Chapter 5
EMPLOYING SCIENTIFIC METHODS

FOR THE TEACHER

Merriam-Webster's Dictionary defines *science* in terms of the *scientific method*, stating that it is the "knowledge or a system of knowledge …obtained and tested through scientific method."[1] An early form of the scientific method was proposed in 1620 by the English Philosopher Francis Bacon in his work *Novum Organum* ("New Instrument"), in which he emphasized the importance of asking questions, making observations, generating possible explanations, and evaluating these explanations in light of additional observations. Today, most science textbooks define the scientific method as a technique in which the researcher defines a problem, makes observations, generates a hypothesis, designs an experiment to test this hypothesis, and uses data from this experiment to draw conclusions concerning the validity of the hypothesis so he or she can answer the research question. The scientific method is often presented in outline form:

> Research Question**:** Define the question to be answered.
> Observations: Make observations related to this question.
> Hypothesis: Offer a possible explanation.
> Experiment: Design an experiment to test the validity of this hypothesis.
> Conclusions: Evaluate the hypothesis in light of experimental data and offer an answer to the research question.

Although many science textbooks imply that there is but one scientific method (generally in this form), the Nobel Prize winning physicist Percy Bridgman states, "... there are as many scientific methods as there are individual scientists." Bridgman says that the scientist "is not consciously following any prescribed course of action, but feels complete

[1] Merriam-Webster, Inc. (2003). *Merriam-Webster's Collegiate® Dictionary, Eleventh Edition*. Springfield MA: Merriam-Webster, Inc.

freedom to utilize any method or device whatever, which in the particular situation before him seems likely to yield the correct answer. In his attack on his specific problem he suffers no inhibitions of precedent or authority, but is completely free to adopt any course that his ingenuity is capable of suggesting to him."[2]

Bridgman's comments are a good reminder that science is a creative endeavor, and that scientists are not restricted to a cookbook methodology in their pursuit of knowledge. None-the-less, the scientific method, as commonly presented, is a good "tool" for learning how to answer problems, and like any tool, is best understood through use. In this chapter students will employ "the scientific method" in a variety of ways to answer real problems. They will also use scientific vocabulary including the key terms listed in table 5.1.

Table 5.1 Key terminology related to "the scientific method"

variable: A variable is something that is capable of changing or varying.

independent variable: This variable is independent of others. A change in the dependent variable does not cause a change in the independent variable. In most graphs it is plotted on the x-axis.

dependent variable: This variable depends on the independent variable. A change in the independent variable may cause a change in the dependent variable.

quantitative variable: A variable with numerical values. (e.g. height, age, temperature, velocity, distance). Quantitative data are displayed in scatter plots or histograms.

categorical (qualitative) variables: A categorical variable includes data that is grouped on a given property, such as genus, chemical family, or population. Categorical data are best displayed in bar graphs or pie charts.

control: A subject or object in an experiment that is not involved in the procedures affecting the rest of the experiment, thus acting as a standard against which experimental results can be compared.

constants: Factors that are held constant during an experiment. To determine the effect of an independent variable on a dependent variable, all other potential factors must be held constant.

[2] Bridgman, Percy. (1980). *Reflections of a physicist.* New York: Arno Press.

5.1 DISCREPANT EVENTS - ESTABLISHING A "NEED TO KNOW"

Early bacteriologists and microbiologists determined to identify microbes involved in disease. Such a task was challenging for early workers, and samples were often contaminated by fungi and other microorganisms. In 1928, a researcher by the name of Alexander Fleming was studying a group of bacteria (*staphylococci*) when he noticed a slight discrepancy in their growth pattern. Bacteria that would normally cover the growth medium were not found near spots of fungal contamination. These observations were not consistent with Fleming's prior experiences and he immediately set out to determine the cause for this discrepancy. After much research, Fleming isolated a substance from the mold that inhibits the growth of bacteria, and named it *penicillin*. Ten years later, English researchers Ernst Chain and Howard Florey demonstrated the therapeutic effects of penicillin in the treatment of bacterial infections. Penicillin became the first widespread antibiotic, and has since saved many lives.

One man's interest in a slight discrepancy (the lack of bacteria surrounding fungal contamination) led to many subsequent discoveries, and ultimately the introduction of antibiotics. Students, like researchers, tend to pay more attention if something does not behave the way they expect it to. Such *discrepant events* engender curiosity and stimulate a *"need to know"*. Those who have a "*need to know*" are likely to investigate further.

Educators employ *discrepant events* in an effort to capture student interest and provide parameters in which students will naturally develop a *"need to know.*" In this section we introduce a few *discrepant events* and many more may be found in the companion volumes, *Hands-On Physics with Real-Life Applications (Cunningham and Herr, 1994),* and *Hands-On Chemistry, with Real-Life Applications (Herr and Cunningham, 1999).*

Activity 5.1.1 – A Reversible, Spontaneous Color Change - Teacher Demonstration
Materials: methylene blue, potassium hydroxide, flasks, dextrose.

We are not accustomed to seeing liquids spontaneously change color, much less revert back to their original color when shaken. In this demonstration the teacher fills a flask with a liquid that turns blue when shaken (figure 5.1A), but reverts to clear when allowed to stand (figure 5.1B). This discrepant event can be used to introduce the importance of observation in the scientific method.

The teacher should put on protective eyewear and a lab coat. Add the following to an Erlenmeyer flask: 200 mL of 0.5 *M* potassium hydroxide (5.7 grams KOH in 200 mL water; allow to cool before adding other substances), 7 grams of dextrose (glucose), and a few drops of methylene blue indicator solution (or approximately 0.5 grams of methylene blue powder). In a basic solution, methylene blue is reduced to its colorless state:

Methylene blue may be subsequently oxidized by shaking the flask vigorously. Atmospheric oxygen dissolves into solution, oxidizing methylene blue to the blue state.

After shaking, allow the flask to stand undisturbed until it returns to clear. This process can be repeated numerous times. When students observe this phenomenon, they will start to ask questions concerning how it works. The teacher can use this discrepant event to whet student curiosity about science, or to launch an exploration of the underlying principles of oxidation and reduction.

Activity 5.1.2 – The Collapsing Can - Teacher Demonstration
Materials: soda can, water, hot plate, beaker tongs, safety goggles, lab coat.

This is a teacher demonstration only. Put on goggles and a laboratory coat. Obtain a large beaker or bucket and fill it with water. Pour water into an empty, opened, aluminum soft drink can to a depth of approximately one centimeter and place the can on a hot plate until the water boils (figure 5.2A). *Do not allow the can to boil dry!* After the water has boiled (watch for steam) for approximately one minute, use tongs to remove the can from the heat source and place it in an upright position with the base in water (figure 5.2B). Students will notice no changes in the can. Repeat the process, only this time invert the can and submerge the opening in the water as illustrated in figure 5.2C. This time the can will immediately collapse! Ask your students to draw a diagram of the experimental setup and indicate where the pressure must be highest and where it must be lowest to produce the observed results.

When one milliliter of water boils (vaporizes) it changes into approximately 1000 milliliters of steam. As the water in the soft drink can boils, it displaces air originally in the can. When the can is sealed and cooled, steam condenses to liquid water, but now occupies only approximately 1/1000th the volume it occupied as steam! In other words, for every milliliter of steam that condenses inside the sealed can, approximately 999 milliliters of vacuum are left behind. The air pressure outside the can remains the same while the pressure inside drops, creating a pressure differential that collapses the can.

Air pressure can also be illustrated in a very dramatic manner by using a resealable metal can such as those used to package paint thinner and other solvents. *The instructor should make certain the can is completely clean and dry prior to the demonstration or else dangerous fumes may enter the atmosphere when the can is heated.* Seal the can and ask a student to crush it with his or her hands. It will be very difficult for the student to do much more than dent the sealed can because the air inside resists compression. Remove the lid and cover the threads with plumber's Teflon tape. Add water to a depth of one centimeter and heat unsealed until the water boils (figure 5.3A). *NEVER HEAT A SEALED CONTAINER!* Using potholders, remove the can from the heat and seal with the lid (figure 5.3B). *Do not reseal the can while it is being heated or an explosion may occur!* As the can is allowed to cool on a bench top, it will gradually collapse as the water vapor condenses and the internal pressure drops to a fraction of the external atmospheric pressure. Cooling the outside of the can with water or a damp cloth will accelerate this process. Students can calculate the force upon the can by calculating the surface area (A) and then solving the equation $F = PA$ where P (atmospheric pressure) is approximately 101,325 N/m2.

Under normal circumstances, empty cans do not spontaneously collapse, so when students observe them imploding in this activity, their curiosity is immediately aroused. You can use this *discrepant event* as an introduction to the importance of observation to scientific method or to introduce students to air pressure and the gas laws.

Activity 5.1.3 – Retinal fatigue - What you perceive is not always real!
Materials: overhead transparency; yellow, green, and black overhead pens; overhead projector.

When photographed with a camera equipped with an electronic flash (strobe), you may have noticed a dark after-image of the strobe long after the flash of light disappeared. The flash is so intense that it fatigues photoreceptive cells in your retina (see figure 5.4) so they are temporarily unresponsive to light. As a result, a black image of the flash appears in your vision. Your retinas may also fatigue after staring at colored objects for long periods of time. However, when you look toward a white surface you will not see a black after-image, but rather one that is the complimentary color of the object you were staring at. For example, if you stare intensely for one minute at a red dot, and then turn your eyes toward a sheet of white paper, you will see a cyan (the complimentary color of red) after-image of the dot. Light reflected from white paper normally stimulates the red, green, and blue cones (photoreceptive cells) of the retina, but if you have first fatigued the red cones by staring at a red object, these cells temporarily will not respond to red light. As a result, only the green and blue cones in that region of the retina are stimulated, causing the image to appear cyan (the combination of green and blue light), the complimentary color of red!

Color an American flag on an overhead transparency using the colors indicated in figure 5.5, or project the flag image from the companion website. Instruct your students to cover one eye, and stare intensely at the middle of the flag with the other. After one minute, remove the transparency and instruct students to keep their eyes focused on the same point on the white screen. They should soon see the American flag, correctly colored in red, white, and blue!

Instruct your students to draw a solid red circle on a white sheet of paper using a marker or paintbrush. They should cover one eye, place the circle in bright light, and stare at it. At the end of one minute, instruct them to quickly refocus on a well-lit sheet of white paper and ask them to identify the color of the after-image (cyan). Repeat this process with green and blue dots and examine the results. Students should identify magenta as the complimentary color of green, and yellow as the complimentary color of blue.

Under normal circumstances we don't see colors where none exist, so when students observe colors when they stare at a sheet of white paper, their curiosity is immediately aroused. You can use this *discrepant event* as an introduction to the importance of observation in the scientific method or to introduce students to vision and retinal physiology.

5.2 DEVELOPING SCIENTIFICALLY ORIENTED QUESTIONS

Michael Faraday (1791-1867) was a British scientist who invented the first electric motor and dynamo, demonstrated the relationship between electricity and chemical bonding, and discovered the effect of magnetism on light. Faraday was not only a brilliant scientist, but also a well-known educator who brought science to the public through lectures he delivered each Christmas season at the Royal Society in London[3]. Faraday's Christmas Lectures were popular because he illustrated concepts with numerous hands-on activities and experiments. Faraday knew the importance of observation in science and began his most famous lecture series by asking his audience to record as many observations as possible about a burning candle. Years later, science teachers continue to use Faraday's activity to encourage the development of observation skills. Douglas Osheroff, the 1997 Nobel prize winner in physics (for discovery of the superfluid phases of ^{3}H) reflected on the importance of this activity in his own intellectual development: "I remember quite well one class assignment: to record our own observations of a burning candle. I knew pretty well how a candle worked, and simply wrote down an explanation of how radiant heat from the flame melted the wax, which was then drawn up into the wick by capillary action, etc. Mr. Hock read my explanation, and then came to me and pointed out that what I had written could not possibly have been drawn from my own observations."[4] Osheroff had not made observations as requested, but had relied on his prior knowledge to explain what he was seeing. Mr. Hock's comments helped Osheroff distinguish observation from inference, and this distinction ultimately helped him in his career as a scientist.

Activity 5.2.1 – Observations of a Candle

Materials: small candle, matches, tongs, beaker, funnel, clay or putty, bromthymol blue or phenol red indicator, test tube clamp, safety glasses, dull butter knife, lamp oil (optional).

The purpose of this activity is to record as many observations of a candle as possible. Refer to table 5.2 for ideas on the types of observations that may be made. Record your observations in a laboratory notebook or worksheet. Firmly plant a candle in a small clump of clay. Using beaker tongs, suspend a clean, cool beaker over the unlit candle as illustrated (figure 5.6A) and record your observations. Repeat the procedure with a

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[3] Faraday, Michael. (1963). *Chemical History of a Candle*. New York: Viking Press.
[4] Osheroff, Douglas. (1997). "Puttering Around in the Basement on the Road to Stockholm", Keynote Address for the California State Science Fair. May 19, 1997.
Photographs of Pasteur, Eijkman and Edison are in the public domain.

funnel on which there are drops of the pH indicator methylene blue or phenol red. Does the indicator change color?

Put on safety goggles and light the candle and record all observations (figure 5.6C, table 5.2). Using beaker tongs, suspend a cooled beaker over the flame as shown in figure 5.6D. What observations can you make about the inside of the beaker? Repeat the procedure with a funnel in which there are drops of bromthymol blue (figure 5.6E).

Place a dry, clean beaker over the flame (figure 5.6F) and make observations as the flame is extinguished. Repeat the procedure with different sizes of glass beakers. Is there any correlation between the size of the glass beaker and the time it takes to extinguish the flame? Remove the beaker, and re-light the candle by placing a match in the smoke near the wick (figure 5.6G). Is it possible to re-light the candle simply by moving the flame into the smoke?

Using a dull knife, cut the wick free from the candle and place one end of the wick in a dish of water. Light the other end of the wick (figure 5.6H). What do you observe? Dry the wick off and place it in a dish of lamp oil and re-light it. What do you observe?

Activity 5.2.2 – Developing questions about the candle.
In his introduction to the classic candle activity, Michael Faraday wrote: “We come here to be philosophers; and I hope you will always remember that whenever results happen, especially if it be new, you should say, 'What is the cause? Why does it occur?' and you in the course of time will find out the answer.” Write down as many questions as you can based upon the observations you made in activity 5.2.1. For example, “What is wax? What is the wick? Why is the wax soft? Why does the wick turn black? Why does the wax melt? Why does the smoke ignite? What is the substance that appears on the glass above the flame? Why does the indicator turn color when placed over the candle? Do all candles burn the same?...”

Table 5.2: Observations to make about a burning candle

flame
initial speed of burning
speed of burning once the wax starts to melt
height of the flame in the open air
colors of the flame
colors of flame light reflected off white paper
quality of light generated by the flame
color distribution within flame
shape of flame
response of flame to air movement
response of flame to water
changes in flame height when beaker is lowered
changes in flame color when beaker is lowered
direction flame burns when candle is tilted
duration of smoke when candle is extinguished
time candle burns under large beaker
time candle burns under medium beaker
time candle burns under small beaker
shape of flame when water is placed in well

condensate
appearance of condensate in beaker
conditions under which condensate forms
location where condensate forms
rate condensate forms
rate condensate disappears if flame is removed

deposits
color of deposits on beaker
location where deposits form
rate deposits form on beaker
conditions under which deposits form
texture of deposits

smoke
color of the smoke
quantity of smoke
distribution of smoke
change in smoke production with funnel
distance from which candle can be relit
color bromthymol blue turns in the smoke

candle (paraffin)
color of candle
texture of candle
shape of the candle
rate candle is consumed
appearance of wax when candle is burning
color of tip of wick when burning
rate candle is consumed if wax in well is drained
rate candle is consumed if wax is not drained
width of tracks left by flowing wax

wick
position of wick of unlit candle
color of wick of unlit candle
structure of the wick of unlit candle
ability of wick to burn if placed in water
ability of wick to burn if placed in lamp fluid
color of base of wick when burning
color of stalk of wick when burning
flow patterns of liquid wax
rate wick burns when not in wax
rate wick burns when in candle
apparent dryness or wetness of base of wick

odors
odors produced by unlit candle
odors produced by burning candle
odors released by extinguished candle

sound
sound produced by burning candle
sound of candle when water is placed in well

heat
heat distribution around flame (top, sides, base)
side of hand that feels heat when near flame

5.3 OBSERVATION VS. INFERENCE

Science is based largely upon *observations* and *inferences*. An *observation* is a record resulting from the study of an event or object, whereas an *inference* is a conclusion that is drawn from evidence or reasoning based upon observations. Unfortunately, many people can not distinguish observations from inferences and use the concepts interchangeably. The following activities are designed to help students understand the differences between observations and inferences, and help them use each appropriately.

Activity 5.3.1– Observations of a "plant"

Place a realistic looking silk plant with flowers in a pot containing soil (figure 5.7A). Place the plant in the front of the class and ask your students to record all of their observations of the plant on a sheet of paper. After a few minutes, ask students to read their observations, and then record them on the board or an overhead transparency. Do not allow any of your students to discuss the "observations" that appear on the list. Because many students do not understand the difference between observation and inference, the list will probably include inferences such as flower scent, root structure, photosynthesis and respiration, in addition to true observations, such as leaf color, leaf shape, and flower color. Once the list is complete, pull the plant out of the pot and pass it around the room (figure 5.7B). It will now be evident that many of the "observations" were merely incorrect inferences made because the students assumed that the plant was real. Draw another column on the list and ask students to identify which of the "observations" should be categorized as inferences.

Activity 5.3.2 – Observations of "raisidia"

"Raisidia" is a humorous activity designed to help students differentiate observations from inferences. Before class begins, place raisins in a cup of tap water for at least 20 minutes. During this time, the raisins hydrate and their densities decrease. Without allowing students to see the raisins, drain off the water and place them in a tall clean clear drinking glass and fill the glass with a clear carbonated drink such as lemon-lime soda or club soda. After the fizzing has subsided and the raisins begin to bob up and down, present the cup to the students and ask them to make as many observations as possible (figure 5.8B). Do not allow them to approach the container. You may wish to tell the students a "tall tale" about how you collected these "creatures" (*raisidia*) in a nearby bog or gutter. When asked to make observations, many will describe how the creatures swim to the surface and dive back, or how they congregate on the bottom before swimming to the top. Record all of the students observations of the "*raisidia*" on the board. After your students complete all of their observations, you may wish to astound them by drinking the contents of the glass. Students will be shocked until you pull out the raisin box and tell them that the "creatures" are actually raisins. Draw another column on the list and have the students identify which of the "observations" should be categorized as inferences.

The English scientist William Henry (1774-1836) observed that the concentration of gas in a solution increases in a linear fashion as the pressure of the gas above the solution increases.

$$C_{gas} = kP_{gas}$$

where C_{gas} = molar concentration of the gas in the solution; k = Henry's law constant for that gas at a particular temperature; and P_{gas} = partial pressure of the gas above the solution.

Carbonated soft drinks are packaged under pressure, forcing a large amount of carbon dioxide to dissolve in solution. When a can of carbonated soft drink is opened, the external pressure is reduced to atmospheric pressure and the carbon dioxide comes out of solution as bubbles (the fizz). Bubbles of carbon dioxide form on the surface of the submerged raisins and the raisins are soon buoyed to the surface where the bubbles break, causing the raisins to sink (figure 5.8C). This activity illustrates Archimedes Principle, which states that an object is buoyed up by a force equivalent to the weight of the fluid displaced. The bubbles on the raisins displace sufficient soft drink so that the buoyant force on the raisins exceeds the force of gravity, and they rise to the surface. When the bubbles break, the raisins displace less fluid and experience a buoyant force that is less than that of their own weight, causing them to sink once again to the bottom. The raisins will continue to bob up and down until the soda becomes flat (no more carbon dioxide escapes from solution).

5.4 BRAINSTORMING AND HYPOTHESIZING

Brainstorming is a group problem-solving technique that involves the spontaneous contribution of ideas from all members of the group. Scientists often hold brainstorming sessions to generate possible solutions to difficult problems, particularly in the hypothesis generation phase of the scientific method. Often the comments of one team member stimulate the thought processes of another, creating a chain-reaction of ideas. The following guidelines should be used in a brainstorming session:

- Do not discuss or evaluate ideas until the brainstorming session is complete.
- Focus on quantity, not quality. You want to get many ideas for discussion.
- Build on the ideas of others, combining or modifying ideas already presented.

In the first activity, students engage in a classic brainstorming session that has been used as a team-building activity in many schools and organizations. Teams are told to imagine that they are part of a lunar exploration mission, and that their craft has experienced mechanical difficulties, leaving them stranded some distance from the lunar research station. They are asked to develop consensus regarding the relative value of various items that may be taken with them from the wreckage on their trek to the research station. The activity presented here is a variation of the original exercise, modified to encourage brainstorming, consensus building, and evaluative reasoning. Before proceeding with the activity, you may wish to show images and videos of the Moon's surface [*sciencesourcebook.com*; or search *lunar photos*] to familiarize students with the lunar environment.

Activity 5.4.1 – Lost on the Moon - brainstorming & consensus building

Divide students into teams of three to five members, and read the following paragraph aloud to the class:

> *"You are members of a scientific team bound for a permanent research station on the surface of the Moon. Unfortunately, your lunar craft malfunctions, forcing an emergency landing in Mare Crisium, approximately 300 km from the research station at Mare Serenitatis. Both you and the research station are currently on the lighted surface of the Moon. During the landing process, much of the equipment aboard has been damaged, and since survival depends on reaching the research station, only the most critical items must be chosen for the trek. Below you will find a list of the 15 items left intact following the emergency landing. As a group, you must reach consensus regarding the relative importance of these items in your mission to reach help at the research station."*

box of matches	*two 45 caliber pistols*	*magnetic compass*
10 kg dehydrated food	*case of dehydrated milk*	*traditional signal flares*
50m of nylon rope	*two 100kg tanks of oxygen*	*first aid kit*
parachute silk	*stellar map*	*solar-powered FM radio*
portable heating unit	*life raft*	*10 liters of water*

(1) <u>Brainstorming</u>: Write down as many ideas as possible regarding the potential use of the 15 items for your trek to the research station. At this time, do not discuss or evaluate the merit of these ideas.

(2) Analysis: Review the maps, photos, movies and data on the Moon available on the website. Record the similarities and differences between the Earth and the Moon with respect to gravity, atmosphere, lighting, radiation, magnetic field, visibility, surface, etc.
(3) Evaluation and consensus building: Discuss the merits of the ideas presented during the brainstorming session and develop a consensus within your group regarding the relative value of each of the items. Place a "1" by the item you value most, and a "15" by the item you value least, recording the rationale for your ranking.
(4) Discussion and defense of position: Compare your ranking with that of other groups. If there are differences, discuss them, presenting reasoned arguments for your ranking.

Activity 5.4.2 – The mysterious bottle - generating a hypothesis
Materials: surgical tubing, pliers, burner, ring stand, nail, beakers, food coloring, utility knife, black electrician's tape, foil

A *discrepant or counter-intuitive event* is a demonstration or activity that produces unexpected results, causing the observer to ask questions. The savvy teacher will use discrepant events to create an environment in which students, rather than the teacher, are asking the questions. The "mysterious bottle" is a discrepant event that can be used as a brainstorming activity in which students build on each others ideas to surmise the contents of a covered container that exhibits some very unusual properties. They then evaluate each other's hypotheses in light of their observations.

The preparation for this activity should be done in a location where none of the students will see how the device is assembled. Obtain a two-liter plastic soda bottle. Put on protective eyewear. Using insulated pliers, hold the tip of a large nail in the flame of a laboratory burner (figure 5.9A), and then use the heated nail to melt a hole in the side (near the base, figure 5.9B) of the two-liter bottle. Slowly move the nail around in a circle until the diameter of the hole is just slightly smaller than the diameter of flexible latex surgical tubing. Using a sharp utility knife or scissors, cut off the top of the bottle as shown. Pinch the end of the tubing so it will fit through the hole, and then pull the tubing until it is positioned as shown in figure 5.9C. Test the seal by adding water to the container. Leakage may occur if you use Tygon© or other stiff plastic tubing, or if the hole is too large.

Empty the bottle and place it on a ring stand equipped as illustrated in figure 5.9C. Place a few drops of blue food coloring in the base of the container and add water until the level is just below the base of the arch in the tubing. Hide the contents of the container from view by wrapping the bottle in aluminum foil and taping the tube that protrudes with black electrician's tape (figure 5.9D).

Place a few drops of red food coloring in a small beaker and add water. Place the full assembly in view of the class. Pour water from the beaker into the bottle until water starts to flow out of the exit tube and into a two-liter collection flask, beaker, or cylinder.

Ask students to record their observations (e.g. amount and color of fluid added, amount and color of fluid that exits). Students will be surprised to see much more water leave the bottle than entered it. Ask students to use these observations when generating ideas regarding the possible contents of the container.

Provide students with overhead transparencies and pens, and instruct them to draw diagrams of what they think may be in bottle. Ask for volunteers to explain their hypotheses using the overhead projector. Encourage the participation of all students and allow them to build on the ideas of others.

After the final presentation, discuss each idea to see if it explains all of the observed phenomenon (increase in amount of fluid, change in color, etc.). Keeping the bottle covered, pour an equal quantity of red water as before into the container. The students will note that nothing comes out of the container. Ask them to evaluate their hypotheses to see if they can explain this new data. The class should be able to rule out many of the hypotheses on the basis of the observations that they have made. After completing this process, ask students to vote on the hypothesis that they believe best explains the observations. Commend students for their contributions and critiques and discuss how scientists use similar processes to generate a variety of hypotheses before focusing in on one to be tested.

Although the primary purpose of this activity is to engage students in brainstorming and hypothesis generation, students will undoubtedly want to see the contents of the bottle to determine if their hypotheses were correct. Remove the aluminum foil and show the simple siphon (figure 5.10). The action of the siphon is dependent upon differences in gravitational attraction upon the fluid in the two arms of the siphon. There is greater pull on the side of the tube with a higher vertical column of water (in this case, the tube exiting the bottle) than there is on the shorter branch (the section inside the bottle). Water exhibits significant cohesive forces that prevent the column of water from breaking. As water starts to flow out the exit tube, water is pulled in through the inlet. The column of water "falls" toward the lowest point in much the way that a short section of rope placed over a railing falls to the side on which more of the rope hangs.

For a siphon to function, there must be a difference in pressure at the two ends of the tubing. In the siphon in this activity, the atmospheric pressure is approximately the same at both ends of the tube, but the liquid pressure is different. Liquid pressure can be calculated by multiplying the density of the fluid ($\rho = 1$ g/cm3 for water) by the acceleration due to gravity ($g = 9.8$ m/s2) by the height differential (h). Thus, a 20 cm column in the intake arm exerts a pressure of approximately 2 kPa (2000 N/m2) while a 30 cm column of water in the exit tube exerts (not to scale shown in diagram) a pressure of approximately 3 kPa (3000 N/m2).

$$\textit{Fluid pressure in intake tube} = \rho g h = (1\,g/cm^3)\ ()\ (0.2m) \approx 2\ kPa$$

$$\text{Fluid pressure in exit tube } = \rho g h = (1\,g/cm^3)\,()\,(0.3m) \approx 3\text{ kPa}$$

Thus, pressure in the intake arm is 99 kPa (101 kPa of air pressure - 2 kPa of water pressure) while pressure in the lower (exit) arm is only 98 kPa (101 kPa of air pressure - 3 kPa of water pressure). Since the net pressure in the intake arm is greater than in the exit arm, water flows towards the exit. The greater the difference in height, the greater the pressure differential, and the greater the rate of flow.

This activity provides a great model for "black-box" research. Researchers are often unable to see the thing that they are studying, and must rely upon observations of inputs and outputs. In this activity, the addition of water is an input, while the water exiting is an output. Scientists draw inferences based upon inputs and outputs, especially when they cannot see the inner workings.

5.5 EXPERIMENTAL DESIGN

Assume that you sit on the council of a major city, and the fire commissioner comes to request more funding to hire additional firemen. In the course of the presentation, the commissioner presents graph 5.11A. On the basis of this data, would you vote to hire more firefighters? Hopefully not! The graph suggests that the numbers of fires in your city are proportional to the number of firefighters. Note that the number of firefighters is plotted on the x-axis, while the number of fires is plotted on the y-axis. By convention, we plot the independent variable (the variable that we change independently of the other) on the x-axis, while plotting the dependent variable (the variable that changes in response to the independent variable) on the y-axis. The data in figure 5.11A suggests that if you hire more firemen (the independent variable), then your city will experience more fires (dependent variable)! As a city council member, you would probably not be re-elected if your constituency learned that you voted in favor of the fire commissioner's request on the basis of this data! If, however, the commissioner presented the data as shown in figure 5.11B, your vote would not provoke concern. This data suggests that as the number of fires (the independent variable on the x-axis) has grown, the city has hired more firefighters (the dependent variable on the y-axis). As you can see, much confusion can be generated when one does not follow the standard convention for plotting data. By convention, the independent variable should be plotted on the x-axis (horizontal axis), and the dependent variable on the y-axis (vertical axis).

Independent variable: Mathematicians traditionally refer to *horizontal axis* of a graph as the *x-axis* or the *abscissa*, while scientists refer to it as the *independent variable*. An independent variable is one that is unaffected by changes in the dependent variable. For example when examining the influence of temperature on photosynthesis, temperature is the independent variable because it does not dependent upon photosynthetic rate. A change in the photosynthetic rate does not affect the temperature of the air!

Experimenters often manipulate independent variables and look for changes in dependent variables in order to understand basic relationships.

Dependent variable: Mathematicians refer to the *vertical axis* of the graph as the *y-axis* or *ordinate*, while scientists refer to it as the *dependent variable*. The dependent variable is dependent upon changes in the independent variable. For example, photosynthesis is dependent upon temperature. A change in air temperature will result in a change in photosynthetic production.

Constants: To conduct an experiment it is necessary to keep factors other than the independent variable constant. For example, if a food scientist is studying the relationship between the concentration of preservative and the growth rate of bread mold, it is important that the temperature, humidity, light and other factors be the same for all bread used in the study. If these are not kept constant, then it is impossible to determine the effect of the variable that you are intending to test.

Controls: Experiments also require a control, or specimen that is not subjected to the procedures affecting the rest of the experiment, thus acting as the standard against which the results are compared.

Activity 5.5.1 – Interpreting graphs

Figures 5.12A-5.12H show the data from a variety of experiments and studies. For each of graph, identify (1) the independent variable, (2) the dependent variable, (3) list things that must be held constant, (4) describe an experiment that would produce such data and (5) give a simple interpretation of the data.

5.6 INDEPENDENT VARIABLES

In 1976, the United States celebrated its 200th anniversary, and many people flocked to Philadelphia, to celebrate and commemorate the signing of the Declaration of Independence. Shortly after the celebrations, 180 people who had attended the American Legion Convention in Philadelphia contracted pneumonia-like symptoms, thirty-four of who eventually died from related complications. "Legionnaires disease" prompted a massive medical investigation. Researchers knew that all who had suffered from Legionnaires disease had attended the American Legion convention, but beyond that, they did not have much information. Was the disease caused by an environmental toxin, a virus, bacteria, or other pathogen? Was it transmitted by food, water, air, or direct contact? To find the cause, medical researchers isolated and studied single variables, and then studied these in conjunction with others. After much methodical research, scientists were successful in identifying the disease agent (the bacteria *Legionella pneumophila*) and the environmental parameters (mists containing the bacteria) that set the stage for this deadly outbreak.

As with Legionnaire's disease, most real-life problems are complex and contain many variables, each of which may influence the outcome, either individually or in conjunction with other variables. In this activity you will be confronted with a complex situation in which many things happen simultaneously, and you must use a methodical approach of isolating variables to determine the causes of the phenomena you see.

Activity 5.6.1 – Isolating variables in a complex chemical reaction
Materials: re-sealable sandwich bags, plastic spoons, plastic beral pipettes, anhydrous calcium chloride, sodium bicarbonate, phenol red solution (0.01 gram solid phenol red/liter of solution), beakers

Put on a laboratory coat and protective eyewear. Place 5 grams (approximately a teaspoon) of sodium bicarbonate ($NaHCO_3$) in one corner of a zip lock bag, and an equal amount of anhydrous calcium chloride in another, being careful not to mix the powders. Place a plastic beral pipette filled with phenol red solution (made by dissolving 0.1 gram of phenol red powder in 100ml of water) in the bag with the tip positioned so no solution leaks into the powder. Seal the bag and mix all the components as rapidly as possible. Once the contents are thoroughly mixed, set the bag on a table and record any changes (e.g. color, temperature, appearance) you observe in table 5.3.

Although a variety of changes occur when the phenol red, sodium bicarbonate and calcium chloride are mixed, it is not possible to determine the specific causes of each change because there are too many variables. For example, is the observed color change due to the mixing of phenol red solution with sodium bicarbonate, the mixing of phenol red solution with calcium chloride, the mixing of sodium bicarbonate and calcium chloride, or the mixing of all three items? To answer such questions, it is necessary to change one variable at a time while controlling, or keeping constant, the rest. For example, rather than mixing all three substances together at once, try mixing small quantities of pairs of chemicals independently in small beakers, and then mixing the resulting mixtures with the remaining substance.

Mix phenol red and sodium bicarbonate and report your observations in table 5.3. Mix phenol red and calcium chloride in a separate bag and record your observations. Finally, mix sodium bicarbonate and calcium chloride without any phenol red and again record your observations.

Repeat the original process, but starting with a mixture of two substances as shown in table 5.4. Record your observations in the appropriate columns and then add the final substance to each mixture as specified in the table.

(1) Which combination is necessary for the formation of a precipitate?
(2) Which combination(s) is/are exothermic (temperature rises)?
(3) Which combination(s) is/are endothermic (temperature drops)?
(4) Is a precipitate formed as a result of mixing two powders, a powder and phenol red, or the two solutions?

(5) Is gas formed as a result of mixing the two powders, a powder and phenol red, or the two solutions? Explain.

Table 5.3 Observations of mixing components

phenol red	*sodium bicarbonate*	*calcium chloride*	*color*	*temperature* ↑ *indicates rise* ↓ *indicates loss*	*appearance (gases, precipitates, etc.)*
♦	♦	♦			
♦	♦				
♦		♦			
	♦	♦			

Table 5.4 Observations of mixing a mixture with a single component

sodium bicarbonate phenol red	*calcium chloride, phenol red*	*calcium chloride, sodium bicarbonate*	*calcium chloride*	*sodium bicarbonate*	*phenol red*	***color***	***temperature*** ↑ *indicates rise* ↓ *indicates loss*	***appearance*** *(gases, precipitates, etc.)*
♦			♦					
	♦			♦				
		♦			♦			

5.7 WRITING CLEAR PROCEDURES

In September of 1999, the Mars Global Surveyor, a 125 million dollar NASA spacecraft, disappeared as it was about to enter orbit around the red planet. When an investigation was performed, it was learned that Lockheed Martin Corporation, the company that built the spacecraft, had programmed it using pounds of thrust, a customary or English system of measuring force, while the navigators at Jet Propulsion Laboratory were assuming it was programmed in newtons, a metric unit of measuring thrust. This major loss highlighted the need of scientists and engineers to communicate in clear and unambiguous terms. The following activities help students learn the difference between ambiguous and unambiguous procedures and observations.

Activity 5.7.1 – Assembling a peanut butter and jelly sandwich
Tell your students to write instructions for the construction of a peanut butter and jelly sandwich. Collect their papers and select a few for illustration. Read the instructions and follow them in a manner consistent with the writing, not necessarily with the intent of the author. For example:

> Student Instruction: Place a dinner plate on a flat table surface.
> Your response: *Place the plate upside down on the table.*
>
> Student Instruction: Take two pieces of bread from the loaf.
> Your response: *Grab two pieces of bread through the wall of the bag.*
>
> Student Instruction: Put peanut butter on the bread.
> Your response: *Place the unopened container of peanut butter on the slice of bread.*
>
> Student Instruction: Spread the peanut butter on the bread with the knife.
> Your response: *Hold the blade and spread the peanut butter with the handle.*
>
> Student Instruction: Spread jelly on the other slice of bread.
> Your response: *Spread jelly on the crust of the other slice.*
>
> Student Instruction: Place the two pieces of bread together.
> Your response: *Place the two pieces together, but with the peanut butter and jelly on the outsides.*

Use this humorous activity to illustrate the importance of writing instructions or recording observations in a precise and unambiguous manner. You may wish to share the following set of more precise procedures with your students.

1. Place a plate on a table with the concave side facing up.
2. Gently hold a loaf of bread on the table with your non-dominant hand.
3. Using your dominant hand, twist the tie-wire counter-clockwise until it is completely unwound.
4. Using your dominant hand, remove the tie and place it on the table.
5. Using your dominant hand, remove the second and third slices of bread from the sack through the opening.
6. Lay both pieces of bread flat on the plate.
7. Grasp the jar of peanut butter with your non-dominant hand.
8. Place the palm of your non-dominant hand on the side of an unopened jar.
9. Grasp the lid of the jar with your dominant hand and twist the cap in a counter-clockwise direction until the jar opens, and set the cap down on the table.

10. Release your dominant hand, and use it to grasp the handle of the knife and dip the blade into the peanut butter, scooping out approximately 2 tablespoons of peanut butter.
11. Spread peanut butter that is now on the knife blade as evenly as possible onto the upper surface of one slice of bread.
12. Repeat steps 7-11, substituting jelly for peanut butter, and applying jelly to the exposed face of the second slice of bread.
13. Place the faces of the bread together with the peanut butter and jelly sides in the middle.

Activity 5.7.2 – Writing unambiguous procedures
Pierre Fermat (1601-1665) was one of the most famous number theorists who ever lived, but unfortunately he was not a great communicator and published only one mathematical paper in his entire life. One of Fermat's most famous unpublished works is known as Fermat's Last Theorem which states that:

$$x^n + y^n = z^n$$

has no non-zero integer solutions for x, y and z when n > 2. Fermat wrote: "I have discovered a truly remarkable proof which this margin is too small to contain." Unfortunately, he never documented his proof, and for centuries mathematicians have been seeking to re-discover it! Scientists, like mathematicians, need to document their work and share it with others. Scientists need to clearly explain their observations, experimental procedures and findings. In this activity you will repeat the process in the preceding activity, although you will be writing instructions for one of the following: (1) putting on a jacket, (2) shuffling a deck of cards, or (3) drawing a map to your home. You directions should be unambiguous so that they can be followed without any assumptions.

5.8 USING HISTORY TO TEACH SCIENTIFIC METHODS

Isaac Newton, one of the most influential physicists of all time, said: "If I have seen farther than other men, it is because I have stood upon the shoulders of giants." Newton, like all scientists, did not make his discoveries in a vacuum, but relied heavily upon the methodologies, data and conclusions of others who had gone before him.

Although educators often do a good job introducing their students to the conclusions of scientists, most do not take time to introduce the methodologies and thought processes that lead to these conclusions. Unfortunately, this may lead students to believe that science is merely a set of conclusions rather than a vital endeavor of discovery.

An apprentice electrician learns the trade not by merely analyzing wiring diagrams or finished circuits, but by watching and imitating the procedures practiced by a master electrician. In a similar manner, a surgical intern learns surgery not by looking at the results of a successful surgery, but by accompanying an experienced surgeon through diagnostic and surgical procedures. To learn science, students need to observe not only the conclusions of scientific research, but also the processes that lead to these conclusions. In the activities that follow, students are lead through historical accounts of major discoveries, and must learn to ask and answer appropriate questions the way the original scientists did.

Activity 5.8.1 – Tracking Down the Cause of Beriberi Disease
It is suggested that the teacher read the narrations and questions and ask for student responses. The questions are designed to reflect those raised by the original researchers.

Narration (1): The Republic of Indonesia encompasses the world's largest archipelago, a chain of islands on the equator north of Australia, stretching one-eighth of the Earth's circumference. Indonesia is the fifth most populated country in the world and was the largest Dutch colony before it gained its independence in 1949. In 1602 (18 years before the Mayflower sailed to America) Dutch merchants formed the Dutch East Indies Company to protect a lucrative trade that they had established with the people of those islands. The Dutch who came to live or trade in the Indonesian archipelago soon learned of numerous diseases never seen in their native Holland. One of the most famous diseases was *beriberi*, an often fatal condition marked by extreme weakness. The Dutch wanted to find the cause of this dreaded disease so they might also be able to find a cure.

By the mid-nineteenth century, French scientist Louis Pasteur (figure 5.13A) had demonstrated that fermentation (the production of alcohol in aging plant material) and putrefaction (the rotting of food) were caused by microscopic organisms in the air. The work of Pasteur and others lead to the establishment of germ theory, which suggests that many diseases are caused by microorganisms. The Dutch East Indies Company was aware of Pasteur's work and commissioned a team of scientists to go to the archipelago to identify the germ causing *beriberi*. Assume that you were one of the researchers on this team as you address the following questions.

> Question: What is the research question that must be answered? *Note to teacher:* *Research begins with a research question or problem. Just as a golfer needs to see the flag of the next hole before teeing off, so a researcher needs to develop a research question before initiating research. In projects like this, students often raise questions that are too specific. For example, their first question might be "Is beriberi caused by mosquito bites?" or "Is it transmitted through the water?" Guide your students to ask more general questions so they can gather sufficient data to proceed.*
> Possible student responses:
> - What is the germ that causes *beriberi*?
> - What is the cause of *beriberi*?

Narration (2): In the late eighteen hundreds, the Dutch research team arrived in Java, the most heavily populated island of the Indonesian archipelago. Before the team could find the germ responsible for beriberi, it was first necessary to collect more data and make more observations.

> Question: What additional observations would you need to make if you were a member of this research team?

Possible student responses:

- What are the symptoms of *beriberi*?
- What are the characteristics of those who have *beriberi* and the characteristics of those who do not have *beriberi*?
- Where is *beriberi* most common?
- Is beriberi correlated with any environmental conditions such as water supply, sanitation, light, etc.?

Narration (3): The Dutch researchers noticed that *beriberi* is accompanied by muscle weakness, weight loss, nervous disorders and ultimately paralysis and death. They found that *beriberi* was common on Java, the heavily populated island that was the seat of the colonial government. They looked for correlations between *beriberi* and various environmental factors (sanitation, water quality, air quality, light intensity, etc.) but found none.

Question: The research team was commissioned to find the germ that caused *beriberi*. What would you do try to find the germ? *Note to teacher: Students should see the need for a control in both observation and experimentation. For example, it is not sufficient to look at the body fluids of sick people alone, because there is no basis of comparison, and no way of concluding if something is abnormal unless you first establish what "normal" is.*

Possible student responses

- Compare the body fluids and tissues of healthy people with those who have *beriberi*.
- Examine under a microscope the saliva, blood, and urine of diseased patients.

Narration (4): Using microscopes, the research team observed the blood, urine and saliva of diseased individuals but found no germs. Finally, after nine months, they left their youngest member, Christiaan Eijkman (figure 5.13B) in charge of the tiny research station and went home to Holland. Eijkman continued his research for ten years.

Question: If you were Christiaan Eijkman, what would your next step be? *Note to teacher: Students often think that if an experiment does not go as planned, it is a failure. Thomas Edison, perhaps the world's greatest inventor, had numerous "failed experiments" in his efforts to invent a light bulb, but said "I have not failed. I just found 10,000 ways that won't work." Edison did not view negative results with distain, and said "I am not discouraged, because every wrong attempt discarded is another step forward."*

Possible student responses

- Collect more data. Make more observations.
- Determine if there are other organisms that demonstrate beriberi characteristics.

Narration (5): Eijkman continued to collect more data on the characteristics of beriberi and those who had it. While working at the research station, Eijkman noticed that some of the chickens living at the research station contracted beriberi-like symptoms. Many of the chickens were sick for several months and some died, while others recovered. Eijkman tried to correlate the onset of the sickness with environmental variables and noticed that the chicken's got sick only after a shipment of their red rice failed to arrive, and they were fed higher grade polished white rice instead. (In nature, rice is covered by a red or brown husk. Polishing removes the husk and allows rice to be stored much longer with a lesser risk of spoilage.) When the superintendent of the research station noticed that they were being fed polished white rice he reordered a shipment of unhusked red rice to reduce his costs. Eijkman noticed that the health of the chickens recovered after they were fed the unhusked rice. Most people would have shrugged off this observation, but Eijkman recognized its significance. As Thomas Edison said, "The eye sees a great many things, but the average brain records very few of them." Eijkman did not have an "average brain!"

Question: What could cause the chickens to recover when fed the brown rice?

Possible student responses

- There may have been a germ in the white rice that was causing the sickness, and this germ was not present in the red rice.
- Perhaps beriberi is not caused by a germ, but by a lack of something that exists in unhusked rice.

Narration (6): Eijkman was not certain that the symptoms exhibited by the sick chickens were due to beriberi, but decided to investigate further. He noticed that chickens at the research station survived almost entirely on a diet of rice, and determined to see if there might be a link between diet and the disease. Eijkman examined health reports from Indonesian prisons and noticed that beriberi was reported in 34 of 63 prisons where polished rice was served, but was rarely reported among 27 other prisons where red, unhusked rice was served. The prisoners, like the chickens at his research station, survived on a diet consisting almost entirely of rice.

Question: What can you hypothesize about the possible cause of beriberi?

Possible Answers:

- There is a poison in rice that is countered by an antidote in the husk.
- Beriberi is not caused by a germ or a poison, but rather by the lack of some substance found in unhusked rice.

Narration (7): Eijkman hypothesized that beriberi was not caused by germs, but rather by toxins in the polished rice that were checked by antidote substances in the unhusked rice. Eijkman designed an experiment to find the toxin.

Question: How would you design an experiment to find a toxin in the white rice?

Note to the teacher: Students should mention two treatments, one with the presumed toxin, and one without it (control). Emphasize the need for controls when designing an experiment. Without a control, it is impossible to interpret the results. Emphasize that it is necessary to change only one variable at time. If two or three potential toxins are tested at a time, it will be unclear which one has caused the problem.

Possible student responses:

- Separate the components of rice and feed each to a different group of chickens.

Narration (8): In his experiment, Eijkman separated healthy chickens into three groups and fed one group only whole grain rice, a second group only rice with the husk removed, and a third group only rice from which both the outer husk and the inner silver skin membrane were removed. Table 5.5 shows the results of his study.

Table 5.5 Results of Christiaan Eijkman's experiment

Group	diet	result
Group 1	Unhusked whole grain rice	remained healthy
Group 2	Rough rice: rice with husk removed	remained healthy
Group 3	Polished rice with husk and silver skin (pericarpium) removed	demonstrated beriberi-like symptoms

Question**:** What can you conclude from Eijkman's data?
Possible student responses:

- Beriberi is not caused by a germ or toxin, but by the absence of something found in the silver skin.

Narration (9): Eijkman's research indicated that there is a vital substance in the pericarpium (silver skin) of rice that prevents the onset of beriberi. Later, this substance became known as a "vital-amine", or vitamin. Although the specific chemical was not yet identified, the concept of vitamins was introduced for the first time. The Inspector-General of Public Health in the Dutch East-Indies ordered that all prisoners receive unhusked rice, and within a very short time beriberi disappeared from the prison system. It was later shown that this same vital substance could be found in barley, prompting the Japanese navy to include barley with polished rice in the food given to sailors, thereby eliminating beriberi from their navy.

Eijkman originally set out to find the germ responsible for beriberi, but instead discovered that the disease was caused by the absence of a "vital substance" (vitamin). In 1929, Christiaan Eijkman was awarded the Nobel Prize in physiology and medicine for the discovery of vitamins, a group of organic substances essential in small quantities for animal nutrition and metabolism. Years later, Casimir Funk, a Polish emigrant to the United States, identified Eijkman's vital material as thiamine, or vitamin B-1.

Eijkman's research can be used to help us understand other historical occurrences as well. As early as the 5^{th} century BC, Hippocrates described a condition now known as scurvy, characterized by bleeding gums, hemorrhaging, and death. Scurvy became a dreaded disease among all who embarked on long voyages. On one of Christopher Columbus's voyages some Portuguese sailors developed scurvy and requested to be dropped off on one of the newly discovered islands so they could die on land, rather than at sea. On a later voyage, Columbus returned to the island and found the men alive and healthy, and named the island Curacao, meaning "cure". In the middle of the eighteenth century, the Scottish physician James Lind noted that sailors given a diet rich in citrus fruit rapidly recovered from the dreaded scourge. In response to Lind's work, the British navy soon required crews to carry citrus such as lime on all voyages, and the British sailors thus acquired the nickname "limeys".

Question: Is there any relationship between these cures for scurvy and the cure that Eijkman found for beriberi?

Possible student responses:

- Yes. Scurvy, like beriberi, is due to a vitamin deficiency (lack of vitamin C). Prior to refrigeration, sailors survived on diets consisting of fish, salted meats, and hard tack, but no vitamin-rich fruits or vegetables. Columbus' abandoned crew members were able to eat vitamin-rich fruits on Curaco, prompting their recovery from scurvy. In a similar manner, James Lind's patients recovered because of the vitamin C in their citrus-rich diets.

Activity 5.8.2 – The scientific method seen in other discoveries

A review of activity 5.7.1 shows that Christiaan Eijkman did not follow the steps of the scientific method in rigid order, but rather used scientific methods as they were appropriate. Although each path to discovery is unique, just as each scientist is unique, methods of science are found in each discovery. Select one of the discoveries below, and research how the discovery was made. Identify the (1) research question, (2) key observations, (3) hypotheses, (4) experiment, and (5) conclusions that were made.

(a) Insulin - Frederick Banting
(b) Pulsars - Jocelyn Bell
(c) Nylon - Wallace Carothers
(d) Electron, isotopes - J.J. Thompson
(e) Other Galaxies - Edwin Hubble
(f) Polio Vaccine - Jonas Salk
(g) DNA - James Watson and Francis Crick
(h) Electromagnetism - Hans Christiaan Orsted

5.9 INDIRECT EVIDENCE - "BLACK BOX" EXPERIMENTS

In science texts you will find diagrams showing the cross-section of the Earth (figure 5.14A), electron orbital clouds (figure 5.14B), and the position of our Solar System within in the Milky Way Galaxy (figure 5.14C). Most readers accept such diagrams without asking how we know what the core of the earth looks like if no one has ever been there, or how we can diagram the structure of an atom if it is too small to be seen, or how we can determine our position in the Milky Way if it is impossible to move outside of it to get a view. These are but of few of the many instances in which scientists must draw conclusions on the basis of indirect evidence. Experiments in which the researcher can neither see nor measure the object of interest are referred to as "black box" experiments. In such instances, researchers must make inferences from inputs, outputs, and other indirect evidence.

Activity 5.9.1 – Determining the contents of a "black-box"

Materials: shoe boxes, duct tape, adhesive (panel adhesive, hot glue, etc.), 2" x 2" board and saw or children's blocks, marble

Teacher preparation: Ask students to bring shoeboxes to class. Using a wood saw, cut 2-inch lengths from a 2" x 2" board (available at most hardware or home improvement stores). Using paneling adhesive, hot glue, or similar adhesive, position the blocks in the base of each box according to the plans shown in figure 5.15A. Place one marble or ball bearing in each box and seal the box with duct tape. Mark the design pattern on the lid using a code so students will not know the design but you will be able to check without opening the box. Alternatively, students can prepare these boxes by gluing children's building blocks or other similar objects to the floors of the boxes. Distribute one box to each lab group.

Student participation: Determine the internal structure of your box by evidence (sound, vibrations, etc.) produced by the moving marble. You may use any technique you wish as long as it does not damage the box or break the seal (figure 5.15B). Draw a diagram indicating where you believe the blocks are located. Compare your diagram with the correct one as recorded by your teacher. Were you able to determine the positions of the hidden blocks? If so, you did so on the basis of indirect evidence because you never opened the box.

Activity 5.9.2 – Determining the structure of the atom with indirect evidence

Materials: peg board, dowels, marbles, graph paper and rulers (27.4).

In 1897, the English physicist Joseph John Thomson confirmed the existence of the electron, a fundamental particle of matter with a negative charge. Thomson believed that an atom was a uniform sphere of positive matter in which negative electrons were embedded, somewhat like raisins in a bowl of pudding (figure 5.16A). In his model, the positive and negative charges were evenly distributed in space. Consequently, a particle with positive charge traveling through the space occupied by the negative and positive charges would be traveling through a "neutral zone" because the effects of the positive and negative charges would cancel and the particle would experience no unbalanced force to move it one way or another. In other words, a positive particle would move straight through the "plum pudding" model, experiencing no deflection.

In the early part of the twentieth century, English physicist Ernest Rutherford investigated the structure of the atom by shooting alpha particles (positively charged helium ions; helium nuclei) through very thin foils of gold and other metals. Most of the incoming alpha particles passed through the foil either undeflected or with only a slight deflection, as would be predicted by the Thomson model. However, there were some startling occurrences in which the alpha particles were deflected at large angles and, at times, straight back in the direction from which they had come! (figure 5.16B). Rutherford explained these results by proposing that the atom is mostly empty space (which explains why most of the alpha particles pass through undeflected) with positive charges concentrated in a dense central core (which explains why positively charged alpha particles are occasionally deflected or reflected).

Rutherford never saw an atom, but inferred its structure by observing the interaction of alpha particles with atoms. Rutherford's classic "black box" experiments revolutionized our understanding of the atom. The following "black box" experiment imitates Rutherford's original experiment. Students are asked to determine the position of pegs ("nuclei") in a hidden pegboard by studying their interaction with marbles ("alpha particles").

Students should work in pairs for this activity. Obtain three pegs and a peg board that has at least five holes on a side (minimum of 25 holes per board, approximately 3 centimeters apart). Wooden pegs may be made by cutting and sanding dowels that have a diameter similar to the holes in the peg board. The pegs should be long enough that marbles can freely move under the apparatus when set up as shown in figure 5.17A. While one student looks away, the other places three pegs randomly in peg board holes and turns the board over, placing it so that the pegs are lying on a flat surface and the board is parallel to the desk surface. A sheet of graph paper should be placed on the board to hide the holes. Without looking under the board to see the position of the pegs, the second student should now roll marbles under the pegboard at selected intervals and record on the graph paper the original path of the marble and any resulting deflections. To ensure that marbles travel straight, they should be launched between two straight edges (figure 5.17B). This activity should be repeated for at least two adjacent sides of the peg board. If the ball is deflected, it indicates that there is a peg in that row or column. Analyze the results to identify the positions of the pegs. Repeat the procedure until you can accurately determine and record the positions of all three pegs.

5.10 EVALUATING HYPOTHESES

Perhaps the most prodigious inventor of all time was Thomas Alva Edison, holder of 1,093 patents, and inventor the first reliable electric light bulb (figure 5.18), movie camera, and sound recording device (phonograph). Although the public remembers Edison for his numerous inventions that revolutionized the way we live and work, scientists remember him primarily for the development of the first industrial research laboratory. Edison assembled a wide array of chemists, physicists, inventors, machinists, botanists, materials experts, and other professionals from around the world to work at his laboratories in Menlo Park and East Orange, New Jersey. In Edison's laboratories, everyone had to be a team player. Edison and his research associates set research agendas, determined job descriptions, worked together towards common goals, and in a short time introduced the world to a dazzling array of useful inventions. Today, Edison's model is used worldwide as engineers and scientists work together with common objectives. The power of scientific teamwork was profoundly illustrated when NASA's (National Aeronautics and Space Administration) team of engineers and scientists landed men on the Moon, and when a nationwide team of biologists announced the sequencing of the human genome. The activity that follows illustrates the value of teamwork and the need to re-evaluate hypotheses in light of new data.

Activity 5.19.1 – Tangrams & teamwork

Teacher preparation: This activity must be prepared in advance by the teacher. Download the tangram sheet from the companion website or make your own using the scale diagram in figure 5.19, making certain each piece is labeled appropriately. Cut the shapes as shown and make a set of five envelopes for each team as follows: (a) I,E,H; (b) A,A,A,C; (c) A,J; (d) D,F; (e) B,C,F,G. Indicate the contents of each envelope by writing the components on the outside. Separate students into teams of five and read the following instructions.

- Each team member gets one of the envelopes.
- Each team must assemble five separate squares from the pieces provided.
- Each team member must construct a square. You can not work on others' squares.
- You may not talk or make gestures.
- You cannot take any pieces from another student – you can only give pieces.

(1) What does this teach about scientific teamwork?
(2) What does this teach about the scientific method?

Note to teacher: Although a variety of squares can be made from the pieces of paper provided, not all are part of the final five-square solution. Therefore, if one student constructs a square that is not part of the solution, and is unwilling to break his or her square and distribute the pieces to team mates, the team can never construct all five squares. Participants must keep their attention on the group goal of constructing all five squares, and be willing to give up their own work to achieve the final team goal.

This exercise is an excellent tool in teaching teamwork, a necessary element in any modern research laboratory. Students must look at the needs of the group, not just their own needs, if their team is to be successful in achieving the final goal. They must pay careful attention to the needs of others and be willing to disassemble their own squares to provide pieces needed by others.

This exercise is also an excellent way to introduce the need to maintain flexibility when developing hypotheses. Although a hypothesis may appear to explain experimental results, it may have to be replaced by a different hypothesis that is more consistent with the data. Students who are unwilling to disassemble their own "hypotheses" (in this case the squares they have made) will be unable to reach a final conclusion.

ANSWERS

5.1.1-5.1.3 The activities in this section are designed to develop a need to know. Although this is difficult to quantify, the teacher will know when it has occurred by student attitudes and the questions they raise

5.2.1 This activity has been used throughout the years to encourage students to make careful and comprehensive observations. By observing both the unlit and the burning candle, students can see the influence of the flame. Table 5.2 is a partial list of the types of observations that can be made. You may wish to award points on the quantity of observations, detracting points for statements that are not observations (inferences, inaccurate observations, irrelevant comments.)

5.2.2 Students should generate a wide variety of questions. The following information may help the teacher prepare for such questions. The cotton wicks of some new candles are dipped in paraffin, while others are not. If there is no paraffin in the wick, it will burn rather rapidly until the heat from the flame starts to melt the paraffin below it. The wick is a string, and liquid paraffin is drawn up it and into the flame by capillary action. The light and heat produced by the combustion of the wick is insignificant compared to the light and heat produced by the combustion of the paraffin. A thin candle will burn much more rapidly than a thick candle because it runs out of fuel quicker. Similarly, a candle will burn down much more rapidly if the melted paraffin is allowed to drain out of the reservoir away from the wick.

Paraffin has a rather low melting point (53°C) and becomes a liquid as the flame approaches. Liquid paraffin flows into the well created by the flame and then moves up the wick by capillary action. As the liquid paraffin approaches the flame, it vaporizes. The flash point of paraffin is 198°C. When it reaches this temperature it combusts:

$$2C_{30}H_{62} + 91O_2(g) \rightarrow 60CO_2(g) + 62H_2O(g)$$

Oxygen and paraffin are consumed and carbon dioxide and water vapor are produced. The condensate that students observe forming on the sides of a cooled beaker placed over the candle is from the water formed during combustion. The carbon dioxide will dissolve into the bromthymol blue droplets placed on the funnel. Dissolved carbon dioxide reacts with water to form carbonic acid (H_2CO_3):

$$CO_2 + H_2O \rightarrow H_2CO_3$$

Bromthymol blue turns greenish as the pH drops due to the formation of carbonic acid. The combustion requires oxygen, and thus the flame will be extinguished if all of the oxygen is consumed. The length of time that a candle will burn when placed under a beaker is directly proportional to the volume of the air trapped in the beaker. Thus, students should notice that the flame burns twice a long when placed under a 1000 mL beaker as when placed under a 500 mL beaker.

Another common product of combustion is soot, a black powdery form of carbon that rises up in fine particles within the flames and smoke. Soot collects on glassware that is held immediately above the flame. Soot production is more rapid when there is less oxygen, and therefore students will notice the rate of soot deposition increases rapidly as oxygen is depleted when a beaker is lowered partially over the flame. Soot and unburned hydrocarbons are released in the smoke of the flame, making it possible to relight a candle by igniting the smoke. It is generally possible to relight a smoking candle from a distance of about 1 centimeter.

5.3.1 Observations may include only those things that are actually observed, such as color, shape, and height. Students should not make inferences, such as growth, root structure, or type of "plant".

5.3.2 Observations may include only those things that are actually observed, such as color, appearance, shape, and movement. Students should not make inferences such as the nature of the *raisidia*, the composition of the liquid, or the composition of the bubbles.

5.4.1 It is likely that each group will derive a different ranking, and these differences can provide an interesting platform for discussion. During the discussion phase, make certain that each team provides a rationale for their rankings. Often, different rankings are a result of different assumptions. Encourage students to state their assumptions and discuss the logic of their responses given these assumptions. Table 5.6 lists potential benefits of the items listed.

Table 5.6 Possible uses of items while on the surface of the Moon.

two 100kg tanks of oxygen	Oxygen is necessary for respiration. One can survive only about five minutes without oxygen.
10 liters water	Water is necessary for all biological processes. Without water, one can survive only about 5 to 9 days.
stellar map	A stellar map can be used to orient oneself for the journey to the research station.
10 kg dehydrated food	Food is required for energy for the long trek, but some students will note that it will be impossible to eat food unless it can be delivered to the mouth without breaking the seal of the astronaut's suit. Some

	students may rank this item low, supposing that there will be no way to prepare it outside of the pressurized environment of the space capsule.
solar-powered FM 2-way radio	The FM radio can be used to transmit a distress signal to the research station. FM radios, however, transmit only by line of sight, which will be more difficult to obtain on the Moon given the greater curvature of the Moon's surface. The lack of an atmosphere should not hamper FM transmission because FM signals do not reflect off the ionosphere (which does not exist on the Moon) as do AM signals.
50m of nylon rope	Rope maybe useful for climbing or tying things together.
first aid kit	The first aid kit will be of value only if it is designed to be used with space suits. Conventional first aid kits will be useless since astronauts will not be able to open their suits to apply bandages, etc.
parachute silk	Due to the lack of atmosphere, the solar radiation on the lighted side of the Moon is very intense, and the silk can provide a good shelter from the solar rays.
life raft	Life rafts often contain compressed carbon dioxide, which may have use a propellant. The raft can be used to carry other items.
traditional signal flares	Signal flares can be used to make distress signals. Flares produce their own oxygen and may therefore work in the atmosphere-free environment of the Moon.
two 0.45 caliber pistols	Some students will argue that these can be used for self-propulsion, but they would be of very limited value. Oxygen is released from the chemicals in the gunpowder, allowing the pistols to work on the surface of the Moon.
case of dehydrated milk	This could provide some nutrition if there is a way to mix it and ingest it in the absence of atmospheric pressure.
portable heating unit	Most portable heating units emit infrared radiation, but unfortunately most of this heat would probably reflect off the surfaces of the space suits, and therefore have little effect on keeping the astronauts warm.
magnetic compass	There are no magnetic poles on the Moon, so a magnetic compass would be useless.
box of matches	Matches require oxygen to burn, and therefore would be useless in the oxygen-free environment of the Moon.

5.4.2 Students will explain their drawings using the overhead projector.

5.5.1 Graphing and experimental design:

(a) (1) pH of water, (2) height of plants, (3) type of plant, age of seeds, temperature, light, soil, etc., (4) Seeds of the same plant were grown in containers that were given water of different pH. (5) The growth of this species is a function of the pH of the water it receives. When pH is too low or too high, growth is little, but when the pH is in an intermediate zone, growth is significant.

(b) (1) altitude, (2) molecules of ozone destroyed per CFC molecule, (3) source of air, ozone concentration, temperature, light intensity, etc., (4) A series of chambers are established with atmospheric conditions of differing altitudes. An equal amount of CFC is introduced into each and the level of ozone is measured after a given time. (5) Chlorofluorocarbons (CFCs) are stable molecules that served as coolants in air conditioning units and propellants in aerosol cans. Although CFCs do not interact with ozone at lower elevations, they cause significant degradation at higher elevations. Since ozone protects us by filtering ultraviolet light, such research has lead many countries to ban various uses of CFCs.

(c) (1) voltage, (2) current, (3) resistance, circuit design, etc., (4) The current in a circuit is measured as you increase the voltage. (5) An increase in voltage causes an increase in current. Physicists know this relationship as Ohm's Law, $V=IR$.

(d) (1) year car was manufactured, (2) the concentration of hydrocarbons in the exhaust, (3) make and model of car, manner in which exhaust is measured, etc., (4) The exhaust of new cars is analyzed as they roll off the production lines. The average hydrocarbon exhaust data for each production year is plotted. (5) Each year the automobile manufacturer in this study produces cars with lower hydrocarbon emissions.

(e) (1) wavelength of light, (2) rate of photosynthesis, (3) temperature, type of plant, way in which photosynthesis is measured, etc., (4) Plants are grown in a growth chamber with all conditions being similar except the wavelength of light to which they are exposed. (5) Plants grow fastest in relatively short and long wavelength light, and slower in mid-wavelength light.

(f) (1) carbon dioxide concentration, (2) rate of photosynthesis, (3) type of light, temperature, humidity, soil moisture, etc., (4) Plants are grown in controlled chambers of differing carbon dioxide concentration. (5) At low and mid-carbon dioxide concentrations, an increase in the carbon dioxide concentration results in an increased rate of photosynthesis, but at high carbon dioxide concentrations the rate changes little.

(g) (1) number of cigarettes smoked per day, (2) percent of population with emphysema, (3) This is a study rather than an experiment. Since it is unethical to perform such experiments on humans, one can collect human-data only by examining statistics from the population. To minimize the influence of other factors, one could study only individuals from the same gender, occupation and age; (4) Conduct a survey in which you ask people how many cigarettes they smoke per day on average, and whether or not they experience emphysema (5) Emphysema is a lung disorder in which there is a loss in the oxygen-absorbing air-sacs known as alveoli. The data suggests that smoking causes emphysema.

(h) (1) height of the forest tree canopy, (2) number of bird species identified, (3) type of forest, location, climate, technique for counting species, (4) Identify the number of bird species found within given plot of land. Measure the average height of the forest canopy. Repeat these measurements for other regions within the forest. (5) As a forest matures and the canopy gets higher, it supports a greater diversity of bird species.

5.6.1 Phenol red solution is primarily water, and both calcium chloride and sodium bicarbonate dissolve within it. The dissolution of calcium chloride is an exothermic process and produces heat (temperature rises):

$$CaCl_2 + H_2O \rightarrow Ca^{+2}(aq) + 2Cl^{-}(aq) + heat$$

The dissolution of sodium bicarbonate, however, is an endothermic process and consumes heat (temperature falls):

$$NaHCO_3 + H_2O + heat \rightarrow Na^{+}(aq) + HCO_3^{-}(aq)$$

The observed temperature changes are due primarily to the interaction of these two reactions. The calcium ions then react with the bicarbonate ions to produce a white precipitate (calcium carbonate), water, and carbon dioxide gas. Carbon dioxide is the gas that causes the zip-lock bag to expand. Calcium carbonate is the precipitate that settles in the bottom of the bag.

$$Ca^{2+}(aq) + 2HCO_3^{-}(aq) \rightarrow CaCO_3(s) + H_2O(l) + CO_2(g)$$

The carbon dioxide produced in this reaction reacts with water to form carbonic acid (H_2CO_3), which turns phenol red from red to yellow.

$$CO_2 + H_2O \rightarrow H_2CO_3$$

As a result of their research, students should be able to isolate the variables responsible for different phenomenon and answer the questions:

(1) Calcium ions and bicarbonate ions react to produce calcium bicarbonate, a white precipitate.
(2) The dissolution of calcium chloride in water is exothermic.
(3) The dissolution of sodium bicarbonate in water is endothermic.
(4) The precipitate (calcium carbonate) is formed by mixing two solutions (sodium bicarbonate and calcium chloride solutions).
(5) Carbon dioxide is produced only when the two solutions are mixed.

5.7.1 After two or three tries, students should be able to write unambiguous instructions for assembling a peanut butter and jelly sandwich.
5.7.2 Students should be able to write unambiguous procedures for each of the activities.
5.8.1 This is an interactive discussion. No written response is required.
5.8.2 Students will write a history of one of these great discoveries, clearly identify the 1) research question, (2) key observations, (3) hypotheses, (4) experiment, and (5) conclusions that were made.
5.9.1 After they make their observations, students should draw diagrams of the contents, including the positions and relative sizes of each object in the box, and then copy these diagrams to transparencies so they can be projected and discussed by the class. Students should explain the various techniques used in the developing their hypotheses. Some students may determine the center of gravity by balancing the box on their finger and then making inferences about the distribution of masses within. Other students may tilt the box gently back and forth and listen for when it hits obstructions. Still others may shake, rotate, or slide the box to gather information. Following the discussion, you may wish to open the boxes to show students their internal design.

5.9.2 Students should correctly locate the position of the pegs ("nuclei") on the graph paper by noting the rows and columns in which marbles ("alpha particles") are deflected or reflected.

5.10.1 (1) This activity shows that researchers must work together to solve problems. When an individual is unwilling to share his or her information with others, the team goal cannot be achieved. One should look at the needs of the team, and not just at his or her own needs. (2) The scientific method is not linear. Often times one has to redesign experiments or re-evaluate hypotheses in light of new data. The researcher must be flexible and willing to reassess his or her ideas in light of empirical data.

REFERENCES