Activity #1 - Introduction to the Scientific Method

Learning Goals:

- To become familiar with the basics of the scientific method
- To use the scientific method to explore a practical laboratory problem
- To develop skills working in small groups

Lab Background:

All branches of scientific inquiry may be divided into two main groups: the empirical sciences and the non-empirical sciences. Biology, along with chemistry, physics and their related disciplines, is an empirical science with the objectives to explore, explain, describe and predict the occurrences in the universe. For valid evidence, empirical science depends on events that can be observed either directly or by the use of instruments that extend the perception of the observer. The non-empirical sciences of logic and pure mathematics do not depend on this sort of evidence for proof of propositions. Biological knowledge is based on situations in which an individual made and recorded an observation.

Ultimately, then, scientists rely on sense organs, or "Doors of Perception", to use Aldous Huxley's phrase, to understand the world. However, technology has extended the perceptual limits and the sensitivity of man's sensory equipment. The microscope and telescope have greatly augmented the resolution of the vertebrate eye and ushered in great advances in many fields of science. Our eyes are not receptive to electromagnetic wavelengths above 760 nanometers (nm) such as infrared radiation, which the rattlesnake detects and uses to locate warm-blooded prey. Nor can we perceive wavelengths below 380 nm such as ultraviolet radiation, which the honeybee can see and use for orientation on cloudy days. Instruments can, however, detect and measure these wavelengths, thus extending our sensory range.

We lack sense organs to deal with certain basic aspects of reality. Magnetism was not part of the world that primitive man perceived, because he lacked sensory equipment to observe it. Only after the invention of instruments (e.g., compasses) that converted this non-sensible form of energy into one humans could perceive could we obtain sufficient data to understand and use magnetism. It is interesting that certain creatures evidently possess sense organs which allow them to detect the earth's magnetic field. Pigeons seem to have a built-in compass that they can use for orientation on completely overcast days. There are doubtless other forms of energy of which we are unaware due to a lack of appropriate sensory equipment, and until devices are invented to transform these bits of reality into forms we can observe, they can never become a part of our world. **From the outset, a scientist must recognize his or her complete dependence on sensory data**.

I. The Conceptual Framework of Science

Accurate, unbiased observation is a characteristic of extreme importance in science. Without it, any attempts to generalize about these observations would be fruitless. Suppose we were each presented with a different leaf and asked, disregarding any preconceptions of what a leaf is, to describe it accurately. Even with a "simple" object such as a leaf, the task would be a large one. Humans have a distinctly visual approach to the world, and this would probably be apparent in the visual nature of much of our leaf description. Few of us would think to smell, taste, or feel the leaf and include these data in our description, but these are also valid ways to collect observations.

Even if we had been examining leaves from different species of plants, we could, upon pooling our data and analyzing it, find a core of features that all leaves have in common. These features would constitute our concept of a leaf. If our leaf concept is a good one, it could be used to characterize all newly discovered objects as leaves and non-leaves. With a large number of concepts such as this, stored for future use, observational data can be pigeonholed conveniently. A new object is either familiar or unfamiliar, living or nonliving, red or non-red, etc. This process of taking newly encountered stimuli and comparing them with previous experiences, generalized into concepts, is efficient and has probably evolved as the best way for organisms to deal with a heterogeneous environment. Is not what we consider reality the total of such learned concepts? Of these mental images that make up our conceptual framework, some have greater generality than others. For example, we have concepts of <u>hardness</u>, <u>inside</u>, and <u>outside</u>, <u>shape</u> and <u>place</u> which have great generality and apply to many things in our experience. An extremely fundamental concept is that of a <u>thing</u>.

Scientists also deal with reality by comparing newly encountered data with generalized concepts. However, because of the critical importance of accurate observational data, scientists are much more painstakingly precise in their formulation and use of concepts. For example, instead of simply stating that leaves are green (at least sometimes), scientists might be inclined to extract, identify and quantify the actual pigments present. The concept of heat and cold is common to us all, but when expressed in terms of another concept called degrees, it has much more precision. The precise definition of temperature required the invention of the thermometer, which sharpened our own sensory equipment, to allow this precision. In summary, scientists are more rigorous than the general population in defining concepts. That a leaf is a modified branch subtending a bud may not be immediately apparent, but it is the most inclusive definition.

II. The Scientific Method

Recognizing the importance of empirical evidence, let us consider the "scientific method". A scientist, **after becoming familiar with a particular set of previously made valid observations**, usually directs his attention to a subset of these established facts. This subset suggests a **question** which the scientist tentatively answers in the form of an **hypothesis**. The nature of this hypothesis determines what has to be done in order to test the validity of the hypothesis. For example, upon considering that all of the leaves observed had a system of tubes branching out from the main stem, one might ask the question "what is the function of these branching tubes?" As one tentative answer to this question, a research hypothesis (H_r) is stated. **The research hypothesis is stated in general terms and often suggests an experiment that could test the hypothesis.** In reference to the question posed above,: one possible research hypothesis might be

H_r: These tubes are responsible for conducting vital substances to different parts of the leaf.

One means of searching for evidence would be to take two plants with healthy-looking similar leaves and on the leaves of one plant, cut each of the main tubes just above where they leave the stem. This plant would be termed the experimental. To the leaves on the other plant, you would do nothing and this would act as the control against which you could compare the experimental. You would also be careful to keep both plants under exactly the same environmental conditions, so that the only difference between the two groups would be one factor. Your research hypothesis predicts that cutting the tubes should interrupt the flow of vital substances to the leaf and have some observable effect.

Experimental outcome predictions constitute **two additional hypotheses, the null hypothesis (H_o) and the alternative hypothesis (H_a).**

The **null hypothesis (H_o)** is the hypothesis of no differences and it is stated in anticipation of being rejected (i.e., there is a difference).

The **alternative hypothesis (H_a)** is the prediction of the expected result of the experiment if your research hypothesis is correct.

Therefore, **if the evidence allows you to reject H_o, you can accept H_a.**

In reference to this particular investigative design, the null hypothesis would be stated:

H_o: There will be no observable differences between the plants with the cut tubes and the intact control plants.

The alternate hypothesis would take the form,

H_a: The plants with cut tubes will be less healthy than the intact control plants.

If after a period of time, you find that the leaves of the experimental plant are not different in appearance from those of the control plant, you could conclude that H_o was correct. If your research hypothesis (H_r) were true, one prediction (P_1) would be that the leaves of the experimental plant would have died or would have suffered some observable adverse effect when compared with those of the control plant.

1. If H_r is true, then so is H_a.

But (as the evidence indicates) H_a is not true.
Therefore, H_r is not true. (i.e. the research hypothesis has been rejected)

However, if the H_a is in fact observed, you cannot conclude that your research hypothesis is true. **One can never conclusively prove a hypothesis**. The following argument is deductively invalid:

2. If H_r is true, then so is H_a.
(As the evidence shows) H_a is true.
Therefore, H_r is true.

One could never be completely certain that the leaves did not die by sheer coincidence or due to some other unknown effect.

It can, however, be said that argument 2 suggests or indicates with greater probability that the research hypothesis was correct. Doing the above experiment with 10 plants in each group would also lend greater credibility to the research hypothesis, but it could never prove it.

It is also important not to over-generalize results. Conclusions drawn from data collected under one set of conditions may not be valid under different conditions. This is often the case in fields such as genetics and evolution. Certain forms of genes (alleles) may be detrimental under one set of circumstances, but beneficial under another. A classic example of this is Sickle Cell hemoglobin. Individuals with two copies of the sickle cell allele (homozygotes) suffer from anemia, but are also resistant to malaria. Individuals with one copy of the sickle cell allele and one normal allele (heterozygotes) do not suffer from anemia but are still resistant to malaria. If one lives in an area where malaria is common, carrying the sickle cell allele is advantageous, which is why it is more common in such areas.

So, despite what you may hear or read, **science never proves anything conclusively**. Scientists deal in terms of probability. We shall learn more about the importance of statistics in establishing levels of certainty for given outcomes later in this course.

Let us review the whole process again. First, observations are made. These observations suggest a question which is tentatively answered in the form of a research hypothesis. The next step in the scientific method involves stating the research hypothesis in a testable form and searching for evidence that will determine if the predictions made by the research hypothesis are correct. Hypothesis-testing takes two general forms which we will, for convenience, call the experimental approach and the non-experimental approach. See Figure 1.1 for a scheme of the scientific method. The scientist evaluates the hypothesis in light of the data, and revises the hypothesis if necessary, re-testing the revised hypothesis. The last step in the scientific method is to communicate your results to the scientific community.

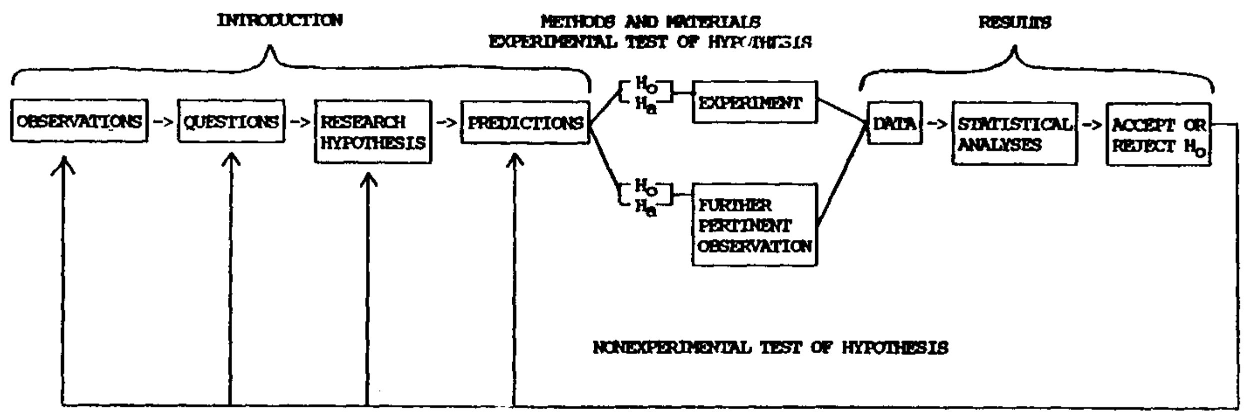

FIGURE 1.1 SCHEMA OF THE SCIENTIFIC METHOD
(Note that the results from one investigation usually lead to additional investigations.)

The experimental approach that we have illustrated above involves establishing two situations that differ with respect to only one factor (variable). This factor will determine if the prediction of the hypothesis is correct. The situation with the varying factor is referred to as the **experimental group**. The unmanipulated situation from which the experimental group varies is called the **control group**. Any difference between the experimental group and the control group should be due to the single varying factor, the factor that will test the research hypothesis.

The factor that is manipulated or controlled by the experimenter is the **independent variable.** This is the variable being investigated; in the example above, the independent variable is whether or not the vein was cut. The **dependent variable** is the factor being measured, which is dependent on the independent variable. In our leaf example, the dependent variable could be the turgor or health of the leaf. That is, the health of the leaf is dependent on whether or not the vein has been cut.

In many areas of science, it is impossible to use the experimental approach to hypothesis testing, usually because it is not feasible to create an experimental group (that is, to impose a treatment). This is clearly the case with sciences involving interpretations of past events such as geology. In the biological sciences, hypotheses in the disciplines of evolution, ecology and animal behavior are frequently not amenable to experimental testing, and must be approached using a **non-experimental or observational approach**. For example, it has been observed in many species of hawks that the female is significantly larger that the male. It has been hypothesized that this size difference allows the male and female hawks to capture prey of different sizes, with the female taking the larger prey, the male, smaller prey. One possible advantage of this would be less direct competition for food between a pair of hawks as they try to raise their young. But how could this hypothesis be tested experimentally? Still, the hypothesis makes certain **predictions** which, if found to be correct, test the probable validity of the hypothesis. What are some of the predictions testing the above hypothesis? How would you gather the necessary data?

The **non-experimental**, or **observational**, approach to hypothesis testing, like the experimental approach, involves a search to determine if the predictions made by the research hypothesis are correct. The search usually involves going out into the real world and making additional observations. If male and female hawks take different-sized prey, one should be able to observe it, either by directly determining what the birds are eating or by examining the non-digestible remains (castings) of what they have eaten. The null and alternative hypothesis in this case would be stated:

H_o: There will be no observable size difference in the prey captured by male and female hawks.

H_a: There will be an observable size difference in the prey captured by male and female hawks.

Both approaches are concerned with determining if the predictions of a hypothesis are correct. The experimental approach involves manipulating some characteristic of the phenomenon being studied and comparing it with the unmanipulated state. The non-experimental approach involves making additional pertinent observations suggested by the research hypothesis. Both approaches are valid scientifically. One of the major biological theories of all time, natural selection (Darwin, circa 1860), was formulated with a non-experimental approach.

III. Non-scientific approaches to problem solving

Science differs from many other areas of human endeavor in that it is evidence based, is testable, and allows one to make predictions. Non-scientific concepts such as beauty, morality, spirituality, and love typically do not have the characteristics described above. One example that has been in the news recently is “Intelligent Design,” which holds that some aspects of living organisms are too complex to have arisen via non-directed evolutionary mechanisms and therefore must have been designed by a “creator.” How can this idea be tested? What predictions does it make? Is this science? Should it be taught in science classrooms? In the 2005 federal court case of *Kitzmiller versus the Dover Board of Education*, the judge ruled that Intelligent Design is not a science, and therefore cannot be mandated to be discussed in public school science classrooms. You should be able to distinguish between scientific and non-scientific methods.

IV. Lab Exercises

This exercise will give you some practice in applying the principles of the scientific method, and in the development of hypotheses. To accomplish this you will need to both read about an organism of your choice and make some initial observations. We will do this now and over the course of the semester. For each experiment, we will identify a research hypothesis, null hypothesis, alternate hypothesis, independent and dependent variables. After each experiment, we will consider follow-up studies to address questions raised by our initial work. During week 12, you will submit a proposal detailing a follow-up study to be conducted during week 13 which will then be written up as a formal lab report.

Let us begin with a "thought experiment": an analysis of a piece of moldy bread.
The scientific method begins with a thorough and detailed analysis of the subject being studied.
First, we make observations. **What are the characteristics exhibited by growing mold?**

The problem to solve is: **What can be done to prevent the growth of mold?**

The next step in the scientific method is to combine the new observations with background knowledge (when have you observed moldy bread before? What circumstances may have promoted the growth of the mold? What other types of foods get moldy, which ones do not get moldy?) and **develop a research hypothesis**. Brainstorm within your group and develop several hypotheses (write them below, and use the back of the sheet for extra space if needed) about things that could control the growth of mold. After a few minutes, we will combine ideas from the entire lab.

Next we will design experiments to test these hypotheses. Good experiments have the following characteristics:

1. **Controls**—serve as points of reference
   negative control—result being measured should not be observed (e.g. bread not sprayed with mold spores should not grow mold)
   positive control—result being measured should be observed (e.g. bread sprayed with mold spores should grow mold at room temperature)..

2. **Law of parsimony**—only one variable should be tested in a given experiment. If more than one parameter is varied, how would you know which one caused the effect?
   --also known as Ockham's razor, or as KISS

3. **Independent variable**—parameter that is varied by the experimenter

4. **Dependent variable**—parameter being measured—it is dependent on the independent variable.

In the space below, write out the hypothesis that your group will test and design an experiment to test it—Be creative! One of the members of your group should be prepared to explain your experiment to the rest of the class.

The following materials are available for this "thought experiment":

- "natural" wheat bread, wheat bread with preservatives, white bread with preservatives, sourdough bread
- 37°C incubator (human body temperature), 30°C incubator (slightly warmer than room temperature), 5°C cold room (refrigerator temp), -20°C freezer
- brown paper bags (dark), wet paper towels (humid), desiccator chamber (dry), anaerobic chamber (no oxygen)
- antibiotic solutions, anti-fungal substances
- if you would like something not listed above, please ask!

In setting up your experiments, please take into account that all bread treatments would be done in sealed plastic zip-lock bags.

Additional factors to consider for your experiment:

- What if there is growth on all treatments? How could you determine the effect of specific treatments?
- Would the length of incubation make a difference? Should the samples be checked daily?

1. Based on your hypothesis, *list what you intend to do to each piece of bread on a separate row in the table below*.

2. Identify your **positive** and **negative** controls—and remember that some experiments will require more than one of each kind of control.

3. Predict the results of your experiment and record them in the table below.

4. After a limited time, your professor will come to each group and tell you the result that would be observed for each treatment.

Treatment	Expected result	Observed result

Was your hypothesis correct? If not, how could you modify your hypothesis? Do your results raise any new questions or suggest any new experiments?

Summary Questions

These are your best way of preparing for the quiz next week!

1. Name the steps used in the Scientific Method.

2. Explain the difference between a research hypothesis, the null hypothesis, and the alternative hypothesis.

3. What is the purpose of a control in an experiment?

4. Describe an example of how we use elements of the scientific method in our everyday thinking.

5. What types of questions cannot be addressed using the scientific method?

6. Why can it be said that the scientific method is self-correcting?

7. How does a hypothesis differ from a guess? How does it differ from a theory?

8. Why do bakeries include preservatives in bread?

9. Why do some bakeries not use preservatives?

10. Mold is a type of fungus, as is the organism that causes athlete's foot. Why not include the active ingredient from Micatin (an athlete's foot remedy) in bread?

11. What types of tests do you think would need to be conducted before a new preservative could be used to prevent the growth of mold in bread?

For additional practice with hypothesis development and the scientific method:
See the online exercises at the McGraw-Hill Connect web site:
http://connect.mcgraw-hill.com

Supplemental Exercise:

Examine the cartoon on the next page.

1. Discuss the research hypothesis, null hypothesis, and alternative hypothesis implied in the cartoon. Is this research hypothesis testable? If you believe so, then explain what sorts of observations you would make to test it.

2. Scientists seek to provide evidence to "support" hypotheses. Why don't scientists say that their evidence "proves" hypotheses?

3. Which of the following are experimental tests, and which are naturalistic observations?

a. Measurements made on the bones of an extinct species are compared with similar measurements made on the bones of a related living species.

b. The activity of white blood cells in a blood sample taken from stressed rats is compared with the activity of white blood cells taken from unstressed rats.

c. A group of animals is fed a certain chemical to see whether they will get cancer as a result.

d. A list of the species found in a particular square meter near the coast is compared with another list of species found 20 meters farther inland.

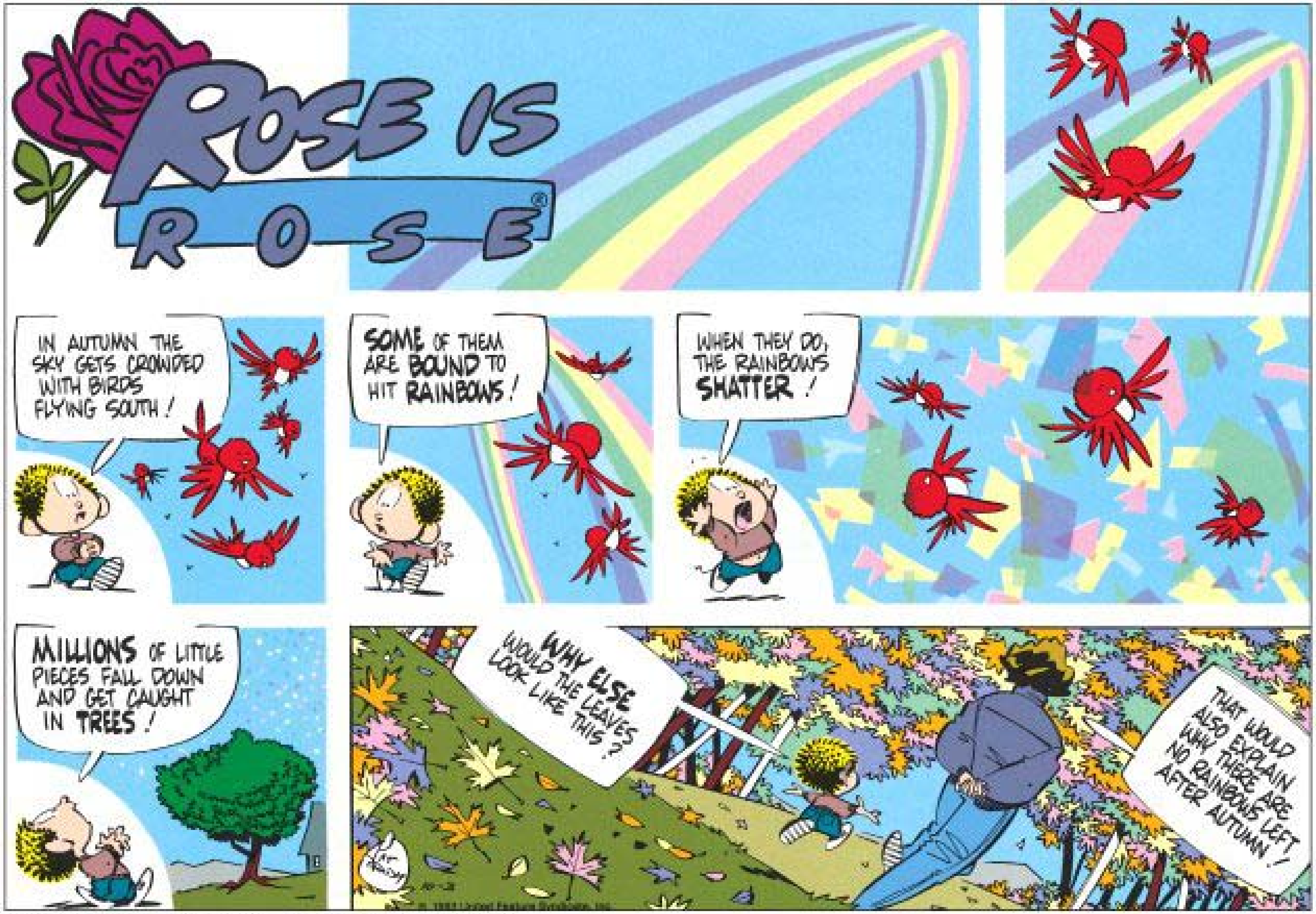

Figure 1-1 Biology Today, 3/e (© 2004 Garland Science)