The Process of Scientific Inquiry

Before coming to lab, you should read through all of Lab Topic 1.

Introduction

Scientific inquiry is a particular way of answering questions. It can't be used for all types of questions. The questions that can be answered by science must meet specific guidelines and scientific investigations must be carried out using certain rules. When an investigation is designed properly and meets these guidelines, then the results are acceptable to other scientists and are added to the body of scientific knowledge. If an investigator cannot show that his or her experiment was done according to the guidelines, then the results of that experiment will not be recognized as valid by other scientists.

The purpose of such guidelines can be understood by comparing them to sports records. For example, a new record set in a track and field event only counts if the meet was approved by the governing body that sets the guidelines. The site and equipment used are scrutinized to be sure that they are within the regulations and the athlete is tested for use of illicit substances. Only when these required conditions are met is the record certified as valid.

In this laboratory you will learn about the basic elements of scientific inquiry and how to apply this process to solving problems.

Outline

Exercise 1.1: The Black Box

Exercise 1.2: Defining a Problem

Exercise 1.3: The Elements of an Experiment

Exercise 1.4: Designing an Experiment

Exercise 1.5: Application of Scientific Inquiry

EXERCISE 1.1

The Black Box

Objective

After completing this exercise, you should be able to

1. Explain the scientific inquiry method, which you apply to various examples in this exercise.

You will use the "black box" exercise as a model of how scientific inquiry is carried out. Each lab team has a container with one or more objects sealed inside. Each team also has an empty container of the same type and a plastic bag holding objects that might be inside the sealed container. Your task is to devise a way to find out what is in the box without opening it. The steps listed below give you some idea of how to proceed. Answer the questions to keep a record of what you did.

Procedure

1. Make observations.

   Investigate the container by any means available to you *except* opening the container.

   What are your observations?

   How did you make your observations?

   What other methods that are not available to you right now might be used to make observations?

   Why is making observations an important first step in solving this problem?

2. Make a guess about the contents of the box.

What did you base your guess on?

3. For now, you still can't open the sealed container. How can you test whether your guess is correct?

4. Use the method you described in step 3 to check your guess. Record your results below. Was your guess correct? How sure are you?

5. If you aren't sure you know yet what is in the box, what should you do next?

6. Short of opening the box, what's the best you can do to find out what's in it?

7. Suppose you tell your instructor what you have concluded is in the box, and he or she says that you are wrong. What are some things that could have led you to make the wrong conclusion?

8. Summarize the methods you used to solve the problem of the black box.

The steps you used to determine the contents of the black box are similar to the procedure followed in one type of scientific investigation. The investigator poses a question—for example, "What is in the box?" From the question and preliminary observations, the investigator makes an educated guess (known as a hypothesis) about the answer. She then devises an experiment to test the hypothesis, performs the experiment, and draws a conclusion from its results. The hypothesis may be revised, and further experiments may be done if the results are not conclusive. Eventually the investigator reaches a point where she is confident that her conclusions are correct.

In Exercises 1.2 and 1.3 you will learn to recognize the elements of a good scientific investigation. In later laboratories you will design your own investigations.

EXERCISE 1.2
Defining a Problem

Objectives

After completing this exercise, you should be able to

1. Identify questions that can be answered through scientific inquiry and explain what characterizes a good question.
2. Identify usable hypotheses and explain what characterizes a good scientific hypothesis.

Every scientific investigation begins with the question that the scientist wants to answer. The questions addressed by scientific inquiry are based on observations or on information gained through previous research, or on a combination of both. Just because a question can be answered doesn't mean that it can be answered *scientifically*. Discuss the following questions with your lab team and decide which of them you think can be answered by scientific inquiry.

What is in the black box?

Are serial killers evil by nature?

What is the cause of AIDS?

Why is the grass green?

What is the best recipe for chocolate chip cookies?

When will the Big Earthquake hit San Francisco?

How can the maximum yield be obtained from a peanut field?

Does watching television cause children to have shorter attention spans?

How did you decide what questions can be answered scientifically?

A scientific question is usually phrased more formally as a **hypothesis,** which is simply a statement of the scientist's educated guess at the answer to the question.

A hypothesis is usable only if the question can be answered "no." If it can be answered "no," then the hypothesis can be proven false. The nature of science is such that we can prove a hypothesis false by presenting evidence from an investigation that does not support the hypothesis. But we cannot prove a hypothesis true. We can only support the hypothesis with evidence from *this particular investigation.* For example, you used hypotheses to investigate the contents of your sealed box. A reasonable hypothesis might have been, "The sealed box contains a penny and a thumbtack." This hypothesis could be proven false by doing an experiment: putting a penny and a thumbtack in a similar box and comparing the rattle it makes to the rattle of the sealed box. If the objects in the experimental box do not sound like the ones in the sealed box, then the hypothesis is proven false by the results of the experiment, and you would move on to a new hypothesis. However, if the two boxes do sound alike, then this does not prove that the sealed box actually contains a penny and a thumbtack. Rather, this investigation has supplied a piece of evidence in support of the hypothesis.

You could test almost any hypothesis you made by putting objects in the empty box. What one hypothesis could *not* be proven false by experimentation?

You may now open the sealed container. Was your final conclusion about its contents correct?

If your conclusion has now been disproven, explain how you reached an erroneous conclusion. (You may have found that your conclusion was wrong in spite of accurate observations and careful experimentation. Conclusions reflect the best evidence available at the time.)

Can you think of any areas of scientific inquiry where a new technology or technique might challenge or disprove hypotheses that are already supported by experimental evidence?

The scientific method applies only to hypotheses that can be proven false through experimentation (or through observation and comparison, a different means of hypothesis testing). It is essential to understand this in order to understand what is and is not possible to learn through science. Consider, for example, this hypothesis: More people behave immorally when there is a full moon than at any other time of the month. The phase of the moon is certainly a well-defined and measurable factor, but morality is not scientifically measurable. Thus there is no experiment that can be performed to test the hypothesis. Propose a testable hypothesis for human behavior during a full moon.

Which of the following would be useful as scientific hypotheses? Give the reason for each answer.

Plants absorb water through their leaves as well as through their roots.

Mice require calcium for developing strong bones.

Dogs are happy when you feed them steak.

An active volcano can be prevented from erupting by throwing a virgin into it during each full moon.

The higher the intelligence of an animal, the more easily it can be domesticated.

The earth was created by an all-powerful being.

HIV (human immunodeficiency virus) can be transmitted by cat fleas.

EXERCISE 1.3

The Elements of an Experiment

Objectives

After completing this exercise, you should be able to

1. Define and give examples of dependent, independent, and standardized variables.
2. Identify the variables in an experiment.
3. Explain what control treatments are and why they are used.
4. Explain what replication is and why it is important.

Once a question or hypothesis has been formed, the scientist turns his attention to answering the question (that is, testing the hypothesis) through experimentation. A crucial step in designing an experiment is identifying the variables involved. **Variables** are things that may be expected to change during the course of the experiment. The investigator deliberately changes the **independent variable.** He measures the **dependent variable** to learn the effect of changing the independent variable. To eliminate the effect of anything else that might influence the dependent variable, the investigator tries to keep **standardized variables** constant.

Dependent Variables

The **dependent variable** is what the investigator measures (or counts or records). It is what the investigator thinks will vary during the experiment. For example, she may want to study peanut growth. One possible dependent variable is the height of the peanut plants. Name some other aspects of peanut growth that can be measured.

All of these aspects of peanut growth can be measured and can be used as dependent variables in an experiment. There are different dependent variables possible for any experiment. The investigator can choose the one she thinks is most important, or she can choose to measure more than one dependent variable.

Independent Variables

The **independent variable** is what the investigator deliberately varies during the experiment. It is chosen because the investigator thinks it will affect the dependent variable. Name some factors that might affect the number of peanuts produced by peanut plants.

In many cases, the investigator does not manipulate the independent variable directly. He collects data and uses the data to evaluate the hypothesis, rather than doing a direct experiment. For example, the hypothesis that more crimes are committed during a full moon can be tested scientifically. The number of crimes committed is the dependent variable and can be measured from police reports. The phase of the moon is the independent variable. The investigator cannot deliberately change the phase of the moon, but can collect data during any phase he chooses.

Although many hypotheses about biological phenomena cannot be tested by direct manipulation of the independent variable, they can be evaluated scientifically by collecting data that could prove the hypothesis false. This is an important method in the study of evolution, where the investigator is attempting to test hypotheses about events of the past.

The investigator can measure as many dependent variables as she thinks are important indicators of peanut growth. By contrast, she must choose only one independent variable to investigate in an experiment. For example, if the scientist wants to investigate the effect that the amount of fertilizer has on peanut growth, she will use different amounts of fertilizer on different plants; the independent variable is the amount of fertilizer. Why is the scientist limited to one independent variable per experiment?

Time is frequently used as the independent variable. The investigator hypothesizes that the dependent variable will change over the course of time. For example, she may want to study the diversity of soil bacteria found during different months of the year. However, the units of time used may be anywhere from seconds to years, depending upon the system being studied.

What was the independent variable in your black box investigation?

What was (or were) the dependent variable(s)?

Identify the dependent and independent variables in the following examples (circle the dependent variable and underline the independent variable):

Height of bean plants is recorded daily for 2 weeks.

Guinea pigs are kept at different temperatures for 6 weeks. Percent weight gain is recorded.

The diversity of algal species is calculated for a coastal area before and after an oil spill.

Light absorption by a pigment is measured for red, blue, green, and yellow light.

Batches of seeds are soaked in salt solutions of different concentrations, and germination is counted for each batch.

An investigator hypothesizes that the adult weight of a dog is higher when it has fewer littermates.

Standardized Variables

A third type of variable is the **standardized variable.** Standardized variables are factors that are kept equal in all treatments, so that any changes in the dependent variable can be attributed to the changes the investigator made in the independent variable.

Since the investigator's purpose is to study the effect of one particular independent variable, she must try to eliminate the possibility that other variables are influencing the outcome. This is accomplished by keeping the other variables at constant levels, in other words, by *standardizing* these variables. For example, if the scientist has chosen the amount of fertilizer as the independent variable, she wants to be sure that there are no differences in the type of fertilizer used. She would use the same formulation and same brand of fertilizer throughout the experiment. What other variables would have to be standardized in this experiment?

Predictions

A hypothesis is a formal, testable statement. The investigator devises an experiment or collects data that could prove the hypothesis false. He should also think through the possible outcomes of the experiment and make **predictions** about the effect of the independent variable on the dependent variable in each situation. This thought process will help him interpret his results. It is useful to think of a prediction as an if/then statement: *If* the hypothesis is supported, *then* the results will be . . .

For example, a scientist has made the following hypothesis: Increasing the amount of fertilizer applied will increase the number of peanuts produced. He has designed an experiment in which different amounts of fertilizer are added to plots of land and the number of peanuts yielded per plot is measured.

What results would be predicted if the hypothesis is supported? (State how the dependent variable will change in relation to the independent variable.)

What results would be predicted if the hypothesis is proven false?

Levels of Treatment

Once the investigator has decided what the independent variable for an experiment should be, he must also determine how to change or vary the independent variable. The values set for the independent variable are called the **levels of treatment.** For example, an experiment measuring the effect of fertilizer on peanut yield has five treatments. In each treatment, peanuts are grown on a 100-m^2 plot of ground, and a different amount of fertilizer is applied to each plot. The levels of treatment in this experiment are set as 200 g, 400 g, 600 g, 800 g, and 1000 g fertilizer/100 m^2.

The investigator's judgment in setting levels of treatment is usually based on prior knowledge of the system. For example, if the purpose of the experiment is to investigate the effect of temperature on weight gain in guinea pigs, the scientist should have enough knowledge of guinea pigs to use appropriate temperatures. Subjecting the animals to extremely high or low temperatures can kill them and no useful data would be obtained. Likewise, the scientist attempting to determine how much fertilizer to apply to peanut fields needs to know something about the amounts typically used so he could vary the treatments around those levels.

Control Treatments

It is also necessary to include **control treatments** in an experiment. A control treatment is a treatment in which the independent variable is either eliminated or is set at a standard value. The results of the control treatment are compared to the results of the experimental treatments. In the fertilizer example, the investigator must be sure that the peanuts don't grow just as well with no fertilizer at all. The control would be a treatment in which no fertilizer is applied. An experiment on the effect of temperature on guinea pigs, however, cannot have a "no temperature" treatment. Instead, the scientist will use a standard temperature as the control and will compare weight gain at other temperatures to weight gain at the standard temperature.

For each of the following examples, tell what an appropriate control treatment would be.

1. An investigator studies the amount of alcohol produced by yeast when it is incubated with different types of sugars. Control treatment:

2. The effect of light intensity on photosynthesis is measured by collecting oxygen produced by a plant. Control treatment:

3. The effect of NutraSweet sweetener on tumor development in laboratory rats is investigated. Control treatment:

4. Subjects are given squares of paper to taste that have been soaked in a bitter-tasting chemical. The investigator records whether each person can taste the chemical. Control treatment:

5. A solution is made up to simulate stomach acid at pH 2. Maalox antacid is added to the solution in small amounts, and the pH is measured after each addition. Control treatment:

Replication

Another essential aspect of experimental design is **replication.** Replicating the experiment means that the scientist repeats the experiment numerous times using exactly the same conditions to see if the results are consistent. Being able to replicate a result increases our confidence in it. However, we shouldn't expect to get exactly the same answer each time, because a certain amount of variation is normal in biological systems. Replicating the experiment lets us see how much variation there is and obtain an average result from different trials.

A concept related to replication is **sample size.** It is risky to draw conclusions based upon too few samples. For instance, suppose a scientist is testing the effects of fertilizer on peanut production. He plants four peanut plants and applies a different amount of fertilizer to each plant. Two of the plants die. Can he conclude that the amounts of fertilizer used on those plants were lethal? What other factors might have affected the results?

When you are designing experiments later in this lab course, consider sample size as an aspect of replication. Since there are no hard and fast rules to follow, seek advice from your instructor regarding the number of samples and the amount of replication that is appropriate for the type of experiment you are doing. Since the time you have to do experiments in lab is limited, inadequate replication may be a weakness of your investigations. Be sure to discuss this when you interpret your results.

Methods

After formulating a hypothesis and selecting the independent and dependent variables, the investigator must find a method to measure the dependent variable; otherwise, there is no experiment. Methods are learned by reading articles published by other scientists and by talking to other scientists who are knowledgeable in the field. For example, a scientist who is testing the effect of fertilizer on peanuts would read about peanut growth and various factors that affect it. She would learn the accepted methods for evaluating peanut yield. She would also read about different types of fertilizers and their composition, their uses on different soil types, and methods of application. The scientist might also get in touch with other scientists who study peanuts and fertilizers and learn about their work. Scientists often do this by attending conferences where other scientists present results of investigations they have completed.

In this course, methods are described in the lab manual or may be learned from your instructor.

Summary

Figure 1.1 summarizes the process of scientific investigation. The process begins and ends with the knowledge base, or what is already known. When a scientist chooses a new question to work on, he first searches the existing knowledge base to find out what information has already been published. Familiarity with the results of previous experiments as well as with the topic in general is essential for formulating a good hypothesis. After working through the rest of the process, the scientist contributes his own conclusions to the knowledge base by presentations at professional meetings and publication in scientific journals. Because each new experiment is built upon past results, the foundation of knowledge grows increasingly solid.

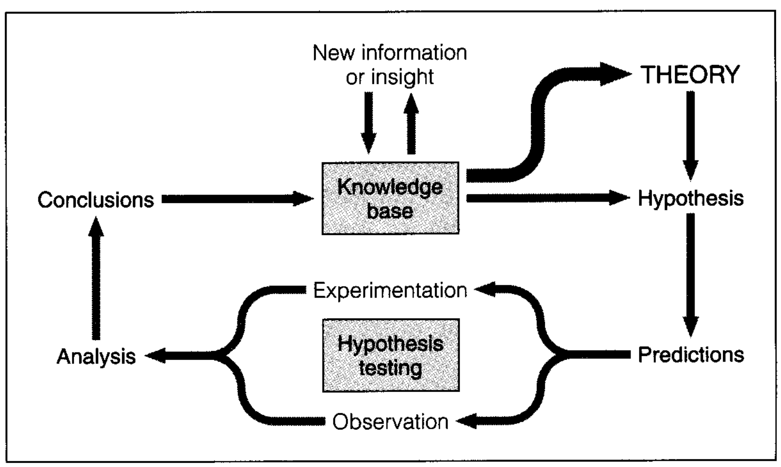

Figure 1.1.
Summary of scientific inquiry.

Scientific knowledge is thus an accumulation of evidence in support of hypotheses; it is not to be regarded as absolute truth. Hypotheses are accepted only on a trial basis. When you read about current scientific studies in the newspaper, keep in mind that the purpose of the media is to report news. In science, "news" is often preliminary results that are therefore quite tentative in nature. It is not unusual to hear that the results of one study contradict another. Some results will hold up under future scrutiny and some will not. However, this does not mean that scientific knowledge is flimsy and unreliable. All scientific knowledge falls somewhere along a continuum from tentative to certain, depending on the evidence that has been amassed. For example, it takes an average of 12 years to get a new drug approved by the FDA as researchers progress through laboratory evaluation of possible compounds, animal studies, and an escalating series of trials in humans. Even so, there are cases of drugs being recalled when new information is discovered. In a way, every medicine you take is still being tested—on you. We don't object to this because we feel confident that the knowledge base is firm, that the science is "done" to an acceptable degree.

EXERCISE 1.4
Designing an Experiment

Objectives

After completing this exercise, you should be able to

1. Given a proposed experiment, critique the experimental design.
2. Given a method for measuring a dependent variable, design an experiment.

Science is almost always a collaborative effort. Teams of scientists work together to solve problems; often these teams include scientists-in-training (graduate students). Working with others brings a variety of perspectives, knowledge bases, and experiences to bear on the problem. When scientists propose a project, they may seek funding from an agency such as the National Science Foundation. In this process, the team's proposal is reviewed by other scientists, who decide whether the problem is worth addressing, whether the proposers have the knowledge required to address it, and whether the design of the experiments is scientifically sound. When scientists have finished an investigation, they present the results to other scientists in the field by making oral presentations at conferences and by publishing articles in scientific journals.

Whether you are going to be a scientist or not, you will find many of the skills that scientists use are applicable to your own career. Most jobs require cooperative effort of some kind, just as you will collaborate with your lab team. Effective communication skills are especially important. You will almost certainly have occasion to present your work or defend your ideas to your coworkers and supervisor.

When you are asked to design an experiment in this course, your lab team will be provided with possible dependent variables and methods and procedures that you can use to measure them. You will decide what independent variable might affect these results. For example, if the topic being studied is the circulatory system, pulse rate and blood pressure might be the dependent variables that you measure to assess cardiovascular fitness. Your lab team would decide what factors (the independent variables) might affect a person's pulse rate and/or blood pressure and then design an experiment to test the effect of one of these factors.

Before you design your own experiments in later laboratories, you will work with your lab team in this part of the laboratory to critique a proposed experiment. This exercise is a rough draft of a proposal that could be improved. Use your knowledge of the scientific process to revise this experiment.

Sample Proposal

Hypothesis

Athletes have better cardiovascular fitness than nonathletes.

Dependent Variable(s)

Pulse rate, blood pressure.

Independent Variable

Athletic training.

Control(s)

Subjects who have had no athletic training (to have a comparison group of subjects); readings taken before exercise (to get a baseline measurement for each subject).

Replication

Three subjects will be used in each group. Each subject will perform the exercise once.

Brief Explanation of Experiment

The pulse rate and blood pressure of athletes and nonathletes will be measured. The subjects will then perform 5 minutes of aerobic exercise. The pulse rate and blood pressure of each subject will be measured again immediately after exercise.

Predictions

We think that the pulse rates and blood pressure of athletes will be lower after exercise and will return to normal rates more quickly than those of nonathletes, indicating better cardiovascular fitness of athletes.

Method

1. Recruit three athletes to be subjects. Our lab team will be the nonathlete subjects.
2. Record resting pulse rate and blood pressure for each subject.
3. All subjects will run up and down the stairs for 5 minutes.
4. Pulse rate and blood pressure of each subject will be measured immediately after the exercise.
5. Pulse rate will continue to be taken until it returns to the resting value. The time taken for each subject's pulse to return to normal will be recorded.
6. Measure and record blood pressure for each person when the resting pulse rate is reached.

Tables Designed to Collect Data

	Resting blood pressure	Resting pulse rate
Athlete 1		
Athlete 2		
Athlete 3		
Tom		
Jennifer		
Eric		

	Blood pressure after exercise	Pulse rate after exercise
Athlete 1		
Athlete 2		
Athlete 3		
Tom		
Jennifer		
Eric		

	Time to reach resting pulse	Blood pressure at resting pulse
Athlete 1		
Athlete 2		
Athlete 3		
Tom		
Jennifer		
Eric		

List other independent variables that might be investigated using these techniques of measuring pulse and blood pressure.

EXERCISE 1.5
Application of Scientific Inquiry

Objective

After completing this exercise, you should be able to

1. Evaluate research reported in the media using the criteria provided in this exercise.

If you are not a science major, you may be asking why you should learn how scientific inquiry works. One reason is that understanding the science process gives you perspective on the scientific knowledge described in your textbook. When you read a science textbook you are only seeing the tip of the iceberg. Beneath all of that information lies a vast foundation of observation, experimentation, and analysis. Each experiment that you do in lab should give you a tiny taste of how the information in your textbook came to be there—how we know what we know.

Understanding scientific inquiry matters in a personal sense, too. You may never be a producer of scientific knowledge—a scientist—but you make decisions daily as a consumer of science. Do the vitamins and minerals added to Cap'n Crunch cereal make it a health food? Will zinc lozenges shorten my cold? Should I have the Big Mac or the grilled chicken salad? Do I want fries with that? Should I walk to class or drive my SUV? Does it matter whether I get more than 5 hours of sleep a night? Should I steer clear of genetically engineered food? Is a soft drink that has ginseng or ginkgo biloba in it worth the extra cost? Understanding the state of the research can help you make informed choices about issues that affect your health, your wallet, and your impact on our environment. In this exercise, you will learn how to evaluate the science supporting matters that affect you personally.

From Exercises 1.3 and 1.4 you know how to evaluate whether an experiment is designed properly. But accounts of scientific studies in magazines and newspapers don't always provide those details. Some other factors to look for include the following:

Where was the study carried out and who funded it? For objectivity, look for studies funded by competitive agencies such as NIH (National Institutes of Health) and NSF (National Science Foundation). These government-funded organizations require peer review of proposed experiments. That is, a group of knowledgeable scientists determines funding based on criteria such as experimental design and the qualifications of the investigators to perform the experiments. On the other hand, some funding groups have a vested interest in the outcome of research.

How large was the sample size? As you have learned, conclusions drawn from a large sample are more reliable than conclusions from a small sample. Small studies are not bad science, their results are simply more preliminary than those from large studies.

Where was the study published? The most reliable sources are peer-reviewed journals. Knowledgeable scientists critique each article submitted to determine whether it merits publication. Other types of publications do not require the same rigorous screening. For example, an industry newsletter or a Web site promoting herbal supplements will probably not offer a thorough and objective review of the research.

Procedure

Your instructor may have asked you to find a news article yourself, or she may have one to assign to you. In either case, read the article and briefly describe the following aspects of the science reported on. (Your article may not include all of these.)

Experimental Design:

Independent variable —

Dependent variable(s) —

Standardized variables —

Control treatment —

How large was the sample size?

Where was the study carried out, and who funded it?

Where was the study published?

How convinced are you by the results reported in the article? Rate your conclusion on a scale of 0 (this isn't even science!) to 3 (I would base a personal decision on these results). Explain how you arrived at your rating.

Questions for Review

1. A group of students hypothesizes that the amount of alcohol produced in fermentation depends on the amount of glucose supplied to the yeast. They want to use 5%, 10%, 15%, 20%, 25%, and 30% glucose solutions.

   a. What is the independent variable?

   b. What is the dependent variable?

c. What control treatment should be used?

d. What variables should be standardized?

2. Having learned the optimum sugar concentration, the students next decide to investigate whether different strains of yeast ferment glucose to produce different amounts of alcohol. Briefly explain how this experiment would be set up.

3. A group of students wants to study the effect of temperature on bacterial growth. To get the bacteria, they leave petri dishes of nutrient agar open on a shelf. They then put the dishes in different places: an incubator (37°C), a lab room (21°C), a refrigerator (10°C), and a freezer (0°C). Bacterial growth is measured by estimating the percentage of each dish covered by bacteria at the end of a 3-day growth period.

   a. What is the independent variable?

   b. What is the dependent variable?

   c. What variables should be standardized?

4. A team of scientists is testing a new drug, XYZ, on AIDS patients. They expect patients to develop fewer AIDS-related illnesses when given the drug, but they don't expect XYZ to cure AIDS.

   a. What hypothesis are the scientists testing?

   b. What is the independent variable?

   c. What is the dependent variable?

d. What control treatment would be used?

e. What variables should the researchers standardize?

5. A group of students decides to investigate the loss of chlorophyll in autumn leaves. They collect green leaves and leaves that have turned color from sugar maple, sweet gum, beech, and aspen trees. Each leaf is subjected to an analysis to determine how much chlorophyll is present.

   a. What is a reasonable hypothesis for these students?

   b. What is the independent variable?

   c. What is the dependent variable?

   d. What would you advise the students about replication for this experiment?

6. A scientist wants to study mating behavior in crickets. She hypothesizes that males that win the most male-vs.-male contests mate with the most females. She observes the crickets to obtain data. For each male, she counts the number of male-male fights he wins and the number of females he mates with.

   a. What is the independent variable?

   b. What is the dependent variable?

   c. What constitutes replication in this experiment?