Suggested Major Laboratory Explorations

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1. INVESTIGATING MEASUREMENTS AND UNCERTAINTY

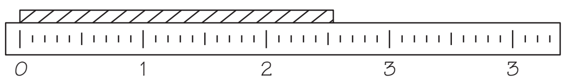
INTRODUCTION

Precision and uncertainty

Physics can claim to be one of the most precise sciences. For example, by laser pulse reflection the distance to the Moon is known to about 1 cm, and some physical constants are known to one part per billion. But there is a paradox.

On the one hand, obviously most experimental work in physics involves measurement. Reliable measurements are essential for the accumulation of accurate data that can lead to major laws and theories, and for the testing of new theories. Many of the measurements in physics involve such basic properties as distance, time, mass, voltage, and temperature. From these, more complicated properties, such as speed, force, and energy, can be constructed.

On the other hand, measuring instruments are never able to help us obtain absolutely exact measurements of any quantity, no matter how carefully made or how sophisticated the instruments may be. Every measuring instrument has a limit to its *precision*. For instance, look carefully at the divisions or marks on a meter stick. The numbered divisions are centimeters (1 cm = 0.01 m). The smallest divisions are millimeters (1 mm = 0.1 cm). Can you read your meter stick more accurately than to the nearest millimeter? If you are like most people, you read it to the nearest mark of 0.1 cm (the nearest millimeter) and *estimate* the next digit between the marks for the nearest tenth of a millimeter (0.01 cm), as illustrated in the diagram below.



In the same way, whenever you read the divisions of any measuring device, you should read accurately to the nearest division or mark and then estimate the next digit in the measurement. Then probably your measurement, including your estimate of a digit between divisions, is not more than half a division in error. It is not likely, for example, that in the above diagram you would read more than half a millimeter away from where the edge being measured comes between the divisions. In this case, in which the divisions on the ruler are millimeters, you are at most no more than 0.5 mm (0.05 cm) in error. So, in recording this measurement, you would record the best estimate of the distance and indicate the likely error as plus or minus 0.05 cm. This is written

$$2.58 \pm 0.05 \text{ cm.}$$

The ± 0.05 is called the *uncertainty* of your measurement. The uncertainty for a single measurement is commonly taken to be half a scale division. With many measurements, this uncertainty may be even less.

Error and uncertainty for repeated measurements of a single quantity using a single instrument

Many experiments involve a series of repeated measurements of a quantity, such as the distance traveled by an object in uniform motion in fixed time intervals. However, because of the precision of the instruments, or simplifications such as the neglect of air resistance, or simple carelessness, the recorded measurements are often not identical.

For instance, suppose you measure the length of a book page four times and obtain the following values: 27.61 cm, 27.59 cm, 27.70 cm, and 27.64 cm.

Is there any way to decide from the data which is the "true" value for the length of the page? Unfortunately, the answer is no. But we can pick the average value as most likely the closest to the true value, on the assumption that half the time the measurement will be too high, and half the time too low. (This assumption becomes more likely, the more measurements we include.) In our example, the average is 27.635 cm. However, since our data are given only to the second decimal place, we are allowed only four significant figures. We must round off 27.635 cm to 27.64 cm. The average value is selected as the accepted value of our measurement.

How can we indicate the possible error in our accepted value as represented by the variation in our individual measurements? The difference between each measurement and the accepted value is −0.03 cm, −0.05 cm, 0.06 cm, 0.00 cm. The average of these differences, *without regard to sign* is 0.035 cm. This average deviation is taken as the experimental error for these measurements of a single quantity. The result of this measurement would then be given as the average value, plus or minus the average deviation, rounded off to the hundredth decimal place

$$27.64 \pm 0.04 \text{ cm.}$$

Relative error: Comparing an experimental result with an "accepted value"

Finally, there is an experimental error that is associated with the relative deviation of a measured quantity from the standard value for that quantity. For instance, the generally accepted value for the acceleration of gravity (as a result of many measurements) is 9.8 m/s^2; but in an experiment you might obtain a value for the acceleration of gravity of 9.7 m/s^2 (both at sea level). The difference between your result and the accepted result is 0.1 m/s^2. Is your result off by a lot or by a little? It depends upon how much difference there is in comparison with the number. The ratio of the difference to the size of the accepted value, expressed as a percent, is known as the *relative error*. It may be defined in symbols as follows:

$$\text{relative error} = \frac{|\text{experimental value} - \text{accepted value}|}{\text{accepted value}} \times 100\%.$$

In our example

$$\text{relative error} = \frac{|9.7 \text{ m/s}^2 - 9.8 \text{ m/s}^2|}{9.8 \text{ m/s}^2} \times 100\%$$

$$= \frac{|-0.1 \text{ m/s}^2|}{9.8 \text{ m/s}^2} \times 100\%$$

$$= \frac{0.1}{9.8} = \times 100\% = 0.01 \times 100\% = 1\%.$$

In the following you will explore these concepts with some concrete examples.

Exploration

1. Your instructor will have set up various stations around the room. At each one, you are to make a measurement. Everyone will use the same instrument located at each station. The stations might include measurements of a voltage across a resistor in a circuit with a constant current, the temperature of ice water, and the length of a strip of paper.
2. You may work together on this, but each student should make each measurement and record the result in a table in his or her notebook. The table should include the object measured, the precision of the instrument you used, and the result of your measurement with the uncertainty and units indicated. Make your measurements as carefully as possible.

Together in class

1. After you have completed your measurements, your instructor will collect the results and write them in a large table on the board. He/she will select one of the measurements that has an accepted or a predicted value, such as the voltage, which may be compared with the result obtained from Ohm's law.
2. Working with your instructor, you will obtain the best value for the voltage and the average of the class's measurements.
3. The class will also obtain the experimental error in the result from the average deviations of the measurements from the average value for the voltage.
4. Together with your instructor plot the class's results for the voltage, indicating the value and the frequency that each value appeared. This

will result in a "curve." Indicate on the graph the position of the average value and the experimental error on each side of the average.

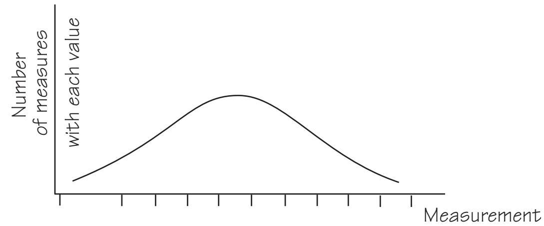
5. Finally, since in this case there is a theoretically predicted value for the voltage, given the current and resistance in the circuit, obtain the relative error of the class's result for the voltage.

Now you try it

1. Find the class's experimental result for the other two quantities measured and the experimental error in both cases.
2. Plot the results for both measurements, indicating the value and the frequency that each value appeared. Indicate the average values and the errors on each "curve."
3. Examine the class's results for each of the objects measured. What do you observe? Did everyone obtain exactly the same results? If not, why do you think this is so?
4. Is there an accepted value for either of these measurements? If so, find the relative error.

Think about it

1. When we obtain and plot a lot of data as in the above, an "error curve" or "bell-shaped curve" is formed. This is an important concept in the understanding of all types of measurement.



2. Sometimes the scores of all members of a class of substantial size on a test are also plotted on a curve of this type, and grades are computed on the basis of where the scores fall on the curve in relation to other students in the class. This is sometimes called "grading on the curve." What are some of the advantages and disadvantages of this type of grading system?
3. Your friend who has not had this course measures the width of a standard 8½ × 11 in sheet of paper one time with a metric ruler and obtains 21.5 cm. How would you explain to your friend that the "true" width of the sheet of paper might not be 21.5 cm?
4. How would your friend obtain the most likely value for the width, along with the error?

2. EXPLORING MOTION (CHAPTER 1)

A. Observing Motion

How can we recognize and distinguish acceleration, deceleration, and uniform motion? In order to answer this question, at first in *qualitative* terms, assemble the apparatus and place the cart on the track with the timing tape attached, but with the timer off.

1. Give the cart a push and describe what happens to the speed of the cart.
2. Now try it again with the timer on. The timer tells us where the tape (hence the cart) was at each tenth of a second. Describe what happens to the distance the cart travels in each $1/10$ s at the start, middle, and end of the run.
3. Compare your answers to Questions 1 and 2. How would you recognize that an object is *decelerating*?
4. Now lift up the timer end of the track to its highest position. Give the cart a push to describe what happens to the speed of the cart as it moves down the track.
5. Now try it again with the timer on. Describe what happens to the distance the cart travels in each $1/10$ s at the start, middle, and end of the run.
6. Compare you answers to Questions 1 and 2. How would you recognize that an object is *accelerating*?
7. From the above, how would you recognize *uniform speed*, in which there is no acceleration or deceleration?
8. What would you have to do to give a cart uniform speed?
9. Try to obtain uniform speed before turning on the timer. Then, when you think you have obtained it, turn on the timer and compare the results with your answer to Question 8. You may have to try this several times to obtain an as close to uniform motion as possible.

B. Uniform Speed

Instead of analyzing a photograph, as in Section 2.3, you will use the timer to analyze the motion of the cart you observed in Part A. A timer places a dot on the tape every $1/10$ s. Each dot tells us where the tape (hence, the cart) is at each $1/10$ s. So the distance from the start of the tape to a dot tells us how far the cart has moved since the timer was turned on.

1. Notice that the timer tape introduces a lot of friction, which acts to decelerate the motion. Attempt to compensate for this friction and

obtain a motion for the cart that is as uniform as possible (see Part A). Turn on the timer and let it record the motion. Remove the tape and mark the starting dot.

2. Place a meter stick alongside the tape, starting with zero at the starting dot. The distance of each dot from the start provides a position reading for the cart at each 1⁄10 s to the end of the run. Let's see if there is a relationship between these two variables.
   Use the symbol d for the position reading of each dot, and the symbol t for the time reading that goes with it.

Draw a table, like the table in Section 1.3, and record the values of d and t for the entire run. (Leave room on the right for three more columns.) Be sure to include the units in your table. Use only the metric scale for distances.

3. Add two more columns to your table. One is for Δd, the distance traveled in the each time interval (the distance covered between times when the dots are produced). Another column is for Δt, the corresponding time interval. Indicate the units.
4. Why is the top line of the table in the text left blank?
5. Examine your data so far and carefully describe the motion of the cart overall and during the early, middle, and later parts of the motion.
6. Now add a fifth column to your table for the rate or the average velocity, v_{av}, in each time interval, and complete the table. Indicate the units.

Drawing conclusions

7. Once again examine your results. What can you say about the average speed of the cart during the run? Take into account the variations due to the uncertainty in the measurements of distance.
8. What is the overall average of the separately obtained average speeds? What is the average of the values in the fifth column? Write this at the bottom of that column.
9. Now obtain the average speed for the entire run from the total distance covered and the total elapsed time.
10. How does the overall average of the average speeds (Question 8) compare with the average speed for the total run (Question 9)?
11. Is the answer to Question 10 what you expected?
12. Can you give an experimentally testable definition of uniform speed?
13. Is the velocity vector in this case also uniform? How do you know?

Picturing the motion

1. If you graphed the distance and time measurements for the data in your table, what do you expect the resulting graph to look like?
2. Now plot such a graph using the first two columns in your table. Place the distance on the vertical axis and the corresponding time on the horizontal axis. Be careful to label the axes and the units and to fit the data onto the axes so that the data points do not go off the end, nor are they "scrunched" into one corner.
3. If the data points are in a line, use a ruler to draw a straight line through them. If they are not, draw a smooth curve.
4. Using your graph, describe the motion of the cart throughout the run.
5. For a straight section of the line on your graph, obtain the speed of the cart from the slope of the line.
6. Compare the speed with the average speeds in the table for that segment of the motion. Finally, compare it with the overall average of the average speeds. Take into account the uncertainties in measurement.
7. Is this what you expected to obtain? Try to account for any differences that you see.
8. Finally, obtain the *instantaneous speed* of the cart from the graph at a chosen instant of time. Indicate the instant of time and show how you obtained the speed.

Using a spreadsheet

1. Using the spreadsheet functions and features, recreate your data table above. Have the program automatically compute the values for Δd, Δt, and v_{av}, as well as the overall average velocity.
2. Use the program to create automatically a distance–time graph and to compute the slope of the line. If you are adept at using macros, create a pop-up data-input table that is activated by a "button" and then automatically enters the data in the proper cells on the table.
3. Save your work for Part C.

C. Now You Try It

Design an experiment to examine the motion of an object, other than a cart. The object might be a ball rolling down the hallway, a car traveling on a road, or a person riding a bike or roller blading or swimming or walking.

You will need to measure the time at which the person or object reaches various distances from the starting point. Your instructor can help you find any equipment you might need.

In a brief report, describe the purpose of your experiment, your procedure, the data you obtained, your analysis of the data using both a table and a graph, your conclusions based on the data and graph, and the difficulties encountered, and sources of error.

If you used the spreadsheet in Part B, replace the old data with your data in this part of the experiment, and allow the spreadsheet to analyze your data automatically.

D. Changing the Speed

This investigation will parallel the study of uniform speed in Part B, but it will involve uniform acceleration instead of uniform speed.

Since the force of friction plays a large part in the motion of a cart dragging a piece of tape, we can balance the friction force with the force of gravity. This can be done by raising one end of the track or table so that the force of gravity balances the force of friction retarding the motion, as in Part A of this investigation. Alternatively, a hanging mass may be attached by a string to the cart over a pulley.

1. With the timer tape attached but the timer off, give the cart a push and attempt to obtain acceleration, either by increasing the incline or by increasing the mass of the hanging weight. When you have achieved accelerated motion, start over: turn on the timer and let it record the motion. Remove the tape and mark on it the point where the measurements start.
2. Place a meter stick alongside the tape, starting with zero at the start of the timer marks. As before, the distance of each dot from the start corresponds to the position of the cart at that instant of time.

   As before, create a table displaying the position (d) corresponding to each dot, the time reading (t) that goes with it, the time interval Δt between successive dots, the distance Δd traveled in each time interval, and the average speed in each time interval, which is $v_{av} = \Delta d/\Delta t$. Be sure to indicate the units for each column.

3. Examine your data so far and describe the motion of the cart overall and during the early, middle, and later parts of the motion.
4. Now add a sixth column to your table for the rate of change of the average speed, that is, the average acceleration in each time interval which is, by definition, $a_{av} = \Delta v_{av}/\Delta t$. Complete the table.

Drawing conclusions

5. Examine your results. What can you say about the overall average acceleration of the cart during the entire run? Take into account the variations due to the uncertainty in the measurements of distance.
6. If any of your values for Δv_{av} came out negative, what does this mean?
7. If any of your values for a_{av} came out negative, what does this mean?
8. What is the overall average of the individual average accelerations? Write this at the bottom of the last column of your table.
9. Now obtain the average acceleration for the entire run from the total change in speed and the total elapsed time from start to finish.
10. How does the average in Question 9 compare with the overall average acceleration for the total run (Question 8)?
11. Is your answer to Question 9 what you expected?
12. Can you give an experimentally testable definition of uniform acceleration?
13. On a sketch of your apparatus draw and label an arrow representing the acceleration vector. Is the acceleration vector in this case uniform? How do you know?

Picturing the motion

1. If you graphed the average speed against the corresponding time measurements in your table, what do you expect the resulting graph to look like?
2. Now plot a graph of the average speed, v_{av}, and the total elapsed time, t, for each velocity from your table. Place the speed on the vertical axis and the time on the horizontal axis. Be careful to label the axes and the units and to fit the data onto the axes so that the numbers do not go off the end nor are they "scrunched" into one corner.
3. If the data points are in a line, use a ruler to draw a straight line through them. If not, draw a smooth curve.
4. Using your graph, describe the motion of the cart throughout the run.
5. For a straight section of the line on your graph, obtain the acceleration of the cart from the slope of the line.
6. Compare the acceleration for that segment of the motion with the average acceleration in the table. Finally, compare the acceleration with the overall average of the average accelerations. Take into account the uncertainties in measurement.
7. Is this what you expected to obtain? Try to account for any differences that you see.
8. Finally, obtain the *instantaneous acceleration* of the cart from the graph at a chosen instant of time. Indicate the instant of time and show how you obtained the acceleration.

Using a spreadsheet

As in Part C, use a spreadsheet to recreate your table, once the data are provided, and to render a velocity–time graph and the slope of the resulting line.

E. Now You Try It

Design an experiment to examine the acceleration (or deceleration) of an object. The object might be a ball rolling down an inclined plane, or a speeding cart that rolls onto a rough surface, or a person speeding up and slowing down deliberately as they walk, ride a bike, jog, or roller blade a brief distance.

You will need to measure the time and distance. Your instructor can help you find any equipment you might need.

In a report describe the purpose of your experiment, your procedure, the data gathered, your analysis of the data using both a table and a graph, your conclusions based on the data and graph, and the difficulties encountered and sources of error.

If you created the spreadsheet in Part D, replace the data with your new data and allow the spreadsheet to perform an automatic analysis.

F. Checking Galileo's Result

You saw in Section 1.9 of the textbook that Galileo could not test his hypothesis directly that free fall is an example of uniformly accelerated motion. Instead, he had to test it indirectly by studying the motion of a rolling ball on an inclined plane.

But there was another difficulty: He could not measure short time intervals during the motion or the corresponding distances traveled in order to obtain the changes in speed. He found a way around this problem, too: he derived a formula that did not include speed at all. It included only the total time (t) and the total distance (d) covered in that time, in addition to the acceleration (a). If the acceleration is uniform for the entire time and distance, and the object starts from rest at time 0 and distance 0, Galileo obtained the formula

$$d = \tfrac{1}{2}at^2.$$

Then, in either a thought experiment or a real experiment (historians still debate this), Galileo studied a ball rolling down a long inclined plane at various angles of incline. He hypothesized that, if the acceleration is constant for a fixed inclination, the distance covered and the square of the time needed should be directly proportional to each other, the constant of proportionality being $\frac{1}{2}a$:

$d \propto t^2$.

Indeed, this is what can be obtained experimentally. Galileo claimed that this relation also applied to freely falling objects if air resistance and friction are neglected. Devise an experiment to check Galileo's result using an inclined plane. Your instructor will have some equipment available for you to use. Since the distances are short and the falling objects are heavy, you will not need to worry about air resistance or friction.

Cautions

When testing different inclines, do not go over about 20° inclination, because beyond that the ball will begin to slide as well as roll, which changes the experiment.

Because of inherent uncertainties in the measurements, take at least four readings for each distance and time, then average the results.

Extrapolating to free fall

Although he could not test higher inclinations of the incline, Galileo noticed that the acceleration increased roughly as the angle of the incline increased. (This is true only for small angles.)

From your results, is it reasonable to conclude that an "incline" of 90°, when free fall occurs, will also be an example of uniform acceleration? Why or why not?

3. EXPLORING THE HEAVENS (CHAPTER 2)

INTRODUCTION

Each of the following inquiries may be performed as individual units. In addition, the tasks outlined in each unit may be divided among various groups.

A. The Seasons in the Heliocentric System

Celestial observations were made for thousands of years by Egyptian, Mayan, and Chinese people (and others). In this exploration we shall repeat some of their efforts with apparatus different but not more sophisticated than theirs (but during a relatively brief time).

The "planetarium" is a very helpful, hands-on working model of the relative positions of the Sun, Earth, and Moon in the heliocentric system. The distances, however, are not to scale.

1. Notice that N–S axis of the Earth is tilted at 23½° to the plane of its orbit around the Sun. Move the model representing the Earth around the Sun. What do you observe about the axis of the Earth as it moves around the Sun?
2. Now place the Earth in the position on its orbit where the North Pole is pointing most directly at the Sun. Draw a sketch of this arrangement in your notebook. Then, using a straight edge and a different pen or pencil, draw a series of parallel lines from the Sun across the entire width of the Earth. These will represent rays of light from the Sun. Since the Sun is actually much farther away from the Earth than in this model, the rays from the Sun are effectively parallel.
3. Examine your drawing. Where on the Earth do the Sun's rays hit most directly? Where do they hit least directly?
4. Where will the temperature on the Earth's surface be the warmest, where will it be the coldest?
5. To the people in the northern hemisphere, what season is it on this day? What about in the southern hemisphere? What is the special name for this day?
6. Will the time of illumination by the Sun's rays during a day be any longer in the northern hemisphere at any other position on the Earth's orbit than at this position? Try some other positions to test your answer.
7. From your drawing can you tell where on the Earth the Sun would be directly overhead at noon?
8. Is there any place on the Earth where the Sun never sets?
9. Is there any place where it never rises?

A second situation

This time, move the "Earth" to the position on its orbit where its north pole is pointing at the greatest angle *away* from the Sun. Draw a sketch of this arrangement in your notebook. Then, using a straight edge and a different pen or pencil, draw a series of parallel lines from the Sun across the entire width of the Earth. These will represent rays of light from the Sun.

Work through Questions 3–8 above for this arrangement.

Two other positions

Let the "Earth" now move forward slowly in its orbit. Notice the behavior of the N–S axis. Stop the motion when the Earth has moved about one-quarter of the way around its annual orbit and three-quarters of the way around. At these point the Sun's rays should be hitting a level surface at the equator at a 90° angle (the Sun is directly overhead).

1. Draw a sketch of the Earth–Sun relationship at one of these two positions and include the direction of the Earth's axis.

2. Draw another sketch, as before, of the Earth and Sun, along with a series of parallel lines representing the rays of light from the Sun.
3. Examine your drawing. Where on the Earth do the Sun's rays hit most directly? Where do they hit least directly?
4. Compare the amount of daylight in the northern hemisphere with the amount in the southern hemisphere?
5. To the people in the northern hemisphere, what season do you think it is on this day? What about in the southern hemisphere? What special names do these 2 days have?

Inquiry

1. Find your location on "Earth." As the Earth revolves around the Sun in 1 year, predict what will happen to the length of the day at your location on Earth during that year.
2. Now move the Earth around its orbit and identify its position at each of the four seasons.
3. As seen from your location on Earth, how does your prediction compare with your observations about the time of daily sunlight during the course of 1 year?

Solar noon

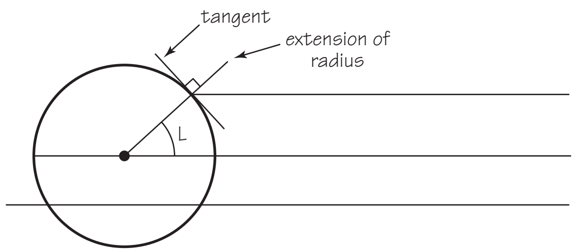
Solar noon is the time during the day when the Sun is at its maximum "altitude," the angle of the Sun with respect to a plane to the horizon. Solar noon may not occur exactly at 12:00 noon, or at 1:00 p.m. if Daylight Savings Time (DST) is in effect.

1. Why wouldn't solar noon occur everywhere in your time zone at exactly at 12:00 noon (or 1:00 p.m.)? At a given location on Earth, could it occur at 12:08 p.m. (1:08 p.m. DST)?
2. In your local newspaper find the time when the Sun will next rise and set. Since the Sun appears to move in a circle across the sky, solar noon will be the time exactly half-way between rising and setting. Figure out when this will be.
3. Use the length of the shadow cast by a tree or a stick you have placed in the ground to gain a qualitative measure of the altitude of the Sun ½ hr before the predicted solar noon, at solar noon, and ½ hr after solar noon. Does this confirm your prediction of solar noon in Step 2? *Caution:* Never look directly at the Sun, even with sunglasses. It can cause permanent eye damage. This is only a qualitative measurement.

A geometric inquiry

1. Draw the Earth represented by a perfect circle, and draw the equator through the center. Locate your latitude on the Earth and draw and label the latitude angle with respect to the equator. Now draw a line

that is an extension of the equator all the way to the edge of the paper. This line will also represent a ray of light coming from the Sun at solar noon on the Vernal Equinox. Draw another line from the edge of the paper, parallel to this one, hitting the Earth at your location. This represents a ray from the Sun at your location at solar noon on the Vernal Equinox. Using geometry, find the altitude of the Sun with respect to the horizon at your location at solar noon on the Vernal Equinox.



An Example
L = Latitude angle at your location

2. During the course of a year will the Sun ever be directly overhead at solar noon at your location on the Earth?
3. To check your answer to Question 2, find by construction the altitude of the Sun at its highest point in the sky in your hemisphere—that is, on either the Summer or Winter Solstice. On this day the Sun's rays are exactly perpendicular to a plane surface at noon at 23½° north (or south) latitude. Using this information and your latitude, find the altitude of the Sun with respect to the horizon at your location at solar noon on the Summer or Winter Solstice.
4. Do the same for the opposite solstice.
5. Describe the changes in the Sun's altitude at solar noon at your location during an entire year. Be precise about the maximum and minimum values.

B. Observing the Sun's Apparent Motion

1. On a clear day, find in a newspaper the time when the Sun is scheduled to set. Go outside at that time, and just after the Sun has set (so you are not looking at it directly), record the date, time, and position

Caution: Never look directly at the Sun; it can cause permanent eye damage. Do not depend on sunglasses or fogged photographic film; they do *not* provide enough protection. In this experiment you will never need to look directly at the Sun.

where it has set. In most places today, the horizon is obstructed by buildings or trees. In these cases, the "setting" of the Sun will involve its disappearance behind the object obstructing the horizon. In this case, record the position by noting exactly where the Sun disappears behind a building or tree or fence. Even better, if you have a compass, record the angle at which the Sun sets on a scale from 0° to 360° (due north is 0° or 360°, due east is 90°, due south is 180°, and due west is 270°). Draw a simple sketch of the horizon and indicate the location where the Sun set. Note also your exact observation point. (You could also do this experiment just before sunrise, if that is more convenient.)

2. Predict how you would expect these observations to change, if at all, 1 week later.
3. Actually repeat these observations once a week on the same day for 1 or, preferably, 2 months. Some scheduled days you may not be able to make the observations if the sky is overcast. In that case, observe on the next available day (or the day before if the forecast is for cloudy conditions).
4. Record how the position and time of the Sun's setting has changed from the week before. How do your observations compare with what you expected?
5. At the end of the observation period, draw some general conclusions about the changing position of the Sun's setting and the length of the day with reference to the season in which you made these observations.
6. The title of this investigation is "Observing the Sun's Apparent Motion." Your laboratory partner might argue that it is really the Earth that is moving and the Sun that is stationary. Is there any way to determine from your observations whether it is really the Sun or the Earth that is moving? Which is the more plausible from your observations?
7. How do your observations fit with the heliocentric theory, in which the Earth is indeed rotating on its axis and the Sun is stationary?

C. Observing the Sun Pass through Solar Noon

You will need a large sheet of cardboard (sometimes known as "oaktag"), a pointed stick about 25 cm in length, a meter stick, a penny, a piece of string, and tape.

Caution: Once again, never look directly at the Sun; it can cause permanent eye damage. Do not depend on sunglasses or fogged photographic film; they do *not* provide enough protection.

In this experiment you will observe the motion of the Sun as it crosses solar noon. But you will do this only indirectly by observing the motion of the shadow cast by the Sun onto the cardboard sheet.

1. As you saw in the earlier section on solar noon, the time of solar noon is around our clock-time of 12:00 noon, or 1:00 p.m. if DST is in effect. But, because of the width of your time zone on the Earth's surface, solar noon at your location is very probably not exactly on the hour by the clock. To anticipate this, you will begin the investigation 30 min before the hour and continue until 30 min after the hour.
2. Find a level, preferably a paved area, with an unobstructed view of the Sun when it is overhead on a clear day. Before starting, note the location of the Sun in the sky in relation to the "cardinal points" (north, south, east, west). How do you expect the Sun to move from its present position during the course of this experiment?
3. Hold the pointed stick upright and notice the shadow the Sun casts. From your answer to Question 2, how do you expect the shadow to change during the course of this experiment?
4. Place the cardboard behind the stick so that the shadow falls on the cardboard and there is room on the cardboard for the expected movement of the shadow. Hold the cardboard in place with weights or books, so that it does not move during this experiment. Also mark the exact position of the end of the stick at the edge of the cardboard.
5. It is important that the stick is always in the same location and perpendicular to the ground. To help ensure that the stick is perpendicular, tape a penny to the string and tape the other end of the string near the upper end of the pointed stick. The penny and string should now lie flat against the stick as long as it remains perpendicular. Now you are ready to begin.
6. Beginning exactly 30 min before the predicted solar noon, set up the stick and mark the approximate point of the end of the shadow. (The end of the shadow is actually a bit fuzzy, because the Sun is a bright ball, not a point source of light, so the several shadows cast by different parts of the Sun overlap to form the shadow on the cardboard.) Use the meter stick to draw on the cardboard a line connecting the end of the shadow with the position of the low end of the stick. Record the time on the line, and in your notebook. Record also the length of the line.
7. Repeat this procedure exactly every 5 min for 1 hr. (If the motion of the shadow takes it off the cardboard, reposition the cardboard and start again.)
8. From the type of observations you have made so far, how would you

know approximately when solar noon occurred? Write down the approximate time.

9. Why is this only the approximate time of solar noon?
10. How would you determine from your data the direction of due north and due south? Indicate the cardinal points on your cardboard.
11. Your instructor may review with you the definition of the tangent of an angle in trigonometry. How could you use this definition to determine the altitude of the Sun (angle with respect to the horizon) at solar noon?
12. Find the altitude of the Sun at solar noon.
13. How did the actual motion of the shadow compare with your expectations?
14. Is there any way to determine from your observations of the Sun's moving shadow whether it is really the sun or the Earth that is moving? Which is the more plausible from your observations?
15. How do your observations fit with the heliocentric theory, in which the Earth is moving and the Sun is stationary?

D. Phases of the Moon

1. The phases of the Moon, as seen from the Earth, occur because of the different positions of the Moon in relation to the Sun and Earth during the course of its monthly orbit around the Earth. Use the planetarium to observe how the Moon's phases change as seen from the Earth during the course of one orbit of the Moon around the Earth.
2. Sketch the relative positions of the Earth, Moon, and Sun at full moon, half moon, and new moon.
3. What would the positions of the three objects be for the appearance of the Moon in which one-quarter, and three-quarters, of the Moon's face is visible? Is there more than one position for each?

Now you try it

1. During the course of 1 month, either in the evening or in the morning, observe the Moon and sketch its phases; record the corresponding date and time. Note or guess the approximate location of the Sun at each observation.
2. From the position of the Sun and the brightened portion of the Moon, sketch the positions of the Sun, Moon, and Earth for each observation.
3. How does the position of the Moon in the sky in relation to the Sun change from day to day?
4. Assume that the Sun is stationary. Is there any way to determine from your observations whether it is really the Moon or the Earth that is moving? Which is the more plausible from your observations?

5. Ancient observers (and some people to this day!) believed the phases of the Moon are caused by the interposition of the Earth in the path of light beams from the Sun to the Moon. Give some arguments against this view.
6. Why are there only occasional eclipses of the Sun at new moon, and occasional eclipses of the Moon at full moon? Answer this in terms of
   (a) the geocentric system, and
   (b) the heliocentric system.
7. Draw the relative positions of the Sun, Moon, and Earth at the occurrence of solar and lunar eclipses. Include rays of sunlight representing the limits of the shadows in each case.

E. The Motion of an Outer Planet

You saw in Section 2.4 that, seen from the Earth, the planets appear to "wander," that is, they appear to fall behind the stars each day, as do the Sun and Moon. This is called their eastward drift. But every once in a while, they also tend to move forward (to the west) faster than the stars. This is called their retrograde motion. The result is a looping or S-shaped motion as seen against the background of the stars. (See the text Section 2.4).

You also saw how Ptolemy explained this motion in the geocentric view by placing the planet on a circle that rode on another circle. (See figure 2.7 in the text.) Copernicus presented a quite different explanation in the heliocentric model, one that is also more plausible (and the one we accept today.)

Below is a top-view diagram of the Earth, Mars, and the Sun in the heliocentric model (not to scale). The diagram shows several locations of the Earth and the planet Mars at intervals of 1 month apart. The background of stars is also represented.

1. Which path represents the orbit of the Earth, and which represents the orbit of Mars? In which direction is each planet traveling? Explain your reasoning.
2. Copy the diagram onto a separate sheet of paper. Number the positions at each month from 1 to 7 for the Earth and Mars.

3. For each month shown on the diagram, draw a straight line from the Earth to the corresponding position of Mars, continuing the line to the background of stars. Each line represents the line of sight for an astronomer on the Earth who is observing Mars against the background of the stars. Number the ends of the lines from 1 to 7.
4. From the lines of sight you have drawn, determine how Mars appears to change location with respect to the background stars. Explain your reasoning.
5. During which of the months shown, if any, does Mars appear to move *eastward* with respect to the background of stars (eastward drift)? Explain how you can tell from your diagram.
6. During which of the months shown, if any, does Mars appear to move *westward* with respect to the background of stars (retrograde motion)? Explain your reasoning.
7. Do any of these answers change if the experiment is done on the Earth's southern hemisphere?

Evaluating your results

1. What was the purpose of this laboratory exploration?
2. Summarize the overall steps as well as the procedure in your own investigation in relation to the purpose of this exploration.
3. What conclusions did you make? What is the supporting evidence for them? What are the sources of error?
4. What difficulties did you encounter? How did you overcome them? How could this exploration be improved?
5. Connections: How does this laboratory relate to the material in the textbook and to your own daily experiences?

4. SKYGLOBE: A COMPUTER PLANETARIUM (CHAPTER 2)

Skyglobe is a computer planetarium that simulates many of the astronomical observations discussed in the text. It is by no means a substitute for actual observations, which physically connect you to the real universe which is our home. But the program does allow you to obtain a sense of what you would see if you were observing the actual events. Study each observation for a while and try to imagine yourself being outside and looking up at the sky on a beautiful clear evening.

Because of the complexity of the calculations involved in displaying the observations, *Skyglobe* is a DOS-based program (written in Assembly language). So when you start it up, the computer switches to the DOS operating system. It will switch back when you exit.

STARTING AND SETTING UP THE PROGRAM

After you have started the computer and it has completed booting to Windows, click the Start button, then click Run. Type the location of the program, then click OK or press Enter.

The program starts in a full-screen DOS window. Press the space bar to make the logo disappear.

Except where requested, do not use the mouse, as it changes the angle of observation too quickly.

You can exit the program at any time by pressing Esc twice.

The upper left corner indicates some of the settings. We will change most of them.

Set up the program by pressing the following

NumLock	Turn it off (so the green light goes off).
F1	Remove the help list of key commands. (You can access it anytime by pressing F1 again.)
+ (at right of keyboard)	Press several times to increase number of stars to maximum.
L	To obtain a list of locations from which to observe. Go to a city closest to your location using the arrow keys or the mouse and click or hit Enter.
F6	Remove the Sun's ecliptic path, the dotted red line. (We'll leave the planets and their names.)
N	This will place you facing due north.

The circular green line is your horizon line. You cannot see anything below the horizon line (even though the program shows some stars).

Up and down arrows	These raise and lower your view of the sky. Place N at the bottom of the screen.

The red lines are drawn to indicate the various constellations.

C	To remove or replace most of the constellations. Note the locations of the Big Dipper and Little Dipper.
F10	Removes all constellations and returns them. Leave them turned off for now.
F9	Remove names of constellations.
F8	Remove star names.

The grid lines are some of the latitude and longitude lines of the celestial sphere.

F7	Remove the grid lines on the celestial sphere for now.
F4	Remove the deep-space objects, which we can't see anyway without a telescope.
K	Turns the Milky Way on and off. Be sure it is on.
M, D, H, T	Sets date and time forward. Shift-M, D, T, or H moves each one backward. Be sure it's set to the current date and time.

The little green + sign is the Zenith (90° altitude), and the green line is the horizon (0°).

You are now ready to begin.

OBSERVING THE CELESTIAL SPHERE

The settings you just entered enable you to see the celestial sphere as it would look right now at your location, facing due north, if the Sun were not visible and no buildings were in the way.

1. Look in the other directions on your horizon plane by pressing S, E, W. You can also slowly "turn" in different directions by pressing the left and right arrow keys, ← and →. Try both of these.
2. If it is still daylight outside, observe the position of the Sun in the southern sky. Place the mouse over the Sun, and its altitude and azimuth will be given in the lower left corner. Record the result. (The azimuth runs from 0 at north to 180, due south, to 359.)
   Altitude:
   Azimuth:
3. Are the Moon and any planets above the horizon at this time? Which ones?
4. Return to looking due north, by hitting N. Place N on the bottom of the screen, if it is not there already, by using the arrow keys. Press C several times until just the Big and Little Dippers and a few other constellations appear.

   You can now set the celestial sphere in motion by pressing A. To stop it, press A again. However, the motion will probably be too fast to be meaningful. Slow it down to "slow motion" by pressing shift ←. You can speed it back up, if necessary, by pressing shift →.

   Observe for a while what happens to the stars and constellations as time advances. While the sphere is rotating, turn the grid lines on and off by pressing F7.

In what general direction are the stars moving?
What do you observe about the motion of the sphere?
Do all of the visible stars and constellations rise and set each day?

5. Stop the motion by pressing A. Place the mouse over the central star and look in the lower left corner of the screen.
   What star is this?
   What is its altitude?
   How does its altitude compare with the latitude of the location nearest you?
   How could you use the Big and Little Dippers to find this star?
   Try to find this star tonight, if it is a clear night and if your view is not blocked.
6. Set the celestial sphere in slow motion again (A). Now look to the E, S, W. Turn the grid lines on and off (F7). What is the apparent motion of the stars as observed in each of these directions? (Stop the motion when you finish.)
7. Now let's look at the celestial sphere after traveling to two other important locations.
   Press L to obtain the location list. Select "More Locations," the North Pole at bottom right.
   Be sure the Little and Big Dippers and a few other constellations are on by pressing C.
   Where is the "central star" from Question 5 in relation to the zenith?
   Set the sphere in slow motion once again, turning the grid lines on and off. Look in all four cardinal directions and use the left or right arrow key to turn completely around in a circle.
   Is there any difference in your observations in any direction?
   How could you describe the overall motion of the celestial sphere as seen from the North Pole?
8. Press L and go to an observation point on the Equator. Where is the "central star" this time?
   Set the sphere in motion. Look at each of the four cardinal directions. Notice that the central grid line (celestial equator) is directly on the E and W points. Describe the apparent motions of the stars at each of the cardinal points.
   How could you describe the overall motion of the celestial sphere as seen from the equator?
9. Finally, return to the location nearest you (press L). Perform the same observations as in Questions 7 and 8. How could you now describe the overall motion of the celestial sphere as seen from this location?
10. How could these observations be used to argue that we are observing the celestial sphere from a position on a sphere?

OBSERVING THE APPARENT MOTION OF THE SUN

Set the date to today's date and the time to 12:00 noon, if Standard Time, or to 1:00 p.m., if DST. Use the M, D, H, and T keys to do this. If you overshoot a setting, use the shift key with M, D, H, or T to go backward.

Look to the south (press S) and turn on the grid lines (F7). Be sure the ecliptic path (red line) is still off (F6). Turn off all constellations (F10).

1. Is the Sun due south in the sky at noon today? If not, why not?
2. Is the Sun directly overhead (at the zenith) at noon today?
3. Use the mouse to place the cursor on the Sun. What are the altitude and azimuth of the sun at noon today?
   Altitude:
   Azimuth:
4. Notice where the Sun is in relation to a few nearby stars. You can move the celestial sphere ahead exactly 24 hr by pressing the D key. Press the D key several times, pausing briefly each time to observe the position of the Sun in relation to the nearby stars. Try this again a few more times. (Ignore the planets for now.)

   Carefully describe what you observe about the position of the Sun in relation to the fixed stars.
5. Turn on the ecliptic path (red line) by pressing F6. Hold down the D key and observe the motion of the Sun. (Again ignore the planets and the Moon, which flies across the screen every month.) Remember that each jump forward of the sphere represents the motion of an entire day.

   Is the Sun staying up with the stars, or is it falling behind? What is this motion called?
6. Observe the motion of the Sun for an entire year against the background of the celestial sphere. Notice how the altitude of the Sun changes as it moves eastward along the ecliptic path. (There are two jumps by an hour each year as the time shifts into and out of DST, indicated by D in front of the time.)
7. Return to today's date and time and continue to look south. Find the date and altitude of the Sun at solar noon on the two solstices during the next year.
   Summer Soltice:
   Winter Solstice:

Caution: NEVER LOOK DIRECTLY AT THE SUN. It can damage your eyes permanently. Therefore, briefly glancing past it, obtain only a *very approximate* confirmation of (a).

8. At your location is the Sun ever directly overhead at any time during the year? (Remember that the green + mark is the zenith point.) What is the highest it ever gets in the sky?
9. Return to today's date and time.
   (a) What is the location of the Sun right now? (Change your view with the arrow keys, if necessary.)
   (b) What time will (or did) the Sun set today?

   If feasible, go outside right now and *approximately* confirm (a). If feasible, confirm prediction (b) either by direct observation or, if necessary, in a newspaper.

OBSERVING THE APPARENT MOTION OF THE MOON

Find the location of the Moon by pressing F, then select Moon. Use the arrow keys to place the moon in a comfortable viewing position for when the sphere begins to turn.

Notice where the Moon is in relation to a grid line. Then press A and move forward in time exactly 24 hr. You can use shift → to speed up the motion.

1. What two motions does the Moon exhibit relative to the stars?
2. Leave the Sun's ecliptic path on (F6). Carefully notice the location of the Moon in relation to a longitude line. Press D, pausing briefly to count each time, as you advance a day at a time. Carefully keeping your eye on the grid line as the Moon disappears.

   How many days does it take for the Moon to be completely "lapped" by the stars? This is known as a lunar month.
3. The Moon moves near the sun's ecliptic. Why don't we observe lunar or solar eclipses every month.
4. Finally, set the date to today and the time to sometime this evening when you will have a chance to observe the Moon (if it's not cloudy and if the Moon is not in new phase).

   What will be the location of the Moon at that time?

   Confirm your prediction this evening.

OBSERVING THE PLANETS

1. Return to today's date and set the time for around noon. Find the Sun. Turn the grid lines off and turn off all constellations (F10), but leave the ecliptic path on (F6).
2. Note the location of the planet Mercury. Advance by days at a time by holding down the D key and carefully observe the apparent motion of Mercury. (Again ignore the Moon's rapid motion across the screen.)

3. Using the A and D keys, carefully attempt to observe all three motions of Mercury: the daily westward motion, eastward drift, and retrograde motion.
4. Sketch the path of motion that you observe for Mercury over the course of time. Include the Sun and the ecliptic in your sketch.
5. Try to observe the retrograde motion of another planet.

Now you try it

Go to a date of your choosing (such as your birth date) at your location and record when the Sun rises and sets, the time and altitude of the Sun at solar noon, and the Moon and any planets that are visible in the sky at sunset.

5. EXPLORING FORCES (SECTION 3.4)

In this investigation, as is often done in scientific research, you will first confirm previously obtained results (here, those discussed in Section 3.4 of the textbook). Then you will go on to explore new territory, using the results you obtained from the first part of this investigation.

Question: An unbalanced force causes an acceleration. How are force and acceleration related to each other? To investigate this, you will apply different forces to a given mass, then the same force to different masses, observing the accelerations that result. Let's start with an unbalanced force on one object.

A. Acceleration With a Constant Force Acting On a Constant Mass (1.0 kg)

We do not want any part of the force that we apply to the cart to be balanced out by friction, nor do we want gravity to add to the force. So, before starting, we'll arrange the set-up so that gravity on the cart balances the force of friction on the cart.

1. How would you arrange the apparatus so that the effects of gravity and of friction balance?
2. How should the cart move when the effects of gravity and of friction just balance?
3. Use the available masses to obtain a total mass for the cart, with its load, of just 1.0 kg.
4. On the basis of your above answers, carefully arrange the cart and track

so that the balance of the forces described above is achieved as closely as possible. Note that, if you are using a tape to record the time intervals, it should be included as a source of friction.

5. Now obtain by experiment the average acceleration of the cart (mass of 1.0 kg) when you apply a constant force of, say, 1.0 N parallel to the track by means of the spring scale. Remember that to obtain the average acceleration, you must start with the observed distance and the time, and then obtain from your data the average velocity, the change in average velocity, the average acceleration for each time interval, and the overall average acceleration. Construct a table for your data and obtain the overall average acceleration for this force.
6. From your results so far, what do you conclude about the validity of Newton's second law of motion regarding the relationship between a constant force and the acceleration of a given mass?

B. Acceleration with Different Forces Acting On the Same Mass (1.0 kg)

So far, you have investigated the effect of only one force on the acceleration of the 1.0 kg cart.

1. If you applied larger and smaller forces to the cart, what do you predict will happen to the acceleration of the cart on the basis of Newton's second law?
2. How would you test these predictions? (You may want to refer to Part A.)
3. Discuss the testing procedure with your group and with your instructor. Once you have decided upon a procedure, proceed with the test.
4. Construct appropriate tables to display your data. Construct a summary table, showing the different forces applied and the resulting average accelerations for the 1.0 kg mass. You might use a spreadsheet program to present your data, if this is available and your instructor recommends it.
5. Examine your data and compare your results with your predictions in Questions 1 and 2 above. Discuss the reasons for any disagreement with what you expected to find. What are the sources of error?

Finding a pattern

1. You now have the results for the average accelerations on the 1.0-kg mass caused by different forces. Is there a pattern in the relationship between force and acceleration for a single mass?

2. To see any pattern more clearly, create a graph with force on the *y*-axis and average acceleration on the *x*-axis. Take care in constructing the scales and labeling the axes. If the data points appear to fall on a straight line, use a ruler to draw a straight line through the data points.
3. What does this pattern tell you about the relationship between the two variables, force and acceleration?
4. Now obtain the slope of the line and be careful to include the units of the slope.
5. Express the relationship between the force and the acceleration as an equation, and including the actual mass of the cart in this equation.
6. How does your result compare with Newton's second law of motion? Discuss whether it confirms the law or conflicts with it, and why.

C. Acceleration with Different Masses and the Same Force

So far you have found the relationship between forces and accelerations for one mass.

In this investigation you will test the relationship to see if it holds for other masses, as it should if it is a law of nature. This procedure is common in actual research: first testing a result to see if it holds in one case, then testing to see if it holds in other cases under various conditions.

You will test only two other masses. (You may perform other tests if you wish.)

1. Chose other total masses for the cart that are simple multiples of each other and of the 1-kg mass used in Part A; for example, 2.0 kg, 0.5 kg.
2. As before, arrange the apparatus so that the effects of friction are balanced out by the effects of gravity.
3. Using the same amount of force as in Part B (1.0 N) on each total mass of the cart, obtain the overall average acceleration of the cart from the distance and time data.
4. Create a summary table of the different masses, including the mass in Part B, and the corresponding overall average accelerations. Can you discern a pattern in the relationship between mass and acceleration?
5. In order to obtain a clearer picture of the relationship, graph your results. From the type of line formed by this graph, what do you conclude about the relationship between mass and acceleration?
6. How does your conclusion compare with what you might expect from Newton's second law?
7. Theoretically, what should be the value of the slope of the line? Obtain the slope of the line. Does it equal this expected quantity?

D. Conclusions

1. Write your conclusions regarding:
   (a) the relationship between force and acceleration, from Part B;
   (b) the relationship between mass and acceleration, from Part C;
   (c) the overall relationship between force, mass, and acceleration.
2. Does this experiment so far confirm or deny Newton's second law of motion? Explain.

E. Exploring the Unknown

Once scientists are confident of a general result, they can rely on it as a tool for exploring the unknown. Newton's second law of motion has been tested and confirmed so many times in many different situations that it now accepted as a law of nature (at speeds much less than the speed of light).

1. Your instructor will give you an unknown mass to place on the cart. Using your results above, design an experiment to obtain the value of the mass (without using a scale) and then carry it out.
2. Confirm your result by using a scale. What are your conclusions about using Newton's law?
3. Once you know the mass, you can predict the acceleration it will have when a known force is applied to it.
4. Design an experiment to do just that and carry it out. (Again, use a spreadsheet if available and recommended by your instructor.)
5. What do you conclude from this result?

F. A Practical Application

Place a volunteer from the class on a smoothly running cart or on roller blades or on a scooter. On a stretch of sidewalk or other open area, measure out a distance of 10 m.

1. When your volunteer is on wheels and some distance from the measured 10 m, push him or her from rest until you reach the 10-m measured stretch, then release the volunteer to cover the 10-m stretch at constant speed. Using two stop watches, record:
   (a) the time during which the acceleration occurred;
   (b) the time it takes your volunteer to cover the 10-m stretch;
   (c) the time it takes your volunteer to stop after completing the 10-m stretch.

   Record also the total mass of your volunteer and the device on which they are riding.

2. From these data obtain:
   (a) the acceleration of the volunteer;
   (b) the force required to produce this acceleration;
   (c) the amount of force required to stop the volunteer. What provides this force?
3. Why is the mass in Newton's second law sometimes called "inertial mass"?
4. Describe with the aid of a sketch the action and reaction forces in the process of accelerating your volunteer.

6. EXPLORING FORCE, WORK, ENERGY, AND POWER (CHAPTERS 3, 5, SECTION 6.3)

How are all of the basic physical concepts of force, work, energy, and power related to each other? The textbook states that work done by a force on an object is defined as the force exerted times the distance the object moves under the action of the force. The textbook also referred to two types of mechanical energy: potential energy and kinetic energy.

Write down in your own words the definitions of these other concepts below. Refer to the textbook as needed, but put these in your own words. If it is still not clear to you what these concepts actually mean, ask for help.

Force:
Work:
Kinetic energy:
Potential energy:
Power:
Law of conservation of energy:

A. The Force of a Spring

In this exploration you will investigate how the above concepts apply to a simple mechanical device—a spring. Just as scientists do in investigating a new phenomenon, you will make observations, develop and test hypotheses, change your hypotheses as needed, draw conclusions, and apply your conclusions to new situations.

Since the concept of force is essential to the concept of work, we first need to obtain an expression for the amount of force that a spring exerts when it is pulled off equilibrium (or squeezed together).

1. Pull on the two different springs to obtain a sense of how the force changes as the spring is stretched more and more. Try this several times.

(Do not pull the spring so much that it is bent and does not go back to its original position.) What do you conclude about the force as you increase the elongation of the spring?

2. Your answer to the above question can be regarded as a rough hypothesis about the force exerted by a stretched spring. Now you will test this hypothesis and obtain an exact relationship between the force and the elongation of the spring.
3. It is difficult to measure the force exerted by your hand. Instead you will use several masses, each of which, by its weight, owing to the gravitational pull of the Earth, will exert a precise, measurable force on the spring. The weight of an object on the Earth's surface is equal to the mass m of the object times the acceleration of gravity, g. Or

$$W = m \times g.$$

In this equation g has a constant value at a given location. In general, it is taken to be $g = 980\ \text{cm/s}^2$.
4. If the mass is not given on each of the available masses, measure the masses in grams using a scale.
5. Place the shorter spring on a cross bar and hook the 50-g hanger to the end of the spring. In order to give the spring a stretch before starting the investigation, place the 500-g mass on the hanger. This will be the starting position. We will define this as the position when there is *zero added mass* on the spring, even though we know that there are already 550 g attached to the spring.

   Measure the length of the spring from its top to the end of the spring (not to the end of the hanger).
6. Now place increasing amounts of added mass on the hanger from 100 g to 500 g in 100-g intervals. In each case the elongation of the spring increases. Measure the length of the spring, again from the top of the spring to the end of the spring.
7. Create a table with four columns in which to present your data, giving the units in each case:
   - In the first column, list the mass added to the hanger and 500-g mass, starting with zero mass.
   - Leave the second column blank for now.
   - In the third column give the total length of the spring corresponding to each mass. Call it l.
   - In the fourth column give the *increase* in length l with each mass, call it x. For zero added mass, $x = 0$.
8. The second column of your data table will list the weight of each mass. Call it the force F. Using the definition of the weight, find the

weight for each mass and present the results in the table, including the units.

In this experiment we are measuring mass in grams, distance in centimeters, and time in seconds. Using these measures, in the metric system the unit of weight (and any other force) is

$1\ \text{g cm/s}^2$ which has a special name; it is called a "dyne."

Revising your hypothesis

Carefully examine the results in your table and compare with your earlier tentative hypothesis (Question 1). What do you conclude from your table about the stretch of the spring as the force increases?

Examining the data

1. Your table gives the increase in the length of the spring for added weight (force) applied to it. In order to see more clearly how the two variables of force and length increase (x) are related, we can use graphical representation of the data, in other words, a graph.
2. Using a sheet of graph paper, place the added force (weight), F, on the vertical axis and the increase in length, x, on the horizontal axis. Then plot your data. Use a ruler to connect your data points.
3. Examine the result of your graph. How would you now revise your earlier hypothesis about the relationship between the F on a spring and the increased length, x?

Obtaining a precise equation

1. If your graph turned out to be close to a straight line, you can obtain an exact equation relating the two variables by obtaining the slope of the line. Call the slope of the line k. Here $k = \Delta F/\Delta x$. Obtain the value of k, including its units, and write an equation relating the force, F, and the increase in the length of the spring, x. Show all your work.
2. If the length of the spring with zero added force (neglecting the initial weight added) is *defined* as zero length, then all increases are measured from zero length. So Δl, which we have called x, is simply l. Rewrite the above equation for the situation when l is measured from the position $l = 0$. This equation was first obtained by Newton's colleague Robert Hooke in the 1600s. It is known as *Hooke's law*.

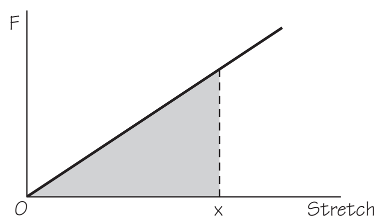
Using Hooke's law

1. How could Hooke's law be used to measure the unknown weight of an object?
2. Find the unknown mass of the object.

B. Work and Energy (Chapter 5)

Attach the spring to the crossbar and attach the hanger and the 700 g of mass to the spring. Observe that the spring extends and comes to rest.

1. The weight of the mass that you attached to the spring does work on the spring, while stretching it. What happened to the energy that was created by this amount of work? Did it disappear?
2. We want to find a value for the work performed by each added mass as it stretches the spring. Unfortunately, to obtain the amount of work done, we cannot simply multiply the amount of stretch, x, times the force, F, because the force is constantly increasing as the spring stretches. Instead, the amount of work can be represented by the area in the triangle under the graphed line:



Work is numerally equal to the area = ½(base)(height)
= $\frac{1}{2}x\,(k\,x) = \frac{1}{2}k(x)^2$.

3. Using this equation and your data from Part A, obtain the amount of additional energy stored in the spring for each mass that you added (beyond the initial mass). Present your results in a table and include the units. The table should have four columns: the mass applied to the spring, the force, the increase in length (x), and the work done, $W = \frac{1}{2}k(x)^2$.
4. When a weight is at rest on the spring, we say it is in equilibrium. What does Newton's first law of motion say about the forces on a weight at equilibrium?

Observing energy transformations

1. With an added mass of 200 g on the hanger (in addition to the initial mass), gently pull the spring slightly off equilibrium and let it go. What do you observe?
2. Using either energy or work concepts, what is happening during the motion of the spring right after you release it as it moves back to the point of equilibrium?

3. What is happening in terms of either energy or work during the part of the motion from equilibrium to the top of the oscillation?
4. Starting from your initial pull off equilibrium, carefully trace all of the energy transformations that are occurring and where they occur. Assume that the mechanical energy is conserved.
5. Where does each of the following have its largest and smallest values?
   (a) the elastic potential energy of the spring;
   (b) the kinetic energy of the mass;
   (c) the gravitational potential energy of the mass.

Obtaining quantitative results

1. With the 200-g additional mass still on the spring, pull the spring off equilibrium by exactly 3.0 cm and let it go. See if you can find a way to give a quantitative value to the maximum amount of the following. (These numbers will be very large, because the units used, ergs, are very small.)
   (a) the elastic potential energy of the spring;
   (b) the gravitational potential energy of the spring.
2. What is the speed of the mass as it passes through equilibrium?

C. Now You Try It (Section 6.3)

Power is defined as the rate of doing work. Two examples might be a person walking up a flight of stairs and another person running up the same flight of stairs. In both cases they perform the same amount of work, but they apply different amounts of power. In order to see this, examine the difference.

1. Find a staircase in your building. After measuring the height of one step, obtain the height from one floor to the next.
2. Let one student casually walk up the stairs. Then let the same or another student run up the same flight of stairs. Time each student with a stopwatch.
3. You will need to convert the weight of the student(s) to newtons.
4. From these data, obtain the work performed and the power output of each student for their ascent. Show your calculations.
5. Compare each with the power output of a 100-W light bulb.

D. Devise Your Own Experiment

Devise an experiment to measure the power output of a person riding a bicycle. Describe exactly what you would do, and how you would obtain your results.

Try the experiment if time and equipment permit.

7. FINDING THE MECHANICAL EQUIVALENT OF HEAT (SECTION 6.1)

INTRODUCTION

Scientific research may involve a variety of aims. Some research is directed at finding whether known laws of nature hold under extreme conditions; other research may seek to test a new theory or prediction, or to understand a puzzling or new phenomenon; and some research is undertaken to obtain a precise measurement of a given quantity or variable. This investigation is similar to the last of these. It involves a measurement of the quantity known as the mechanical equivalent of heat—one of the fundamental constants of nature.

Before starting: review the section on scientific notation in "Reviewing Units, Mathematics, and Scientific Notation."

Mechanical work and heat are different manifestations of one overall concept—energy. Although each is a manifestation of energy, they are measured in different units. In the study of mechanical work, we speak of foot-pounds, ergs, or joules. In the study of heat, we speak of calories, kilocalories (equal to 1000 calories), or Btus (British thermal units). Briefly defined, 1 cal is the amount of heat required to raise the temperature of 1 g of liquid water 1°C.

Since heat and work are both manifestations of energy, we should be able

to convert from one system of units to the other. That is, there should be a conversion factor that tells us how much heat energy is equivalent to a certain amount of work, and vice versa. Unfortunately, there is no theoretical procedure that gives us this factor. We have to resort to experiment. By directly measuring the amount of heat produced by a given amount of work, we can find a numerical factor with which we can multiply calories of heat to obtain the equivalent number of ergs or joules of work. This factor has been named "the mechanical equivalent of heat." In this experiment we will make a direct measurement of this factor.

The mechanical equivalent of heat was first measured by Joule in England in 1840, and many times thereafter. The method by which he achieved his most accurate result was one in which a mass of water was churned by a set of paddle wheels set in rotation by a series of falling weights. The heat developed in the water came as a result of the work done on the water by the paddle wheels, kept churning by their connection to the weights as they fell.

The mechanical equivalent of heat (J) is today usually defined in joules per calorie and the accepted value is $\mathcal{J}$ = 4.19 joules/calorie—which is very close to Joules' original result. However, this mixes units of the mks (joules) and the cgs (calories) systems of metric units. The measurements in our experiment will be done using centimeters and grams, so we will want $\mathcal{J}$ in cgs units. Since calories are already in cgs units, we only need to transform joules into ergs to obtain $\mathcal{J}$ in the proper units. Since 1 J = 10^7 ergs, what is the value of $\mathcal{J}$ in cgs units?

$\mathcal{J}$ = ____________________________ erg/cal.

The mechanical equivalent of heat may be defined in symbols by the relationship

$$W = \mathcal{J}Q,$$

where W is the amount of mechanical work in ergs, Q is the equivalent number of calories of heat, and $\mathcal{J}$ is the conversion factor, the mechanical equivalent of heat.

Or, one may write

$$\mathcal{J} = \frac{W}{Q}.$$

The above indicates that $\mathcal{J}$ can also be thought of as the number of ergs of work necessary to produce the same effect on a system as that produced by the absorption of 1 cal of heat.

INVESTIGATION

Materials

Bits of copper and tin, PVC tubes of 1-m length with corks or stoppers to insert in each end, thermometer, meter stick, beakers, plastic cup.

Procedure

In this experiment, the mechanical equivalent of heat is to be obtained by measuring the heat produced by the expenditure of a definite amount of work. Quantities of first lead shot and then copper bits are allowed to fall many times from end to end in a cardboard tube. Knowing the mass of each metal and the length of fall, one can calculate the mechanical work done on each metal by gravity. By measuring the temperature change of each metal resulting from this work, the heat energy gained can be determined from the known specific heat of the metal.

The specific heat has the symbol C, which is not to be confused with the kilocalorie of the Celsius unit. The specific heat of any substance is defined as the amount of heat in calories required to raise the temperature of 1 g of the substance by 1°C. Thus, the amount of heat Q absorbed by each metal with a temperature change of ΔT is

$$Q = mC\Delta T,$$

where m is the mass of the metal, C is the specific heat (given in the table below), and ΔT is the increase in temperature.

To compensate for heat gained from and lost to the room, the shot will first be cooled below room temperature.

Part I

Since there are many pieces of metal falling down a narrow tube, they cannot all fall the entire length of the tube. To determine the average distance that a piece falls with the corks inserted in each end, perform the following measurements, recording them in the data table on the following page.

1. Place one of the corks tightly into the end of the tube and, inserting the meter stick, measure the length to the opposite end. Call this l_1.
2. Remove the meter stick and, holding the cork in place, carefully pour the tin bits into the tube. Holding the tube vertically, measure the distance again to the open end of the tube. Call this l_2.
3. Half the difference between the two distances in Steps 1 and 2 is the position of the average piece of lead from the bottom of the tube. Let $(l_1 - l_2)/2 = h$.
4. Place the other cork securely into the other end. Measure the amount of cork (c) that enters the tube. Subtract this amount from l_1.

5. When flipping the tube, the average piece of metal will fall from a position h above the bottom of the tube to a position h above the cork at the other end of the tube. The average distance that it falls is thus the net distance in Step 4, less $2h$. Call this distance d.

	TIN	*COPPER*
1. Finding average distance of fall, d.		
(a) l_1		
(b) l_2		
(c) $(l_1 - l_2)/2 = h$		
(d) $d = l_1 - c - 2h$		

(Write your result for (d) in row 1 of the table on the next page.)

Part II

You will now measure the mass and temperature of the tin pieces.

6. Determine the mass of the tin by weighing it in the beaker. Since the scale reads only to 300 g, you must weigh the tin in two or more batches. Then subtract the number of weighings times the mass of the beaker. Record your data in the data table.
7. Before beginning, cool the tin in the ice bath, being careful to keep the tin dry. Pour the tin from the beaker into the plastic cup. Insert the thermometer probe into the tin pieces in the plastic cup, covering it as much as possible with the tin. When the tin has reached a temperature around 4° below room temperature, record the temperature in the table. You are now ready to begin.
8. Remove the thermometer and pour the tin into the long tube, holding the cap tightly on the tube at the opposite end. Be careful not to lose any of the bits. Place the other cap tightly on the tube.
9. Holding the caps tightly in place to prevent any bits from escaping, sharply flip the tube over to a vertical position *100* times, keeping careful count. Try not to allow the tin to slide down the tube. Perform each inversion quickly in such a manner that all the pieces fall vertically from one end to the other. Do not raise or lower the tube during the inversions.
10. Carefully but quickly pour the tin back into the beaker. Measure and record the final equilibrium temperature.
11. Using your measurements, calculate the work done on the lead shot (Step **10** in the table); the heat Q produced by this work (Step **11** in the table); and the mechanical equivalent of heat (Step **12** in the table).

Part III

Repeat the above procedure using the copper bits.

Data and Analysis

	TIN	*COPPER*
1. Average distance of fall, *d*.		
2. Mass of metal and beaker		
(a) First batch		g
(b) Second batch		g
(c) Third batch		g
(d) Total		g
3. Mass of beaker		g
4. Mass of metal		g
5. Initial temperature of metal		°C
6. Number of times the metal falls		N
7. Final temperature of the metal		°C
8. Specific heat of metal (cal/g°C)	**0.054**	**0.092**
9. Acceleration of gravity (*g*)	**980**	**980** cm/s^2
10. Work done on the metal $W = Nmgd$		erg
11. Heat produced by this work $Q = mC\Delta T$		cal
12. Mechanical equivalent of heat $\mathcal{J} = \frac{W}{Q}$		erg/cal

13. Mechanical equivalent of heat, average of your results for two metals in the above table: ________________erg/cal.

14. Mechanical equivalent of heat, accepted value: ________________erg/cal.

THOUGHT QUESTIONS

1. How do the measured and accepted values for J compare? Express this as a relative error (percentage difference).
2. List some of the sources of experimental error in this experiment.
3. Why did we use a PVC tube and not an aluminum tube?
4. An unknown metal has a specific heat only half that for tin. If you performed this experiment on the metal, would you expect the temperature increase to be less than, equal to, or greater than that for lead? Explain.
5. Joule's biographer reports that Joule took a thermometer with him on his honeymoon to the Swiss Alps in order to measure the temperature increase of water landing at the base of a high water fall. Niagara Falls is 59-m high (5900 cm). If Joule were to honeymoon at Niagara Falls, what temperature increase of the water would he find? What assumptions should be made in this measurement? Use the accepted value of J.

   (*Hint:* Note that $mgd = JQ = JmC\Delta T$, and C for water is 1 cal/(g°C). Thus, $\Delta T = gd/JC$. Note that you do not need to know the mass of the water!)

8. EXPLORING HEAT TRANSFER AND THE LATENT HEAT OF FUSION (CHAPTER 7, SECTION 16.2)

INTRODUCTION

Most substances can appear in three states, or phases: solid (frozen), liquid, and vapor (gas). The amount of heat energy—or, in the old caloric theory, the amount of caloric fluid—that each atom possesses determines the state of the substance: the least energy in the solid state, the most energy in the gaseous state.

Heat flowing from one substance to another often simply warms up the substance that gains the heat, increasing its temperature. However, if sufficient heat is absorbed, the substance can undergo a change of state, e.g., from solid to liquid, or from liquid to vapor. In this case, the added heat does not increase the temperature of the substance while the change of state takes place. Instead it serves to break up the structure of the substance as it transfers to the next state. For instance, a certain amount of heat energy is required simply to melt a substance in a frozen state, turning it into liquid at the same temperature. Since this heat seems to "disappear" (i.e., the temperature does not change during the phase transition), it is called "latent" heat.

There are three parts to this investigation.

PART I. HEAT TRANSFER IN AIR

As everyone knows, hot water in contact with air will cool down. This is said colloquially because heat gradually "flows" from the hot water to the cooler air. The reverse occurs when cold water is exposed to air.

But does the heat "flow" as quickly in each direction?

Does the presence of frozen ice in cold water have any effect on the rate of temperature change?

1. Before you start, how would you answer each of these questions?
2. Now let's see what actually happens in each of these three cases. The three cases are:
   (a) plain hot water;
   (b) a mixture of ice and cold water;
   (c) plain cold water.
3. Use the insulated cups, hot water, and crushed ice to prepare each of these situations. Why should you keep the lids on the cups until you are ready to begin?
4. Since you are investigating the rate of heat transfer in these three situations, the time will be an important factor, as well as the temperature. Before starting, create a table in which to record the temperature and the time for each cup.
5. Record the starting temperature in each cup, the room temperature, and the time.
6. Now *remove the tops from the cups*, so that heat can flow from and to the room.
7. Continue to measure the temperature of the water in each cup every minute for 5 min, and record.
8. Put these cups in a safe place to the side (*without tops*). During the rest of the experiment, continue to measure the temperature of each cup about *every 10 min* until after you have finished Parts II and III of this experiment. Be sure to record both the temperatures and the times of observation in the data tables. (This will require some organization of time and equipment by your group.)

Analysis

1. After you have completed all measurements. You can observe and compare any trends more easily if, *on a single sheet* of graph paper, you plot the temperature on the vertical axis and the elapsed time in minutes on the horizontal axis (starting time is 0 min) for each of the three sets of data. Draw a smooth curve through each set of points. Label your axes and curves. Also indicate room temperature on your graph and draw a horizontal line at that temperature.

2. Examine your results. Describe any differences you see between the three curves.
3. How do results compare with what you expected to find (Question 1)?
4. How would you account for the differences between these three curves, using the kinetic–molecular theory and the idea of latent heat?

PART II. CONSERVATION OF HEAT IN MIXTURES

(Remember to continue recording every 10 min the temperature of the water and the time of observation for the three cups in Part I.)

In this part of the experiment, you will test whether or not heat is conserved (not lost) when it flows from a liquid at high temperature to another liquid at a lower temperature.

In this case, the two samples of liquid are both water. They will be mixed together until they reach a uniform temperature (this is when heat ceases to flow). To determine if heat is conserved, we can compare the observed final temperature with the value predicted on the assumption that heat is conserved. Naturally, there is some systematic error, since some heat is lost to the air and surroundings. So the predicted and observed values may not exactly match. But if they are close, then we know that heat was conserved within the limits of experimental uncertainty.

As discussed in the text, when heat flows into or out of any substance without a change of phase, its temperature changes. The amount of heat, Q, is proportional to the temperature change, $\Delta T = T_f - T_i$. If ΔT is positive, heat flows into the body; if ΔT is negative, heat flows out. The amount of heat is also proportional to the mass m, and there is a proportionality constant C, which is different for each substance and is called the specific heat. Thus

$$Q = mC\Delta T.$$

Since we don't yet know the starting temperatures of the liquids, we can't make any predictions at this time. We will have to start with observation, then compare with our predicted result for this particular case.

1. Using a graduated cylinder and insulated cups with tops, prepare 50 ml of hot water and 50 ml of cold water without ice. (Be careful not to burn yourself in obtaining the hot water.)
2. Measure and record the temperature of the water in each cup.
3. Now pour one cup into the other, keeping the top on as much as possible.
4. Record the equilibrium temperature.

5. Now repeat this procedure, but use *different* quantities of cold and hot water, for example, 75 ml cold water and 25 ml hot water, and record your measurements. Create a table in which to present your data in both cases.

Analysis

1. Now let's see if *experimentally* the heat gained by the cold water is equal to the heat lost by the hot water. To do this, use the equation for the heat gained or lost, $Q = mC\Delta T$, to find the heat gained by the cold water and the heat lost by the hot water.

   Here m is the mass of each amount of water, C for water is just 1 cal/(g°C), and $\Delta T = T_f - T_i$. Negative values for ΔT and Q simply indicate a loss of heat.

   (It is fortunate that the metric units are defined in such a way that for water 1 ml contains 1 g of water. The specific heat C for water is defined by convention to be 1 cal/g°C.)

   Trial 1
   $Q_c = m_1 C\Delta T_c =$,
   $Q_h = m_2 C\Delta T_h =$.

   Trial 2
   $Q_c = m_1 C\Delta T_c =$,
   $Q_h = m_2 C\Delta T_h =$.

2. If heat is conserved in each mixture, how should you be able to determine this from the above calculations?
3. Taking into account uncontrolled losses and gains of heat, from your results so far would you say that heat was conserved or not in each case?
4. If the two numbers in each case are not exactly equal, how much net heat was lost or gained? Indicate whether heat is lost or gained.

   Trial 1:
   Trial 2:

Making a theoretical prediction

You can calculate *theoretically* what the value of the equilibrium temperature T_e in Trial 1 *should have been* by assuming that heat is conserved and that absolutely no heat is lost or gained from the surroundings.

If heat is conserved, then

heat gained = heat lost

$$m_1 C\Delta T_c = -m_2 C\Delta T_c,$$

$$(T_e - T_1) = (T_2 - T_e).$$

C cancels out since only liquid water is used; no change of state occurs. The masses also cancel out, since they are both the same (50 ml = 50 g). This is now an equation for one unknown, T_e, since all of the other factors are known from the above table.

Substitute in your values for T_1 and T_2 from Trial 1 above and solve the equation for the unknown T_e.

Comparing the theoretical and experimental results

1. How does the observed final temperature compare with the predicted value in Trial 1?
2. *Taking experimental error into account*, what does this say about the conservation of heat in mixtures?

Extra credit

Make the same prediction of the equilibrium temperature in the case of Trial 2 above. Note that *C* cancels out again, but that the masses are now different.

PART III. LATENT HEAT OF FUSION OF ICE

(Remember to continue recording every 10 min the temperature of the water and the time of observation for the three cups in Part I.)

A. Observing Latent Heat

1. If you placed several ice cubes in a glass or metal container and started heating the container, the ice would melt. That's obvious, but what will happen to the temperature of the mixture of ice and liquid water as the ice melts?
2. Now try the above experiment. Record the temperature every few minutes, until several minutes after all of the ice is melted.
3. Compare your observations with your prediction in Question 1.
4. How would you explain what you observed?

Extra Credit

Make a graph of your results as a function of time.

B. Measuring Latent Heat

In this part of the experiment, you will actually measure the latent heat of fusion of ice. We will make several assumptions about the melting process, based on Parts I and II. The main assumption is the conservation of heat, with only negligible loss of heat to the surroundings. By observing the cooling of hot water, when an ice cube at melting temperature (0°C) is placed into it, we also assume that all of the heat extracted from the hot water is used for the melting of the ice cube, followed by the heating of the water from the melted ice (which starts at 0°C) to the equilibrium temperature of the mixture. This may be expressed as follows in symbols and words:

$$Q(\text{lost by hot water}) = Q(\text{latent of ice}) + Q(\text{gained by cold water obtained from melted ice})$$

or

$$Q(\text{latent of ice}) = Q(\text{lost by hot water}) - Q(\text{gained by cold water obtained from melted ice}).$$

Since there is no temperature change of the ice while the ice melts, the heat Q required to melt the ice is the number of calories per gram. Instead of Q, the symbol for latent heat is usually given as L. The value of L, the latent heat of fusion of per gram of ice, has been found experimentally to be

$$L = 79.4 \text{ cal/g}.$$

If there is more or less than 1 g of ice, the heat required to melt the ice is simply

$$Q(\text{to melt ice of mass } m) = mL.$$

Thus, to turn 10 g of ice at 0°C into 10 g of water at the same temperature requires an amount of heat equal to $Q = mL = 794$ cal. Note that water obtained from melting ice is always at an initial temperature of 0°C.

We can now rewrite the earlier equations for heat transfer in the melting of an ice cube in hot water as follows:

$$Q(\text{lost by hot water}) = mL + Q(\text{gained by cold water obtained from melted ice})$$

or

$$mL = Q(\text{lost by hot water}) - Q(\text{gained by cold water obtained from melted ice}).$$

The two expressions for heat on the right side of the last equation, Q(lost by hot water) and Q(gained by cold water obtained from melted ice), involve the familiar relationship $Q = mC\Delta T$.

In order to obtain the value of L from the second equation, we need to know the masses of the ice cube and the hot water, and the change of temperature of the hot water and the cold water from the melted ice cube.

Now you try it

Find the latent heat of fusion of ice, L. Start by measuring the mass and temperature of 100 ml of hot water (be sure not to include the container in the mass). Obtain an ice cube and allow it to begin melting, which indicates that it is at the melting temperature of 0°C. Drop the ice cube into the water and measure the equilibrium temperature after all of the ice has melted. Find the mass of the ice and resulting water by measuring the new mass of the water and subtracting the initial mass of the hot water from your measurement. Create a table in which to present all of your measurements. Finally, using the data in your table, calculate each of the two heat expressions on the right side of the above equation, then solve for L.

This will require some thought and discussion, and perhaps some help, but you should be able to carry this out and obtain a fairly good result.

Analysis

1. How does your result for the latent heat L compare with the accepted value? Express your answer as a percentage difference.
2. How do you account for the variation from the accepted value?
3. Calculate your contribution to the net entropy gain of the universe in the melting of the ice cube. Note that $\Delta S = \Delta Q/T$, where T is kelvins (not celsius). At the freezing point of water $T(\text{K}) = 0°\text{C} + 273°\text{C}$.

(Complete Part I of this investigation.)

9. INVESTIGATING WAVES (CHAPTER 8)

PART I. WAVES ON SPRINGS

Many waves are too fast or too small to observe easily. Using a long metal spring and a Slinky you can make large waves that move slowly enough to study.

A. Longitudinal Waves

1. Together with a partner, pull the Slinky out across the laboratory table or on the floor to a length of about 14 ft (6 m). (Do not pull it so far that the spring is bent.) Create a longitudinal pulse from one end by grasping the stretched spring about 20 cm from the end with your free hand. Pull the spring together toward your end, then release it, being careful not to let go of the fixed end with your other hand.
2. Try this from either end and then from both ends simultaneously. Write down everything you observe.

3. What happens when the two waves meet? This is called *interference*.
4. In order to see the longitudinal wave more easily, tie pieces of string to a loop of the spring at several places. What do you observe about their motion as the pulse passes?
5. Does a pulse carry matter all along its path, or does it carry something else? Explain your reasoning.

B. Transverse Waves

1. Leave the strings attached to the Slinky. To create a single transverse pulse, move your hand quickly back and forth once at right angles to the stretched spring. Try this from each end of the Slinky, while the other end is held steady.

   Perform experiments to answer the following questions about transverse pulses.

   (a) What is the motion of the attached strings as a transverse pulse passes by?

   (b) Does the size of the pulse change as it travels along the spring? If so, in what way?

(c) Does the pulse *reflected* from the fixed far end return to you on the same side of the spring as the original pulse, or on the opposite side?

(d) What happens when two pulses on opposite sides of the spring interfere? Try to draw what happens before, during, and after.

(e) What happens when two pulses on the same side of the spring interfere? Again, try to draw this.

C. Standing waves

1. Use the thin helical spring. Note that it is much more taut than the Slinky. Again with a partner, stretch it to about 14 ft (6 m). Repeat your observations and conclusions about transverse pulses. Is the speed of the pulses any different compared with the Slinky?
2. By vibrating your hand steadily with the same amplitude, back and forth perpendicular to the spring, you can create a train of pulses, a *periodic wave*. When this wave reflects off the opposite, fixed end, it interferes with itself and forms a *standing wave*. Try this.

3. A standing wave is also created if periodic transverse waves are sent from both ends of the spring. The waves must be of the same size and the frequency. Try this.
4. In either case, how does the frequency of the oscillation affect the wavelength of the standing wave? Can you express this as a proportionality?

PART II. WAVES ON WATER

So far you have observed reflection, refraction, and interference of waves moving along one dimension. In order that you can make more realistic comparisons with other forms of traveling energy, especially light waves, you can first observe the same wave properties spread out over a two-dimensional surface, the surface of water.

Pulses, waves, and interference

1. Put a large yellow or other bright color cafeteria tray on a horizontal table and fill it with water almost to the top, but don't fill it to the top. Orient the tray sideways in order to minimize the effects of reflection off the sides of the tray.
2. To see what a single pulse looks like on water, gently touch the surface with the eraser of a pencil or the cap end of a ball-point pen. Then with the pipette dropper held only about a centimeter above the surface, let a single drop of water fall onto the surface. Sketch and describe the pulses on the water surfaces which you observe.
3. Using two pipette droppers at opposite sides of the tray, let a single drop of water fall onto the surface simultaneously from each dropper. Carefully observe what happens when the two pulses meet. Describe and sketch your observations before, during, and after the interaction. This is an example of *interference*.
4. You can generate a single straight pulse by moving the small plastic ruler back and forth sharply once in the water. Use the large ruler to act as a barrier in the water, about 8 in from the source. Then observe what happens when a continuous series of straight pulses forming a periodic wave strikes the barrier.
5. By changing the frequency of the motion of the small ruler, you can set up a standing wave. Sketch and describe your observations.

Diffraction patterns

Orienting the tray sideways as before, use a continuous series of straight pulses forming a periodic wave to observe what happens in the following situations. Describe and sketch what you see. These are examples of *diffraction*.

1. Use the larger ruler to generate a periodic wave that hits the smaller ruler straight on. Observe what happens on the sides of the barrier.
2. Place the 100 g mass in the water to act as a small barrier. Create straight waves of wavelength about the size of the mass, striking the mass. Observe and sketch what you see.
3. Now allow the straight waves to strike a barrier with a gap in the middle that is about the size of a wavelength. Use two small rulers to form the barrier and gap.

Interfering waves from point sources

1. Set up a standing wave in the tray by using a pencil eraser or a ballpoint pen as a single point source. Strike the surface gently at a constant frequency near one of the long sides of the tray. Change the frequency and observe what happens to the wavelength. Describe and sketch your observations.
2. Observe what happens when the waves emitted simultaneously by two point sources near each other interfere. Use two pipettes or two pencils held together by their points so as to form a double source. Vibrate the source rapidly near one side of the tray to set up the standing wave interference pattern on the surface of the water.

   If you look carefully, you can observe the patterns of constructive and destructive interference (nodal lines) that spread across the tray to the opposite side. Notice how they form a pattern that is much wider than the distance between the two point sources. Carefully sketch what you observe and label the lines representing constructive and destructive interference. What type of line is at the center of the pattern?

Now you try it

Investigate any other properties of one- or two-dimensional waves that you would like to know more about.

1. Write down a question in advance.
2. Describe what you did to answer it.
3. Describe the answer you found. Draw the result, if appropriate.

Thought question

If the tray had been filled with small particles instead of liquid, in what ways would particles behave differently from water waves in some of the above observations?

10. SPACETIME: A COMPUTER EXCURSION INTO RELATIVITY THEORY (CHAPTER 9)

Spacetime is a DOS program created by Professor Edwin F. Taylor and his students at MIT. It is used under license from Physics Academic Software, American Institute of Physics, College Park, MD.

STARTING AND EXITING THE PROGRAM

After you have started the computer and it has completed booting to Windows, click the Start button, then click Run. Type the location of the program, then click OK or press Enter. The program starts in a full-screen DOS window.

Make sure "1 Run SPACETIME" is highlighted, then press Enter twice. Then press any key.

You can exit the program at any time, by typing Q. Then hold down the Ctrl key and type C.

THE DISPLAY

The display you see is called the *Highway Display*. The large blank area in the middle of the window represents a "superhighway" running from left to right across the screen. Different lanes on the *Highway* are for objects traveling at different speeds. Objects lying on the horizontal line through the middle of the screen are on the center strip of the *Highway* and do not move. They are at zero velocity relative to the computer screen (and to you). Objects above the center move to the right; the farther above the center, the faster they move. Objects in the very top lane move to the right with the speed of light; only light flashes (and neutrinos) can occupy this lane.

Objects below the center of the screen move to the left; the farther below the center, the faster they move. Objects in the very bottom lane move to the left with the speed of light; only light flashes (and neutrinos) can occupy this lane.

The *Highway* convention is British, but modified; vehicles drive on the left side, but slow lanes are near the center strip, fast lanes are near the edge of the road.

To understand what appears on the *Highway*, think of a movie of all the objects traveling along the *Highway*. At any given instant, you are looking at a single "still picture" of the movie. As you change the time, you change the movie as you progress from one still to the next. You are going to learn how to make such movies and how to step time forward and backward through the stills of the movie.

A vertical ruler, at the left of the screen, shows β (Greek beta), the velocity as a fraction of the speed of light: $\beta = v/c$. β is also indicated at the bottom of the screen. The range of β extends from $+1$ at the top ($v = c$, light moving to the right), through 0 at the center, to -1 at the bottom ($v = -c$, light moving to the left). Notice that this is not a linear scale; equal vertical lane separations do not correspond to equal changes in β. This is done so that more of the interesting velocities near $\beta = v/c = 1.0$ can fit on the screen. The other parameter is called γ (gamma). It is equal to $1/\sqrt{1 - \beta^2}$.

The square object at the center of the screen represents the Earth. The vertical red line indicates the position $x = 0$. The number inside the Earth's square represents the time registered on a clock attached to the Earth. The Earth starts the position $x = 0$ at time $t = 0.0$. We'll let the units on the clock represent minutes.

You're now ready to start.

RELATIVITY OF LENGTH

Press R (for rod). A cross bar appears.

Press → several times to move the rod to the position $x = +4.0000$. You can see it on the x-axis, or read the position at the bottom of the screen.

Press Enter to set the rod at this position.

A rectangle appears representing a rod at $x = 4.0$ and $v = 0$ relative to the Earth.

We'll place a second rod at a different place:

Press R. A crossbar appears.

Press the up arrow to set $\beta = +0.9000$ (or $v = 0.9000c$), as indicated at the bottom of the screen.

Press ← several times to move the rectangle to $x = -4.0000$, also indicated at the bottom of the screen.

Hit Enter. Another rectangle appears.

It is a rod of the same length as the first rod when at rest on the Earth, but now we have a "snapshot" of the rod flying toward the Earth at $v = 0.9c$ as seen from the Earth.

Now let time move forward by holding down the up arrow. What has happened to this identical moving rod as seen from the stationary Earth?

Notice that there is an effect only on the length of the rod, not on its width.

Release the up arrow and press zero (0) to return to time 0.0 on the Earth.

Changing reference frames

Suppose you could jump from the Earth to the moving rod, so that you are riding at rest on it (at rest in its reference frame) and the Earth and the first rod are now moving toward you.

Will there be any change in the length of the first rod as measured by you? If so, what change?

Will there be any change in the distance between the Earth and the first rod? If so, what change?

Now let's make the jump:

Press F6 to select an object.

Press C to select the moving rod. A box appears around it to indicate selection.

Type J to jump to the frame of the moving rod. Now it's at rest on the center line and the Earth and first rod are in the speed lanes moving to the left.

What has happened to the length of the previously moving rod? Why?

What has happened to the length of the previously stationary rod? Why?

What has happened to the distance between the Earth and the rod moving with it? Why?

What has happened to the time registered on the Earth's clock?

(The reason for this is the relativity of simultaneity. A clock on the rod at rest and a clock on the moving Earth are not synchronized.)

Press the up arrow to let time move forward.

Return to time 0.0 by pressing 0.

Now jump (press J) to rod B, which is at rest relative to the Earth, and note your observations about the Earth and the other rod.

Trying different relative speeds

Press N twice to start over.

Now place rods at different distances from Earth and different speeds up to the highest + and − values for β you can obtain.

What happens to the lengths of the rods as β increases? Why?

What happens to the widths of the rods as β increases? Why?

What is the highest value for β that you can obtain? Why can't you go any higher?

RELATIVITY OF TIME

Press N twice to start over, with the Earth at rest in the center at $x = 0$ at time $t = 0.0$.
Press C (for clock). A crossbar appears.
Use the arrows to move it to $x = -4.0000$ and $\beta = +0.900$.
Press Enter to place the clock in this position.
Notice that the time indicated on the moving clock is not 0.0 but 8.3 min. Again, this is because of the relativity of simultaneity. We cannot synchronize a moving clock with a stationary clock.

Write the starting times of the Earth clock and the moving clock in the table below:

Table of clock readings. Clock is moving relative to stationary Earth.

	Start	*Stop*	*Elapsed time*
Earth's clock			
Moving clock			

Now press the up arrow to let time move forward on the Earth to 9.0 min as the moving clock flies to the right past the Earth at speed $v = 0.9c$.
If you pass 9.0, move time backward by pressing the down arrow (unfortunately not possible in real life).
Record the new clock readings in the above table and obtain the elapsed time recorded by each clock.
What do you conclude about the rate of the moving clock compared with the rate of the Earth's clock at rest?

Changing the reference frame

Suppose you jumped from the Earth to the moving clock, so that you are riding at rest on it (at rest in its reference frame) and the Earth is now moving toward you.

From this perspective, will there be any change in the rate of the two clocks from what you just observed? If so, what change do you predict?

Let's make the jump, as before.
Press 0 to go back to time 0.0 on the Earth's clock.
Press F6 then B to select the moving clock (B).
Jump to the moving clock by pressing J.

You now have a still picture of the previously moving clock, which is now at rest in your reference frame on the center line, with the Earth and its clock moving toward you from the right.

Again the two clocks are not synchronized, and you can see a contraction in the distance between your clock and the Earth.

Record the starting time on the two clocks in the table below:

Table of clock readings. Earth is moving relative to stationary clock.

	Start	*Stop*	*Elapsed time*
Earth's clock (moving)			
Stationary clock			

- Now let time move forward for a while by pressing the up arrow. *Stop the motion before the Earth goes off the screen.*
- Record the new clock readings in the above table and obtain the elapsed time recorded by each clock.
- What do you conclude about the rate of the clock on the moving Earth compared with the rate of the clock at rest relative to you?
- Compare your two observations of the rate of time as measured from the two reference frames of the Earth and the clock. Is there a contradiction, or are they consistent with each other?
- When you are finished, press N twice to return to the opening screen.

OPTIONAL

A TRIP TO ALPHA CENTAURI: THE TWIN PARADOX

Now let's take a longer trip. The visible star nearest to our Sun is Alpha Centauri, about 4 light years distant. You will remain on Earth while your identical twin will travel on the Space Shuttle at a speed of $v = 0.9c$ to Alpha Centauri and back. Assume that the distance units on the x-axis display are light years and the time units on the clocks are years.

- As before, the reference clock in the center of the start-up screen represents Earth.
- Press C, then use the up arrow, and Enter, to place a second clock, representing Alpha Centauri, on the center strip ($\beta = 0$) at a distance of 4 light years to the right of Earth ($x = +4.0$).

(Notice that this time the two clocks are synchronized, since they are at rest relative to each other.)

Now prepare the Space Shuttle for the trip to Alpha Centauri.

Press S (for Space Shuttle) and use the up arrow to move the Space Shuttle straight up to the speed lane $\beta = +0.900$ at the Earth's position, at $x = 0.0$.

Press Enter to create the Space Shuttle.

Press the up arrow four or five times to step time forward. Watch the Space Shuttle move toward Alpha Centauri from you position on Earth. Note that its clock runs slower than the clocks at rest, as we expect.

We need details of the Space Shuttle's position in order to line it up with Alpha Centauri. Get the Space Shuttle details this way:

- Press F6, then press S to select the Space Shuttle.
- When the box appears around the Space Shuttle, press I for information.
- Details of the Space Shuttle's position, speed, and time will appear across the bottom of the screen. This information is updated as you move the Space Shuttle toward Alpha Centauri.

Keep changing time until the Space Shuttle is approximately lined up with Alpha Centauri (when its position is approximately $x = 4$ as shown at the bottom of the screen). The lineup with Alpha Centauri will not be perfect, actually $x = 4.0500$.

Now we need to turn the Space Shuttle around by placing it in a lower lane so that it can head for home.

Press P. A crossbar appears at the position of the Space Shuttle.

Move the cursor down with down arrow key until it is in a lane below the center strip with $\beta = -0.900$. (Note the minus sign.)

Press Enter, when you get to the correct lane.

Now the Space Shuttle is turned around and ready to head for home.

Press the up arrow to move time forward again.

Bring the Space Shuttle back to Earth ($x = 0$).

Welcome your twin home after all this time.

Read the number of years on the Earth's clock and the number of years on the Space Shuttle's clock. These are the number of years that have passed for each clock.

Earth's clock: ____________________________

Space Shuttle's clock: ____________________

Who has aged less: you or your twin, the Space Shuttle pilot?

But wait a minute. Your twin could say that he or she had actually gone nowhere, but that it was the Earth that had flown 4 light years away and returned. So, when you return, riding with the Earth, it is you who should be younger, not your twin.

Obviously you both can't be younger. So who's right? This is a way of phrasing the so-called *Twin Paradox.*

Let's try to see this from your twin's perspective.

Press 0 to reset the time to zero.
Press F6, then S to select the Space Shuttle, if it's not already selected.
Press J to jump to the Space Shuttle.

Now the Space Shuttle is at rest with respect to you on the center line at $x = 0$. Earth is lined up just below you, at $x = 0$ but in a leftward-moving lane. Alpha Centauri is in the same lane as Earth, but farther to the right.

Earth and Alpha Centauri are moving in your rest frame; therefore, the distance between them is contracted, just as the length of a moving rod was contracted.

Now hold down the up arrow to replay the movie of the earlier trip to Alpha Centauri and back to Earth, this time while riding on the Space Shuttle.

The Earth will turn around automatically and return to the Space Shuttle.

The Earth is always the object to the left of Alpha Centauri. Try to line it up just above the Space Shuttle in the center of the screen.

The motion is very rapid because the distances are contracted. If you want to repeat the motion, press 0 (zero), then the up arrow.

Now what are the times registered on each of the clocks?
Which twin would be younger?

How can we resolve the twin paradox?

The answer is that the two situations are not quite identical. There is a crucial difference between the motion of the twin who left on the Space Shuttle and the motion of the twin who stayed at home. The twin who stayed at home remained at zero or constant velocity for the entire time. But the twin who left on the Space Shuttle had to turn around, and when the Space Shuttle turned around, he or she experienced an *acceleration*. Because of the acceleration both twins can then determine that it was really the one on the Space Shuttle who traveled while the other one stayed at home. Therefore the traveling twin will be younger.

11. EXPLORING ELECTRIC CHARGES, MAGNETIC POLES, AND GRAVITATION (CHAPTER 10)

A. Comparing the Three Forces

- In what ways are the gravitational, electric, and magnetic forces similar to one another?
- In what ways are they different?

1. Your instructor will provide you with a variety of small objects to subject to electric, magnetic, and gravitational forces. By observing what happens in each case, you will be able to draw some conclusions in answering the above questions.
2. In order to organize your observations, construct a table in your notebook with four columns. Label the first column "Objects" and list all of the objects you have. Label the other columns "Gravitational Force," "Electric Force," and "Magnetic Force."

Gravitational force

1. How could you determine whether or not an object is subject to the gravitational force of the Earth? In the second column of your table, indicate which of the objects is subject to the gravitational force downward toward the Earth.
2. Was there anything you had to do to initiate the gravitational force to act on the objects?

Electric force

1. Separate the objects from each other. Rub the clear plastic (acrylic) rod with the silk, or the dark plastic (delvin) rod with the fur. Pass the rod over each object and observe what happens. If there is an attraction upward, this is the result of an *electrical interaction* between the rod and the object. The upward motion is due to an *electric force*. Indicate in your table which objects respond to an electric force.
2. Compare the electric force upward to the rod with the gravitational force downward to the Earth. Which force is stronger?
3. Is it possible that the electric force is actually due to a gravitational attraction of the objects to the rod? Explain.
4. Was there anything you had to do to initiate the electric force?

Note: The term *charge* is used to describe the property of an object that enables it to engage in electrical interactions with other objects. Notice that the other object does not have to be charged, although it can be. You'll see examples later in this investigation.

The rubbing of the rod produces a build up of charge on the rod. This charge is often called an *electrostatic charge*, since the charge is static (not moving). You encounter an electrostatic charge when you experience electrostatic cling on a cold day with low humidity, or after running a comb through your hair. Humidity enables the charge to escape from the rod by clinging onto water molecules in the air. The charge can be produced again by rubbing (friction).

Magnetic force

1. Perform the same test on the objects as you performed with the electric force, only this time use the bar magnet. Write your results in the table.
2. What do you conclude from your results about the types of objects that are subject to the magnetic force? What types of objects are not subject to the magnetic force?
3. Compare the magnetic force upward to the bar magnet with the gravitational force downward to the Earth. Which force is stronger? Explain your reasoning.
4. Is it possible that the magnetic force is actually due to a gravitational attraction of the objects to the magnet? Or an electrical attraction of the objects to the magnet? Explain in each case.
5. Was there anything *you* had to do to initiate the action of the magnetic force?

Conclusions

On the basis of your observations so far, as recorded in your tables and in your answers to the questions, answer the two opening questions:

- In what ways are the gravitational, electric, and magnetic forces similar to each other?
- In what ways are they different?

B. Like and Unlike Charges

- How many types of electric charges are there?
- How do they alter the direction of the electric force?

1. You can easily generate an electrostatic charge by pulling a piece of Scotch tape off a clean dry surface. Take a piece of Scotch tape, about

5 to 8 cm in length. Bend the end of it over to form a little "handle." Tape it onto a clean table top or other surface, then peel it off briskly and stick it to the crossbar, just below the "handle." Be careful not to let the tape curl back to touch your hand or any other object. If it does touch another object, or if you need to recharge it, simply stick it again to the surface and briskly peel it off.

2. After you have prepared one tape, prepare a second tape pulled from the same surface. Bring it near the first tape (sticky sides facing away). What do you observe?
3. Construct a table listing at least three different surfaces—such as wood, glass, plastic—in the first column, and the same surfaces across the top. Now compare strips pulled from the same and different surfaces, and record your results in the table. Do not let the strips touch each other.
4. Strips that are pulled from the same surface always have like charges, since they are prepared in exactly the same way. What do you conclude about the electric force between like charges?
5. Strips pulled from different surfaces usually may have unlike charges. What do you surmise from your observations about the force between unlike charges?

How many?

Let's see if we can determine how many different types of charges there are.

1. You can create unlike charges by again using Scotch tape. Stick one piece of tape (with a handle) to a surface. Then stick another piece directly over it. Keeping both pieces stuck together, briskly pull both pieces of tape together off the table. Now carefully separate the two pieces. Do not allow them to curl back to your hand or to touch each other after separated.

   After they are separated, bring the two strips near each other, back to back. What do you observe?
2. What does your observation tell you about the nature of the charges on the two strips? (Repeat this again, until you are convinced of your conclusion.)
3. If you found these charges to be unlike and mutually attracting, you can use them to test other charges. To do so, prepare another two strips of unlike charges and place them carefully on the crossbar. Replace or recharge them as necessary in the following.
4. Construct a table with different charged objects in the first column and Strip 1 and Strip 2 in the next two columns. Bring the charged clear and plastic rods (using silk and fur, respectively) near each strip and

observe what happens. Do not touch the strips with the rods. Try charging other objects, such as a balloon or a comb, by friction and bring each one near the charged strips of Scotch tape. Observe whether the interaction with the strip is attractive or repulsive with each strip. Be sure that each object is indeed charged. Record the result in your table.

Conclusions

1. Carefully examine your table. What conclusions can you draw from this?
2. Is there any charged object that repels or attracts *both* strips?
3. If a charged object attracts one of the two strips, what does it do to the other strip. Is there any exception to this?
4. You saw previously that like charges always repel. What do your observations say about unlike charges?
5. What do you conclude from your observations about the number of different types of charges? Support your conclusion.

   Note: By agreement, the two different charges have been called "positive" and "negative." But they could have been called "red" and "green," or "up" and "down," or any other names. Ben Franklin chose "positive" and "negative" for various historical reasons. The "positive" charge has been defined as the charge produced on the clear rod when rubbed with silk. The negative charge is defined as the one produced on the dark plastic rod when it is rubbed with fur.

   The electrical interaction between these types of charges is either attractive (between unlike charges) or repulsive (between like charges).
6. How would you now answer the opening questions to this section, and what evidence would you use to support your conclusions?
   - How many types of charges are there?
   - How do they affect the attractive or repulsive nature of the electric force?

C. Neutral Objects

You have learned that all matter is made up of atoms, which contain charges inside them. However, the atoms themselves are usually neutral, because the positive charge of the nucleus is exactly balanced by the negative charge of the electrons orbiting the nucleus. Some materials can have some of their electrons removed when they are rubbed with another material. This is how objects are made to carry net electric charge.

A neutral object has no charges added or removed, so it has a net charge of zero. This does not mean that it has no charge in it. It simply means that the numbers of like and unlike, positive and negative, charges are equal.

What happens when you bring a charged object near a neutral object?

1. To find out, attach the aluminum ball on the thread to a crossbar and bring a charged rod near it but without touching the ball. What do you observe?
2. Now bring the other type of rod (with an opposite charge) near the ball. What do you observe?
3. Does this violate our recent conclusion that "we have never found a charged object that either attracts or repels both of the two strips that attract each other"?

   Note: The answer is no. The key word in the conclusion is *charged* object. The object tested is a neutral object, one without net charge. What is happening here is that the charged glass rod (positive) is attracting the negative charges in atoms of the ball, and repelling the positive charges. The negative charges move toward the front of the ball, and the positive charges toward the back. Because the electric force is proportional to $1/r^2$ (see Section 3.4), the attractive force is stronger than the repulsive force, because the negative charges are closer (r is smaller) to the positive glass rod than the positive charges.
4. Make sure the ball is electrically neutral by holding it in your hand for a moment. Charges from your hand will cancel out any net charge on the ball. Recharge the dark plastic rod with the fur and this time touch the ball, after bringing it close. Carefully observe what happens before and after you touch the ball.
5. How would you explain this?

   Note: Remember, the clear rod charged with silk is (by definition) positive, so negative charges are drawn to the front of the ball. When the rod touches the ball, some negative charges move to the rod, leaving behind a ball that now has a net positive charge; the ball is then repelled by the positive rod.
6. To test this explanation, try the experiment again. This time, bring the negatively charged plastic rod (the dark plastic rod rubbed with fur) near the ball. What do you observe?
7. Does this agree or disagree with the explanation?

D. Magnets

Now let's look at some of the similar properties of magnets.

Properties

1. Using two bar magnets, examine the attractions and repulsions between the ends as well as the middle of each magnet. Be careful to experience

yourself the actual push and pull. If the magnets are strong enough, attempt to experience why scientists (such as Faraday) believed that there is a “field” that exerts the repulsion. Lift up one magnet by the other. What does this say about the strength of gravity on the magnet compared to magnetism?

Like and unlike poles
How many poles does a magnet have?

2. To find out, tie one magnet in the middle and hang it from the crossbar. Place a sticker near one end of the magnet to distinguish the two sides. Now bring one end of the other magnet near the marked end. What do you observe?
3. Now bring the other end of the magnet in your hand toward that end. What do you observe?
4. Repeat this for the other end of the dangling magnet, and record your observations.
5. Is there any side to a magnet that attracts both ends of another magnet or repels both ends?
6. Is there any end of a magnet that attracts one end and does not repel the other?
7. What do you conclude from this?

   Note: The end sides of a magnet are called the *poles* of the magnet. As with charges, like poles repel and unlike poles attract. One pole is called the “north” pole and the other pole is called the “south” pole. There was a good reason for this. As discussed in Section 10.1 of the text, Gilbert discovered that the Earth itself is a magnet. The end of the magnet that seeks the geographic North Pole of the Earth is called the “north-seeking pole.” It is actually the “south pole” of the magnet. The pole that seeks the Earth’s South Pole is the magnet’s “north pole.”
8. Using the little compass, determine the directions of north, south, east, and west in your room. Be sure that you are far away from any nearby magnets. Now compare the approximate alignment of the dangling bar magnet with the geographic directions. (Be sure the string is not twisted.) Use a piece of tape to indicate which end of the bar magnet is its north pole and which is its south pole.
9. To continue the investigation in Part A, do magnets have an effect on the electrically charged Scotch tapes? Prepare Scotch tapes with unlike charges and see if there is any effect. What do you conclude from this about the electric and magnetic forces?

E. Magnetic Fields

You may already have experienced the repulsion generated by the magnetic field between the opposite poles of two bar magnets. Can a thin piece of material block the magnetic field?

1. To find out, place a sheet of paper vertically near the dangling magnet, then bring the other bar magnet close to the first magnet but behind the sheet of paper. Does the paper block the field?
2. Try some other objects, such as aluminum foil, glass, a piece of copper, or steel, a hand, etc. Which ones block the field and which do not?
3. You can trace out the field by using iron filings spread over a transparency or a piece of paper lying on top of the magnet. *Do not put the filings directly on the magnet(s)*. Sprinkle the filings over the transparency lying on top of a single bar magnet and sketch the result.
4. Place two like poles near each other. Place a sheet of paper or a transparency over the region between them and use the iron filings to sketch the result.
5. Do the same with unlike poles near each other, but not touching.
6. What are the characteristics of the field for attraction and repulsion?

Mapping the field

1. The magnetic field is a vector, and you can "map" the field near a bar magnet by using a small compass. The direction of the magnetic field at any point is defined as the direction in which the north pole of a compass at that position is pointing. The compass needle is tangent to the magnetic field line at that position. Note that the end of the compass that points to the magnetic north of the Earth is actually the south pole of the compass needle.
2. Using the small compass, plot the magnetic field at various positions around a bar magnet and draw your result. Indicate the direction of the field at each position, and the north and south poles of the bar magnet. Draw your result here.

12. INVESTIGATING ELECTRIC CURRENTS I (CHAPTERS 10, 16)

A. Let There Be Light!

You are given a battery, a light bulb, and some wires. The battery has a voltage of only 1.5 V and will not cause a shock or any harm to you.

Working together, think of the right arrangements ("circuits") to get the light bulb to light; then try them.

Sketch each arrangement that you try, including those that do not work.

When you find an arrangement that works, try to find another, similar arrangement that will also work.

Conclusions

1. What is the common feature of the arrangements that work?
2. What is the common feature of the arrangements that do not work?

B. The Bulb and Battery Holders

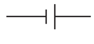
For convenience in making electrical connections, bulbs are usually screwed into sockets and batteries placed into holders.

1. Carefully examine the bulb socket and the battery holder. Then place the bulb and battery into their holders and hook up the wires to obtain the lighted bulb. Include a switch in order to open or close the "circuit."
2. Why is this arrangement called a "circuit"?
3. The protrusion on one end of the cylindrical battery is the positive end of the battery. The flat rear side is the negative end. Sketch the circuit again and trace the current flow through the circuit from the positive end of the battery through the switch and bulb and back to the negative side of the battery.

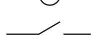
Note: The current enters the bulb through the pointed metal protrusion at the base, and it leaves through the metal threads of the base that are screwed into the holder.

C. Circuit Diagrams

Instead of drawing realistic sketches, engineers have invented a way of diagraming circuits that includes special symbols for each component in the circuit. Here are some of the symbols and the components they represent:


a DC battery or power source; the long line represents the positive side.


a light bulb.


a switch.

This is what a light bulb circuit would look like with these symbols:

Here are some circuit diagrams:

1. In which of the above diagrams would the light bulb light after closing the switches? In which one would it not light?
2. How can you tell from a circuit diagram whether or not the bulb will light?
3. What do the terms "closed circuit" and "open circuit" mean?

   Here are several more electrical symbols and the objects they represent:

   a resistor.

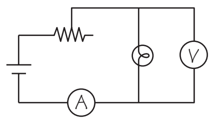
   a variable resistor (allows changing the resistance).

   a voltmeter (measures the potential difference in volts).

   an ammeter (measures the current in amperes).

4. Use the circuit board, the bulb holder, and other components to make the following circuits.

   In each case the bulb should light. If it does not light, check to make



6. Using Ohm's law, $V = IR$ (V is potential difference in volts, I is the current in amperes, and R is the resistance in ohms), obtain the resistance of the light bulb from your circuit.

Please note:

(a) If you are using analog meters, the ammeter and voltmeter have positive (red post) and negative (black post) sides. In any circuit, the positive side should always be closest to the positive side of the power source. If this is reversed, the needle on the scale will go in the negative direction, and may be damaged.

Therefore, when you close the switch, watch the needle. If it goes negative, instantly open the switch and reverse the leads to the meter.

(b) Each of the meters has scales for different amounts of current and voltage. If you close the switch and the needle is pinned to the right, off the scale, instantly open the switch and transfer the meter to the highest scale.

D. The Light Bulb's Power

After you have found the resistance of the light bulb, you decide to apply your result to the useful task of finding out how much power the bulb consumes. You remember from the text that the power output is the square of the current times the resistance

$$P = I^2R.$$

1. For the current you are using, what is the power output of the bulb? Show your work.
2. You leave the bulb on for 10 s. How much energy is released by the bulb?
3. Is this energy all in the form of light energy, or is it converted into other forms of energy? How do you know?

E. Thought Questions

1. An insulator does not allow any significant current to pass through it. What is its resistance?

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2. A superconductor allows all of the current to pass through unhindered. What is its resistance?
3. Voltage is the amount of work required to move a charge from one point to another. Why does a larger resistance require a larger voltage to yield the same current?

13. INVESTIGATING ELECTRIC CURRENTS II (CHAPTER 10)

IDEAS

In electricity there are two concepts that are basic to all other studies. These are voltage (potential difference) and current. The first refers to the work necessary to move a unit of positive charge from one point to the other; the second refers to the amount of electric charge that is transported per second between the two points in question. One is measured in volts, the other in amperes. One ampere is 1 coulomb per second.

Is there a relationship between the voltage and the current between two points? In 1851 Georg Ohm discovered that there is. If one measures the voltage on and the current through several objects, such as a copper wire, a salt solution, and a bar of silver, no relationship seems to exist between the measured volts and amps. However, by keeping the copper wire as a constant factor and varying the amount of voltage, while noting the amount of current that flows through the wire, Ohm found a simple relationship, known as "Ohm's law," between the volts and amps for the copper wire. According to this law, the voltage is directly proportional to the current, where the constant of proportionality is the resistance.

This may be expressed in symbols as follows:

$$V \propto I \qquad \text{or} \qquad V = IR,$$

where V is the voltage, I is the current, and the constant R is the resistance of the wire. Resistance is measured in units of "ohms," 1 Ω, whereby 1 Ω = 1 V/A. We will test this relationship and utilize it in today's experiment.

We are going to follow the way actual research is done when a new law is proposed. First, in Part I, you will test the law to see if it is valid. Then, in Part II, you will assume it is valid and make predictions to see if they are accurate. Once Ohm's law has passed those two tests, we can be so confident it is valid that we can use it to explore the unknown (Part III)—in this case the value of unknown resistances.

INVESTIGATION

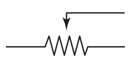
Materials: 12-V power source, switch, variable resistor (rheostat), ammeter, voltmeter, resistors, connectors, circuit board.

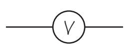
The following symbols are used:

 a DC power source; the long line represents the positive side.

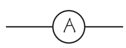
 a resistor.

 a switch.

 a variable resistor (rheostat).



a voltmeter.



an ammeter (mA refers to milliamps or 10^{-3} A).

Before you begin, please note the following concerning the circuit components (assuming you are using analog meters):

- Always leave the switch open while wiring the circuits. Do not close it until the instructor has approved the wiring connections.
- The voltmeter and ammeter have a positive and a negative side. In any circuit, the negative side should always be closest to the negative side of the power source. This is also indicated in the circuits later in these instructions. If you should close the switch and the needle moves to the left, instead of to the right, instantly open the circuit and reverse the leads to the meter.
- Each of the meters has scales for different amounts of current and voltage. In most cases here, the scale to be used is indicated. If it is not, or you are uncertain which scale to use, always start with the scale for the largest amount of voltage or amperage and decrease in sequence as necessary. Also, if you close the switch and the needle is pinned to the right of the scale, quickly open the switch and transfer to a higher scale.
- To help keep the positive and negative sides of the circuit apparent, the circuit board has black and red binding posts. As is standard in electrical equipment, the *black signifies negative, and the red signifies positive.*

The variable resistance, or rheostat, is used not only to vary current in the circuit, but also to protect the meters and other components from an overload. The principle of the rheostat is that the longer the length of wire that the current from the battery must transverse the more the resistance. The length of the wire, hence the resistance, is controlled by the slide wire at the top. When the rheostat is connected at the lower left corner and the top right, all the way to the right is maximum resistance; all the way to the left is minimum resistance. To begin with, slide the wire all the way to the right for maximum resistance (hence minimum current in the circuit).

PART I. OHM'S LAW

You are a researcher in your school's laboratory and Dr. Ohm has just reported in the latest journal that he has concluded from his research that the current and voltage are related to each other for these types of resistors according to the simple relationship

$$V = IR$$

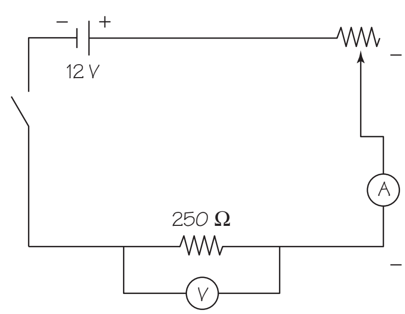
which he is calling "Ohm's law."

You are very excited to read of his discovery, because it relates the three basic electrical properties so simply. However, being a good scientist, you want to check it out for yourself before you accept it.

Here is one way to test to see if Ohm's law is indeed valid.

1. Connect the circuit shown below, placing the power source, open switch, rheostat, 250-Ω resistance, and ammeter in series (i.e., on one continuous line). Note that the voltmeter is connected in parallel with (or across) the resistance being studied. Place the transformer on 12 V, positive (+) polarity. Be sure that the little red light is lit. Do not close the switch until the instructor has approved the wiring.

   Use the *50-mA scale* on the ammeter and the *15-V scale* on the voltmeter.



2. Slowly decrease the variable resistance until the ammeter reads almost full scale. Take six readings of the potential difference across

the 250-Ω resistance and the current through it as the variable resistance is increased.

Reading #	*Voltage* (V)	*Current* (I)
1		
2		
3		
4		
5		
6		

3. To see any regularity in the relation of V and I, plot your values of V and I on a sheet of graph paper, with V on the y-axis and I on the x-axis.
4. Note that, as printed on the resistors, the resistors are accurate only to ±10%. Within this limit of precision, do you see a smooth pattern?
5. If your graph is a straight line, what does this tell you about the relationship between the variables V and I?
6. If your graph is a straight line, find the slope of the straight line and compare with what you would expect the slope to be from Ohm's law.

   Expected result:

   Slope:

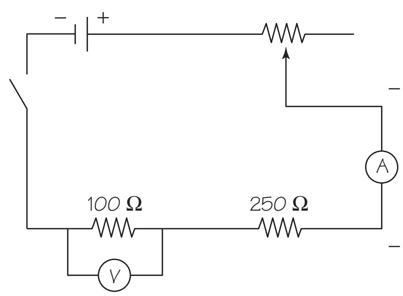
7. Do your data confirm or refute Ohm's law? Explain.
   Turn in your graph with your laboratory report.

PART II. SERIES CIRCUITS

Now that you have tested the validity of Ohm's law, you will want use it to make predictions about series circuits and see if these predictions agree with the observed phenomena.

Two circuit elements are in series if they are connected end to end in a continuous line.

1. Connect the circuit below, this time with the 100-Ω resistor in series with the 250-Ω resistor. Put the variable resistance at maximum before closing the switch. Leave the voltmeter disconnected for the time being. Use the **50-mA scale on the ammeter** and the **15-V scale on the voltmeter.**



2. By changing the variable resistor, *set the current at 25 mA*.
3. Knowing the resistance of each resistor and the current through each one (25 mA), use Ohm's law to predict the voltage drop across each resistor and across both resistors together. Note that they should *not* be the same (why not?), even though the battery voltage stays constant. Show how you got these results in the table below.
4. Now measure the voltage drop across each resistor and across both of them together.

Voltage	*Predicted*	*Observed*
V_1		
V_2		
$V_1 + V_2$		

THOUGHT QUESTIONS

1. So far we have tried one resistance and two resistances in series. Can you make an inductive generalization about Ohm's law—that is, about the relationship between V and I—for any number of resistors in series? Write this as an equation.

PART III. STUDYING UNKNOWN RESISTANCES

Now that you have tested Dr. Ohm's conclusions and used his new law to make predictions that are confirmed by actual measurement, you are confident enough of the validity of Ohm's law to use it as a tool to explore the unknown.

1. In this case the unknown consists of two conductors of electricity with resistances unknown to you. They are a unknown resistor and a con-

ducting solution. Using the equipment available to you, try to determine the resistance of each of these conductors without asking the instructor. Show any calculations you make. Ask the instructor if you are stuck.

Resistance of unknown resistor:

Resistance of conducting solution:

2. Leave the circuit connected for a while to the salt solution. Carefully observe and note everything that you see occurring in the solution.

THOUGHT QUESTIONS

1. An insulator does not allow any significant current to pass through it. What is its resistance? Explain using Ohm's law.
2. A superconductor allows all of the current to pass through unhindered. What is its resistance? Explain using Ohm's law.
3. If voltage is the amount of work required to move a charge from one point to another, why does a larger resistance require a higher voltage to yield the same current?

14. AVOGADRO'S NUMBER AND THE SIZE AND MASS OF A MOLECULE (CHAPTERS 7, 13)

INTRODUCTION

The acceptance of Avogadro's hypothesis enabled the determination of the relative masses of many atoms and molecules. Atomic weights and molecular weights (really "masses") were defined in terms of an accepted standard. The isotope ^{12}C was chosen as the standard and an atom of this isotope was defined as 12.000 u, where u is the standard symbol for atomic mass units (amu).

If the weight of an element is known in amu, then the same number of grams of that element or compound is called the gram atomic weight or the gram molecular weight. Each of these contains a standard "package", or mole, of atoms or molecules. One gram mole of ^{12}C contains a mass of 12.000 g.

It is a fact of nature that 1 g-mol of every substance contains the same number of atoms or molecules. The name *Avogadro's number* was given to the number of molecules or atoms in 1 g-mol. ("Loschmidt's number" refers to the number of atoms in 1 kg-mol). This number has been determined to be 6.02×10^{23}. Thus, for example, 1 g-mol of water, H_2O, would have a gram molecular mass of 2 (H) + 1 (O), or 2 (1.0080) + 1 (15.999) = 18.015 g. Thus, this small amount of water would contain 6.02×10^{23} water (15.999) = 18.015 g. Thus, this small amount of water would contain 6.02×10^{23} water molecules. As you see, Avogadro's number is extremely large, because atoms and molecules are extremely small.

Avogadro's number has been determined by various methods, all of which yield the same results, within the limits of experimental error. The method we shall use, although relatively primitive, yields surprisingly good results which are of the right order of magnitude (power of ten) if the experiment is carefully performed. It utilizes an interesting property of certain large molecules, such as fatty acids. If a drop of fatty acid is placed on the surface of water, it will spread out to form an extremely thin film on the surface of the water. Observations of this sort were recorded as long ago as 1773 by Benjamin Franklin, who noted that one teaspoon of oil spread out to form a film of about 22,000 ft^2 on a pond near London.

That this extremely thin film is probably the thickness of one long-chain molecule may be demonstrated by placing a wire across the surface of a shallow container filled to the brim with water, and allowing a drop of oil to fall on the water to one side of the wire. The oil will spread out over the water surface and attach itself to the wire and to the edges of the container because of intermolecular forces. If the wire is moved to stretch the film, the film breaks in places, and islands of water are visible.

Stearic acid and oleic acid, because of their large intermolecular forces, and their uncomplicated straight chain structure, are often used to study single-molecule films. In this experiment, the fatty acids used must be quite dilute. One drop of *pure* oleic acid will cover a water surface of about 200/m^2 (about 2000 ft^2)!

In this experiment the concentration of oleic acid used is only 0.25% (by volume). The thickness of the film, which is the thickness of one molecule, can be calculated from a measurement of the size of the film made by one drop and a knowledge of the volume and concentration of the drop. If the simplifying assumption is made that the molecules are cubes, than the volume of one molecule can be calculated from the size and thickness of the film. Avogadro's number can be obtained from the known density of oleic acid and its gram molecular weight. Finally, the mass of one molecule can be obtained from Avogadro's number and the molecular weight.

Note: Since we will be multiplying and dividing numbers expressed in scientific notation, do not perform this investigation until you have reviewed the section on scientific notation in the Mathematics Review.

Equipment
Cafeteria tray, medicine dropper bulb, micropipet, 25 ml Erlenmeyer flask and stopper, 10 ml graduated cylinder, powder, 0.25% (volume) solution of oleic acid in methyl or ethyl alcohol.

INVESTIGATION

1. Withdraw about 5 ml of the oleic acid solution from the stock bottle and place in the clean, dry Erlenmeyer flask. Keep this closed with the stopper, when not in use. Otherwise the alcohol will evaporate, changing the concentration of the oleic acid.
2. In the following, use only the micropipet, *not* the medicine dropper. Determine the volume of one drop of oleic acid solution delivered by the micropipet. This can be done by first placing exactly 2 ml of this solution in the 10 ml graduated cylinder. Then count the number of drops necessary to increase this volume to exactly 3 ml. 1 ml is equal to 1 cm^3. In reading the volume, hold the cylinder at eye level and measure to the bottom of the miniscus.
3. Add tap water to the tray until it is completely covered with water up to the rim.
4. Evenly dust the surface with a very thin layer of the powder. The powder makes the boundaries of the oleic acid film easily visible. However, if there is too much powder, it prevents the oleic acid from spreading out completely. Try not to breathe in this powder.
5. Discard the first drop. Then put one drop of oleic acid solution on the surface of the water and wait about 30 s. The alcohol in the solution will evaporate upward and dissolve downward into the water, leaving a layer of pure oleic acid.
6. Measure the diameters of the film in two directions at right angles, record, and average.

DATA AND ANALYSIS (IMPORTANT: YOU MUST SHOW YOUR WORK.)

1. Number of drops in 1 cm^3 of 0.25% oleic acid solution.
2. Volume of one drop of oleic acid solution (in units of cm^3).
3. Volume of pure oleic acid in one drop. This value takes into account the fact that only 0.25% of the volume of the drop is actually oleic acid.
4. Diameters of the film (in cm) in two perpendicular directions.
5. Average diameter and radius of film (in cm).

6. Area of film, assuming a circle

$$A = \pi r^2$$

$$= \quad ,$$

7. Thickness of the film $= \dfrac{\text{volume of the acid}}{\text{area}}$

$$= \quad .$$

8. *Volume of one molecule*, assuming the molecules are cubes and that they are in contact with each other. The thickness of the film tells you the length of the edge of the cube.
9. Gram molecular weight of oleic acid as determined from its formula, which is $C_{18}H_{34}O_2$. Consult the periodic table.
10. Volume occupied by 1 mol of oleic acid. This can be determined from the density (0.098 g/cm^3) and the gram molecular weight.
11. *Avogadro's number:* The number of molecules in 1 mol, assuming the molecules are cubes. This is determined by knowing the volume of one molecule and the volume occupied by a mole of molecules.
12. Write down the accepted value of Avogadro's number.
13. *Mass of one molecule*, determined from your value of Avogadro's number and the molecular weight.

THOUGHT QUESTIONS

1. How do the measured and accepted values of Avogadro's number compare? Note that since we are dealing with such large numbers and making such great assumptions, good agreement is attained if the numbers are within a "ball park" of each other (i.e., within a power of 10).
2. Define Avogadro's number in words.
3. In this experiment, we made a number of simplifying assumptions. What were some of these assumptions? Which were the most important? How would each of these assumptions influence our calculation of Avogadro's constant?
4. To gain an idea how tiny a molecule of oleic acid really is, how many molecules would you have to line up end to end to make 1 mm of length, the smallest interval on a meter stick? Assume the molecules are cubes and use the length of one side determined in Exercise 7.
5. To gain an idea how enormous Avogadro's number is, assume that each molecule of a mole of oleic acid is the size of a cube 1 ft on a side. If Avogadro's number of such cubes were placed into a cubic box,

how long would one side of the box be in feet and in miles (1 mi = 5000 ft)? *Hint*: First find the volume of the box, then find the length of one side by taking the cube root. Compare your result to the size of the Earth (diameter about 8000 mi).

ADDITIONAL INVESTIGATIONS

The following "mini-laboratories" may be utilized or extended to serve as major explorations pertaining to the latter chapters of the textbook.

- ***How Do We Know That Atoms Really Exist? The Brownianscope*** (Chapter 13).
- ***Light and Color*** (Section 14.1).
- ***Spectroscopy*** (Chapter 14).
- ***Radioactivity and Nuclear Half-Life*** (Chapter 17).
- "The Photoelectric Effect," an investigation using light and an electroscope, described by P. Hewitt, in *Conceptual Physics Laboratory Manual* (Boston, MA: Addison-Wesley), pp. 305–307.