Chapter 2: How Science is Done

Scientific research serves two purposes:

1. To investigate and acquire knowledge that is theoretical *and*
2. To perform research that is of practical value

Science has the unique ability to serve humanity. Scientific research results from inquiry. An inquiring mind is thirsty, trying to find answers. An inquisitive person asks questions and wants to find answers. The two most important questions—why and how—are the starting points of all scientific inquiry.

The Scientific Method

Understanding how science is done can help you collect evidence and draw conclusions about scientific problems. In biology, a lot of evidence is gathered through observation. Paying attention to the living world can lead to some very interesting discoveries. However, there are times when collecting data can be more empirical. This means conducting an actual experiment to test a hypothesis.

Called the **scientific method**, this collection of steps is a universal way scientists test their ideas. The scientific method has eight steps:

1. State the problem
2. Collect background information
3. Establish a hypothesis
4. Perform the experiment
5. Analyze the data
6. Repeat the experiment
7. Draw conclusions
8. Report the results

Related to the scientific method is the term "scientific inquiry." While there are several definitions for this term, the overarching idea behind it is that all science starts with a question about the natural world. Things like, "How do sea turtles know on which beach to lay their eggs?" and "What feather coloration best attracts female blue jays?" are questions that can be tested using the scientific method. This is an important feature to remember. All science questions must be testable. Asking, "How much do you love your mom?" is not a testable question because the answer relies more on an intuitive perception than on empirical evidence.

Let us now examine each part of the scientific method to see how they all fit together.

State the Problem

Here, you want to identify some phenomenon that occurs in nature and ask a question about it. You might want to know how elephants select their mates or what the relationship is between acacia trees and certain ants. Most likely, this problem will come from some form of observation that has been made.

Collect Background Information

Once you have identified your problem, you will want to find out if anyone else has asked the same question. Now is the time to hit the library and the Internet to research what has already been done. You may find that many other people have already studied your problem. If that is the case, then you could either accept what they have already found *or* you could carry their research further. Let's say, for example, you wanted to know how long it takes chicken eggs to hatch in an incubator at 37°C. After doing your background research, you find several sources that say it takes 21 days at this temperature. A good scientist would ask himself how this knowledge could be expanded. Maybe you want to know how a change in temperature would change the outcome.

However you decide to change the experiment, you need to do more background research until you find something that has not been done before, but all research does not need to be original. It is perfectly fine to replicate previous investigations. If your results turn out the same way as those from the original study, great! This adds more support for its conclusions. If your results are different, that is perfectly OK, too. This then presents the question, "Why?"

Good science generates more questions than answers.

Establish a Hypothesis

Your hypothesis is what you want to study and what you think is going to happen during the experiment. The simplest, most-straightforward explanation is usually a good place to start.

Examples of good hypotheses include:

- If chicken eggs are kept at 35°C for 21 days, then the number of hatchlings will be reduced.
- If phosphorus and nitrogen are added to the soil, then the overall plant height will increase.
- If bacteria are exposed to periods of radiation, then the frequency of binary fission will increase.

Each statement here presents a conditional part and a determining part. Remember that the most important aspect of a hypothesis is that it must be testable.

The following are examples of bad hypotheses:

- I love chocolate chip cookies. (This is a personal opinion that's untestable.)
- Paramecia have cilia they use to move. (This is an observation, but it doesn't pose a testable hypothesis about the consequences of having cilia.)

Both of these statements are surely observations, but they are missing the testable part.

Perform the Experiment

Now the fun begins! This is the part of the scientific method where you will actually perform your experiment to test your hypothesis. It is important to create an experimental design that will allow you to collect the type of data you want. It is also important for every experiment to have a control, an independent variable, and a dependent variable.

The **control** in an experiment is the setup that remains unchanged. For example, in an investigation testing the impact of nitrogen on plant growth, a control setup would be a plant receiving no nitrogen. By having a setup like this, you can see if the nitrogen is the factor causing the plants to grow.

The **independent variable** is the factor that is being tested. In the aforementioned plant experiment, the nitrogen would be the independent variable. If you also wanted to test other nutrients, those would also be part of the independent variable setup.

The **dependent variable** is the factor that changes in response to the independent variable. Again, in the plant experiment, you want to know how the addition of nitrogen or other nutrients impacts plant growth. The growth of the plants depends on the addition of the nutrients, so it is the dependent variable.

It is very important to only test one independent variable at a time. Think about what would happen if you tested nitrogen and phosphorus at the same time. How would you know which nutrient was causing the plants to grow?

Let's look at another example here. This time, fill out the information as you read through.

Here is the problem statement:

A student wants to investigate how long it takes a colony of bacteria to grow on an agar plate that contains one of three additives.

Here is the background:

It has been shown that certain nutrients when added to agar allow bacterial colonies to increase in size and grow at a more rapid rate.

What is a hypothesis that would test this problem?

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Here is the experimental design:

The student took four agar plates and added nutrient 1 to the first, nutrient 2 to the second, and nutrient 3 to the third. The fourth plate was left alone. The plates were then inoculated with the bacterium and all placed into an incubator at 37°C for 24 hours. The student then counted the number of bacterial colonies on each plate.

What is the control setup in this experiment?

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What is the independent variable?

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What is the dependent variable?

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Here is what you could have said for the hypothesis:

If nutrients are added to the agar plates, then the growth rates of the bacterial colonies will increase.

The control setup is the agar plate without any nutrients added.

The independent variable would be the addition of the nutrients to the agar plates.

The dependent variable is the growth of the bacterial colonies.

How did you do?

Analyze the Data

In this part of the scientific method, you look at the data you have collected to try to organize it. This is *not* the place where you try to figure out what it means. You just want to record it and put it in a form that best represents it. This may include a data table, a graph, a pie chart, or just listing different figures.

The type of graphic representation used to display observations depends on the type of data collected. **Line graphs** compare different sets of related data and help predict data. For example, a line graph could compare the rate of activity of different enzymes at varying temperatures. A **bar graph** or **histogram** compares different items and helps make comparisons based on the data. For example, a bar graph could compare the ages of children in a classroom. A pie chart is useful when organizing data as part of a whole. For example, a **pie chart** could display the percent of time students spend on various after-school activities.

As previously noted, the researcher controls the independent variable. When you create a graph, you place the independent variable on the x-axis (horizontal axis). The dependent variable is influenced by the independent variable and is placed on the y-axis (vertical axis). It is important to choose the appropriate units for labeling the axes. It is best to divide the largest value to be plotted by the number of blocks on the graph, and round to the nearest whole number.

It is likely that you will need to perform some kind of statistical analysis. Typical tests include median, mode, range, and Chi-square. Performing these tests can help to better understand what the numbers and values are that have been collected.

Repeat the Experiment

You will recall from earlier that all hypotheses need to be testable. Well, the experiments that are performed also need to be repeatable. This means that, using your experimental design, any researcher can replicate the experiment exactly the same way that you performed it originally. This is used to validate your results. If you do the experiment one time and discover that chickens hatch just as well at 25°C as they do at 37°C, but nobody can reproduce those results, your experiment will not have a lot of credibility.

The other reason to repeat the experiment is to increase the internal validity of the results. If a test is performed once, then it is highly possible the findings are a fluke of nature. However, if the experiment is performed hundreds of times (or as many as a plausible), and it comes out the same way most of the time, then there is a good possibility that the results are true. Remember this phrase, "the larger the sample size, the more accurate the results."

Draw Conclusions

Now that you have performed the experiment, analyzed the data, and repeated the experiment several times, it is time to figure out what your results mean. Assuming the results were the same, or close, each time you performed the experiment, it is safe to look for trends in the data. Which events happened most often, least often, and were outliers are factors that you should consider. The next thing to do is ask the question, "Why did the results appear as they did?" There is no right or wrong answer to this question, only good answers and bad ones. Your job as the scientist is to come up with possible explanations about why things happened the way they did and then support these claims with evidence.

In the bacterial growth experiment, let's say that colonies with nutrient 1 grew significantly faster than colonies on the other two experimental plates and the control plate. Why would this happen? Well, maybe nutrient 1 caused the genes of the bacteria to duplicate at a faster pace. Maybe the nutrient 1 mutated the bacteria's DNA in such a way that binary fission increased.

At this time, there is no way to know for certain. All you know is that the results of the plate with nutrient 1 added to it were different from those of the other plates. In your conclusion you would address this result, present ideas about why this may have happened, and then provide some further ideas for experimentation. Remember, science generates more questions than it does answers.

Report the Results

One of the most important aspects about the world of science is publishing one's findings. Remember back when you started thinking about what you wanted to investigate? What did you do to find background information? You looked into what had been published about the subject previously. Well, had all of these scientists not reported their findings, you would never have known what was already out there and gone ahead and wasted a lot of time replicating an experiment that had already been done.

There are several places where scientists publish their work. The main one is in a professional journal. A quick search for "academic biology journals" in a search engine brings up titles such as:

The New England Journal of Medicine
The Auk
Animal Behavior
Developmental Biology
The Journal of Cell Biology and Genetics
Marine Ecology Progress Series
Research Journal of Soil Biology
International Journal of Plant Biology and Research

The list goes on and on. These are just some of the printed journals that publish biology research. With the advent of the Internet, there are now thousands more online journals. You can also publish scientific research in books, magazine articles, short papers, and present findings at professional conferences. However it is done, it is arguably the most important step of the scientific method because it lets the rest of the world know what you are doing.

The Scientific Process

Science is limited by the available technology. For instance, it was only with the invention of the microscope that scientists like Robert Hooke and Antonie van Leeuwenhoek discovered cells, which were invisible to the naked eye. As technology improves, it allows more hypotheses to be tested in different ways, which, in turn, can lead to the development of theories and possibly laws. Data collection methods also limit scientific inquiry. Data may be interpreted differently on different occasions. The inherent limitations of scientific methodology produce results or explanations that are subject to change as new technologies emerge.

Hypothesis: An unproven idea or educated guess followed by research to best explain a phenomenon.

Theory: A statement of principles or relationships relating to a natural event or phenomenon that has been verified many times and accepted (for example, the Theory of Evolution, the Cell Theory).

Law: An explanation of events that occur with uniformity under the same conditions (for example, laws of nature, law of gravitation).

Scientific Facts

Facts are not always as finite as they appear. More commonly in science, information is a hypothesis or, once tested and confirmed, a theory. Theories exist for long periods and repeatedly receive challenges. Only when a theory has withstood every challenge and been proven to provide reproducible results does it become recognized as a law. It is the universal recognition that defines a theory as a scientific law.

Scientific Concepts

A concept is a general understanding or belief. Scientists challenge concepts. The purpose of the scientific method is to derive clear, unbiased data. Concepts, on the other hand, may be fraught with personal biases and gray areas, overly simplistic, or too encompassing. A scientist might examine a concept, and then try to confirm it by making and testing a hypothesis. In this way, scientific inquiry is more specific and concepts are more generalized.

Scientific Models

Models are the basis for greater understanding. Models are usually small-scale representations that help us understand a larger system. Models aid us by making unusually large or small items more concrete. Common models include the solar system and the DNA helix. It is important to note that models are created with information. How current and accurate the information is at the time of creation may make the model more or less useful later. For example, although Pluto has been considered a planet for many years, it is now considered a dwarf planet. This is due to the progressive nature of science; the more we learn, the more we are forced to reevaluate.

Biology Does Math Too!

Math, science, and technology share many common themes. All three use models, diagrams, and graphs to simplify a concept for analysis and interpretation. Patterns observed in these systems lead to predictions based on these observations. Another common theme among these three systems is equilibrium. **Equilibrium** is a state in which forces are balanced, resulting in stability. Static equilibrium is stability due to a lack of changes, and dynamic equilibrium is stability due to a balance between opposing forces.

Measurement and Notation Systems

Science uses the **metric system**, since it is accepted worldwide and allows the results of experiments, performed by different scientists around the world, to be compared to one another. The meter is the basic metric unit of length. One meter is 1.1 yards. The liter is the basic metric unit of volume. There are 3.846 liters to 1 gallon. The gram is the basic metric unit of mass. One thousand grams equals 2.2 pounds. The following prefixes define multiples of the basic metric units:

Prefix	Multiplying factor	Prefix	Multiplying factor
deca-	10X the base unit	deci-	1/10 the base unit
hecto-	100X	centi-	1/100
kilo-	1,000X	milli-	1/1,000
mega-	1,000,000X	micro-	1/1,000,000
giga-	1,000,000,000X	nano-	1/1,000,000,000
tera-	1,000,000,000,000X	pico-	1/1,000,000,000,000

The common instrument used for measuring volume is the graduated cylinder. The standard unit of measurement is milliliters (mL). To ensure accurate measurement, it is important to read the liquid in the cylinder at the bottom of the meniscus, the curved surface of the liquid.

The common instrument used in measuring mass is the triple beam balance. The triple beam balance can accurately measure tenths of a gram and can estimate hundredths of a gram. The ruler and meter stick are the most commonly used instruments for measuring length.

How to Manipulate Your Data

Data manipulation is important to experimental study. You will recall from the data analysis discussion above that the purpose of analysis is to look for trends that may appear and to tabulate them into a usable form. Data manipulation begins by altering one variable at a time, and then assessing the results. Are the results similar to the last time? What has changed? Has the situation improved or worsened? This process is part of the scientific method, where scientists make predictions and then experiment to test validity. Quite often, this process takes many alterations, and manipulating the data and experimental parameters is useful. We are fortunate to have technological advances to aid us in this area. Biologists use a variety of tools and technologies to perform tests, collect and display data, and analyze relationships. Examples of commonly used tools include computer-linked probes, spreadsheets, and graphing calculators.

Biologists use computer-linked probes to measure various environmental factors including temperature, dissolved oxygen, pH, ionic concentration, and pressure. The advantage of computer-linked probes, as compared to more traditional observational tools, is that the probes automatically gather data and present it in an accessible format. This property of computer-linked probes eliminates the need for constant human observation and manipulation.

Biologists use spreadsheets to organize, analyze, and display data. For example, conservation ecologists use spreadsheets to model population growth and development, apply sampling techniques, and create statistical distributions to analyze relationships. Spreadsheet use simplifies data collection and manipulation and allows the presentation of data in a logical and understandable format.

Graphing programs are another technology with many applications to biology. For example, biologists use algebraic functions to analyze growth, development and other natural processes. Graphing programs can manipulate algebraic data and create graphs for analysis and observation. In addition, biologists use the matrix function of graphing programs to model problems in genetics. The use of graphing programs simplifies the creation of graphical displays including histograms, scatter plots, and line graphs. Finally, biologists connect computer-linked probes, used to collect data, to graphing programs to ease the collection, transmission, and analysis of data.

While it is useful to manipulate data in discovery efforts, it is never acceptable to fabricate or falsely advertise your data.

Commonly Shared Scientific Ideals

Biological science is closely connected to other scientific disciplines and technology resulting in a tremendous impact on society and everyday life. Scientific discoveries often lead to technological advances. Conversely, technology is often necessary for scientific investigation and advances in technology often expand the reach of scientific discoveries. In addition, biology and the other scientific disciplines share several concepts and processes that help unify the study of science. Finally, because biology is the science of living systems, biology directly affects society and everyday life.

Science and technology, while distinct concepts, are closely related. Science attempts to investigate and explain the natural world, while technology attempts to solve human adaptation problems. Technology often results from the application of scientific discoveries, and advances in technology can increase the impact of scientific discoveries. For example, Watson and Crick used science to discover the structure of DNA and their discovery led to many biotechnological advances in the field of genomics. These technological advances greatly influenced the medical and pharmaceutical fields. The success of Watson and Crick's experiments, however, was dependent on the technology available. Without the necessary technology, the experiments would have been impossible or would have failed.

The combination of biology and technology has improved the human standard of living in many ways, but the negative impact of increasing human life expectancy and population on the environment is problematic. In addition, advances in biotechnology (for example, genetic engineering, cloning) produce ethical dilemmas that society must consider.

The following are the concepts and processes generally recognized as common to all scientific disciplines:

- Systems, order, and organization
- Evidence, models, and explanation
- Constancy, change, and measurement
- Evolution and equilibrium
- Form and function

Because the natural world is so complex, the study of science involves the **organization** of items into smaller groups based on interaction or interdependence. These groups are called **systems**. Examples of organization are the periodic table of elements and the three-domain classification scheme for living organisms. Examples of systems are the solar system, cardiovascular system, Newton's laws of force and motion, and the laws of conservation.

Order refers to the behavior and measurability of organisms and events in nature. The arrangement of planets in the solar system and the life cycle of bacterial cells are examples of order.

Scientists use **evidence** and **models** to form **explanations** of natural events. Models are miniaturized representations of a larger event or system. Evidence is anything that furnishes proof.

Constancy and **change** describe the observable properties of natural organisms and events. Scientists use different systems of **measurement** to observe change and constancy. For example, the freezing and melting point of a given substance and the speed of sound are constant under constant conditions. Growth, decay, and erosion are all examples of natural change.

Evolution is the process of change over a long period of time. While biological evolution is the most common example, one can also classify technological advancement, changes in the universe, and changes in the environment as evolution.

Equilibrium is the state of balance between opposing forces of change. Homeostasis and ecological balance are examples of equilibrium.

Form and **function** are properties of organisms and systems that are closely related. The function of an object usually dictates its form and the form of an object usually facilitates its function. For example, the form of the heart (for example, muscle and valves) allows it to perform its function of circulating blood through the body.

How the Scientific Method Works Outside of Science

We are constantly bombarded with information. There are always news reports describing a study of a new cancer drug, how climate change is impacting the world's oceans, or the relationship between saturated fats and high blood pressure. Many times the information presented on television or in the newspaper is being reported by someone who does not know how to distinguish between science and pseudoscience, nor discriminate which facts may be true.

However one receives data, it is important to think about what has been presented. In the scientific realm, numbers are stronger than words. If you are presenting your own data, be sure to provide support to your claims by providing specific examples that back them up. If you are reading a newspaper story, look for the evidence that will make you believe it to be true. By using the scientific method, you will be more likely to catch mistakes, correct biases, and obtain accurate results. When assessing experimental data, use proper tools and mathematical concepts. Because people often attempt to use scientific evidence in support of political or personal agendas, the ability to evaluate the credibility of scientific claims is a necessary skill in today's society.

In evaluating scientific claims made in the media, public debates, and advertising, one should follow several guidelines. First, scientific, peer-reviewed journals are the most accepted source for information on scientific experiments and studies. One should carefully scrutinize any claim that does not reference peer-reviewed literature. Second, the media and those with an agenda to advance (for instance, advertisers and debaters) often overemphasize the certainty and importance of experimental results. One should question any scientific claim that sounds either too good to be true or overly certain. The media, especially commercials for new drugs, is riddled with the statement "scientifically proven" to show how great a product is. If you are aware of how science really works, you would know that science does not "prove" anything. It can suggest, lead us to believe, or support. To prove something means that every possible thing is known about it, without a shadow of a doubt. Does science work that way?