Chapter 3

HISTORICAL EPISODES

In this chapter, we examine several historical episodes involving theoretical hypotheses. These examples serve several purposes. The most important is to provide a set of *analog models* that may be useful in analyzing reports of new cases. That is, when meeting a new case, we can often find analogies between the new case and one or another of the historical cases. Exploiting such analogies can often help us understand and evaluate the new case quickly. This requires having an analysis of the historical case carefully stored in long-term memory for easy access.

There is a second, more general reason for studying these historical episodes. The conception of science found among scientists and other educated members of the society at large has to a great extent been shaped by the history of science as embodied in episodes such as those we shall be examining. These cases are part of our cultural heritage. Having at least some familiarity with that heritage is part of being a member of the culture. Of course, the sketches that follow are no substitute for a genuine introduction to the history of science. But even an oversimplified understanding of these episodes is better than no understanding at all.

3.1 THE PHASES OF VENUS

One of the founders of modern science was Galileo Galilei, universally known simply as Galileo. He was born in Pisa, Italy, in 1564 and did most of his scientific work in the years 1590 to 1640. To put Galileo in historical perspective, note that Shakespeare was born the same year, Martin Luther had died in 1546, and, of course, Galileo's countryman Christopher Columbus first traveled to the New World in 1492. When the *Mayflower* landed at Plymouth Rock in 1620, Galileo was doing the research that led to his famous *Dialogue on the Two Chief Systems of the World,* first published in 1632. He died in 1642.

When Galileo was born, most people thought that Earth was literally the center of the universe. As a student, Galileo was taught the astronomy of the Greek astronomer Claudius Ptolemy, first published in 140 C.E. In Ptolemy's system, the Sun, Moon, planets, and stars

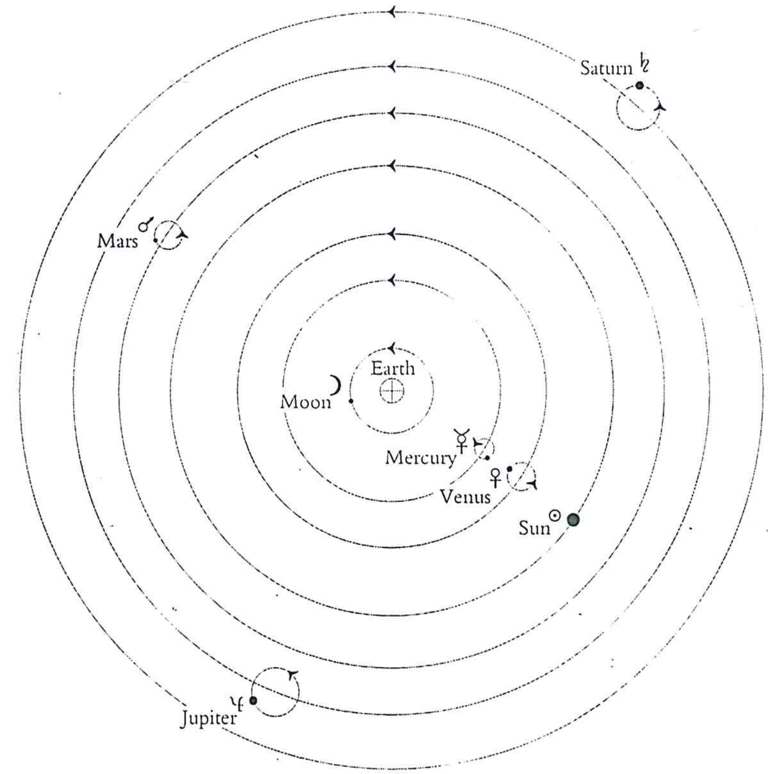

FIGURE 3.1
The Ptolemaic model of the universe.

all revolve about Earth every 24 hours. Figure 3.1 is a sketch of the universe according to Ptolemy.

In 1543, the Polish astronomer Nicolaus Copernicus published his book *On the Revolutions of the Heavenly Spheres,* expounding the view that the Sun is the center of the universe and that the planets, including Earth, revolve in circular orbits around the Sun. On Copernicus' view, the apparent motion of the rest of the universe is due to Earth itself spinning on its own axis once each day. Copernicus lived just long enough to see his book in print. Figure 3.2 is a sketch of the universe according to Copernicus. It is, of course, similar to our current picture of the solar system.

Galileo came to accept the Copernican system early in his life but for a long time kept his opinion largely to himself: In 1589, he became a lecturer in mathematics at the University of Pisa. He studied the properties both of floating bodies and falling bodies and investigated the motions of pendulums. There is a widely believed story about his dropping

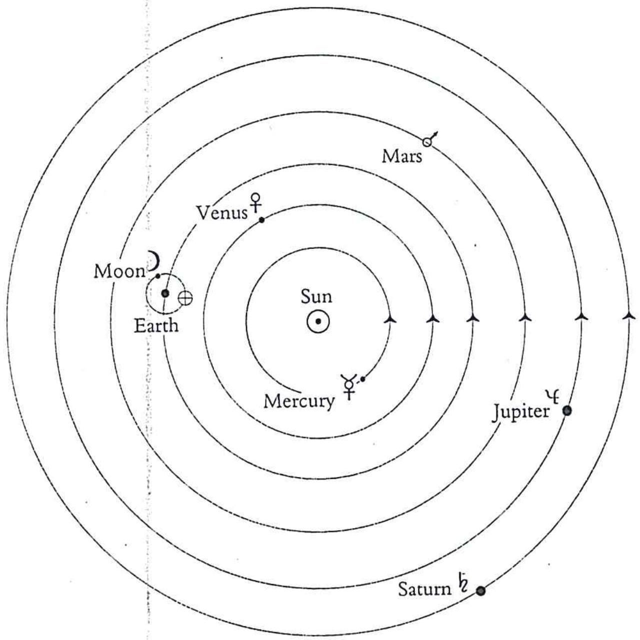

FIGURE 3.2

The Copernican model of the universe.

two bodies of the same material, but of different weights, from the top of the Leaning Tower of Pisa to prove that they would fall at the same rate. This story is most likely not true.

In 1602, Galileo became a professor of mathematics at the University of Padua. In 1604, a new star, which we now take to have been a supernova, appeared in the sky. Galileo studied it intensively. Sometime in 1609, he heard about the invention of a telescope and set out to build one for himself. A year and several telescopes later, he had a fairly good quality instrument with a magnification of about ×33. He turned it to the skies, becoming the first astronomer to use a telescope. He was the first person to see sunspots, mountains on the moon, and the moons of Jupiter.

Recent scholarship indicates that one of Galileo's students first suggested how the telescope might be used in an attempt to determine whether the Ptolemaic or Copernican picture of the universe is correct. In the Ptolemaic picture, Venus revolves in a small orbit (an epicycle) centered on a line connecting Earth and the Sun, as shown in Figure 3.3. It follows that, when viewed from Earth, Venus is mostly dark because it is always illuminated from behind by the sun. At most, only a small crescent-shaped part of Venus will be illuminated. In the Copernican picture, by contrast, there will be times when Venus is almost fully illuminated. This would happen whenever Venus is on the opposite side of the Sun from Earth, as shown in Figure 3.4. One cannot detect these differences with the unaided eye. With a telescope, however, one might be able to see whether Venus ever exhibits a full Venus the way the moon exhibits a full moon.

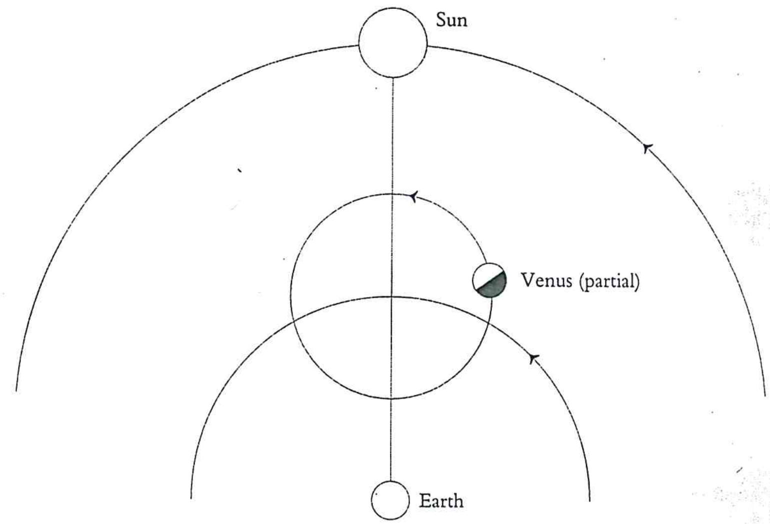

FIGURE 3.3

The Ptolemaic model predicts that we cannot observe Venus fully illuminated.

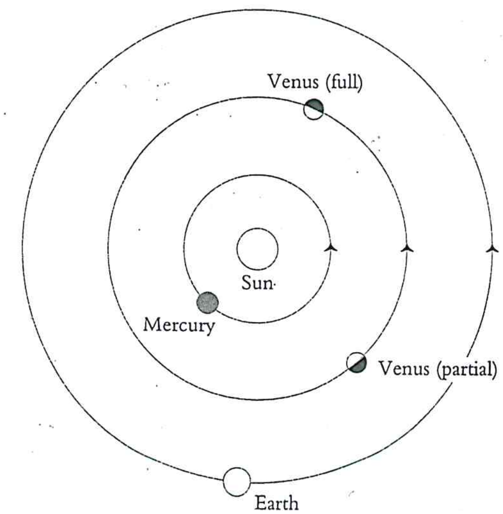

FIGURE 3.4

The Copernican model predicts that we can observe Venus fully illuminated.

There is some historical evidence to the effect that, when the theoretical significance of using his telescope to study Venus was first suggested to Galileo, Venus was, in fact, below the horizon for several weeks. Anxious to claim the discovery for his own, Galileo, nevertheless, reported having made the requisite observations. He did not acknowledge the help of his student. Only later, in the latter part of 1610, did he, in fact, observe Venus go from a relatively dark sphere to a crescent, to a fully lighted sphere, then back through a crescent phase (pointing the opposite direction from before), and finally returning to the original dark phase. James Watson was hardly the first major scientist to go out on a limb in pursuit of an important discovery.

Analysis

This episode sets up quite nicely as a prime example of a crucial experiment. There are two rival models with opposed predictions. The data clearly favor one model over the other.

Step 1. Real World. The real-world objects are the known heavenly bodies near Earth (i.e., the Sun, Moon, and known planets). The theoretical issue is how they are arranged and move relative to one another.

Step 2. Models. There are two models: (1) the Ptolemaic model, in which the Sun, Moon, and planets revolve about Earth (as shown in Figure 3.1); and (2) the Copernican model, in which the planets, including Earth, revolve about the Sun while the Moon revolves about Earth (as shown in Figure 3.2).

Step 3. Predictions. There are likewise two predictions: (1) the Ptolemaic prediction that Venus can never be seen fully illuminated (as shown in Figure 3.3); and (2) the Copernican prediction that Venus can be seen going through a complete set of phases, including being fully illuminated (as shown in Figure 3.4).

Step 4. Data. The data are that Venus exhibits a complete set of phases and is sometimes fully illuminated.

Step 5. Negative Evidence? The data (1) disagree with the Ptolemaic prediction and (2) agree with the Copernican prediction. The data, therefore, provide evidence that the Ptolemaic model does not adequately represent the actual universe.

Step 6. Positive Evidence? The data would be impossible with the Ptolemaic model, and no other plausible models have been mentioned. So the data must be taken as providing positive evidence that the Copernican model provides a good fit to the actual universe.

Popular folklore often portrays Galileo as having slain the dragon of the Ptolemaic system with a single shot from his mighty telescope. Nothing could be further from the truth. Some people were initially convinced of the superiority of the Copernican system, but many more were not. Many questioned whether what Galileo reported seeing were not just reflections in his telescope. Few other people had access to any telescope at all, other than those built by Galileo himself. Again, many people wondered why Venus did not appear to the unaided eye to vary as much in its distance from Earth as required by the Copernican picture. These people were often unimpressed with Galileo's explanation that, because Venus is more fully illuminated when it is on the other side of the Sun, it appears closer than it really is. Finally, many people continued to find it unimaginable that Earth really could be both revolving around the Sun and spinning on its axis at what had to be tremendous speeds. Why do we not feel any such motion? Indeed, why

are we not simply thrown into space by the rapid spinning motion? For these and similar reasons, the Scientific Revolution was not completed for nearly 100 years after Galileo first turned his telescope to the heavens.

In conclusion, something must be said about the opposition of the Catholic Church to Galileo's views. Here again, popular folklore portrays Galileo as the valiant defender of free scientific inquiry against religious dogmatism. The truth is far more complex. Galileo was a deeply religious man. With his blessings, his favorite daughter spent her life in a religious order. For a long time, Galileo thought his work supported the power of the church. Initially, many religious scholars and authorities of the church welcomed his findings. Only later, partly because of the continuing threat of the Reformation begun by Luther and others, did the church attempt to prevent Galileo from teaching or publishing his views. Nor did Galileo do all that he might have to escape the power of the church. In 1610, he used his growing fame to secure a position in Florence, where the influence of the church was much greater than in Padua, which was part of the Venetian Republic. He could later have sought safety and freedom to publish in Venice, or even in Germany, but chose to remain in Florence.

3.2 ISAAC NEWTON AND HALLEY'S COMET

Isaac Newton was born in 1642, the year Galileo died. He brought together the scientific work of the previous century by creating a set of theoretical models that could be applied both to terrestrial objects, such as cannon balls and swinging lamps, and to celestial objects, such as the Moon and the planets. So successful were these models that Newtonian science became one of the main inspirations for the Age of Enlightenment, which lasted for most of the eighteenth century.

NEWTONIAN MODELS

The objects in Newtonian models are called "bodies." Bodies have several important properties, some more familiar than others.

POSITION At any moment of time, every body is said to be located at some point in space. That point is its position at that moment in time.

VELOCITY Velocity is change in position per unit time. One part of velocity is what we commonly call speed (e.g., 50 miles per hour). The other part of velocity is direction. A body moving 50 miles per hour heading north and a body moving 50 miles per hour heading south would have the same speed but opposite velocities because they are moving in opposite directions.

ACCELERATION Acceleration is change in velocity per unit time. A body going from rest to 60 miles per hour in 1 minute would be accelerating at an average rate of 1 mile per hour per second. A body standing still has zero acceleration. So does one moving at a constant 50 miles per hour. A body slowing down has negative acceleration.

MASS Newton was among the first to realize that there is a distinction between mass and weight. Mass is a property that a body possesses all by itself, no matter where in the universe it might be. Newton called it "quantity of matter." The weight of a given body, by contrast, depends on what other body it happens to be near.

MOMENTUM Momentum is defined as the product of mass times velocity. Whatever amount of mass a body has, its momentum is that number multiplied by its velocity. A body standing still has no velocity and thus no momentum, even though it may have a large mass.

FORCE This is the most difficult concept in classical physics. Whole books have been written just on Newton's conception of force, and many others on the concept of force in general. For the moment, we will just say that bodies can produce forces and that force is what makes bodies change their motion.

Having acquired some idea of the kinds of properties bodies exhibit, we turn now to Newton's three *Laws of Motion* and his *Law of Universal Gravitation*. These laws summarize much of what Newton had to say about how bodies behave.

FIRST LAW OF MOTION If there is no force acting on a body, the momentum of that body will remain constant.

This law tells us that if any body is moving with a constant velocity (i.e., at a fixed speed in a straight line), then it will just keep moving at that velocity as long as no force interferes. A special case of this law occurs if a body is at rest (i.e., not moving at all). According to the first law, it must stay at rest until some force acts on it.

SECOND LAW OF MOTION If there is a force acting on a body, that body will accelerate by an amount directly proportional to the strength of the force and inversely proportional to its mass.

This law tells us that the more force you apply to a body, the faster it will accelerate. It also tells us that a given force will accelerate a lighter mass more than a heavier one.

THIRD LAW OF MOTION If one body exerts a force on a second, then the second exerts a force on the first that is equal in strength but in the opposite direction.

This is the famous law of action and reaction: for every action there is a reaction, equal in force but opposite in direction.

Notice that these laws all tell us what a body should do if it is acted on by various forces, but none of them tells us what the forces themselves would be. The law of gravitation, then, describes one kind of force that is produced by every body and acts on all other bodies.

LAW OF UNIVERSAL GRAVITATION Any two bodies exert attractive forces on each other that are directed along a line connecting them and are proportional to the product of their masses divided by the square of the distance between them.

This law tells us that all bodies generate a gravitational force and that the gravitational force between two bodies is greater for larger masses and smaller the greater the distance between them. Dividing by the square of the distance means that doubling the distance between two masses will reduce their mutual force to only one-fourth of what it was. Figure 3.5 illustrates these relationships (insofar as they can be pictured) for the simple case of a system consisting of only two bodies.

This description of Newtonian models makes no explicit reference to any real objects in the world. There is no presumption that anything we would ordinarily call a "body"

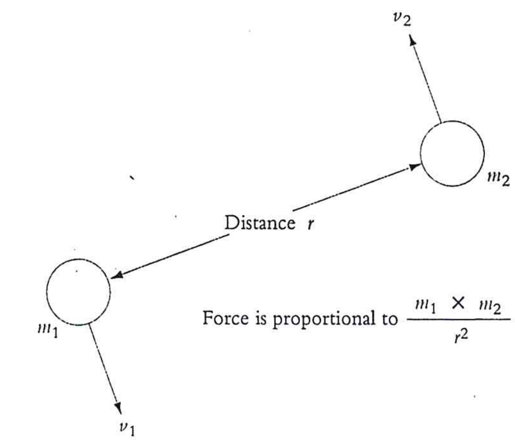

FIGURE 3.5

A Newtonian model for two bodies with gravitational attraction.

behaves like a "body" in Newton's models. So, we have a description of a fairly elaborate set of theoretical models, probably the most famous theoretical models in the whole history of science.

As a matter of fact, many things in the world do behave like systems of Newtonian bodies: the motions of falling weights, the paths of cannon balls, the swings of a pendulum, the revolutions of the Moon, and the motions of the planets. Indeed, because Newtonian models apply to so many things, their use has become part of our everyday understanding of the world. Since the advent of space flight, for example, most people are aware of the difference between mass and weight. Astronauts in orbit around Earth are weightless but obviously not without mass. Similarly, most people know that although astronauts have the same mass both on Earth and on the Moon, they weigh less on the Moon. This is because the Moon has less mass than Earth and thus generates a smaller gravitational force.

Finally, you should make special note of the fact that the above renditions of Newton's laws are given totally in words. No mathematical symbols were used. Yet everyone knows that physics is highly mathematical. How can this be? The answer is that, in fact, there is nothing that can be said using mathematical symbols that cannot be said in words. What matters are the underlying relationships, and these can be described in either words or special symbols. The difficulty is that the use of words is so cumbersome that by merely using words it would be practically impossible to do the calculations required to solve particular problems. For example, all the steps in a simple problem in long division could be written out in words, but you could hardly imagine actually figuring out the answer that way. It takes a special symbolism, really a special language, to do that easily. To achieve a fairly good intuitive understanding of the fundamental relationships, however, a special symbolism is rarely necessary. An intuitive understanding of what is going on is generally enough to be able to evaluate the relevance of new data to any set of models.

HALLEY'S COMET

Newton's work, *The Mathematical Principles of Natural Philosophy,* or *Principia,* an abbreviation of its original Latin title, was first published in 1687. Around 1695, Edmond Halley, an English astronomer and friend of Newton, began applying Newtonian models to the motions of comets. He was probably acting on Newton's own suggestion that comets may be like small planets with very large elliptical orbits. In any case, comets were very interesting objects because they had always been viewed as mysterious, even ominous. Their appearances certainly exhibited no apparent regularity. If Newton's suggestion were correct, however, the behavior of comets would exhibit a great deal of underlying regularity.

Halley began investigating a comet that he had observed in 1682. His observations of 1682 provided a quite precise location for the comet's path relative to the background stars. However, because the comet could be observed only during that small part of its orbit taking it near to the Sun, it was not possible to determine how big the whole orbit might be and, thus, how long it would take for the comet to return. Indeed, it was impossible to determine from those observations whether the orbit was an ellipse, as Newton suggested, or a parabola. Newton's theory allowed the possibility of a parabolic orbit, but such an orbit would mean that the comet would come by only once and then leave the solar system forever. If, however, the orbit were elliptical, the comet should have traveled that same path many times before.

Halley began digging into the records of observations of previous comets. He found 24 recorded observations, going back roughly 150 years, for which the records were precise enough to compare with the observations of 1682. For two of these, one in 1606–1607 and one in 1530–1531, the recorded orbits were very close to that of the 1682 comet. Halley argued that it was extremely unlikely that three different comets should have such similar orbits and concluded that these were three appearances of the same comet in an elliptical orbit with a period of roughly 76 years. He speculated but could not prove that the slight discrepancies in the three orbits were due to gravitational influences from the planets, particularly Jupiter.

But Halley did not stop here. Using the data from all three cases, together with the hypothesis that he was dealing with a system represented by a Newtonian model, Halley calculated the time of the next return. He boldly predicted that the comet should be seen again in the latter part of December 1758. Figure 3.6 will help you to keep in mind the relevant details of this example.

Halley published his work on comets in 1705. It was well received by Newton and the growing band of English Newtonians. It did little, however, to convince the French. Halley died, a respected scientist, in 1743, 15 years before the predicted return of the comet. By this time, even the French were coming around to the Newtonian way of thinking, and Halley's prediction was remembered. In 1756, the French Academy of Science offered a prize for the most accurate calculation of the time the comet would return. The comet reappeared, as predicted, near Christmas 1758 and was officially named "Halley's comet."

Analysis

Step 1. Real World. The real-world object of most direct interest is the path of a comet, particularly the comet observed in 1682.

Step 2. Model. The model was a Newtonian model for two bodies in an elliptical orbit attracting one another by the force of gravity. The two bodies are the Sun and the comet.

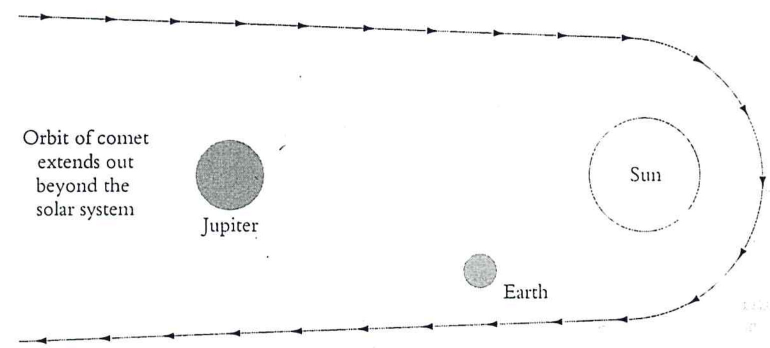

FIGURE 3.6
Halley's comet.

Step 3. Prediction. The prediction was that the comet would return near the end of 1758.

Step 4. Data. A comet with the requisite orbit did appear as predicted.

Step 5. Negative Evidence? No. The data clearly agreed with the prediction.

Step 6. Positive Evidence? The only alternative hypothesis was that another comet with the same orbit just happened to appear right around the predicted time, 76 years later. That seemed to everyone extremely unlikely. So the data provided very good evidence that the Newtonian model fits.

3.3 THE DOWNFALL OF THE PHLOGISTON THEORY

In science, as in everyday life, one tends to remember the winners. The losers are usually forgotten. Some losers, however, are remembered, if only because they had a period of considerable success before their downfall. A famous loser is the phlogiston theory.

Fire, like the motions of the heavens, has always fascinated people. In the Western world, recorded speculation about the nature of fire goes back to the Greeks. We owe to them both the myth of Prometheus and the view that the world is made up of a few separate elements: earth, air, fire, and water. All four are present in the process of combustion. The common-sense view of combustion is that something is driven out of the burning object, leaving only ashes behind.

By the eighteenth century, this something had a well-established name, *phlogiston*—the fire stuff. Assuming that combustible material contains phlogiston explains most of the obvious facts about combustion. Heating drives off the phlogiston into the air; cooling makes it less volatile; smothering holds it in. The well-known fact that a burning candle placed in an enclosed container soon goes out was explained by saying that the enclosed air gets saturated with phlogiston, so that the phlogiston remaining in the wax has nowhere to go.

Phlogiston accounts not only for combustion but also for the very important process of smelting. This is the process by which crude ores are turned into more refined metals. Generally, this is done by carefully heating the ores, together with a measured amount of charcoal, to a controlled temperature. It was claimed that the charcoal contains an excess of phlogiston, which, at moderately high temperatures, leaves the charcoal and combines with the ore to form the metal. This hypothesis was substantiated by the fact that further heating at higher temperatures returns the metal to its original state. The phlogiston is driven out of the metal by the higher temperature. Even rusting was explained as the result of phlogiston slowly escaping from the metal.

These claims may be taken as characterizing *phlogiston models.* Such models lay behind many hypotheses about systems undergoing combustion, rusting, or the process of smelting. The *phlogiston theory* included the general hypothesis that this sort of model fits most cases of combustion, smelting, rusting, and so on. In what follows, we concentrate on combustion.

Combustion is very difficult to study. Most things we commonly burn are made of many different substances and give off many different gases when burned. Moreover, combustion generally is rapid and violent. Progress in such studies required finding some simple, well-controlled subjects for experimentation. In the 1770s, chemists developed a number of techniques for performing such experiments. The leaders were Joseph Priestly in England and Antoine Lavoisier in France. Priestly supported the phlogiston theory; Lavoisier led the revolution that overthrew it.

In the 1770s, using techniques first developed by Priestly, Lavoisier performed several careful experiments with mercury. In one of these experiments, he floated a precisely measured amount of mercury on a liquid and covered it with a glass jar, thus enclosing a known amount of air (Figure 3.7). The mercury was then heated through the glass using the rays of the Sun focused by a powerful magnifying glass (a burning glass). In such circumstances, as Lavoisier well knew, a red powder, or ash, forms on the surface of the mercury. Some of the mercury undergoes a controlled burning.

Applying a phlogiston model to this experiment, we would expect two things. First, the resulting mercury plus red ash should weigh less than the original sample of mercury alone. This is because some phlogiston must be driven off, leaving the ash behind. And the volume of air inside the jar should increase because it now contains the phlogiston that was driven out of the mercury. This means that the level of the liquid inside the jar would drop to make room for the additional "air." When Lavoisier completed the experiment, the water level had gone *up,* and the mercury/ash combination weighed *more* than the original mercury alone.

Analysis

Step 1. Real World. The real-world phenomenon under investigation is the process of combustion. The specific case investigated is the controlled combustion of mercury.

Step 2. Model. The model is a phlogiston model according to which an invisible substance, phlogiston, is given off by various materials, including mercury, when they are appropriately heated.

Step 3. Predictions. The predictions, based on a phlogiston model and the experimental setup, are (1) that the water level under the bell jar should go down (because of the phlogiston added to the air) and (2) that the mercury/ash combination should weigh less than the original mercury alone (because phlogiston has been driven out of the mercury, which became ash).

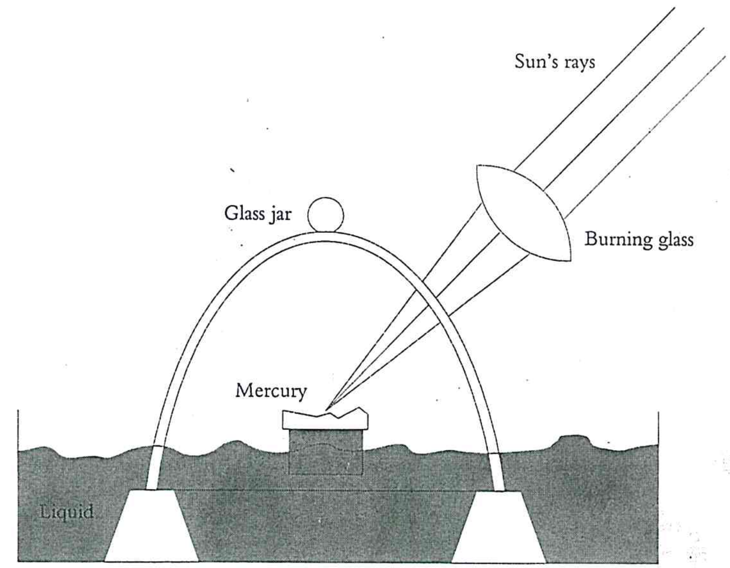

FIGURE 3.7

Lavoisier's experiment.

Step 4. Data. The data are (1) that the water level under the bell jar went up and (2) that the mercury/ash combination weighed more than the original mercury alone.

Step 5. Negative Evidence? The data and the predictions disagree. The data, therefore, provide evidence that the phlogiston model fails to represent the controlled combustion of mercury as carried out in this experiment.

Note that this analysis has only five steps. This happens whenever the analysis ends with evidence against a suggested hypothesis and there is no mention of any alternative supported by the data. Many readers will realize, of course, that there is an obvious alternative to the phlogiston model. According to this alternative model, there is something in the air that combines with the mercury to produce the ash. The water level goes up because the amount of air decreases, and the mercury/ash combination weighs more than the mercury alone because of the added weight of whatever it is in the air that combines with mercury to produce the ash. Lavoisier called this something "oxygen." That is another story.

3.4 DARWIN AND EVOLUTION

The Scientific Revolution of the seventeenth century changed biology as well as physics. But the real revolution in biology did not take place until the middle of the nineteenth century, with Charles Darwin's discovery of evolution by natural selection and Grègor

Mendel's investigations into the mechanisms of inheritance. We look first at Darwin's achievement and then consider Mendel's research.

SPECIAL CREATION

Until the middle of the nineteenth century, throughout Europe and the Americas the primary account of the origin of various life forms on Earth was provided by the Judeo-Christian religious traditions. Regardless of other major differences in beliefs, Catholics, Jews, and Protestants all agreed that life, particularly human life, was the product of a special creative act by a supreme being acting outside the natural order of things. One reason for the widespread belief in special creation was the lack of alternative models that might account for both the great diversity of life forms and the seemingly exquisite fit between organisms and their environment. Fish have gills for living in water, birds have wings to fly, and humans have hands and eyes for finding food and shelter. How could this all have come about without the actions of a divine providence? Darwin provided an alternative model.

DARWIN'S FINCHES

Charles Darwin was born on the same day as Abraham Lincoln in 1809. His was a wealthy British family of physicians and manufacturers. At the age of 16, he was sent to study medicine at the University of Edinburgh. Failing at that, he was sent to Cambridge University to study Divinity, where he was only slightly more successful. His real passion was geology and natural history. In 1831, through the influence of his naturalist friends, he obtained the (unpaid) position of naturalist aboard a British Navy ship, *H.M.S. Beagle,* which was then setting out on an expedition to survey South America and various Pacific islands. The voyage, which took him around the world, lasted 5 years.

One of the more fascinating stops was at the Galapagos Islands, remote Pacific islands roughly 600 miles west of Lima, Peru. Darwin argued that these islands were the relatively recent product of undersea volcanoes. There is one largish island, Albemarle, surrounded by three somewhat smaller nearby islands, and ten or so much smaller outlying islands, a few of these being 100 miles away from the central islands. Figure 3.8 shows the geography of the Galapagos Islands.

The islands exhibited a strange array of plant and animal life, including crabs, iguanas, giant tortoises, mockingbirds—and finches. Darwin and his shipmates collected samples, particularly the birds, which could be fairly easily preserved for the long trip back to England. But neither Darwin nor his companions were completely systematic about noting which birds came from which islands, an oversight he would later regret.

Arriving back in England in 1836, Darwin began what would turn out to be years of work of sorting through his specimens and trying to make sense of all that he had seen. Gradually, he realized the potential importance of the finches. There were, overall, fifteen to twenty different species of finches on the islands. Most of these were to be found on the inner islands. The outlying islands typically exhibited only two or three species each. All the species, however, bore a resemblance to species of finches back on the South American mainland.

The main difference among the various species of finches is the size and shape of their beaks. Moreover, the character of the beaks for different groups of species corresponds to the type of food it eats. For example, members of *Geospiza* have relatively short, sturdy beaks,

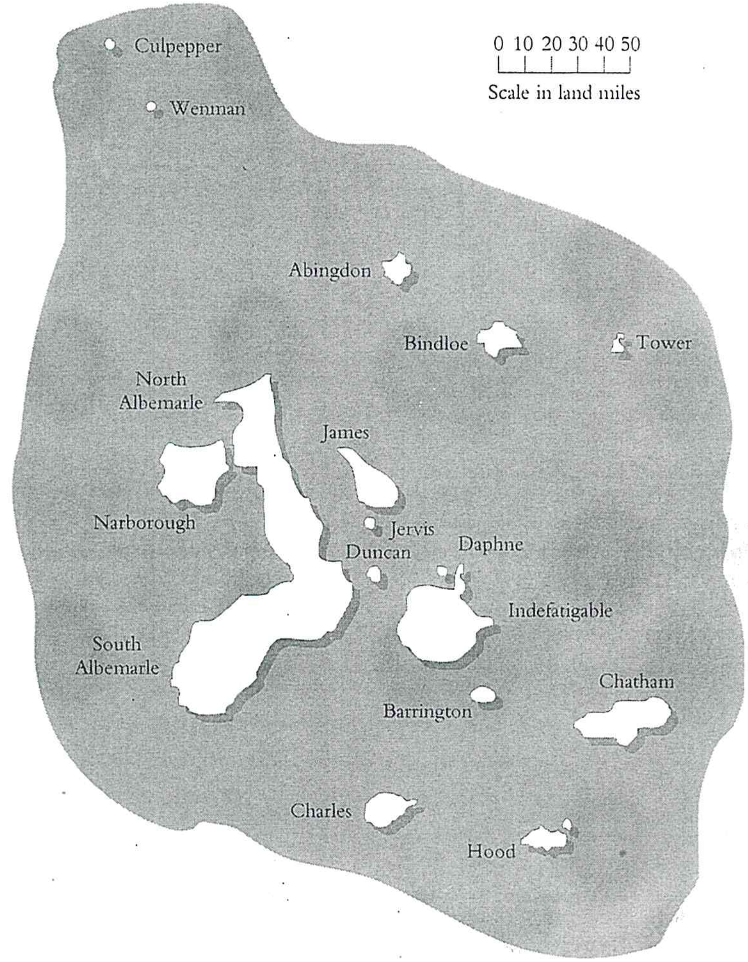

FIGURE 3.8

The geography of the Galapagos Islands.

well adapted for crunching seeds, which are their main diet. Members of *Platyspiza* exhibit a somewhat parrot-like beak suitable for eating leafs, buds, blossoms, and fruits. Again, finches belonging to the group *Cactospiza* possess a woodpecker-like beak, which they use to bore into wood to find insects such as beetles. Members of the group *Certhidea,* by contrast, have only a medium-strong beak suitable for eating smaller, softer insects. Finally, members of *Cactornis* have longish beaks suitable for probing flowers to feed on the nectar or poking into the body of a prickly pear cactus to eat the pulp. Figure 3.9 sketches the differences between

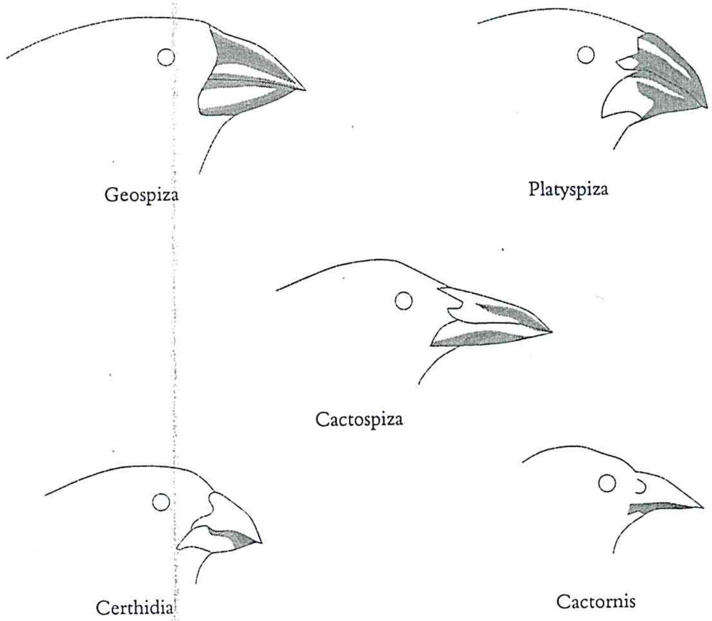

FIGURE 3.9
Differences among the beaks of five groups of Galapagos finches.

these five groups. Both Darwin and later naturalists discovered many more differences of a similar sort.

DARWIN'S MODEL OF EVOLUTIONARY DEVELOPMENT

Although Darwin's family belonged to the wealthy establishment in British society, it had a tradition of antiestablishment freethinking. Darwin's grandfather, Erasmus Darwin, had even published works expounding the view that humans somehow evolved from lower forms of life. At Edinburgh and Cambridge, Darwin associated with several radical thinkers. It was not so surprising, then, that he would seek a *natural,* not a supernatural, explanation for his many empirical findings. What was novel in Darwin's work was the particular model of evolution he developed.

Darwin began thinking about the evolution of life forms at a time when, especially in Britain, ideas of competition in the marketplace were prominent. The idea was that the most successful businesses, and individuals, were those that were most competitive. Darwin was also impressed by the views set out in Thomas Malthus's *Essay on the Principle of Population.* According to Malthus, human populations naturally keep growing to the point where they outstrip the means for their survival. So there are always more people than there is adequate food and shelter. Only the stronger among them can survive.

Darwin applied these ideas to animal populations in general. At any time, he thought, there will be some variation in the traits exhibited by different members of a population. Some of these variations, depending on the particular environment, could be expected to give the individuals possessing them a competitive advantage in securing mates and leaving offspring for succeeding generations. If these traits are inherited, they would be relatively more prevalent in succeeding generations, eventually being shared by most members of the corresponding later population. In this way, a population might, over time, evolve into a different species. That, at any rate, was the model of evolution developed in Darwin's 1859 masterpiece, *The Origin of Species,* published more than 20 years after the voyage of the Beagle.

Evolution, on Darwin's model, is a very slow process. Significant changes in the prevalence of specific traits in a population might take many generations to observe. There was, however, one example of change in organic populations known to all—plant and animal breeding. Darwin had been familiar with the breeding of plants and animals such as dogs and pigeons since his childhood. By deliberately mating animals with desired traits, pigeon breeders, for example, regularly produced highly distinctive variations. If humans could artificially select traits they wished exhibited in their animals, why could not something similar—**natural selection**—happen in nature?

Darwin's observations regarding the size and shape of the beaks of finches were part of the process by which he developed his account of evolution by natural selection and should not be considered as data that resulted from an experimental test of his model. In a book entitled *The Beak of the Finch* (1994), Jonathan Weiner describes the experiments conducted by Peter and Rosemary Grant during the 1970s and 1980s. The Grants, of Princeton University, designed experiments with the intention of testing Darwin's evolutionary model. Following are excerpts from a summary of this research that Weiner published in the *New York Times Magazine* the same year:

> So far the Grants and their team have banded about two dozen generations of finches in the Galapagos—almost 20,000 birds. They are doing what Darwin could not do, going back to the islands again and again; and they are seeing there what Darwin did not imagine could be seen at all.
>
> Back in 1977, for instance, they and their team witnessed a terrible drought in the archipelago. It was a year that highlighted Darwin's "struggle for existence." Flocks of Geospiza fortis, the most common finch of Daphne [island], were reduced from more than 1,000 that January to less than 200 by December. And the birds evolved. The beaks of the next generation were bigger, and proportionately narrower and deeper, which made them better instruments for opening the last tough seeds on the desert island.
>
> No one had ever seen Darwin's process work that fast. And this was not evolution in a test tube, or in a lab cage full of fruit flies, or in the moths of a polluted city. The Grants were watching natural selection in nature, in an environment as pristine as you can find on planet Earth.
>
> A few years later, in 1983, the Grants witnessed a flood: the wettest of the century in the Galapagos. Thunderstorms turned Daphne from desert to jungle almost overnight. In the upheaval, many finches died, while others multiplied. This time the beaks of the next generations of fortis were smaller, which made them better adapted to the wealth of tiny seeds that covered their new green island. Again the birds had evolved, and again the Grants had seen their evolution, measured it, and recorded it in hard numbers.

Analysis

Now let us analyze the data that resulted from the Grants' experimental test of Darwin's model.

Step 1. Real World. The real-world focus of study is the origin of the shape and size of the beaks of finches on the Galapagos Islands.

Step 2. Model. Darwin's account of evolution by natural selection is the model under consideration. According to this model, traits exhibited by members of a population will vary and, depending on the environment, traits that promote survival can be passed along to subsequent generations. Eventually, the inherited traits that provide a competitive advantage will be more prevalent in future generations.

Step 3. Prediction. Upon a dramatic change in the environment and food supply of the finches on the Galapagos, one should observe that the size and shape of beaks in the next generations change so that they can eat the new types of foods that are available.

Step 4. Data. One experimental test described the results of their study after a severe drought: "Flocks of Geospiza fortis, the most common finch on Daphne [island], were reduced from more than 1,000 that January to less than 200 by December. And the birds evolved. The beaks of the next generation were bigger, and proportionately narrower and deeper, which made them better instruments for opening the last tough seeds on the desert island." Another experimental test of Darwin's model occurred after a flood: "In the upheaval, many finches died, while others multiplied. This time the beaks of the next generations of fortis were smaller, which made them better adapted to the wealth of tiny seeds that covered their new green island."

Step 5. Negative Evidence? No. The data agree with the prediction.

Step 6. Positive Evidence? Were the data and prediction likely to agree even if Darwin's model does not really account for the correlation between beak type and the diet of finches on Galapagos Island? Is there another model that accords equally well with the data? To answer these questions, more discussion is required.

The most prominent alternative model that might account for the existence of various well-adapted life forms has always been special creation. Few biologists today, however, take this alternative seriously. Therefore, most contemporary biologists would regard recent studies of Darwin's finches as positive evidence for a good fit between Darwin's model of evolution by natural selection and existing life forms. And, since Darwin's models and special creation models cannot both apply, evidence for Darwin's models is automatically evidence against special creation models. At the level of theory, then, there is a clear conflict between these two approaches to understanding the origin of species.

Although biologists are nearly unanimous about the superiority of natural selection over special creation, members of the public at large remain divided on the issue. This is too big an issue for us to attempt to resolve here, but our general program for analyzing episodes in science allows us to consider several more specific issues.

One such issue is whether Darwin and modern biologists have provided direct evidence against all special creation models. That is, has it been shown that specific predictions of special creation models are mistaken? The problem here is that it is not clear what predictions follow from special creation models. Certainly there is nothing in the basic teachings of the Judeo-Christian tradition that bears directly on the size and shape of the beaks of birds on volcanic islands in the Pacific Ocean. Such things have never been of concern to that tradition. More relevant is the implication of creation models that all species were created about the time Earth itself was created, so there should be no new species showing up later. Yet the fossil record, quite apart from Darwin's theory, clearly exhibits strong evidence of the appearance of new species much later. Following our program, this should be clear evidence against creation models. Nevertheless, since the latter part of the nineteenth century, some Christians have argued for models of a creative process continuing through time. Such models are immune to the evidence showing a more recent creation of new species.

Another issue concerns the eighteenth and nineteenth century project of *natural theology* which argues from the existence of apparent design exhibited among life forms in the natural world to the existence of an intelligent designer. The contemporary version of this view goes under the name of Intelligent Design Theory. Darwin provided a well-developed alternative. On Darwin's alternative model, the fit between organisms and their environment that had been taken to be evidence of supernatural design can equally well be explained as the working of natural selection.

Here is a final analysis of the natural evidence for the hypothesis of special creation after Darwin's work.

Step 1. Real World. The origin and development of life forms on Earth.

Step 2. Model. Life forms have been purposely created by an intelligent supreme being operating outside the normal course of nature.

Step 3. Prediction. Individual life forms should be well-adapted to their environments.

Step 4. Data. Existing life forms are indeed well-adapted to their environments.

Step 5. Negative Evidence? No. The data and prediction agree.

Step 6. Positive Evidence? No. The data are inconclusive as evidence for the hypothesis of special creation because there is an alternative model, Darwin's model of natural selection, which accounts equally well for the data.

Thus, even just the plausibility of Darwin's model renders all the data from the apparent design of organic life inconclusive as evidence for the hypothesis of special creation. This, in itself, was a substantial intellectual achievement.

3.5 MENDELIAN GENETICS

We turn now to the second major development in biology during the nineteenth century. Although Mendel's life largely overlapped Darwin's, his work, in a monastery in central Europe, was lost until the beginning of the twentieth century. As a result, genetics became a twentieth-century science.

MENDEL'S ORIGINAL EXPERIMENTS

Mendel did most of his experimentation on a type of garden pea (*Pisum sativum*). Mendel noted that pea plants exhibit several characteristics that come in pairs, called **traits**. The texture of the peas (which are the seeds of the plant) may be either smooth or wrinkled. Also, the color of the peas can be either yellow or green, and the height of the plants themselves may be either tall or short. To keep things simple, we shall concentrate on only one characteristic, the height of the plants.

Mendel discovered that when short plants are cross-pollinated with other short plants, the resulting seeds always yield short plants. Tall plants, however, seem to come in two types. Some pairs of tall plants produce seeds that yield only tall plants, but other tall plants produce seeds yielding a mixture of tall and short offspring. The short plants, as well as the tall plants that yield only other tall plants, are called **true-breeding** plants, whereas the other tall plants are called **hybrids.**

Experiment showed that if you cross-fertilize the true-breeding tall plants with the short plants (which are also true-breeding), the result is all tall plants. These tall plants, however, are all hybrids. If these hybrid plants are then self-fertilized, the result is a mixture of both tall and short offspring. So, whatever is responsible for determining whether a plant is short or tall seems to be transmitted through a generation of plants that are themselves all tall. The short plants show up again only in the following generation.

Mendel's unique contribution was to isolate the different characteristics of his plants and, then, actually to count the plants exhibiting the different traits. He discovered that the ratio of tall to short in the second generation was roughly 3 to 1. This ratio occurred again and again and with other characteristics besides height. Figure 3.10 shows Mendel's results.

MENDEL'S MODEL

Mendel sought to explain how a trait could be transmitted by plants that did not exhibit that trait. Moreover, the explanation must account for the fact that the "hidden" trait appears in only one-fourth of the members of the succeeding generation. In an attempt to explain these things, Mendel constructed the following model.

Suppose that there are two things that determine which traits associated with any characteristic are actually exhibited. Mendel called these things **factors.** (Factors correspond very roughly to what we now call genes.) Suppose, further, that one factor is associated with being tall and the other with being short. Also, suppose that each individual possesses some combination of two of these two types of factors. Let **H** stand for the factor associated with tall plants and **h** for the factor associated with short plants. Then there are really three different types of individuals: those with two tall-producing factors, those with two short-producing factors, and those with one of each. These three possibilities are shown schematically in Figure 3.11.

Next, assume that on pollination ("mating"), the seeds for the next generation get one factor from each parent. Moreover, assume the selection of a factor from either parent is the result of a **random** process. This is the crucial part of what is usually called **Mendel's law of segregation.** In the formation of the seed that becomes a plant in the next generation, the four original factors (two from each parent) "segregate" themselves randomly into groups of two, one from each parent.

Finally, suppose that those individuals that have one factor of each type (the hybrids) exhibit the trait associated with only one of the two factors. This trait is called the **dominant trait.** The factor associated with this trait is called the **dominant factor.** That one of the factors should be dominant in this sense is known as **Mendel's law of dominance.** The other trait and its corresponding factor are called **recessive.**

Now let us take a new look at Mendel's experiment as pictured in Figure 3.10. This time, however, let us represent each individual by its factors alone. The result is shown in Figure 3.12. Let us go through this diagram carefully. The original parents consist of true-breeding tall and true-breeding short plants. Their union must produce hybrids because the offspring must get one factor from each parent and each parent has only one type to give.

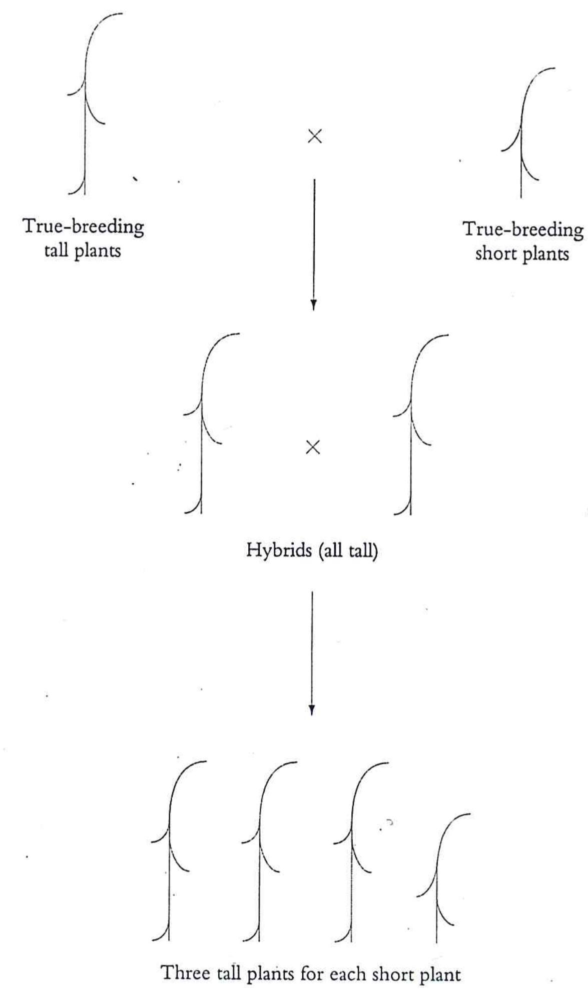

FIGURE 3.10
Mendel's original experiments.

When both parents are hybrids, however, there are four different ways the offspring can get its two factors: a tall from each parent, a tall from the first and a short from the second, a short from the first and a tall from the second, or a short from each. Because, by the law of segregation, these combinations are selected randomly, there should be equal numbers of each of these four types of offspring. However, by the law of dominance, only one of these four types will actually be short. The other three—the one true-breeding tall

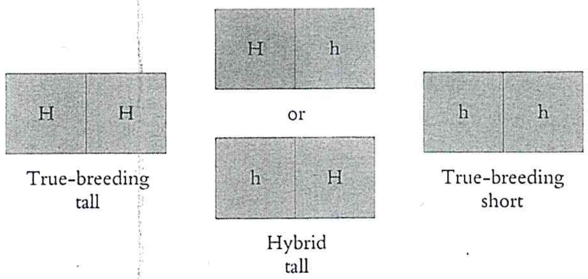

FIGURE 3.11

How Mendel's model classifies individuals by combinations of factors.

and the two hybrids—will all be tall. We thereby obtain the observed result that tall and short plants occur in the third generation in a ratio of 3 to 1.

THE BACKCROSS TEST

Mendel's model suggests another experiment. Why not try crossing the second-generation hybrids with the true-breeding short plants of the parental generation? A quick review of Figure 3.12 reveals what kind of mating this backcross represents. It seems that no one had

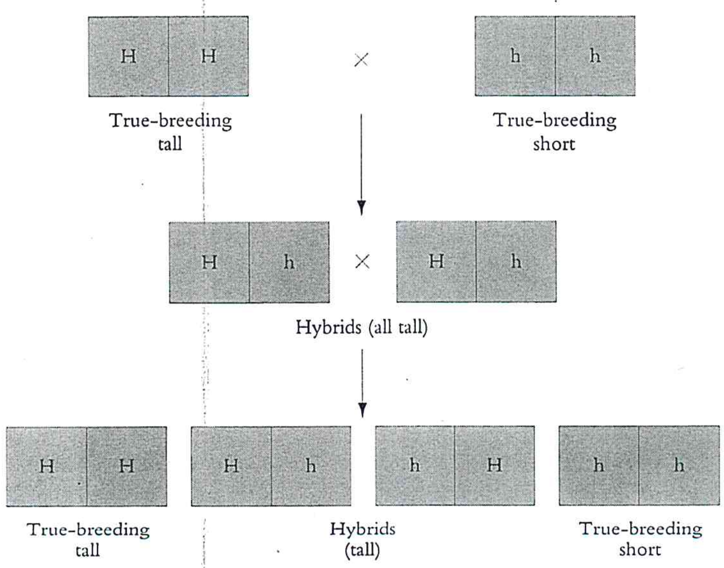

FIGURE 3.12

Mendel's model applied to his original experiments.

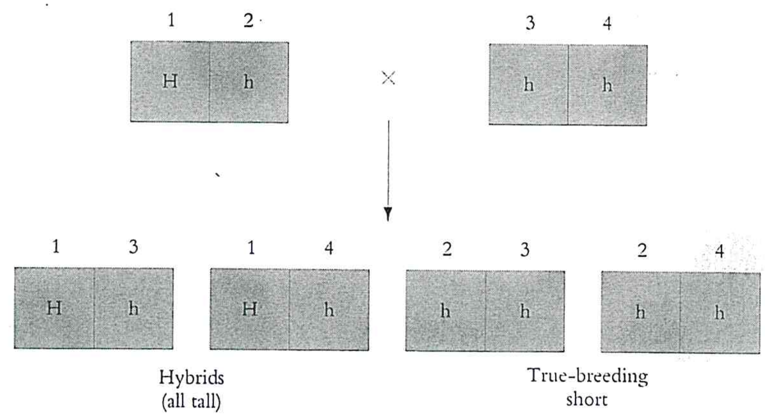

FIGURE 3.13

Mendel's model applied to the backcross experiment.

ever performed this experiment before. Even if it had been performed, no one seems ever to have reported actually counting the resulting plants to see what ratio of tall to short plants would occur.

Let us figure out what ratio Mendel's hypothesis predicts. The experiment is represented symbolically in Figure 3.13. The numbers 1, 2, 3, and 4 are attached to help keep straight the various possible combinations of factors in the offspring.

According to Mendel's model, there are four different possible ways an offspring could get its complement of two factors. According to the Law of Segregation, each of these possibilities is equally likely. So, on the average, there should be equal numbers of each type. Now, as you can see, two of the possibilities yield hybrids, which, by the law of dominance, would be tall. The other two are true-breeding short plants. So the ratio of tall to short plants in this sort of experiment should be 1 to 1. That is, on the average, half should be tall and half short. Mendel reported producing 208 plants by this type of cross-pollination. Of these, 106 were reported to be tall and 102 short. That is surely close enough to call the ratio 1 to 1.

Analysis

There are two sets of data to consider: one set from the original experiments and one set from the backcross experiments.

An important point concerns the procedure Mendel used in constructing his model. He clearly discovered the 3-to-1 ratio *before* he constructed his model. That means he was searching for a model that would yield a prediction of three tall to one short. It is very difficult to say how likely it is that such a search process should lead to a well-fitting rather than a poorly fitting model. The only thing we know for sure is that the procedure Mendel followed was very likely to lead to a model that yields the correct prediction, regardless of how well the model fits. That is because Mendel set out to find a model that would yield the 3-to-1 ratio and would clearly have rejected any model that did not do so. We do not know how many, if any, such models there were. Nevertheless, whatever model he ended up presenting for public scrutiny would be sure to yield the correct prediction, even if it did not fit the case in other respects. The net result is that it is very difficult to assess how much the agreement between the prediction from the model and the original data support a belief in the general correctness of the model. Since these data led Mendel to create his model, we will not include the original experiments in our analysis.

The backcross experiment is significantly different because it was designed to test Mendel's model. For completeness, we will run through the whole analysis.

Step 1. Real World. The real-world process is the inheritance of traits by offspring from sexually reproducing parents.

Step 2. Model. The model is Mendel's two-factor model satisfying the law of segregation and the law of dominance.

Step 3. Prediction. The prediction is that the ratio of tall to short offspring in the backcross experiment should be 1 to 1.

Step 4. Data. The data were 106 tall plants and 102 short plants out of a total of 208 offspring.

Step 5. Negative Evidence? No. The data are in close agreement with the prediction.

Step 6. Positive Evidence? Was the prediction likely to agree with the data even if Mendel's model did not provide a good fit to the real world? Here again, the question requires extra thought.

The worry that the model was itself selected especially because it "predicted" the data is here eliminated. It is clear from all accounts that the model was developed before the backcross experiment. But we still face the fact that there might well be different but equally plausible models that would predict a simple 1-to-1 ratio for the backcross experiment. The case for Mendel's hypothesis is somewhat strengthened by the fact that the model must correctly predict *both* the original 3-to-1 ratio in the standard breeding experiment and the 1-to-1 ratio in the backcross experiment. And that it does. So, lacking any other suggestions of models yielding the correct prediction for both sorts of experiments, we can take the agreement between prediction and data as providing at least moderate support for Mendel's hypothesis.

Mendel worked on *Pisum* from roughly 1856 to 1866. At the time, he was a monk in a monastery in the city of Brno, in what is now the Czech Republic. His account of his discoveries was published in an obscure journal which mailed out 115 copies. Mendel corresponded with one renowned scientist who understood his work. But this scientist was studying another species of plant that, for complex reasons, did not yield Mendel's simple ratios. Indeed, few traits with which we are familiar exhibit such simple patterns of inheritance. In 1868, Mendel was appointed Abbot of his monastery. His official duties so absorbed his energies that by 1871 he was no longer able to continue his experiments. His work was largely forgotten until 1900, when several people independently rediscovered his results. Then began the chain of discoveries that led up to the work of Watson and Crick in the 1950s.

3.6 THE REVOLUTION IN GEOLOGY

At the beginning of the twentieth century, the generally accepted hypothesis about the overall structure of Earth was that it was formed as a molten sphere that gradually cooled and formed a crust—on which we now live. As the sphere continued to cool, it contracted. As the whole sphere contracted inward, the crust cracked and deformed, yielding continents, mountain ranges, and the other major geological features now observed. This is the **contractionist hypothesis.** It is a consequence of contractionism that the continents have always remained more or less stable in their present positions. Once the crust solidified, there seemed no way for oceans or land masses to move around on the surface. This latter hypothesis came to be known as **stabilism.**

We can describe this situation by saying that geologists had developed a *theoretical model* of Earth using an analogy with a molten sphere suspended in space. Physicists and geologists had a fairly good idea of what such a sphere would do. The question was just how similar our actual Earth is to such a model.

Until about 1950, most of our knowledge of Earth's geology could be pretty well explained using contractionist models. But there were some difficulties. For example, (1) there are remarkable similarities in the coastlines and other geological features of widely separated land masses. The fit between the coastlines of eastern South America and western Africa is particularly striking. It is difficult to see why, on a contractionist model, this should be so. (2) There are relatively new mountains running all along the west coast of North and South America, from Chile to Alaska, but only relatively old and less extensive mountains on the east coast. There are also volcanoes and earthquakes along the west coasts but not the east coasts. Why the asymmetry? (3) There are many similar species of plants and animals in places separated by oceans, as in Africa and South America. How could this have come to be?

It was not that contractionists lacked possible answers to these and similar difficulties. The addition of no-longer-existing land bridges to contractionist models, for example, would allow animals and plants to have migrated from one continent to another. But why, then, are there no remaining traces of these bridges?

MOBILISM

In 1915, a German scientist, Alfred Wegener, developed an entirely different model of Earth in a book later given the English title *The Origins of Continents and Oceans.* In contractionist models, the major movements are up and down—oceans sinking and mountains being pushed up. In Wegener's model, the major motions are horizontal. In particular, Wegener argued that the original cooling resulted in one large land mass, which he called Pangaea. This mass, he claimed, subsequently broke up into continents that then drifted to their present positions—and they may still be drifting, although very slowly. This view came to be known as **mobilism.** Wegener was by no means the first person to advocate a mobilist hypothesis, but at the time his was the most elaborate and systematic treatment of this view.

Using a mobilist model, we can easily account for many of those features of Earth that troubled stabilists. (1) The match in the coastlines and general geology of Africa and South America would be the natural result of South America's having split off from what is now Africa and drifted to its present position. (2) The mountain ranges on the west coast of North and South America would be the natural result of the two continents pushing their way west. (3) The similarities in plants and animals now on different continents would be due to their having originally all been together on Pangaea before it broke up. Wegener, therefore, regarded these observations as providing good evidence for a mobilist hypothesis.

Very few scientists in 1915 regarded Wegener's hypothesis as even remotely plausible. The main reason was simply that it seemed impossible that the continents really could move. In the first place, there seemed to be no horizontal forces to push them. Second, the continents are composed of softer material than the ocean floors—the lighter materials having floated to the top when Earth was still molten. How could this softer material push through a harder material? Thus, even if there were something pushing the continents, they would break apart, crushed against the edges of the more solid ocean floors. If geologists were to be convinced that the continents move, they would have to be given both a better model and more powerful data than Wegener had provided. In fact, better models were devised by the time of Wegener's death in 1930, but it took until the 1960s before convincing data could be found.

SEAFLOOR SPREADING

One key to understanding the structure of Earth was the discovery of radioactivity by Marie and Pierre Curie in the 1890s. Radioactivity is caused by the spontaneous decay of atoms of a few heavy elements such as uranium. When this happens, energy is given off and transformed into heat. If there were a reasonable amount of radioactivity taking place within Earth, the inside of Earth would be much hotter than contraction models generally assume. This heat could produce more molten material much closer to the surface than was previously thought possible. And this, finally, allows the possibility of large-scale horizontal movement driven by slow-moving convection currents of molten rock. These implications of radioactivity for drift models were recognized by the late 1920s, but there was no way then to test such speculative ideas. The secret to testing them lay at the bottom of the oceans.

It was not until the development of nuclear submarines in the 1950s that oceanographers obtained detailed knowledge of large ridges running along the ocean floor. One such ridge runs roughly north and south down the center of the Atlantic Ocean. Another lies off the coast of the United States in the eastern Pacific. These ridges were discovered to have a number of special characteristics. For example, a depression runs down the middle of the ridges. The area within the depression, and along the ridge generally, is warmer than the surrounding areas. Also, the magnetism of the floor material alternates as one moves at right angles away from the ridge. Figure 3.14 is a schematic cross-section of a ridge showing these features. What could have produced such ridges?

In 1960, Harry Hess, a respected geologist with a reputation for having a good scientific imagination, proposed a model that he called "geopoetry." In Hess's model, there are convection currents of molten material (produced by radioactive heating) under the ocean floors. Ridges are produced by a rising convection current that then spreads out, forming the ocean floor. The spreading floor then descends back into the core at a trench that might

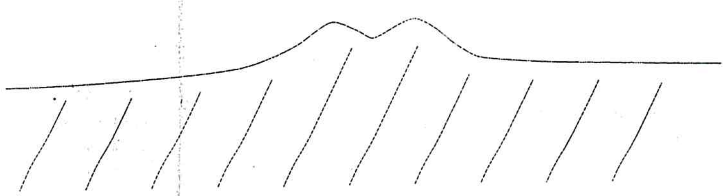

FIGURE 3.14
Schematic cross-section of an oceanic ridge.

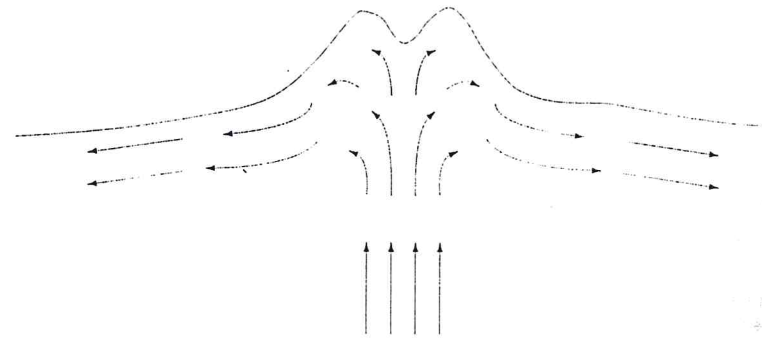

FIGURE 3.15
Hess's model of sea floor spreading.

be several thousand miles away (Figure 3.15). This model immediately accounts for the existence of ridges, their central depression, and the observed temperature differences.

Hess was aware from the beginning that his model fell into the mobilist tradition. An easy elaboration of the model makes possible the horizontal movement of the continents. We need only assume that the continents ride along on a piece of Earth's crust that is pushed by the expanding ocean floor. This model eliminates the need to explain how the continents could plow through the harder ocean floors. They do no such thing. Rather, they ride along on top of the moving harder material.

As an anonymous reviewer of a later paper by another drift supporter put it, this is the kind of thing one might talk about at a cocktail party, but it should not be published in a respectable scientific journal. Most scientists regarded Hess's hypothesis as utterly implausible. How, indeed, could one ever test such a model? The secret lay in the alternating magnetic zones lying along the ridges.

MAGNETISM, GEOMAGNETISM, AND PALEOMAGNETISM

That Earth itself is a large magnet was known during the Scientific Revolution in the seventeenth century. In the 1950s, many scientists were studying the magnetism of Earth (geomagnetism), including the *history* of Earth's magnetism (paleomagnetism). Magnetic material, such as iron, which was originally free to move but then solidified into position, maintains the orientation it had when it solidified. By examining material formed over long periods of time without being disturbed, it is possible to determine how the magnetic field of Earth has changed over millions of years. Samples of such materials (e.g., space around volcanoes) seemed to exhibit a complete (180 degree) reversal of orientation at various times. This indicated that perhaps Earth's magnetic field itself had actually reversed poles several times (i.e., the north magnetic pole became the south magnetic pole and vice versa).

What does this have to do with seafloor spreading and continental drift? It took several years for anyone to see the connection. Then, in 1963, and working completely

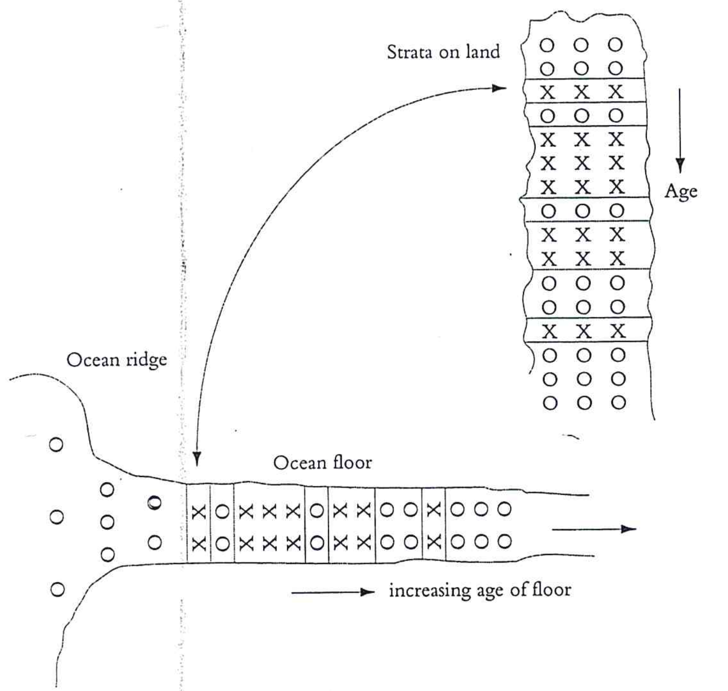

FIGURE 3.16

Predicted correspondence between magnetic records on land and along the ocean floor.

independently, a geologist in Canada (Lawrence Morley) and a geology graduate student in Cambridge, England, (Fred Vine) came up with a model for explaining the alternating strips of differently magnetized materials along the ridges. In their model, the iron in the rising molten material is free to orient itself with Earth's magnetic field at that time. When it reaches the surface, it cools, and the magnetized material gets locked into place. If Earth's magnetic poles reverse, then material coming along later will be oriented in the opposite direction.

If this model is correct, the history of Earth's magnetic field over millions of years would be laid out on the ocean floor in strips parallel to the ocean ridges. Moreover, there should be a correspondence between these alternating magnetic stripes and the alternating magnetic layers found in lava flows near volcanoes (Figure 3.16). All would provide records of the same sequence of global magnetic pole reversals.

Vine (together with his supervisor Drummond Matthews) and Morley published their views in 1963 and 1964, respectively. (Morley actually had the idea first, but his paper was turned down by two journals before it was finally published.) The reception by most geologists and geophysicists ranged from complete disinterest to outright hostility. That there should actually be such a pattern was generally regarded as fantastically improbable.

In the fall of 1965, an oceanographic research ship operated by the Lamont Geological Observatory at Columbia University was recording magnetic effects across the Pacific-Antarctic Ridge in the southeastern Pacific Ocean. By dragging a magnetometer near the ocean floor, they measured the changes in magnetic intensity in the floor moving perpendicularly across and away from a major ridge. When the data were analyzed early in 1966, they revealed a pattern of increasing and decreasing magnetic intensity matching the pattern of magnetic reversals found in minerals on land.

At the same time, other researchers at Lamont began to study the magnetism in core samples earlier drilled into the sediment layer at the bottom of the ocean near the southern tip of South America. Sediment is formed by soft material piling up on the bottom of the ocean and compressing the material underneath, which eventually solidifies. Because such sediment contains traces of magnetic materials, it too should exhibit the reversals in Earth's magnetic field. And, indeed, they found the same pattern of alternating magnetic orientation in the sediment.

The reaction of the geological community was immediate and dramatic. Nearly everyone embraced mobilist models. During the next few years, geologists developed the idea of seafloor spreading into what is now called **plate tectonics.** According to the theory of plate tectonics, Earth's surface consists of several "plates" that slowly move about the surface, constantly changing the configuration of continents and oceans. Much of geological research now involves working out the details of this general theory.

Analysis

There are two sets of data to consider. One focuses on the data Wegener used to create his model of continental drift in the 1920s and will not be included in our analysis. The second focuses on the magnetic data first gathered in the 1960s.

Step 1. Real World. The real-world object is the structure and history of oceans and land masses on the surface of Earth.

Step 2. Model. The model is that developed by Hess, Vine, and others, in which rising convection currents cause the seafloor to spread. The continents, in this model, move by riding on the top of the moving crust caused by the spreading seafloor.

Step 3. Prediction. The prediction, assuming Earth's magnetic field has indeed reversed directions several times in the past, is that alternating strips of normally and reversed magnetic material will be found parallel to oceanic ridges. Moreover, the pattern formed by the varying widths of these strips will match the pattern of magnetism found in successive layers of solidified lava near volcanoes. It would also match the pattern of magnetic materials in deep-sea sediments.

Step 4. Data. The data consist of measurements of magnetic materials on land, along oceanic ridges, and in sediment cores. By using a magnetometer and scanning the ocean floor, a research ship measured "the changes in magnetic intensity in the floor moving perpendicularly across and away from a major ridge." The result was "a pattern of increasing and decreasing magnetic intensity matching the pattern of magnetic reversals found in minerals on land." In addition, core samples from the "sediment layer at the bottom of the ocean near the southern tip of South America" exhibited "the same pattern of alternating magnetic orientation in the sediment" as reversals in Earth's magnetic field.

Step 5. Negative Evidence? No. The data and the predictions agree in great detail.

Step 6. Positive Evidence? Were these predictions likely to agree with the data even if Hess's and Vine's model did not provide a good fit to the real world? No. Even proponents of contractionist models regarded it as extremely unlikely that any such data could ever be found. There were no plausible contractionist models that predicted such data. So the data provided very good evidence that the new mobilist models do fit the actual structure and history of Earth's crust.

EXERCISES

Analyze these reports following the six-point program for evaluating theoretical hypotheses developed in the text. Number and label your steps. Be as clear and concise as you can, keeping in mind that you must say enough to demonstrate that you do know what you are talking about. A simple "yes" or "no" is never a sufficient answer. Some of these reports are taken directly from recent magazine or newspaper articles and are presented here with only minimal editing.

EXERCISE 3.1

The Tychonic System of the World

Most popular descriptions of the scientific revolution of the seventeenth century, like that in this text, follow Galileo's own presentation in concentrating on the conflict between the Ptolemaic and Copernican systems. Yet at the time there was a third alternative, which had been proposed by the equally famous Danish astronomer, Tycho Brahe (1546–1601). In the Tychonic system, Earth remains at the center of the universe and the Sun revolves around Earth. The other five planets, however, revolve around the Sun, not Earth.

Evaluate the evidence for the Copernican system provided by Galileo's observations of the phases of Venus, this time taking into account Tycho Brahe's alternative model (ignoring the Ptolemaic model). Does your analysis provide any help in understanding why it took so long for the Copernican hypothesis to become widely accepted?

EXERCISE 3.2

The Discovery of Neptune

During the first half of the nineteenth century, astronomers were still working out tables and charts giving the positions of the various planets. In this, they were aided by Newtonian theoretical models. But then the outermost planet, Uranus, caused some difficulties. Its observed orbit differed from what it should have been according to the then best-fitting Newtonian models. And the difference was much too great to be attributed solely to inaccuracies in measurement. They were forced to conclude that their current models were not correct. But they did not give up Newton's theory of celestial mechanics. By that time, there had been so many successful predictions using Newtonian models that they were reluctant to conclude that the general theory could be wrong. Around 1843, the English astronomer J. C. Adams and, somewhat later, the French astronomer Leverrier independently calculated that the observed orbit of Uranus could be explained if there were an additional planet beyond Uranus whose gravitational force produced the deviations from the earlier Newtonian predictions—which, of course, assumed no such planet. Using this more elaborate Newtonian model, Adams and Leverrier were able to calculate just where the new planet should be at any particular time. The planet, named "Neptune" by Leverrier, was observed in 1846, just where it was predicted to be.

EXERCISE 3.3

The Missing Planet: The Story of Vulcan

Like the orbit of Uranus, the observed orbit of the innermost planet, Mercury, failed to fit Newtonian models by amounts that could be reliably measured. Fresh from their discovery of Neptune, many astronomers immediately assumed that there must be yet another planet, closer to the Sun than Mercury. Leverrier even named the new planet Vulcan and calculated just where it should be. Although several people claimed to have seen Vulcan, these reports were never substantiated.

EXERCISE 3.4

The Wave Theory of Light: 1818

After a century in the shadow of Newtonian ideas, according to which light is composed of small particles, wave models of light were revived about 1800, first by an Englishman, Thomas Young, and then by a Frenchman, Augustin Fresnel. Fresnel's model was submitted for a prize offered by the French Academy of Sciences. One of the judges for the academy, S. D. Poisson, deduced that according to Fresnel's model, the shadow of a small circular disk produced by a narrow beam of light should exhibit a bright spot right in the center of the shadow. Poisson and the other judges are reputed to have thought that this refuted Fresnel's hypotheses because they had never heard of there being such a phenomenon and regarded it as highly unlikely to exist. No known particle models predicted such a spot. But when the experiment was carried out in carefully controlled circumstances, there was the spot, just as required by Fresnel's model. Fresnel received the prize in 1818.

EXERCISE 3.5

The Wave Theory of Light: 1849

During the first half of the nineteenth century, there was a long controversy over the nature of light. According to Newtonians, light consists of small particles moving at high velocities, so that what we call light rays are really Newtonian particles. The competing theory, advocated mainly by French physicists, was based on the idea that light is really an example of a system of waves, like waves on the surface of a calm lake, in a bowl of jelly, or on a vibrating stretched string. Using standard Newtonian models, it was calculated that light should travel faster in water than in air and by a precisely determined amount. Similarly, using wave models, it was calculated that light should travel slower in water than in air, also by a precisely determined amount. It took until 1849 for anyone to design instruments that could measure the velocity of light accurately enough to detect the predicted differences. When the experiment was finally done, it was found that the velocity of light is lower in water and by the amount claimed by the wave theorists.

EXERCISE 3.6

The Oxygen Theory

Lavoisier was not only interested in refuting the phlogiston theory, he sought also to establish his own oxygen theory. In many respects, oxygen models have just the opposite structure of phlogiston models. According to Lavoisier's oxygen model, when combustion occurs a component of normal air (about one-fifth by his measurements) combines with the combustible material. This component of air came to be called oxygen. Analyze Lavoisier's experiment with mercury as a crucial experiment applied to both phlogiston and oxygen hypotheses. It may help you to know that the red powder that formed on top of the mercury is mercuric oxide.

EXERCISE 3.7

Childbed Fever

During the nineteenth century, many women died from what was then called "childbed fever." The first person who had any success in discovering the cause of this disease was a young Viennese physician, Ignaz Semmelweis. In the years 1844 to 1846, the death rate from childbed fever in the First Maternity Division of the Vienna General Hospital averaged roughly 10 percent. Curiously, the rate in the Second Division, in which women were attended by midwives rather than physicians, was only about 2 percent.

Semmelweis tried in vain for 2 years to discover why the rate should be higher in the "better" division. Then one day a fellow physician received a small cut on the finger from a student's scalpel during an autopsy. The colleague died exhibiting symptoms very much like those of childbed fever. Semmelweis wondered whether the disease might be caused by something in "cadaveric matter" that was being transmitted to the women during childbirth on the hands of the physicians and medical students, who spent every morning in the autopsy room before making their rounds.

Semmelweis reasoned that if this idea were right, the death rate could be cut dramatically simply by requiring the physicians and students to wash their hands in a strong cleansing agent before examining their patients. He then insisted that no physicians enter the maternity ward without first washing their hands in a solution of chlorinated lime, which he assumed must be strong enough to remove whatever it was that caused the disease. It worked. The death rate in the First Division for 1848 was less than 2 percent.

EXERCISE 3.8

The Digestive System

At the beginning of the twentieth century, it was known that the pancreas (a small organ near the stomach) secreted digestive juices into the duodenum (which connects the stomach with the small intestine). This happened whenever partially digested food entered the duodenum from the stomach. The question was whether the signal that started the pancreas working was transmitted by the nervous system or by a chemical substance carried by the blood. At the time, there were known examples of both nerve-stimulated organs and chemical-stimulated organs. No other stimulating mechanism was known. To decide the issue, two physiologists, W. M. Bayliss and E. H. Sterling, cut all the nerves going to and from the duodenum of an experimental animal. All blood vessels to and from the duodenum were left in place. They also inserted tubes to detect flow of digestive juices from the pancreas to the duodenum. The result of this experiment was that when food entered the duodenum of the experimental animals, the pancreas secreted digestive juices in the normal way.

EXERCISE 3.9

Pasteur and Anthrax

Louis Pasteur, who died in 1895, is best remembered as inventor of the process we now call pasteurization. For example, carefully heating milk to about 63°C for 30 minutes and then cooling it rapidly allows the milk to be stored below 10°C for several weeks rather than several days. Pasteur's explanation for why the process works is that the heating debilitates the small organisms, "microbes," that produce the substance that causes milk to go sour.

By 1800, the English physician Edward Jenner had shown that inoculation with relatively harmless cowpox provides humans with immunity to deadly smallpox. Pasteur theorized that smallpox and many other diseases are produced by microbes. He suspected that debilitating, but not killing, the microbes would allow one to generalize Jenner's process of "vaccination" (from *vacca,* meaning *cow*) to other diseases.

In 1880, nearly 10 percent of the sheep, cows, and goats in France were dying of anthrax. From dead animals, Pasteur extracted material containing the anthrax bacillus and experimented with ways of attenuating it. Eventually, he discovered that heating for 8 days at between 42°C and 44°C would do the trick.

To convince the general public of his result, Pasteur arranged a public demonstration experiment. On May 5, 1881, at a farm near the town of Pouilly-le-Fort, 24 sheep, 6 cows, and 1 goat were inoculated with an attenuated anthrax bacillus. On May 31, all 31 inoculated animals, plus a similar assortment of 29 other healthy animals that had not been inoculated, were injected with fully active anthrax bacilli. By the end of the day on June 2, all the unvaccinated sheep were dead and all the unvaccinated cows very sick. All the vaccinated animals were still perfectly healthy. Pictures of healthy animals surrounded by the corpses of those that had not been inoculated made very good press.

By June of the next year, roughly 300,000 animals, including 25,000 cows, had been vaccinated with Pasteur's vaccine. And the mortality rate from anthrax had dropped to nearly 0.5 percent.

EXERCISE 3.10

Island Biogeography

In addition to the Galapagos Islands, Darwin and the *Beagle* also visited the Cape Verde Islands, which lie in the Atlantic Ocean roughly 300 miles west of the coast of what is now Senegal. The two sets of islands are very similar, being geologically relatively young archipelagoes of volcanic origin. Yet the bird species on the two sets of islands are very different. The bird species on the Cape Verde Islands, however, are similar to species on the nearby African continent. In his later work, Darwin took his less extensive observations on the Cape Verde Islands as additional evidence for his theory of evolution by natural selection.

EXERCISE 3.11

A Confirmation of Continental Drift

Some of the best tests of hypotheses involving continental drift have become possible only since the development of accurate methods of determining the age of rocks, methods based on the examination of the products of radioactive decay. The following is taken from an article ("The Confirmation of Continental Drift") that appeared in *Scientific American* for April 1968. The particular hypothesis at issue is that Africa and South America are part of the system of land masses that have broken up and drifted apart. The investigators wrote:

> Of special interest to us at the start was the sharp boundary between the 2,000-million-year-old geological province in Ghana, the Ivory Coast and westward from these countries, and the 600-million-year-old province in Dahomey, Nigeria and east. This boundary heads in a southwesterly direction into the ocean near Accra in Ghana. If Brazil had been joined to Africa 500 million years ago, the boundary between the two provinces should enter South America close to the town of Sao Luis on the northeast coast of Brazil. Our first order of business was therefore to date the rocks from the vicinity of Sao Luis.
>
> To our surprise and delight the ages fell into two groups: 2,000 million years on the west and 600 million years on the east of a boundary line that lay exactly where it had been predicted. Apparently a 2,000-million-year-old piece of West Africa had been left on the continent of South America.

EXERCISE 3.12

Clues to the Drift of Continents and the Divergence of Species

In 1910, Alfred Wegener, a German meteorologist and explorer, began a long quest for evidence supporting the seemingly preposterous notion that the continents drift hither and yon. He eventually found it in a strange guise—the global distribution of marsupials, animals such as kangaroos and opossums that carry their young in a pouch. Marsupials, Wegener pointed out, are largely confined to Australia and South America, which are separated by thousands of miles of ocean. Yet, "even the parasites of the Australian and South American marsupials are the same," he wrote. The phenomenon, he concluded, "dates back to the time when Australia was still joined to South America via Antarctica." That Antarctica provided the link between the Americas and Australia 65 million years ago, long after the great southern continent of the era, Gondwanaland, began breaking up to form Africa, South America, India, Australia, and Antarctica, has now been dramatically confirmed by the discovery of fossil marsupial bones in the one-time land bridge. When Antarctica linked Australia and South America 80 million years ago, it lay in a more hospitable latitude than now, facilitating passage of temperate-zone animals. In 1989, search for fossil evidence of the link, financed by the National Science Foundation, focused on Seymour Island off the Antarctic Peninsula, famous for the fossils of giant penguins. In February, a party led by Dr. William J. Zinsmeister of the Institute for Polar Studies at Ohio State University spent four weeks combing the area. They found nothing until the end of their stay, when they returned to a site rich in penguin remains. Michael O. Woodburne of the University of California at Riverside spotted a marsupial jaw bone. The scientists soon found four fragments from two animals, which resembled a species living during the same era—40 million years ago—at the southern end of South America. The teeth characterize berry-eating marsupials, says Zinsmeister. He believes the animals, about 7 inches long, lived in vegetation near what was then shoreline.

EXERCISE 3.13

Project

Look up an historical account of a scientific episode involving some theoretical hypothesis or theory. You might begin with an account in a standard textbook for a science course. Then you could look up the same episode in an encyclopedia or in a book on the history of science. There may even exist a whole book on the episode in question. Analyze the case following the six-step program developed in the text. Depending on how extensive an example you have uncovered, you may have to do several analyses involving different sets of data or different experiments.