# The Nature of Science

# Chapter 1

In this chapter we will consider what science is and the role that it plays in modern society. We will discuss the impact that science has on how we live and work, the limitations of the scientific worldview, problems with the typical way that the "scientific method" is presented, and the way that science can help us to see connections in the world around us. We will explore key qualities of scientific inquiry, consider examples of those qualities in practice, and discuss ways that sociologists and historians of science have explained the way science has developed over time.

**After reading this chapter you should be able to:**

- Discuss what science is and what it is not.
- Describe key qualities of scientific inquiry and how these qualities interact.
- Explain how scientific thinking evolves over time.

**Consider the following statements about science and the scientific process:**

If I have seen further than others, it is by standing upon the shoulders of giants. I made discoveries by always thinking unto them. I keep the subject constantly before me and wait till the first dawnings open little by little into the full light.

—Sir Isaac Newton

Science is the tool of the Western mind and with it more doors can be opened than with bare hands. It is part and parcel of our knowledge and obscures our insight only when it holds that the understanding given by it is the only kind there is.

—Carl Jung

All of us are watchers—of television, of time clocks, of traffic on the freeway—but few are observers. Everyone is looking, not many are seeing.

—Peter M. Leschak

We are at a critical juncture where there is a rapidly growing need in the technology and science work force, and we cannot afford to waste anybody. Women's and girls' experience is needed to contribute to the development of these fields.

—Linda Basch, Executive Director,
National Council on Research for Women

## What Is Science?

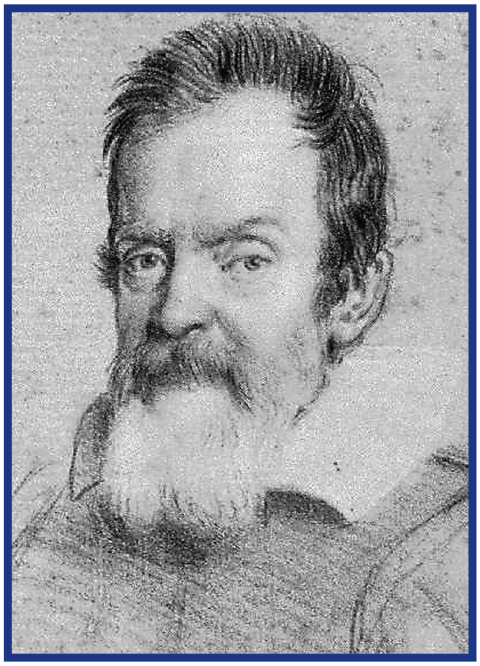
The quotes above paint varied pictures of what science is: a collected body of facts and knowledge for explaining the natural world; a systematic and orderly way of thinking and problem solving; a counterpoint to other ways of knowing, such as religion or historical thinking; or a cultural frame of reference that guides much of modern Western philosophy and thought. What, then, is science?

The *Oxford English Dictionary* (1998) defines science as "those branches of study that relate to the phenomena of the material universe and their laws." Dictionary definitions, however, do not give us a conceptual understanding of the culturally and historically rich enterprise that is science. Science is much more than definitions: science is an integral part of our daily lives. In modern society, it surrounds us in everything we do. This has not always been the case for human beings, nor is it equally the case for all people around the world. Science, as we generally think about it, has existed for only several thousand years—a tiny fraction of the history of humankind.

Modern Western science is an even more recent newcomer, originating in the late Renaissance and Early Modern period (roughly 1550–1700). Beginning with the work of the Italian scientist Galileo (1564–1642; see Image 1.2), and continuing with the discoveries of the Englishmen Sir Francis Bacon (1561–1626; see Image 1.1) and Sir Isaac Newton (1642–1727; see Image 1.3 on page 8), a new way of looking at the world emerged. It was an approach based upon systematic observations and **measurements** that could then codified into a series of rules and principles. These principles gradually came to be divided into distinct disciplines such as physics, chemistry, biology, and Earth and space science. Each discipline has grown and evolved in its own way, developing its own rules, codes, and methods and even sub-dividing into discrete subdisciplines (e.g., molecular biology and organismal biology), yet always remaining part of a larger identifiable whole that is science.

SOURCE: Wikimedia Commons (http://commons.wikimedia.org/wiki/Image:Francis_Bacon.jpg).

**Image 1.1 Sir Francis Bacon (1561–1626)**



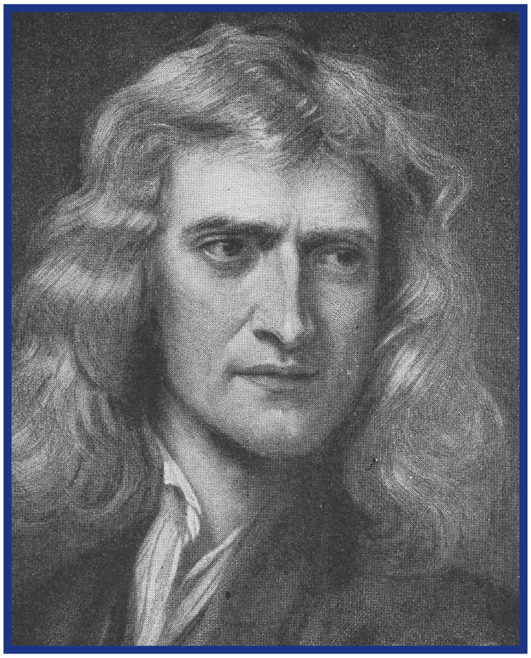
SOURCE: Wikipedia (http://en.wikipedia.org/wiki/Image:Galileo.jpg).

**Image 1.2 Galileo (1564–1642)**

Prior to the rise of modern Western science (i.e., before about 1550), much that we now think of as science was considered to be magic. The science fiction writer Arthur C. Clarke (1985) has commented that "any sufficiently advanced technology is indistinguishable from magic" (p. iv). In Mark Twain's novel *A Connecticut Yankee in King Arthur's Court,* a man born in the late nineteenth century is transported back to the Middle Ages. Even with a limited scientific knowledge, he appears to his medieval hosts to be a magician or wizard.

As a new elementary or middle school teacher, you probably do not have an extensive background in the natural sciences. If you are typical of most college students, you've studied general science and biology, and probably some chemistry and physics, in high school. You have fulfilled your college general science requirement of two or three unrelated science courses as part of your college's general studies program. Science is probably not something you spend a lot of time thinking about, and its applications in your daily life are something you largely take for granted.

Why should science, and more to the point of this book, learning to teach science well, be of interest to you? The answer lies, at least in part, in the degree to which science shapes the world in which we live. Think for a moment about the extent to which your life differs from life just 100 years ago. To begin with, 100 years ago your life expectancy would have been much shorter, probably only about 50 years (possibly far less, depending on the type of work you did). There is a high likelihood that you would have had multiple brothers or sisters, and that one or more of them would have died of natural causes before they reached adulthood. Diseases and illnesses that we take for



SOURCE: Painting by Godfrey Kneller, 1689 (Wikipedia, http://en.wikipedia.org/wiki/File:GodfreyKneller-IsaacNewton-1689.jpg).

**Image 1.3 Isaac Newton (1642–1727)**

granted as being manageable or curable today were fatal just 100 years ago. Polio, for example, killed and debilitated millions until the mid-1950s when Jonas Salk (1914–1995) developed the first effective vaccine. Tuberculosis could be controlled only with the advent of antibiotics in the 1940s (and even today, in parts of the developing world where basic antibiotics can be difficult to come by, tuberculosis still kills two to three million people annually). One hundred years ago, appendicitis or pneumonia would most likely have proven fatal. For many readers of this book, the fact that you are alive today is most likely a direct result of scientific discoveries made in the past 100 years.

Today's highly efficient systems of transportation provide another example of how science has changed our world. Have you traveled on a vacation in the last year or two? Are you attending college or university away from home? Do you routinely travel hundreds of miles or more to visit family or friends? Modern transportation—such as airplanes and automobiles, both relatively recent marvels of science and technology—makes this possible (see Images 1.4, 1.5).

Look at how communication has been revolutionized in just the past decade. Ten years ago, cellular telephones were a novelty item, large and clunky devices of limited range and utility carried by "techno-geeks" and the occasional electrician and telephone repair-person. Today, cell phones are a ubiquitous accessory, carried by nearly every adolescent and adult in the

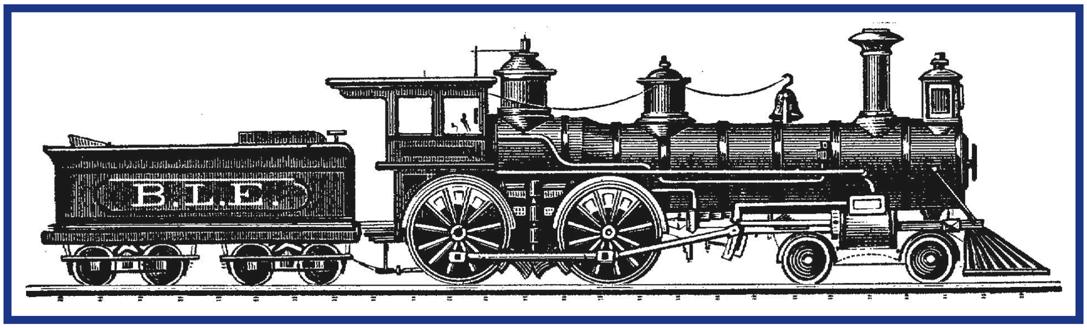
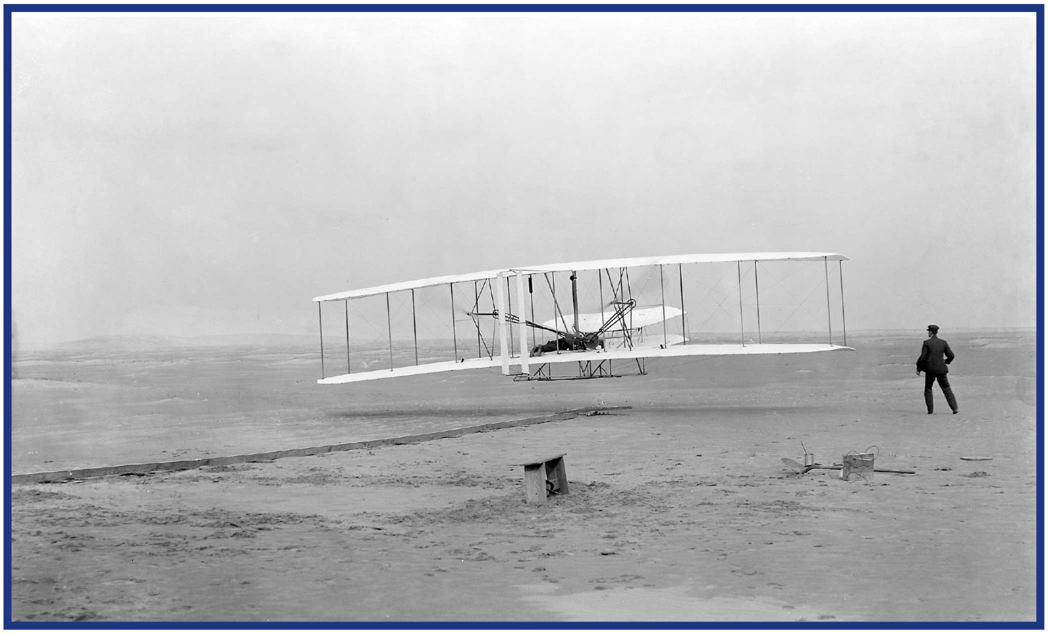



**Image 1.4 Steam-Powered Train**

Think how different life was 100 years ago when steam-powered trains were a prominent means of transportation.



SOURCE: Photograph by John T. Daniels courtesy of the Library of Congress.

**Image 1.5 The Wright Brothers' Aeroplane**
The first powered flight was made on December 17, 1903. Think how the world has changed as a result of the scientific discovery of flight.

developed world (see Image 1.6). iPods have revolutionized the way we discover and listen to music, and e-mail and social networking websites such as Facebook and Twitter are changing the way we keep in touch with friends and family. You are probably well aware of the technology that you use—especially the latest gadgets that you do not yet possess but hope to own soon. You are probably much less aware of the science that underlies this technology.

SOURCE: Photograph by Jean-Marie Buxton.

**Image 1.6 Cell Phone**
Think how access to cell phone technology has changed the life of children as well as adults.

We often underestimate how science and technology, even in their most simple forms, have profoundly shaped our society and culture. We frequently take these results for granted, rather like the fish in the aquarium that does not think about the water in which it swims. Take, for example, the use of hay to feed farm animals. If you are like most people, you probably think that farmers have always used hay. But, in fact, the idea of cutting tall grass and drying and storing it so that domesticated animals could feed on it during the winter was not developed until the Middle Ages. As the physicist Freeman Dyson (1988) explains,

> Nobody knows who invented hay, the idea of cutting grass in the autumn and storing it in large enough quantities to keep horses and cows alive through the winter. All we know is that the technology of hay was unknown to the Roman Empire but was known to every village of medieval Europe. Like many other crucially important technologies, hay emerged anonymously during the so-called Dark Ages. (p. 135)

So, you might say to yourself, why is the discovery of hay so important? Is it possible that its discovery could have had political and social ramifications? That it may have reshaped modern European history and the rise of countries such as Germany, France, and England?

> According to the Hay Theory of History, the invention of hay was the decisive event which moved the center of gravity of urban civilization from the Mediterranean basin to Northern and Western Europe. The Roman Empire did not need hay because in a Mediterranean climate the grass grows well enough in winter for animals to graze. North of the Alps, great cities, dependent on horses and oxen for motive power, could not exist without hay. So it was hay that allowed populations to grow and civilizations to flourish among the forests of Northern Europe. Hay moved the greatness of Rome to Paris and London, and later to Berlin and Moscow and New York. (Dyson, 1988, p. 136)

The discovery of hay as a source of feed for domesticated animals such as horses and cows represents a discovery that profoundly reshaped history. Another seemingly simple discovery that changed European history was the saddle stirrup. First introduced into Europe from Asia during the twelfth century, the stirrup made it possible for knights to ride armored horses without falling off (see Image 1.7). As a result, a new type of warfare was introduced into European culture, in which highly skilled military troops were trained with sophisticated weapons (lances, armor, etc.). The warriors who fought using this new technology required extensive training and a great deal of money to stay active in the field. Social systems involving a noble class, special privileges, and taxation evolved, which redefined the social and political direction of European culture. Without the stirrup, there would not have been knighthood as we know it, and the **evolution** of the social systems of countries such as England, France, and Germany would probably have taken profoundly different directions (White, 1962).

Of course, the wonders of science and its "advances" also cause complications, ethical dilemmas, and sometimes tragedy. Until you owned a car, you likely did not have to worry about paying for gas or insurance. Cell phones will soon be required to contain a global positioning system (GPS) locator, which will allow others to follow your every move. If you are worrying about finding a lost child who is carrying a cell phone, this might be a good thing. But what if you are, for example, a celebrity who is being tracked by a stalker, or simply a citizen whom the government wants to keep an eye on? "Big Brother," in George Orwell's nightmare dystopia *1984,* immediately comes to mind.

SOURCE: Etching by Albrecht Dürer, 1513.

**Image 1.7 Knight, Death, and Devil**

Since the atom bomb was dropped on Hiroshima on August 8, 1945, we have lived under the threat of nuclear annihilation. Every terrorist bombing that takes place around the world is made possible through science, as was the horrific destruction of the World Trade Center buildings on September 11, 2001. As a result of the power that comes from access to scientific and technological knowledge, human beings are now able to destroy the world in which we live (see Image 1.8). As General Omar Bradley (1893–1981) once claimed, "The world has achieved brilliance without conscience. Ours is a world of nuclear giants and ethical infants." Still, this surely does not mean that humankind would be better off without science and technology, only that it is imperative that we be thoughtful about how we use this extraordinarily powerful knowledge.

Taking all of this into account, it is imperative that we, as citizens and teachers, have a clear understanding of the role of science in our lives. Equally important is the ability to communicate this understanding to the students whom we teach. One of the things we would like to emphasize in this textbook is that teaching science is not just about teaching a body of facts, skills, and processes but must also be about teaching the next generation to think about and reflect on the impact that science has on our lives, our work, and our society.

SOURCE: From the National Archives and Records Administration, Records of the Office of the Chief Signal Officer.

**Image 1.8 Nuclear Test, Las Vegas, Nevada, November 1, 1951**

Troops of the Battalion Combat Team, U.S. Army 11th Airborne Division, watch a plume of radioactive smoke rise after a D-Day blast at Yucca Flats.

## Theory Into Practice 1.1

### Nature of Science Cards

As we continue to consider what science is, it may be valuable to pause and reflect upon your own beliefs about science. The following statements represent a variety of perspectives on scientific inquiry and the values and ideas that underlie it. Alternatively, your instructor may have created a set of cards containing these or other statements about science. The procedures for the activity are as follows:

1. Select four science statements with which you agree, or you may be given four random cards:
   - "Only science can tell us what is really true about the world."
   - "Science is fundamentally responsible for most of our modern woes."
   - "Science is a powerful tool for understanding the natural world."

- "Science and religion are fundamentally at odds."
- "Scientific progress has made possible some of the best things in life and some of the worst."
- "Scientists should have much greater influence in government."
- "Scientific knowledge is of much greater value than any other type of knowledge."
- "Science is always changing and therefore is not very reliable."
- "The scientific methods should be followed in all fields of study."
- "Science is one of several valuable ways of knowing."
- "Science and technology always operate in somebody's interest and serve someone or some groups of people."
- "Science begins with observations, which lead to generalizations."
- "Science and technology are two sides of the same coin."
- "Unless an idea is testable it is of little or no use."
- "Good science cannot be done without good theories."
- "Observation is central to all of science."
- "There is no one scientific method."
- "Theories serve to give direction to observations, that is, they tell a person where to look."
- "Facts do not speak for themselves; they must be interpreted by theory."
- "The destruction of nature is often done in the name of scientific progress."
- "The predominance of men in the sciences has led to bias in the choice and definition of the problems scientists have addressed."
- "A scientist should not allow preconceived theoretical ideas to influence observation and experimentation."
- "Money spent on projects such as NASA space flights would be better spent on health care for the needy."
- "If theory without observation is empty, then observation without theory is blind."
- "Scientific knowledge is always objective and self-correcting."
- "Scientific facts are manufactured through social negotiations."
- "Formal and informal networking among scientists is crucial for the success of scientific research."
- "Before beginning an experiment, a scientist should have an expectation of what will happen."
- "Seeing is believing."
- "Women and minorities are underrepresented in science because they have not been treated in the same encouraging ways as have white men."

2. Find a partner (who has also selected four statements or been given four cards) and discuss your statements and why you selected them (i.e., why do you agree with these statements?).
3. Together, select the four statements that both of you can best agree upon (discard the remaining four statements—note that you may have duplicates).
4. With your partner, find another pair of students who have also completed Step 3 and, as a group of four, discuss the eight science statements you have selected.
5. Together, select the four statements that the four of you can best agree upon (discard the remaining four statements).
6. Collectively, write a paragraph titled "What we believe about science." Be sure to include in some way the four statements that you agreed upon. Share this paragraph with the rest of your class, looking for similarities and differences between the various groups' paragraphs.

## What Science Is Not

We have already stated that science is only one possible way of knowing or understanding the world. Science is a rule-bound system guided by specific procedures and checks. Science does not, for example, generally move forward by faith. A scientist may have faith in her ideas, may believe in what she is doing, or may have a hunch about how to proceed, but when doing science, faith alone is not sufficient. The procedures, methods, and reasoning of a scientist must be transparent so that other scientists can subject them to peer review and possible replication. This is not necessarily the case for other ways of knowing. The current cultural debates about whether "intelligent design" should be taught in the science classroom as an alternative to evolutionary theory provides a clear example of this distinction. While many aspects of evolutionary theory can be tested, peer-reviewed, and refined over time, intelligent design must be accepted or rejected primarily on faith. This is not to say that science is a "better" way of knowing than faith-based knowledge, only that there are clear qualities of scientific knowledge that define the boundaries of scientific thinking. When it comes to what is taught in science class, however, it is important to understand this distinction between scientific theory and other ways of knowing. The scientific theory of evolution is one of the fundamental unifying ideas for understanding the diversity of life on Earth. The **scientific** theory of evolution is fundamental not only to the study of biology, but also to the study of geology, astronomy, and to the study of the other scientific disciplines as well. In order to be scientifically literate, students in our schools must be provided with the opportunity to learn what the theory of evolution does and does *not* explain. There are several main points that are often sources of confusion in the public debates on this topic.

1. *The Nature of Scientific Theory*. While in the common vernacular a theory is often considered synonymous with a guess or hunch, **in science** a theory has a more specific meaning. A **scientific** theory must be grounded both in well-established principles and in consistent, repeatable observation and empirical data. Theories are not absolute. They can be and are modified and/or replaced over time by other theories that better fit empirical data and principles. For example, plate tectonics and relativity are currently accepted theories that largely replaced prior theories of plate movement and the nature of time and space, respectively. This does *not* mean, however, that all theories are equally valid or that any possible alternative explanation of natural phenomena should be elevated to the status of **scientific** theory. Scientific theories are modified or replaced only after prolonged scientific debate and interpretation of empirical evidence.

2. *The Nature of Evolution*. Evolution is a broad and multifaceted theory that is used to explain changes in the natural world that have taken place over time. The idea that current life forms have evolved from earlier forms, including the idea that modern *Homo sapiens* has evolved from earlier species of hominids, is just one part of the larger theory of evolution, and is sometimes referred to as descent with modification or evolution through natural selection. Evolution also provides a theoretical framework

for explaining observations and other empirical data on the formation and changes of galaxies, stars, planets, topography, and geography as well as changes in life forms. Convergent and abundant evidence for the nature of these changes can be drawn from a wide range of scientific disciplines including: astrophysics, structural geology, paleontology, biochemistry, molecular biology, organismal biology, and physical and cultural anthropology. Thus, evolution serves as one of the key unifying concepts in science (along with other unifying concepts such as energy flow and systems). As such, an understanding of the theory of evolution, the evidence that supports it, and the questions that remain, such as the processes and mechanisms that have produced some of these changes, must be essential parts of any rigorous program of science education.

3. *Creationism and Intelligent Design.* Science, as a way of knowing, intentionally limits its scope to attempts to understand the natural world based on observable or otherwise empirically measurable data. Science makes no attempt to support or refute claims based on faith, religion, or the supernatural such as found in creationism and intelligent design. Many scientists, both past and present, have held deep religious or spiritual beliefs; they have found ways to reconcile those beliefs with their scientific practice so as to avoid jeopardizing either their faith or the quality of their scientific endeavors. Generally, they accomplished this by keeping these two ways of knowing distinct and separate. Similarly, science education in public schools should not engage in the comparison of fundamentally different ways of knowing. Thus, it is not appropriate to devote **science** class time to interpretations of the natural world that are grounded in non-science ways of knowing. Ideas such as creationism and intelligent design do not meet the definition of **scientific** theory as outlined in Point 1, above. As such, these ideas should not be topics of discussion in the science classroom.

Science is also not about magic. Magic proposes that there are supernatural forces at work in the world and that phenomena can take place or things can be transformed through processes that defy natural explanation. While some science and technology may seem, at first, to be like magic, in the end it must withstand the scrutiny and the explanatory power of natural laws.

Science and magic are often confused and have, at times, even overlapped. In chemistry, for example, many of the physical transformations that early alchemists tried to perform became the foundation for chemical discoveries. Many early scientific discoveries were made by people who were trying to practice what would today be considered magic, rather than science.

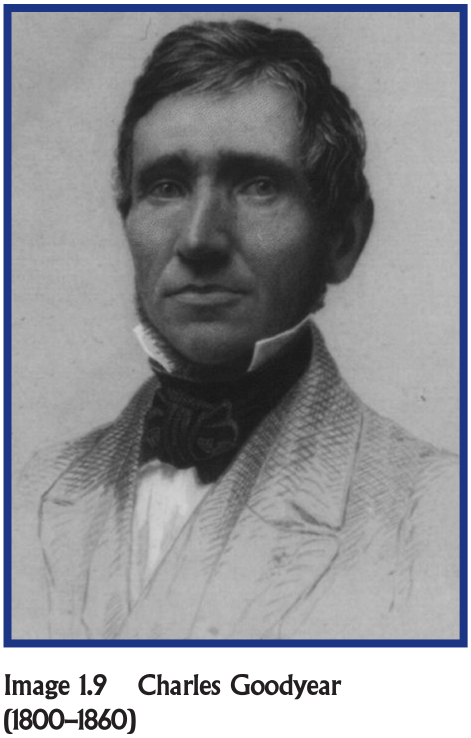
An example is the German alchemist Hennig Brandt (unknown–1692) and his discovery of the **element** phosphorus. Brandt wanted to see whether he could create gold from other, less valuable elements found in nature. He reasoned that because urine from animals—including humans—was gold colored, it would be possible to extract the precious element from it. After collecting large amounts of urine in tubs, he let the urine set until it became a dry paste. Although the dried urine did not contain any gold, it did have an unusual property: It glowed in the dark! The dry paste contained concentrated amounts of the element phosphorus.

It was soon discovered that phosphorus had other properties as well. When exposed to the air, white phosphorus would spontaneously burst into flame. The accidental discovery of phosphorous by an alchemist eventually led to other scientific and practical discoveries, including the invention of the safety match in 1855 by the Swedish inventor John Lundstrom (1815–1888).

Again, we wish to emphasize that although science is a powerful and useful way of knowing, it is not necessarily the best or the only way to understand the world. Historical, theological, aesthetic, intuitive, and other ways of knowing frequently help people to make sense of the world around them. When it comes to explaining causal relationships involving natural phenomena, however, it is generally agreed that scientific methods are the most reliable way of knowing.

## How Science Is Done

We have discussed what science is and what it is not. Now let us turn to the question of how science is done. Scientific inquiry is a process of trying to explain observations made of the natural world around us. There are certain rules involved in this process, including the generation of theory (explanatory hypotheses or predictions), the collection of data through observation and/or measurement, and the analysis and interpretation of those data in an attempt to answer an initial question (other common qualities of scientific inquiry are discussed in more detail under "Qualities of Scientific Inquiry," below). Still, the widely held belief that there is one uniform "Scientific Method" that all scientists use is largely a misconception (or at the very least, a vast oversimplification). As was mentioned earlier, science sometimes advances in part through taking leaps of faith, and sometimes discovery is even the result of pure accident. The vulcanization of rubber, for example, is an essential technology we make use of whenever we drive a car, take off or land in an airplane, or go on a bike ride. Like the discovery of phosphorus by Brandt hundreds of years earlier, the discovery of vulcanized rubber by Charles Goodyear (1800–1860; see Image 1.9) in 1839 was largely an accident.



SOURCE: Engraving by W. G. Jackman courtesy of the Library of Congress.

**Image 1.9 Charles Goodyear (1800–1860)**

Goodyear was trying to find a way to take raw rubber from a rubber tree and turn it into a shock-absorbing covering for the metal wheels that were common on wagons and other wheeled vehicles of the day. Unfortunately, the raw rubber in its unprocessed state was not sufficiently durable to make a good tire. It would quickly wear out and fall apart. Goodyear set about experimenting by mixing the rubber with various chemicals but repeatedly met with failure until he accidentally discovered the solution when he dropped a piece of raw rubber onto a hot stovetop. He "discovered" that by subjecting the rubber to a high **temperature**, he achieved the increased durability he was looking for through a process he came to describe as "vulcanization." What does this anecdote say to us about the process of scientific inquiry? It suggests that scientific discovery is not always (in fact, is rarely) a straightforward, linear process. Scientific inquiry is full of false starts and dead ends. It also can involve luck. However, scientific discoveries, even when made "accidentally," are almost always part of a process of systematic inquiry in which a scientist or group of scientists literally kept their eyes open for new results. As the great French scientist Louis Pasteur put it, "in the field of observation, chance favors only the prepared mind."

Even dreams have sometimes played a role in new scientific discoveries, as can be seen in the case of the benzene ring. Benzene is an industrial solvent used in the production of many plastics; it was discovered in 1825 by the British chemist Michael Faraday, who isolated it from oil gas. The formula of benzene ($C_6H_6$), however, was a mystery for some time after its discovery. Molecular structures were long believed to be linear in nature, a "fact" that could not explain many properties of benzene, nor account for all of its bonds (carbon usually forms four single bonds and hydrogen one).

In one of the most famous instances of dream-discovery, the German chemist Till Kekulé (1829–1896) deduced the ring structure of benzene while sleeping. He described this experience to a meeting of scientists as follows:

> I turned my chair toward the fire place and sank into a doze. Again the atoms were flitting before my eyes. Smaller groups now kept modestly in the background. My mind's eye, sharpened by repeated visions of a similar sort, now distinguished larger structures of varying forms. Long rows frequently rose together, all in movement, winding and turning like serpents; and see! What was that? One of the serpents seized its own tail and the form whirled mockingly before my eyes. I came awake like a flash of lightning. This time also I spent the remainder of the night working out the consequences of the hypothesis. (Von Baeyer, 1989)

Still, as Nobel Prize–winning physicist Richard Feynman (1918–1988) has noted, the scientific community has developed certain ingrained cultural norms that serve to at least partially obscure these "messy" and nonlinear aspects of the scientific process of discovery. In his 1966 Nobel lecture, Feynman claimed,

> We have a habit in writing articles published in scientific journals to make the work as finished as possible, to cover up all the tracks, to not worry about the blind alleys or describe how you had the wrong idea at first, and so on. So there isn't any place to publish, in a dignified manner, what you actually did in order to get on with the work.

Different scientific disciplines also have different norms for conducting inquiry and different limitations on what kinds of experimentation are possible. Some branches of science, such as geology and **astronomy**, are not conducive to controlled experiments. One cannot, for example, change the way a star or a planet behaves to study the result; one can only observe what happens under various conditions that already exist in nature. The early twentieth-century American astronomer Annie Jump Cannon (1863–1941; see Image 1.10) spent 30 years at the Harvard College Observatory **classifying** more than 500,000 stars and creating a catalog of stars that is still used in attempts to understand stellar evolution. Throughout all this work, Cannon never once carried out a true experiment or followed the "scientific method" as it is taught in most science classes.

Still, there are a number of procedural and conceptual activities that are frequently practiced during a scientific investigation: asking questions; hypothesizing; designing experiments; making predictions; using apparatus; observing; measuring; evaluating **accuracy**, prediction, and error; recording and interpreting data; consulting data records; evaluating evidence; verifying evidence; reacting to contradictory or anomalous data; coordinating theory and evidence; performing statistical calculations; and formulating and revising models and theories. While no scientist practices all of these activities during any single experiment, every scientist routinely engages in a variety of these practices. For the purpose of doing science with elementary and middle grade students, we have simplified and condensed these practices into more general qualities of scientific inquiry that we present in the next two sections of the chapter.

SOURCE: Courtesy of NASA.

**Image 1.10 Annie Jump Cannon (1863–1941)**

## Theory Into Practice 1.2

### Hidden Shapes

The following activity is meant to demonstrate how scientific practice often includes a combination of observation and inference.

1. Cut two sets of shapes out of colored paper—one set of regular geometric shapes (circle, square, triangle, and rectangle) and one set of irregular shapes that resemble regular shapes but have missing or additional pieces (see Image 1.11 below for examples).
2. Glue these figures in sets onto pieces of plain white paper.
3. Take two manila office folders and cut or punch numerous small holes in one side and then tape closed two of the three open sides of the folder.
4. Slide the paper with the colored shapes into the folder so that small pieces of the shapes are revealed through the holes.
5. Give each folder to a group of three to five students and ask them to draw a picture of what is on the paper inside the folder using only the information they can observe through the holes (i.e., they cannot remove the paper from the folder).
6. It is likely that based on what they can see, both groups will draw regular geometric shapes because humans naturally seek pattern and order (whether it is there or not).
7. When both groups are done, tell them they can remove the sheet from the folder and compare what they have drawn with what is actually there.

This activity can be used to discuss how scientists often must try to explain phenomena based on only partial information or observation as well as how nature often, but not always, seems to adhere to regular patterns (a topic discussed further in the following section).

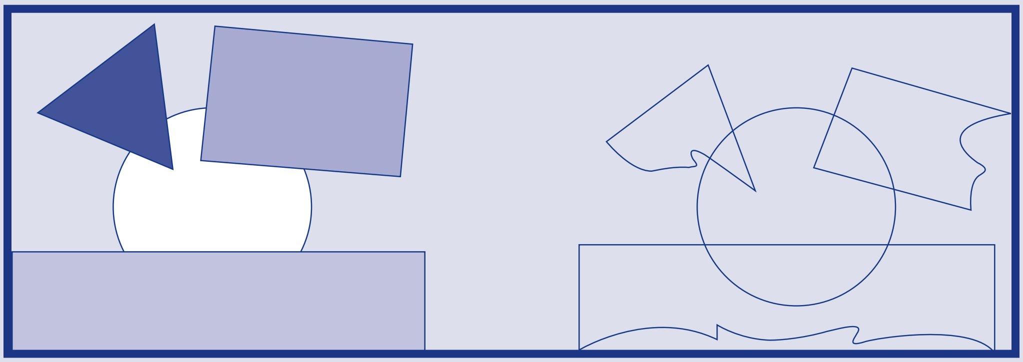


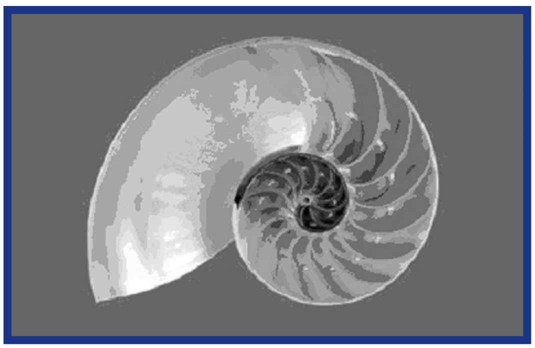
**Image 1.11 Regular and Irregular Hidden Shapes**
The group with the irregular shapes is likely to feel "tricked."

## Patterns That Connect

Our philosophy is that science needs to be understood not just in isolation, but also in its connection to other things. Thus, an invention like the automobile needs to be understood not only in terms of how it functions mechanically, but how it is connected to other things in the world. Think for a moment about how our cities have developed as a result of the invention of the automobile just a little more than 100 years ago. How would they be designed differently if the car had never been invented? What would have been emphasized or omitted? To begin with, our cities would not have superhighways passing through them, gas stations on nearly every major corner, or stoplights. Houses and businesses would need to be designed to be within walking distance of each other, instead of driving distance. On a larger scale, the invention of the automobile has necessitated the importation of oil from foreign countries, involving not only new technologies of exploration, refining, and transportation, but also political negotiations and alliances that probably would not otherwise exist. The invention of the automobile has also led to the increased emission of pollutants into the atmosphere, contributing to the **greenhouse effect** and the warming of the Earth's atmosphere.

As we can see in the example above, understanding the relationship between science and the larger world is an extremely complicated process. The British anthropologist and social theorist Gregory Bateson (1904–1980) provides some insight into how we might think about these relationships. In his book *Mind and Nature,* Bateson (1980) argues that our educational system provides almost no training for the crucial issues we must confront in our lives—what he refers to as "the pattern which connects." He asks, for example, why do our schools so rarely address questions related to social thinking and relationships between seemingly disparate ideas? According to Bateson, if you "break the pattern which connects the items of learning . . . you necessarily destroy all quality." Science can help us to see the patterns in the world around us and to understand our place in it as human beings. But this will only be the case when we teach science in ways that highlight these connections.

Think for a moment about the shape of a chambered nautilus seashell (see Image 1.12). How is it connected to the spiral shape of a galaxy (see Image 1.13)? Are the two related? Did you know that chambered nautiluses and spiral galaxies both conform to the mathematical and architectural ratio known as the Golden Mean? Did you know that the Golden Mean Proportion exists throughout nature? It appears in organic and inorganic **matter**, in the structure of the human body, in the growth patterns of plants and animals, and even in viruses and **DNA**. Did you know that mathematically the pattern of a chambered nautilus or a spiral galaxy is actually a Fibonaccian sequence? The Fibonaccian sequence is a number



SOURCE: Engraving by W. G. Jackman courtesy of the Library of Congress.

**Image 1.12 The Rigid Open Chambers Within a Chambered Nautilus (*Nautilus pompilius*)**

sequence dis-covered by the medieval mathematician Leonardo Fibonacci (1175–1250), in which the first two numbers in a series equals the third number in the same sequence (1, 1, 2, 3, 5, 8, 13, 21, 34 . . . ).

Look, for example, at the rectangle in Image 1.14. It is a Golden Section or Phi (the ratio of 1:1.6180339 . . . ) and is derived from a Fibonaccian sequence.

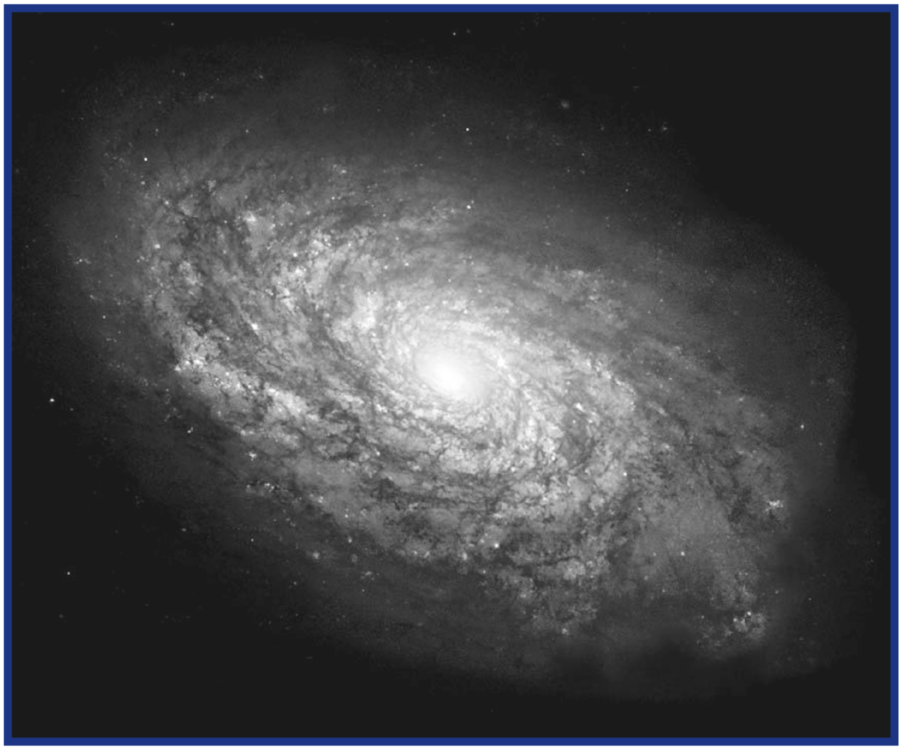


**Image 1.13 The Spiral Galaxy NGC 4414**

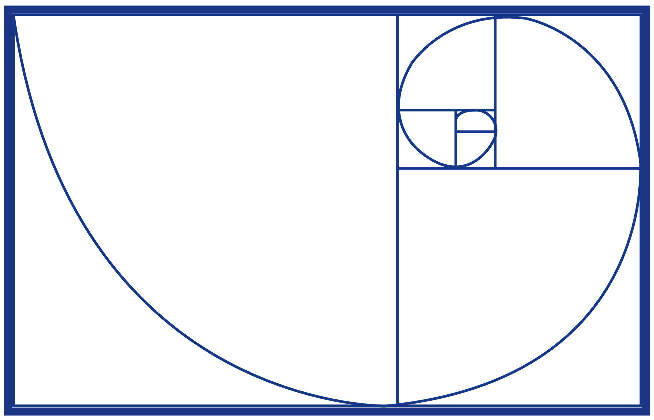


**Image 1.14 Golden Section**

Notice the pattern of squares that make up the rectangle in Image 1.14. What do you observe? Notice also that by drawing an arc across each square between its most distant ends, we create a spiral that is identical in shape to the spiral found in a chambered nautilus or spiral galaxy. Is this simply an incredible coincidence, or is it a "pattern that connects" of the type that Bateson is talking about? What about the shape of a sunflower or the branching of a tree? Did you know that these form Fibonaccian sequences too? Is it possible that there is some sort of scientific law or principle at work here?

## Qualities of Scientific Inquiry

As we have seen, much of the work of science is about discovering the patterns that exist in the natural world around us. But how do we make these discoveries? Scientific inquiry generally holds to certain qualities and practices that improve the likelihood of such discoveries.

### Replicability

If the same procedures are conducted under the same conditions, then the same results should be achieved. This is true for all branches of science. Thus, in billiards, if the cue ball strikes one of the bumpers at an angle of incidence of 45 degrees, then a person with some knowledge of **force** and motion would likely hypothesize that the ball will move off as a result of this collision at an angle of reflection also equal to 45 degrees (see Image 1.15). Whatever the result of the first trial, an interested observer would want to repeat the experiment several times to check the consistency of results. Suppose on the third trial the cue ball strikes the bumper but does not go off at the same angle after the collision. What might have happened? This brings us to a second quality of scientific inquiry: **control of variables**.

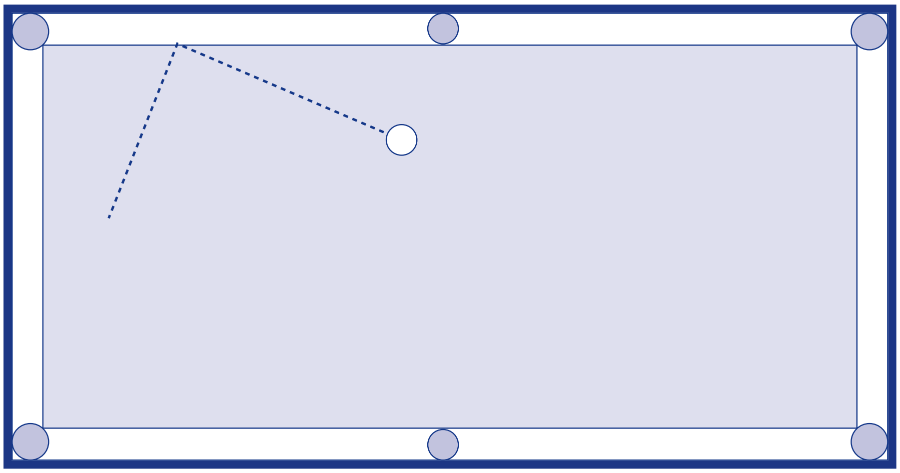


**Image 1.15 Billiard Ball Bouncing Off Bumper**

## Control of Variables

A variable is any factor that could change, intentionally or unintentionally, during the course of scientific inquiry. In the above example of the pool table, the observer's hypothesis—that the cue ball will move off at an angle equal to the angle at which the ball hit the bumper—is only likely to be correct if certain other variables are held constant. Thus, the hypothesis assumes that the table is level, that the surface of the table is smooth and clean, that the bumper is straight, and that the ball is hit evenly with the cue stick without applying significant spin. A scientist conducting an experiment tries to identify all possible variables that could change, control the ones that she can, and take into account those that she cannot control.

## Systematicity

The process of discovery by "messing around with things" is an important part of the creative process found in science as well as in art, literature, and other creative fields. It is an approach that is also consistent with constructivist models of learning based on the theoretical ideas of psychologists such as Jean Piaget (1896–1980) and Lev Vygotsky (1896–1934), scientists whose work has significantly influenced the field of education and whose ideas will be discussed in detail in Chapter 3. While such "messing around" may seem to be haphazard, when it comes to science, this process must be tempered by a certain degree of **systematicity**, or following a previously determined, systematic plan. An example can be found in the work of the well-known American inventor Thomas Edison (1847–1931).

Edison did not simply have brilliant ideas; he worked systematically on problems, trying every possible combination and permutation until he came up with a solution to the problem he was working on. Thus, his invention of the lightbulb was a systematic inquiry in which he tried literally hundreds of different burning filaments inside a **vacuum** chamber. He experimented with a vast range of different materials. One day, he went rummaging around in his wife's sewing basket and pulled out a thin strip of bamboo. He carbonized (burned) it and placed it inside the vacuum flask. The carbon filament of bamboo provided a bright and long-lasting glow, setting Edison on the path that led to the invention of an affordable, commercially available lightbulb. This invention, one that revolutionized the way modern humans live and work, would not have come about were it not for Edison's systematic approach to scientific inquiry.

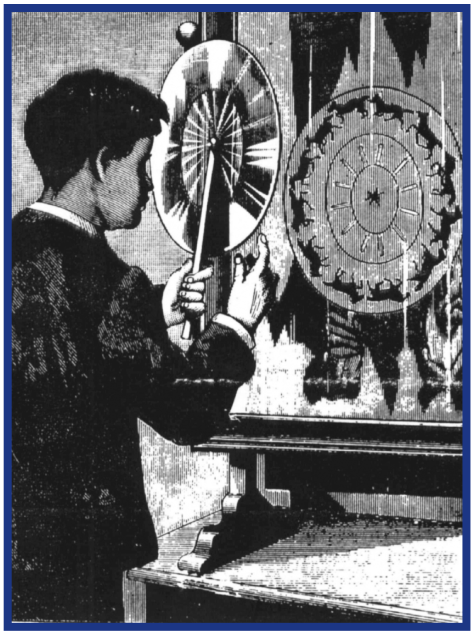
## Communication

Scientific discovery also relies on a continual process of **communication** within the scientific community so that its members can build upon the work of others. Today, such communication is greatly facilitated by technologies such as e-mail, videoconferencing, and air travel. Even hundreds of years ago, however, communication of ideas played a central role in science. In the early nineteenth century, for example, Michael Faraday (1791–1867) had a clear understanding of the electrical experiments that had been conducted previously by people such as Benjamin Franklin (1706–1790), Alessandro Volta (1745–1827), and Antoine Lavoisier (1743–1794). Because they had published their work in detail, Faraday was able to build on their ideas to develop his understanding of electromagnetic properties and to build the first functioning electrical motor.

In our own era, scientific communication has played a critical role in many significant discoveries. The identification and isolation of the AIDS virus in the early 1980s was a direct result of thousands of scientists around the world researching a new and confusing disease, then communicating with each other about what they were finding and eventually identifying its culprit virus. In fact, credit for the final identification of the AIDS virus has been given to two separate scientific labs, one in France (L'Institut Pasteur) and one in the United States (U.S. National Cancer Institute), for their simultaneous work on the disease.

## Creativity

Another important quality of scientific inquiry is **creativity**. An example is the ability to bring things that seem dissimilar or unrelated together in new ways. Scientific inventions frequently result from the integration and refinement of different prior discoveries. One specific example is the invention of the motion picture. The scientific precursor to motion pictures dates back to 1826 and the work of British scientist John Ayrton Paris (1785–1856). Paris was interested in the physiology of the eye. He invented a device called the thaumatrope ("wonder turner" in Greek) to demonstrate the phenomenon of persistence of vision (see Experiment 94 in Chapter 9).



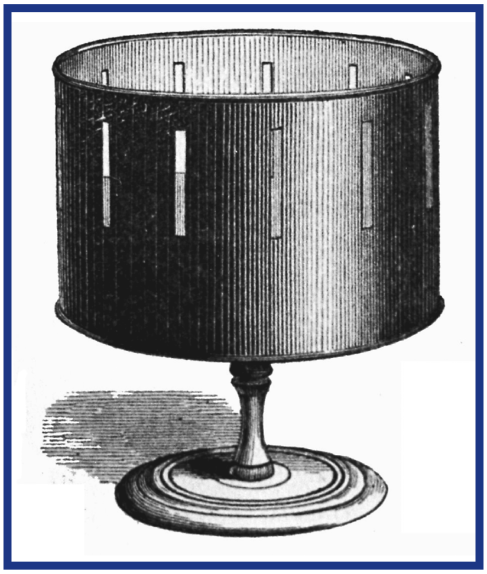
SOURCE: "Phantascope" (1881).

**Image 1.16 A Phantascope**

The thaumatrope then gave rise to the phantascope, a spinning wheel on a handle containing equally spaced vertical slits on one side and a set of sequential pictures (such as a horse galloping) on the other side (see Image 1.16). When this device is put in front of a mirror and spun, the viewer perceives a single, moving picture.

From the phantascope was developed the zoetrope, which was an upright version of a phantascope consisting of a revolving drum with slits in the side through which a sequential picture could be viewed (see Image 1.17).

The zoetrope was then modified so that a light was projected through it and a lens focused the image—essentially, a primitive projector. Modern movies became possible when movement was recorded at high speed on strips of acetate film and then run through a projection device, replicating the principles of the primitive zoetrope projector.



SOURCE: Erle (1884).

Image 1.17 A Zoetrope

While some scientific discoveries create something completely new, like motion pictures, other discoveries evolve from a scientist's desire to improve upon an old idea. Perhaps you have played with a SuperBall—a rubber ball that bounces higher than other balls. The SuperBall was invented by the chemist Norman Stingley in the early 1960s. He had been experimenting with compressing synthetic rubber for industrial uses and came up with a formula that was both resilient and capable of bouncing very high (three times higher than a normal rubber ball). He eventually took his invention to Wham-O, the toy company that manufactured the Frisbee and the Hula Hoop. Wham-O saw the SuperBall's terrific potential as a toy. Since the introduction of the SuperBall, over 20 million have been manufactured (see Experiment 85 in Chapter 9 for an experiment using SuperBalls).

### Informed Skepticism

While good scientists try always to be open to new ideas and new theories that might better explain natural phenomena, their enthusiasm must also be tempered by a sense of skepticism. Within the scientific community, acceptance of new theories is often a lengthy process. It is a process in which the proponents of the new theory attempt to provide evidence that their theory is better at explaining and/or **predicting** observations than other competing theories, as well as explaining how their theory fits in and connects with other existing theories. This process of verification and refutation may take years and can be highly contentious. In fact, the German physicist Max Plank (1858–1947) argued that "a new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it" (Kuhn, 1970, p. 17).

When taken together, these qualities of scientific inquiry—(1) **replicability**, (2) control of variables, (3) systematicity, (4) communication, (5) creativity, and (6) **informed skepticism**—create a productive framework for addressing questions about the physical and natural world, a topic we take up in the next section.

## Combining the Qualities of Scientific Inquiry to Address Scientific Questions

We can see how the six qualities of scientific inquiry work together by considering a pair of case studies—one historical and the other more current.

We draw the first example from the work of the pioneering epidemiologist John Snow (1813–1858). Snow, who was a London physician, became concerned about the many severe cholera epidemics that threatened London during the 1840s. As a physician, he was interested in the cause and transmission of the disease. In 1849, he published a short article, "On the Mode of Communication of Cholera," suggesting that cholera was a contagious disease caused by a poison that reproduced in the human body and was transmitted by water contaminated with this poison. This view was at odds with the commonly held theory that the disease was transmitted by the inhalation of disease-ridden vapors. His work was largely discounted until the next epidemic in 1854, at which point he set out to prove his theory. He began by systematically collecting data and tracing the location of the outbreak by mapping the home address of each person who died from the disease. When he looked at the map after collecting the data, it was very clear that there was a central geographical point around which the deaths had occurred.

Snow discovered that at the center of the neighborhood where the most deaths occurred was a water well that nearly all of the victims had used. He deduced that the well water was infected and responsible for transmitting the cholera. To test this hypothesis, Snow convinced the city officials to remove the handle from the pump to the well (the Broad Street well) to prevent people from using it. The epidemic quickly came under control. His hypothesis seemed to be confirmed. But Snow still needed to consider whether any other variables had affected the situation besides the removal of the pump handle.

Earlier in this chapter, we discussed Gregory Bateson's idea that science is ultimately about discovering the patterns that connect. Snow saw the pattern between the death of the people living around the Broad Street well and his earlier idea that cholera might be a water-borne disease. Snow's work represents scientific thinking at its best—working to discover the patterns that connect. Snow's example also shows how the qualities of scientific inquiry work together to help solve problems. In this case, Snow had to consider the control of variables, the need for systematicity, the clear communication of ideas, the value of thinking creatively, and the need for informed skepticism when considering the previously accepted theories of the spread of cholera.

A second, more recent example of how the qualities of scientific inquiry come together in our attempts to solve scientific problems can be seen in the case of cold fusion. In 1989, two chemists working at the University of Utah, Martin Fleischmann and Stanley Pons, claimed to have developed an apparatus for producing "cold fusion" in their lab. Cold fusion is the creation of a nuclear fusion reaction at relatively low temperatures—usually nuclear fusion requires temperatures similar to those found in the Sun. In effect, Fleischmann and Pons were claiming that they could now harness the power of the Sun without the dangers or the multi-billion dollar price tag of experiments with "hot fusion." Their announcement of this achievement was met at once by both excitement and informed skepticism within the scientific community. Fleischmann and Pons communicated their findings and their apparatus design to scientists at other institutions. In order to verify Fleischmann and Pons's findings, other groups of scientists attempted to replicate their work.

While several labs at first seemed to be getting positive results from their experiments, other labs were failing to find the expected amounts of either heat or nuclear **isotopes** that would prove that nuclear fusion was actually taking place. It gradually became clear that many of the supposedly positive results could be explained away by experimental errors. The results of Fleischmann and Pons's experiment were called into question. Eventually, the scientific community came to the conclusion that the two scientists had been in error. Cold fusion remains an elusive and theoretically questionable possibility. In this case, the scientific community used all of the qualities of scientific inquiry—replicability, control of variables, systematicity, communication, creativity, and informed skepticism—to question, test, and eventually reject the claims initially made by Fleischmann and Pons.

The case of cold fusion and many other cases of scientific discovery are not quite as clear-cut as they may seem on the surface. As historians of science Harry Collins and Trevor Pinch (1993) point out, using replicability to ascertain the existence of a phenomenon may be problematic when the phenomenon's existence is in doubt. If you are trying to detect something that you are not sure is there, does a negative result mean that, in fact, it is not there? Or, does it simply mean that you didn't use the "right" procedure or did not have a sensitive enough instrument? Thus, in the case of cold fusion, believers in the positive results obtained by Fleischmann and Pons could explain away the negative results of other groups as being due to faulty procedures or slight differences in the conditions under which the experiment was conducted (remember the earlier example of the slightly angled pool table bumper). True replicability means that everything is held exactly the same. This can be much more problematic than it first appears. In the case of the Fleischmann and Pons experiment, the University of Utah where the research was conducted is perched high in the Rocky Mountains. Potential replicators of the study at MIT, for example, were working at sea level. What if altitude made a critical difference in the results? Those who failed to find evidence of cold fusion, however, could just as easily argue that they found nothing because there was nothing to find and that it was Fleischmann and Pons who had been in error in their measurements. Thus, while the qualities of scientific inquiry may seem to be clear rules that govern scientific practice, in fact, they are more like guidelines that will vary depending on the situation and the questions being explored. Science is a rule-bound system, but it is also a human enterprise. The "rules" of nature may be absolute, but our growing understanding of those rules often requires negotiation.

## Theory Into Practice 1.3

### The Hypothesis Box

This activity is meant to model the so-called black-box effect that experimental scientists must sometimes contend with. Sometimes it is possible to control the starting conditions of an experiment and then, after some period of time, observe the outcome of the experiment without observing what took place between the starting point and the end point—what takes place in between is thus a "black box" that cannot be penetrated, and what takes place "inside" must be inferred.

1. Construct the box as per Image 1.18 using six funnels, coffee filters, rubber tubing (must be able to fit over the outflow of the funnels), and a large cardboard box.
2. Prepare the box in advance of its use by placing coffee filters in three of the four interior funnels and placing four or five drops of food coloring in the center of each of the coffee filters (a different color in each filter) and corking (or otherwise sealing) the outflow from the fourth of the interior funnels.
3. Tell the class that you are going to pour something into the top funnel of the hypothesis box several times and that after carefully observing the procedure, they will have to draw a diagram of what they believe is happening inside the box.
4. Be sure the hose from the top funnel is pointing into one of the four internal funnels. Ask for a student volunteer to hold a beaker under the bottom outflow tube, and pour several ounces of water into the top funnel—water of the first color should come out the bottom.
5. While the students are distracted observing the beaker of colored water, quietly turn the top funnel to the second position so that the tube is pointing toward the second color funnel.
6. Tell the class you are going to pour liquid in the top a second time and that they should observe closely. Have a second volunteer hold a second beaker under the outflow, and students should be quite surprised to see water of a different color come out.
7. While the students are distracted observing the second beaker of colored water, again quietly turn the top funnel to the third position. This should be the corked funnel, but could also be the third color. Repeat Step 6, but if it is the corked beaker, you should act surprised this time.
8. Repeat the above steps for the fourth position (either the third color or the stopped funnel).
9. Ask students to draw a diagram of what they believe the inside of the box looks like. Compare their diagrams, and finally, discuss how the box is like the way science sometimes works.
10. After the discussion, you can either show students the inside of the box right away or make the point that in science, the scientist doesn't always get the chance to "look into the box" right away and must sometimes move on with only partial information. Waiting at least until the next class period to show the class the inside of the box will make the activity more memorable for students and further emphasize the concept.

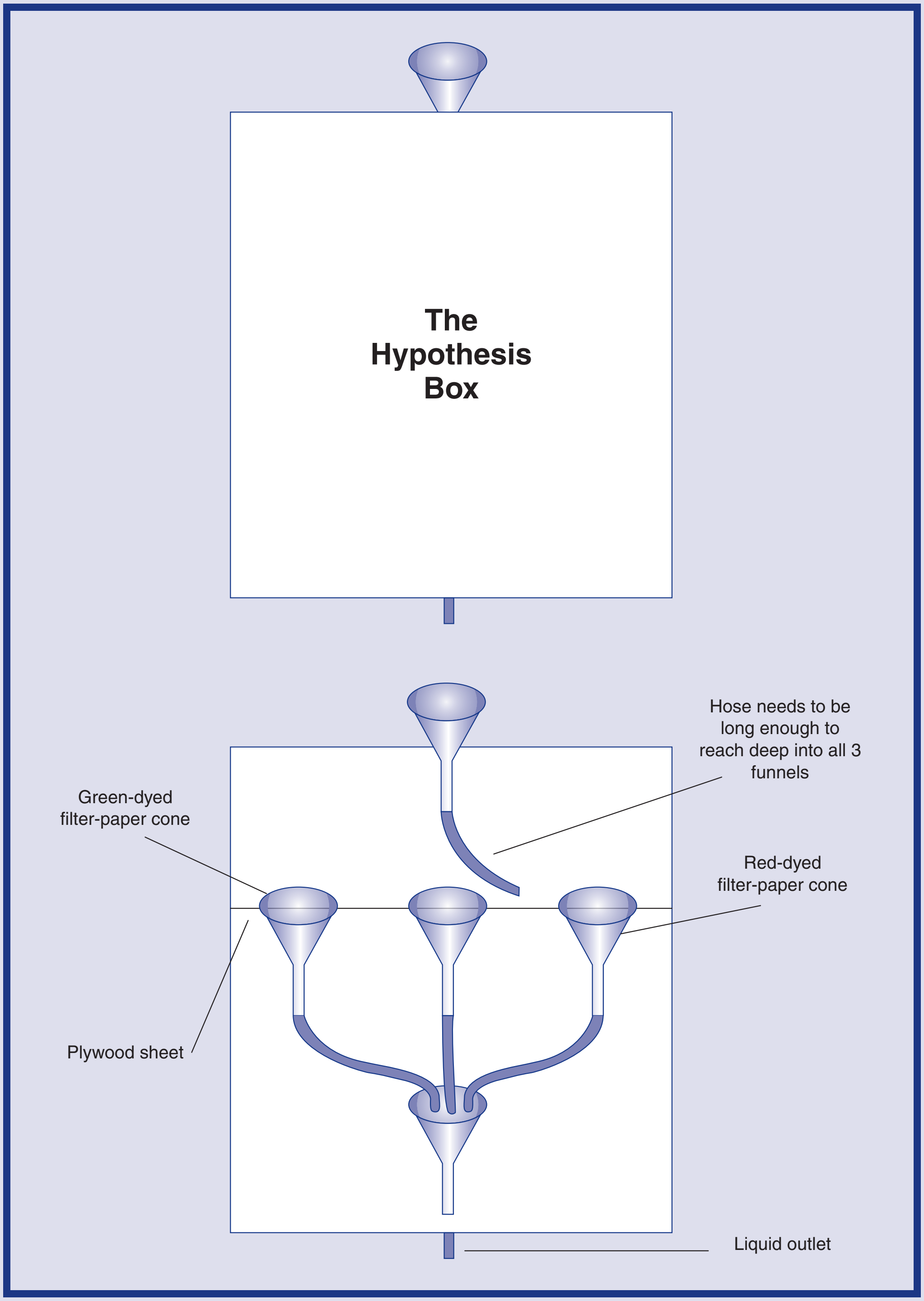



Image 1.18 Hypothesis Box: Internal and External Views

## Paradigms and Paradigm Shifts in the Nature of Science

Thus far, we have shown through stories and examples that science has a common core of ideals and practices that can be used to evaluate the quality of a given scientific inquiry, but that scientific practice also varies from discipline to discipline, with quality sometimes being determined by negotiated consensus within a given scientific community. A number of historical studies have contributed to our developing understanding of the nature of science, the two most famous of which are discussed below.

Sociologist Robert Merton (1910–2003) proposed four norms that he thought were the driving forces behind scientific progress: (1) **universalism**, the idea that scientific results should be analyzed objectively and be verifiable or repeatable, without regard to the scientist's personal or social attributes; (2) **communism**, the idea that science is a communal activity in that scientists share their work with their community for the common good; (3) **disinterestedness**, the idea that scientists should have no emotional or financial attachments to their work; and (4) **organized skepticism**, the idea that scientists should wait until "all the facts are in" before a judgment is made about a particular theory (Merton, 1973, p. 267). Despite being focused on an idealized account of science rather than on scientists' actual practice, Merton's norms became widely accepted as a description of how science was done and are still often referenced today.

Merton's somewhat idealistic view of science was later challenged by another sociologist named Michael Mulkay. Mulkay argued that Merton's vision of science was at least partially inaccurate, but that it was preserved in the scientific community because it helped scientists in three ways: (1) it raised scientists' social status; (2) it increased scientists' political power; and (3) it enhanced the status of scientific knowledge (Mulkay, 1979). Mulkay proposed that while Merton's norms can serve as guiding principles for scientific inquiry, there also exists a set of four "counter-norms" that can work against Merton's norms when scientists (as human beings) take actions to advance their professional careers. Science may generally be portrayed as an objective search for truth about the workings of the natural world, but scientists are people like any others, who can be driven by the same desires for fame, wealth, and power.

Finally, no discussion of the nature of science would be complete without considering the work of the historian of science Thomas Kuhn (1922–1996). In his now famous book, *The Structure of Scientific Revolutions* (1970), Kuhn explored actual cases from the history of science, making a number of claims that flew in the face of the conventional understandings of science practice. Kuhn's main thesis was that science does not build upon itself in a linear fashion, but rather that it builds gradually for a time through routine science practice and then takes revolutionary leaps in unexpected directions during episodes of **paradigm shifts**. Thus, all scientific understanding must be viewed as specific to a given historical period and paradigm, rather than considered "finished" achievements that will remain unchanged. Kuhn also pointed out that agreement, or consensus, within the scientific community is the key to validating new knowledge claims, and that the criteria used in reaching this consensus are based on shared values as well as reasoned judgment.

According to Kuhn (1970), during the early stages of any field of science, researchers interpret their observations in many different ways

(p. 17). After the initial stage of a field's development, however, these differences largely disappear as the field agrees upon a certain paradigm as the "correct" way to make sense of these observations. Kuhn also claimed that "to be accepted as a paradigm, a theory must seem better than its competitors, but it need not, and in fact never does, explain all the facts with which it can be confronted" (p. 17). At a future point, a new paradigm might be introduced that fundamentally changes the way the field explains and interprets these observations. Thus, scientific discovery often involves thinking about things in totally new ways. While it is important to look for patterns in science, it is also important to look for anomalies or things that do not agree with our assumptions.

Thus, the advancement of science is often based on breaking out of existing paradigms or models—in other words, thinking in new ways about things that are familiar. Some examples might help you understand the process a bit more clearly. There is a famous puzzle from the nineteenth century known as the "Columbus Egg Problem." Christopher Columbus is reported to have asked Queen Isabella of Spain how an egg could most easily be made to stand upright. The answer involves "thinking outside the box"—by hard-boiling the egg and then lightly breaking its bottom, just enough so that the egg stays put. You may think that this is cheating, but no one said that the egg couldn't be boiled or that the bottom of the egg couldn't be broken. (You may want to challenge your students with this puzzle some day, but be prepared to clean up some broken eggs!)

Another example of breaking out of traditional ways of thinking (paradigms) is the classic puzzle of "connect the dots." The puzzle asks the viewer to connect nine points in the form of a square using just four straight lines that cannot cross each other (see Image 1.19). See how long it takes you to do it (and remember to "think outside the box!").

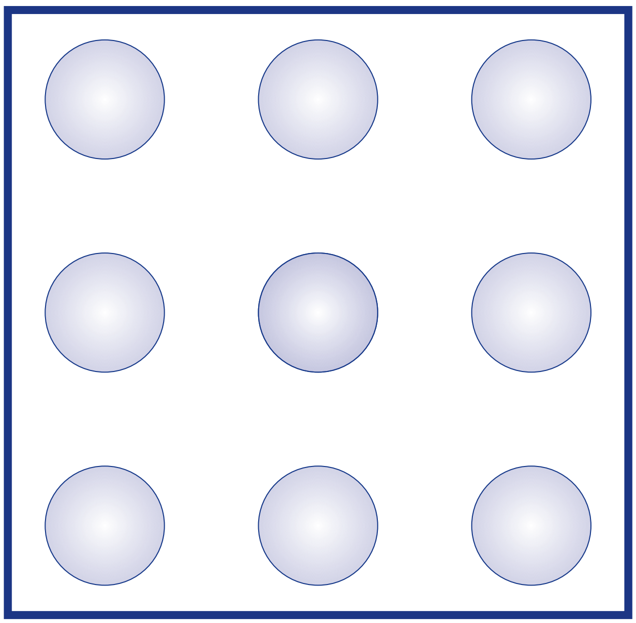


**Image 1.19 Thinking Outside the Box**

The observant reader will have noticed that in our discussion of the historical development of scientific inquiry, we have relied on examples from the work of scientists who are overwhelmingly white males of European descent. Does this mean that women and people of color have not made significant contributions to the development of science? As will be discussed in Chapter 4, there are several reasons why members of certain groups, women and people of color among them, have historically been underrepresented, both in terms of their actual participation in science and in terms of the credit they have been given for what they have legitimately accomplished. The most famous example of this is the case of Rosalind Franklin (1920–1958) and the discovery of the DNA double helix (a story that is taken up in more detail in Chapter 4). Even in the case of astronomer Annie Jump Cannon discussed earlier in this chapter, despite the recognition she receives now for her work in stellar classification, during her lifetime she was not able to hold a regular university faculty position and spent her entire career as a "research assistant" instead of as a professor. Underrepresentation and outright discrimination in the history of science is just one more example of how science is a human endeavor. While the guidelines, norms, and qualities of scientific inquiry are meant to support scientific work in being an objective search for understanding the workings of the natural world, the actual practice of science, by normal men and women, is also influenced by the normal range of human desires.

## Summary

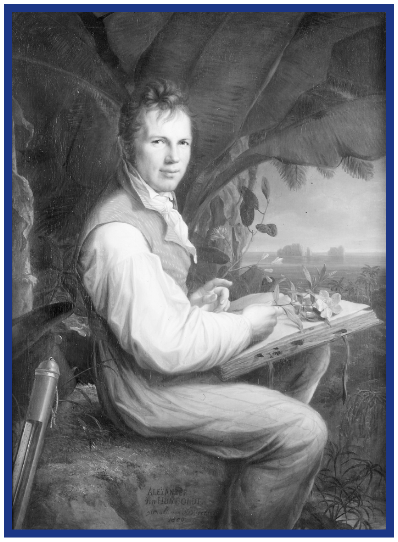
In this chapter, we have discussed seven themes related to the nature of science. We considered the relatively short history of modern Western science and the enormous impact it has had on how humans live and work. We considered other ways of knowing and discussed the limitations of the scientific worldview. We explored the fallacy of the "scientific method" as an invariant procedure for doing science, explaining instead how science is done through a mix of procedures and hunches, both following protocols and taking leaps of faith. This was followed by a discussion of the work of the social theorist Gregory Bateson and his belief that the fundamental role of education is to learn to make connections between seemingly unrelated things, an aspect of education that is often overlooked in today's schooling. We discussed six qualities of scientific inquiry, *replicability, control of variables, systematicity, communication, creativity*, and *informed skepticism*. We then provided two examples of how those qualities of scientific inquiry come together in practice: the work of the epidemiologist John Snow and the experiments by Fleischmann and Pons involving cold fusion. Finally, we highlighted the work of the historian of science, Thomas Kuhn, who revolutionized the way we understand how scientific disciplines are organized and how major conceptual changes (paradigm shifts) take place within those fields.

## Reflecting on Science

1. The nature of science means different things to different people. What does it mean to you? Write a short description of your understanding of what science is. Give it to someone (not in your class) to read and see whether it makes sense to him or her. Try to explain anything that he or she finds confusing.
2. Can you think of any times when you have used the process of scientific inquiry (outside of a school setting)? Describe the situation and how and why you used scientific inquiry.
3. Numerous historical examples of scientific discovery were presented in this chapter. Which one did you find most interesting and why? What does this example say about scientific inquiry?
4. What do you believe to be the greatest benefit to our society resulting from a scientific discovery? Why do you feel this way?
5. What do you believe to be the greatest problem faced by our society resulting from a scientific discovery? Why do you feel this way?

## Learning Science Online: Researching Scientist Biographies

While conducting modern science is largely a collaborative process, breakthroughs of scientific discovery have always been and continue to be based on the work of individuals dedicated to the systematic pursuit of knowledge in a specific area. Using the Google search engine, go online to search for sources of information on a scientist who is of particular interest to you. For example, you might choose Alexander von Humboldt (see image 1.20) who was the first botanist to scientifically classify the plants of Latin America and describe how they were different from the plants of Europe.Use at least three different sources and cross-reference the information for consistency. Create a report in the form of a PowerPoint slideshow, a web-enabled slideshow, or an interactive electronic brochure. Then create a class website where you can post your "virtual scientist museum" for others to see.



SOURCE: Painting by Friedrich Georg Weitsch, 1806.

**Image 1.20 Portrait of Alexander von Humboldt (1769–1859), Biologist and Geologist**

You can choose a scientist from the list below or pick another of your choosing:

| Scientist | Discipline |
|---|---|
| Albert Einstein | Physics |
| Neils Bohr | Atomic Theory |
| Charles Darwin | Evolution |
| Louis Pasteur | the Germ Theory of Disease |
| Sigmund Freud | Psychology of the Unconscious |
| Galileo Galilei | Astronomy |
| Antoine Laurent Lavoisier | Chemistry |
| Johannes Kepler | Astronomy |
| Nicolaus Copernicus | Astronomy |
| Michael Faraday | Electricity |
| James Clerk Maxwell | Electromagnetic Theory |
| Claude Bernard | Modern Physiology |
| Werner Heisenberg | Quantum Theory |
| Linus Pauling | Chemistry |
| Rudolf Virchow | Cell Theory |
| Erwin Schrodinger | Wave Mechanics |
| Ernest Rutherford | Structure of the Atom |
| Paul Dirac | Quantum Electrodynamics |
| Andreas Vesalius | Anatomy |
| Tycho Brahe | Astronomy |
| Comte de Buffon | Natural History |
| Ludwig Boltzmann | Thermodynamics |
| Max Planck | Quantum Theory |
| Marie Curie | Radioactivity |
| William Herschel | Astronomy |
| Charles Lyell | Geology |
| Pierre Simon de Laplace | Newtonian Mechanics |
| Edwin Hubble | Astronomy |
| Francis Crick | Molecular Biology |
| Enrico Fermi | Atomic Physics |
| Leonard Euler | Mathematics |
| Justus Liebig | Chemistry |
| Alexander von Humboldt | Biologist and Geologist |
| Arthur Eddington | Astronomy |

| Scientist | Discipline |
|---|---|
| William Harvey | Anatomy |
| Albrecht von Haller | Medicine |
| August Kekule | Chemical Structure |
| Dmitri Mendeleev | Chemistry |
| James Watson | the Structure of DNA |
| John Bardeen | Superconductivity |
| John von Neumann | Computing |
| Richard Feynman | Quantum Theory |
| Alfred Wegener | Geology |
| Stephen Hawking | Quantum Cosmology |
| Anton van Leeuwenhoek | Biology |
| Edward O. Wilson | Sociobiology |
| Frederick Gowland Hopkins | Vitamins |
| Gertrude Belle Elion | Pharmacology |
| J. Robert Oppenheimer | the Atomic Era |
| Edward Teller | the Bomb |
| Florence Rena Sabin | Medical Researcher |
| Ernst Haeckel | the Biogenetic Principle |
| Jonas Salk | Vaccination |
| Emil Kraepelin | Twentieth-Century Psychiatry |
| Maria Goppert Mayer | Physicist |
| Francis Galton | Eugenics |
| Alfred Binet | the I.Q. Test |
| Alfred Kinsey | Human Sexuality |
| Alexander Fleming | Penicillin |
| B. F. Skinner | Behaviorism |
| Wilhelm Wundt | Psychology |
| Jane Goodall | Primatologist |

## Internet Connections: Nature of Science Resources

AAAS Project 2061 on the Nature of Science
http://www.project2061.org/tools/sfaaol/chap1.htm

National Science Teachers Association (NSTA) Position Statement on the Nature of Science
http://www.nsta.org/positionstatement&psid=22

Nature of Science Lessons from Indiana University
http://www.indiana.edu/~ensiweb/natsc.fs.html

Lessons for Teaching the Nature of Science from University of California, Berkeley
http://evolution.berkeley.edu/evosite/nature/index.shtml

Comparison of Different Ways of Knowing from Arkansas Science Teachers Association
http://users.aristotle.net/~asta/science.htm

Evolution, Inquiry, and the Nature of Science
http://books.nap.edu/html/evolution98ev016.html

Quackwatch Notes on the Nature of Science
http://www.quackwatch.org/01QuackeryRelatedTopics/science.html

## Student Study Site

The companion website for *Teaching Science in Elementary and Middle School* (2nd edition) can be found at: http://www.sagepub.com/buxton2e.

Visit the web-based student study site to enhance your understanding of the chapter content and to discover additional resources that will take your learning one step further. Study materials include

- Video demonstrations of experiments
- Interactive self-quizzes to test your understanding of chapter material
- Full PDF journal articles related to core content
- Web resources, and more

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