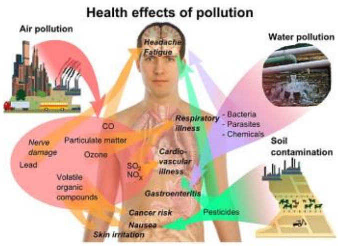
Chapter 1: Introduction to Biology
Lesson 1.3: The Nature of Science




The goal of science is to learn how nature works by observing the natural and physical world, and to understand this world through research and experimentation. Science is a distinctive way of learning about the world through observation, inquiry, formulating and testing hypotheses, gathering and analyzing data, and reporting and evaluating findings. We are all part of an amazing and mysterious phenomenon called "life" that thousands of scientists everyday are trying to better explain. And it's surprisingly easy to become part of this great discovery! All you need is your natural curiosity and an understanding of how people use the process of science to learn about the world.

Lesson Objectives

- Identify the goal of science.
- Describe how scientists study the natural world; using the scientific method.
- Explain how and why scientists do experiments.
- Describe types of scientific investigations.
- Explain what a scientific theory is.

Vocabulary

- dependent variable
- evidence
- experiment
- homeostasis
- hypothesis
- independent variable
- observation
- prediction
- science
- scientific law
- scientific theory

INTRODUCTION

Did you ever wonder why giraffes have such long necks or how birds learn to sing their special songs? If you ever asked questions such as these about the natural world, then you were thinking like a scientist. Young children constantly ask "why" questions. You may not realize it, but you are performing experiments all the time. For example, when you shop for groceries, you may end up carrying out a type of scientific experiment. If you like Brand X of salad dressing, and Brand Y is on sale, perhaps you will try Brand Y. And then if you like Brand Y, you may buy it again even when it is not on sale. If you did not like

Brand Y, then no sale will get you to try it again. Your conclusions are essentially based on an experiment. To find out *why* a person makes a particular purchasing choice, you might examine the cost, ingredient list, or packaging of the two salad dressings.

The word *science* comes from a Latin word that means ''knowledge." Science is a distinctive way of gaining knowledge about the natural world that starts with a question and then tries to answer the question with evidence and logic. Science is an exciting exploration of all the whys and hows that any curious person might have about the world. Science is a way to get some of those "whys" answered. You can be part of that exploration. Besides your curiosity, all you need is a basic understanding of how scientists think and how science is done, starting with the goal of science.

THE GOAL OF SCIENCE

The goal of science is to understand the natural world. To achieve this goal, scientists make certain assumptions. They assume that:

- Nature can be understood through systematic study.
- Scientific ideas are open to revision.
- Sound scientific ideas withstand the test of time.
- Science cannot provide answers to all questions.

There are many different areas of science, or *scientific disciplines*, but all scientific study involves: asking questions, making observations, relying on evidence to form conclusions, and being skeptical about ideas or results. Skepticism is an attitude of doubt about the truthfulness of claims that lack empirical evidence. Scientific skepticism also referred to as skeptical inquiry, questions claims based on their scientific verifiability rather than accepting claims based on faith or anecdotes. Scientific skepticism uses critical thinking to analyze such claims and opposes claims which lack scientific evidence.

Nature Can Be Understood

Scientists think of nature as a single system controlled by natural laws. By discovering natural laws, scientists strive to increase their understanding of the natural world. Laws of nature are expressed as scientific laws. A scientific law is a statement that describes what always happens under certain conditions in nature.

An example of a scientific law is the law of gravity, which was discovered by Sir Isaac Newton (see **Figure 1.16**). The law of gravity states that objects always fall towards Earth because of the pull of gravity. Based on this law, Newton could explain many natural events. He could explain not only why objects such as apples always fall to the ground, but he could also explain why the moon orbits Earth. Isaac Newton discovered laws of motion as well as the law of gravity. His laws of motion allowed him to explain why objects move as they do.

Figure 1.16: Did Newton discover the law of gravity when an apple fell from a tree and hit him on the head? Probably not, but observations of nature are often the starting point for new ideas about the natural world.

Scientific Ideas Can Change

Science is more of a process than a set body of knowledge. Scientists are always testing and revising their ideas, and as new observations are made, existing ideas may be challenged. Ideas may be replaced with new ideas that better fit the facts, but more often existing ideas are simply revised. For example, when Albert Einstein developed his theory of relativity, he didn't throw out Newton's laws of motion. Instead, he showed that Newton's laws are a part of a bigger picture. In this way, scientists gradually build an increasingly accurate and detailed understanding of the natural world.

Scientific Knowledge Can Withstand the Test of Time

Many scientific ideas have withstood the test of time. For example, about 200 years ago, the scientist John Dalton proposed atomic theory—the theory that all matter is made of tiny particles called atoms. This theory is still valid today. There are many other examples of basic science ideas that have been tested repeatedly and found to be true. You will learn about many of them as you study biology.

Science Cannot Answer All Questions

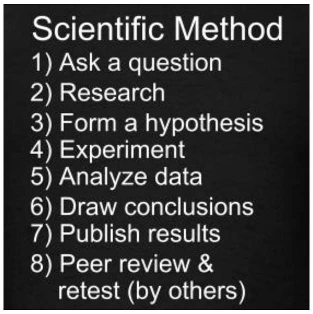
Science rests on evidence and logic, so it deals only with things that can be observed. An observation is anything that is detected either through human senses or with instruments and measuring devices that extend human senses. Things that cannot be observed or measured by current means—such as supernatural beings or events—are outside the bounds of science. Consider these two questions about life on Earth:

- Did life on Earth evolve over time?
- Was life on Earth created through another method?

The first question can be answered by science on the basis of scientific evidence and logic. The second question could be a matter of belief. Therefore, it is outside the realm of science.

THE SCIENTIFIC METHOD

There are basic methods of gaining knowledge that are common to all of science. At the heart of science is the scientific investigation, which is done by following the scientific method. A scientific investigation is a plan for asking questions and testing possible answers. It generally follows the steps listed in **Figure 1.17.** See http://www.youtube.com/watch?v=zcavPAFiG14& for an overview of the scientific method.



Scientific Method
1) Ask a question
2) Research
3) Form a hypothesis
4) Experiment
5) Analyze data
6) Draw conclusions
7) Publish results
8) Peer review &
retest (by others)

Figure 1.17: Steps of a Scientific Investigation. A scientific investigation typically has these steps.

Scientific Investigations

The scientific method is not a step by step, linear process. It is a way of learning about the world through the application of knowledge. Scientists must be able to have an idea of what the answer to an investigation is. Scientists will often make an observation and then form a hypothesis to explain why a phenomenon occurred. They use all of their knowledge and a bit of imagination in their journey of discovery.

Scientific investigations involve the collection of data through observation, the formation and testing of hypotheses by experimentation, and analysis of the results that involves reasoning. Scientific investigations begin with observations that lead to questions. We will use an everyday example to show what makes up a scientific investigation. Imagine that you walk into a room, and the room is dark.

- You observe that the room appears dark, and you question why the room is dark.
- In an attempt to find explanations to this phenomenon, you develop several different *hypotheses*. One hypothesis might state that the room does not have a light source at all. Another hypothesis might be that the lights are turned off. Still, another might be that the light bulb has burnt out. Worse yet, you could be going blind.

- To discover the answer, you experiment. You feel your way around the room and find a light switch and turn it on. No light. You repeat the experiment, flicking the switch back and forth; still nothing.
- This means your first two hypotheses, that the room is dark because (1) it does not have a light source; and (2) the lights are off, have been rejected.
- You think of more experiments to test your hypotheses, such as switching on a flashlight to prove that you are not blind.
- In order to accept your last remaining hypothesis as the answer, you could predict that changing the light bulb will fix the problem. If your predictions about this hypothesis succeed (changing the light bulb fixes the problem), the original hypothesis is valid and is accepted.
- However, in some cases, your predictions will not succeed (changing the light bulb does not fix the problem), and you will have to start over again with a new hypothesis. Perhaps there is a short circuit somewhere in the house, or the power might be out.

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See http://www.youtube.com/watch?v=KZaCy5Z87FAhttp://www.youtube.com/watch?v=KZaCy5Z87FA for an overview of the scientific method. The general process of a scientific investigation is summed up in **Figure 1.18.**

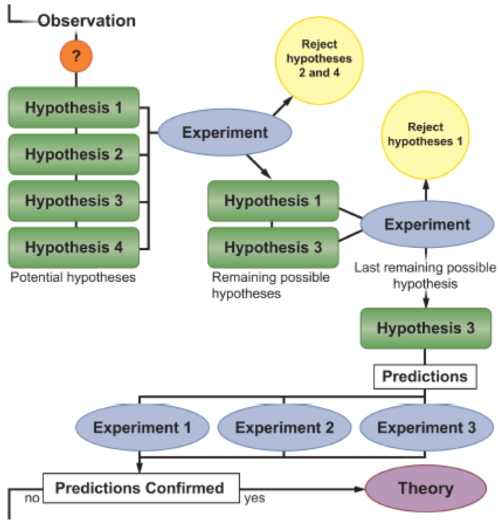

Figure 1.18 The general process of scientific investigations. A diagram that illustrates how scientific investigation moves from observation of phenomenon to a theory. The progress is not as straightforward as it looks in this diagram. Many times, every hypothesis is falsified which means the investigator will have to start over again.

Table 1.2 Common Terms Used in Scientific Investigations

Term	Definition
Scientific Method	The process of scientific investigation.
Observation	The act of noting or detecting phenomenon by the senses. For example, taking measurements is a form of observation.
Hypotheses	A suggested explanation based on evidence that can be tested by observation or experimentation.
Scientific Reasoning	The process of looking for scientific reasons for observations.
Experiment	A test that is used to rule out a hypothesis or validate something already known.
Rejected Hypothesis	An explanation that is ruled out by experimentation.
Confirmed Hypothesis	An explanation that is not ruled out by experimentation, and makes predictions that are shown to be true.
Inference	Developing new knowledge based upon old knowledge.
Theory	A widely accepted hypothesis that stands the test of time. Theories are often tested, and usually not rejected.

Making Observations

A scientific investigation typically begins with observations. You make observations all the time. Let's say you take a walk in the woods and observe a moth, like the one in **Figure 1.19**, resting on a tree trunk. You notice that the moth has spots on its wings that look like eyes. You think the eye spots make the moth look like the face of an owl.

Figure 1.19: Does this moth remind you of an owl?

Asking a Question

Observations often lead to questions. For example, you might ask yourself why the moth has eye spots that make it look like an owl's face. What reason might there be for this observation?

Forming a Hypothesis

The next step in a scientific investigation is forming a hypothesis. A hypothesis is a possible answer to a scientific question, but it isn't just any answer. A hypothesis must be based on scientific knowledge, and it must be logical. A hypothesis also must be falsifiable. In other words, it must be possible to make observations that would disprove the hypothesis if it really is false. Assume you know that some birds eat moths and that owls prey on other birds. From this knowledge, you reason that eye spots scare away birds that might eat the moth. This is your hypothesis or prediction.

A prediction is a statement that tells what will happen under specific conditions. It can be expressed in the form: *If A is true, then B will also be true.* Predictions are based on confirmed hypotheses shown to be true or not proved to be false. For researchers to be confident that their predictions will be useful and descriptive, their data must have as few errors as possible. Accuracy is the measure of how close a calculated or measured quantity is to its actual value. Accuracy is closely related to precision, also called reproducibility or repeatability. Reproducibility and repeatability of experiments are cornerstones of scientific methods. If no other researcher can reproduce or repeat the results of a certain study, then the results of the study will not be accepted as valid. Results are called valid only if they are both accurate and precise. A useful tool to help explain the difference between accuracy and precision is a target, shown in **Figure 1.20**. In this analogy, repeated measurements are the arrows that are fired at a target. Accuracy describes the closeness of arrows to the bulls eye at the center. Arrows that hit closer to the bulls eye are more accurate. Arrows that are grouped together more tightly are more precise.

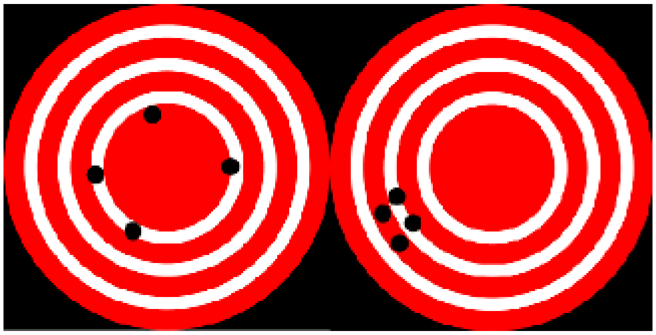

Figure 1.20 A visual analogy of accuracy and precision. Left target: High accuracy but low precision; Right target: low accuracy but high precision. The results of calculations or a measurement can be accurate but not precise; precise but not accurate; neither accurate nor precise; or accurate and precise. A collection of bulls eyes right around the center of the target would be both accurate and precise.

Testing the Hypothesis

To test a hypothesis, you first need to make a prediction based on the hypothesis. A prediction is a statement that tells what will happen under certain conditions. It can be expressed in the form: If A occurs, then B will happen. Based on your hypothesis, you might make this prediction: If a moth has eye spots on its wings, then birds will avoid eating it.

Next, you must gather evidence to test your prediction. Evidence is any type of data that may either agree or disagree with a prediction, so it may either support or disprove a hypothesis. Assume that you gather evidence by making more observations of moths with eye spots. Perhaps you observe that birds really do avoid eating the moths. This evidence agrees with your prediction.

Evaluating Hypotheses

Scientific methods require hypotheses that are falsifiable, that is, they must be framed in a way that allows other scientists to prove them false. Proving a hypothesis to be false is usually done by observation. However, confirming or failing to falsify a hypothesis does not necessarily mean the hypothesis is true.

For example, a person comes to a new country and observes only white sheep. This person might form the hypothesis: “All sheep in this country are white.” This statement can be called a hypothesis, because it is falsifiable - it can be tested and proved wrong; anyone could falsify the hypothesis by observing a single black sheep. If the experimental uncertainties remain small (could the person reliably distinguish the observed black sheep from a goat or a small horse), and if the experimenter has correctly interpreted the hypothesis, finding a black sheep falsifies the “only white sheep” hypothesis. However, you cannot call a failure to find non-white sheep as proof that no non-white sheep exist.

Scientific Reasoning

Any useful hypothesis will allow predictions based on reasoning. Reasoning can be broken down into two categories: deduction and induction. Most reasoning in science is done through induction.

Deductive Reasoning (Deduction)

Deduction involves determining a single fact from a general statement; it is only as accurate as the statement. For example, if the teacher said she checks homework every Monday, she will check homework next Monday.

Deductions are intended to have reasoning that is valid. The reasoning in this argument is valid, because there is no way in which the reasons 1 and 2, could be true and the conclusion, 3, be false:

- Reason 1: All humans are mortal.
- Reason 2: Albert Einstein is a human.
- Conclusion: Albert Einstein is mortal.

Inductive Reasoning (Induction)

Induction involves determining a general statement that is very likely to be true, from several facts. For example, if we have had a test every Tuesday for the past three months, we will have a test next Tuesday (and every Tuesday after that).

Induction contrasts strongly with deduction. Even in the best, or strongest, cases of induction, the truth of the reason does not guarantee the truth of the conclusion. Instead, the conclusion of an inductive argument is very likely to be true; you cannot be fully sure it is true because you are making a prediction that has yet to happen.

A classic example of inductive reasoning comes from the philosopher David Hume:

- Reason: The sun has risen in the east every morning up until now.
- Conclusion: The sun will also rise in the east tomorrow.

Inductive reasoning involves reaching conclusions about unobserved things on the basis of what has been observed already. Inferences about the past from present evidence, such as in archaeology, are induction. Induction could also be across outer space, as in astronomy, where conclusions about the whole universe are drawn from the limited number of things we are able to observe.

Experiments

Figure 1.21 shows a laboratory experiment involving plants. An experiment is a special type of scientific investigation that is performed under controlled conditions, usually in a laboratory. Some experiments can be very simple, but even the simplest contributed important evidence that helped scientists better understand the natural world. An example experiment can be seen here http://www.youtube.com/watch?v=F10EyGwd57M&feature=related or can be seen at http://www.youtube.com/watch?v=dVRBDRAsP6U

Figure 1.21: A laboratory experiment studying plant growth. What might this experiment involve?

A scientific experiment must have the following features:
- a control, so variables that could affect the outcome are reduced
- the variable being tested reflects the phenomenon being studied
- the variable can be measured accurately, to avoid experimental error
- the experiment must be reproducible.

An experiment is a test that is used to eliminate one or more of the possible hypotheses until one hypothesis remains. The experiment is a cornerstone in the scientific approach to gaining deeper knowledge about the physical world. Scientists use the principles of their hypothesis to make predictions, and then test them to see if their predictions are confirmed or rejected.

Scientific experiments involve controls, or subjects that are not tested during the investigation. In this way, a scientist limits the factors, or *variables* that can cause the results of an investigation to differ. A variable is a factor that can change over the course of an experiment. Independent variables are factors whose values are controlled by the experimenter to determine its relationship to an observed phenomenon (the dependent variable). Dependent variables change in response to the independent variable. Controlled variables are also important to identify in experiments. They are the variables that are kept constant to prevent them from influencing the effect of the independent variable on the dependent variable.

For example, if you were to measure the effect that different amounts of fertilizer have on plant growth, the independent variable would be the amount of fertilizer used (the changing factor of the experiment). The dependent variables would be the growth in height and/or mass of the plant (the factors that are influenced in the experiment). The controlled variables include the type of plant, the type of fertilizer, the amount of sunlight the plant gets, the size of the pots you use. The controlled variables are controlled by you, otherwise they would influence the dependent variable.

In summary:
- The independent variable answers the question ”What do I change?”
- The dependent variables answer the question ”What do I observe?”
- The controlled variables answer the question ”What do I keep the same?”

Variables

An experiment generally tests how one variable is affected by another. The affected variable is called the dependent variable. In the plant experiment shown above, the dependent variable is plant growth. The variable that affects the dependent variable is called the independent variable. In the plant experiment, the independent variable is fertilizer—some plants will get fertilizer, others will not. In any experiment, other factors that might affect the dependent variable must be controlled. In the plant experiment, what factors do you think should be controlled? (*Hint:* What other factors might affect plant growth?)

Sample Size and Repetition

The sample in an experiment or other investigation consists of the individuals or events that are studied. Typically, the sample is much smaller than all such individuals or events that exist in the world. Whether the results based on the sample are true in general cannot be known for certain. However, the larger the sample is, the more likely it is that the results are generally true. Similarly, the more times that an experiment is repeated and the same results obtained, the more likely the results are valid. This is why scientific experiments should always be repeated.

Experimental Design

Controlled Experiments

In an old joke, a person claims that they are snapping their fingers ”to keep tigers away,” and justifies their behavior by saying, ”See, it works!” While this experiment does not falsify the hypothesis ”snapping your fingers keeps tigers away,” it does not support the hypothesis either, because not snapping your fingers will also keep tigers away. It also follows that not snapping your fingers will not cause tigers to suddenly appear.

To demonstrate a cause and effect hypothesis, an experiment must often show that, for example, a phenomenon occurs after a certain treatment is given to a subject, and that the phenomenon does not occur in the absence of the treatment.

One way of finding this out is to perform a controlled experiment. In a controlled experiment, two identical experiments are carried out side-by-side. In one of the experiments the independent variable being tested is used, in the other experiment, the control, or the independent variable is not used.

A controlled experiment generally compares the results obtained from an experimental sample against a control sample. The control sample is almost identical to the experimental sample except for the one variable whose effect is being tested. A good example would be a drug trial. The sample or group receiving the drug would be the experimental group, and the group receiving the placebo would be the control. A placebo is a form of medicine that does not contain the drug that is being tested.

Controlled experiments can be conducted when it is difficult to exactly control all the conditions in an experiment. In this case, the experiment begins by creating two or more sample groups that are similar in as many ways as possible, which means that both groups should respond in the same way if given the same treatment.

Once the groups have been formed, the experimenter tries to treat them identically except for the one variable that he or she wants to study (the independent variable). Usually neither the patients nor the doctor know which group receives the real drug, which serves to isolate the effects of the drug and allow the researchers to be sure the drug does work, and that the effects seen in the patients are not due to the patients believing they are getting better. This type of experiment is called a double blind experiment.

Controlled experiments can be carried out on many things other than people; some are even carried out in space! The wheat plants in **Figure 1.22** are being grown in the International Space Station to study the effects of microgravity on plant growth. Researchers hope that one day enough plants could be grown during spaceflight to feed hungry astronauts and cosmonauts. The investigation also measured the amount of oxygen the plants can produce in the hope that plants could become a cheap and effective way to provide oxygen during space travel.

Figure 1.22 Spaceflight participant Anousheh Ansari holds a miniature wheat plant grown in the Zvezda Service Module of the International Space Station.

Experiments Without Controls

The term experiment usually means a controlled experiment, but sometimes controlled experiments are difficult or impossible to do. In this case researchers carry out natural experiments. When scientists conduct a study in nature instead of the more controlled environment of a lab setting, they cannot control variables such as sunlight, temperature, or moisture. Natural experiments therefore depend on the scientist's observations of the system under study rather than controlling just one or a few variables as happens in controlled experiments.

For a natural experiment, researchers attempt to collect data in such a way that the effects of all the variables can be determined, and where the effects of the variation remains fairly constant so that the effects of other factors can be determined. Natural experiments are a common research tool in areas of study where controlled experiments are difficult to carry out. Examples include: astronomy -the study of stars, planets, comets, galaxies and phenomena that originate outside Earth's atmosphere, paleontology - the study of prehistoric life forms through the examination of fossils, and meteorology - the study of Earth's atmosphere.

In astronomy it is impossible, when testing the hypothesis ”suns are collapsed clouds of hydrogen”, to start out with a giant cloud of hydrogen, and then carry out the experiment of waiting a few billion years for it to form a sun. However, by observing various clouds of hydrogen in various states of collapse, and other phenomena related to the hypothesis, such as the nebula shown in **Figure 1.23**, researchers can collect data they need to support (or maybe falsify) the hypothesis.

Figure 1.23 The Helix nebula, located about 700 light-years away in the constellation Aquarius, belongs to a class of objects called . Planetary nebulae are the remains of stars that once looked a lot like our sun. When sun-like stars die, they puff out their outer gaseous layers. These layers are heated by the hot core of the dead star, called a white dwarf, and shine with infrared and visible colors. Scientists can study the birth and death of stars by analyzing the types of light that are emitted from nebulae.

An early example of this type of experiment was the first verification in the 1600s that light does not travel from place to place instantaneously, but instead has a speed that can be measured. Observation of the appearance of the moons of Jupiter were slightly delayed when Jupiter was farther from Earth, as opposed to when Jupiter was closer to Earth. This phenomenon was used to demonstrate that the difference in the time of appearance of the moons was consistent with a measurable speed of light.

Natural Experiments

There are situations where it would be wrong or harmful to carry out an experiment. In these cases, scientists carry out a natural experiment, or an investigation without an experiment. For example, alcohol can cause developmental defects in fetuses, leading to mental and physical problems, through a condition called fetal alcohol syndrome.

Certain researchers want to study the effects of alcohol on fetal development, but it would be considered wrong or *unethical* to ask a group of pregnant women to drink alcohol to study its effects on their children. Instead, researchers carry out a natural experiment in which they study data that is gathered from mothers of children with fetal alcohol syndrome, or pregnant women who continue to drink alcohol during pregnancy. The researchers will try to reduce the number of variables in the study (such as the amount or type of alcohol consumed), which might affect their data. It is important to note that the researchers do not influence or encourage the consumption of alcohol; they collect this information from volunteers.

Field Experiments

Field experiments are so named to distinguish them from lab experiments. Field experiments have the advantage that observations are made in a natural setting rather than in a human-made laboratory environment. However, like natural experiments, field experiments can get contaminated, and conditions like the weather are not easy to control. Experimental conditions can be controlled with more precision and certainty in the lab.

Modeling

Another way to gain scientific knowledge without experiments is by making and manipulating models. A model is a representation of part of the real world. Did you ever build a model car? Scientific models are something like model cars; they represent the real world but are simpler than the real world. This is one reason that models are especially useful for investigating complex systems. By using a model, scientists can better understand how the real system works. An example of a scientific model is shown in **Figure 1.24**. Do you know what systems these two models represent?

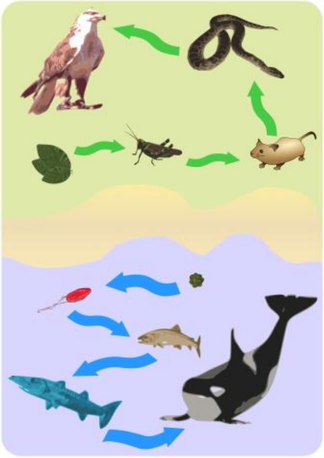

Figure 1.24 Food Chains. These two food chains represent complex systems in nature. They make the systems easier to understand. These are simple conceptual models. Models of very complex systems are often based on mathematical equations or computer simulations.

Like a hypothesis, a model must be evaluated. It is assessed by criteria such as how well it represents the real world, what limitations it has, and how useful it is. The usefulness of a model depends on how well its predictions match observations of the real world. Even when a model's predictions match real-world observations, however, it doesn't prove that the model is true or that it is the only model that works.

Experimental Error

An error is a boundary on the precision and accuracy of the result of a measurement. Some errors are caused by unpredictable changes in the measuring devices (such as balances, rulers, or calipers), but other errors can be caused by reading a measuring device incorrectly or by using broken or malfunctioning equipment. Such errors can have an impact on the reliability of the experiment's results; they affect the accuracy of measurements. For example, you use a balance to obtain the mass of a 100 gram block. Three measurements that you get are: 93.1 g, 92.0 g, and 91.8 g. The measurements are precise, as they are close together, but they are not accurate.

If the cause of the error can be identified, then it can usually be eliminated or minimized. Reducing the number of possible errors by careful measurement and using a large enough sample size to reduce the effect of errors will improve the reliability of your results.

Drawing Conclusions

Evidence that agrees with your prediction supports your hypothesis. Does such evidence prove that your hypothesis is true? No; a hypothesis cannot be proven conclusively to be true. This is because you can never examine all of the possible evidence, and someday evidence might be found that disproves or refutes the hypothesis. Nonetheless, the more evidence that supports a hypothesis, the more likely the hypothesis is to be true.

Communicating Results

The last step in a scientific investigation is communicating what you have learned with others. This is a very important step because it allows others to test your hypothesis. If other researchers get the same results as yours, they add support to the hypothesis. However, if they get different results, they may disprove the hypothesis. When scientists share their results, they should describe their methods and point out any possible problems with the investigation. For example, while you were observing moths, perhaps your presence scared birds away. This introduces an error into your investigation. You got the results you predicted (the birds avoided the moths while you were observing them), but not for the reason you hypothesized. Other researchers might be able to think of ways to avoid this error in future studies.

SCIENTIFIC THEORIES

With repeated testing, some hypotheses may eventually become scientific theories. A scientific theory is a broad explanation for events that is widely accepted as true. To become a theory, a hypothesis must be tested over and over again, and it must be supported by a great deal of evidence. People commonly use the word *theory* to describe a guess about how or why something happens. For example, you might say, ''I think a woodchuck dug this hole in the ground, but it's just a theory." Using the word *theory* in this way is different from the way it is used in science. A scientific theory is more like a fact than a guess because it is so well-supported. There are several well-known theories in biology, including the theory of evolution, cell theory, and gene theory. You will read about all three of these theories in the next lesson. A video explaining scientific theories can be seen at:
http://www.youtube.com/watch?v=S5YGhprR6KE.

Constructing Theories

In time, a confirmed hypothesis may become part of a theory or may grow to become a theory itself. Scientific hypotheses may be mathematical models. Sometimes they can be statements, stating that some particular instance of the phenomenon under examination has some characteristic and causal explanations. These theories have the general form of universal statements, stating that every instance of the phenomenon has a particular characteristic.

A hypothesis may predict the outcome of an experiment in a laboratory or the observation of a natural phenomenon. A hypothesis should also be falsifiable, and one cannot regard a hypothesis or a theory as scientific if it does not lend itself to being falsified, even in the future. To meet the "falsifiable" requirement, it must at least in principle be possible to make an observation that would disprove the hypothesis. A falsifiable hypothesis can greatly simplify the process of testing to determine whether the hypothesis can be proven to be false. Scientific methods rely heavily on the falsifiability of hypotheses by experimentation and observation in order to answer questions. Philosopher Karl Popper suggested that all scientific theories should be falsifiable; otherwise they could not be tested by experiment.

A scientific theory must meet the following requirements:
- it must be consistent with pre-existing theory in that the pre-existing theory has been experimentally verified, though it may often show a pre-existing theory to be wrong in an exact sense
- it must be supported by many strands of evidence rather than a single foundation, ensuring that it is probably a good approximation, if not totally correct.

Also, a theory is generally only taken seriously if it:
- allows for changes to be made as new data are discovered, rather than claiming absolute certainty.
- is the most straight forward explanation, and makes the fewest assumptions about a phenomenon (commonly called "passing the Occam's razor test").

This is true of such established theories as special relativity, general relativity, quantum mechanics, plate tectonics, and evolution. Theories considered scientific meet at least most, but ideally all, of these extra criteria. In summary, to meet the status of a scientific theory, the theory must be falsifiable or testable.

Examples of scientific theories in different areas of science include:
- **Astronomy**: Big Bang Theory
- **Biology**: Cell Theory; Theory of Evolution; Germ Theory of Disease
- **Chemistry**: Atomic Theory; Kinetic Theory of Gases
- **Physics**: General Relativity; Special Relativity; Theory of Relativity; Quantum Field Theory
- **Earth Science**: Giant Impact Theory; Plate Tectonics

Currently Unverifiable Theories

The term theory is sometimes stretched to refer to theoretical speculation which is currently unverifiable. Examples are string theory and various theories of everything. String theory is a model of physics, which predicts the existence of many more dimensions in the universe than the four dimensions that current science understands (length, width, height, and space-time). A theory of everything is a hypothetical theory in physics that fully explains and links together all known physical phenomena.

For a scientific theory to be valid it must be verified experimentally. Many parts of the string theory are currently untestable due to the large amount of energy that would be needed to carry out the necessary experiments as well as the high cost of conducting them. Therefore string theory may not be tested in the foreseeable future. Some scientists have asked if it even deserves to be called a scientific theory because it is not falsifiable.

Superseded Theories

A superseded, or obsolete, scientific theory is a theory that was once commonly accepted, but for whatever reason is no longer considered the most complete description of reality by mainstream science. It can also mean a falsifiable theory which has been shown to be false. Giraffes, shown in **Figure 1.25** on the next page, are often used in the explanation of Lamarck's superseded theory of evolution. In Lamarckism, a giraffe is able to lengthen its neck over its life time, for example by stretching to reach higher leaves. That giraffe will then have offspring with longer necks. The theory has been superseded by the understanding of natural selection on populations of organisms as the main means of evolution, not physical changes to a single organism over its lifetime.

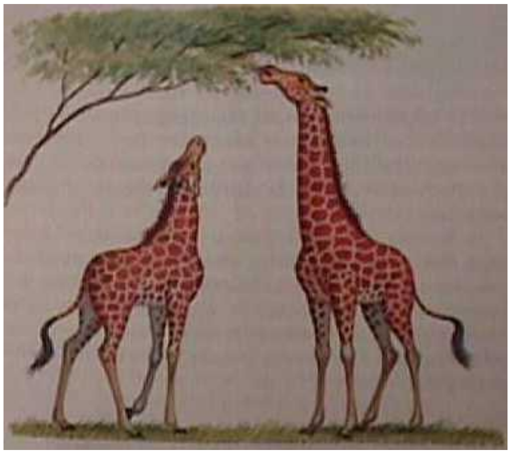

Figure 1.25: Superseded theories like Lamarck's theory of evolution are theories that are now considered obsolete and have been replaced by newer theories that have more evidence to support them; in Lamarck's case, his theory was replaced by Darwin's theory of evolution and natural selection, which will be discussed in later chapters .

SCIENTIFIC LAWS

Scientific laws are similar to scientific theories in that they are principles which can be used to predict the behavior of the natural world. Both scientific laws and scientific theories are typically well-supported by observations and/or experimental evidence. Usually scientific laws refer to rules for how nature will behave under certain conditions. Scientific theories are more overarching explanations of how nature works and why it exhibits certain characteristics.

A physical law or law of nature is a scientific generalization based on a sufficiently large number of empirical observations that it is taken as fully verified. Isaac Newton's law of gravitation is a famous example of an established law that was later found not to be universal—it does not hold in experiments involving motion at speeds close to the speed of light or in close proximity of strong gravitational fields. Outside these conditions, Newton's laws remain an excellent model of motion and gravity.

Scientists never claim absolute knowledge of nature or the behavior of the subject of the field of study. A scientific theory is always open to falsification, if new evidence is presented. Even the most basic and fundamental theories may turn out to be imperfect if new observations are inconsistent with them. Critical to this process is making every relevant part of research publicly available. This allows peer review of published results, and it also allows ongoing reviews, repetition of experiments and observations by many different researchers. Only by meeting these expectations can it be determined how reliable the experimental results are for possible use by others.

APPLYING CONCEPTS: Bio-Inspiration: Nature as Muse

For hundreds of years, scientists have been using design ideas from structures in nature. Now, biologists and engineers at the University of California, Berkeley are working together to design a broad range of new products, such as life-saving milli-robots modeled on the way cockroaches run and adhesives based on the amazing design of a geckos foot. This process starts with making observations of nature, which lead to asking questions and to the additional aspects of the scientific process. *Bio-Inspiration: Nature as Muse* can be observed at: http://www.kqed.org/quest/television/bioinspiration-nature-as-muse.

Lesson Summary

- The goal of science is to understand the natural world through systematic study. Scientific knowledge is based on evidence and logic.
- Scientists gain knowledge through scientific investigations. A scientific investigation is a plan for asking questions and testing possible answers.
- Scientists use experiments to test hypotheses under controlled conditions. Experiments are often done in a lab.
- In a controlled experiment, two identical experiments are carried out side-by-side. In one of the experiments the independent variable being tested is used, in the other, the control, or the independent variable is not used.
- Any useful hypothesis will allow predictions based on reasoning. Reasoning can be broken down into two categories: deduction and induction. Most reasoning in science is formed through induction.
- A variable is a factor that can change over the course of an experiment. Independent variables are factors whose values are controlled by the experimenter to determine its relationship to an observed phenomenon (the dependent variable). Dependent variables change in response to the independent variable.
- Other types of scientific investigations include natural studies and modeling. They can be used when experiments are difficult to do.
- Scientific theories are broad explanations that are widely accepted as true. This is because they are supported by a great deal of evidence.

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