LABORATORY EXPLORATIONS

Physics is an experimental science. With few exceptions, the great advances in physics have arisen in close association with experimental evidence. Direct, hands-on experience with the phenomena is essential to understanding concepts in physics.

GOALS OF THE LABORATORY EXPLORATIONS

Most of you will be pursuing careers in fields other than physics, perhaps in other sciences: medicine, the liberal arts, business, or teaching. Whatever your personal goal, these explorations will provide a useful introduction to the fundamental principles of physics and to the principles underlying experimentation of any kind. Here are some of the goals of the laboratory work:

- *Conceptual Learning.* The explorations are meant to provide hands-on experience and to help reinforce some of the fundamental concepts you are learning in the other parts of the course.
- *Collaborative Learning.* Collaboration in small groups is a very beneficial way of learning. Working in groups should also help you develop collaborative skills that are vital to success in many lifelong endeavors.
- *Experimental and Analytical Skills.* During the course of this semester you will be making observations, recording measurements, analyzing experimental results, and drawing conclusions at various levels of sophistication, ranging from purely qualitative to highly quantitative.

Suggested Mini-Laboratory Explorations

1. OUR PLACE IN SPACE (SECTIONS P.2, 14.4)

Most drawings of the solar system are badly out of scale, because it is impossible to show both the sizes of the Sun and planets and their relative distances on an ordinary-sized piece of paper. Constructing a simple scale model of the distances and sizes of objects in the solar system will help you develop a better picture of the real dimensions of the solar system—in a sense, your greater home.

A. Scale of Distances

1. To begin, find a straight stretch of sidewalk, street, empty ball court, stadium, etc., that is at least 102 yd, or 60 m, in length. This can also be done on a football field or another open area having an equivalent length.
2. The table on the next page lists the radii of the orbits of all the planets, in miles and kilometers. Convert these distances to "scale" inches or centimeters, where 1 in = 1,000,000 mi, or 1 cm = 1,000,000 km.
3. Calculate the distance between planets, scaled to inches or centimeters. Using the new scale, measure and label strings to represent the distances between each pair of planets.
4. Beginning with the Sun, lay out the scale distances in the entire solar system on the sidewalk, street, field, etc., you have chosen, and mark the location of each planet. Include the Earth's moon, which is about 384,000 km, or 240,000 mi, from the Earth.
5. Survey your result and record your observations.
6. The nearest star to our Sun is Alpha Centauri. How far away from the Sun would this star be on your scale? (See Section 2 of the Prologue.)
7. Using the scale on a local map, or driving in a car or bus, find a landmark or building that is approximately at the position of Alpha Centauri on your scale.
8. What fraction of a light year is represented by the distance between the Earth and the Sun?
9. The distance to the farthest part of the visible universe, as observed by the Hubble Telescope in space, is about thirteen billion light years. How many inches or centimeters would this be on your scale? How many miles or kilometers would this be?

B. Scale of Sizes

Let a tennis ball about 7 cm in diameter represent the Sun. Since the diameter of the Sun is about 1,400,000 km, in this model 1 cm will represent about 200,000 km. The Earth has an approximate diameter of 13,000 km, so on this scale model it would have a diameter of only 0.065 cm. This is about the size of a pinhead.

The table below lists the approximate diameters of the planets and our Moon. Fill in the table, giving the approximate size on this scale. Try to find a sample object of this size, and use it in your scale model of distances.

C. The Size of An Atom (Section 14.4)

1. Using the same method as above, create a scale model of the distances involved in a hydrogen atom, the smallest atom. Use a handbook or ref-

A Scale Model of the Solar System

Object	*Solar Average Distance* *km* ($\times 10^6$)	*mi* ($\times 10^6$)	*(cm/in)*	*(approx. km)*	*Diameter Model (cm)*	*Sample Object*
Sun	—	—		1,400,000	7	Tennis ball
Mercury	58	36		4,600		
Venus	107	67		12,000		
Earth	150	93		13,000	0.065	Pinhead
Mars	228	141		6,600		
Jupiter	780	484		140,000		
Saturn	1408	879		120,000		
Uranus	2870	1780		48,000		
Neptune	4470	2790		45,000		
Pluto	5886	3674		1,300		

erences in the text to find the size of the nucleus (a single proton) and of an electron, and the radius of the first Bohr orbit of the electron.

2. Assign a reasonable scale to these measurements, then lay out the distance scales on the long sidewalk or street or field you have chosen.
3. Record your impressions of the result.

2. REVIEWING GRAPHS (CHAPTER 1 AND MAJOR LABORATORIES)

You may want to read first the section on graphs in the essay "Reviewing Units, Mathematics, and Scientific Notation."

The following table records the growth of a tomato plant from a seedling of zero height over a period of 7 weeks.

Week	*Approx. height (cm)*
1	7
2	14
3	22
4	29
5	35
6	42
7	50

1. Examine the data and draw some conclusions about the trend over the period of observation.

2. By inspection of these data, what would you expect the graph to look like?
3. Now make such a graph, or "picture," of the data by placing the week on the horizontal axis and the height on the vertical axis. The horizontal axis should be divided evenly into weeks, starting from 0. The vertical axis should also be divided evenly. Start the vertical axis at 0 cm. Make sure that the numbers (data) fill as much of each axis as possible without going beyond the end. Label the axes and their units.
4. Graph each pair of points and connect the points.
5. Describe in your own words what the plant did during this period. Was its growth exactly the same each week? What was the overall trend?
6. Do your observations of the graph in Question 5 agree with your expectations in Question 2?

You know from the study of graphs that any time you obtain a straight line, the two variables are considered to be "proportional," or in symbols: $y \propto x$. We can replace the proportional sign, $\propto$, by an equals sign, $=$, if we multiply the x variable by a constant. Call the constant m. So, instead of

$$y \propto x,$$

we have

$$y = mx.$$

If the line intersects the y-axis at the value $y = b$, then we have the equation

$$y = mx + b.$$

You may recognize this as the general formula for a straight line. How do we obtain the value of m? As you may recall, it is just the numerical value of the "slope" of the line.

7. The data points on your graph probably do not form an exact straight line, since the slope tends to vary slightly from week to week. However, we can find the "average slope" by choosing the slope between the first and last data points. Find this average slope.
8. Using your result for the average slope, and assuming an approximate straight line for the graph, write an equation for the approximate straight line. Extrapolate your data back to height at week 0. Including the y intercept, b, in your equation.

9. When a graph involves time on the x-axis, the slope has a special meaning. It tells us the *rate* that the y variable is changing, for example, in units of centimeters per second for speed, or centimeters per week week in our case. What was the overall rate of growth of the plant during this period?
10. You now have an exact equation for the height of the plant for the period of its recorded growth. Using your equation, what would be the height of the plant 4 weeks from the last data point, assuming this trend continued? One year? (This absurd result shows the weakness of "linear extrapolation" in many situations.)

Now you try it

1. Obtain your own data on a variable that changes over a period of time. Examples might include the daily temperature, the growth of a baby, the maximum height of a local tide, the ups and downs of the stock market, etc. Examine the numbers and attempt by inspection to predict what a graph of these data will look like. Then graph the result and compare with your prediction.
2. You may know that an object moving from rest with constant acceleration (a) covers the distance d in the time interval t given by Galileo's famous equation

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

Here is a table of distances covered during different time intervals for an object moving with constant acceleration from rest. Find the acceleration by the graph method.

Distance covered (cm)	*Time interval (s)*
3.60	0.1
14.5	0.2
32.0	0.3
57.5	0.4
90.2	0.5
129.5	0.6
176.4	0.7
230.0	0.8
291.5	0.9

Using a spread sheet

1. If your class has access to computers and to a so-called spreadsheet program, enter the table of data for the tomato plant in the spreadsheet.

2. Use the graphing function of the spreadsheet to create a graph of data similar to your earlier graph. Make sure the program labels the axes.
3. In what ways, if any, does the spreadsheet graph differ from your own graph? Examine, for instance, the spacing of data on the x-axis.
4. Define a cell on the spreadsheet in such a way that it gives the slope of the line between any two of your data points, and provide a label in a neighboring cell.
5. Try this again with your own data, obtained above.

3. FALLING OBJECTS (SECTION 1.9)

The study of falling objects is an important part of Chapter 2. It is the gateway (and was historically) to understanding the new mechanics.

1. Try dropping different types of objects at the same time from the same height and compare when they hit the ground. Is there any difference? If there is, what do you think are the reasons for the difference?
2. Predict what will happen if you drop a book and a piece of unfolded paper simultaneously to the floor from the same height.
3. Try this. Is the result what you predicted? Explain what happened.
4. Now crumple up the paper tightly into a ball and try the experiment again. Explain what you observe.
5. It has been reported that, in order to slow down the fierce speeds of serve during world championship tennis, the size of the official tennis ball is to be increased by a small amount. Explain how this would accomplish the purpose.
6. Using Galileo's formula $d = \frac{1}{2}at^2$, explain why two objects dropped from the same height should hit the ground at the same time. What assumption is necessary?

4. KEPLER'S THIRD LAW (SECTION 2.10)

Review Kepler's third law of planetary motion in the text.

1. A table of the periods and radii of the orbits of the planets, and of the distances of the Sun and fixed stars, is given in Section 2.6, as first obtained by Copernicus. Examine the data in this table, from the Sun to

the planets and fixed stars. What is the harmony that Copernicus saw in these numbers?

2. What is an "astronomical unit" (AU)? How large is it?
3. If you know the radii of the orbits and the periods of all the planets, how could you test the accuracy of Kepler's third law? Using the method you devised, test the law using the data in the table in Section 2.6.

   Notice, however, that the periods of planets are given in days for some planets and years for others, while all of the radii are in AU. The periods must all be in the same unit for this comparison. Chose a convenient unit and then convert the periods to that unit before testing the data.
4. What do you conclude about the validity of Kepler's third law? Give the reasons for your conclusion.

5. RELATIVE MOTION (CHAPTER 2, AND SECTIONS 3.9, 9.3)

In this investigation two different observers will observe the same event, but report seeing two different phenomena. The difference between these two observers is that the first observer is at rest relative to the event, while to the second observer the event is in motion relative to that second observer.

The event will be a ball dropping to the ground. The first observer will be the person who drops the ball as he or she walks forward at constant speed and direction. The second observer will be a person standing still in the room.

1. One person walks forward on a straight line at constant speed while holding the ball over his head and to one side. While steadily walking forward, he lets the ball drop, and he carefully watches its motion.
2. At the same time, a student standing in the room near the walking student is also carefully observing the motion of the ball. Each observer should then draw the path of the ball as he or she observed it, from the position of the hand on release to the place where the ball landed.
3. Record your observations, repeating the experiment several times if necessary.
4. Compare the observations made by the observers, one moving, the other stationary relative to the horizontal motion of the ball. What do you conclude about the effect that relative motion has on the observations of two different observers?

5. If, instead of walking, the first observer was inside a ship moving smoothly forward relative to the shore, would his observation on the trajectory of the ball give any clue that he is actually moving with respect to the shore?

Now you try it
Repeat the above observations and analyses, only this time the walking student will toss the ball straight up and catch it as it returns to his hand.

Thought Experiments

1. One argument against the moving Earth was that a ball dropped from a high tower would land behind the tower, since the tower is moving forward during the time the ball is dropping. Since, in fact, the ball always lands at the base of the tower, people concluded that the Earth cannot be moving. Does the first part of this experiment support or refute that argument?
2. Two observers are observing the setting of the Sun as seen by a person on Earth. One observer is on Earth, but the other is on the Moon. How does each one account for the observation of the first observer, that the Sun is "setting"?
3. If you are the observer on Earth, is there any way that you could determine whether it is the Sun or the Earth that is moving as the Sun "sets"?
4. The opening sentence of this mini-laboratory states: "In this investigation two different observers will observe one and the same event, but report seeing two different phenomena." How can this be? How would you explain it to someone?

6. GALILEO AND INERTIA (SECTIONS 3.1, 3.8, 3.9, 5.9, 5.10)

A. The Pendulum

The text describes an experiment with a pendulum in which the string hits a peg at the center of the line.

Observe two or three swings of a pendulum without the peg, and compare the height to which the bob rises on each side. Allowing for friction and air resistance, are they nearly equal?

Now let the string hit a peg or other obstruction, and compare the height to which the pendulum bob rises on each side.

Again taking friction and air resistance into account, what do you conclude from this experiment?

B. Two Inclined Planes

Galileo reasoned that he should obtain the same result as above if, instead of a pendulum, he used a ball rolling on two inclined planes facing each other.

1. Test this result by letting a ball roll down one incline and up the other. The inclines must be arranged so that there is a smooth transition at the bottom from one to the other. Carefully observe the starting and stopping points.
2. Taking all factors into account, do your observations confirm Galileo's prediction?
3. Galileo then predicted that this result should be the same, even if the angle of the second incline with respect to the horizontal is much less than the first one. Test this prediction and write your conclusion.
4. Finally, Galileo predicted that the same result should hold, even with a zero incline of the second inclined plane (a flat table). In a laboratory where the curvature of the Earth can be neglected, he predicted that the ball will keep on rolling in a straight line at uniform speed until it is stopped by a wall or falls off the table). Try it. Does Galileo's statement seem reasonable?

C. Kinetic and Potential Energy (Sections 5.9, 5.10)

1. Examine the results of this experiment by using the concepts of kinetic energy and potential energy.
2. Explain why, neglecting friction and air resistance, the pendulum and the ball always rise to the same height on both sides, even with a peg in the way or with a different incline.

7. FINDING THE CENTRIPETAL ACCELERATION VECTOR (SECTIONS 3.3, 3.12)

Take a ball and string and whirl the ball in a vertical circle in a counterclockwise direction. Make sure that the direction of the ball, moving at any point on the circle, is not pointing at anyone else or any fragile objects in the room.

When you are certain it is safe to do so, release the ball just when it is at the top of its circular motion. Carefully note the direction in which the ball moves. Do this several times, carefully observing each case.

1. How does the ball move immediately after you release it?
2. Draw a circle and an arrow representing the velocity vector, which will be tangent to the circle at the point where you released it. The length of the arrow represents the speed. Let this be 5 cm. Its direction will represent the direction in which the ball moved. Label this vector $\mathbf{v}_1$.
3. Where would the ball be if you had released it a fraction of a second later? Draw an arrow to represent the velocity vector at that point. Since the speed is constant, the length of the arrow should be the same; but the direction should be different. Label this vector $\mathbf{v}_2$.

Acceleration is a vector, and it is defined as the change in the velocity vector per unit of time.

$$\mathbf{a} = \frac{\Delta \mathbf{v}}{t} = \frac{\mathbf{v}_2 - \mathbf{v}_1}{t}.$$

In the case of centripetal acceleration, the velocity is changing in direction but not in speed. Assume the time interval is 1 s, and solve for $\mathbf{v}_2$:

$$\mathbf{v}_2 = \mathbf{v}_1 + \mathbf{a}t.$$

This equation states that the second velocity vector is the vector sum of the first velocity vector and the acceleration vector multiplied by the time elapsed. In other words, the acceleration (times time) transforms the initial velocity $\mathbf{v}_1$ into the final velocity $\mathbf{v}_2$.

Let's find out what vector quantity we need to add to.

As discussed in Section 3.3, the representations of vectors by arrows can be moved around on a piece of paper, as long as the same length is maintained and as long as they remain parallel to the original vector. The vector arrows are added by placing them together head to tail to form a chain. The sum or resultant is then represented by the vector arrow that goes from the starting tail to the ending head.

In this case we know the starting vector ($\mathbf{v}_1$) and the resultant vector ($\mathbf{v}_2$). But we don't know the second vector ($\mathbf{a}t$) that adds to $\mathbf{v}_1$ to obtain $\mathbf{v}_2$. We'll find out what it is by drawing.

1. Move the arrow for vector $\mathbf{v}_1$ to another place on the paper, keeping the same length and direction. The arrow $\mathbf{v}_2$ will represent the resultant. It will connect the tail of $\mathbf{v}_1$ to the head of $\mathbf{a}t$.

2. Draw arrow $\mathbf{v}_2$, placing its tail at the tail of $\mathbf{v}_1$, keeping the same direction and length as the original.
3. Arrow $\mathbf{a}t$ will make up the difference. Draw $\mathbf{a}t$ from the head of $\mathbf{v}_1$ to the head of $\mathbf{v}_2$. Label it $\mathbf{a}t$. This arrow represents the direction and magnitude of the acceleration vector (times the elapsed time).
4. Place a dot on the circle between the positions of $\mathbf{v}_1$ and $\mathbf{v}_2$. Move the arrow representing $\mathbf{a}t$ to the circle at that point, placing its tail on the dot. Be sure to keep the same direction and length as in your drawing.
5. Draw a tangent to the circle at the position of arrow $\mathbf{a}t$. What angle does it form with $\mathbf{a}t$?
6. You will recall from geometry that a radius is always perpendicular to the tangent of a circle at that point. What do you conclude about the direction of the acceleration vector $\mathbf{a}$ for uniform circular motion?

On what line does it always lie?
Why is it called "centripetal acceleration"?

8. THREE STATES OF MATTER (CHAPTER 7, SECTION 16.2, MAJOR LABORATORY "HEAT TRANSFER AND LATENT HEAT OF FUSION")

1. In what ways do solids, liquids, and gases differ from one another?
   Adding heat to a substance usually causes the temperature of a substance to rise. It might also cause the state or "phase" of the substance to change. In the following you will constantly add heat to ice until it melts in water, then continue adding heat until the water boils and finally evaporates completely.
2. Predict what a graph of the temperature, plotted over the entire time of the experiment, will look like.
3. Now place some crushed ice in a pyrex glass container, put a thermometer in the ice, and gently apply heat until all of the ice melts, then boils, then evaporates. Carefully record the temperature and the time every 10 s until all of the water has boiled away. Note the time when each of the phase transitions occurs. (Take care with the source of heat and the boiling water.)
4. Construct a graph of the temperature versus the time and indicate what is happening during each block of time.
5. Compare the results with your predictions in Question 2.
6. Attempt to account for what you observe by using the kinetic–molecular theory of matter.

9. HOW DO WE KNOW THAT ATOMS REALLY EXIST? THE BROWNIANSCOPE* (SECTION 7.8, CHAPTER 13)

The Brownianscope is a 200-power microscope that is able to focus on a chamber at one end containing microscopic smoke particles. The smoke particles are about 50,000 to 100,000 times larger than the air molecules. If the air molecules really do exist, then, in analogy with Einstein's results for small objects such as pollen grains suspended in a liquid, the smoke particles suspended in air should exhibit random motions caused by the random bombarding they receive from fast-moving air molecules. This scope is designed to test this predicted observation.

1. To create the smoke for the chamber, burn two matches about half way down, then blow out the flame. Holding the chamber over the smoke, capture the smoke, then (keeping it vertical) place the chamber over the end of the microscope.
2. Point the objective lens of the microscope at the bare light bulb for a light source. Wrap your fingers around the other end to block out the light from the source. If you wear glasses, try to observe this without them.
3. Try to focus the microscope on the smoke particles in the chamber. Note that, because of the arrangement of the optics, they will appear light against a dark background.
4. What do you observe?
5. How would you account for your observations?

10. LIGHT AND COLOR (CHAPTER 8, PART 2; SECTION 14.1)

The amount of refraction that a light wave experiences when it moves from air into glass, then back into air, depends upon the frequency of the light wave. We can use this dependence to separate visible white light into its constituent frequencies, which we observe as colors. This is the principle behind the operation of a *glass prism*. In a diffraction grating, the light waves diffract into different angles depending upon the frequency of the light. The result is the separation of the light into its constituent frequencies,

* Available inexpensively from Frey Scientific, Beckley Cardy Group, Mansfield, OH, 1-888-222-1332. A bare light bulb is also needed.

which we again observe as colors. This is the principle behind the *diffraction grating*. Both of these devices enable us to observe the *visible spectrum*.

1. Use the prism and the diffraction grating to observe the visible spectrum. For the prism you will need direct sunlight for the best result. For the diffraction grating, use any artificial light source. DO NOT LOOK AT THE SUN THROUGH THE DIFFRACTION GRATING!
2. What do you think would happen if you filtered the incoming light through a color filter?
3. Use one of the color filters and record your result.

Adding and subtracting colors

1. Your instructor may have different color filters which can be placed over the light of an overhead projector. What happens as the filters are added?
2. Shine white light through a color filter onto objects of the same and different colors in a darkened space. Record your observations. How would you explain what you observe?

11. SPECTROSCOPY (CHAPTER 14)

Equipment: A diffraction-grating spectroscope (Cenco Scientific), a light bulb source, a discharge lamp, and single-element source, flourescent lights in room (optional).

A spectroscope is a device for viewing the spectrum and measuring the frequencies or wavelengths of the light observed. Our spectroscope uses a diffraction grating. The numbers on the scale read from 4 to 7, indicating wavelengths from 400 nm to 700 nm (nm is the abbreviation for nanometer, which is 10^{-9} m.)

1. Use the spectroscope to observe the visible spectrum emitted by the incandescent light bulb. Record the wavelength at the center of each of the colors you observe. (Do not use a flourescent light or the Sun.)
2. Observe the spectrum emitted by a flourescent light (if one is available). How does it differ from the spectrum emitted by the light bulb?
3. Your instructor will set out a discharge lamp emitting rays from a single element. Observe the spectrum of the element and record the wavelengths of the observed lines. What you see is the visible portion of the bright-line or emission spectrum of that element.
4. Again observe the spectrum from the flourescent light. How would you account for what you see?

5. How does Bohr's quantum model of the atom account for the emission spectrum you observed? Why are there lines only at certain frequencies?

12. RADIOACTIVITY AND NUCLEAR HALF-LIFE (CHAPTER 17)

This investigation uses plastic simulated atoms in a kit provided by Frey Scientific, S16402. An age determination using the decay of carbon-14 is simulated through instructions provided with the kit.