CHAPTER ONE

Science in Perspective

It is the mark of an educated mind to rest satisfied with the degree of precision which the nature of the subject admits and not to seek exactness where only an approximation is possible.

—*Aristotle*

Science ↑ Technology

Science and technology are pretty much the same thing, aren't they?

No.

Although the technology that dominates modern culture is driven by science's understandings of the universe, technology and science spring from entirely different motivations. Let's put the substantial differences between science and technology into perspective. While science is practiced primarily because of the fundamental desire of human beings to know and understand the universe, technology is pursued because of the fundamental desire of human beings to influence the human condition. That influence may take the form of earning a living, helping others, or even exercising power over others for personal gain.

While individuals often find themselves practicing "pure" science and "applied" science at the same time, the institution of science can carry on basic research without necessarily having an eye to eventual

products. A nineteenth-century British chancellor of the exchequer, William Gladstone, remarked to Michael Faraday about his basic discoveries linking electricity and magnetism: "This is all very interesting, but what good is it?" Faraday replied, "Sir, I do not know, but some day you will tax it." About half the current wealth of developed nations comes from Faraday's connection of electricity and magnetism.

Before scientific understandings are translated into technology, additional considerations are necessary. Besides the question of what gadget *can* be designed, there's the question of what *should* be built, a question that is properly the province of the field of ethics. Ethics is part of another whole area of people's intellectual activities: the humanities. The major difference between science and the humanities is objectivity. Science strives to study the operation of the universe as objectively as possible, while the humanities have no such goal or requirement. To paraphrase Margaret Wolfe Hungerford (nineteenth-century Irish romance novelist), "Beauty [and truth and justice and fairness and . . .] is in the eye of the beholder."

Science is far from a monolithic entity. Natural sciences study our surroundings as well as people in their functional similarity to other life-forms, whereas human sciences study people's rational/emotional behavior and the institutions set up by people for social, political and, economic interactions. Figure 1.1 is a graphical representation of these relationships.

While this neat characterization is helpful in understanding overall relationships, the real world is considerably more complex. Ethics helps

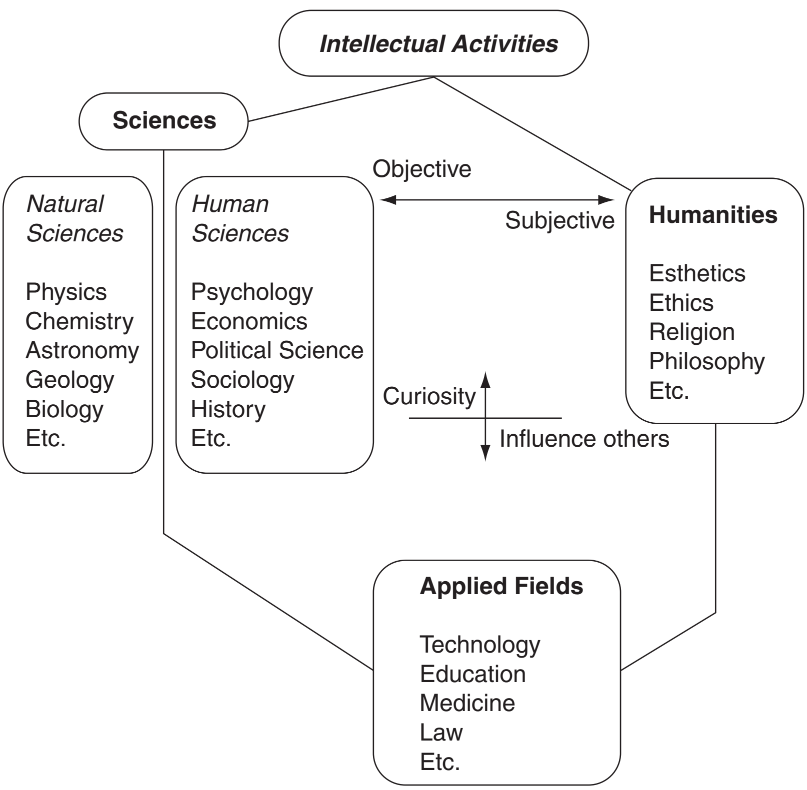


FIGURE 1.1. Intellectual Activities

dictate what topics are researched, what research methods are used, and what applications are prohibited because they are deemed potentially too dangerous to human welfare. Economics and political science also play major roles because science can only study what the culture is willing to support in terms of capital equipment, personnel, and political acceptability.

Science's Operating Procedure

The success of science in analyzing the workings of the universe is a result of the dynamic interplay between observations and ideas. This interactive process is known as the *scientific method.* (See Figure 1.2.)

During the *observation* step, some specific occurrence is perceived by the human senses with or without the aid of instrumentation. While the natural sciences have a large number of identical subjects to observe (think carbon atoms), the human sciences have a smaller number of distinctly different subjects (think human beings, even identical twins).

Human thought processes being what they are, data will be collected for just so long before the mind, in its search for order, begins to construct patterns or explanations. This is called the *hypothesis* step. The logic that uses specific observations to construct a general hypothesis is inductive reasoning. It involves making generalizations and is therefore the most precarious type of reasoning. While some people make an art form of jumping to

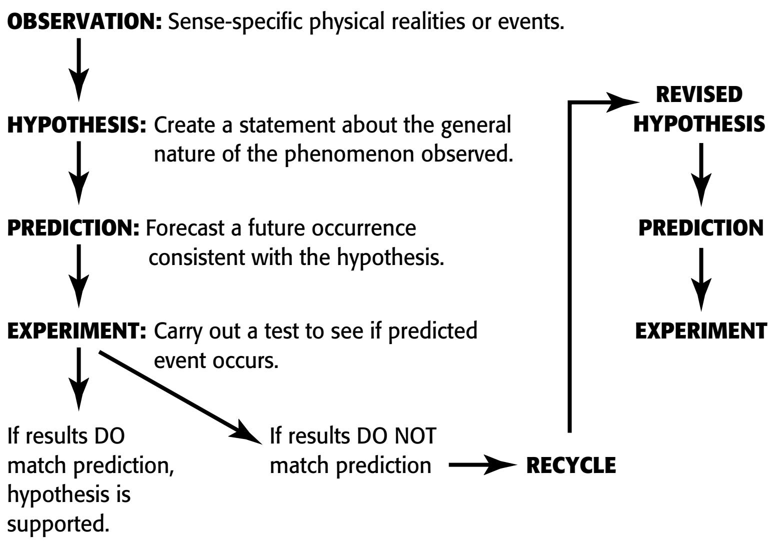


FIGURE 1.2. Scientific Method Overview

conclusions, within the context of the scientific method, such activity is restricted because succeeding steps bring the hypothesis back to reality.

Often the hypothesis is framed in whole or in part in a different language from that used in everyday speech. The language used is mathematics. Because mathematical skills require a great deal of effort to acquire, explaining scientific hypotheses to people not trained in mathematics requires translation of mathematical concepts into conversational language. Unfortunately, the meaning of the hypothesis may suffer in the process.

Once a hypothesis is formed, it can be used to forecast some future event that is expected to occur in a particular way if the hypothesis is true. This *prediction* can be derived from the hypothesis using deductive reasoning. For example, Newton's second law says $F = ma$. So, if $m = 3$ units and $a = 5$ units, then F should be 15 units. Carrying out this step is an appropriate task for computers, which operate on the basis of deductive reasoning.

After the prediction is made, the next step is to perform an *experiment* to see if the prediction is supported by evidence. Some experiments may be easy to design, but in many cases they are extremely hard to carry out. While intricate and expensive labor-intensive scientific instruments that generate much valuable data have been constructed, it is often difficult to obtain funding and then to invest the effort and patience needed to make sense of the huge amount of information obtained. Natural sciences have the advantage of being able to isolate the object of their study (think test tubes), while human sciences often have to contend with numerous variables simultaneously filtered through the minds of different people having individual agendas (think surveys).

Once the experiment phase is completed, the result is compared with the prediction. Since the hypothesis is general and the experimental results are specific instances, a result in which the experiment matches the prediction doesn't prove the hypothesis, it merely supports it. On the other hand, if the experimental result doesn't match the prediction, some aspect of the hypothesis must be false. This feature of the scientific method, called falsifiability, places a stringent requirement on hypotheses. As Albert Einstein said, "No amount of experimentation can prove me right, one experiment can prove me wrong."

A hypothesis that is shown to be false in some way must be recycled—that is, it must be modified slightly, changed radically, or abandoned altogether. The judgment about how much change is appropriate can be an extremely difficult call. Recycled hypotheses will have to work their way through the sequence again and again and either survive or fail subsequent prediction/experiment comparisons.

Another facet of the scientific method that keeps the process on target is *replication.* Any observer suitably trained and equipped should be able to repeat prior experiments or predictions and obtain comparable results. In other words, constant rechecking occurs in science. For example, a team of scientists at Berkeley Lab in California attempted to synthesize a new element by bombarding lead targets with an intense beam of krypton ions and analyzing the resulting products. The Berkeley scientists announced the synthesis of element 118 in 1999.

Synthesis of a new element is important news because of the element's novelty. In this case, its synthesis would also support previous ideas about the stability of heavy elements. Scientists at other laboratories (GSI in Germany, GANIL in France, and RIKEN Lab in Japan), however, were unable to duplicate the reported synthesis of element 118. An augmented Berkeley Lab team repeated the experiment. It, too, failed to reproduce the earlier reported results. The Berkeley team reanalyzed the original experimental data using revised software codes and were unable to confirm the existence of element 118. It retracted its claim. This refining process indicates that science's quest to understand the universe is, and must be, never-ending.

Sometimes predictions as well as experiments are rechecked. In February 2001, Brookhaven National Laboratory in New York reported an experimental result for a property known as the magnetic moment of the muon (a negatively charged particle similar to the electron, but considerably more massive) that was slightly larger than the prediction from the Standard Model of particle physics (more about this model in chapter 2). Because the Standard Model's prediction had been matched by experimental results to an extremely close tolerance for many other particle properties, this discrepancy in the magnetic moment of the muon strongly implied that the Standard Model was flawed.

The prediction of the magnetic moment of the muon was the result of a complex and lengthy calculation carried out independently by groups in Japan and New York in 1995. In November 2001, these calculations were repeated by physicists in France. The French physicists discovered an erroneous minus sign on one of the terms and posted their results on the World Wide Web. As a result, the Brookhaven group rechecked its own calculations, acknowledged the mistake, and published corrected results. The net effect of this correction was to reduce the disagreement between the prediction and the experiment. The Standard Model awaits, and must withstand, future challenges as science's never-ending search continues.

The Scientific Method in Action

Let's take a look at a classic example of the scientific method at work on a step-by-step basis.

OBSERVATION J. J. Thomson, the director of the Cavendish Laboratories in England just before the turn of the twentieth century, observed a beam of light in a cathode ray tube (forerunner of the modern TV picture tube). Since the beam (1) deflected toward positively charged electrical plates and (2) hit its target, producing individual flashes of light, it had to consist of negatively charged particles, which were called *electrons* by nineteenth-century Irish physicist George FitzGerald in his comments on Thomson's experiment. (The name *electron* had been proposed earlier as a unit of electrical charge by another Irish physicist, George Stoney.)

HYPOTHESIS Since atoms are uncharged (neutral), and Thomson had found negatively charged particles within them, he deduced that there must be some positive charge in atoms as well. Thomson theorized in 1903 that the positive charge was smeared throughout the whole atom, with the negatively charged electrons embedded inside the positive material. This depiction resembled a traditional British dessert and was therefore referred to as the Thomson Plum Pudding Model of the Atom.

PREDICTION Ernest Rutherford was an expert on positively charged particles known as alpha particles. At the beginning of the twentieth century, he predicted that if these particles were shot at atoms consisting of the sparse and smeared-out positive charge of the Thomson Plum Pudding Model, it would be like shooting pool balls at fog. Most would rip right through; very few would be deflected even slightly.

EXPERIMENT In 1909, Hans Geiger and Ernest Marsden set up an apparatus to shoot alpha particles at a thin sheet of gold atoms. The results were quite different from what they expected. Some alpha particles were deflected at large angles, and some even bounced back. Rutherford said, "It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you."

RECYCLE The Thomson Plum Pudding Model of the Atom was replaced by the Rutherford Solar System Model, in which the positive charge was concentrated in a relatively tiny nucleus at the center of the atom and the electrons (analogous to planets) moved in circular orbits around the nucleus (analogous to the Sun). Later in the twentieth century, as a result of subsequent prediction and experiment sequences, the Rutherford Solar System Model of the Atom was replaced by other models. Whenever experimental evidence doesn't match the prediction of an existing hypothesis, it's time to recycle the hypothesis.

Similarly, Isaac Newton's motion analysis and James Clerk Maxwell's electricity and magnetism classic hypotheses were interpreted to mean that space and time were absolute—an attractive notion. Einstein's Special Theory of Relativity replaced these comfortable absolutes with counterintuitive and philosophically unsatisfying relative quantities. The main reason relativity was accepted was that its prediction matched experimental evidence.

In spite of the popularity of an earlier idea, the celebrity status of a theory's proponents, the unattractiveness of a new theory, the political views of an idea's author, or the difficulty in understanding the idea, the bottom line is: *Experimental evidence rules.*

Complications

The scientific method we've presented here is a rational reconstruction of the way science actually works. This idealization of the process is neater than the one that occurs in the day-to-day world. Many people may be involved and lengthy periods of time may elapse between steps that don't occur sequentially. Nevertheless, the opportunity to look back over science's development affords us the luxury of 20/20 hindsight.

A number of complicating factors must be considered. First of all, science makes several philosophical presuppositions with which some philosophers disagree. Science presumes the existence of an objective reality independent of the human observer. Without such objectivity, otherwise identical observations and experiments repeated in various labs could differ, and it would be impossible for researchers to come to a mutually agreed on hypothesis. Further, science presumes that the universe is and has always been governed by a set of fixed laws, and that these laws are ones humans are capable of understanding. If the universe's governing principles were without pattern, or if we couldn't make sense of them, no hypotheses would emerge from science's efforts. Since our understanding of these laws seems to be growing, and predictions based on them are supported by experiments, these presumptions seem reasonable.

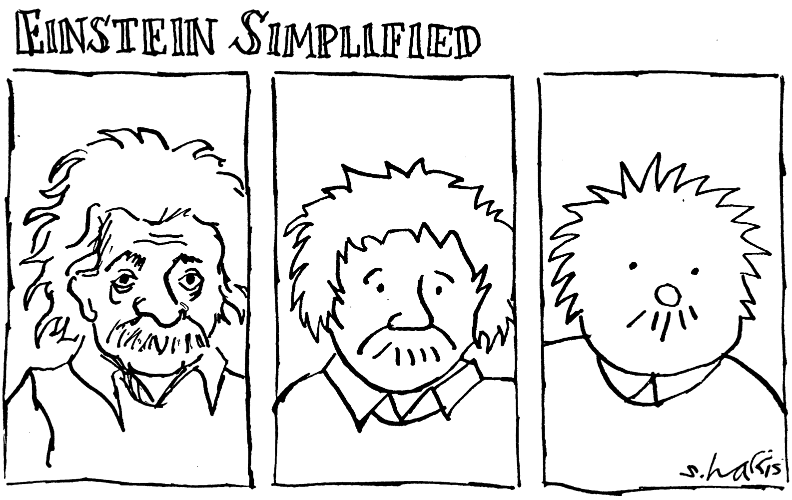
Because science's hypotheses deal with events occurring over a broad span of time, many deal with past events that cannot be directly checked by experiment. The usual solution to this problem is to cross-check hypotheses from several sciences, seeking mutual agreement. For example, the more than 4-billion-year age of Earth is supported by astronomers' measurement of helium abundance in the Sun, geologists' measurement of plate movements, and biologists' measurement of coral growth.

Especially because experimental results are unavailable for some phenomena (for example, from the distant past when there were no human observers or from an inaccessible part of the universe), more than

"WELL, I'VE BEEN THINKING HARDER THAN YOU HAVE, AND MY THOUGHT EXPERIMENT DISPROVES YOUR THOUGHT EXPERIMENT."

one hypothesis can be advanced to explain some event. The ticklish situation of having multiple hypotheses coupled with no possibility of experimental resolution is dealt with by a principle of scientific economy referred to as Ockham's Razor. The English philosopher William of Ockham (1285–1349) was a Franciscan monk who often used a common medieval principle in his philosophical writings: "Plurality should not be assumed without necessity." The military has given this principle a simpler and more direct expression: KISS—Keep It Simple, Stupid; or Keep It Short and Sweet. Expressed either way, it gives guidance in the absence of experimental evidence. If several hypotheses exist, and no experiment can be performed to choose between them, choose the simplest one.

Experience has shown this course to be wise. For example, in 1971, the X-ray-measuring satellite *Uhuru* found unexpectedly strong X-ray radiation referred to as Cygnus X-1 from the constellation Cygnus (the Swan). There was no apparent source for these X rays, which turned out to emanate from seemingly empty space near the supergiant star named HDE 226868, located about 8,000 light-years from Earth. (See Idea Folder 14, Compiling Star Catalogs, for an explanation of the HDE designation.) One hypothesis to explain this result was that HDE 226868 had an invisible companion. This phantom attracted mass that spewed out of HDE 226868. As this material was drawn into the unseen companion, its temperature increased enough to emit X rays. A different hypothesis requires at least two unseen bodies interacting with HDE 226868—a



normal star too dim to be seen and a rotating neutron star (the core of a star after it has lived out its life cycle and collapsed into a neutron ball) called a pulsar. These three bodies, arranged in a particular fashion, could emit X rays similar to the ones measured.

Cygnus X-1's distance renders it inaccessible to direct testing, not to mention that all its radiation was emitted around 8,000 years ago. So, which of the competing hypotheses is justified? On the basis of experimental support, either one. Using Ockham's Razor, the simpler explanation involving only one body is deemed more likely. Thus, Cygnus X-1 became the first recorded instance of an unseen companion known as a *black hole.* Subsequently, more than 30 such objects have been found under similar circumstances.

Ockham's Razor functions only when appropriate experimental support is unavailable. Its operating principle is to choose the simplest hypothesis consistent with the observations. It cannot, however, rule out other hypotheses supported by evidence, regardless of the hypothesis's more complicated nature. It cannot overrule experimental support, either. Occam's Razor is certainly less desirable than solid experimental evidence, but sometimes it's all we've got.

Unsolved Problems

Now that you have seen how science fits into the overall scheme of human intellectual activity and how it operates, you can appreciate that its open architecture allows many different paths to an increased understanding of the universe. New observations are made. Existing hypotheses are silent about these phenomena. New hypotheses are formulated to replace the silence with effective ideas. Predictions are improved. Innovative experimental apparatus is designed. All these activities lead to hypotheses that more accurately reflect the operation of the universe. The overall objective of these activities is to make sense of the universe, from its most minute details to its broadest sweep.

Science's hypotheses can be considered answers to questions or problems about the universe. Our aim here is to explore the *five biggest problems* that are at present unsolved. By "biggest," we mean the ones that have the broadest explanatory power, are the most difficult, have the most far-reaching implications, are the most critical to our understanding, or have the most potential applications. We will limit our exploration to the one biggest unsolved problem from each of the five natural sciences and try to describe the kind of progress we can anticipate toward each one's solution. Certainly the human sciences, humanities, and applied fields have important unsolved problems (for example, the nature of consciousness), but these are beyond the scope of this book.

Here are our candidates for the *biggest unsolved problem* in each of the five natural sciences, along with our justification for their selection.

PHYSICS: Motion-related properties of masses, such as velocity, acceleration, and momentum, are well understood, as are kinetic and potential energy of masses. The nature of mass itself, which is a property of many but not all of the fundamental particles of the universe, is *not* understood. The biggest unsolved problem in physics is: Why do some particles have mass while others have none?

CHEMISTRY: Chemical reactions of both nonliving and living entities have been studied extensively, with much success. The biggest unsolved problem in chemistry is: By what series of chemical reactions did atoms form the first living things?

BIOLOGY: The genome, or molecular blueprint of many life-forms, has recently been mapped. Genomes encode information about a life-form's collective proteins, or proteome. The biggest unsolved problem in biology is: What is the complete structure and function of the proteome?

GEOLOGY: The plate tectonics model satisfactorily describes the effects of interactions between the outermost of Earth's layers. But Earth's atmospheric phenomena, most notably weather patterns, seem to defy attempts to formulate models that lead to reliable predictions. The biggest unsolved problem in geology is: Is accurate long-range weather forecasting possible?

ASTRONOMY: Although many aspects of the universe's overall structure are well known, its dynamics are less well understood. Recent discoveries that the universe's expansion rate is increasing make it likelier that the universe will expand forever. The biggest unsolved problem in astronomy is: Why is the universe expanding faster and faster?

Many other interesting questions related to these problems will arise along the way, some of which may turn out to be the biggest questions of the future. These will be discussed briefly in Idea Folders at the end of the book.

William Harvey, the seventeenth-century English physician who discovered the nature of blood's circulation, said, "All that we know is still infinitely less than all that remains unknown." Stay tuned as new questions arise faster than old ones are answered. As science's circle of light expands, so does the circumference of darkness it encounters.