Some Interesting Questions

The greatest value of evolution is that it explains many of the mysteries of the living world. There are many questions that defy understanding until they are examined in the light of evolution. We will investigate much of the evidence in support of evolution later, but at this time it might be interesting to consider just a sampling of the fascinating questions that can be understood through the lens of evolution.

Male bees and wasps do not have a stinger. How do we explain this observation? In the context of evolution, the answer is quite simple. The stinger evolved from a modified egg-laying device that was used by the ancestors of bees and wasps to insert eggs into plants and other insects. Since males do not lay eggs, they did not have this egg-laying device and, therefore, did not evolve a stinger (Figure 1.1).

The bones of a bat wing and a whale flipper are more similar to the bones in
The similarity of the bones in a bat wing, whale flipper, and human arm demonstrates that they are more closely related to each other than the bat wing is to a bird wing or the whale flipper is to a fish fin (not shown). The bones are the humerus (gray), radius (blue), ulna (pink), carpals (yellow), metacarpals (green), and phalanges (brown). [Volkov Petrovich]

Baleen whales do not have teeth, but they have long plates of flexible material called baleen that hangs down from their upper jaws. Baleen is used to filter food (small plants and animals) from the ocean water. The fetus of a baleen whale develops a full set of teeth that are not covered by enamel and never erupt through the gums, but are completely absorbed before birth (Figure 1.3). How does evolution explain these teeth? The fossil record shows us that the ancestors of all types of whales had teeth, and this toothed
ancestry is still displayed in the embryonic development of baleen whales. In addition, baleen whales have teeth forming genes that are non-functional.

Dolphins do not have hind legs. So why do dolphin embryos develop hind leg buds that never develop into legs? The early development of a dolphin proceeds much like any other mammal. It even has hind leg buds which develop into hind legs in other mammals (Figure 1.4). However, the leg buds of dolphins are absorbed in later embryonic stages and never develop into legs. This is strong evidence of their four-legged ancestry.

Many of the life forms found on islands are unique. How did these life forms originate? Most islands have been isolated for millions of years. If some type of plant or pair of animals happened to reach the island and was able to become established, its descendants would have evolved into new species as they adapted to their new environment. If there are several islands in the group or different environments on one of the larger islands, several closely related species will likely evolve. Examples of animals confined to specific islands include a family of Hawaiian birds called the honeycreepers, the Darwin finches of the Galapagos Islands, the extinct Dodo of Mauritius (Figure 1.5) and its close relative, the extinct Rodrigues Solitaire, the kiwis and the extinct moas of New Zealand, insectivorous mammals called solenodons of Cuba and Hispaniola, the lemurs of Madagascar, and the kangaroos of Australia. In Chapter 9 many of these animals will be discussed.

How do we explain the observation that each chromosome replicates itself before meiosis? This replication appears to be a complication that is not necessary. Meiosis is the process by which eggs and sperms are formed in

**Figure 1.4 Spotted Dolphin Embryo** The early development of a dolphin proceeds much like any other mammal. Hind leg buds are formed (circled), but are later absorbed. [J.G.M.Thewissen/NEOMED]

**Figure 1.5 Dodo** On the island of Mauritius, the flightless Dodo evolved from a pigeon ancestor about 10 million years ago. It was about one meter tall. Within 60 years of its discovery, it had been driven to extinction. The last sighting was in 1662. DNA evidence suggests that the Nicobar Pigeon, found on several islands off Southeast Asia, may be its closest living relative. [Ballista]
higher forms of life. The complexity of meiosis can be understood if we view meiosis as a slight modification of simple cell division, a process we call mitosis. Meiosis evolved from mitosis. (See Chapter 6)

Whales do not have back legs. Then why do they have pelvic bones that are buried in muscle tissue and are not attached to any other bones? Whales evolved from four legged mammals that were the ancestors of all modern day whales and dolphins. The hind limb bones of these mammals have not been entirely lost (Figure 1.6).

Boa constrictors have rudiments of hind legs, and two lungs (Figure 1.7). How are these structures explained? Although all snakes have two lungs, in most snakes one lung is greatly reduced in size to make the body more streamlined. Again, in the context of evolution we know that snakes evolved from walking lizards that possessed two lungs, four legs, and a pelvis. The boa constrictor is a primitive snake that is not as highly evolved as other snakes. Their leg bones and pelvic bones have not been completely lost.

Some salamanders that live in caves have non functional eyes covered by skin (Figure 1.8). How do we explain this? These blind salamanders must have evolved from salamanders that had functional eyes. Since they spend their life in dark caves, eyes are not useful. In a dark environment, eyes might even be a disadvantage to these salamanders since their eyes could easily be injured in the
dark and get infected. This type of injury could potential put the salamander’s life at risk.

The cave salamander’s eyes that no longer function as eyes are called vestigial structures. Vestigial structures no longer perform their original function. Many are nonfunctional, or their function is greatly reduced. Some vestigial structures may be used for other simple purposes. For example, the vestigial hind legs of the python protrude from the snake’s body, and their ends are covered by spurs that are used in mating (Figure 1.9).

There are many examples of vestigial structures in nature that provide evidence of the evolutionary process. Many birds have lost the ability to fly, as their wings are too small to sustain flight. Rails that managed to reach many isolated islands evolved into flightless species (Figure 1.10). There are also flightless ducks, flightless pigeons like the Dodo, and even a flightless parrot (the Kakapo of New Zealand). Unfortunately, since the arrival of humans, many of these flightless birds have become extinct.

Fossils are found in layers of sedimentary rock, and there is a very definite pattern to the layering. For example, dinosaur bones are never found in rock layers that contain the bones of elephants, horses, humans, or any of the other large mammals whose bones are so common in younger (higher) layers. How was this pattern created? We conclude that dinosaurs lived before the large mammals evolved. After the dinosaurs became extinct, the larger mammals evolved and when these mammals died, some of their bones were trapped in layers of sediment on top of the dinosaur bones.

**Figure 1.8 Texas Blind Salamander** This cave salamander has lost its eyesight, and its vestigial eyes are covered with skin. [Joe N.Fries/USFWS]

**Figure 1.9 Anal Spurs** The anal spurs of an albino Burmese Python. [Dawson]

**Figure 1.10 Flightless Rails** The poorly named Tasmanian Nativehen (top) is only found on the island of Tasmania, but a hen is a female bird and they are not all hens. [Edodridge] The Takahe (below) is only found in New Zealand.
Sharks shed their teeth and millions of fossil shark teeth have been found in certain fossil bearing layers. However, none are found with the trilobite fossils of the earlier time periods we call the Cambrian and Ordovician. This is no mystery if we realize that sharks evolved about a hundred million years after the first trilobites appeared. In Chapter 7 we will study some of the details of the fossil record.

How does evolution explain the Giant Panda’s thumb? The so-called thumb is a modified wrist bone called the radial sesamoid, but it does serve the purpose of aiding the panda as it feeds on bamboo leaves (Figure 1.11). Evolution does not always lead to the best solution to a problem. Indeed, evolution often does not lead to any solution at all, as evidenced by the great numbers of species that have become extinct throughout history. Many of the uniquely adapted island animals have become extinct since the introduction of foreign species by humans in more recent times. Some of the introduced species are obviously better suited to life on the islands than are many of the native species.

Most people know that there are no penguins in the Arctic and no Walruses in the Antarctic. Kangaroos are only found in Australia, and Giraffes are only found in Africa. You will not see Tigers in Africa and sloths only live in South America. The reason so many plants and animals are only found in specific regions on the Earth can be easily explained in terms of continental drift and evolution. We will investigate this subject in Chapter 9.

The Words We Use

Since we will be dealing with information from the discipline of science, an understanding of the methods, vocabulary, and reasoning used in science is essential. As with any discipline, there are many words used in science that may be unfamiliar to the nonscientist. Unfortunately, even scientists have distorted the meanings of some words through casual use.

When certain words gain a measure of prestige, they may be used to help sway the listener to a particular point of view. For example, calling a survey a scientific survey may cause it to carry more weight with the general public. The word scientific has been used so carelessly that many people no longer clearly understand its meaning.

We use words to sway opinions or even mislead our listeners. If an advertisement reads, Free Pizza, does it really mean you will get a pizza without paying anything? Not likely! If you read the fine print, the ad probably means that you get the free pizza only after you buy something first, like another pizza (Figure 1.12). In other words, for a certain amount of money, you can buy two pizzas. If that is what was meant, why didn’t the ad say two pizzas for the regular price of one?

Figure 1.11 Panda's Thumb Not a real thumb, but a modified wrist bone used to grasp bamboo, the panda's favorite food. Evolution does not always find the best solution. The right front paw is shown. The "thumb" is the pad on the right. [Kelly Yates]
Does the word *free* accurately describe the offer?

Many statements in advertising are carefully designed to get your attention or mislead the potential customer. It has become an accepted practice to try to create an illusion about an item that may not accurately reflect the true nature of the product. The intention is to mislead the public to sell a product.

Words used improperly to create an impression eventually lose their original meanings and become less useful in communication. What does the word *free* mean? When words are used in a careless manner, it becomes extremely difficult to understand what is being said. Understanding the exact definitions of words is a prerequisite for accurate communication. Many arguments are brought to a quick end or become less intense when the parties involved carefully define the words they are using. Sometimes they even discover that they agree on the issue.

Because some words are not precisely defined, it is often difficult to decide if they apply. To illustrate, let us ask: What is a scientist? Is an engineer a scientist? Is a physician a scientist? They are not generally considered to be scientists, however, some engineers and some physicians are scientists. Is a student who has taken a biology course a scientist, or a student with an undergraduate degree in chemistry? Is the holder of a doctorate in physics a scientist? These, like many questions, cannot always be answered with a simple yes or no.

In this book, our main objective is to gain an in-depth understanding of evolution. Is evolution a theory or a fact? As we continue, we will discuss the meanings of several words such as fact and theory that are often misunderstood, but are extremely important if we are to understand the nature of science. In many cases, even members of the scientific community may not agree on the usage of the terminology. Our goal is to establish a mutual understanding of how these words will be used in subsequent chapters of this book.

**Data and Its Interpretation**

An important aspect of science is the collection of information or data while performing experiments and making observations. Data collection is often called the *fact* gathering phase of science. However, the word fact is not precisely defined in science. Most *facts* in science are pieces of information that most scientists would call data.

A certain degree of interpretation by the observer often accompanies the presentation of scientific data. Those not familiar with scientific methods can sometimes confuse the data with the conclusions based on the data. To illustrate the terms we have been discussing, consider the following example.

If someone sees a dead limb fall from a tree during a thunderstorm, the observer might say it is a fact that this particular limb fell from that particular tree. However, would a person who did not see the limb fall consider it a fact?
For the following discussion, let us suppose that no one actually saw the limb fall, but we find the dead limb lying under a tree. Would we then conclude that the limb fell from that particular tree? It is possible that the wind blew the limb from a nearby tree, or perhaps some animal carried it from a more distant tree (Figure 1.13).

Before we conclude anything, we will need to make more observations and perform some experiments. Suppose we observe that the tree is a Sugar Maple, and we determine that the limb came from a Sugar Maple. We also search the surrounding area and are unable to discover any other Sugar Maples. After collecting this data, could we conclude that the limb came from that Sugar Maple? Perhaps, but it is still possible that someone carried the limb from another Sugar Maple quite a distance away, or perhaps the limb came from a nearby tree that we overlooked in our search.

Searching for something without success does not always demonstrate that the thing was not there. If I search my house for my car keys and fail to locate them, I cannot be sure that they are not in the house. On the other hand, if I search my house for a lost elephant and fail to find it, I would be very sure that the elephant was not in the house.

When we draw conclusions based on a search, we must consider the nature of the object and the nature of the search area. Were we looking for a needle in a haystack or a needle in a teacup? Perhaps we need to collect more data.

Suppose we examine the limb and the tree with a microscope and discover that the break on the limb matches a break on the tree. We even decide to analyze samples of the tree and the limb, and we find they are the same chemically. With this additional data, even the most ardent skeptic would probably be convinced that the limb came from the tree under which it was found. However, it is still possible that the limb was broken off an identical tree, and the break just happened to match a break on the tree to which the limb was transported. Remember, no one saw it fall from the tree.

However, the probability that this remarkable set of coincidences took place is so remote that few would doubt that the limb did indeed fall from the Sugar Maple. Nevertheless, a more correct statement would be to say that, based on our interpretation of the observations, we conclude that the limb fell from the Sugar Maple under which it was found. Note also that we did not prove that the limb fell from the tree. We do not prove things in science! We only gather data that supports our interpretation of the observations. In casual discussions, the word fact is often used when either data or interpretation of an observation is a more accurate description.

Most people think it is a fact that the Earth orbits the Sun. Eventually, certain observation were made that did support the idea. We do not usually give the evidence when we say that the Earth orbits the Sun. However, this statement is more accurately described as an interpretation of the observational

![Figure 1.13 Dead Limb on the Ground](JCB)
data, or a conclusion supported by the data.

The Naming of Ideas

There is much more to science than just the collection and interpretation of data. The real power of science comes from our ability to predict the outcome of experiments and observations even before they are performed. To accomplish this feat, we need a statement or formula that will tell us how to make the prediction. These statements are given many names: postulates, theories, principles, or laws.

In some science books you may even find an outline of how the naming of these ideas is supposed to evolve. After some initial investigations, a scientist will formulate an idea or educated guess that is supposed to be called a hypothesis. When the hypothesis is supported by a large number of observations or experiments, the hypothesis is supposed to become a theory. If the theory makes accurate predictions over a long period of time and becomes universally accepted by the scientific community, the theory is supposed to become a law or principle.

Although this procedure may sound like a reasonable system, no official scientific group is commissioned to make the necessary decisions about just when these name changes are to be made. Consequently, the word theory is used for a wide range of ideas. Many new ideas with little supporting evidence are called theories, and some of the most widely accepted ideas in science are also called theories. The scientific community does not have a definite vocabulary to differentiate between a highly successful theory and a new idea that has little supportive evidence.

If scientists do not have a clear naming system, we should not be surprised that statements such as the one claiming that evolution is only a theory can mislead a nonscientist.

A speculation with little supporting evidence should be called a hypothesis or simply a speculation, but these are such weak words that few people use them. Most new ideas reported in scientific journals are called theories by their author, probably because the word theory carries more weight than the words conjecture and speculation.

Even though science has failed to provide us with a standardized vocabulary in this area, we will discuss some of the words that are commonly encountered in science.

Postulates

Physics is a discipline that strives to fully understand the basic rules under which the various components of the Universe operate. The job of a physicist is to observe, classify, and experiment with objects in nature, and to formulate general statements that explain the behavior of these objects. The most fundamental of these general statements are known as postulates or axioms. Postulates are assumptions that can be used to accurately predict the results of experiments and observations made in the natural Universe. As was noted above, the scientific vocabulary has not been carefully defined, and postulates are often called theories, laws, or just equations. Postulates differ from interpretations of observations in that postulates are comprehensive statements that allow the scientist to make predictions even before observations or experiments are performed. For example, a physicist
can use the postulate of gravity to predict where a planet will be located at any time in the future. This postulate is called the law of gravity.

Theories

Sometimes the word theory and postulate are used interchangeably, but sometimes the word theory is used when a more comprehensive concept is implied. When physicists refer to the theory of quantum mechanics, they are not just alluding to the basic postulates of quantum mechanics, but also the predictions and investigations that are associated with this area of study. In nonscientific discussions, theory is often used to imply a wild speculation, but in science, a theory is often a well-verified idea. The nonscientist should be aware of the wide range of meanings that this word encompasses. As with many scientific terms, there is no official definition for the word theory.

As noted, the word theory is sometimes used to describe a comprehensive area of study. The theory includes all the basic postulates of the theory, any predictions that the postulates imply, observational data associated with these postulates, and interpretations of that data. Examples of comprehensive theories include the theory of special relativity and the theory of quantum mechanics. Ironically, these two theories provide our most accurate description of the mechanical workings of the Universe!

Many of the postulates that were formulated in earlier times were called laws. Some postulates that are commonly referred to as laws include, Newton’s law of gravity, the laws of thermodynamics, Coulomb’s law, Ohm’s law, and Newton’s laws of motion. These laws are not fundamentally different from the postulates associated with various comprehensive theories such as the theory of quantum mechanics or the theory of general relativity that have been proposed in more recent times. In fact, all the laws listed above have been found to be incorrect under certain circumstances, and newer theories are more accurate descriptions of nature.

The word law is no longer used for new ideas, perhaps because so many laws have been found to be incorrect, or at least limited in their application. Nonscientists often have the mistaken idea that a law is somehow more valid or factual than a theory. However, laws are not more valid than theories, and in some cases the reverse is true.

In 1916, Albert Einstein introduced the world to a new theory called the general theory of relativity (Figure 1.14). Today, this theory represents the most accurate description we have of gravity. The postulates of Einstein’s theory more accurately describe gravity
than does Newton’s law of gravity. Einstein’s theory gives the correct answer to several gravitational problems that cannot be accurately answered using Newton’s law of gravity. One of these problems was recognized soon after Newton proposed his law.

As Mercury orbited the Sun, astronomers noticed that it did not follow the exact path predicted by Newton’s law of gravity (Figure 1.15). Because of its outstanding success in explaining so many other observations, people were reluctant to believe that Newton’s law was incorrect.

Other explanations for Mercury’s strange behavior were proposed. One solution to the problem required the existence of another planet near the Sun. However, astronomical searches failed to discover any objects of the size required to explain the observed deviations in Mercury’s orbit. Finally, Einstein’s general relativity theory explained the peculiar motion.

If Newton’s law of gravity is not correct, why do we still teach it? Unless a problem involves extremely strong gravitational forces, or other very specialized conditions, Newton’s law of gravity can approximate Einstein’s theory quite well. Newton’s law is a special case of Einstein’s theory. So you see, Newton’s law is not incorrect in most cases, but it does have certain restrictions, and we cannot apply it to every gravitational problem as originally hoped. In addition, Newton’s law has a great advantage over Einstein’s theory in that it can be stated in a much simpler form and, therefore, it is easier to understand than Einstein’s theory.

Finally, the mathematics used in association with Newton’s law is much simpler than the mathematics required by Einstein’s theory. The difference in mathematical complexity is similar to the difference between high school math and college calculus. For most problems dealing with gravity, both theories give essentially the same answer. Therefore, we merely determine under what circumstances it is permissible to apply Newton’s approximation and use it only in those cases.

Because scientists have failed to carefully define these terms, the public generally believes that a scientific law is an absolute truth when in actuality, most scientific laws are not completely correct. On the other hand, the general public tends to think of theories as being more speculative, but some theories provide us with our most accurate descriptions of nature. In science, most of the truly great ideas are called theories!

Although we have briefly discussed comprehensive theories, remember that the scientific community is not in uniform agreement as to the accepted usage of the word theory. Often it is used for every idea in science. For example, some scientists speculate that
a large asteroid or comet collided with the Earth about 65 million years ago, and the resulting explosion caused the extinction of the dinosaurs. This extinction theory is similar to our tree limb example. Given enough data, we might conclude that the asteroid theory is correct. (There is already a great deal of evidence in support of this extinction theory.) An important difference between simple ideas and comprehensive theories is that comprehensive theories can be used to make numerous predictions about the outcomes of future studies. Many of the simple ideas in science that are often called theories lead to few if any predictions.

When the general public reads about a theory that the evolution of intelligence might be due to the complexities faced by apes in their search for a varied diet, and then a scientist tries to tell those people that gravity is also a theory, is it any wonder that there is some confusion? With such casual usage of the word theory, is it any surprise that creationists are able to cast doubt on evolution by simply stating that it is only a theory? The implication being that it is not a fact like gravity, but some wild speculation. Ideas of restricted application should not be called theories. Less confusion would arise in both the scientific and nonscientific communities if such ideas were consistently referred to as hypotheses or speculations or conclusions based on observations.

A hypothesis is a simple idea that is proposed to explain certain observations. Most hypotheses are of the type that if enough additional data were gathered to support it, we would consider it to be a conclusion based on the observations. Copernicus speculated that the planets orbit the Sun. His original idea may have been a hypothesis, but we now have enough evidence in support of this hypothesis that most scientists consider it a conclusion based on the observations. Since our current theory of gravity predicts that the Earth should orbit the Sun, our observations support the theory of gravity.

The Postulates of a Theory

The postulate formulating stage in the scientific process involves a type of reasoning known as inductive reasoning. After sufficient data has been gathered on certain objects or events, inductive reasoning is used to formulate a general postulate (or postulates) that will predict the behavior of these objects. Inductive reasoning is the reasoning we use to formulate a general statement based on specific observations. Simply stated, it is the reasoning of experience. We have all heard that experience is the best teacher, however, like so many old sayings this one is extremely unreliable. Conclusions based on experience are often in error!

We will look at a very simple example to illustrate the process of using inductive reasoning to formulate a postulate. Suppose we observe the dogs in our neighborhood and notice that all of them are covered with brown fur. Because of the data we have collected, we might propose a postulate, which states that all dogs are brown (Figure 1.16). We would very likely be accused of being a little hasty in basing our postulate on such a limited amount of data, but the above example does illustrate the inductive process, and the fallibility of inductive reasoning.

Scientific postulates must explain all of what has been observed or demonstrated in past experiments, but
to be widely accepted by the scientific community, a postulate must be able to correctly predict future discoveries, or the results of future experiments. In the above example, our dog postulate would predict that all the dogs we see in the future should be brown. Suppose we observe more dogs (collect more data), and they all are brown. Although this data does not prove that our postulate is correct, it does give us more confidence in our postulate.

Notice that it is impossible to prove that a postulate is true in all cases. Considering our dog postulate for example, even if we were to search for years, how could we prove that we had seen every dog in the world? How could we prove that all future dogs will be brown, or that all the dogs that lived in the past were brown? A postulate is a statement that cannot be proven. However, as more of its predictions are verified, we gain more confidence in the postulate.

What happens if we observe something that contradicts a postulate? For example, suppose we observe a dog that is not brown. Of course this piece of data would prove that our postulate must be wrong, but there are two options open to us. We might have to throw out the postulate and start over, but it might be possible to amend the postulate to cover the observed exceptions. Perhaps the dogs that are not brown have long hair. Our new restricted postulate might state that all short-haired dogs are brown. Since the new postulate is restricted to short-haired dogs, it cannot be applied to long-haired dogs. (We might also have to carefully define what is meant by short hair.)

The distinction between a scientific postulate and a conclusion based on observational evidence can be fuzzy. A postulate is an assumption we make because it explains many of our observations, while a conclusion based on the evidence is a specific statement that we accept as true because the evidence is so overwhelming. In the tree-limb example, one could always argue that there is not enough evidence to say that the limb came from the tree in question. Since no one saw the limb fall, some might say that they do not believe that the limb fell from that tree. However, if no amount of evidence will satisfy us, we will make little progress toward understanding the mysteries of the Universe.

Postulates such as those associated with Einstein’s theory of general relativity cannot be proven correct in all circumstances. It would be impossible to accurately investigate all the gravitational problems in the Universe and prove that the postulates give the exact answer in every situation. If postulates (and, therefore, the theories to which they apply) cannot be proven, why do scientists have such a great deal of confidence in many of them? The answer is quite simple. Theories that are widely accepted by the scientific community have been used to make many accurate predictions about future investigations. However, there is always a possibility that some future prediction will invalidate the theory or a part of the theory.
A comprehensive scientific theory creates a unified picture out of many observations, some of which may seem totally unrelated. The reason for the success of science can be traced to the ability of theories to predict the results of future experiments and observations. An understanding of a few scientific theories will enable a scientist to explain and predict the results of innumerable experiments. Millions of individual pieces of data and hundreds of thousands of problems can be unified into an understandable picture by a few comprehensive theories.

When a scientific theory has an overwhelming amount of supportive evidence, some may be tempted to say that the theory has become fact. However, theories never become facts. As we have stated, the word fact is best avoided in science, and probably should be avoided in other disciplines as well.

Testing a Theory

If postulates are statements that can never be proven, under what conditions would scientists accept a theory based on these postulates? As stated above, the real test of a theory is how well it explains and predicts the results of experiments and observations.

Scientific theories contain general postulates that are used to make specific predictions. This phase in the scientific process involves the reasoning of logic that we call deductive reasoning. Deductive reasoning is logical reasoning that uses one or more general statements (called premises) to formulate a specific conclusion or prediction. A premise can be either a postulate or an observation.

To illustrate, let us return to our postulate that all short-haired dogs are brown. If someone tells us that Rover is a short-haired dog, then according to our dog postulate and the observation that Rover is a short-haired dog, we would predict that Rover must be brown. We have not proven that Rover is brown. We have only concluded that Rover must be brown if our premises are correct. If a conclusion based on deductive reasoning is found to be incorrect, one or more of the premises (either the postulate or the observation, in this example) must be incorrect. As we noted earlier, postulates may turn out to be wrong since inductive reasoning was used to formulate them.

The next stage in the scientific process is to attempt to verify the prediction. In our dog theory, for example, Rover should be examined. If Rover is not brown, of course our postulate is in trouble, and it must be discarded or modified again. However, if we can verify that Rover is brown, we will have an additional piece of data to support our theory, and our confidence in the validity of the basic postulates of the theory will be slightly increased. The most widely accepted scientific theories have made many accurate predictions, increasing our confidence in the theory.

An example of this predictive process occurred in the mid-1800s. Newton’s law (postulate) of gravity stated that every object in the Universe should attract a given object. For example, the Sun, Moon, and every other object in the Universe attracts the Earth. However, after calculating the forces on Uranus due to the Sun and all the known planets, it was observed that Uranus did not follow the predicted orbit. Using only Newton’s equation (postulate) of gravity, calculations showed that the deviations in the orbit of Uranus could be explained if it were being attracted by a more distant planet. The location of the mystery planet was calculated, and that
computations led to the discovery of Neptune in 1846 (Figure 1.17). Though the discovery of Neptune did not prove Newton’s law of gravity, it gave scientists more confidence in the theory.

Falsifiable or Predictive Theories

To be of any practical use to scientists, the postulates of a valid scientific theory must be stated in such a way that definite predictions can be made and verified. For example, the theory of gravity says that any two objects in the Universe will attract each other with a certain force, not most of the time, or if they feel like it at the moment, but absolutely always. Every time someone tests the theory of gravity, the results must always fit precisely with the predictions of the theory (assuming the experiment was performed carefully). Just one indisputable experiment that does not fit the predictions of a theory is all it takes to invalidate the theory. We should point out, however, that if data from an experiment does not seem to fit a widely accepted theory, the theory is not immediately canned. Usually, it is the data or its interpretation that is eventually shown to be in error, not the theory.

Since a scientific theory must make definite predictions, the possibility that one of these predictions will turn out to be incorrect always exists. If even one well verified prediction is found to be wrong, we must conclude that the theory is false. Theories that make definite predictions are vulnerable to falsification and are said to be falsifiable.

Being falsifiable means that it must be conceivably possible to prove a theory false. Notice that although it is not possible to prove that a theory is correct, it must be conceivably possible to prove that a theory is false. Of course, a theory found to be false would no longer be an accepted theory. We sometimes say that scientific theories must be testable. Testable not only means that a theory must make accurate predictions, but it also implies that certain observations could disprove the theory. In our dog theory, simply locating a short-haired dog that is not brown would disprove the theory. Therefore, our dog theory makes definite predictions and is said to be falsifiable.

Theories with postulates that could never be proven incorrect are of no value in science. As a simple example of such a theory, I might claim that a family of elves lives in my house (Figure 1.18). These elves come out at night and play with various items, but they are very careful to replace everything when they finish. They hide whenever anyone comes near, which is why it is impossible to detect their presence. No one has ever seen them, and no one ever will because they are too clever. If you devise a plan to...
photograph them, or catch them, or detect their presence in any way, they will find you out and foil your plans. As you can see, the postulates of this theory have been carefully stated so that it is impossible to prove them incorrect. I do not wish to enter into a discussion about the validity of the elf theory, but merely wish to state that it is not a scientific theory. A theory such as this one extends beyond the realm of science.

Religions are generally based on non-falsifiable postulates that cannot be studied scientifically. For example, the idea (postulate) that some prayers are answered is not falsifiable. Apparently all prayers are not answered, and there is no way of predicting exactly which prayers will be answered. Since the statement that some prayers are answered does not make definite predictions, this idea is not falsifiable. Although the prayer idea is not falsifiable, it may still be true that some prayers are answered. However, it is not a scientific postulate and cannot be studied by traditional scientific methods.

**Historical Narratives**

When making investigations in a scientific manner, reproducing the exact event of interest is not always possible. Suppose you are interested in how a particular vase shattered as it fell from a table. When it hit the floor the pieces flew in all directions and scattered around the room. You can mark the position of each piece, weigh it, note its orientation, and make other measurements that might be relevant to the collision. You can study the data from this event, but you cannot repeat the experiment. You might even make some interesting discoveries by studying the data from the collision. For example, the number of pieces as a function of their weight might be interesting, or a plot of the number of pieces as a function of their distance from the impact point might present an interesting pattern. However, you cannot repeat the original collision. Many investigations in science are constrained by the realization that certain events took place that cannot be exactly repeated. The evidence for such events must be measured, analyzed, and conclusions must be drawn without the luxury of repeating the experiments. These non-repeatable events are historical in nature.

Historians tell us that many Europeans became aware of the New World after a man named Christopher Columbus sailed to America in the year 1492 (Figure 1.19). Is this statement a conclusion based on the evidence, a portion of a historical account, or something else? There is a great deal of evidence to support this statement about Columbus, but it is not a conclusion in quite the same sense as the statement that says the Earth orbits the Sun. At any given time, a scientist can make the measurements (collect...
the data), which can be interpreted as evidence that the Earth orbits the Sun.

The evidence that Columbus sailed to America, however, is of a different nature. One can look up old papers and make inquiries that might lead one to conclude that Columbus did sail to America, but there are no experiments that can be carried out today to demonstrate that Columbus sailed to America in 1492. Perhaps all the papers were forged. The Columbus expedition could have been a well-orchestrated hoax (although someone must have told Europe about America). Assuming the Columbus event did take place, it cannot be repeated. We must be satisfied with studies based on the data that remains.

By their very nature, historical events cannot be verified by the same methods used to verify other predictions. Since historical events have already taken place and cannot be repeated, historical accounts merely attempt to create a consistent picture from the available data. In science, that generic word *theory* is often called to action when referring to historical accounts. We will call these theories historical narratives to differentiate them from non-historical scientific theories, such as the theory of general relativity or the theory of electricity and magnetism.

Non-historical scientific theories attempt to explain the results of scientific experiments, and historical narratives attempt to construct a self-consistent picture that agrees with all the evidence. In certain areas of science we encounter various historical narratives. These narratives include the Big Bang that describes the formation and early evolution of the Universe, continental drift as it attempts to reconstruct the shapes and locations of the continents in ages past, and organic evolution that attempts to reconstruct the family trees of various organisms. The tree-limb illustration that we used earlier was an example of a historical narrative.

Since these narratives describe events in times past, they often contain many details. To ascertain one detail of the narrative, sufficient evidence must be available to allow one to draw a conclusion. Reaching this conclusion is similar to reasoning used in a court of law. Insufficient evidence requires that no conclusions can be reached about that particular detail. For example, the current data is insufficient to determine who invented the wheel or when it happened.

If enough details are known, historical narratives can be used to make certain predictions, just as is done with non-historical scientific theories. For example, if Columbus did open up the Americas to Europe in 1492, we would not expect to find evidence of English firearms in North America before 1492. We would not expect to find evidence of horses in the Americas before the voyage of Columbus, and we would not expect to

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*Figure 1.19 Columbus Lands in the Americas A part of the historical narrative. [John Vanderlyn]*
find evidence that Europeans knew of American turkeys, corn, or tobacco before 1492.

Like the Columbus story, a major portion of evolution is a historical narrative. The general idea of evolution is that the first life forms were very simple, but the descendants of these early forms changed in various ways, and some groups evolved into very different looking organisms. Present day organisms are the modified ancestors of earlier life forms. Darwin called this idea descent with modification. Studies in the field of evolution attempt to discover just what changes have occurred, when they took place, and if these new pieces of information are consistent with the other details of the emerging evolutionary narrative.

Because of its predictive ability, the evolution narrative is one of the most valuable theories in all of science. The theories of quantum mechanics and special relativity are probably the most essential of all the physical theories, and evolution performs a similar role in biology. Even fragmented knowledge of the evolution narrative allows one to make numerous predictions and greatly increases one’s understanding of the living world.

For example, evolutionary evidence leads us to conclude that humans evolved from an ape-like ancestor a few million years ago. Since other evidence suggests that dinosaurs became extinct about 65 million years ago, we can predict that no evidence of humans associating with dinosaurs will ever be found. In addition, if humans and chimpanzees evolved from a common ancestor only five to eight million years ago, we would predict that their body chemistry should be very similar. It should be much more similar than the body chemistry of a human and a dog for example. Many of these chemical tests have been performed, and as we will see, the results are consistent with our expectations.

If a jury weighs the evidence and finds a defendant guilty, the crime cannot be repeated to check the verdict. Likewise, when scientists weigh the evidence and conclude that mammals evolved from reptiles, we cannot repeat history to check the conclusion. The events have already happened, and we cannot repeat the experiment. We can only study the evidence and try to assemble the pieces into a consistent picture.

There are, however, important differences between a legal trial and the scientific investigation of evolution. The scientific evidence is always available to scientists for examination, and the search for new evidence continues in a never-ending process. Although conclusions are drawn along the way, the jury of scientists is always deliberating. Some additional piece of evidence may show that a conclusion is incorrect. A scientific trial is always in session.

The details of evolutionary changes are quite numerous and involved, and many questions have not been answered at this time. For example, did mollusks evolve from segmented worm-like ancestors, from a type of flatworm, or from some other group of organisms? Many relationships are not known at present, but many have been painstakingly pieced together from the fossil record and molecular studies. Evolution, like any viable branch of science, is an ongoing study.

On our scientific journey, we will explore some of the evidence that has been used to reconstruct the evolutionary history of life. As with any historical narrative, the story is not complete. Many of its gaps must await new discoveries before we are able to
fill in the details, and many gaps may never be filled since some evidence may have been destroyed.

Ockham’s Razor

Given any body of evidence, it is sometimes possible to formulate more than one postulate to explain the data. For example, in our illustration of the tree limb, it is possible that the tree limb was carried a great distance and laid under the Sugar Maple. Perhaps life forms from another world brought the limb from their home planet and left it under the tree. When two or more explanations describe the observations, we find that nature seems to prefer the simpler one. The principle of picking the simplest explanation or theory is known as Ockham’s Razor (or Occam’s Razor).

Ockham’s Razor explains why most scientists remain skeptical that some UFO’s are space ships from other worlds (Figure 1.20). Even if there are life forms on other planets scattered throughout the Universe, the energy and time required to travel even from a nearby star would make the trip extremely difficult and, therefore, highly improbable. Because a visit by beings from another world would be such an extremely incredible accomplishment, (certainly one of the most remarkable events in recorded history), the evidence for such a visit would have to be absolutely beyond reproach to gain wide acceptance.

A few ambiguous pieces of evidence are not sufficient to be interpreted as a visit by creatures from another world. Invoking Ockham’s Razor, we interpret most UFO sightings as lights, meteors, airplanes, or other common phenomenon. Some sightings must remain just what the name says, unidentified flying objects. Even though we may not be able to explain all UFO sightings, there is not enough evidence to jump to the remarkable conclusion that they are the space ships of visitors from another world.

Newton’s law of gravity carried with it the implication that the Earth must orbit the Sun. However, if you choose to believe that the Earth is fixed in space and does not move, the theory could be modified to accommodate this belief. All that is really needed is a footnote, which says that the Earth is special (for some unknown reason) and acts differently than all the other objects in the Universe. The fixed Earth theory would be more complicated than Newton’s law of gravity, and Ockham’s Razor requires us to pick the simpler theory.

Einstein’s formulation of his general theory of relativity also illustrates the use of Ockham’s Razor. When Einstein first proposed his theory, it was used to
calculate the large-scale structure of the Universe. To the surprise of Einstein, the only possible solutions to his equations required that the Universe be either expanding or contracting. A stable solution was not possible. Instead of making the bold prediction that one day observations would show that the Universe is either expanding or contracting (we now know that it is expanding), Einstein added another term (called the cosmological constant) to his equations that permitted a static solution. Einstein later called the addition of this term his greatest blunder. With the discovery that the Universe is expanding, Einstein’s extra term was no longer necessary. Although keeping a small cosmological constant could have satisfied the observations, applying Ockham’s Razor we pick the simplest equation by removing the cosmological constant.

Fixing the Rules

Science encompasses many widely varying areas of study. From physics to biology, the theories of science must be consistent with each other. An observation in biology cannot contradict one of the theories of physics. Likewise, one theory in physics cannot contradict another. In the past, great strides in science have sometimes taken place because of the discovery of an inconsistency. James Clerk Maxwell, one of the truly great minds in science, discovered that the four laws of electricity and magnetism were not consistent with each other (Figure 1.21). Maxwell was able to correct this inconsistency, by modifying a law known as Ampere’s law (another law that was wrong). He was then able to write four consistent equations that contained all the information needed to describe the electric and magnetic properties of matter. These four equations (known as Maxwell’s equations) are the basic postulates of the theory of electricity and magnetism.

However, Maxwell’s equations were not consistent with the equations that Newton used to describe the motion of objects under the influence of various forces.

When an observer watches the motion of an object (an airplane for example), Newton’s equations of motion are used to describe the position, speed, and acceleration of the airplane. If a second observer, who is moving relative to the first observer, watches the same airplane, the second observer uses a similar set of equations to describe the motion he sees. Notice that among other things, the two observers will not measure the same speed for the airplane, since the observers are moving relative to each other. For example, an observer moving toward the airplane will
measure a faster speed for the plane than an observer who is not moving toward the airplane (Figure 1.22).

The equations used by the two moving observers are related to each other by another set of equations that we call transformation equations. They are called transformation equations because they transform the equations of one observer into the equations of the other observer.

Scientists noticed that the equations that transformed Newton’s equations of motion were not the same as the transformation equations that were used for Maxwell’s equations. This inconsistency guided Einstein in the formulation of his special theory of relativity. Einstein discovered that Maxwell’s equations were correct, and that Newton’s laws of motion were wrong. However, Newton’s laws of motion are still being taught, because Einstein’s equations reduce to those of Newton when the speeds involved are small compared to the speed of light.

Therefore, Newton’s equations give an answer that is accurate enough for most of the problems encountered in everyday life. This example is another case in which the theory of Einstein is more accurate than the laws of Newton.

Evolution has been attacked, because some claim that it violates the second law of thermodynamics. If there were a real conflict, one of the two would have to be altered or discarded. The origin of this claimed violation seems to be a failure by some to fully comprehend how to apply the second law. Fortunately, neither has to be discarded because evolution does not violate the second law.

In one of its popularized forms, the second law of thermodynamics states that natural processes tend to move an isolated system toward a state of greater disorder. However, the disorder that the second law refers to is at the microscopic level. Furthermore, disorder is a very poor word to use when discussing the second law.

It is easy to confuse someone by using examples like tidying up your room (Figure 1.23) or watching a car in a junkyard fall apart (both are
macroscopic examples). Is the thermodynamic disorder increasing or decreasing in these examples? We will see in a moment.

The physical quantity that measures the disorder of a system is called the entropy. The second law says the entropy of a closed system must either increase or stay the same, but it cannot decrease. So, if one thing loses entropy, something else in the system must gain entropy. We often talk about the change in entropy when something happens.

For solids and liquids, the amount of energy they gain or lose is related to their change in entropy. For example, consider a hot cup of coffee sitting on a table. As the coffee cools, it gives energy to the surrounding air. The loss in entropy of the coffee is proportional to the energy it disperses into the environment. As energy is dispersed by the coffee, the entropy of the coffee decreases. On the microscopic level, the molecules are less chaotic, but the entropy of the surrounding air increases.

Obviously, if it is cold enough outside, a glass of water set outside will eventually freeze as it disperses energy into the surrounding environment. The entropy of the ice will then be less than the entropy of the original glass of water.

Similarly, if you drop a rock, it gains energy of motion as it falls. Ultimately, after the rock hits the ground, the net result will be a slight decrease in the entropy of the rock since the rock has dispersed some of its gravitational energy into the environment. In a hydroelectric plant, the gravitational energy given up by falling water is harnessed to generate electricity.

So, a messy room with many things thrown on the floor will have a lower entropy than a room with the clothes hanging neatly in a closet. Likewise, an engine lying in pieces on the ground is in a lower entropy state than an engine suspended in a car. We now see how order and disorder can be very misleading terms.

You can calculate the entropy of a glass of water by doing a thought experiment. Imagine removing energy from a glass of water. As the energy is removed, the temperature drops until it reaches the freezing point. As more energy is removed the water freezes, but ice still contains much energy. Water ice is much warmer than carbon dioxide ice (commonly called dry ice). If we keep removing energy, the temperature of the ice continues to drop.

Eventually you will reach a point where no more energy can be removed. The temperature at this point is called absolute zero or zero Kelvin (K). It is the lowest temperature any object can possibly have. Its entropy is zero!

Now that we have the ice at 0 K, let us begin to add a little energy (the unit of energy is called a Joule). Suppose we add enough energy to raise the temperature to 1 K. We divide the energy added by the temperature (1 K) and write it down. We continue adding small amounts of energy, dividing by the temperature, and recording the numbers. These numbers are the changes in entropy of the ice and then of the water. When we reach room temperature, adding up the numbers will give the entropy of the glass of water at room temperature. Room temperature is about 293 K or 20 °C or 68 °F.

Obviously if you start with twice as much water you will have to add twice as much energy to bring it up to room temperature. Therefore, twice as much water will have twice as much entropy.

As plants and animals grow, their entropy increases, (they become more disordered). This is because the entropy of water (the main ingredient
in life forms), is proportional to the mass of the object.

Therefore, the entropy of a 100 kilogram adult is more than the entropy of a 10 kilogram child. In fact, about 10 times more. What does it mean to say the adult is ten times more disordered than the child? When this adult dies and becomes a pile of dust, the dust will have a much lower entropy (have more order) than either the child or the adult. These examples illustrates why order and disorder are such poor word choices for entropy.

The Sun is dispersing energy to the rest of the Universe, so its entropy must be decreasing (Figure 1.24). If the entropy of a star continually decreases, how could a star exist? Doesn’t a star have to obey the second law of thermodynamics that says the entropy of a closed or isolated system must increase? The question is easily answered if we consider the entire Universe.

The Sun disperses a great deal of radiation (light) energy out into the Universe. If we calculate the change in entropy of the entire Universe, which has been changed by the radiation from the Sun, we find that the entropy of the entire Universe is indeed increasing with time, but there are many smaller pockets within the Universe where the entropy is decreasing. Some of these smaller pockets are places where stars shine, and water freezes.

Therefore, the entropy of the Sun or any star can decrease with time, as long as the entropy of the entire Universe increases. This example illustrates the kinds of errors that can easily result when we try to summarize a rather sophisticated theory, like the second law of thermodynamics, with a short descriptive sentence.

The argument against evolution is that evolution is a process that seems to produce more complex organisms as time passes. However, we have just seen that a large complex organism has more entropy than a small simple organism. Complex and simple are also very poor words to use when talking about the second law. As we will see, evolution involves changes in the DNA of organisms. This is a random process and has nothing to do with the second law of thermodynamics.

Neither the Sun nor the Earth is an isolated system, and evolution does not take place on an isolated Earth. The energy supplied by the Sun obviously plays an important role in many events (like growth and evolution) that take place on the Earth.

Not only must all scientific theories and ideas be consistent with one another, they are also assumed to be universal in their application. Unless evidence is presented to the contrary, we assume that the rules do not change with time or from place to place within the Universe. As we look at distant stars and galaxies, we find that their behavior can be explained using the same physical theories that operate here on Earth. We have no reason to

![Figure 1.24 Entropy of the Sun](http://example.com/sun_entropy.jpg) The Sun’s entropy is decreasing since it is dispersing energy to the rest of the Universe. The entropy of the entire Universe, however, is increasing. The photo shows the Sun during one of its more active times. A large prominence (cloud of hot gas) can be seen rising from its surface (upper left). [STEREO Project/NASA]
believe that gravity or electric charges behave differently at other locations in the Universe. Indeed, we see stars orbiting other stars, in obvious submission to the law of gravity.

The light we see today coming from the most distant galaxies, left these objects billions of years ago, and yet that light appears to have been produced by the same kinds of atoms that we find here on Earth. We, therefore, assume that the rules by which nature operates do not change with time or location. This assumption does not mean that the Universe is static. Objects change continually, but we have no evidence to suggest that there have been changes in the laws of physics that determine the behavior of these objects.

We have gone out of our way to describe how theories could be proven wrong and how they may have to be modified as we discover new information. However, we know the major theories of science are substantially correct since they are able to describe nature amazingly well. Even Einstein’s ideas, as revolutionary as they were, did not cause us to throw out Newton’s work. As we stated earlier, Newton’s laws are still used in most everyday situations.

Evolution

The idea of evolution was originally introduced as an interpretation of certain observations from the fields of paleontology (the study of fossils) and biology, especially the geographical distribution of different plant and animal species. Today, evolution incorporates information from many other disciplines as well.

Although scientists discussed evolution before Darwin’s time, Charles Darwin and Alfred Wallace formulated the first reasonable explanation for the evolutionary process. Their idea was that natural selection caused evolution. Darwin’s book, *On the Origin of Species by Means of Natural Selection*, was originally published in 1859.

Years before, Jean Baptiste de Lamarck had proposed that evolution occurred because organisms have some inner urge to become more complex. Lamarck apparently believed that the *Supreme Creator of all life* instilled this inner power in the organism. Lamarck is often credited with the idea that acquired characteristics are inherited, although this idea was widely held by many others of his time.

The inheritance of acquired characteristics states that changes caused by the environment can be passed on to the offspring. For example, if an individual uses a given set of muscles until the muscles become enlarged, the offspring of this individual may inherit a slightly enlarged set of muscles. Since there seems to be little evidence to support it, Lamarck’s idea is not held in high esteem by the scientific community.

Darwin formulated the idea of natural selection by observing organisms in nature. He noticed that the individuals in a given population of organisms displayed a great deal of variation. For example, variations in size, color, and physical abilities such as speed and strength. Interestingly, when Darwin proposed the process of natural selection, he did not know that genes controlled the variations of a trait. Darwin also realized that all organisms produce more offspring than could possibly survive to reproduce.

Although the number of organisms in a population fluctuates somewhat, the average number must be stable over relatively long periods of time. If a population was not stable, either their
numbers would decrease and the population would likely become extinct or their numbers would increase and eventually exhaust their food supply.

Populations are stable if each mating pair produces an average of two offspring that survive to reproduce (Figure 1.25). Since a single female can produce large numbers of offspring in her lifetime, most offspring must die before they are able to reproduce. In recent times the number of humans has grown explosively because the average couple has produced more than two surviving offspring.

Darwin reasoned that those individuals who are best suited to the environment would have a better chance of surviving to the reproductive age. Those individuals will be the ones that produce young and, therefore, pass their traits on to the next generation.

For example, animals that eat the leaves of certain tall trees might have an advantage if they were taller and could more easily reach the highest leaves. This advantage might be especially important during times when food is scarce, and other animals had eaten most of the lower leaves. The taller animals of the group would have a better chance of surviving and passing their genes for height to the next generation. Over the years, we might expect the population to evolve into very tall animals. A scenario similar to this simplified one could explain the evolution of the giraffe.

Although our scenario may sound reasonable, such stories are speculative in that they attempt to explain why things happen, whereas science primarily attempts to describe how things happen.

As we have explained, there is an important difference between scientific data and a scientific theory. If you drop a rock and watch it fall to the ground, you have collected a piece of data for your scientific journal. If you carefully observe the path taken by a rifle bullet after it leaves the barrel of a gun, you have more data for your journal. However, if we wish to explain how the rock and the bullet behave, we use the theory of gravity. Natural selection is a theory that explains the evolution of a population.

When we discuss evolution, or what some scientists carelessly refer to as the fact of evolution, we are referring to the changes in life forms that have occurred through time. Did some type of evolutionary process produce the life forms we see today? In other words, do the life forms living today share a common ancestor from the past? For example, do birds and reptiles share a common ancestor from the distant past? Since we did not directly observe a population of reptiles evolve into a population of birds, some might say that we cannot answer this question. However, the data in support of evolution is so overwhelming that the vast majority of scientists have little doubt that evolution did take place. (Remember the tree-limb example above.)
The fossil record provides ample evidence to support the conclusion that life forms have changed substantially through time. This conclusion based on the observational data is the general theme of the historical narrative of evolution.

The most widely accepted theory for the observed changes is natural selection as proposed by Charles Darwin. Natural selection is not a broad general statement that can be used to make definite predictions, but simply a set of conclusions based on observations. However, just as Copernicus suggested that the Earth orbited the Sun before the relevant observations were made, Darwin suggested the idea of natural selection before much data had been collected to support the idea. That foresight is what separates Newton, Einstein, and Darwin from the rest of us who are much better at hindsight.

We have learned a great deal about biology since Darwin’s time, and our knowledge of natural selection has increased as well. With our current knowledge, natural selection can be summarized as follows:

1. Individual members of a given population display a great deal of variation, and genes control most of these differences.
2. All organisms produce more offspring than could possibly survive to the age of reproduction.
3. Those individuals that are best suited to the environment will have a better chance of producing offspring and passing their advantageous traits (genes) on to the next generation.

Statements 1 and 2 are simply conclusions based on observations that were made even before the time of Darwin. However, an analysis of statement 3 has led some to believe there is a problem with natural selection. It has been pointed out that advantageous traits are defined to be traits that are more likely to be passed on to the next generation. Statement 3, therefore, appears to be a repetitious statement or a tautology. (An example of a tautology is the statement that says all bachelors are single.)

The important part of statement 3, however, is that it says some traits are more likely than certain other traits to be passed on to the next generation. In other words, Darwin saw evolution as a directed process rather than a purely random process. If evolution were purely random, then all traits would have the same probability of being passed to the next generation.

Darwin decided to place the label advantageous on those traits that were more likely to be passed to the next generation. For example, in the arctic, where the ground is often covered with snow, the trait of white hair might be passed to the next generation preferentially over the trait of black hair. No matter what name you give to these traits, if white hair genes are more often passed to the next generation, the population will change over time. The population will evolve! Eventually, all the individuals in the population will have white hair, and the genes for black hair will disappear from the population.

Since Darwin proposed his idea, many examples supporting this type of differential selection have been documented. For example, a species of moth known as the Peppered Moth lives in the woods of England. This moth generally has white wings flecked with darker spots, but a few are dark gray to black in color (Figure 1.26). The lighter varieties blend in well with the tree trunks on which the moths are often found, making them difficult to spot by their natural predators. Therefore, the lighter moths are more likely to survive and pass
Groups of finches on the Galapagos Islands have been studied extensively, and it has been documented that certain bill sizes have a higher probability of being passed on to the next generation. During several drought years it was observed that the relative numbers of seed producing plants changed. As the size of the available seeds changed, the survival rates of the birds with different size bills changed also. When most of the available seeds are large, those birds with the larger bills have more reproductive success. The population evolved as the environmental conditions changed.

When most of the available seeds are small, those birds with smaller bills are more successful. A permanent change in the weather would eventually produce a permanent change in the bill size of finches.

Evolution of many other groups of organisms has been well documented. In just a few decades, codling moths, that once attacked only apples, have evolved races that feed on plums and walnuts. Many insects have evolved varieties that are resistant to certain insecticides, and strains of bacteria have become resistant to certain drugs. It should be noted that natural selection only explains how populations evolve, but we are often tempted to explain why the changes occurred. In other words, we often attempt to figure out why a certain trait is advantageous. It seems fairly obvious that the dark peppered moths had an advantage because they were harder to see on the soot-covered trees. However, trying to figure out why a certain group of reptiles evolved feathers is more speculative. We may be able to determine how it happened, but trying to explain why is much more difficult and uncertain. Many lively discussions involve the why questions.
The above examples of evolution are so well documented that even hard-core creationists accept them as examples of evolution. However, they do not believe that many small changes similar to the ones we have observed can accumulate to the point where one population evolves into a different species.

The word microevolution has been coined to describe those small changes that have not yet produced new species, while evolution above the species level is called macroevolution. Microevolution has been observed, but macroevolution above the species level has not been directly observed. (Actually, a condition called polyploidy can produce a new species of plant in just one generation. This condition will be discussed in Chapter 10.)

Many people have little trouble visualizing how a population of moths can change color over the years in response to industrial pollution, but they have a hard time visualizing how many of these small changes can produce a new species or a new family of organisms. They find it difficult to imagine how thousands of little changes could eventually transform one group of mammals into dogs and an identical group of mammals into cows. Indeed, it would be very hard to visualize how these changes could have occurred if new genes were not introduced into the population from time to time.

These new genes are produced by mutations, and we will discuss some of the ways mutations arise in Chapter 5. Using a little math it can easily be shown that if just two or three mutations were injected into each of two populations every generation, the two populations would be as different as dogs and cows in less than 100 million years. This number of mutations is consistent with the numbers observed. We will address this topic in Chapter 10.

Evolution says that all the organisms we see today evolved from life forms of the past. A group of today’s organisms is different than its ancestors. We would expect a population of zebras living today to be significantly different from its ancestral population of say 500,000 years ago. Today’s population could be so different that we might classify them as a different species.

It should be noted that we are using the word population, not individual. The word evolution is used to describe the changes that occur over time to a given population of organisms. As it matures, a single organism may change significantly during its own lifetime, but these are not the changes of evolution. Populations evolve, individuals mature.

Evolution and Probabilities

The gene pool of a population of organisms is the collection of all the genes possessed by the breeding members of the population. As the members of the population mate, have offspring, and die, the gene pool changes. A population will evolve if its gene pool changes over time. The evolution of a population of organisms is really just a problem based on statistical probabilities. Is it possible for you to flip a normal penny and have it come up heads every time? Although theoretically possible, it is highly unlikely that the penny would never come up tails, just as it is highly unlikely that a population could remain unchanged through time.

Mutations introduce new genetic variations into a population, and natural selection is the driving force that causes a population to evolve in a
certain direction. However, even if natural selection were not operating, a population that reproduces sexually would have to evolve due to the random nature of sexual reproduction. If new genetic variations were not continually created by mutations, every population of organisms would eventually become homogeneous.

Consider some population of organisms (for example an isolated population of dogs). When a pair of these dogs has babies, each offspring will receive half of his or her chromosomes from each parent. (Many genes are linked on structures called chromosomes.) The genetic composition of each offspring is a purely random process. Since it is unlikely that both parents would pass on all of their chromosomes to their offspring, some of their chromosomes (and the genes on them) will be lost when the parents die (Figure 1.27).

In each generation, chromosomes can be lost by this random process until every chromosome pair is identical and the population becomes homogeneous. At that point, all the individuals would have identical genes except for those differences on the chromosomes that determine the sex of the organism. This process of homogenization must eventually occur because of the random nature of egg and sperm formation, the random nature of fertilization, and the fact that all the chromosomes (and their genes) in one generation are not always passed to the next generation.

The only thing that keeps this homogenization from occurring is the introduction of new genetic material through mutations. These mutations introduce new variations into the population. Therefore, the genetic makeup of the population (its gene pool) changes with time. In other words, the population evolves. The observation that populations of organisms are not homogeneous is strong evidence that new mutations are being continually introduced into the populations and that the populations are evolving. Notice that a population would evolve even without the introduction of mutations, but the evolution would be towards a more homogeneous population.

Evolution is like a dice game where each organism brings its own dice. (The dice are like the genes of the organisms.) If some individual can run faster, or is more camouflaged, or can see better, or has some other trait that gives them an advantage over the other members of the population, it is like that individual is playing with loaded dice (or has advantageous genes). It is more likely to be a winner, and being a winner means it is more likely to survive and reproduce, thus passing the loaded dice on to its offspring and the next generation. An organism that does not have loaded dice (no advantageous genes) is more likely to lose the game (it will not have offspring that survive to reproduce), and the unloaded dice will be lost. This is how the gene pool changes and the population evolves.

The only difference between microevolution and macroevolution is one of degree. In a few years or a few
hundred years a population evolves a little bit, but in a few thousand years or a few tens of thousands of years, a population evolves so much that we might call it a different species. Macroevolution is not easily observed simply because it takes a longer time to happen than the time over which we have been making careful observations.

Many organisms living today look and behave very much like their ancestors, others have changed a great deal in appearance. The rate at which a group of organisms changes in appearance is certainly not the same for every group of organisms.

Life forms that look very similar to their ancestors are often referred to as primitive, but this word is in many ways an unfortunate choice. Less specialized or less evolved would be better descriptions. As used here, the word primitive is not meant to imply that the organism is in any way less suited for its mode of life than we are for ours. Many populations of organisms become well adapted to their own little niche and subsequently undergo few obvious changes.

The word advanced is often used for organisms or parts of organisms that have changed a great deal from their ancestors. Again, this word should not be interpreted as meaning better, but just different. Terms like greatly modified or more specialized would be more accurate descriptions than advanced. Horses have more advanced feet (more highly evolved) than do primates such as humans. Our hands and feet have the same number of bones as did the earliest mammals, but the bones in the foot of the horse have been greatly modified from the primitive condition of early mammals. The dinosaurs were more advanced than the primitive bacteria. However, the dinosaurs are extinct while many bacteria are doing quite well.

How, Why, and Who

As we said earlier, often we are unable to determine why things happen, but asking the why questions and discussing the various possibilities generates excitement. For example, why are most mammals color blind? Why did certain reptiles evolve into birds? As one might imagine, a great deal of disagreement as to the causes of the observed changes exists. Upon hearing these arguments, the general public may be left with the impression that scientists are disagreeing on whether evolution actually took place, when they are merely arguing about which mechanisms were more important, or just how quickly these changes were brought about.

As we discuss topics related to evolution in the subsequent chapters of this book, we will present evidence that demonstrates evolution has happened, and we will also describe the mechanisms believed to be responsible for the observed changes. Remember, while the evidence that evolution happened is overwhelming, the reasons why certain changes occurred are often very speculative.

Because of its rather complex nature, we will incorporate the historical narrative of evolution, the important evolutionary principles (such as natural selection), and the ideas about why the changes occurred into an integrated summary and call it the evolutionary theory. Most scientists undoubtedly have this type of comprehensive picture in mind when they speak of the theory of evolution.

In terms of contributing to our understanding of what we observe in the living world, all other ideas become insignificant when compared to evolution. Simply stated, evolution makes sense out of our observations in the fields of biology, biochemistry, and
paleontology. Studying biology without a thorough understanding of evolution would be like studying chemistry without an understanding of the periodic table of the elements, or like studying the motions of the planets without comprehending Newton’s *law* of gravity and the *laws* of motion.

As we observe a leaf floating to the ground, we can describe its path using gravity and air resistance. The blowing breeze can be described by the air masses set into motion by the Sun’s energy and the rotation of the Earth. We can explain how the leaf is no longer needed by the tree and is shed as the tree becomes dormant during the winter months. However, if someone asks why the leaf falls, we cannot really answer that question. A physicist might reply that it is due to gravity. But why was gravity made to work the way it does? The physicist might go on to explain about the gravitational interaction and mumble something about the Earth and the leaf exchanging gravitons, but he is still only describing how gravity behaves, not why the rules of gravity exist. We do not know why there is gravity or why atoms seem to be composed of positive nuclei and negative electrons. We can only describe how they work.

As stated earlier, science tries to answer how questions, but not why questions. However, if we try to classify all questions into the *how* group and the *why* group, we will soon encounter difficulties.

For example, what do we know about mammal vision? We know that there are light receptors in the eye that respond to the light energy entering the eye. These receptors send signals to the brain, and the brain interprets the signals into a visual picture. From experimentation we know that the black-and-white receptors in the eye (called rods) are more sensitive to light than the color receptors (called cones).

In addition, we observe that most mammals are active in the morning, night, and evening hours when the light is less intense and colors are more subdued. It seems reasonable to conclude, therefore, that rod vision (black-and-white vision) would be more useful than color vision under these circumstances. Are we only able to determine how mammals see, or do we have some idea why their vision is dominated by rods? In other words, do we know why most mammals are color blind?

Although this book is not intended to be a creation versus evolution book, another important aspect of science should be pointed out. Science can explain how things operate, and sometimes perhaps it can explain why things happen the way they do, but it certainly does not presume to know if someone created the rules that all objects are forced to obey, or who that someone is.

Who made the Universe, the Sun, the Earth, the plants, and the animals (including humans)? As scientists we cannot answer that who question. Most religious people believe that there is a God who created the life of this Earth, and that He also formulated the law of gravity and all the other physical principles that we and all other objects in the Universe are compelled to obey. No scientist can argue scientifically that they are wrong. We cannot scientifically disprove the existence of a God. As we have seen, these beliefs lie outside the realm of scientific investigation. Remember, religions are based on non falsifiable ideas and cannot be investigated by the methods of science.

Does evolution conflict with the idea that a God created everything we observe? The answer to this question
depends on your exact view of creation (Figure 1.28). If God made the living creatures of the world, then as scientists we can only determine how He did it. The preponderance of the evidence points to evolution as the method used to create the vast array of creatures that now inhabit the Earth. Contrary to popular belief, evolution does not dispute the existence of God as the creator of all things. Evolution merely attempts to describe how the creation was accomplished.

In some religions, there have been interpretations of dogma or scriptures that conflict with evolution. For example, evolution may conflict with some interpretations of the book of Genesis in the Bible, namely that the Universe, the Earth, and all the living organisms were created in just six consecutive 24-hour days. Others, however, claim that the Hebrew word, which is translated as day, can also mean a long time. No matter how one interprets these passages, an overwhelming amount of scientific evidence points to a very old Earth and Universe. If the Earth and Universe are not billions of years old, then God has added apparent age to the Universe to deceive us. Why would God create humans with a curious mind and then deliberately try to deceive those who dare inquire into the secrets of the Universe?

As we will see, the evidence indicates that the various life forms were not all created at the same time. The earliest organisms that we have discovered were one-celled organisms, and increasingly complex forms appeared over hundreds of millions of years. If the Earth and all its living organisms were created in just six consecutive 24-hour days, then why does all the evidence indicate that these spectacular changes occurred over millions of years?

Surely we do not live in a Universe created by a dishonest God. In science, we assume that the evidence was created by events that happened in the past and that some supreme being did not create the evidence to appear that something happened when it did not. A devious God could have created us a few seconds ago with a programmed memory of things that never took place.

In addition to the six consecutive 24-hour days, there are many passages in the Bible that apparently cannot be taken literally. For example Psalm 93:1
Ecclesiastes 3:14 says, “I know that everything that God does will remain forever, there is nothing to add to it and there is nothing to take from it, for God has so worked that men should fear him.” This statement was once used to support the belief that animals could not become extinct since God made them. We now know that many creatures have become extinct. Sadly, humans are now devastating vast areas of the world and causing the extinction of many of the unique and wonderful creatures that inhabit this planet we call Earth. Humans are the only animals capable of comprehending the concept of God, and yet many seem to have little reverence for the creation that some attribute to Him.

Some have claimed that evolution makes God unnecessary. However, one could just as easily support the claim that discovering the details of evolution elevates the image of God, and increases our appreciation and reverence for His work. Instead of picturing God in a playroom making various animals out of clay, He becomes the great designer who formulated the rules, knowing what would be produced and how it would happen. In this context, evolution is the wonderful story of the creation of God’s creatures.

Recently, creationists have been advocating an idea called intelligent design. The idea is that when one studies nature, many complicated ideas and intricate patterns are revealed. Indeed, many of the details are so complicated that we do not understand them at this time. Many diseases have not been cured, many other problems have not been solved, and our understanding of some scientific topics is very rudimentary. Intelligent design proponents believe that the complexity of nature speaks of an intelligent designer who is God.

It is possible that an intelligent designer formulated the principles that rule the Universe, but the introduction of an intelligent designer does not replace or even augment our understanding of gravity, electricity and magnetism, chemical bonding, evolution, or any other scientific idea. It does not make it easier for us to find cures for diseases such as AIDS, cancer, and Alzheimer’s disease, or guide us in our search for the basic laws that govern the Universe. In addition, the introduction of an intelligent designer is a not a falsifiable theory, so the idea cannot be disproved. It is, therefore, outside the realm of science. If an intelligent designer designed the Universe, then the mission of the scientific community is to discover the details of that design and to study the creation process used to implement that design.

Just as it appears that the laws of physics were used to form the stars and planets, a preponderance of the evidence points to evolution as the process that was used to shape the living world. The idea that life forms were created by evolution may seem hard to believe. However, many ideas in biology are even more unbelievable. It is certainly an even more amazing idea to think that a person who is made of hundreds of trillions of cells could have been created from a single cell formed by the union of an egg and sperm. Yet biologists tell us that is exactly how many life forms are created. The amazing process of reproduction perpetuates life, and the evidence tells us that evolution is the process by which new diverse life forms are created.
Evolution is a process of change. Change is observed in many parts of the Universe. The Earth changes, the stars change, life forms change, and even the Universe as a whole has evolved over time. Before life could form and prosper on Earth, the proper conditions had to be prepared. Many important events contributed to the establishment of these conditions, some of which occurred long before the first organisms appeared in Earth’s early seas. A few important events that we would like to investigate occurred in the first few minutes after the formation of the Universe itself. Our investigation will begin there.