CHAPTER 1

Science: A Way of Knowing

How do you know what you know?

GREAT IDEA

Science is a way of asking and answering questions about the natural universe.

TECHNOLOGY How can we design more efficient power plants? (Ch. 4)	**PHYSICS** What forces exist in the universe? (Ch. 8)
BIOLOGY How do complex organisms develop from a single cell? (Ch. 25)	**ASTRONOMY** What will be the ultimate fate of the universe? (Ch. 15)
CHEMISTRY How can we combine atoms to form new materials? (Ch. 11)	**HEALTH & SAFETY** What causes cancer? (Ch. 24)
ENVIRONMENT Do human activities affect Earth's global climate? (Ch. 19)	
GEOLOGY What dynamic processes occur in Earth's deep interior? (Ch. 17)	

● = **applications of the great idea discussed in this chapter** (blue: left column)

● = **other applications, some of which are discussed in other chapters** (olive: right column)

SCIENCE THROUGH THE DAY

Sunrise

Sunlight streams through your east window. As you wake up, you remember it's Saturday. No classes! And you're headed to the beach with friends. It looks like it's going to be a beautiful day, just like the weather forecast promised.

We take so much about the natural world for granted. Every day the Sun rises at a precisely predictable time in the east. Every day the Sun sets in the west. So, too, the phases of the Moon and the seasons of the year follow their familiar repetitive cycles.

Ancient humans took note of these and many other predictable aspects of nature, and they patterned their lives and cultures accordingly. Today, we formalize this search for regularities in nature, and we call the process science.

Natalia Guseva/Adobe Stock

1.1 The Role of Science

Our lives are filled with choices. What should I eat? Is it safe to cross the street? Should I bother to recycle an aluminum can, or should I just throw it in the trash? Every day we have to make dozens of decisions; each choice is based, in part, on the knowledge that actions in a physical world have predictable consequences. By what process do you make those decisions?

Making Choices

When you pull into a gas station, you have to ask yourself what sort of gasoline to buy for your car (Figure 1.1). Over a period of time you may try many different types—different brands, regular or premium, different levels of ethanol—observing how your car responds to each. In the end, you may conclude that a particular brand and grade suits your car best, and you decide to buy that one in the future. You engage in a similar process of inquiry and experimentation when you buy shampoo, pain relievers, athletic shoes, and scores of other products.

These simple examples illustrate one way we learn about the universe. First, we look at the world to see what is there and to learn how it works. Then we generalize, making rules that seem to fit what we see. Finally, we apply those general rules to new situations we've never encountered before, and we fully expect the rules to work.

There doesn't seem to be anything Earth-shattering about choosing a brand of gasoline or shampoo. But the same basic procedure of asking questions, making observations, and arriving at a conclusion can be applied in a more formal and quantitative way when we want to understand the workings of a distant star or a living cell. In these cases, the enterprise is called science, and the people who study these questions for a living are called scientists.

AP Images/Jeff Chiu

FIGURE 1.1 Even something simple like choosing a brand of gasoline can involve observation and experiment.

Why Study Science?

Science gives us our most powerful tool to understand how our world works and how we interact with our physical surroundings. Science not only incorporates basic ideas and theories about how our universe behaves, but it also provides a framework for learning more and tackling new questions and concerns that come our way. Science represents our best hope for predicting and coping with natural disasters, curing diseases, and discovering new materials and new technologies with which to shape our world. Science also provides an unparalleled view of the magnificent order and symmetry of the universe and its workings—from the unseen world of the atomic nucleus to the inconceivable vastness of space.

Pick up your local newspaper any morning of the week and glance at the headlines. On a typical day you'll see articles about the weather, environmental concerns, and long-range planning by one of your local utility companies. There might be news about a new treatment for cancer, an earthquake in California, or new advances in biotechnology. The editorial pages might feature comments on cloning humans, arguments for a NASA planetary mission, debates about teaching evolution, or perhaps a trial involving DNA fingerprinting. What do all of these stories have in common? They may affect your life in one way or another, and they all depend, to a significant degree, on science.

We live in a world of matter and energy, forces and motions. The process of science is based on the idea that everything we experience in our lives takes place in an ordered universe with regular and predictable phenomena. You have learned to survive in this universe, so many of these scientific ideas are second nature to you. When you drive a car, cook a meal, or play a pickup game of basketball, you instinctively take advantage of a few simple physical laws. As you eat, sleep, work, or play, you experience the world as a living biological system and must come to terms with the natural laws governing all living things.

So why should you study science? Chances are you aren't going to be a professional scientist. Even so, your job may well depend on advances in science and technology. New technologies are a driving force in economics, business, and even many aspects of law: new semiconductor technology, agricultural methods, and information processing have altered our world. Biological research and drug development play crucial roles in the medical professions: stories about genetic diseases, flu vaccines, viral epidemics, and nutritional information appear in the news every day. Even professional athletes must constantly evaluate and use new and improved gear, rely on improved medical treatments and therapies, and weigh the potential medical risks of legal performance-enhancing drugs. By studying science, you will not only be better able to incorporate these advances into your professional life, but you will also better understand the process by which such advances were made.

Science is no less central to your everyday life away from school or work. As a consumer, you are besieged by new products and processes, not to mention a bewildering variety of warnings about health and safety. As a taxpayer, you must vote on issues that directly affect your community—energy taxes, recycling proposals, government spending on research, and more. As a living being, you must make informed decisions about diet and lifestyle. And as a parent, you will have to nurture and guide your children through an ever-more-complex world. A firm grasp of the principles and methods of science will help you make life's important decisions in a more informed way. As an extra bonus, you will be poised to share in the excitement of the scientific discoveries that, week-by-week, transform our understanding of the universe and our place in it. Science opens up astonishing, unimagined worlds—bizarre life forms in deep oceans, exploding stars in deep space, and aspects of the history of life and our world more wondrous than any fiction.

1.2 The Scientific Method

Science is a way of asking and answering questions about the physical universe. It's not simply a set of facts or a catalog of answers, but rather a process for conducting an ongoing dialogue with our physical surroundings. Like any human activity, science is enormously varied and rich in subtleties. Nevertheless, a few basic steps taken together can be said to comprise the **scientific method**.

Observation

If our goal is to learn about the world, then the first thing we have to do is look around us and see what's there. This statement may seem obvious to us in our modern technological age, yet throughout much of history, learned men and women rejected the idea that you can understand the world simply by observing it.

Some Greek philosophers living during the Golden Age of Athens argued that one cannot deduce the true nature of the universe by trusting the senses. The senses lie, they would have said. Only the use of reason and the insights of the human mind can lead us to true understanding. In his famous book *The Republic,* Plato compared human beings to people living in a cave, watching shadows on a wall but unable to see the objects causing the shadows (Figure 1.2). In just the same way, he argued, observing the physical world will never put us in contact with reality, but will doom us to a lifetime of wrestling with shadows. Only with the "eye of the mind" can we break free from illusion and arrive at the truth, Plato argued.

In the Middle Ages in Europe, a similar frame of mind was to be found, but with a trust in received wisdom replacing the use of human reason as the ultimate tool in the search for truth. A story (probably apocryphal) about an Oxford College debate on the question "How many teeth does a horse have?" underscores this point. One learned scholar got up and quoted the Greek scientist Aristotle on the subject, and another quoted the theologian St. Augustine to put forward a different answer. Finally, a young man at the back of the hall got up and noted that since there was a horse outside, they could settle the question by looking in its mouth. At this point, the manuscript states, the

School of Athens, detail of the centre showing Plato and Aristotle with students including Michelangelo and Diogenes, 1510–11 by Raphael (Raffaello Sanzio of Urbino) (1483–1520). Web Gallery of Art/Wikimedia/Public Domain

FIGURE 1.2 Plato argued that humans observing nature were like men watching shadows on the wall of a cave.

assembled scholars "fell upon him, smote him hip and thigh, and cast him from the company of educated men."

As these examples illustrate, many distinguished thinkers have attacked the problem of learning about the physical world without actually making observations and measurements. These approaches are perfectly self-consistent and were pursued by people every bit as intelligent as we are. They are not, however, the methods of science, nor did they produce the kinds of advanced technologies and knowledge that we associate with modern societies.

In the remainder of this book, we differentiate between **observations**, in which we observe nature without manipulating it, and **experiments**, in which we manipulate some aspect of nature and observe the outcome. An astronomer, for example, observes distant stars without changing them, while a chemist may experiment by mixing materials together and seeing what happens.

Identifying Patterns and Regularities

When we observe a particular phenomenon over and over again, we begin to get a sense of how nature behaves. We start to recognize patterns in nature. Eventually, we generalize our experience into a synthesis that summarizes what we have learned about the way the world works. We may, for example, notice that whenever we drop something, it falls. This statement represents a summary of the results of many observations.

It often happens that at this stage scientists summarize the results of their observations in mathematical form, particularly if they have been making quantitative **measurements**. Every measurement involves a number that is recorded in some standard *unit of measurement*. In the case of a falling object, for example, you might measure the time (measured in the familiar time unit of seconds) that it takes an object to fall a certain distance (measured in the distance unit of meters, for example). More examples of units of measurement are given in Appendix B.

TABLE 1.1

Measurements of Falling Objects

Time of Fall (seconds)	Distance of Fall (meters)
1	5
2	20
3	45
4	80
5	125

Quantitative measurements thus provide a more exact description than just noticing that the object falls. The standard scientific procedure is to collect careful measurements in the form of a table of data (see Table 1.1). These data could also be presented in the form of a graph, in which distance of the fall (in meters) is plotted against time of the fall (in seconds; Figure 1.3). As we explore the many different branches of science, from physics to biology, we'll see that most scientific measurements require both a number and a unit of measurement, and we'll encounter many different units in the coming chapters.

After preparing tables and graphs of their data, scientists would notice that the longer something falls, the farther it travels. Furthermore, the distance isn't simply proportional to the time of fall. If one object falls twice as long as another, it will travel four times as far; if it falls three times longer, it will travel nine times as far; and so on. This statement can be summarized in three ways (a format used throughout this book):

In words: The distance traveled is proportional to the square of the time of travel.

In equation form:

$$\text{distance} = \text{constant} \times (\text{time})^2$$

In symbols:

$$d = k \times t^2$$

The constant, *k,* has to be determined from the measurements. We'll return to the subject of constants in the next chapter.

Identifying a regularity in nature may take a long time, since it requires an accumulation of experience in a particular area. Furthermore, scientists may go through several phases in their thinking. At first, they may make a *hypothesis*, an educated guess as to what the regularity they are studying will turn out to be—"I think that if I drop things they will fall." Given enough confirmation, the hypothesis can be upgraded to a regularity.

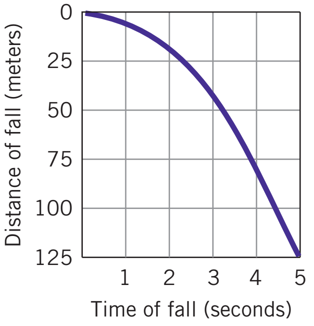

FIGURE 1.3 Measurements of a falling object can be presented visually in the form of a graph. Time of fall in seconds (on the horizontal axis) is plotted versus distance of fall in meters (on the vertical axis).

HOW TO READ A GRAPH

In this book we will often present data in the form of graphs like the one shown in Figure 1.3. Here's how to read a graph:

The first step is to find out what is being presented and what the units are. In the line graph shown in the figure, for example, the vertical axis represents the distance (in meters) that an object has fallen since it was released and the horizontal axis represents the time it has been falling in seconds. If you want to find out how far the object has fallen in a given time—two seconds, for example—you start at the two second mark on the horizontal axis and then move straight up or down until you encounter the curve. At this point you move horizontally to the left until you reach the vertical axis, at which point you read the distance on the vertical axis. In this case, we find that the object will have fallen a little less than 25 meters in two seconds.

Mathematics: The Language of Science

To many people science brings to mind obscure equations written in strange, undecipherable symbols. The next time you're in the science area of your college or university, look into an advanced classroom. Chances are you'll see a confusing jumble of formulas on the blackboard. Have you ever wondered why scientists need all those complex mathematical equations? Science is supposed to help us understand the physical world around us, so why can't scientists just use plain English?

Take a stroll outside and look carefully at a favorite tree. Think about how you might describe the tree in as much detail as possible so that a distant friend could envision exactly what you see and distinguish that tree from all others.

A cursory description would note the rough brown bark, branching limbs, and canopy of green leaves, but that description would do little to distinguish your tree from most others. You might use adjectives such as *lofty*, *graceful*, or *stately* to convey an overall impression of the tree (Figure 1.4). Better yet, you could identify the exact kind of tree and

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FIGURE 1.4 There are many ways of describing a tree.

kozmoat98/E+/Getty Images

FIGURE 1.5 One way of looking at a tree is to think about the lumber it might produce.

specify its stage of growth—a sugar maple at the peak of autumn color, for example—but even then your friend has relatively little to go on.

Your description would be far more accurate if you gave exact dimensions of the tree—measurements expressed in units, such as its height, the distance spanned by its branches, or the diameter of the trunk. You could document the shape and size of leaves, the thickness and texture of the bark, the angles and spacing of the branching limbs, and the tree's approximate age. You could approach measuring the tree from other perspectives as well—by calculating the number of board feet of lumber the tree could yield (Figure 1.5), or how much life-supporting oxygen the tree produces every day. Finally, you could talk about the basic molecular processes that allow the tree to extract energy from sunlight and carry out the other chemical tasks we associate with life.

As we move through these descriptions of the tree, our language becomes more and more quantitative. In some cases, such as supplying a detailed description of the tree's shape or its chemistry, that description could become quite long and cumbersome. That's why scientists employ **mathematics**, which is a concise language that allows them to communicate their results in compact form and often, as an added benefit, allows them to make very precise predictions about expected outcomes of experiments or observations. But anything that can be said in an equation can also be said (albeit in a less concise way) in a plain English sentence. When you encounter equations in your science courses, you should always ask, "What English sentence does this equation represent?" Learning to "read" equations will keep the mathematics from obscuring the simple ideas that lie behind most equations.

ONGOING PROCESS OF SCIENCE

Redefining the Kilogram

If you are going to use mathematics to describe the world, you will need to have a system of units in terms of which everything is measured. On a more personal level, as soon as human being developed commerce, they needed to define commonly accepted weights and measures. After all, if you agree to pay someone for a pound of fruit, you need to have some confidence that you will get as much fruit as you pay for.

The earliest civilization in the Middle East, the Sumerians, developed systems of standardized weights and measures. In the Magna Carta, published in England in 1215 and generally recognized as one of the founding documents of modern democratic society, we find the following obligation agreed to by King John:

> *(35) There shall be standard measures of wine, ale, and corn throughout the kingdom. There shall also be a standard width of dyed cloth . . . Weights are to be standardised similarly.*

The modern outgrowth of these measures was created in 1875 at what is called the "Metre Convention," an international conference that included 17 industrialized nations. Its goal was to establish a uniform system of weights and measures throughout the world. The International Bureau of Weights and Measures, located near Paris, was placed in charge of maintaining these standards. The most fundamental units measure time (the second), distance (the meter), and mass (the kilogram).

Initially, the second was defined in terms of Earth's rotation, the meter as the distance between two scratches on a platinum-iridium bar maintained in the Bureau's basement, and the kilogram as the mass of a block of the same material. This solution established universal units for the entire Earth, but it wasn't very convenient. Throughout the mid-twentieth century, scientists searched for definitions that could be reproduced in individual laboratories across the globe.

In 1967, the second was defined as the time it takes 9,192,631,770 crests of light from a cesium 133 atom to pass a given point. Then, in 1983, the meter was defined to be the distance light travels inf 1/299792458 of a second. Both of these standards could be duplicated in any suitably equipped laboratory. That left the kilogram as the only fundamental unit still languishing in that French vault.

It wasn't until 2019, in fact, that a new definition of the kilogram put that block of metal in a museum. The measurement of mass in the new system involves balancing electrical and gravitational forces in a device called a Kibble balance. The advantage of this system is that the kilogram is defined in terms of fundamental physical constants, including one called Plank's constant which we will encounter in Chapter 9, rather than in terms of a human made artifact.

STOP & THINK! **What fundamental units beside the second, meter, and kilogram do you suppose scientists might want to standardize?**

Development of a Theory

Once scientists have established a regularity in nature, they can go on to ask an important question: What must the world be like in order for this regularity to exist? They will, in other words, construct a theory—a mental (and usually mathematical) picture of how the world operates. In the next chapter, for example, we will see how the English scientist Isaac Newton formulated a theory about why things fall—a far reaching theory embodied in what we now call the law of universal gravitation. As we shall see below, a theory must be tested against nature, but once it has met this test it represents our best guess as to what the world is like.

We are already encountering terms that we often use when talking about the scientific process, and the way these terms are used are often different from the way they are used in everyday speech. For the sake of clarity, we define some of these terms as follows:

Fact: A statement of something that happens in nature—"I dropped my keys and they fell."

Hypothesis: A conjecture, based on past observations or theoretical considerations, about something that will happen—"If I drop my keys again, they will fall."

Law and **Theory**: Scientists, who are normally extremely careful about data and calculations, don't pay a lot of attention to the way they use these terms. In general, whatever label is applied to a set of ideas when it is first proposed usually sticks to it, regardless of how well it fares in making predictions. Thus, "theory" can refer to a fully fleshed out (but as yet untested) hypothesis like the so-called string theories we'll discuss in Chapter 13. It can also, however, refer to a set of ideas that have met many experimental tests and are widely accepted by scientists, such as the theory of general relativity (Chapter 7) and the theory of evolution (Chapter 25). The term "law" is generally used to refer to statements that have met many tests, such as the law of universal gravitation, which we will discuss in Chapter 2. It is important to realize, however, that there is no real distinction in scientific usage between a generally accepted theory and a generally accepted law, nor is there any implied ranking between them. For example, the *law* of universal gravitation is actually part of the much broader and more complete *theory* of general relativity.

Prediction and Testing

In science, every idea must be tested by using it to make **predictions** about how a particular system will behave, then observing nature to see if the system behaves as predicted. The theory of evolution, for example, makes countless specific testable predictions about the similarities and differences of modern living organisms, as well as the nature and distribution of extinct fossil organisms.

Think about the hypothesis that all objects fall when they are dropped. That idea can be tested by dropping all sorts of objects (Figure 1.6). Each drop constitutes a test of our prediction, and the more successful tests we perform, the more confidence we have that the hypothesis is correct. As long as we restrict our tests to solids or liquids on Earth's surface, then the hypothesis is consistently confirmed. Test a helium-filled balloon, however, and we discover a clear exception to the rule. The balloon "falls" up. The original hypothesis, which worked so well for most objects, fails for certain gases. And more tests would show there are other limitations. If you were an astronaut in a space shuttle, every time you held something out and let it go, it would just float in space. Evidently, our hypothesis is invalid in the orbiting space shuttle as well.

This example illustrates an important aspect about testing ideas in science. Tests do not necessarily prove or disprove an idea; instead, they often serve to define the range of situations under which the idea is valid. We may, for example, observe that nature behaves in a certain way only at high temperatures or only at low velocities. In these sorts of situations, it usually happens that the original hypothesis is seen to be a special case of a deeper, more general theory. In the case of the balloon, for example, the simple "things fall down" will be replaced by a much more general theory of gravitation, based on statements called Newton's laws of motion and the law of universal gravitation—laws we'll study in the next chapter. These laws of nature describe and predict the motion of dropped objects both on Earth and in space and, therefore, are a more successful set of statements than the original hypothesis. We will discuss them in more detail in the next chapter.

We will encounter many such laws and theories in this book, all backed by millions of observations and measurements. Remember, however, where these laws and theories

Photri/Age Fotostock America, Inc.

FIGURE 1.6 Equations allow us to describe with precision the behavior of objects in our physical world. One such equation predicts the behavior of falling objects.

come from. They are not written on tablets of stone, nor are they simply good ideas that someone once had. They arise from repeated and rigorous observation and testing. They represent our best understanding of how nature works.

We never stop questioning the validity of our hypotheses, theories, or laws of nature. Scientists constantly think up new, more rigorous experiments to test the limits of our theories. In fact, one of the central tenets of science is this:

- **Every law and theory of nature is subject to change, based on new observations**.

This is an extremely important statement about science, and one that is often ignored in public debates. It means that it must be possible, in principle, that every statement in a scientific model *could* be false. You should, in other words, be able to imagine an experimental outcome that would prove the statement false, even if that outcome never happens in the real world.

Consider the theory of evolution (see Chapter 25), which makes countless predictions about the historical sequence of organisms that have lived on Earth. According to the current model of life's evolution, for example, dinosaurs became extinct millions of years before human beings appeared. Consequently, if a paleontologist found a human leg bone in the same geological formation with a *Tyrannosaurus rex,* then that discovery would call into question the theory of evolution.

The Scientific Method in Operation

These elements—observation, regularity, theory, prediction, and testing—together comprise the scientific method. In practice, you can think of the method as working as shown in Figure 1.7. It's a never-ending cycle in which observations lead to theories, which lead to more observations.

If observations support a theory, then more tests may be devised. If the theory fails, then the new observations are used to revise it, after which the revised theory is tested again. Scientists continue this process until the limits of existing equipment are reached, in which case researchers often try to develop better instruments to do even more tests. If and when it appears that there's just no point to going further, the hypothesis may be elevated to a law of nature.

It's important to realize, however, that while the orderly cycle shown in Figure 1.7 provides a useful framework to help us think about science, it shouldn't be thought of as a rigid cookbook-style set of steps to follow. Science can be every bit as creative an endeavor as art or music. Because human beings do science, it involves occasional bursts of intuition, sudden leaps, a joyful breaking of the rules, and all the other characteristics we associate with other human activities.

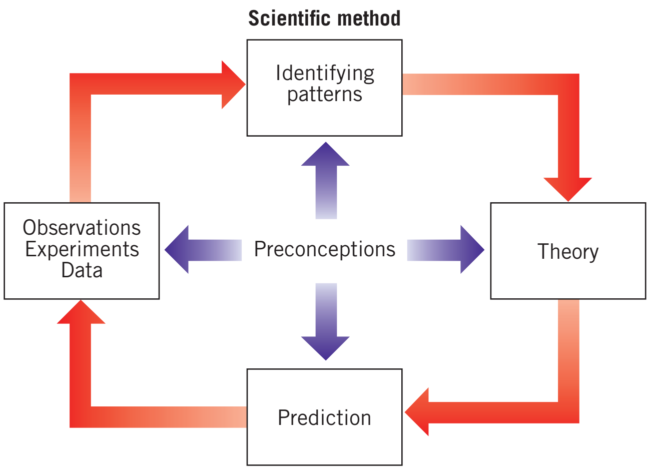


FIGURE 1.7 The scientific method can be illustrated as an endless cycle of collecting observations (data), identifying patterns and regularities in the data, creating theories, making predictions, and collecting more observations.

Several other important points should be made about the scientific method:

1. Scientists are not required to observe nature with an "open mind," with no preconceptions about what they are going to find. Most experiments and observations are designed and undertaken with a specific hypothesis in mind, and most researchers have preconceptions about whether that hypothesis is right or wrong. Nevertheless, scientists have to believe the results of their experiments and observations, whether or not they fit preconceived notions. Science demands that whatever our preconceptions, we must be ready to change those ideas if the evidence forces us to do so.
2. There is no "right" place to enter the cycle. Scientists can (and have) started their work by making extensive observations, but they can also start with a theory and test it. It makes no difference where you enter the cycle—eventually the scientific process takes you all the way around.
3. Observations and experiments must be reported in such a way that anyone with the proper equipment can verify the results. Scientific results, in other words, must be **reproducible**, and they must be reproducible by anyone with appropriate equipment and training, not just the original experimenters.
4. The cycle is continuous; it has no end. Science does not provide final answers, nor is it a search for ultimate truth. Instead, it is a way of producing successively more detailed and exact descriptions of wider and wider areas of the physical world—descriptions that allow us to predict more of the behavior of that world with higher and higher levels of confidence.

THE ONGOING PROCESS OF SCIENCE

Free Air Carbon Enrichment

An important experimental technique in the sciences is to compare two systems that differ in only one aspect. For example, you might look at two identical plants, but supply only one with a specific chemical. In such an experiment the plant without the chemical would be called the "control." The inclusion of controls is an important part of the scientific process.

In Chapter 19, we will see that the amount of carbon dioxide in Earth's atmosphere is increasing due to humanity's use of fossil fuels. Since carbon dioxide is essential for plant growth, it is reasonable to suppose that increasing carbon dioxide will increase plant growth across the globe, and, indeed, laboratory experiments seemed to confirm this expectation.

But will plants in real ecosystems behave like plants in a laboratory? This question can only be answered by experiment. Free Air Carbon Enrichment Experiments (FACE) are designed to answer this question by adding carbon dioxide to plants growing in natural ecosystems and comparing their growth to plants exposed to normal amounts of carbon dioxide.

One of the earliest such experiments was set up in 1994 by Duke University in North Carolina. Seven plots of pine forest were set up, with carbon dioxide being pumped into three and no carbon dioxide being added to the other four. In this case the enriched plots showed an increase of 50% in photosynthesis and a 27% increase in biomass.

Since that early work, FACE experiments have been run with all sorts of plants growing in all sorts of ecosystems. As often happens in biological experiments, the results of the experiments are complex. Depending on the kind of plant involved, the availability of water and nutrients, and the details of the ecosystem, enhancements over controls ranging from a few percent to 50% have been measured. Scientists are now involved in trying to find the general rules that govern this complex behavior.

SCIENCE IN THE MAKING

Dimitri Mendeleev and the Periodic Table

Discoveries of previously unrecognized patterns in nature, a key step in the scientific method, provide scientists with some of their most exhilarating moments. Dimitri Mendeleev (1834–1907), a popular chemistry professor at the Technological Institute of St. Petersburg in Russia, experienced such a breakthrough in 1869 as he was tabulating data for a new chemistry textbook (Figure 1.8).

The mid-nineteenth century was a time of great excitement in chemistry. Almost every year saw the discovery of one or two new chemical elements, and new apparatuses and processes were greatly expanding the repertoire of laboratory and industrial chemists. In such a stimulating field, it was no easy job to keep up to date with all the developments and summarize them in a textbook. In an effort to consolidate the current state of knowledge about the most basic chemical building blocks, Mendeleev listed various properties of the 63 known chemical elements (substances that could not be divided by chemical means). He arranged his list in order of increasing atomic weight and then noted the distinctive chemical behavior of each element.

Examining his list, Mendeleev detected an extraordinary pattern: elements with similar chemical properties appeared at regular, or *periodic,* intervals. In one group of elements, including lithium, sodium, potassium, and rubidium (he called them group-one elements), all were soft, silvery metals that formed compounds with chlorine in a one-to-one ratio. Immediately following the group-one elements in the list were beryllium, magnesium, calcium, and barium—group-two elements that form compounds with chlorine in a one-to-two ratio, and so on.

As other similar patterns emerged from his list, Mendeleev realized that the elements could be arranged in the form of a table (Figure 1.9). Not only did this so-called periodic table highlight previously unrecognized relationships among the elements, it also revealed obvious gaps where as-yet undiscovered elements must lie. The power of Mendeleev's periodic table of the elements was underscored when several new elements, with atomic weights and chemical properties just as he had predicted, were discovered in the following years.

The discovery of the periodic table ranks as one of the great achievements of science. It was so important, in fact, that Mendeleev's students carried a large poster of it behind his coffin in his funeral procession.

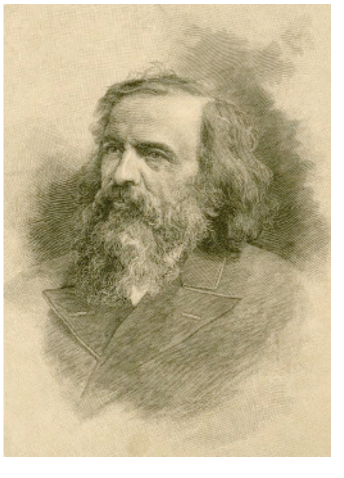


FIGURE 1.8 Dimitri Mendeleev recognized regular patterns in the properties of known chemical elements and thereby devised the first periodic table of elements.

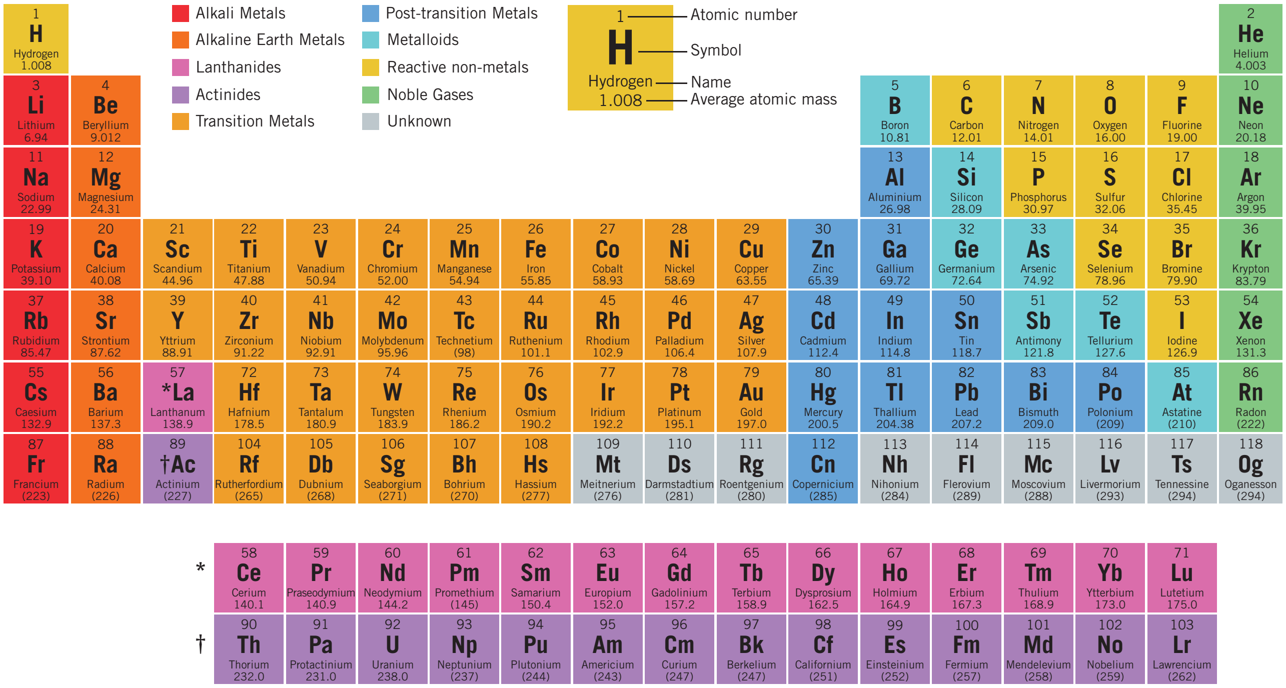


FIGURE 1.9 The periodic table systematizes all known chemical elements.

THE SCIENCE OF LIFE

William Harvey and the Blood's Circulation

It's common knowledge that blood circulates in your body, but stop and think for a moment. How do we know? One of the great puzzles faced by scientists who studied the human body was deducing the role played by the blood. English physician William Harvey (1578–1657) gave us our current picture of the pattern of circulation, in which blood is pumped from the heart to all parts of the body through arteries, and returned to the heart through veins. His experiments reveal the scientific method at work.

Prior to Harvey's work, several competing hypotheses had been proposed. Some scientists had taught that blood didn't move at all, but simply pulsed in response to pumping of the heart. Others taught that the arteries and veins constituted different systems, with blood in the veins flowing from the liver to the various parts of the body, where it was absorbed and its nutrients were taken in. Harvey, on the other hand, adopted the hypothesis that blood circulates through a connected system of arteries and veins. When confronted with such conflicting hypotheses, a scientist must devise experiments that test the distinctive predictions of each competing idea.

To establish the circulation of the blood, Harvey first performed careful dissections of animals to trace out the veins and arteries. Second, he undertook studies of live animals, often killing them so that he could observe the veins and arteries as the heart stopped beating. Then, as now, animals were sometimes sacrificed to advance medical science (see Investigation 7). Finally, Harvey performed a series of experiments to establish that blood in the veins did indeed flow back to the heart, rather than simply being absorbed in tissue like a stream of water in the desert. One of those experiments is shown in Figure 1.10. A tourniquet was applied to a subject's arm, and he was asked to squeeze something so that the veins filled with blood and "popped." (You have probably done the same thing when having blood drawn in a doctor's office.) Harvey would then press down on the vein and note that it would subside (indicating that the blood was leaving it) on the side toward the heart. This result is just the opposite of what would occur if blood were flowing from the liver to the extremities. Based on this experiment, and many others like it, Harvey eventually concluded that blood circulates continuously.

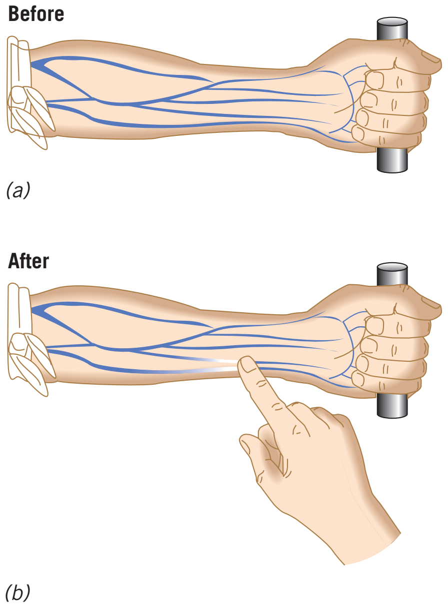


FIGURE 1.10 One of William Harvey's famous experiments on the circulation of the blood tested the hypothesis that blood flows from veins to the heart. Harvey first applied a tourniquet to a subject's arm and had the subject squeeze something to raise the veins *(a)*. Pressing down on the vein caused it to gradually subside *(b),* indicating that the blood was indeed flowing back to the heart.

SCIENCE BY THE NUMBERS

The Circulation of the Blood

William Harvey was partially motivated in his studies of the circulation of the blood by some simple mathematical calculations. At the time, the accepted dogma, promulgated by the great Roman physician Galen centuries before, was that blood was made in the liver and flowed outward to the cells, where it was largely consumed. Harvey took hearts from cadavers he was dissecting and measured the amount of water they could hold. It turned out that a normal heart can hold about 2 ounces of fluid. Harvey knew that the heart in a normal adult beats about 72 times a minute (you can check your own pulse to verify this number). Thus, in 1 minute, the amount of blood pumped by the heart must be

$$72 \text{ beats} \times 2 \text{ ounces/beat} = 144 \text{ ounces/minute}$$

There are 16 ounces in a pound, so

$$144 \text{ ounces/minute} \times 1/16 \text{ pound/ounce} = 9 \text{ pounds/minute}$$

There are 60 minutes in an hour and 24 hours in a day, so in one day the heart must pump

$$9 \text{ pounds/minute} \times 60 \text{ minutes/hour} \times 24 \text{ hours/day} = 12{,}960 \text{ pounds per day}$$

Harvey knew that no one can take in this much food in a day, so the sort of "one-way" circulation and consumption of blood Galen had posited simply couldn't be right. It made much more sense to have the heart pump the same supply of blood around continuously. (For historical accuracy, we should note that there was an ill-defined way in Galen's physiology for some blood to return to the liver—think of something like the ebb and flow of the tide—but the idea that the blood was consumed in the body remained central.)

1.3 Other Ways of Knowing

Scientists discover laws that describe how nature works by performing reproducible observations and measurements. Every idea in science must be subject to this kind of testing. If an idea cannot be tested in a manner that yields reproducible results, even if that idea is correct, then it simply isn't a part of science.

Different Kinds of Questions

The first step in any scientific investigation is to ask a question about the physical world. A scientist can ask, for example, whether a particular painting was completed in the seventeenth century. Various physical and chemical tests can be used to find the age of the paint, study the canvas, X-ray the painting, and so on. The question of whether the painting is old or a modern forgery can indeed be investigated by the scientific method.

But the methods of science cannot answer other equally valid questions. No physical or chemical test will tell us whether the painting is beautiful or how we are to respond to it. These questions are simply outside the realm of science.

The scientific method is not the only way to answer questions that matter in our lives. Science provides us with a powerful way of tackling questions about the physical world—how it works and how we can shape it to our needs. But many questions lie beyond the scope of science and scientific methods. Some of these questions are deeply philosophical: What is the meaning of life? Why does the world hold so much suffering? Is there a God? Other important personal questions also lie outside of science: What career should I choose? Whom should I marry? Should I have children? Scientific information might influence some of our personal choices, but we cannot answer these questions fully by the cycle of observation, hypothesis, and testing. For answers, we turn instead to religion, philosophy, and the arts.

Symphonies, poems, and paintings are created to be enjoyed and are not, in the end, experiences that need to be analyzed scientifically. This is not a criticism. These art forms address different human needs than science, and they use different methods. The same can be said about religious faith. Strictly speaking, there should be no conflict between the questions asked by science and religion, because they deal with different aspects of life. Conflicts arise only when people attempt to apply their methods to questions where those methods aren't applicable.

Pseudoscience

Many claims of natural phenomena, including extrasensory perception (ESP), astrology, crystal power, reincarnation, or many other notions you see in the tabloids at supermarket checkout counters, fail the elementary test that defines the sciences. None of these subjects, collectively labeled **pseudoscience**, can be tested in the sense that we are using the term (Figure 1.11). There is no reproducible test you can imagine that will convince

uguhan/Getty Images

FIGURE 1.11 Fortune telling, astrology, and other activities at this psychic's shop in Hollywood are examples of pseudoscience.

people who believe in these notions that their ideas are incorrect. Yet, as we have seen, the central property of scientific ideas is that they are testable and could be wrong, at least in principle. Pseudoscience lies outside the domain of science and falls instead in the realm of belief or dogma.

In the following "Science by the Numbers" feature we examine the nature of one pseudoscience, astrology. When confronted with other kinds of pseudoscience, you can ask a number of questions to come to your own conclusions:

1. Are the "facts" true as stated?

   The first step is to be sure that the facts stated in support of a pseudoscientific claim are actually true. For example, the Great Pyramids of Egypt are frequently the subject of these sorts of arguments. In one version, it is argued that the pyramids must have been built by extraterrestrials because, among other things, their bases are perfect squares and laying out a perfect square was beyond the capability of Egyptian engineers. In fact, according to modern surveys of the pyramids, the longest side of the Pyramid of Cheops is 8 inches longer than the shortest side—it is not a perfect square at all. Digging out the true facts can sometimes be tedious, but it is a necessary first step.

2. Is there an alternative explanation?

   In dealing with UFO sightings, it often happens that you can't prove that the object seen wasn't a UFO, but there exists a "normal" explanation for the same event. For example, a light in the sky could be an extraterrestrial spaceship, but it could also be the planet Venus (the most commonly reported UFO). In this case, it is necessary to invoke a doctrine called the "burden of proof." If someone makes a claim, it is up to that person to establish the claim: it is not up to you to disprove it. Furthermore, the more far-reaching the claim, the higher the standard of proof becomes. In the words of the noted planetary astronomer and public television science educator Carl Sagan (1934–1996), "Extraordinary claims require extraordinary proofs."

3. Is the claim falsifiable?

   As we stated above, a central aspect of the scientific method is that every scientific statement is subject to experimental or observational tests, so that it is possible to imagine an experimental result that would prove the statement wrong (although whether that result will ever actually be seen is a separate question). Such statements are said to be *falsifiable*. Statements that are not falsifiable are simply not part of science. For example, some creationists talk about the doctrine of "created antiquity," by which they mean that the universe was created to look *exactly* as if it were billions of years old, even though it was really created by God a few thousand years ago. This statement is not falsifiable, and therefore this doctrine is not part of science.

STOP & THINK! **Can any experiment or observation (in principle) show created antiquity to be false?**

4. Have the claims been rigorously tested?

   Many pseudoscientific claims are based on anecdotes and stories. An example is provided by the practice known as "dowsing" or "water witching," in which someone walking on the surface (usually holding a forked stick) can detect the presence of underground water. Stories about this practice can be found in almost any rural area of the United States. Yet when the Committee for the Scientific Investigation of Claims of the Paranormal (CSICOP; now Committee for Skeptical Inquiry) conducted controlled tests in which water pipes were buried beneath a plowed surface, dowsers did no better than chance at locating the water. Tests like these are difficult to arrange, and often do not get much publicity, but they are worth looking for (see, for example, http://www.csicop.org).

5. Do the claims require unreasonable changes in accepted ideas?

Often a pseudoscientific claim will seem to explain a small set of facts but at the same time will require that a much wider assortment of facts be ignored. The psychiatrist Immanuel Velikovsky, for example, looked at stories in ancient texts and tried to alter astronomy (violating most of the laws of physics in the process) in order to preserve the texts as literal statements of fact, rather than as allegory or metaphor. From a scientific perspective, it is much more reasonable to accept the well-verified laws of physics and give up the literal reading of the text.

SCIENCE BY THE NUMBERS

Astrology

Astrology is a very old system of beliefs that most modern scientists would call a pseudoscience. The central belief of astrology is that the positions of objects in the sky at a given time (a person's birth, for example) influence a person's future (Figure 1.12). Astrology as it has been practiced in the Western world developed as part of a complex set of omen systems used by the Babylonians, and it was practiced by many famous astronomers well into modern times.

As Earth travels around the Sun, the stars in the night sky change. The band of background stars through which the Sun, the Moon, and the planets appear to move is called the zodiac. The stars of the zodiac are customarily divided into 12 constellations, which are called "signs" or "houses." If you could block out the light of the Sun, these stars would appear (as they do during a total solar eclipse). You would then notice the Sun's position to lie within a certain zodiac constellation, just as the Moon and planets do at night. Furthermore, if you watched the Moon and planets from night to night, you would see them appear to move through these constellations.

At any time, the Sun, the Moon, and the planets all appear in one of these constellations, and a diagram showing these positions is called a horoscope. Astrologers have a complex (and far from unified) system in which each combination of heavenly bodies and signs is believed to signify particular things. The Sun, for example, is thought to indicate the outgoing, expressive aspects of one's character, the Moon the inner-directed ones,

The signs of Zodiac Miniature from "Breviaire d'Amor" by Ermengol de Beziers (Matfre Ermengau) (died 1322) (fol 44r), 13th century Royal Library of the Monastery of Escorial (Escorial), Spain/Matfre Ermengaut (d.1322)/AGENZIA FOTOGRAFICA LUISA RICCIARINI/ Biblioteca Monasterio del Escorial, Madrid, Spain/Bridgeman Images

FIGURE 1.12 Astrology is a pseudoscience that is based on the belief that the positions of astronomical objects influence our personal lives.

and so on. When this system was first introduced, the constellation in which the Sun appeared at the time of your birth was said to be your "Sun sign," or, simply, your "sign." Today, the position of the Sun in the sky has shifted due to the motion of Earth's axis, but the original dates for the "signs" are still used.

Scientists reject astrology for two reasons. First, there is no known way that planets and stars could exert a significant influence on a child at birth. It is true, as we shall learn in Chapter 2, that they exert a miniscule gravitational force on the infant, but the gravitational force applied by the delivering physician (who is smaller but much closer) is much greater than that exerted by any celestial object.

Second, and more importantly, scientists reject astrology because it just doesn't work. Over the millennia, there has been no evidence at all that the stars can predict the future.

You can test the ideas of astrology for yourself, if you like. Try this: Have a member of the class take the horoscopes from yesterday's newspaper and type them on a sheet of paper without indicating which horoscope goes with which sign. Then ask members of your class to indicate the horoscope that best matches the day they actually had. Have them write their birthday (or sign) on the paper as well.

If people just picked horoscopes at random, you would expect about 1 person in 12 to pick the horoscope corresponding to his or her sign. Are the results of your survey any better than that? What does this tell you about the predictive power of astrology?

1.4 The Organization of Science

Scientists investigate all sorts of natural objects and phenomena: the tiniest elementary particles, microscopic living cells, rocks and minerals, the human body, forests, Earth, stars, and the entire cosmos. Throughout this vast sweep, the same scientific method can be applied. Men and women have been carrying out this task for hundreds of years, and by now we have a pretty good idea about how the many parts of our universe work. In the process, scientists have also developed a social structure that provides unity to the pursuit of scientific knowledge, as well as recognition of important disciplinary differences within the larger scientific framework.

The Divisions of Science

Science is a human endeavor, and humans invariably form themselves into groups with shared interests. When modern science first started in the seventeenth century, it was possible for one person to know almost all there was to know about the physical world and the "three kingdoms" of animals, vegetables, and minerals. In the seventeenth century, Isaac Newton could do forefront research in astronomy, in the physics of moving objects, in the behavior of light, and in mathematics. Thus, for a time prior to the mid-nineteenth century, scholars who studied the workings of the physical universe formed a more or less cohesive group, calling themselves "natural philosophers." But as human understanding expanded and knowledge of nature became more detailed and technical, science began to fragment into increasingly specialized disciplines and subdisciplines.

Today, our knowledge and understanding of the world is so much more sophisticated and complex that no one person could possibly be at the frontier in such a wide variety of fields. Today most scientists choose a major field—biology, chemistry, physics, and so on—and study one small part of the subject at great length (Figure 1.13). Each of these broad disciplines boasts hundreds of different subspecialties. In physics, for example, a student may elect to study the behavior of light, the properties of materials, the nucleus of the atom, elementary particles, or the origin of the universe. The amount of information and expertise required to get to the frontier in any of these fields is so large that most students have to ignore almost everything else to learn their specialty. Even so, many of the

FIGURE 1.13 Scientists work at many different tasks.

most interesting problems in science, from the origin of life to the properties of matter to curing cancer, are interdisciplinary, and require the collective efforts of many scientists with different specialties.

Science is further divided because scientists within each subspecialty approach problems in different ways. Some scientists are *field researchers*, who go into natural settings to observe nature at work. Other scientists are *experimentalists*, who manipulate nature with controlled experiments. Still other scientists, called *theorists*, spend their time imagining universes that might exist. These different kinds of scientists need to work together to make progress.

The Branches of Science

Several branches of science are distinguished by the scope and content of the questions they address:

Physics is the search for laws that describe the most fundamental aspects of nature: matter, energy, forces, motion, heat, light, and other phenomena. All natural systems, including planets, stars, cells, and people, display these basic phenomena, so physics is the starting point for almost any study of how nature works.

Chemistry is the study of atoms in combination. Chemicals form every material object of our world, while chemical reactions initiate vital changes in our environment and our bodies. Chemistry is thus an immensely practical (and profitable) science.

Astronomy is the study of stars, planets, and other objects in space. We are living in an era of unprecedented astronomical discovery thanks to the development of powerful new telescopes and robotic space exploration.

Earth Sciences is the study of the origin, evolution, and present state of our home, planet Earth. Many earth science departments also emphasize the study of other planets as a way to understand the unique character of our own world. The earth sciences include fields like geology, oceanography, and meteorology that used to be thought of as separate disciplines.

Biology is the study of living systems. Biologists document life at many scales, from individual microscopic molecules and cells to expansive ecosystems.

In spite of this practical division of science into separate disciplines, all branches of science are interconnected in a single web of knowledge. Most natural processes can only be studied by resorting to an integrated approach. Understanding such diverse topics as changes in the global climate, the availability of natural resources, the safe storage of nuclear waste, and the discovery of alternative sources of energy requires expertise in physics, chemistry, geology, and biology. All of the sciences are integrated in the natural world.

The Web of Knowledge

The organization of science can be compared to an intricate spider web (Figure 1.14). Around the periphery of the web are all the objects and phenomena examined by scientists, from atoms to trees to comets. Moving toward the web's center, we find the cross-linking hypotheses that scientists have developed to explain how these phenomena work. The farther in we move, the more general these hypotheses become and the more they explain. Radiating out from the center of the web, connecting all the parts and holding the entire structure together, we find a small number of very general principles that have attained the rank of laws of nature.

No matter where you start on the web, no matter what part of nature you investigate, you will eventually come to one of the fundamental overarching ideas that intersect at the central core. Everything that happens in the universe happens because one or more of these physical laws is operating.

The hierarchical organization of scientific knowledge provides an ideal way to approach the study of science. At the center of any scientific question are a few laws of nature. We begin by looking at those laws that describe everyday forces and motions in the universe. These overarching principles of science are accepted and shared by all scientists, no matter what their field of research. These ideas recur over and over again as we study different parts of the world. You will find that many of these ideas and their consequences seem quite simple—perhaps even obvious—because you are intimately familiar with the physical world in which these laws of nature constantly operate.

After introducing these general principles, we look at how the scientific method is applied to specific physical systems in nature. We examine the nature of materials and the atoms that make them, for example, and we look at the chemical reactions that form them. We explore the planet on which we live and discover how mountains and oceans, rivers and plains are formed and evolve over time. And we examine living organisms at the scale of molecules, cells, organisms, and ecosystems.

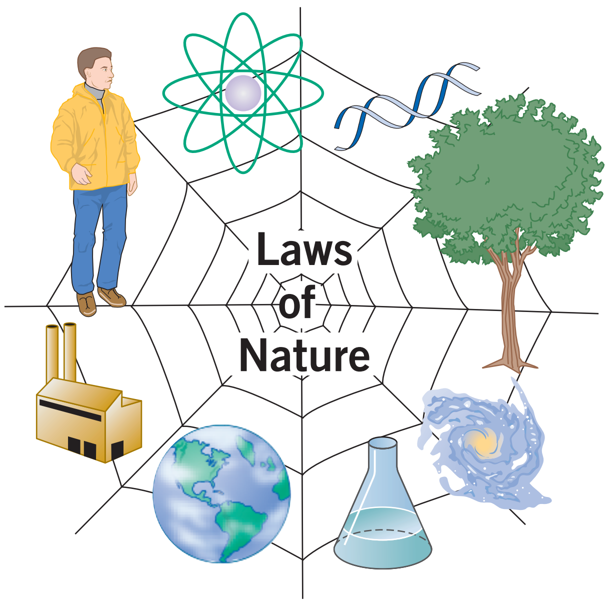


FIGURE 1.14 The interconnected web of scientific knowledge.

By the time you have finished this journey, you will have touched on many of the great discoveries about the physical universe that scientists have deduced over the centuries. You will explore how the different parts of our universe operate and how all the parts fit together, and you will know that there are still profound and fascinating unanswered questions that drive scientists today. You will understand some of the great scientific and technological challenges that face our society, and more importantly, you will know enough about how the world works to deal with many of the new problems that will arise in the future.

Basic Research, Applied Research, and Technology

The physical universe can be studied in many ways, and many reasons exist for doing so. Many scientists are simply interested in finding out how the world works—in knowledge for its own sake. They are engaged in **basic research** and may be found studying the behavior of distant stars, obscure life forms, rare minerals, or subatomic particles. Although discoveries made by basic researchers may have profound effects on society (see the discussion of the discovery of the electric generator in Chapter 5, for example), practical applications are not the primary personal goal of most of these scientists.

Many other scientists approach their work with specific practical goals in mind. They wish to develop **technology,** in which they apply the results of science to specific commercial or industrial goals. These scientists are said to be doing **applied research**, and their ideas are often translated into practical systems by large-scale **research and development (R&D)** projects.

Government laboratories, colleges and universities, and private industries all support both basic and applied research; however, most large-scale R&D (as well as most applied research) is done in government laboratories and private industry (Table 1.2).

Funding for Science

An overwhelming proportion of funding for American scientific research comes from various agencies of the federal government—your tax dollars at work (see Table 1.3).

TABLE 1.2

Major Research Laboratories

Facility	Type	Location
Argonne National Laboratory	Government/University	Near Chicago, IL
AT&T Bell Laboratories	Industrial	Murray Hill, NJ
Brookhaven National Laboratory	Government	Long Island, NY
Carnegie Institution	Private	California, Maryland, and Washington, DC
Dupont R&D Center	Industrial	Wilmington, DE
Fermi National Accelerator Lab	Government/University	Near Chicago, IL
IBM Watson Research Laboratory	Industrial	Yorktown Heights, NY
Keck Telescope	University	Mauna Kea, HI
Los Alamos National Laboratory	Government	Los Alamos, NM
National Institutes of Health	Government	Bethesda, MD
National Institutes of Standards and Technology	Government	Gaithersburg, MD
Oak Ridge National Laboratory	Government	Oak Ridge, TN
Stanford Linear Accelerator	Government/University	Stanford, CA
Texas Center for Superconductivity	University	Houston, TX
United States Geological Survey	Government	Reston, VA
Woods Hole Oceanographic Institution	University	Woods Hole, MA

TABLE 1.3

Your Tax Dollars: 2013 Federal Science Funding

Total Federal Research and Development Funding by Agency for 2013

Agency	Amount in Millions of Dollars
Department of Defense	65,540
Department of Health and Human Services	29,802
National Aeronautics and Space Administration	10,999
Department of Energy	10,705
National Science Foundation	5,329
Department of Agriculture	1,818
Department of Commerce	1,297
Department of Homeland Security	684
Department of Transportation	818
Department of the Interior	785
Department of Veterans Affairs	1,164
Smithsonian Institution	168
Environmental Protection Agency	530

In 2013, the U.S. government's total research and development budget was about $130 billion. The *National Science Foundation,* with an annual budget of about 5.3 billion dollars, supports research and education in all areas of science. Other agencies, including the National Institutes of Health, the Department of Energy, the Department of Defense, the Environmental Protection Agency, and the National Aeronautics and Space Administration, fund research and science education in their own particular areas of interest, while Congress may appropriate additional money for special projects.

An individual scientist seeking funding for research will usually submit a grant proposal to the appropriate federal agency. Such a proposal will include an outline of the planned research together with a statement about why the work is important. The agency evaluating the proposals asks panels of independent scientists to rank them in order of importance, and funds as many as it can. Depending on the field, a proposal has a 5% to 20% chance of being successful. This money from federal grants buys experimental equipment and computer time, pays the salaries of researchers, and supports advanced graduate students. Without this support, much of the scientific research in the United States would come to a halt. The funding of science by the federal government is one place where the opinions and ideas of the citizen, through his or her elected representatives, have a direct effect on the development of science.

As you might expect, scientists and politicians engage in many debates about how this research money should be spent. One constant point of contention, for example, concerns the question of basic versus applied research. How much money should we put into applied research, which can be expected to show a quick payoff, as opposed to basic research, which may not have a payoff for years (if at all)?

Communication Among Scientists

Sometimes it's easier to do your homework with other students than by yourself, and the same is true of the work that scientists do. Working in isolation can be very hard, and scientists often seek out other people with whom to converse and collaborate. The popular stereotype of the lonely genius changing the course of history seldom describes the world of the working scientist. The next time you walk down the hall of a science department at your university, you will probably see faculty and students deep in conversation, talking and scribbling on blackboards. This direct contact between colleagues is the simplest type of scientific communication.

Scientific meetings provide a more formal and structured forum for communication. Every week of the year, at conference retreats and convention centers across the country, groups of scientists gather to trade ideas. You may notice that science stories in your newspapers often originate in the largest of these meetings, where thousands of scientists converge at one time, and a cadre of science reporters with their own special briefing room is poised to publicize exciting results. Scientists often hold off announcing important discoveries until they can make a splash at such a well-attended meeting and press conference.

Finally, scientists communicate with each other in writing. In addition to rapid communications such as e-mail, telephone, and social media, almost all scientific fields have specialized journals to publish the results of research. The system works like this: When a group of scientists finishes a piece of research and wants to communicate their results, they write a concise paper describing exactly what they've done, giving the technical details of their method so that others can reproduce the data and stating their results and conclusions. The journal editor sends the submitted manuscript to one or more knowledgeable scientists who act as referees. These reviewers, whose identities are not usually revealed to the authors, read the paper carefully, checking for mistakes, misstatements, or questionable procedures. Each reviewer then sends the editor a list of necessary modifications and corrections. If they tell the editor that the work passes muster, it will probably be published. In many fields papers are published online almost immediately, with archival paper copies following some weeks later. This system, called **peer review**, is one of the cornerstones of modern science.

Peer review provides a clear protocol for entering new results into the scientific literature. Little wonder then that scientists get so upset when one of their colleagues tries to bypass the system and announces results at a press conference. Such work has not been subject to the thorough review process, and no one can be sure that it meets established standards. When the results turn out to be irreproducible, overstated, or just plain wrong, it damages the credibility of the entire scientific community. So, if you read about a new discovery in the newspaper or on the Internet and you can't track the story back to a published, peer-reviewed journal article, then you should question the veracity of that finding.

THINKING MORE ABOUT BASIC RESEARCH

Modern science can be very expensive. The kind of orbiting astronomical observatories described in Chapter 14 and the Large Hadron Collider discussed in Chapter 13 can cost many billions of dollars. These sorts of machines are devoted to basic research, to discovering the fundamental laws that govern the operation of the universe. We simply don't know whether those discoveries will ever have a practical benefit for humanity at some time in the future. This is a feature of basic research.

It's not hard to justify spending money on research when an obvious benefit is in the offing—a new drug or a faster computer, for example. But how do you justify spending that money when there is no obvious and immediate benefit?

Those who oppose large expenditures on basic research argue that the world faces many serious problems that have to be solved right now, and maintain that the benefits of basic research are too tenuous and too far in the future to justify spending money now. Those who support these expenditures argue that basic research has always provided the foundation from which practical benefits flow, and that not funding it now will impoverish future generations.

What proportion of the money spent on scientific research do you think ought to be directed toward work that will have no obvious immediate benefits? How do you balance the immediate benefit of working on current problems against the long-term benefits that have always flowed from basic research? Who do you think ought to make such decisions?

RETURN TO THE INTEGRATED QUESTION

How do you know what you know?

- We obtain knowledge of our world in many ways: through experience, received wisdom, scientific observations and experiments, or as Plato suggested a reliance on reason and intuition. All of these methods have limitations.
  - The scientific method was developed to overcome the inherent limitations in our attempts to gain knowledge of the world.
  - Science uses mathematics to quantify observations so that patterns and regularities may be systematically identified.
  - Prediction and testing develop and refine scientific knowledge.
  - Competition between rival theories and hypotheses fuel scientific progress, while communication between researchers leads to a greater knowledge and understanding of our world.
  - All scientific laws and theories are subject to change with improved observations and measurements, which advance our scientific understanding of our world.
  - Researchers communicate their results via peer-reviewed publications. The process of publication codifies our knowledge while disseminating valuable information to the world at large.
- Science attempts to answer questions using observable facts, reproducible experiments, logical hypotheses, and testable predictions. Nevertheless, there are many questions that science cannot answer (e.g., is there a God?).
  - Other "ways of knowing," including art, philosophy, ethics, and religion, address different kinds of questions and thus complement science.
  - Science is not the only method for gaining an understanding of the world in which we live. Nevertheless, it is an invaluable tool that provides an unparalleled framework for acquiring knowledge of our physical world.

Summary

Science is a way of learning about our physical universe. The *scientific method* relies on making *reproducible observations* and *experiments* based on careful *measurements* of the natural world. Once scientists have collected a number of *facts*, which are confirmed observations about the natural world, then they can form a *hypothesis*—a tentative educated guess about how the world works. Hypotheses, in turn, lead to *predictions* that can be tested with more observations and experiments. A scientific *law* arises when numerous measurements point to a regular, predictable pattern of behavior in nature, whereas a scientific *theory* is a well-substantiated explanation of the natural world based on a large number of independently verified observational and experimental tests. Laws and theories, no matter how successful, are always subject to further testing. The language of *mathematics* is universal and standardized into units. These units can change with advancements in science and technology. This language guides experimental analyses and the development of theories. Science and the scientific method differ from other ways of knowing, including religion, philosophy, and the arts, and differ from *pseudosciences*.

Science is organized around a hierarchy of fundamental principles. Overarching concepts about forces, motion, matter, and energy apply to all scientific disciplines, including *physics, chemistry, astronomy, geology,* and *biology*. Additional great ideas relate to specific systems—molecules, cells, planets, or stars. This body of scientific knowledge forms a seamless web, in which every detail fits into a larger, integrated picture of our universe.

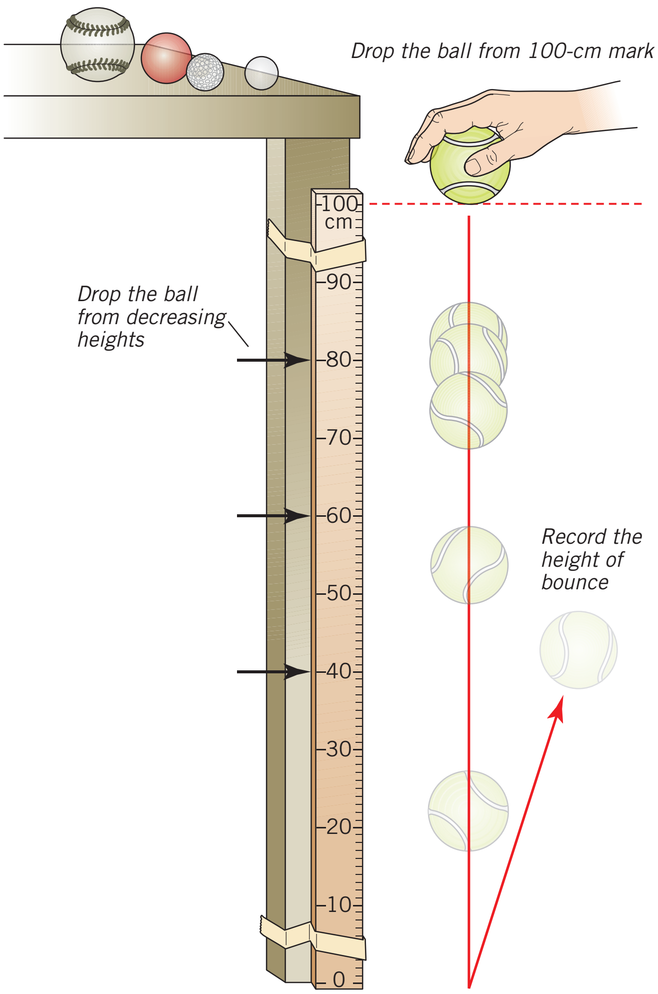
Scientists engage in *basic research* to acquire fundamental knowledge, as well as *applied research* and *research and development (R&D)*, which are aimed at specific problems. *Technology* is developed by this process. Scientific results are communicated in *peer-reviewed* publications. The federal government plays the important role of funding most scientific research and advanced science education in the United States.

Key Terms

scientific method
observations
experiment
measurement
mathematics
fact
hypothesis
law
theory
prediction
reproducible
pseudoscience
physics
chemistry
astronomy
earth sciences
biology
basic research
technology
applied research
research and development (R&D)
peer review

DISCOVERY LAB

Does the material of a ballaffect its bounce? Perform an experiment to see if your hypothesis holds true. For this experiment you will need a tennis ball, golf ball, ping pong ball, bouncy ball, soft ball, meter stick, and masking tape. Tape the meter stick to a table leg so that the 100 centimeter end is facing up. Hold the tennis ball so that its bottom is level with the 100 centimeter mark. Drop the ball and read the height of the bounce to the nearest centimeter. Record the bounce height. Repeat the process of dropping the ball 3 to 5 more times. In order to obtain accurate results, get to the level of the ball to read the height. After repeating the experiment 3 to 5 times for 100 centimeters, repeat the same investigation by changing one of the independent variables. In this experiment, your independent variable will be the ball type. Determine which ball has the greatest bounce. Now try dropping the ball from decreasing heights of 80 centimeters, 60 centimeters, and 40 centimeters and measure the bounce of the ball each time. Why is repetition important? What was kept constant? To visually demonstrate your quantitative data, make a graph of the average bounce versus height from which the ball was dropped. What if you changed other variables such as the type of surface on which the ball is bounced, the size of the ball, the mass of the ball, or the temperature of the ball? Did your data agree with your hypothesis or was it disproved? Think of all the steps taken in this experiment that make up the scientific process.



Review Questions

1. Why was the definition of the kilogram updated and why is that scientific advancement so important?
2. In what ways does your everyday life involve science?
3. How might the ancient Greek philosopher Plato, a medieval scholar at Oxford, and the Italian scientist Galileo have differed in the importance each placed on the role of rational processes, observations, and received wisdom in the study of nature?
4. What is the first step in any scientific investigation? Why is this step fundamental to the scientific method?
5. How might a scientist find patterns in nature? By what means might he or she determine regularities?
6. Why is mathematics considered the "language of science"?
7. Write an equation in words and then in symbols for the following sentence: The price of coffee beans is equal to the weight of the beans times the price of the beans per pound.

8. What are the steps in the development of a theory? What is the difference between a scientific theory and a theory in a nonscientific sense?
9. What are the branches of science? In terms of the "Web of Knowledge," how are they organized?
10. Describe the steps of the scientific method. Why can we think of the scientific method as a cycle?
11. Describe the roles of hypotheses, theories, and predictions in the scientific method.
12. Describe the difference between an observation and an experiment.
13. What is the purpose of testing an idea in science? Think about the scientific method. What are the potential outcomes of repeated and rigorous testing of an idea or observation?
14. What does it mean to say that not all questions can be answered using the scientific method?
15. What does it mean for a statement to be falsifiable? Give an example of a statement that is not falsifiable.
16. Describe the difference between basic and applied research. Give examples of basic and applied research that may be undertaken in the fields of agriculture and public health.
17. In what ways do scientists communicate with their colleagues? Why is peer review and communication amongst researchers an essential ingredient in scientific progress?
18. How are astrology and astronomy different? Are both astrology and astronomy considered to be branches of science? Why or why not?

Discussion Questions

1. Advocates of Creation Science, widely regarded in the scientific community as a pseudoscience, in turn describe Evolution as tantamount to a religious belief that requires faith to be considered true. What evidence can you think of that supports Evolution as a theory and what do you think could potentially falsify it? Likewise, what do you think could falsify Creation Science?
2. Which of the following statements could be tested scientifically to determine whether it is true or false?
   - **a.** Women are on average shorter than men.
   - **b.** Most of the Sun's energy is in the form of heat energy.
   - **c.** Unicorns are now extinct.
   - **d.** Beethoven wrote beautiful music.
   - **e.** Earth was created over 4 billion years ago.
   - **f.** Earth was created in a miraculous event.
   - **g.** Diamond is harder than steel.
   - **h.** Football is a better sport than baseball.
   - **i.** God exists.
3. What role did observation play in the creation of the periodic table by Dimitri Mendeleev? What was the significance of the creation of the periodic table in the advancement of knowledge in the field of chemistry?
4. In 1935, Yukawa Hideki predicted the existence of a sub-atomic particle known as a "meson" and described some of its expected characteristics. Following the discovery of such particles bearing those properties, Yukawa was awarded the 1949 Nobel Prize in Physics. Subsequently, Yukawa's rationale for the existence of the meson was shown to be wrong. Would it be reasonable to say Yukawa's meson theory failed to advance our understanding of sub-atomic physics?
5. How did William Harvey use experimentation to find how blood circulates in the human body? What role did previous scientific hypotheses play in the development of Harvey's hypothesis that blood circulates through a connected system of arteries and veins?
6. Categorize the following examples as basic or applied research:
   - **a.** The development of carbon capture and utilization technologies
   - **b.** The discovery of a new species of beetle
   - **c.** A study of the effects of wildlife disease on bat populations
   - **d.** The discovery of a new antibiotic compound
   - **e.** The discovery of a new chemical compound
   - **f.** Improvement in hybrid electric vehicle technologies
7. The development of biological controls for agricultural pests Issues involving climate science play a significant role in American political discussions and the development of economic policy. In your opinion, how significant is the scientific consensus on this issue in determining public policy?
8. Recent research indicates that "gut health" is intricately linked to overall health and well-being. Many over-the-counter prebiotic or probiotic products claim to promote improved "gut health." How might you test these statements in a laboratory? Would this be a form of basic or applied research?
9. Research into human genetics is starting to allow scientists to manipulate the human genome. While this ability has the potential to minimize or even eradicate congenital diseases, it may also be used to manipulate non-medical conditions such as eye color or height. To what extent should religious, moral, and ethical beliefs play a role in determining limitations on genetic manipulation?
10. Isaac Newton once said, "If I have seen further, it is by standing on the shoulders of giants"? What does this statement tell us about the way that science progresses over time?
11. Which branch of science do you think has had the most impact on your day-to-day existence? Describe instances in your daily life where you use the results of physics, chemistry, biology, geology, and astronomy.
12. Are both basic and applied research necessary? Do you think it is more important for funding to be granted to basic research or applied research projects? Should more or less funding be allocated for either or both types of research? Explain.

13. Why is "peer review" so important to the scientific community? Is the peer review system overly stifling or onerous? If so, how could it be improved without impairing its current utility?

14. Why are standardized units so important? Give an example of an instance from your daily life in which you use standardized units. What might happen if standardized units did not exist?

15. An American football star from the 1970's and 1980's, Lyle Alzado, had begun using steroids in the late 1960's. He blamed the use of steroids for the brain tumor that led to his death at age 43. However, current scientific research doesn't show a statistical correlation between steroid use and the development of brain tumors. Does this negate Alzado's contention about the cause of his death?

16. The German-American rocket scientist Wernher von Braun was once quoted as saying, "Basic research is what I am doing when I don't know what I am doing." What do you think he meant?

17. After getting approval to perform tests on humans, a pharmaceutical company devises an experiment to test the level of impairment of mental acuity people experience after consuming a certain drug by having them take a test with differing amount of the drug in their systems. Which of the following best describes the control group for this experiment?

a. People who take the highest dose

b. People who take the lowest dose

c. People who take no dose

d. People who don't take the test

18. Prior to the discovery of oxygen as a chemical element, the theory of why materials burned was known as the "Phlogiston Theory." This theory said that a substance that could be burned contained phlogiston, which was consumed in the process of combustion, leaving behind the non-phlogiston residue. How could the Phlogiston Theory be falsified?

19. Consider an experiment in which you drop an ordinary sheet of paper and then drop the same sheet of paper but after it has been crumpled up. Devise a hypothesis for this phenomenon and then make predictions of possible experiments based on it.

Problems

1. Amanda is a college student who keeps a diary of her daily caloric intake over the course of a month. In the first week of one particular February, she averaged 1500 calories per day. The next week, faced with a stressful period of exams, she averaged 1800 calories per day. She tried to make up for it the following week by averaging 1400 calories per day. In the final week of the month, she returned to what she felt was her usual average of 1500 calories per day. What is an efficient way for Amanda to display her data? What other measurements should she consider recording to give her a fuller description of caloric consumption and usage?

2. Compare data from your science classes *versus* your non-science classes. For instance, examine the male-to-female ratios in each type of class. Try to get other students to help out with their classes so as to increase your sample size. What expectations do you have? How do the actual data compare to your expectations?

3. Pick one of your favorite kinds of music and describe it using adjectives that you feel aren't scientifically measurable. Next, describe the music in ways that you feel could be scientifically measured. Try to make measurements of some of these characteristics. For the ones you can't measure, what equipment do you think you would need to carry out these measurements?

4. In 2020, the U.S. Department of Defense released three declassified videos showing unidentified flying objects (UFOs) filmed in 2004 and 2015. The videos show unauthorized aircrafts flying in U.S. airspace, displaying flight patterns and characteristics that are not known to be U.S. advanced technology. Citing safety concerns, the Department of Defense launched a task force to investigate UFO activity in American airspace. How can the Department of Defense use the scientific method to address these concerns? What types of questions should the taskforce be asking and what measurements can be made to distinguish whether or not these objects were extraterrestrial in origin?

5. Isaac Newton's 2nd Law of Motion says that the acceleration a an object experiences is proportional to the total force F acting on the object and inversely proportional to the mass m of the object. Identify the mathematical expression that embodies this idea.

a. $a = Fm$

b. $a = F/m$

c. $a = (1/F) * (1/m)$

d. $aFm = 1$

Investigations

1. What is the closest major government research laboratory to your school? What is the closest industrial laboratory? Describe one research project that is now underway at one of these laboratories.

2. What are the major science departments at your school? How many professors are performing research in each department? Are these professors doing basic or applied research? Describe a program of scientific research carried out by a member of your school's faculty. How is the scientific method employed in this research?

3. Identify a current piece of legislation relating to science or technology (perhaps an environmental or energy bill). How did your representatives in Congress vote on this issue?
4. Look at a recent newspaper article about a scientific subject. What federal agency funded the research? Is the research basic or applied?
5. Find a science story in a newspaper or popular magazine. Who were the scientists who conducted the research? Where did they do the work?
6. Consider the way that scientists are portrayed in any recent film. Were you convinced by these portrayals? Why? How do these portrayals compare with the faculty doing research at your school?
7. Was Harvey justified in his use of animals in studies of the circulatory system? What limits should scientists accept in research using animals?
8. What organizations (e.g., institutional animal control and review boards) at your school protect research animals from unnecessary harm? What specific drugs, medicines, and procedures were developed using animal research?
9. Design an experiment to test the relative strengths of three different kinds of aluminum can. What data would you need to collect? What laboratory equipment would you need? How might you present these data in tables and graphically?
10. Malaria is a deadly infectious disease caused by a parasite transmitted through the bites of infected female *Anopheles* mosquitoes. This curable and preventable disease is responsible for over 400,000 deaths annually, the majority of which are children under 5 years of age. The majority of cases occur in sub-Saharan Africa, with regions in Southeast Asia, the Mediterranean, and the Americas also experiencing cases of malaria. The annual malaria research budget in the United States is only a fraction of the funding dedicated to cancer, heart disease, and AIDs. Should the United States devote more research funds to this disease? Why or why not? Can we use the scientific method to address the challenges that this disease presents?
11. Does your school recycle? If so, why? What are the benefits of recycling paper, metal, or plastic? Is there a benefit to recycling paper since we can always grow more trees?
12. Think of an idea or a topic in which you are interested. Go to Google Scholar: http://scholar.google.com/ and search peer-reviewed journals to read about how research scientists with your interests have studied the idea.