RESEARCH EXERCISE : Scientific Investigation

Objectives

After completing this reading, you should be able to:

1. Identify and characterize questions that can be answered through scientific investigation.
2. Define *hypothesis* and explain what characterizes a good scientific hypothesis.
3. Identify and describe the components of a scientific experiment.
4. Design and critique a scientific experiment.

Introduction

Biology is the study of the phenomena of life, and biologists observe living systems and organisms, ask questions, and propose explanations for those observations. Science assumes that biological systems are understandable and can be explained by fundamental natural rules or laws. Scientific investigations share some common elements and procedures, which are referred to as the ***scientific method***. Not all scientists follow these procedures in a strict fashion, but each of the elements is usually present in some form. Science is a creative human endeavor that involves asking questions, making observations, developing explanatory hypotheses and predictions, and testing those hypotheses and predictions. Scientists closely scrutinize investigations in their field, and each scientist must present his or her work at scientific meetings or in professional publications, providing evidence from observations and experiments that supports the scientist's explanations of biological phenomena.

In this reading, you will not only review the process that scientists use to ask and answer questions about the living world, but you will review the knowledge necessary to conduct and critique scientific investigations.

QUESTIONS AND HYPOTHESES

This exercise explores the nature of scientific questions and hypotheses. Before we start our lab, read the explanatory paragraphs and then be prepared to present your ideas in the class discussion.

Asking Questions

Scientists are characteristically curious and creative individuals whose curiosity is directed toward understanding the natural world. They use their study of previous research or personal observations of natural phenomena as a basis for asking questions about the underlying causes or reasons for these phenomena. For a question to be pursued by scientists, the phenomenon must be well defined and testable. The elements must be measurable and controllable.

There are limits to the ability of science to answer questions. Science is only one of many ways of knowing about the world in which we live. Consider, for example, this question: Do excessively high temperatures cause people to behave immorally? Can a scientist investigate this question? Temperature is certainly a well-defined, measurable, and controllable factor, but morality of behavior is not scientifically measurable. We probably could not even reach a consensus on the definition. Thus, there is no experiment that can be performed to test the question.
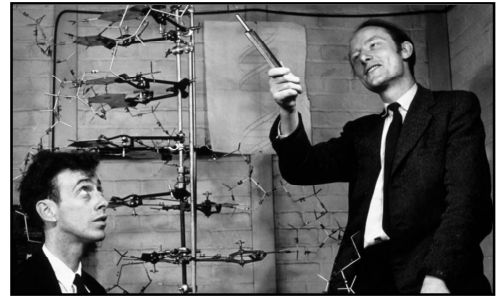
Developing Hypotheses

As questions are asked, scientists attempt to answer them by proposing possible explanations. Those proposed explanations are called **hypotheses.** A hypothesis tentatively explains something observed. It proposes an answer to a question. Consider the following question: "What is the function of spines on cacti?" One hypothesis, based on this question, might be "spines on cacti impede herbivores from eating the cacti." The hypothesis has suggested a possible explanation for the observed spines.

A scientifically useful hypothesis must be testable and falsifiable (able to be proven false IF the explanation in indeed incorrect). To satisfy the requirement that an incorrect hypothesis be falsifiable, it must be possible that an experimental test can be designed in such a way that the results do not support the incorrect explanation. In our example, if spines are removed from test cacti, and the cacti are still not eaten by animals, then the hypothesis has been falsified. Clearly, the explanation for why cacti have spines hasn't been validated.

On the flip side, *even though an hypothesis can be falsified [proved as incorrect], hypotheses can never be proven true*. The evidence from an investigation can only provide support for the hypothesis. In our example, if cacti without spines were eaten whereas the cacti with spines was not, the hypothesis, that spines prevent herbivores from eating the cacti, has not been proved, but has been supported by the evidence. Other explanations for the observation that cacti have spines are still possible and still must be excluded, and new evidence from additional experiments and observations might falsify this hypothesis at a later date. Maybe cacti have spines because spines help better prevent water loss compared to flat-shaped leaves in arid environments. In science seldom does a single test provide results that clearly support or falsify a hypothesis. In most cases, the evidence serves to modify the hypothesis or the conditions of the experiment. Even when an experiment supports a hypothesis, the experiment should be replicated to see if the same results are obtains to lend greater validity to the explanation for the phenomena in question.

Science is a way of knowing about the natural world (Moore, 1993) that involves testing hypotheses or explanations. The scientific method can be applied to the unusual and the commonplace. You use the scientific method when you investigate why your once-white socks are now blue. Your hypothesis might be that your blue jeans and socks were washed together, an assertion that can be tested through observations and experimentation.

Students often think that controlled experiments are the only way to test a hypothesis. This is ideal, but in the real world sometimes it can get complicated to set up an experiment with an independent variable that is manipulated as desired by the researcher. The test of a hypothesis may, therefore, include experimentation, additional observations, or the synthesis of information from a variety of sources. Many scientific advances have relied on other procedures and information to test hypotheses. For example, James Watson and Francis Crick developed a model [in their case a physical 3-dimensional structure] that was their hypothesis for the structure of DNA. Their model could only be supported if the accumulated data from a number of other scientists were consistent with the model. Actually, their first model (hypothesis) was falsified by the work of Rosalind Franklin. Their final model was tested and supported not only by the ongoing work of Rosalind Franklin and Maurice Wilkins, but also by research previously published by Erwin Chargaff and others. Watson and Crick won the Nobel Prize for their scientific work. They did not perform a controlled experiment in the laboratory, but tested their powerful hypothesis through the use of existing evidence from other research and data being collected. Methods other than experimentation are acceptable in testing hypotheses. Think about other areas of science that require comparative observations and the accumulation of data from a variety of sources, all of which must be consistent with and support hypotheses or else be inconsistent and falsify hypotheses.

The information in your biology textbook is often thought of as a collection of facts, well understood and correct. It is true that much of the knowledge of biology has been derived through scientific investigations, has been thoroughly tested, and is supported by strong evidence. However, scientific knowledge is always subject to novel experiments and new technology, any aspect of which may result in modification of our ideas and a better understanding of biological phenomena. The structure of the cell membrane is an example of the self-correcting nature of science. Each model of the membrane has been modified as new results have negated one explanation and provided support for an alternative explanation.

Designing Experiments to Test Hypotheses

The most creative aspect of science is designing a test of your hypothesis that will provide unambiguous evidence to falsify or support a particular explanation. Scientists often design, critique, and modify a variety of experimental design before they commit the time and resources to actually perform a single experiment. In this exercise, you will follow the procedure for experimentally testing hypotheses, but it is important to remember that other methods, including observation and the synthesis of other sources of data, are acceptable in scientific investigations.

An experiment involves having a hypothesis to test, defining variables, outlining a procedure, deciding on the materials needed, and determining controls to be used as the experiment is performed. Once the experiment is defined, the investigator predicts the outcome of the experiment based on the hypothesis. After the experiment is conducted, the results can be compared to the prediction, thereby testing the validity of the hypothesis or explanation.

Read the following description of a scientific investigation of the effects of sulfur dioxide on soybean reproduction. You will determine the types of variables involved and the experimental procedure for this experiment and for others.

Making Predictions

The investigator never begins an experiment without a prediction of its outcome. The **prediction** is always based on the particular experiment designed to test a specific hypothesis. Predictions are written in the form of if/then statements: "If the hypothesis is

true, then the results of the experiment will be," for example, "if cactus spines prevent herbivory, then removal of the spines will result in cacti being eaten in increased quantities by the particular herbivore used." Making a prediction provides a critical analysis of the experimental design. If the predictions are not clear, the procedure can be modified before beginning the experiment. A researcher needs to make sure the experiment tests the hypothesis and measures the effects of the independent variable [treatment] being manipulated instead of inadvertently testing the effects of some other variable.

To evaluate the results of the experiment, the investigator always returns to the prediction. If the results match the prediction, then the hypothesis is supported. If the results do not match the prediction, then the hypothesis is falsified. Either way, the scientist has increased knowledge of the process being studied. Many times the falsification of a hypothesis can provide more information than confirmation, since the ideas and data must be critically evaluated in light of new information.

EXERCISE: PRACTICING THE SCIENTIFIC METHOD

Read the following example and answer the questions that follow. You should be prepared to discuss your answers.

**INVESTIGATION OF THE EFFECT OF SULPHUR DIOXIDE ON
SOYBEAN REPRODUCTION**

Agricultural scientists were concerned about the effect of air pollution, sulfur dioxide in particular, on soybean production in fields adjacent to coal-powered power plants where this chemical was produced. Based on initial investigations, they proposed that sulfur dioxide in high concentrations would reduce reproduction in soybeans. They designed an experiment to test this hypothesis (Figure 1). In this experiment, 132 soybean plants, just beginning to produce flowers, were divided into groups, the **experimental groups or treatment groups** [which received a certain level of the treatment] and the no treatment or **control group** [which does not receive the treatment].

The 132 treated plants in this air pollution experiment were divided into four groups of 33. One group of 33 treated plants was placed in a fumigation chamber and exposed to 0.6 ppm (parts per million) of sulfur dioxide for 4 hours to simulate sulfur dioxide emissions from a power plant. The experiment was repeated on two remaining treated groups of 33 each. The no-treatment plants, the control group, were placed similarly in groups of 33 in a second fumigation chamber and simultaneously exposed to filtered air for 4 hours. Following the experiment, all plants were returned to the greenhouse. When the beans matured, the number of bean pods, the number of seeds per pod, and the weight of the pods were determined for each plant.
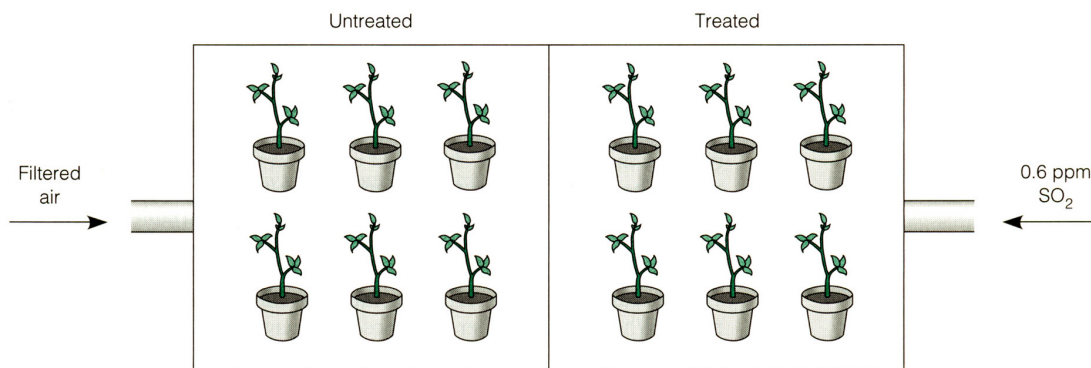

Figure 1. Experimental Design for soybean experiment. Soybeans were fumigated for 4 hours.

Determining the Variables

Read the description of each category of variable; then identify the variable described in the preceding investigation. The variables in an experiment must be clearly defined and measurable. The investigator will identify and define *dependent, independent, and controlled variables* for a particular experiment.

a)   The Dependent Variable

Within the experiment, one variable will be measured or counted or observed in response to the experimental conditions. This variable is the **dependent variable**. For the soybeans, several dependent variables are measured, all of which provide information about reproduction. What are the dependent variables in this experiment?

b) The Independent Variable

The scientist will choose one variable, or experimental condition, to manipulate. This variable is the variable used to test the investigator's hypothesis and is called the **independent variable.** The experimental group [sometimes also called the treatment group] receives the **treatment**, they receive the levels of the independent variable decided on by the experimenter. What was the independent variable in the investigation above?

Can you suggest other variables, besides the independent variable chosen, that the investigator might have changed or that may vary in this experiment that would have an effect on the dependent variables too?

Provide a thorough explanation of why exactly is it important to have only one independent variable?

Why then is it acceptable though to have more than one dependent variable?

c) The Controlled Variable

Consider the variables that you identified as alternative independent variables. Although they are not part of the hypothesis being tested in this investigation, they would have significant effects on the outcome of this experiment. These variables, called **extraneous variables**, must, therefore, be kept constant during the course of the experiment [at least the levels of each of these variables should be the same between the control and the experimental/treatment groups]. These variables are then known as the **controlled variables or constants.** The underlying assumption in experimental design is that the selected independent variable is the only variable you are testing to see if it causes a change in the dependent variable. This is only true if all other variables are controlled and are not allowed to vary differently between subjects in the experimental/treatment group vs. the control group. What are five variables that should be controlled in this experiment?

For each of the five you listed above, how would you run the experiment so as to make sure these variables do not influence your dependent variable differently in the control vs. the experimental/treatment group?

Some variables can vary from subject to subject and between your control vs. experimental/treatment group, but the researcher can't fully control them to prevent them from influencing the dependent variable and thus the data collected. These specific types of extraneous variables are known as **confounding variables**. Identify a confounding variable that cannot be controlled for and that may affect the dependent variables in this experiment. Be sure to explain why the researcher was not able to control this variable.

<u>**Choosing or Designing the Procedure**</u>

The **procedure** is the stepwise method, or sequence of steps, to be performed for the experiment. The procedure is the step-by-step instructions on how to conduct the experiment. It should be recorded in a laboratory notebook before initiating the experiment, and any exceptions or modifications should be noted during the experiment. The procedures may be designed from research published in scientific journals, through collaboration with colleagues in the lab or other institutions, or by means of one's own novel and creative ideas. The process of outlining the procedure includes determining how subjects will be selected and deciding what the control treatment(s) are, levels of treatments are, how the treatment will be administered, what the numbers of replications will be etc…

a) Level of Treatment

The value set for the independent variable is called the **level of treatment.** For this experiment, the value was determined based on previous research and preliminary measurements of sulfur dioxide emissions. The scientists may select a range of concentrations from no sulfur dioxide to an extremely high concentration. The levels should be based on knowledge of the system and the biological significance of the treatment level. What was the level of treatment in the soybean experiment?

b) Replication

Scientific investigations are not valid if the conclusions drawn from them are based on one experiment with one or two individuals. Generally, the same procedure will be repeated several times (**replication**), providing consistent results. Since science relies heavily on repetition to add validity to your results, you never want to have just one subject in your control and in your treatment groups. Ideally, **each group being tested has a minimum of 30 subjects**, if more are not available. Furthermore, ideally the experiment is run more than one time even with multiple subjects per group.

If the data collected changes every time you replicate the experiment, some extraneous variable must be affecting the dependent variable and this extraneous variable must try to be controlled. Of course, even when extraneous variables are controlled for, scientists do not expect exactly the same results since individuals and their responses will vary normally. Results from replicated experiments, even well designed experiments with all possible extraneous variables controlled for, are usually **averaged** and may be further analyzed using **statistical tests**. Describe how replication achieved in the soybean experiment?

c) Control

The experimental design includes a **control** in which the independent variable is held at an established level or is omitted altogether when possible]. For example, if the effect of pH on plant height is being tested, the experimental group may be grown in soils of different pHs [levels 2, 5, 8, and 11]. The control may be grown then in the neutral pH of 7 since there can't be a soil with zero pH [no matter the soil, there will be a certain measurement of H^+ ions, whether a lot or a little]. However, if the experiment is testing the effect of fertilizer on plant height, then the experimental group may receive a certain amount of fertilizer while the control group receives no fertilizer at all. The data collected from the control group will be compared to the data collected from the experimental group. The control's data serves as a benchmark for comparison. The existence of this group allows scientists to the decide whether any observed effect on the dependent variable seen in the experimental group is really due to the independent variable manipulations alone. In the case of the soybean experiment, what was the control group and what was the control "treatment" or the level of the independent variable given to this group of subjects?

Explain the difference between the control and the controlled variables discussed previously?