vertical displacement also increases. They should also observe an indirect relationship between both width and thickness as it relates to displacement.

Students should either linearize the data by creating a calculated column or use the curve fitting tools to determine the mathematical relationship between displacement and each variable.

The resulting model should (ideally) be in the form: $\Delta = AFL^3/bh^3$. Where F is the force applied, L is the span, b is the base width, and h is the height of the beam. The parameter A is a constant of proportionality that incorporates the modulus of elasticity (E). This attribute will be explored in more detail in Investigation 3 of this book. Students can enter all of the values for a given beam under a certain load and then algebraically determine the value of A.

SAMPLE RESULTS

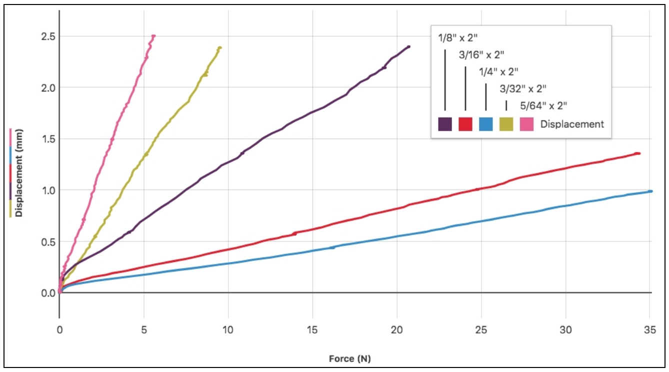


Figure 1 Five data sets of displacement versus force

This data set may or may not be part of the students' evaluation since it is not a variable of the beam. However, it is interesting to note that the relationship is proportional and that the beam behavior is "Hookian" (follows Hooke's Law) in the ranges of forces tested.

Figure 2 Five data points with an inverse curve fit showing the relationship between beam width and displacement

The power curve fit for the data shows an inverse relationship between beam and width displacement. Note that the beam length and height are kept constant during this investigation.

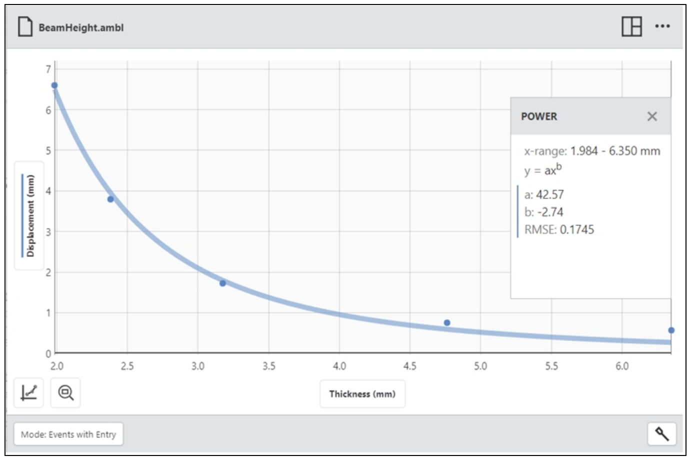


Figure 3 Beam height versus displacement

Students may not have previously encountered an inverse-cubed relationship.

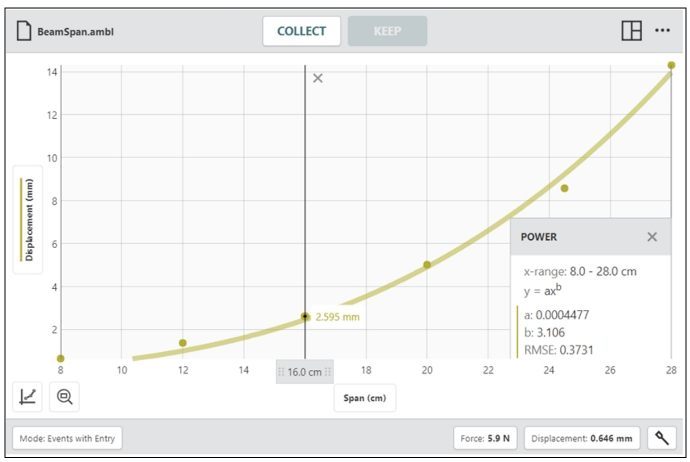


Figure 4 Span versus displacement

The span between the supports of the beam and the resulting displacement results in a cubed relationship.

TIPS

1. Follow these safety recommendations found in the Go Direct Structures & Materials Tester *User Manual* for additional best practices:
   - Wear safety glasses.
   - Any tackle connected to the Structures & Materials Tester using threaded parts should be attached so that a sufficient amount of the threaded component is engaged.
   - Quick links should be secured and not left open.
2. Basswood is generally preferred over balsa wood. Balsa wood tends to be soft and brittle, can break under relatively small forces, and contains a large degree of variation.

3. Thin pieces of wood work best. All experiments can be done with wood with a thickness of 0.25 in (5 mm) or less. Using thin pieces will also allow you to keep the load forces smaller so that not as much energy is released in the event of beam failure.

4. Although not included in the materials list, a precision measurement device, such as a Vernier caliper or micrometer, can be used to more accurately measure the dimensions of the beams.

5. In this activity, there is no need to apply forces that will bend the beams to the breaking point. The beams can be used in multiple activities.

6. The experiments described in this activity make use of a U-bolt and quick link (found in the Structures & Materials Tester tackle kit) to securely connect the beams to the device. It is not necessary to consider the weight of this tackle in the calculations of force. The added weight will affect the intercept of the equation, but not the relationship between force and displacement.

EXTENSION

Students should find that stacking individual beams gives an inverse square relationship, rather than an inverse cubed relationship observed for solid beams. This illustrates the importance of the internal forces acting on a center loaded beam.

Beam Deflection: Investigating Cross-Sectional Shape

Have you ever gone past a construction site or driven over a bridge and noticed that the supporting beams in a structure can be designed with a variety of cross-sectional shapes? In this activity, you will explore how changing the cross section of a beam affects the amount of deflection (or "bendiness") a beam exhibits under a load. Your goal is to develop a model that will allow you to predict the relative deflection of a center-loaded beam supported on both ends based on its cross section shape.

PRELIMINARY OBSERVATIONS

1. Apply a force to the center of a rectangular beam that is wider than it is tall. Observe how hard it is to bend the beam. Gather as much observational data as is reasonable given your constraints.
2. Turn the beam so that it is taller than it is wide. Apply the same force as before to the center of the beam and compare your observations to those for step 1.
3. Discuss your observations with your group or class. Consider the following questions:
   a. How is this different from your investigation of rectangular beams in Investigation 1?
   b. Beams come in a variety of shapes. Reflect on beams you have seen in your school, home, or community. What shapes have you observed? Document your thoughts about the advantages and disadvantages of these various beam designs.

INVESTIGATION

You will investigate three or four beams with different cross-sectional shape to test and explore how shape affects the flexibility of the beam:

1. Develop a procedure for your investigation.
   - Include the question you will investigate.
   - Articulate your hypothesis, and, if appropriate, propose a relationship between variables.
   - List the measurement equipment you will use.
   - Decide how much data to take in order to have enough information to satisfy your purpose and stand up to questioning by your peers.
   - Remember to change only one independent variable at a time.
2. You will need to build the beams using materials provided by your teacher.
   - They should all be constructed using the same amount of wood of the same species.
   - You must be able to test the beams using the equipment provided by your teacher.
3. Carry out the investigation.

ANALYSIS

The variable being changed is not a simple measurement that can be easily quantified. You may want to try to find a surrogate measurement or simply qualitatively describe the different beams being tested.

- Devise criteria that you will use to compare the results.
- Reflect on any results you found interesting or surprising. What insights do these results provide?
- Summarize your findings.

EXTENSION

Consider the beams you created and predict their ability to withstand a load. Rank them from weakest to strongest. Test your hypothesis by applying a force to the beams until they fail. Summarize your findings regarding how flexibility and ultimate strength are (or are not) related. Document your observations and findings.

Beam Deflection: Investigating Cross-Sectional Shape

OVERVIEW

The goal of this activity is for students to first recognize that beams used in construction have specific shapes and are not generally simple rectangles. Students identify different shapes of beams they encounter and build three or four different beams to investigate how the shape of a beam affects its rigidity/flexibility. In the Preliminary Observations, students observe the difference between a beam that is taller than it is wide and compare it to a beam that is wider than it is tall.

This investigation should result in a quantitative understanding of how the cross-sectional shape affects the flexibility of a beam.

This investigation was adapted from *Materials Testing: Beams to Bridges with Go Direct® Structures & Materials Tester*, Experiment 02. Learn more at **vernier.com/gdx-vsmt-bb-e**

WHAT SHOULD STUDENTS KNOW BEFORE DOING THIS ACTIVITY?

Students should have an intuitive grasp of the individual factors that affect the flexibility of a beam. If they have conducted Activity 19 (not required), they will have developed a model that considers the characteristics that affect the flexibility of a rectangular beam. Students do not need to be familiar with area moments of inertia, I.

INSTRUCTOR INFORMATION

This activity provides an opportunity for students to gain a qualitative understanding of how cross-sectional shape affects the flexibility of a beam. Depending on your goals and the sophistication of your students, students may begin to develop an idea as to how the area moment of inertia is determined. Show students how to set up Graphical Analysis and the Go Direct Structures & Materials Tester, if necessary, as well as how to zero the sensors before starting data collection.

Although the goal of the activity does not include the development of a model of area moment of inertia, you may wish to bring this into the conversation at some point. Our recommendation is to discuss this at the end of the activity, leaving the students with the opportunity to reflect on it in light of their lab experience. Again, the relationship for a rectangular beam can be described as follows:

$$\Delta S = \frac{FL^3}{48EI}$$

Students who have previous knowledge of the mass moments of inertia (relative to rotational inertia) may benefit from an explanation of how the two are related and how they are different.

LEARNING OUTCOMES

- Students will engage in an inquiry activity to develop a model based on observations (of their own devising) from the physical world.
- Students will understand the factors that affect the deflection of a center-loaded beam, supported on both ends, with identical volume and mass of material, but with varied cross-sections.
- Students will construct a model representing the relationship of the factors related to cross-section shape affecting the deflection of center-loaded beams.

NEXT GENERATION SCIENCE STANDARDS

Disciplinary Core Ideas	Crosscutting Concepts	Science and Engineering Practices
ETS1.A. Defining and Delimiting Engineering Problems ETS1.B. Developing Possible Solutions ETS1.C. Optimizing the Design Solution	Patterns Cause and effect Scale, proportion, and quantity Systems and system models	Asking questions and defining problems Developing and using models Planning and carrying out investigations Analyzing and interpreting data Using mathematics and computational thinking Constructing explanations and designing solutions Engaging in argument from evidence Obtaining, evaluating, and communicating information

ESTIMATED TIME

The project is designed to be completed in two 45-minute periods. This project requires that students construct three or four beams with different cross-sectional shape. These can be constructed in approximately 20–30 minutes and then should be allowed to dry overnight. The subsequent testing and analysis can generally be completed in one additional 45-minute period.

MATERIALS

Make the following materials available for student use. Items in bold are needed for the Preliminary Observations.

computer, Chromebook, or mobile device
Graphical Analysis
Go Direct Structures & Materials Tester (GDX-VSMT)
rectangular beam, 8' long 2×4, or some other rectangular beam
material to construct beams

PRELIMINARY OBSERVATIONS

In the Preliminary Observations, students are instructed to observe the bending of a rectangular beam initially oriented with the widest side horizontal, and then set on edge. Ideally, choose a beam that can be tested on the Structures & Materials Tester so students can design their own beams based on their observations of your demonstration.

An engaging alternative demonstration is to have a student stand on an 8' long 2×4. Proper safety instructions are essential if you decide to use a 2×4 for the demo: 1) Brace the 2×4 so that it does not tip in either orientation, 2) ensure that the student stands only in the center of the beam, and 3) have spotters available to allow the student to balance themselves.

You may also wish to conduct a field trip around your school to identify beams and truss systems in the building.

IMPLEMENTATION

After the Preliminary Observations and discussion, frame the investigation. Challenge the students to identify several beam shapes that they have observed in use. From this list, you may want to assign beam shapes to be tested or leave it up to your student groups to determine the shapes they will test.

Provide students with materials and any constraints you wish to impose on their investigations. If left entirely to their own devices, students may introduce extraneous variables that can make it difficult to draw conclusions from the data. For this reason, we recommend establishing certain constraints, such as requiring that all beams be constructed of the same amount of material.

ANALYSIS

The investigation of beam shape should result in a graph of displacement *vs*. force so that the degree of deflection for different beams can be compared.

As students reflect on their results they should conclude that

1. Beam shape does affect beam deflection
2. A rectangular beam on its narrow side bends less than an identical beam on its wide side.
3. A box beam and an I beam with the same amount of material oriented vertically will have similar deflection response to a vertical force.
4. Ideally, students will determine that the more a beam is aligned with the direction of the applied force, the less it will bend.

SAMPLE RESULTS

The following graphs show sample data. Student groups should present their results and question other groups about the experimental design decisions that they made. Requiring each student to participate in presenting and questioning can raise participation rates, but may cause some discomfort in students if they are unfamiliar with the inquiry nature of the activity. It may be helpful to model good questioning by posing Socratic-style questions such as, "We see that the flexibility of the box beam and I beam are similar. Do you think they also have the same ultimate strength? Why do you think that is the case?" and making it clear that "wrong" answers will not affect student's grades. Creating a safe environment for asking questions and positing answers will help students both learn engineering principles and grow as scientists.

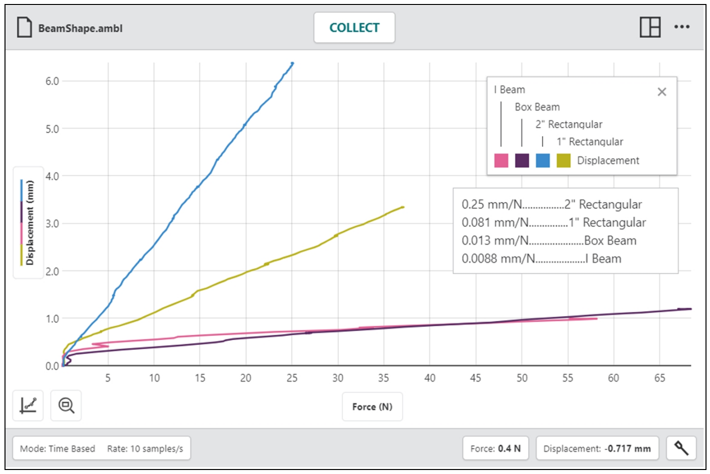


Figure 1 The beams are tested through their elastic region so that the slope represents their "spring constant." Notice that the plots for the Box Beam and the I Beam have very similar slopes.

TIPS

When setting up the Preliminary Observation, a beam 1" wide by ¼" thick clearly shows the difference in deflection and will stand on edge reasonably well.

If you use a 2×4 for the Preliminary Observation, you may find it useful to create a stand for each end of the beam so that it is held securely in both orientations. Make sure to use spotters to assist in balancing the student who is standing on the beam.

EXTENSION

Generalizing from one set of results, the yield strength for three of the beams was approximately the same. This implies that the primary benefit achieved from the different configurations was the amount of flex involved before failure occurred.

The exception to this summary is the 1" × ¼" beam, which failed at a significantly lower force. This beam was made from solid material (not laminated).

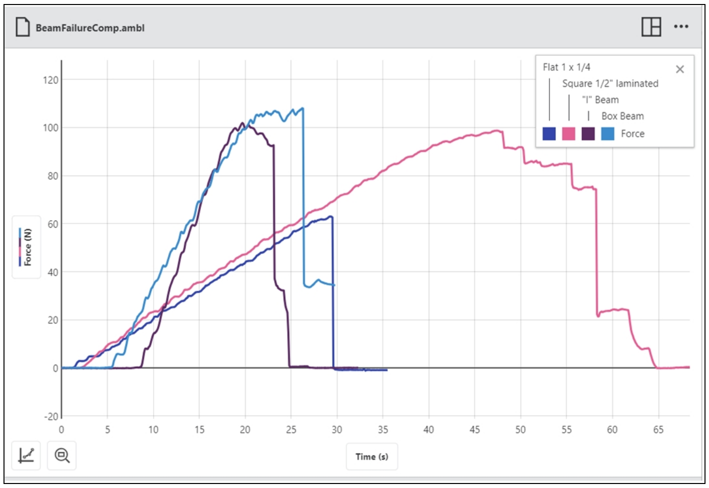


Figure 2 Student results will vary depending on adhesives, materials, and construction techniques used.

Project: Maximum Energy Output

Generating electricity from fossil fuels (primarily coal and natural gas) produces carbon dioxide (CO_2) and an array of other pollutants that are injected into the atmosphere each year. The Intergovernmental Panel on Climate Change (IPCC) estimates that 20–25% of the CO_2 produced by humans comes from the generation of electricity around the world. Increasing CO_2 concentrations in the atmosphere is one of the key drivers of climate change.

While electricity generation produces a significant amount of the CO_2 released by humans, there are millions of people around the world who do not currently have access to electricity. When individuals or communities seek out reliable electricity, they have a variety of options, including generators that run on gasoline or diesel. Developing ways to efficiently produce electricity from renewable sources, such as wind or solar power, can greatly improve people's quality of life and ability to sustainably support themselves and their communities.

Wind turbines are a rapidly maturing technology that can help reduce the carbon footprint of electricity generation and bring electricity to even the most remote communities. In this project, you will construct a small wind turbine that maximizes energy output at low and high wind speeds. This turbine could be used to provide energy that would charge small electronics or provide lighting. During the project, you will work with your group to design, test, and then optimize your wind turbine design. At the end of the project, you will submit a set of deliverables.

DESIGN REQUIREMENTS AND CONSTRAINTS

- Turbine diameter: No larger than 50 cm
- Wind speed range: 2–6 m/s
- Output: Unregulated Direct Current
- Generator: Any available DC generator or you can build your own generator
- Turbine must be robust enough to withstand outdoor conditions over time
- Turbine should track the wind direction (yaw)
- Do not exceed the project budget

DELIVERABLES

- Prototype
- Detailed design specifications (so the unit can be replicated)
- Expected energy output over a 24 hour period at wind speeds of 2 m/s, 4 m/s, and 6 m/s
- Social and environmental impact statement on the benefit of your design

Project: Maximum Energy Output

The goal of this project is for students to design and build their own wind turbines. You may or may not decide to let them use KidWind kit parts. We have capped velocity at 6 m/s as this is the wind speed of a standard household box fan. We also set the maximum rotor diameter at 50 cm, which is appropriate because it is the size of most household box fans. You may wish to edit the parameters to fit your situation.

Students will need to consider the following as they construct their wind turbines:

Towers: Students can make a tower out of practically anything. They must make sure the turbine has a firm base or that it can be attached securely to a base. The tower must be tall enough that the blades do not hit the base/ground/table top and sturdy enough that it can withstand stress from the wind.

Generators: A generator is the device that converts mechanical energy into electrical energy. Student turbines will generate electricity using a generator of their choice. Students can choose any commercially available DC generator or even build their own.

Drivetrain: Students must decide to build a direct drive or a geared drivetrain. Gears can significantly increase the rotational speed of the generator and therefore power output, but gear boxes can be challenging to build. Students can use gears or pulleys for the systems.

Blades: Blade design has a huge impact on turbine power output. As students build their turbines, they will want to perform experiments to see which blades work best.

The experiments in this book were selected to provide a sampling of Vernier experiments that cover several subjects and key scientific concepts. The downloaded zip file contains PDF files of the student experiments. You can print the PDF, distribute it to students electronically, or post the file to a password-protected class web page or learning management system.

This project was adapted from *Renewable Energy with Vernier*, Experiment 15. Learn more at **vernier.com/rev**

ESTIMATED TIME

We estimate that this project can be completed in 7 to 10 class periods. Students may need 4 to 5 class periods to construct a good turbine. They will need one class period to collect data and then one to two periods to refine their design. Finally, students will need one class period to complete their report and calculations.

You can vary the complexity and time to complete the project through the materials you provide. For example, if you have KidWind Advanced Wind Experiment Kits, you could use the generators, gearboxes, and towers that come with the kits. This would allow you to focus on maximum energy output related to the design of the blades and spend less time on tower and generator design.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Asking questions and defining problems Developing and using models Planning and carrying out investigations Analyzing and interpreting data Using mathematics and computational thinking Constructing explanations and designing solutions Engaging in argument from evidence Obtaining, evaluating, and communicating information	PS3.A Definitions of Energy (HS-PS3) PS3.B Conservation of Energy and Energy Transfer (HS-PS3) ETS1.A Defining Engineering Problems ETS1.B Developing Possible Solutions ETS1.C: Optimizing the Design Solution	Patterns Cause and effect Scale, proportion, and quantity Systems and system models Energy and matter Structure and function Stability and change

SUGGESTED PROJECT PLAN

1. Assign students a research project in which they are expected to research the purpose of a wind turbine. Students should be able to define the problems addressed by a wind turbine, including global, social, and environmental issues that would be affected by using wind energy as an energy source. A great way to start this activity is by reading the book, *The Boy Who Harnessed the Wind*, by William Kamkwamba. It is a true story of a young boy in Malawi who builds his own turbine to charge small electronics in his house.

2. It can be very useful to perform some basic turbine experiments on blades, generators, and gearboxes to understand how they affect turbine performance. This can be in done in a more structured or a more inquiry-based fashion before students try to build a final turbine to test for this project. Other experiments in this book that use wind turbines can be good tools.

3. Give students time to design and build the wind turbine based on the design requirements (The student experiment includes a list of requirements and constraints, but you may have additions or changes based on how you do the project.). You will want to consider providing materials and/or setting a budget to limit how much students can spend on materials.

4. Once students have constructed a wind turbine, they will need to do performance testing. As wind turbines can rotate at a high rate of speed and things can come off if not well attached, the testing area should be set up with strict safety rules. Based on testing, students will need time to make refinements to their turbine.

5. After refinements, students will need to collect data for their best turbine setup. Based on this data they will need to extrapolate and determine how much energy their turbine could generate based on the wind speed they are testing.

6. Give students an opportunity to develop and present a social and environmental impact statement on the benefits of their design. In the report, ask students to share ideas on what they would improve if they had more time. This can give you insights into how they are interpreting their data.

PROJECT TIPS

1. The KidWind organization has developed a national competition, called the KidWind Challenge, that offers students hands-on opportunities to apply their knowledge of renewable energy through friendly and challenging competitions. To learn more about the KidWind Challenge, visit **www.kidwind.org/challenge**

2. Consider developing a rubric with which to grade students' projects. Possible criteria include:
   - Energy production at low speeds and high speeds
   - Quality of construction
   - Cost of construction
   - Durability
   - Aesthetics
   - Evaluate quality of each component: blades, drive train, and/or tower
   - Integration of wind turbine design theory

3. Perfecting blade performance can take quite a while because of the number of variables. Students will need a significant amount of time to "discover" an optimal design if they have not experimented with blade variables in earlier activities.

4. By far the most complicated part of building a wind turbine from scratch is creating the gearbox. If this is the first year you are doing this project or your students are relatively new to the design process, we recommend either using KidWind Advanced Wind Experiment Kits or allowing only direct drive systems with different generators. As you and your students become more experienced, you can add in more complexity.

5. Power output from the generator is dependent on the load that is applied to the turbine. Maximum power will depend on the load. For this project, instruct students to use the ideal load for their generator.

6. The generators that come with the KidWind Advanced Wind Experiment Kits have maximum outputs of approximately 2 W (10–15 V at 100–150 mA, when spinning at very high RPM (8,000–12,000 RPM)). There are many other DC motors available that you can use as generators. They will all perform differently under load and have varying torque requirements. Experimenting with generators can be very interesting.

7. As it can be challenging to measure energy output for 24 hours, students will need to collect data for a specific amount of time and extrapolate. This type of experimentation also assumes that the wind will blow at the same speed all day, which would rarely happen in real life.

8. To produce a more realistic testing environment you could have students set up their turbines outside for a number of hours and see how much energy they produce. This can be challenging and show students the weaknesses in their design as the device needs to react to different wind speeds, wind gusts, and rapid changes in wind direction.

9. If you want to improve your knowledge, considering reading the books, *Wind Power for Dummies*, by Ian Woofenden and *Homebrew Wind Power*, by Dan Bartmann, Dan Fink, and Mick Sagrillo.

EQUIPMENT TIPS

1. Set up a safe testing area.
   - Clear the area of debris and materials.
   - Instruct your students to not stand in the plane of rotation of the turbine blades. Also tell them that they should not touch the blades while they are spinning. Blades can be moving very fast and can hurt if they hit someone.
   - Provide safety goggles for your students. Students should wear safety goggles when they are working with a turbine that is spinning.

2. An energy sensor makes it very simple for students to determine power and energy output. Keep in mind that Vernier energy sensors have an input limit of ±30 V and ±1 A. KidWind generators almost always stay below these limits, but if you are using other generators, test them with a multimeter so you do not damage the sensor. The Go Direct Energy Sensor has a 1 W internal 30 Ω resistor. We recommend using a power resistor connected to the External Load terminals if students are regularly exceeding 1 W of power production.

3. We recommend the Vernier Variable Load (order code: VES-VL) as a way to determine the optimal resistance for the generators, especially if you are allowing students to experiment with different generators. The Vernier Resistor Board can also be used to relatively easily determine the optimal resistance for each generator.

4. If you are requiring students to present energy output projections at different wind speeds, we recommend using an anemometer to collect wind speed measurements and tailoring the requirements to wind speeds you are able to produce.

5. If you have a mix of KidWind Advanced Wind Experiment Kits and Basic Wind Experiment Kits, you can combine materials if building turbines from scratch. Hubs, gears, and drive shafts from all KidWind wind experiment kits will work together.

Calibrating a Sensor

INTRODUCTION

Vernier sensors utilize natural phenomena to create an electric signal that correlates to a sensor reading. For example, strain gauges are devices that change their electrical resistance depending on how much tension is applied to the instrument. You can therefore determine the amount of force being applied by measuring the voltage of the strain gauge.

In Activity 2, "Using Vernier Sensors with Arduino," you started with the sensor reading (the count) from the Arduino and converted that to a voltage. In this activity you will complete the process by creating an equation to convert the voltage to an actual sensor reading.

OBJECTIVES

- Understand how a sensor works
- Convert the output of the Arduino into a sensor reading

MATERIALS

SparkFun RedBoard (or equivalent) with USB cable and power supply
Vernier Analog Protoboard Adapter or Vernier Interface Shield
Vernier Gas Pressure Sensor
Chromebook or computer with Arduino software
Graphical Analysis app (optional)

BACKGROUND AND PRELIMINARY ACTIVITY

The majority of Vernier LabQuest sensors require a 5 V source and output a signal that ranges from 0 to 5 V. The relationship between sensor voltage and the measurement (in proper sensor units) can be determined by evaluating the voltage at known values for the sensor.

For example, when the Gas Pressure Sensor is at rest at 101.3 kPa (1 atmosphere), it registers a voltage of 2.46 V. When the sensor is measuring a pressure of 202.6 kPa (2 atmospheres), the voltage is 4.42 V.

It will be useful to graph these data points using either the following empty graph or Manual Entry mode in Graphical Analysis app. If using the following graph, label the axes and set the scale. The x-axis should be the voltage and the range will be from 0 V to 5 V. Determine an appropriate scale for the y-axis. Mark the pair (2.46 V, 101.3 kPa) and the pair (4.42 V, 202.6 kPa) and draw a line through these two points.

PROCEDURE

Step 1: Connect hardware and software

a. Open the Arduino IDE software and connect your Arduino and sensor.

b. Select the board and COM port from the Tools menu.

c. Open the sketch you saved at the end of Activity 2.

Step 2: Collect and graph additional data points

In addition to the two points you graphed in the Preliminary Activity, try conducting a quick experiment to collect two additional points: the voltage at your current atmospheric pressure and the voltage at a pressure as close to zero (a vacuum) as possible. Having four points will allow you to confirm the relationship between voltage and pressure rather than relying solely on the information given to you.

a. For the first data point determine the voltage for ambient pressure:
   i. Remove the syringe from the sensor if it is connected. This exposes the sensor to atmospheric pressure.
   ii. Compile and upload the sketch. Then, open the Serial Monitor. Note the voltage in the Serial Monitor.
   iii. Find a barometer or look up a local weather source online and determine the atmospheric pressure in your location. Be sure to convert it to units of kPa, if necessary.
b. For the second data point, you will create a vacuum (pressure ~0 kPa) using the syringe:
   i. Depress the syringe completely, and then screw it onto the sensor connector.
   ii. Carefully draw the syringe plunger back as far as you can while maintaining the airtight connection. Note the voltage in the Serial Monitor.
c. Add both data points to your graph.

REVIEW

1. Based on these few data points is it reasonable to think that the relationship between voltage and the sensor reading is linear? ____________________________
2. Assume for the moment that this relationship is linear and extend the line to cover the range of the sensor: What do you expect the pressure to be when the voltage is 3.5 V? ___________________
3. Adjust your line of best fit, if necessary, and create an equation for this line using the slope-intercept form: Pressure = slope x voltage + y intercept ________________________________

Step 3: Modify the sketch to display the pressure with correct units

a. In the loop() function of your sketch, declare another variable "sensorReading." This variable will need to be "declared" as a "float". It should look like this:

```
float sensorReading = xxxx*sensorVoltage + yyyy;
```

   where `xxxx` is the slope and `yyyy` is the intercept from your equation. **Note**: Remember to end the line of code with ";".

b. Change the code to print this value instead of the voltage.

c. Test your code by uploading and running the sketch. According to the ideal gas law, pressure and volume are inversely related. For example if you reduce the volume by half, the pressure doubles. Experiment with your syringe to verify that the sensor readings follow this relationship. Document your results of several pairs of data in Table 1.

Table 1		
Volume	Pressure	Pressure × Volume

d. Save this sketch with a unique name.

OPTIONAL EXTENSION

Complete the following extension if it is assigned by your instructor.

Go to **https://www.vernier.com/manuals/gps-bta** and read the section on How the Sensor Works in the Pressure Sensor user manual. Then, identify an electronic sensor that uses a different technology from the Gas Pressure Sensor. Conduct some investigative research online to determine how the sensor works and document your findings.

Teaching Coding with Vernier and Arduino

This experiment was adapted from *Vernier Coding Activities with Arduino®: Analog Sensors*, Experiment 03. Learn more at **vernier.com/vca-as-e**

INTRODUCTION

These activities are designed to provide an introduction to coding as well a lesson in sensor technology using Vernier sensors and Arduino microcontrollers. Students get excited when they see coding come to life through hands-on technology. Integrating Vernier sensor technology with Arduino connects the physical world to the computer-centric activity of learning to code.

Arduino has developed both its hardware and software as open source. The SparkFun RedBoard is equivalent (although not identical) to the Arduino Uno, and when using the Arduino software, it should be treated as an Uno.

In this series of activities from *Vernier Coding Activities with Arduino®: Analog Sensors*, students learn about sensor technology and coding with our fun, interactive approach. Teaching students about the underlying physics in our technology opens the door for them to explore and become interested in how technology works.

Students need access to the following equipment for these activities:

- SparkFun RedBoard (or equivalent) with USB cable and power supply
- Vernier Analog Protoboard Adapter or Vernier Interface Shield
- Vernier Gas Pressure Sensor
- Chromebook or computer with Arduino software

Figure 1 Connecting a Vernier Gas Pressure Sensor to a Protoboard Adapter (left) and Interface Shield (right)

ACTIVITIES

There are eight activities in this series. Students begin with the basics of coding with an Arduino and quickly move to integrating our sensors into code. Your students will also be introduced to fundamental coding structures and learn how to access the VernierLib library.

1	Introduction to Arduino Programming	Students learn how to connect Arduino to their computer or Chromebook and modify the Blink program. Success in this activity enhances student confidence in the activities that follow.
2	Using Vernier Sensors with Arduino	Students are introduced to methods for connecting Vernier sensors to Arduino and observe the output from the sensor in the Serial Monitor.
3	Calibrating a Sensor	Students learn how Vernier sensors convert electrical signals into sensor readings.
4	Displaying Data	Students gain practical experience formatting output in the Serial Plotter and the Serial Monitor.
5	Functions: Part 1	Students explore integrating functions into their code to simplify the structure and make it easier to interpret.
6	Functions: Part 2	Students learn how to pass data from a function to another location in their code. They explore the difference between local and global variables.
7	Output and Logic Statements	Students learn how to designate and control output devices (LEDs) based on sensor values.
8	Using the VernierLib Library	Students are exposed to the tools that are incorporated in the VernierLib library and how to access these tools.

COMPUTER SCIENCE TEACHERS ASSOCIATION (CSTA) STANDARDS

CSTA Standard		Activity
3A-AP-13	Create prototypes that use algorithms to solve computational problems by leveraging prior student knowledge and personal interests.	2, 3, 5, 6
3A-AP-15	Justify the selection of specific control structures when tradeoffs involve implementation, readability, and program performance, and explain the benefits and drawbacks of choices made.	5, 6
3A-AP-16	Design and iteratively develop computational artifacts for practical intent, personal expression, or to address a societal issue by using events to initiate instructions.	2, 4, 7
3A-AP-17	Decompose problems into smaller components through systematic analysis, using constructs such as procedures, modules, and/or objects.	1, 2, 3, 4, 5, 6, 7, 8
3A-AP-21	Evaluate and refine computational artifacts to make them more usable and accessible.	2, 3, 4, 6, 7, 8
3A-DA-11	Create interactive data visualizations using software tools to help others better understand real-world phenomena.	2, 3, 4
3B-AP-13	Illustrate the flow of execution of a recursive algorithm.	7
3B-AP-16	Demonstrate code reuse by creating programming solutions using libraries and APIs.	8
3B-DA-05	Use data analysis tools and techniques to identify patterns in data representing complex systems.	3, 4
3B-DA-06	Select data collection tools and techniques to generate data sets that support a claim or communicate information.	3

TIPS AND OTHER RESOURCES

Software

Arduino microcontrollers can be programmed from several editors. The most common approach is to use a version of the Arduino IDE (Integrated Development Environment). The Arduino IDE is compatible with computers running Windows, macOS, and Linux. Download the appropriate version at **https://www.arduino.cc/en/Main/Software**

The Arduino Web Editor is also available from that web page. It is hosted online and requires a user web account. If using a Chromebook, you will need to install a plug-in, which currently requires a monthly fee. The Web Editor has many of the same features as the downloadable version. The most notable difference is that it does not include a Serial Plotter, which is used in Activity 4 "Displaying Data."

Specifying Boards and COM Ports

Here are a few helpful tips for connecting your Arduino to your computer or Chromebook. Your initial connection requires that you specify Arduino Uno as your board and to select the COM port the board uses. The board can be identified using a drop-down menu in both the software download and in the Web Editor.

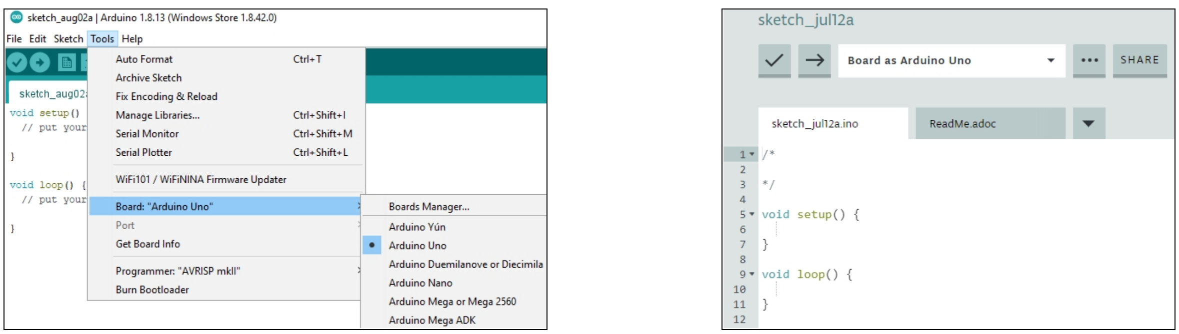


Figure 2 Selecting the appropriate Arduino board (Arduino IDE, left; Web Editor, right)

The Web Editor automatically detects and selects the correct COM port, displaying it in the menu. However, in the Arduino IDE, you will need to select the COM port. There can be several COM ports identified, making it challenging to determine the correct port. It is helpful to disconnect the Arduino board from the computer and then reconnect it to determine its associated port.

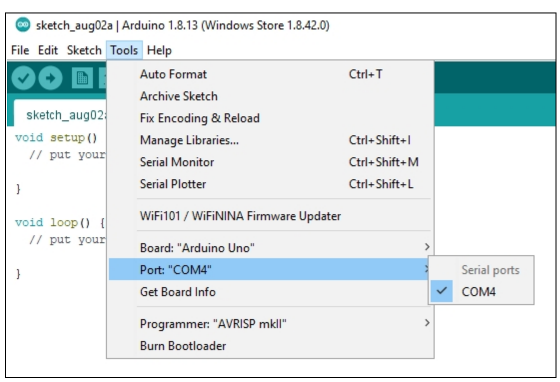


Figure 3 Identifying the COM port in the Arduino IDE software

Using Other Vernier Sensors

These activities were developed for use with the Vernier Gas Pressure Sensor (order code: GPS-BTA), but they can easily be modified to work with other Vernier analog sensors. Here are some points to be aware of:

- Vernier analog sensors are those with a "-BTA" at the end of the order code. Order codes are typically printed on the sensors. For example, the order code for the Dual-Range Force Sensor is DFS-BTA.
- Most analog sensors have a "negative slope" calibration curve. Our experience is that students can become more confused when trying to apply data to determine the calibration equation when the sensor has a negative slope calibration curve. This is one reason that we chose the Gas Pressure Sensor for this set of activities.
- Most of our sensors have a linear relationship between voltage and the sensor reading. This makes the process of determining the calibration equation reasonably easy. One notable set of exceptions are our temperature probes, which have a very complicated non-linear calibration equation. In most cases, you can find the calibration equation in the sensor's user manual on the Vernier website.
- The activities in this book are designed for our LabQuest family of sensors. Our Go Direct sensors do not communicate with the Arduino Uno board. (The order codes for Go Direct sensors start with "GDX-".)

Resources

You will find additional resources, ideas, and projects at
https://www.vernier.com/engineering/arduino/

The Arduino website has a wealth of useful information. There are reference materials and forums among other resources available. Visit **https://www.arduino.cc/**

ACTIVITY SPECIFIC SUPPORT

This activity builds on the previous activity to develop a calibration equation from data collected from the sensor and known atmospheric conditions.

Once students have collected data to determine the calibration curve, they will modify the sketch from Activity 2 to output a sensor value rather than a voltage. Note that students can modify the line of code that converts count to voltage or simply add another line of code to convert voltage to the sensor reading. We calculated the voltage and then the sensor reading in the code shown below. The calibration equation used here is from the user manual.

```
void loop() {
   // read the input on analog pin 0:
   float sensorValue = analogRead(A0);
   float sensorVoltage = sensorValue * 5.0 / 1023;// Converts the count to
     the sensor voltage
   float sensorReading = 51.71*sensorVoltage - 25.86; // Converts voltage to
     kPa pressure
   // print out the value you read:
   Serial.println(sensorReading);
   delay(500);        // delay in between reads in milliseconds
}
```

ANSWERS TO QUESTIONS

Students should create a graph of the voltage and pressure values using the graph grid provided in the student activity, Vernier Graphical Analysis, or any graphing program of your choice. Graphical Analysis is our free graphing and data-collection software. It is available for computers, Chromebooks, and mobile devices; visit **www.vernier.com/ga4** to download the appropriate version.

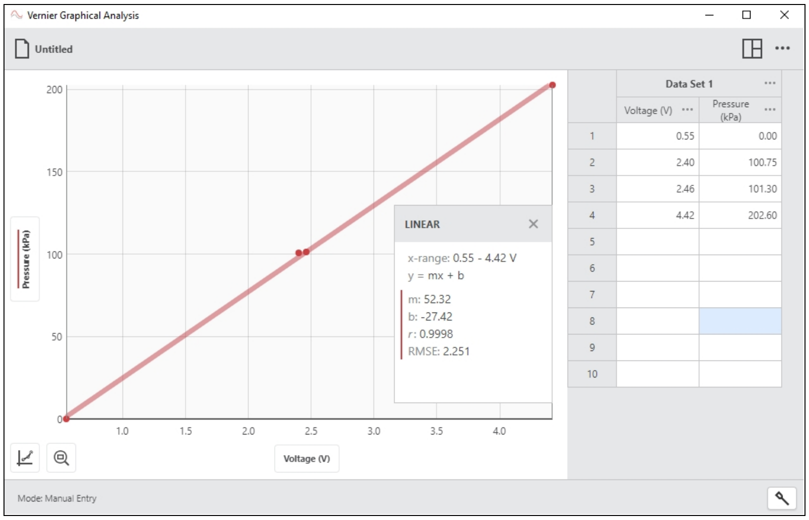


Figure 4 Plotting data in Manual Entry mode in Vernier Graphical Analysis app

1. Students may correctly answer that three or four data points are not adequate to determine that the relationship between voltage and pressure is linear. However, they should recognize that there is no evidence that it is not linear.
2. The pressure that corresponds with 3.5 V is approximately 155 kPa.
3. The slope of the line is 52.3 with an intercept of –27.4, making the calibration equation:

$$\text{Pressure (kPa)} = 52.3\ \text{kPa/V} \times \text{Voltage} - 27.4\ \text{kPa}$$

How the Sensor Works

The sensor in this unit has a membrane that flexes as pressure changes. This sensor is arranged to measure absolute pressure. One side of the membrane is a vacuum, while the other side is open to the atmosphere. The sensor produces an output voltage that varies in a linear way with absolute pressure. It includes special circuitry to minimize errors caused by changes in temperature.