

1 What Is Science?

Science is not inevitable; this question is very fruitful indeed.

Edgar Zilsel (1)

Science is humanity's greatest invention. When difficult decisions are to be made, everyone says that they want to "follow the science." But what is science? The Merriam-Webster online dictionary defines science as "knowledge about the natural world based on facts learned through experiments and observation" (2). The word itself is derived from the Latin word *scientia*, which means "knowledge." However, as Carl Sagan observed, "Science is more than a body of knowledge. It is a way of thinking" (3). Thus, Great Britain's Science Council has defined science as "the pursuit and application of knowledge and understanding of the natural and social world following a systematic methodology based on evidence" (4). This is an improvement, but perhaps goes too far in emphasizing the process over scientific knowledge itself.

Thomas Huxley suggested that science is merely "common sense clarified" (5), although common sense tells us many things that science has shown to be untrue, such as that the Sun travels around the Earth (6). Science rises beyond mere observation, intuition, and association. Science is a way of acquiring knowledge that is progressive, cumulative, testable, and predictive. Fields that call themselves sciences share certain elements in common, including facts, theories, methods, practices, and predictions. The most persuasive characteristic of science is that it

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works. Science underlies all technology, from the light-emitting diode illuminating this room to the laptop on which this chapter is being composed, or the cellphone giving a reminder about an imminent meeting. Yet science is much more than technology, and its relationship to technology is complex (Box 1.1). Science allows the recognition of principles that make the natural world comprehensible. That doesn't mean that science is always right, not by a long shot. Scientific knowledge is always tentative and subject to change. But evidence of the power of the scientific method is all around us, and even when science leads to errors, the method itself embodies the means to correct its mistakes.

The scientific method was not invented all at once, but rather evolved over time with refinement from a range of sources. The scientific method has not arisen in every civilization. In fact, most scientific knowledge has been acquired only during the past 400 years, less than one-quarter of 1% of the time that our species has

Box 1.1 Science and technology

Science and technology are often mistakenly viewed as synonymous. Whereas a definition of science is elusive, the definition of technology is easier. Technology is “the application of scientific knowledge for practical purposes” (24). Hence, while science and technology are intimately associated, the two can exist independently. For example, the ancient world had the technology to construct majestic buildings and structures such as pyramids and the Great Wall of China without a formal understanding of the laws of physics. The Industrial Revolution was catalyzed by the invention of the steam engine, which was created by tinkering without any knowledge of thermodynamics. In fact, the field of thermodynamics emerged afterwards to explain phenomena observed in steam engines and in efforts to optimize their efficiency. On the other hand, major advancements in science often find no immediate technological applications. Einstein's theory of general relativity, formulated in 1916, did not find a clear technological application until the development of a geopositioning system in the 1970s required synchronization of clocks on Earth and in orbit, which run differently depending on the gravitational field that they experience. In 2016, gravitational waves were first detected using remarkable technology in the form of paired interferometers, constructed by highly exacting tolerances prescribed by physical laws, but these have yet to find a technological application. Today, much scientific research is dependent on technology made possible by our scientific knowledge.

inhabited the earth. In their books *The Unnatural Nature of Science* and *Uncommon Sense*, the embryologist Lewis Wolpert and the physicist Alan Cromer, despite their different perspectives, both trace the origins of science to ancient Greece (6, 7). Plato regarded reason as the most powerful capacity of human beings, Thales of Miletus attempted to describe the nature of the world, and Aristotle defined humans as rational animals. Aristotle distinguished *induction*, the inference of universal principles from particular observations, from *deduction*, in which general principles are used to make predictions in specific situations. Most of what Aristotle had deduced turned out to be incorrect, but his mode of thinking laid a foundation for others to follow. Modern scientists use induction to develop theories and hypotheses, which can then be tested experimentally to arrive at deductions (Fig. 1.1). Greek mathematicians developed the concept of mathematical proof, which allowed the systematic application of logic to deduce a level of knowledge that is regarded as the truth (Box 1.2). Another tradition that arose in ancient Greece was rhetoric, in which oratory was used for the purpose of persuasion. When modern scientists perform experiments and interpret results, they are carrying on the great ancient Greek traditions of reason (*logos*) and persuasion (*rhetor*).

During the so-called Dark Ages in Europe, Islamic scholars helped to preserve and further develop these concepts. Science and mathematics flourished in the Arab world in the Middle Ages (8), building upon earlier intellectual traditions to

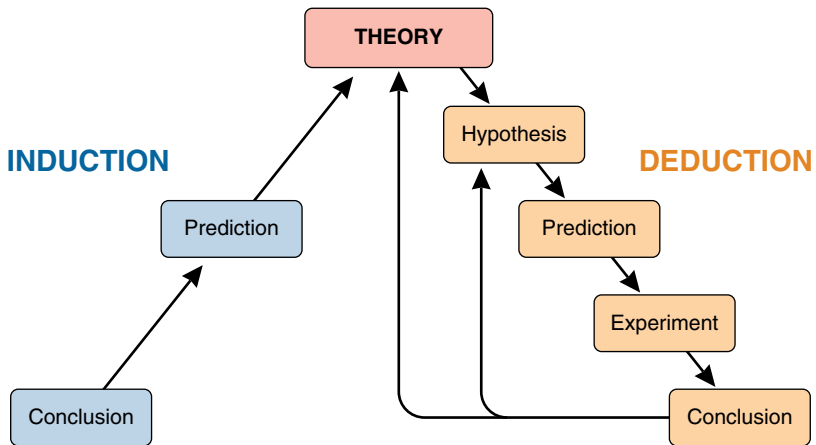


FIGURE 1.1 Inductive versus deductive reasoning. In inductive reasoning, particular observations are used to infer universal principles or theories. In deductive reasoning, hypotheses lead to predictions that are tested experimentally. The results of experiments in turn may be used to revise hypotheses and theories.

Box 1.2 Mathematics and science

In 1960, the physicist Eugene Wigner penned an influential essay titled “The Unreasonable Effectiveness of Mathematics in the Natural Sciences” (25), in which he noted how mathematical relationships pervade the natural sciences and, once identified, are predictive of new relationships and findings in nature. The relationship between science and mathematics may be viewed as essential, dependent, intricate, synergistic, and even symbiotic. Science depends on mathematics, and advances in science and technology further the development of mathematics, as evidenced by the ever-increasing reliance of mathematics on computers to probe its secrets, such as finding ever-larger prime numbers. At the heart of the matter is the fundamental question of whether the essence of the natural world is mathematical. The ancient cult of Pythagoras viewed the world as mathematical and promoted its understanding through mathematics, a world view with echoes in Plato’s allegory of the cave, in which a perfect world lies just beyond the senses. The ability to express a scientific finding in the precise notation of mathematics is considered an apotheosis in modern science. The increasing recognition that we live in a probabilistic universe has reinforced the notion that both discovered and as yet undiscovered mathematical relationships underlie everything in the natural world, something that Pythagoreans would have embraced and appreciated. Although a detailed treatment of the relationship between mathematics and science is beyond the scope of this book, we encourage budding scientists to learn as much mathematics as they can.

create a body of knowledge that was communicated to Europeans through trade and contacts in the Iberian Peninsula. This eventually blossomed into what is recognizable as modern science during the Scientific Revolution in Western Europe. Two influential publications were Francis Bacon’s *Novum Organum*, published in 1620 (9), and Rene Descartes’ *Discourse on the Method*, published in 1637 (10). *Novum Organum* proposed an inductive method for understanding natural phenomena in which relevant facts were systematically assembled and categorized according to their association with a phenomenon of interest to generate axioms based on empirical data. *Discourse on the Method* proposed that problems be divided into smaller parts so that the simpler parts might be solved first and urged scientists to begin any inquiry from a skeptical perspective. Scholars continue to debate why the Scientific Revolution occurred in Western Europe rather than elsewhere. Contributing factors include the continuum with classical Greek

philosophy, the increasing prominence of academic institutions, the development of printing and the increasing availability of books, a growing crisis between religious and humanistic world views, and the rise of capitalism, which lessened deference to authority and brought scholars and craftsmen together. The result was the emergence of a critical mass of practitioners of the scientific method who gave the revolution an unstoppable momentum (Box 1.3).

Box 1.3 Was science inevitable?

This chapter has emphasized the Western roots of modern science. That the Scientific Revolution occurred in 17th-century Europe in unquestioned, but contributions from many civilizations and cultures made this revolution possible (26). We have already mentioned the critically important contributions of Islamic scholarship. In addition, Chinese civilization developed science-enabling technologies such as the magnetic compass, the printing press, and papermaking, which allowed global exploration and efficient communication. As Bacon recognized, “Printing, gunpowder, and the compass ... changed the appearance and state of the world” (9). Chinese astronomy was also highly developed and precisely recorded a supernova in the year 1054, which created the Crab Nebula. It is noteworthy that there is no record of this event in Western records despite what must have been the spectacular event in the night sky, with the appearance of a new, very bright star that was visible during daytime. This curious and mystifying omission from European records may reflect that it conflicted with philosophical-religious consensus at the time, which held that the heavens were eternal and constant. Indian contributions to mathematics, such as the concept of zero, the decimal system, and advanced notation systems, were essential for later advances in theoretical physics (27). In the Americas, the Mayan civilization developed highly advanced astronomy and mathematics, along with the sophisticated engineering expertise to build magnificent cities. Ancient Africans developed advanced astronomy and metallurgy (28). In Oceania, ancient Polynesians mastered navigational skills that allowed them to travel to remote, isolated islands. Hence, the impulse to develop mathematics and science may be seen everywhere that humans settled and built civilizations and reflects the indomitable human curiosity. The will to do science, like the will to make music, can be viewed as a universal human trait. However, in contrast to the development of scientific concepts and mathematics in other

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Box 1.3 (Continued)

societies, the Scientific Revolution gave rise to unique new insights, formalisms, and ways to investigate the world—the creation of the modern scientific method and scientific disciplines and institutions. The Scientific Revolution allowed humanity to overcome the limits of intuitive thinking, which serves us well in many situations but can lead us astray when trying to understand natural phenomena.

To return to Edgar Zilsel’s question at the beginning of this chapter, we must consider the uniqueness of the Scientific Revolution. While there is abundant evidence of curiosity, ingenuity, creativity, and mathematics in many human civilizations, what we call modern science has arisen only once. This alone suggests that science was not an inevitable consequence of the evolution of human thought. Accordingly, science should not be taken for granted. Why it arose in 17th-century Europe, rather than in other scientifically and mathematically sophisticated societies, remains a fascinating and open question. It is probably not a coincidence that Europe during this period also witnessed new technologies like the printing press and telescope, brutal wars of religion, and the upheaval of medieval theology by the Protestant Reformation. Modern science may owe its existence to an unusual confluence of technological, historical, and sociological events.

In the 1920s, a school of philosophy known as *logical positivism*, with centers in the European capitals of Vienna and Berlin, asserted that truth must be demonstrated by direct observation or logical proof. Thus, scientific knowledge was favored over other forms of knowledge. In the classic formulation of the scientific method, science consists of careful observation and description, formulation of a hypothesis, and experimental testing of predictions. An implicit assumption is that experimental results can be replicated by others (chapter 7). Although this so-called “hypothetico-deductive” approach is not the only way of doing science, it is what many people think of when referring to the scientific method.

Logical positivism ultimately fell out of favor among philosophers of science, although its influence on 20th-century philosophy of science is undeniable. One reason for the decline of logical positivism is an inability to provide a clear demarcation between science and nonscience. Any definition of science must be able to distinguish it from pseudoscience, such as astrology, alchemy, creationism, and homeopathy. In fact, separating pseudoscience from science can be difficult since those disciplines have many of the trappings of science, including theory, method, and practice (see chapter 16). For the Austrian philosopher Karl Popper, the issue

of demarcating science from nonscience was a central issue. He was concerned that a statement can never be definitively verified, only falsified (11). In his classic example, no amount of evidence can ever prove the assertion that all swans are white, but the assertion may be disproved by the sighting of a single black swan. Reliance on verification cannot distinguish science from pseudoscience, as pseudoscience may use inductive reasoning to generate false theories and selectively collect observations that appear to verify them. Instead, Popper proposed that scientific assertions should be falsifiable if shown to conflict with observable evidence (or even theoretically observable evidence). This concept has proven popular with scientists. However, falsifiability has its limitations and fails to describe much of what scientists actually do. Furthermore, the quest for falsification itself can be an impossible journey. For example, the statement that all iron has ferromagnetism cannot be falsified unless all iron in the universe is examined, which is an impossible task.

The physicist and philosopher Thomas Kuhn argued that much of “normal science” consists of puzzle-solving rather than testing for falsifiability, and that it is the feature of puzzle-solving that best provides a basis for the demarcation of science (12). Kuhn also proposed that scientists are guided by *paradigms*, broadly explanatory models or theories that can periodically undergo a radical change when they no longer conform to objective reality (see further discussion in chapter 11). Kuhn’s views have also been challenged. The concept of paradigms implies an element of subjectivity in science and has been used by postmodernists to question whether science is superior to other forms of knowledge. In fact, Paul Feyerabend declared that a definition of science is impossible, and that the only principle is “anything goes” (13). Rather than specifying criteria to define science, the physicist John Ziman opted for a social definition consisting of a consensus among competent researchers (14).

While each of these efforts ultimately falls short of providing a universally satisfying definition of science, one can take a pragmatic approach to identifying core principles that distinguish science from nonscience (15). Conserved characteristics of science, such as an absence of supernatural explanations, measures to reduce the risk of bias, receptivity to new evidence, and support from independent forms of evidence, can help to distinguish science from pseudoscience. Although the world may indeed be “awash in bullshit,” as some authors claim (16), science provides the tools to distinguish truth from bullshit. Nevertheless, as we will discuss in detail in later chapters, it can be challenging to distinguish good science from bad or fraudulent science, and the problem is even more daunting for nonscientists. Most nonscientists lack a sufficient understanding of the scientific method and the mathematics of uncertainty to critically evaluate scientific information, and people who trust science are not necessarily immune to misinformation (17).

Science as it is presently understood possesses several essential characteristics: (i) an assumption that nature can be understood without having to invoke supernatural forces; (ii) a requirement for supporting evidence; (iii) arguments that conform to logical chains of reasoning; (iv) accumulation of knowledge that can change and undergo refinement over time as a result of new ideas or observations and improvements in methodology; and (v) predictive power. Expertise is valued in science, but authority is not (chapter 28). A characteristic of science that sets it apart from other human endeavors is that it embraces the notion that all knowledge is provisional and that answering one scientific question inevitably leads to another (Box 1.4). Bias refers to any process that can improperly influence scientific inquiry and lead to erroneous conclusions. Accordingly, bias is to be avoided as much as possible, and potential sources of bias must be identified. For example, simple measures such as the inclusion of control groups, randomization, and blinding can help to control for selection bias, but there are many other potential forms of bias (18). As science has advanced, the development of probability, Bayesian analysis, and other statistical tools has allowed increasing rigor and the estimation of scientific certainty (Box 1.5).

Box 1.4 Science and uncertainty

The acknowledgment of uncertainty and that one might be wrong is as important for science as the quest for knowledge. Many ancient cultures were certain that the Earth was flat, with the heavens above and the ground below—until the 6th century BCE, when the pre-Socratic Greek philosopher Anaximander suggested that the Earth is suspended in space, with celestial bodies situated all around. Although he did not realize that the Earth is spherical or that it orbits around the Sun, his insight was nevertheless a revolutionary idea that enabled subsequent advances in Greek astronomy. His contemporary Pythagoras subsequently taught that the Earth is spherical, and this idea spread so that Pliny the Elder could state in the 1st century CE that this fact was universally accepted. In contrast, although Aristarchus of Samos proposed a heliocentric model of the universe in the 3rd century BCE, his notion was rejected in favor of the geocentric models of Aristotle and Ptolemy, and Aristarchus would not be vindicated until Copernicus published *De Revolutionibus Orbium Coelestium* 1,800 years later. Why did geocentrism persist for so long when it conflicted with the measured

movement of the planets, in particular the periodic retrograde motion of Mars? Ptolemy was so certain of geocentrism that he created an extraordinarily complex explanation in which planets traveled in small epicycles that traveled around the Earth. When this also proved inadequate to account for planetary motion, additional epicycles were added, so that epicycles were traveling in epicycles around other epicycles. In retrospect, this model violates the principle of parsimony and is ludicrously wrong. However, it also illustrates the danger of certainty. As the theoretical physicist Carlo Rovelli has observed: “Science is not about certainty. Science is about finding the most reliable way of thinking at the present level of knowledge. ... In fact, it’s the lack of certainty that grounds it” (29).

While science allows us to conclude some things with reasonable certainty, such as that the Earth orbits the Sun, even that knowledge is temporal and provisional, as the solar system is evolving. In a few billion years, the Sun will exhaust its fuel and is expected to expand into a red giant and swallow the Earth. An essential feature of science is the humility to remain open to new evidence and ideas.



Ancient Roman mosaic from 3rd century CE depicting Anaximander holding a sundial. Courtesy of GDKE-Rheinisches Landesmuseum Trier, Thomas Zühmer.

Box 1.5 Where do formulas in science come from?

Laws in science are often stated as formulas that relate a fact to a set of variables. Examples are Newton's and Einstein's famous formulas for force ($F = ma$, or force = mass \times acceleration) and energy ($E = mc^2$, or energy = mass \times square of speed of light), respectively. So, a reasonable question to ask when thinking about science is: Where do these relationships come from? Certainly, they are not written down in nature until they come from the minds of scientists. Richard Feynman addressed this question in one of his famous Messenger Lectures, "The Character of Physical Law," given at Cornell University on November 9, 1964 (30). According to Feynman, the first step is to "guess," and then to compare the results of the equation to experimental data and see what happens. If the formula's predictions match the experimental results, the formula may be right. If the results are discrepant, then the formula is wrong and must be discarded. This reveals the insight that mathematical relationships can explain laws of nature. Scientists tinker with variables to see what works and validate formulas by careful observation and measurement. However, Feynman may have overstated things a bit when he said, "First, we guess it." An equation represents a highly educated guess, not just intuition. For instance, Newton's second law of motion can be inferred by the observation that a change in the momentum of an object varies directly in proportion to the force exerted on the object but inversely in proportion to its mass. All that's left is to collect observations and determine whether a coefficient is required. Ohm's law, in which current or flow varies in proportion to voltage but inversely in proportion to resistance, is analogous. Feynman was simply restating inductive inference from observation, which leads to hypothetical formulas or laws that can be tested experimentally (Fig. 1.1).

Hence, there may be different routes to finding an equation that describes nature. We could imagine that the sequence to finding a law of nature and representing it mathematically follows the sequence of observation, insight, tinkering with equations, and validating with experimental data. In this sequence, the first step, observation, can involve the collection of data that provide the basis for writing down formulas until one fits the data and making predictions that can be validated by subsequent experiments. The universe functions by unwritten laws that the human mind can discern, write down, and use to explain natural phenomena.

It is also important to remember that science aims to accurately describe physical reality but does not provide answers to questions of morality. In the 18th century, the Scottish philosopher David Hume discussed this as the “is-ought problem” (19); in other words, one cannot conclude what *ought* to be on the basis of what *is*. For questions of right and wrong, science and ethics may be viewed as separate *magisteria* (20), although science can certainly be informed by an application of ethical principles, and neuroscience may one day provide a biological explanation for human ethical behavior. In addition to adhering to principles of research integrity (see chapters 18 and 29), scientists have a responsibility to understand the ethical and social dimensions of their work and to ensure that scientific knowledge is used wisely and in the public interest (21).

The coexistence of science with religion has often been fraught, and that tension has led to conflict, as evidenced in the struggles between Galileo and the Inquisition and more recently between evolution and creationism. Stephen Jay Gould introduced the concept of “NOMA,” or *nonoverlapping magisteria* (20), to argue that science and religion occupy different spheres of human action and thought. However, just as defining science is difficult, drawing a bright line of separation between science and religion is not always straightforward, and each may intrude on the other. Religion relies on received wisdom that is permanent and dependent on the supernatural, whereas science produces knowledge based on observable evidence, which is always provisional and subject to change as new information becomes available. The NOMA concept requires adherents of science and religion to agree to accept their limitations, e.g., Galileo’s assertion that “the intention of the Holy Spirit is to teach us how one goes to heaven, not how the heavens go” (22). However, NOMA often fails in practice because science and religion encounter irreconcilable conflicts with regard to fundamental questions such as the origin of life, and science and faith are fundamentally incompatible at an epistemological level. Nevertheless, science and religion can find many areas of common ground (23), and frequently manage to coexist peacefully, even within the same individual. This is fortunate, as both science and religion have much to offer humanity.

In summary, science is a body of knowledge, a way of thinking, and a method for studying and understanding the natural world. Just as scientific knowledge has evolved over time, undergoing constant testing, reinforcement, and refinement from the contributions of innumerable scientists, so have the scientific method and the definition of science evolved over time. Although scientific revolutions occur only rarely (more on this topic in chapter 11), scientific knowledge and methodology continue to grow and advance with every passing year. With all that in mind, we shall now explore in detail how science can be done well or poorly and used for good or ill, and what that may mean for both science itself and society as a whole.

