

Chapter 12

Inquiry in the Natural Sciences

What's to Come:

- Evaluating Scientific Claims and Theories
- Argument to the Best Explanation
- Testability, Fruitfulness, and Peer Review
- Basic Concepts of Statistical Inference

"I Hate Science!"

Winnie, Juanita, and Stephen are sitting in the college cafeteria. Juanita has the college calendar open in front of her.

Juanita: I see here that we're required to take at least one science course. Ugh! Boring!

Stephen: But there's no way round it. You have to take one.

Winnie: What do you mean, boring? Science is great. It's the main way we understand the world. And scientists make real progress in their investigations. Not only that, but what they learn is amazing. The details of the world are mind-boggling and it's scientists who uncover them.

Stephen: Boy, I can see you're a real believer.

Juanita: Science is simply boring. There's nothing but a bunch of facts that you have to memorize. There's no discussion, no difference of opinions, no imagination. Just here's the way it is—memorize it and remember it for the final exam.

What Do You Think?

Do you think that science is simply a mass of facts to be memorized? Why or why not?

Winnie: It sounds as if you didn't really learn about science in high school. Science requires a huge amount of imagination and insight. The mysteries that science uncovers are amazing. Science tells us how animals evolve, how mountains are built, how oceans are formed, how your body works.

Stephen: It makes you realize how complex and intricate the natural world is.

Winnie: What's boring is the way science is often taught. No one had any idea of the size and age of the universe until scientists figured it out. Have you seen those pictures from the Hubble telescope?

Stephen: They're incredible. Nature is awe inspiring.

Winnie: And just think about it. These are pictures of stars that are millions of light years away. I mean, they may have exploded by the time we see them.

Juanita: But it's all so cut and dried. In my literature class, we can discuss what was motivating Hamlet or why *Catcher in the Rye* is a good book. In science class, you're just told stuff—and it's impossible to remember all the details.

Winnie: You've obviously had some bad learning experiences with science classes. I think one problem is that no one told you about the history of scientific discoveries. There are lots of debates in science, but what tends to be taught is the stuff that's been settled. If you look at history, though, you'll see that there were great debates. And if you do some inquiring, you'll see that there are still debates. Like the debates about "dark matter" or why the dinosaurs disappeared.

Juanita: How could I do that? Science is so difficult to understand. All that math and stuff.

Winnie: Not all science is like that. You should try reading about how scientists make discoveries. A good introduction might be the history of geology. I have my prof's lecture notes right here if you want to have a look. One thing you'll see is that scientists follow the principles of inquiry.

Inquiry in Geology I: Hutton

This is a page from Winnie's geology notes:

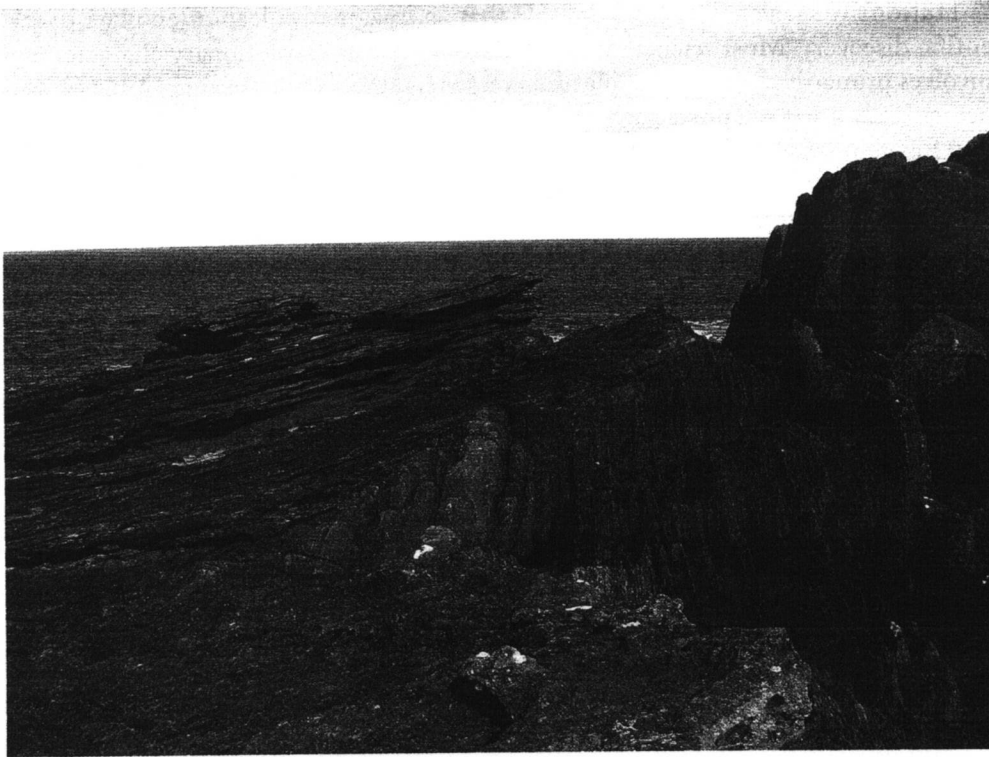
Hutton

There are many stories from the history of science that illustrate how scientific inquiry takes place and exemplify its main features. One story begins with James Hutton (1726-1797), who is usually described as the founder of the science of geology. His work in the late 18th century is a good example of scientific practice and imagination.

At the time Hutton began his research, Biblical scholarship had determined that the earth was a mere 6000 years old. Hutton developed a dramatically different view.

Hutton noticed that there were two different kinds of rocks on his two farms and hypothesized that there must be a place where these two kinds meet. His inquiry was successful, and he found what is now called an "unconformity." There were horizontal layers of gray shale piled on top of vertical layers of red sandstone, as shown in the photo.¹ In addition, he noted elsewhere that there were fingers of granite running into the sandstone. From these and other observations, he concluded the following:

1. The lower, upturned sandstone layers must have been deposited a long time ago, tilted, and then eroded down.
2. These sandstone layers must then have been covered with new layers of sedimentation that had also eroded and created the upper layers.



3. The fingers of granite meant that the granite must have been molten at some time and, therefore, that there must be great heat in the Earth where this process could occur. In addition, from observation of the current, almost undetectable rate of erosion and depositing of sand in the oceans, he reasoned that all these processes would involve enormous amounts of time.

In 1788, he presented his theory in a paper submitted to the newly formed scientific organization, the Royal Society of Edinburgh. His insights required not merely keen observational ability but a dramatic and imaginative break with the views of the day.²

Hutton's work illustrates some of the key aspects of scientific inquiry:

1. Hutton's reasoning was based on observation, and not, for example, biblical scholarship.
2. His theory was offered as the best explanation available at the time for a number of observations (see Chapter 5 on argument to the best explanation).
3. His theory was fruitful, leading to many other insights; for example, it explained the location of fossils and eventually became part of the basis for Darwin's theory of evolution.
4. He brought these results to his expert peers for critical scrutiny.

Hutton's work also illustrates the role that an imaginative leap often plays in scientific discovery. Most science does not have quite this revolutionary character and involves primarily the careful application of general theories to specific problems. But occasionally great scientists such as Copernicus, Galileo, Newton, Hutton, Darwin, and Einstein make an imaginative breakthrough of this dramatic sort, which is called a "paradigm shift."³

What Do You Think?

What way does Hutton's work exhibit an imaginative leap?

In science, context plays a key role. Context determines the burden of proof that a theory faces, and the available technology can facilitate or limit what can be investigated scientifically. While Hutton's story illustrates some general aspects of science, it leaves out the crucial role that technology can play. Hutton was able to make his observations with his own eyes, but much of scientific progress depends on the use of special tools which enable or facilitate observation, including telescopes for viewing the celestial world, microscopes for viewing the microworld, and, more recently, particle colliders for examining the structure of subatomic particles, and DNA sequencing for investigating human origins and biological structure. The role that available technology plays in science is one important way in which historical context affects scientific discovery.

As noted above in the case of Hutton, great breakthroughs in science often require a significant revision of the current understanding of the world. The ease with which one can do this depends not only on the intellect, imagination, and character of the investigator but also on the degree to which the view conflicts with well-established views. This illustrates another important influence of historical context on scientific inquiry.

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Technology in Science

Galileo's great observation that there are moons revolving around Jupiter depended on his use of a telescope that he made himself. As Galileo states, "On the 7th day of January in the present year, 1610, in the first hour of the following night, when I was viewing the constellations of the heavens [sic] through a telescope, the planet Jupiter presented itself to my view, and as I had prepared for myself a very excellent instrument, I noticed a circumstance which I had never been able to notice before, namely that three little stars, small but very bright, were near the planet. . . ."

Not only did optical technology enable early scientists to observe and generate new theories of the cosmic world; it also enabled them to peer into the micro-world of living organisms, such as bacteria, which are invisible to the naked eye. In the late eighteenth century, a Dutch lens grinder, Anthony van Leeuwenhoek (1632–1723), using an early microscope, observed algae in a rain barrel and bacteria in plaque taken from people's teeth—including from two old men who had never brushed their teeth in their lives!⁴

The Basics of Scientific Reasoning: Arguments and Evaluation

The term “science” covers a wide range of endeavors, from archeology to zoology. It ranges in natural science from the study of basic particles of matter by physicists to the study of the vastness of the universe by astronomers and astrophysicists, and in social science from the study by psychologists of how individuals make choices to the study of complex social systems by sociologists, anthropologists, and economists. The range of scientific inquiry is vast.

Nonetheless, despite what you may have heard about the scientific method, there is no well-defined *method* common to these various disciplines. What, then, distinguishes scientific inquiry from inquiry in other disciplines? One distinguishing feature relates to the kind of claims dealt with by scientific inquiry. Scientific inquiry deals with questions of fact and the explanation of facts.⁵

Another dominant characteristic of science is its approach to establishing its claims, that is, the nature of the reasons and arguments and the kinds of criteria used to evaluate claims.

In principle, all scientific disciplines ground their claims on observation. That is why they are called *empirical* sciences (from the Greek word *empeirikos*, which means “experience”). These observations can involve collecting data about poverty among single mothers or collecting bits of carbon at an archeological dig. Observation can involve little white dots on a photographic plate or visual observations of star clusters. The range of relevant observations is very large. What distinguishes scientific observations from everyday observations is that they are done with systematic care and precision.

Scientific theories involve more than a summary of observations, however. Scientists use observations primarily as the basis for creating and testing theories. In our study of inquiry, we are interested in how scientists test and establish their theories. The basic method is the method we discussed in Chapter 5: argument to the best explanation.

What Do You Think?

Explain the method of argument to the best explanation.

Whether discussing the big bang theory or the causes of cancer, scientists will endeavor to show that the theory they favor provides the best available explanation of the phenomenon being studied. Thus the history and the state of the controversy in which the scientific theory is put forward play a crucial role in the evaluation of scientific theories.

Another essential aspect of science is its approach to and method of criticism. Scientific claims must face not only the test of observation (as Galileo notes) but also the test of expert peer review. Scientists publish their findings in peer-reviewed journals so other experts can assess whether their data are credible and whether their theory constitutes *the best explanation*. Scientists understand that science progresses not only by amassing support for theories but also, crucially, by eliminating false theories. In fact, one famous philosopher of science argued that “falsifiability” was the key characteristic

of scientific reasoning. He argued that science progresses because theories are stated clearly enough that observations can show that some scientific claims are wrong.

This approach to science is also illustrated by a recent remark by a scientist studying Pluto:

Francis Nimmo, a science team member who initially predicted that Pluto's surface would look far less interesting based on its size and projected heat loss over billions of years, said he was not at all disappointed by the curveball New Horizons has flung at his theories. "I'm delighted," Dr. Nimmo said. "It's much more fun to be wrong than to be right because if you're wrong that means you've learned something."⁷

The process of ongoing peer review is another central aspect of the context in which scientific inquiry is practiced.

Dialogue in Science

The dialogical dimension of scientific inquiry is demonstrated very clearly in this dialogue written by Galileo Galilei, in which he argues for the Copernican view that the Earth and other planets revolve around the sun. In order to make this argument, he must defend the Copernican view against the prevalent Aristotelian picture of the universe. In the excerpt of the dialogue below, Salviati argues that the existence of sun spots constitutes evidence that heavenly bodies can change, while Simplicius calls on the authority of Aristotelian teaching that the heavens are unchanging. This dialogue also demonstrates how the appeal to sensory evidence began to be relied upon in early modern science in contrast to the previous appeal to abstract argument alone.

Galileo Galilei: "Dialogue Concerning the Two Chief World Systems" (1632)⁶

Simplicius: To tell the truth, I have not made such long and careful observations [of sun spots] that I can qualify as an authority on the facts of this matter; but certainly I wish to do so, and then to see whether I can once more succeed in reconciling what experience presents to us with what Aristotle teaches. For obviously two truths cannot contradict one another.

Salviati: Whenever you wish to reconcile what your senses show you with the soundest teachings of Aristotle, you will have no trouble at all. Does not Aristotle say that because of the great distance, celestial matters cannot be treated very definitely?

Simplicius: He does say so, quite clearly.

Salviati: Does he not also declare that what sensible experience shows ought to be preferred over any argument, even one that seems to be extremely well founded? And does he not say this positively and without a bit of hesitation?

Simplicius: He does.

Salviati: Then of the two propositions, both of them Aristotelian doctrines, the second—which says it is necessary to prefer the senses over arguments—is a more solid and definite doctrine than the other, which holds the heavens to be inalterable. Therefore it is better Aristotelian philosophy to say, "Heaven is alterable because my senses tell me so," than to say, "Heaven is inalterable because Aristotle was so persuaded by reasoning." Add to this that we possess a better basis for reasoning about celestial things than Aristotle did. He admitted such perceptions to be very difficult for him by reason of the distance from his senses, and conceded that one whose senses could better represent them would be able to philosophize about them with more certainty. Now we, thanks to the telescope, have brought the heavens thirty or forty times closer to us than they were to Aristotle, so that we can discern many things in them that he could not see; among other things these sun-spots, which were absolutely invisible to him. Therefore we can treat of the heavens and the sun more confidently than Aristotle could.

Sir Karl Raimund Popper (July 28, 1902–September 17, 1994) was an Austrian-British philosopher and professor. He is generally regarded as one of the twentieth century's greatest philosophers of science. Popper is known for his rejection of the classical inductivist views

on the scientific method. Instead he favored empirical falsification, which means that a theory in the empirical sciences can never be proven, but it can be falsified. This implies that a theory can and should be subjected to decisive experiments which can potentially falsify it.

While there are many similarities between how the social sciences and natural sciences approach inquiry, there are enough differences that we will treat these two disciplinary categories in different chapters. This chapter will deal with inquiry in the natural sciences, and we will discuss inquiry in the social sciences in Chapter 13.

Argument to the Best Explanation in the Natural Sciences

As discussed in Chapter 5, argument to the best explanation is a method that we all use in a wide variety of situations. Whether we are trying to figure out what caused the First World War or what caused the water stains on the ceiling, we will usually review a number of candidate explanations. Take the water stain on the ceiling. Was there a leak in the roof? Was a pipe leaking? Did the ceiling always have this stain and we just never noticed it before? We would probably reason as follows: "I doubt that I failed to notice the stain. Also, when I touch it, it feels wet. The stain on the ceiling in the kitchen is under the bathroom so it could well be a pipe that is leaking. It is less likely that the roof over the bathroom is leaking and the water is somehow coming down to the kitchen." I can now go upstairs and check for leaks. If I find a leaky pipe, I can reasonably conclude that the best explanation of the water stain is the leaky pipe (although, of course, the roof and the pipe could both be leaking. Clearly, though, the first thing I should do is fix the pipe).

This simple, practical example illustrates the reasoning process that characterizes scientific investigation: the development of various hypotheses and a winnowing down to the best explanation.

**Apply Your
Understanding
Exercises 1**

Inquiry in Geology II: Plate Tectonics

The history of geology provides a clear example of how scientific investigation employs this reasoning process. The recent acceptance of the theory of plate tectonics as an explanation for a range of phenomena from earthquakes to mountain formation has brought geology to popular attention. That the Earth is billions of years old and that continents move are both staggering insights into the workings of the Earth. The process leading to their acceptance was a long and complex one that required careful observation, improved technology, and great collective efforts and the sharing of information from a wide range of disciplines. The recent history of geology illustrates just such a process.

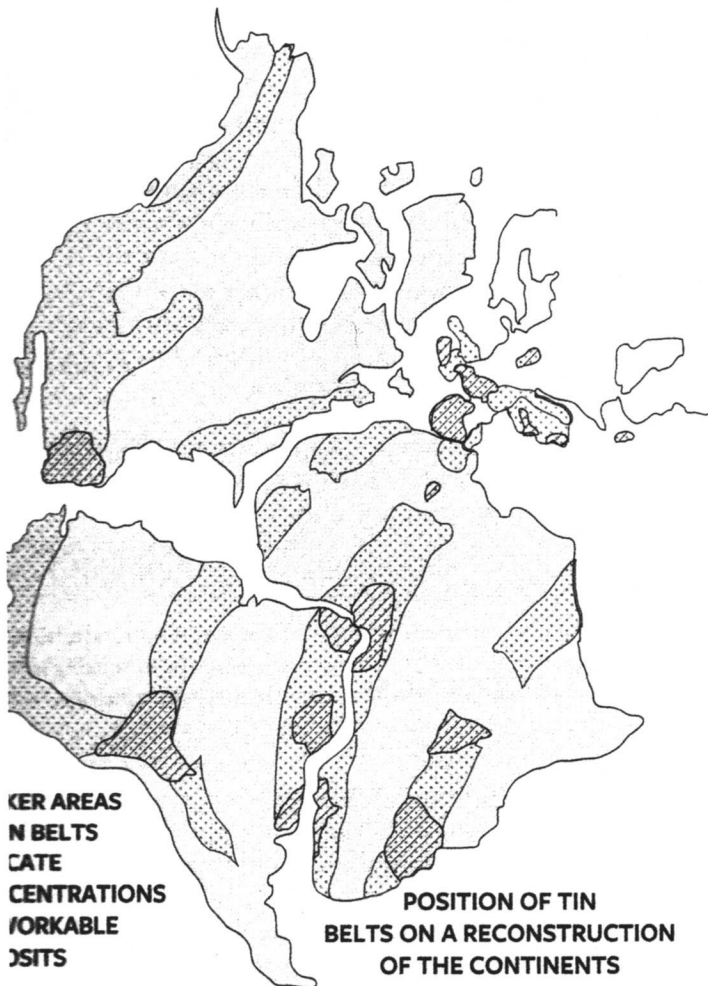
Here is another excerpt from Winnie's geology notes:

Hess

Until the 1960s, geologists did not accept what we have come to know as the theory of plate tectonics. Some earlier geologists speculated that there had been continental movement. However, there was no theoretical model that could explain how such enormous objects as continents could move around. So those ideas were not credited. Yet anyone who looked at a map of the Earth could see that the continents seemed to be separated pieces of a large puzzle.

In 1912, Alfred Wegener proposed a theory of continental drift to account for the apparent fact that continents such as Africa and South America appear to fit together. He is often credited as the father of plate tectonics, but there were earlier theorists looking at the maps of the past who also speculated that the continents fit together.⁸

How the Continents Previously Fit Together

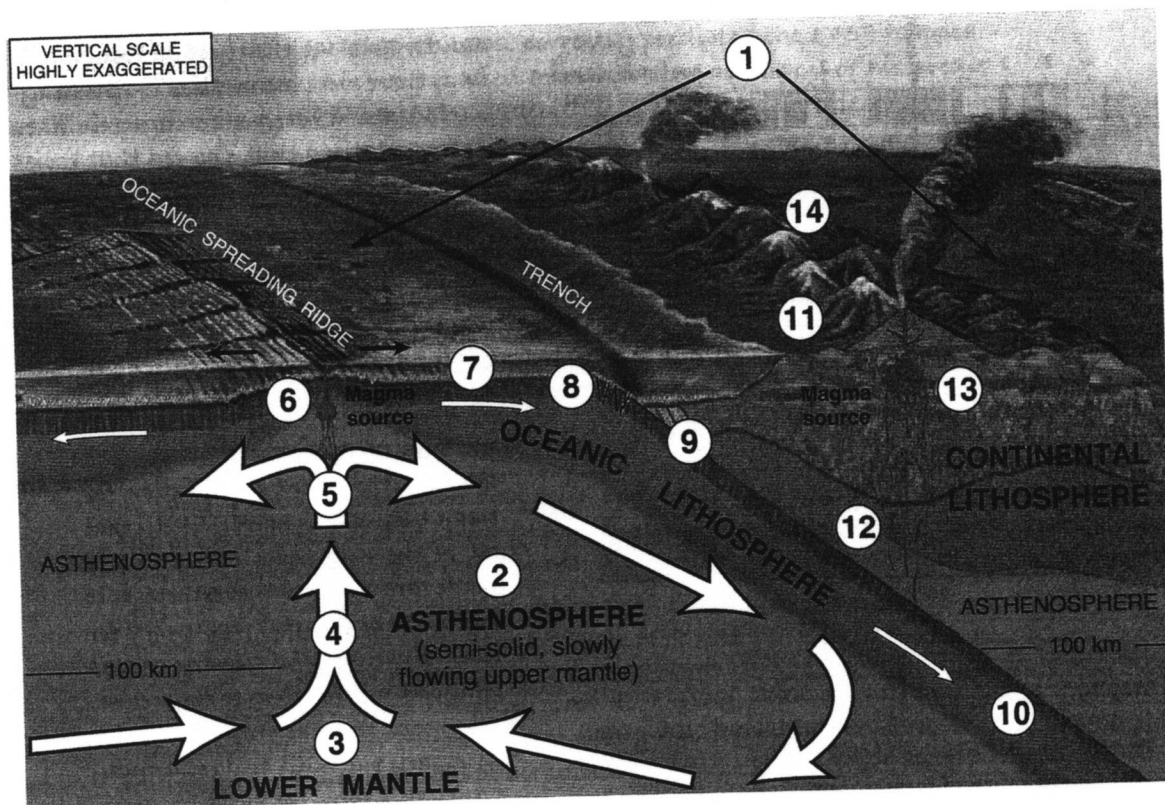


e: Roberts, The Macmillan Field Guide to Geological Structures, 105

What Wegener added to the theory was the observation that the rock formations and fossilized plants and animals showed appropriate similarities at matching continental margins. Because he was unable to give an account or model of how such enormous things as continents could "drift" around the world, his theories were largely rejected and even treated with derision. His theories explained some observations, but they were not credited because they could not be made coherent with what was then believed about the physical structure of the oceans and continents.

His theory was revived in the 1960s with American geologist Harry Hess leading the way. Hess proposed that the recently discovered mid-oceanic ridges were spreading and that the continents were sitting on plates that were propelled by the slowly moving "currents" of the underlying mantle.⁹

As Hess acknowledged in his seminal paper, this theory was initially speculative and contrary to current theories.¹⁰ But it did have the virtue of being the most reasonable inference from existing knowledge. Hess states:



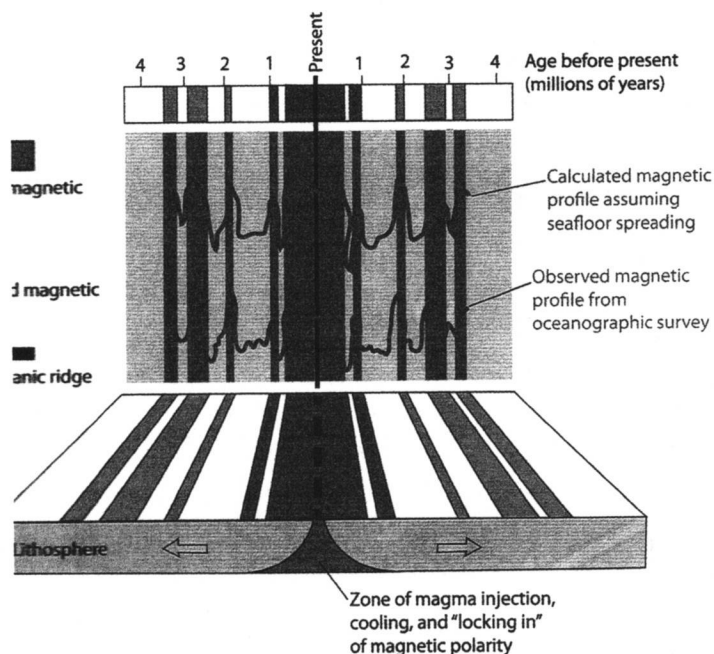
A model for the continents "floating" on the mantle.

Mantle convection is considered a radical hypothesis not widely accepted by geologists and geophysicists. If it were accepted, a rather reasonable story could be constructed to describe the evolution of ocean basins and the waters within them. Whole realms of previously unrelated facts fall into a regular pattern, which suggests that close approach to satisfactory theory is being attained.¹¹

Hess' theory provided a way to account for the observations of Wegener and for an increasing collection of surprising anomalies—data for which there was no satisfactory explanation according to accepted theories—about the magnetic orientation of rocks. It turns out that basalt (the kind of rock that is produced by volcanoes) contains magnetite which, as the name suggests, behaves as though composed of small compass needles that oriented themselves towards the North Pole when the basalt was hot before it solidified. For reasons still not well understood, every few hundred thousand years, the North and South Poles switch positions so that a compass needle which had pointed north would, after the switch, point south. The magnetite in the basalt, therefore, reveals the location of the pole at its moment of solidification.¹²

In addition, the orientation of the magnetite is not only horizontal but also vertical. The closer the basalt is to the poles when it solidifies, the more vertical the orientation of magnetite "compass needles" whether near the North or

An *anomaly* is data for which is not a satisfactory explanation according to accepted theory.



served magnetic profile (blue) for the ocean floor across the Pacific Rise is matched quite well by a calculated profile (red) on the Earth's magnetic reversals for the past 4 million years assuming constant rate of movement of ocean floor away from a hypothetical spreading center (bottom). The remarkable similarity of these two profiles provided one of the clinching arguments in support of the seafloor spreading hypothesis.¹³

South Pole. At the time of Hess' writing, there were anomalies in the magnetic data. There were magnetic data accumulating that showed that rocks near the equator had formed at locations much nearer the poles than their current locations. Since continental movement had been rejected, there was no adequate explanation for these observations. Hess sums up as follows at the end of his paper:

In this chapter the writer has attempted to invent an evolution for ocean basins. It is hardly likely that all of the numerous assumptions made are correct. Nevertheless it appears to be a useful framework for testing various and sundry groups of hypotheses relating to the oceans. It is hoped that the framework with necessary patching and repair may eventually form the basis for a new and sounder structure.¹⁴

What Do You Think?

What were the reasons and evidence in support of Hess' theory of continental drift? What was the main reason counting against the view?

Hess' theory demonstrates important aspects of a successful new theoretical model:

1. It should provide a more comprehensive explanation of current information, including hitherto inexplicable observations.
2. It should also be able to generate new predictions that can be tested.

Hess' theory accomplished both, and within a year of the publication of Hess' paper, new magnetic readings at the spreading ridge in the middle of the Atlantic showed that the ocean floor was indeed moving (see illustration). Hess' work is an example of paleogeology, the study of the geological history of the planet (from the Greek *paleo*, meaning "ancient"). Finding new evidence that supports the theory in a discipline like paleogeology is similar to making successful predictions in a science such as physics.

When Halley, using Newton's laws, correctly predicted the 1759 reappearance of the comet that is now named after him, the accuracy of his prediction provided a great boost to the credibility of Newton's theories.¹⁵

Although theories about historical processes such as plate tectonics do not depend on predictions about future events for their support, a similar method of confirmation is used. In the case of plate tectonics, Hess' theory of seafloor spreading was quickly confirmed, not by successful predictions of future events but by the discovery of additional data that supported his theory. In this case, new measurements of ocean floor changes in magnetism showed that the ocean floor was, indeed, moving away from the oceanic ridges. A U.S. Geological Services article about Hess' discovery summarizes in this way:

In 1962, Hess was well aware that solid evidence was still lacking to test his hypothesis and to convince a more receptive but still skeptical scientific community. But the Vine-Matthews explanation of magnetic striping [the change in magnetic orientation of the magnetite as one moved farther from the spreading ridge, as seen in the illustration on p. 302] of the seafloor a year later and additional oceanic exploration during subsequent years ultimately provided the arguments to confirm Hess' model of seafloor spreading. The theory was strengthened further when dating studies showed that the seafloor becomes older with distance away from the ridge crests. Finally, improved seismic data confirmed that oceanic crust was indeed sinking into the trenches, fully proving Hess' hypothesis, which was based largely on intuitive geologic reasoning. His basic idea of seafloor spreading along mid-oceanic ridges has well withstood the test of time.¹⁶

It should also be noted that not only did Hess' theory fit new data, but it has since demonstrated great explanatory power. Plate tectonics has yielded new explanations of earthquakes, mountain building, and volcanoes. As with Newton's and Darwin's great insights, a wealth of phenomena now became comprehensible. This aspect of the theory is often called "fruitfulness"—the capacity of a theory to support a wide variety of research possibilities and to provide a large range of explanatory insights.

The story of Hess' work illustrates a number of aspects of scientific inquiry. It shows again that detailed and precise observation, powerful explanatory models, technology, peer review, and imagination all play important roles in scientific progress and theory confirmation.¹⁷

The Structure of Inquiry: Plate Tectonics

Let's see how our structure of inquiry applies to the development and confirmation of the theory of plate tectonics.

What Is the Issue? What Kinds of Claims and Judgments Are at Issue? There were two questions:

1. Had the continents moved over time? If they had, scientists could explain a considerable amount of the observational information (e.g., the matching of mineral deposits, the magnetic anomalies).
2. Was Hess' model of continents "floating" on a viscous mantle the best explanation?

Scientists create models to provide explanations. These models can be pictures or other physical models, or they can be complex mathematical models run on a computer.



These are both factual questions, one about the facts of the matter and the other about the best explanation. This illustrates the fact that scientists want to know not only what happened (is happening, will happen) but also why it is happening. What is the causal explanation? While the answers to these questions will always be factual, explanations will often take the form of models (e.g., the model of the atom as a kind of solar system, global warming as the product of a greenhouse-like phenomenon). These models can be pictures or other physical models, or they can be complex mathematical models run on a computer, and they can provide the basis for understanding the phenomenon and for suggesting other data (e.g., predictions) that would be the case if the model is correct.

Hess' key claim was that the continents were moved by a current in the viscous mantle under the Earth's crust.

What Is the Context of the Issue? The context was, first of all, an existing view that the continents could not have moved because there appeared to be no mechanism for such movement. There was, however, some theoretical tension because of the considerable as yet unexplained evidence that the continents had been together at some earlier time. Such a collection of dissonant information is a fertile situation for scientific progress.

Second, there was new information about the nature of the ocean floor and magnetic inconsistencies. The rapid acceptance of the theory resulted from both the unsatisfactory state of previous explanations and the almost immediate discovery of confirmatory data of the spreading of the ocean floor.

What Are the Relevant Reasons and Arguments on Various Sides of the Issue? The two basic views were the floating continents view and the stationary continents view. The main argument for the stationary view was that there was no known physical model to account for any movement. The evidence that the continents had once been in a different position than they are now was considerable, but acceptance of that idea was blocked by the lack of a feasible mechanism to explain the movement.

The new evidence of ocean floor movement provided powerful support for the drift thesis. Additional evidence emerged rapidly, showing that the oceanic plates were moving under the continental shelf. This information enabled the theory to provide additional explanations for how the majority of mountains were formed and earthquakes were generated. The powerful explanatory breadth of the theory added considerable support for the moving continents view.

How Do We Comparatively Evaluate the Various Reasons and Arguments to Reach a Reasoned Judgment? Scientists evaluated the two competing theories (i.e., continents moved, continents didn't move) in terms of their explanatory power and their consistency with observations. The test of each theory was not simply that it fit with existing data but that it generated new hypotheses that could be tested, such as the magnetic striping of the area around midocean ridges. The ability of a new explanatory model both to explain numerous facts and to provide a basis for further inquiry makes it very attractive to scientific investigation.

During the period of development of the plate tectonic model, even non-scientists inquiring into this controversy might have been able to track the increasing success of the theory in the scientific literature. More likely, they would have had to seek the views of contemporary geologists. A look at the citation index¹⁸ to see what geologists were saying about Hess' paper would also have helped. The rapidity with which his view received supporting evidence suggests that many recognized the power of his view and were willing to explore its implications. A review of the contemporary geological literature would have revealed this. This example demonstrates how a layperson can be in a position to inquire even into those scientific debates which are contemporary and controversial.

**Apply Your
Understanding
Exercise 3**

Reasoned Judgment and Scientific Inquiry

Now that we have looked at a few historical examples from science, we can identify some of the crucial elements of a scientific inquiry. But first, we should point out that not all scientific inquiries result in such grand theories as plate tectonics or the bacterial cause of disease (some aspects of which are reviewed below). Much of science is about establishing a very particular claim working within a well-established theoretical framework. As laypeople intent on making use of scientific information in our inquiries, we will usually be concerned with particular scientific claims, for example, whether a particular gene is responsible for a particular illness, whether vaccination is an effective public health policy, and whether cell phones cause brain cancer. Assessing these more common types of claims, claims which do not involve any dramatic change of theory, is similar to the assessment of the more theoretical and revolutionary claims that we have looked at so far, except that the assessment of these more common claims involves less emphasis on criteria that are more relevant to the assessment of new theories, such as the criteria of fruitfulness (see page 308) discussed below.

Causal Explanations

In many ways, the scientific identification of cause is quite similar to the more common sense approach to identifying causes that we discussed in Chapter 5.

What Do You Think?

What are the criteria used to evaluate general causal claims?

Reduction refers to the idea in science that observable processes, like illness and biological growth, can be explained in terms of more basic, often invisible processes at the cellular or chemical level.

Scientists use basically the same criteria, but they have refined these common sense considerations. Science is not just about facts. It is also about making sense of the facts in a way that explains them and can then be further tested. One way in which scientific explanations tend to differ from more common sense explanations is in the presumption that observable phenomena can often be explained in terms of unobservable microprocesses. Science tends to progress by providing explanations with increasing levels of detail. In biology, for example, the theory of genes added enormously to Darwin's theory of natural selection. Later, the discovery of DNA added a detailed chemical model for understanding the way that genes work. The tendency of scientific explanations to be based on increasingly smaller microphenomena is sometimes identified as **reduction**. The idea of reduction in science is that observable processes, like illness or biological growth, can be explained in terms of more basic, often invisible processes at the cellular or chemical level. Successful reduction involves the increased understanding that is achieved by identifying the microprocesses which explain the larger macrophenomena.

What Do You Think?

What are some examples in science of microprocesses being used to explain larger, macrophenomena?

For example, we use the activity of microscopic bacteria to explain macrophenomena like a runny nose and a cough and the movement of electrons to explain the macrophenomenon of lightning.

Testability and Falsifiability

The first thing any theory must do is fit the known facts. But the second requirement for a theory is that it must be testable. Testability requires that a theory or claim be able to identify the kind of observational evidence that will support it and the kind that will count against it—what would falsify it. Thus a theory should provide a basis for inferring more possible claims that can be tested. Testing does not necessarily involve experiments, although experiments are a particularly good way to test a theory. Contrary to what you may have heard, not all science is based on the experimental method. As you see from the history of geology, science can make great progress without necessarily using experiments. Nonetheless, experiments have played a crucial role in much scientific advance.

One requirement for testability is precision. The more precise a prediction is, the more easily it can be falsified and, should it prove true, the more credibility it establishes for the theory. For example, the ability of physicists using Newton's laws to

make incredibly accurate predictions of the behavior of spacecraft continues to confirm Newton's laws.¹⁹ The success of Einstein's theory of general relativity in predicting a precise, but very small, bending of light as it went past the sun added immensely to its early credibility.

Experiments

Experiments involve testing a theory or claim by varying only one factor, the one that we hypothesize is the cause in question, and seeing if this results in predicted changes in the outcome.

What Do You Think?

What are some of the advantages of experiments to test a theory or claim?

Experiments are valuable because you can much more easily test a claim if you can control everything in the lab. Experiments enable us to minimize the problem of competing explanations for an outcome, which is often called in scientific studies the problem of **confounding factors**. A confounding factor is any factor other than the cause being studied that could be part of the explanation for the observed outcome.

But experiments are only applicable to a limited range of phenomena, so scientists use a variety of methods to test claims. The main method of testing that scientists use is attempting to identify the best explanation for the phenomena being studied (as discussed in Chapter 5). This may involve making predictions based on the theory and seeing if they occur. Or it may involve making inferences about further information that we might find given a particular claim or theory. This method was illustrated in the example we just read: a test of Hess' theory was finding other evidence of the movement of the continents such as seafloor spreading. What is crucial to the testing of a scientific theory is that there are implications which can be tested against additional observations. Often figuring out what these implications are and how to test them requires great ingenuity and imagination. But the best scientific insights provide the basis for many such inferences.

A **confounding factor** is any other than the one being studied that could be part of the explanation for the observed outcome.

Early Experiments

One of the more famous early experiments in the history of science was conducted by an Italian poet, Francesco Redi, who was addressing the then popular view that living creatures could spontaneously emerge from matter. He used his experiment to prove that maggots in meat did not spontaneously develop in meat but resulted from flies laying eggs. Here is how the Encyclopaedia Britannica describes the experiment:

In 1668, in one of the first examples of a biological experiment with proper controls, Redi set up a series of flasks containing different meats, half of the flasks sealed, half open. He then repeated the experiment but instead of sealing the flasks, covered half of them with gauze so that air could enter. Although the meat in half of the flasks putrefied, he found that only in the open and uncovered flasks, which flies had entered freely, did the meat contain maggots.²⁰

Fruitfulness

Related to testability is a much broader concept, fruitfulness. This is a criterion especially applicable to theories. A theory is fruitful when it does not just imply a few facts that can be tested but suggests a whole research project filled with explanations of diverse phenomena. Both Hutton's and Hess' hypotheses proved enormously fruitful in explaining a wide range of disparate phenomena. As mentioned, Hutton's work opened the way for another extremely fruitful insight, Darwin's theory of natural selection. The great insights of science result not only in a particular explanation but in theories that suggest innumerable possibilities for further understanding and research.

Peer Review

Related to testability and argument to the best explanation is peer review. Scientists must publish peer-reviewed articles in professional journals, which are read by peers who examine the arguments and evidence further. These readers see whether the evidence adequately supports the claims or whether there are other competing explanations that haven't been addressed. This willingness to subject claims to ongoing peer review is not unique to science, but it is crucial to the establishment of credible scientific claims. What is somewhat unique to science is that there is often a "convergence" among peers on the correctness of a claim as a result of explanatory success and repeated testing. Claims may be initially greeted by skepticism, but if they survive the peer review process and other investigations and research, their credibility is enhanced. Enduring claims that have survived extensive research enter the body of knowledge used by scientists and are worthy of confident belief.

**Apply Your
Understanding
Exercise 4**

Characteristics of Scientific Inquiry

- causal explanations
- testability
- fruitfulness
- peer review

“Evolution”

Winnie, Stephen, and Juanita continue their conversation about the study of science.

Juanita: I admit learning about the history of geology did teach me things about the world that I didn't know. And there wasn't any math. I did have to look up a few things, but basically I could understand it. It really was amazing that they found those splits in the middle of the ocean—and that all this explains earthquakes and volcanoes. So OK, maybe science isn't all that bad.

Winnie: And if we study biology, we see a much more complex and beautiful world of plants and animals with all their remarkably developed abilities and intricate designs. It makes you feel in awe of nature.

Stephen: Right! And it provides clear proof of the existence of a creator, a magnificent creator who designed living things in all their complexity and intricacy.

Winnie: Now just a minute, Steve. Thanks to Darwin, science can now explain why the natural world is so full of the wonderful things that we see. Darwin showed that there was no need for the creator to explain the vast variety of species on Earth.

Stephen: One thing I do know is that evolution is just a theory, and it's a theory with a lot of holes in it. Scientists try to cover up those holes, but they're there, and they show that there must be other forces at work to produce such an intricate and well-functioning entity as a human body. I mean, look at the eye. Do you really expect me to believe that the human eye was created by blind chance?

Juanita: You know the old story that millions of monkeys slaving away endlessly on computers would never write a play of Shakespeare?

Winnie: I agree—they wouldn't. But that's not Darwin's theory. I think we should make an inquiry into the theory of evolution and see just what the issues are, what the history of this debate is, and what the evidence is pro and con.

Stephen: Sure. I'm glad to take on evolution.

Inquiry into the Theory of Evolution

What Is the Issue? What Kinds of Claims and Judgments Are at Issue?

Winnie: OK. So let's get clear on the issue. The question is whether the natural world is the result of divine creation or the result of a process of evolution and natural selection as Darwin argued.

Stephen: Natural selection, whatever that is, versus God's creation as an explanation of the natural world.

Charles Darwin, 1809–1882, a British naturalist, is famous for his theories of evolution and natural selection. Like several scientists before him, Darwin believed that life on Earth evolved (developed gradually) over millions of years from a few common ancestors. In 1831, Darwin set out on *H.M.S. Beagle* on a British science expedition around the world. In South America, Darwin found fossils of animals that were extinct but similar to modern species. On the Galapagos Islands in the Pacific Ocean, he noticed plants and animals of the same general type as those in South America. Darwin studied plants and animals everywhere he went, collecting specimens to study later. Upon his return to London in 1836, Darwin carefully reviewed his notes and conducted thorough research of his specimens. This study provided evidence for his theories of evolution and natural selection, which he published in his book, *On the Origin of Species* in 1859.²¹

Winnie: Now you need to know that Darwin's theory is not that humans and other species were created by blind chance, some kind of cosmic fluke. That's not the theory of natural selection.

Juanita: It's not?

Winnie: No, it isn't. In his book *On the Origin of Species*, Darwin goes into the argument in depth, laying out his evidence in great detail and constantly addressing objections. It's really a fantastic study in argumentation. All I can give you now is a fairly crude summary of his argument. You should read the book.

Juanita: Sounds kind of heavy.

Stephen: You can just give us the short version.

What Are the Relevant Reasons and Arguments on Various Sides of the Issue?

Winnie: The first thing Darwin points out is how animal breeders are able to breed dramatically different creatures than what they start with. Look at the incredible variety of dogs which are produced by human breeding. Since there's such variability in offspring that breeders can modify breeds through "human selection," nature can do the same thing through "natural selection." A chance variation in new generations that gives a creature an advantage in a particular environment will tend to help that creature prosper and reproduce, and those that don't have the advantage will tend to die off. This is true of both plants and animals. So that's his theory: species change and are created by a slow incremental process of natural selection favoring some variations over others. The process involves literally billions of years.

Juanita: That's pretty amazing.

Winnie: Let me give you an analogy, though it isn't Darwin's. Think of the odds of getting four aces when you're dealt four cards. Assuming no one is cheating, the odds are pretty astronomical. But suppose you just keep getting dealt four cards over and over, and when you get an ace you keep it; then you're dealt four more cards, and when you get a second ace, you keep that too. Obviously by this process, it would be inevitable that you'd eventually get four aces in a reasonable number of deals. Four

aces on one deal is a “miracle.” Four aces after many deals and “ace selection” is just what you’d expect. And that’s how evolution proceeds, by small modifications, keeping the successful ones and getting rid of the unsuccessful.

Stephen: OK, I get the theory. Nice analogy, but why should I believe this is how it really happened?

What Is the Context of the Issue?

Winnie: Good question. I think we should look at the arguments and context. The concerns you’re raising were ones that Darwin was quite aware of when he published *On the Origin of Species*. He knew that he was up against the belief in creationism, which was really strong at the time. In fact, you really can’t understand his book if you don’t know the creationist/Genesis theory that he was up against and how widely it was accepted among scientists of that time. One of the most striking aspects of *On the Origin of Species* is how careful Darwin is to acknowledge and address objections to his theory.

What Do You Think?

Why did Darwin’s theory have to meet a strong burden of proof?

Darwin’s theory was put forth at a time when the creationist account (an excerpt of which is found below) was widely believed by both laypeople and scientists. Because it was a challenge to existing scientific views and dominant religious views, Darwin accepted that his theory had to meet a strong burden of proof.

The Creation

Excerpts from the Judeo-Christian account in Genesis, Chapter 1 (King James Version)

1 In the beginning God created the heaven and the earth.
3 And God said, Let there be light: and there was light.
11 And God said, Let the earth bring forth grass, the herb yielding seed, and the fruit tree yielding fruit after his kind, whose seed is in itself, upon the earth: and it was so.
14 And God said, Let there be lights in the firmament of the heaven to divide the day from the night, and let them be for signs, and for seasons, and for days, and years:
20 And God said, Let the waters bring forth abundantly the moving creature that hath life, and fowl that may fly above the earth in the open firmament of heaven.
21 And God created great whales, and every living creature that moveth, which the waters brought

forth abundantly, after their kind, and every winged fowl after his kind: and God saw that it was good.
24 And God said, Let the earth bring forth the living creature after his kind, cattle, and creeping thing, and beast of the earth after his kind: and it was so.
26 And God said, Let us make man in our image, after our likeness: and let them have dominion over the fish of the sea, and over the fowl of the air, and over the cattle, and over all the earth, and over every creeping thing that creepeth upon the earth.
27 So God created man in his own image, in the image of God created he him; male and female created he them.
31 And God saw every thing that he had made, and behold, it was very good.

How Do We Comparatively Evaluate the Various Reasons and Arguments to Reach a Reasoned Judgment?

Winnie: Do you remember the concept of argument to the best explanation? Darwin's strategy was a clear case of that. He shows that the creationist accounts can't explain what we know about species and the fossil record but his theory can. In other words, his theory is better than the competing explanations.

Juanita: I don't understand the bit about the fossil record.

Winnie: A big problem for the creationists even in Darwin's day was the evidence from fossils. The creationist theory required all species to have been created at once. But what the fossil record showed is that there were creatures deeper in the rocks—so, from an earlier time—which were different and quite a bit simpler than those further up the rocks. And, very importantly, the remains of humans didn't show up until quite high in the fossil record. Most of the earlier fossils also were not like anything currently living, so they were species that had come and gone. In Darwin's time, no one knew how very old the Earth was. But thanks to Hutton and the theory of sedimentation, which you were just reading about, Juanita, many people realized that the Earth must be at least millions of years old. So it seemed that there would have been enough time for these species to change and to come and go. The creationist theory can't explain the fossil record, but Darwin can.

Stephen: Of course, I know a bit about Genesis. Not that I believe that it's literally true. I am more in favor of a view called "intelligent design," which is much more scientific. My view is simply that you can't explain the existence of the natural world merely by an appeal to evolution and natural selection. It's just too amazing. Lots of scientists agree with that as well. For instance, Michael Behe,²² as well as others, argues that at least some parts of the world are just too intricate and complex to be simply the result of chance and natural selection. It's not plausible that complex creatures like ourselves could have been produced by this slow, incremental process.

Winnie: Again, Darwin saw these objections coming. Let me read to you from Chapter 6, which Darwin called "Objections." You'll see how Darwin uses argument to the best explanation. He shows that he sees all the objections to this theory, and then he replies to each one.

LONG before having arrived at this part of my work, a crowd of difficulties will have occurred to the reader. Some of them are so grave that to this day I can never reflect on them without being staggered; but, to the best of my judgment, the greater number are only apparent, and those that are real are not, I think, fatal to my theory.

These difficulties and objections may be classed under the following heads: Firstly, why, if species have descended from other species by insensibly fine gradations, do we not everywhere see innumerable transitional forms? Why is not all nature in confusion instead of the species being, as we see them, well defined?

Secondly, is it possible that an animal having, for instance, the structure and habits of a bat, could have been formed by the modification of some animal with wholly different habits? Can we believe that natural selection could produce, on the one hand, organs of trifling importance, such as the tail of a giraffe, which serves as a fly-flapper, and, on the other hand, organs of such wonderful structure, as the eye, of which we hardly as yet fully understand the inimitable perfection?

Thirdly, can instincts be acquired and modified through natural selection? What shall we say to so marvellous an instinct as that which leads the bee to make cells, which have practically anticipated the discoveries of profound mathematicians?

Fourthly, how can we account for species, when crossed, being sterile and producing sterile offspring, whereas, when varieties are crossed, their fertility is unimpaired?

Organs of extreme perfection and complication. To suppose that the eye, with all its inimitable contrivances for adjusting the focus to different distances, for admitting different amounts of light, and for the correction of spherical and chromatic aberration, could have been formed by natural selection, seems, I freely confess, absurd in the highest possible degree. Yet reason tells me, that if numerous gradations from a perfect and complex eye to one very imperfect and simple, each grade being useful to its possessor, can be shown to exist; if further, the eye does vary ever so slightly, and the variations be inherited, which is certainly the case; and if any variation or modification in the organ be ever useful to an animal under changing conditions of life, then the difficulty of believing that a perfect and complex eye could be formed by natural selection, though insuperable by our imagination, can hardly be considered real. How a nerve comes to be sensitive to light, hardly concerns us more than how life itself first originated; but I may remark that several facts make me suspect that any sensitive nerve may be rendered sensitive to light, and likewise to those coarser vibrations of the air which produce sound.²³

Note how Darwin uses argument to the best explanation. It indicates that he clearly sees a possible objection to his theory and then goes on to reply to each one.

Problems and anomalies that cannot currently be explained by a theory are not sufficient to show that a theory should be rejected or that another explanation is the best explanation. There are an enormous number of phenomena that we cannot explain.²⁴ For example, we still don't have an adequate explanation of why cells become cancerous—but we would surely not want to credit this puzzle to a *bad designer*. The existence of currently inexplicable phenomena is part of the normal scientific process. There is an enormous burden of proof on anyone who wishes to reject a well-established and fruitful theory. Rejecting a theory like natural selection at this time in history would require an enormous set of conflicting observations *and* an alternative theory that had more explanatory and predictive power.

Stephen: But what about the problem that science is supposed to explain the underlying mechanisms for phenomena? Darwin didn't have any way of explaining how traits got changed or passed on or anything.

Winnie: You're right. That was a crucial weakness in Darwin's theory. But in the twentieth century, this problem was solved with Mendel's theory of genetics and the biochemistry of DNA. So now Darwin's theory has all the ingredients of a well-established scientific theory. It's been enormously fruitful, it explains a vast range of phenomena, and it's led to the discovery of underlying microexplanations.

Stephen: OK, so Darwin's made some good arguments for his theory. And he's stuck to the basic strategy of argument to the best explanation. But that doesn't mean his theory isn't just a theory and that there aren't problems with the theory that no one can explain.

at Do You Think?

What way is Stephen committing the fallacy of equivocation in his use of the term "theory"?

Winnie: You seem to be using the word "theory" in the sense of an unconfirmed or untested hypothesis. Like a detective who has a theory about the crime.

Stephen: Right. Is there anything wrong with that? I mean, we don't talk about Newton's theory of gravity—we talk about his law of gravity. Gravity isn't a theory.

Winnie: True, but to understand that you need to look at the history of science again. Newton talked about laws because he believed he was revealing God's laws—the laws which the celestial bodies obeyed. By the time we get to Darwin, Darwin knows he's not articulating God's laws. He's putting forward a powerful scientific theory. The distinction in science is between well-established theories and those that are not well established or are even false. The word "theory" isn't used in science to put down a scientific claim or suggest it's not credible. Darwin's theory is extremely well established and enormously fruitful. It's a model of a highly successful account of the natural world.

Calling a scientific theory a "theory" is not to suggest that it is especially uncertain or unjustified. There are well-established theories and new and poorly established theories. In addition, theories of great fruitfulness such as natural selection and Newtonian mechanics, when confronted with problems and anomalies, are most likely to be adapted rather than replaced by a totally different theory. Abandoning evolutionary theory for a spiritual account of evolution is not like abandoning one theory in science and replacing it by another, such as we saw with Hess and plate tectonics. It means abandoning scientific explanation altogether.

Stephen: But not all scientists believe Darwin's theory.

Winnie: I'm sure you're right. And a few of those doubters have made great efforts to try to undermine confidence in evolutionary theory in favor of some kind of intelligent design version of creationism. But when they do that, they're not really doing science. They've taken a theological viewpoint.

Stephen: That's sounds like a scientific prejudice to me. They're showing that evolutionary theory can't explain certain things and that the best explanation is an intelligent designer. Why isn't that science? Isn't that what scientists do—show problems with theories and offer better explanations?

Winnie: Yes and no. For example, some scientists disagree with the idea that evolution happens in a fairly uniform manner. They believe that evolution goes forward in fits and starts because the fossil record seems to reveal periods of relative species stability and then periods of dramatic increase and change in species. But none of these scientists doubts the basic causal processes of natural selection. Rather, they're trying to come up with a similar, physical, Darwinian account of these periods of relatively

great change.²⁵ That's quite different from saying that Darwin's theory can't explain something at this point in time, so we must abandon the search for physical causes and go with divine intervention.

Stephen: But what's wrong with that? If we couldn't explain the development of the eye without a designer, then it would just be good science to accept the designer explanation.

Winnie: Nice try, but notice that the designer theory isn't really an explanation. It doesn't tell us how the eye was made—just poof, the eye. It doesn't explain the variations among light-sensing creatures. It doesn't tell us why the eagle sees better than we do. It's the opposite of a fruitful theory. It's just this: "God did it. Now stop asking questions."

Stephen: So when there are problems with a scientific theory, one which is well established anyway, we just dismiss the problem?

Winnie: I didn't say that. Problems are what make science interesting. Figuring out how to explain things we don't currently understand is the business of science. But moving to intelligent design is to abandon the project. Even the intelligent design people don't deny the fossil record or that many species exhibit descent with modification. They just pick on a few examples that may pose a challenge and say that Darwin's theory can't explain that, so there must be divine intervention.

Stephen: OK, so maybe intelligent design has some problems. But I still like the idea of a divine creator.

Spiritual explanations lack the kind of fruitfulness we find in Darwin's approach. They do not yield new insights or predictions about other phenomena. Once we postulate the intelligent designer as an explanation, nothing else follows from it that enables us to make predictions or have insight into other aspects of the world. Naturalistic theories, in contrast, are fruitful, having models that lead to new explanations and predictions.²⁶

Apply Your Understanding
Exercises 5, 6,

Science and Statistics

While the theories of plate tectonics and natural selection illustrate many aspects of inquiry in the natural sciences, there is at least one key aspect omitted: statistical methodology. Statistical methodology is seldom central in chemistry and physics although statistical modelling plays a key role in quantum theory in physics. Statistical methodology is, however, important in many other sciences. Statistics plays a key role in an area like population biology, which is currently one of the central domains for the application and advancement of the theory of natural selection. As we will see in the next chapter, statistics also plays a key role in inquiry in the social sciences. Below, we introduce statistical reasoning by looking at the application of statistics to epidemics. This application of statistics grew into the discipline of epidemiology, and it is epidemiology that provides many of the studies on health now published so frequently in the media.

"And I Really Hate Statistics!"

Juanita: Well, that stuff on Darwin and geology was actually pretty interesting, but thank goodness there was no math. As I think about it now, it was the math in science class that really turned me off.

Winnie: I'm sorry you feel that way, Juanita, because math is central to a lot of science. Without precise calculations, scientists couldn't make the kind of predictions they do and we wouldn't have the kind of technology we have. It took a lot of math to make that cell phone you're so fond of.

Juanita: But you just showed me two examples of science without any math.

Winnie: Good point. You can understand a great deal of science without any math. Maybe science courses should emphasize that. But math, and especially statistics, play a crucial role in many sciences, especially the social sciences.

Juanita: Statistics—ugh! They're impossible!

Winnie: You have my sympathy. Statistics can be boring and incomprehensible. But with even a little understanding, you can make a lot more sense of what scientists are saying. Have you ever heard of Florence Nightingale?

Juanita: Of course. She founded the nursing profession, didn't she?

Winnie: Yes, but she was also one of the first people to use statistics to change public policy. She used graphs to show how the British Army hospitals were killing more soldiers than were dying on the battlefield.

Juanita: How did she do that?

Winnie: Well, I've got some more notes for you to read about the early days of the use of statistics in science that will help you understand. And don't worry—there are no numbers or formulas.

Juanita: I'll give it try, but I don't know. . . .

Early Medical Statisticians²⁷

While there were many practitioners of medical statistics in the mid-nineteenth century, one of the most renowned was Florence Nightingale, who is remembered most for her work of establishing nursing as a profession. Nightingale also made brilliant use of statistics, examining the deaths of soldiers in the Crimean War and demonstrating that the English government's negligent treatment of their soldiers caused more deaths than the enemy did. By instituting improved hygiene among the soldiers in the hospital in Scutari, Turkey, she was able to reduce the mortality rate from 40 percent to 2 percent and, of course, prove it with statistics.

Nightingale went on to use her statistical acumen to press successfully for significant changes in the treatment of British soldiers. As part of that effort, she created a whole new form of graphic presentation of statistics, making her the mother of "forensic graphing." As a leading statistician of the day, she worked with William Farr, another medical statistician. Farr, in turn, worked with John Snow, who is often credited as the father of epidemiology—originally the study of the spread of disease (epidemics), though now more generally the statistical study of health.

Inquiry and Statistics: Snow and the Search for the Cause of Cholera

Here is another page from Winnie's notes.

Science and Statistics

The statistical approach to studying phenomena such as the spread of disease was first developed in the mid-nineteenth century. A striking example of the early use of statistics in studying health was John Snow's search for the cause of cholera. Snow is famous for identifying and statistically demonstrating that the terrifying cholera epidemic in London was spread by the consumption of polluted water.

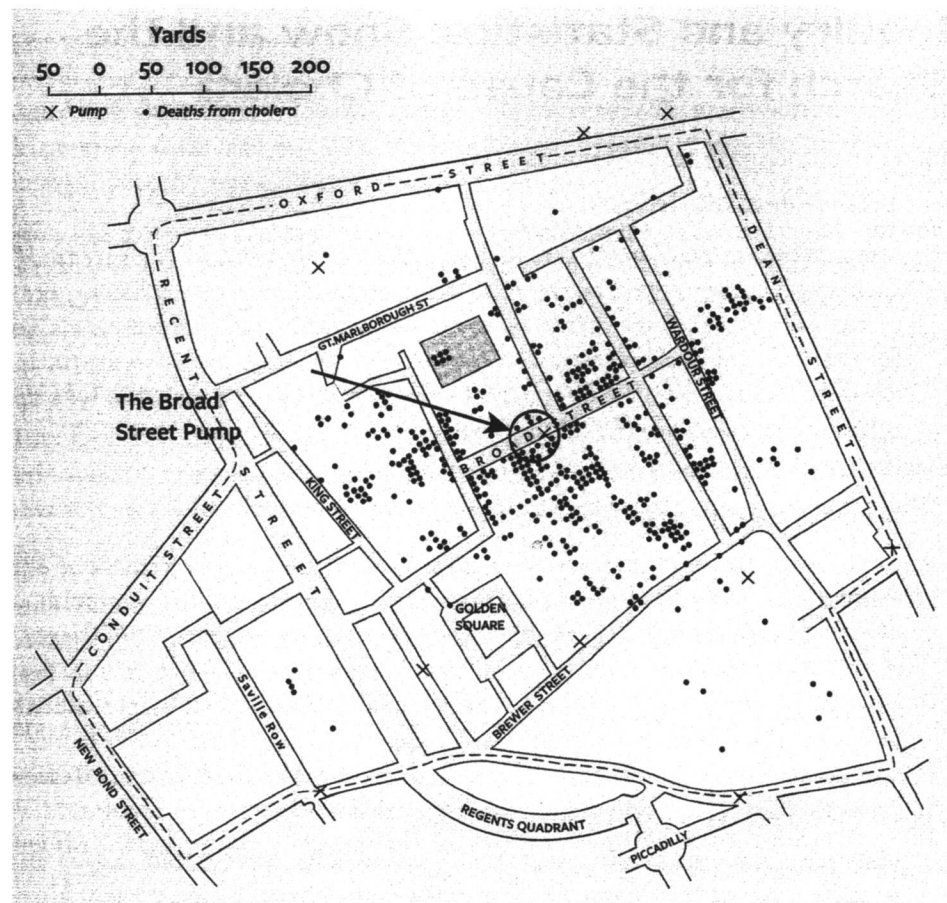
Snow: The Search for the Cause of Cholera

In the mid-1800s, there were two competing theories of the cause of cholera epidemics. This was at a time before the identification of the microbial cause of the disease, or even the acceptance of germs as the cause of illness. The dominant theory at the time was the miasma theory—that epidemics were caused by bad air. This theory, championed by many theorists including William Farr, had some statistical support in that those closer to the river seemed more prone to illness. This fit with the view that bad air descended from higher regions and was more concentrated at lower regions.

John Snow, an eminent London physician who had treated many cholera patients, noted that they first reported stomach pains and then diarrhea. This led him to suspect that ingestion, not air, was the source of the disease. He also observed that in one group of row houses, one side of the block had experienced widespread disease yet only one person on the other side had become ill. He noted that sewage on the infected side flowed into the well used by people on that side of the street but not into the well on the other side.

Snow, with the help of Farr, also collected and published statistical data from the 1849 cholera outbreak which supported his theory of water-borne illness but was unable to make any headway against the dominant miasma view. When the epidemic struck again in 1854, Snow and the registrar's office (led by Farr) worked together to determine whether there was a relationship between certain sources of water (namely the Southwark and Vauxhall Water Company, whose water contained London sewage) and cholera deaths. Snow was quickly able to establish that mortality among those consuming water from the Southwark and Vauxhall Water Company's water was five to ten times that of those drinking water from other suppliers. Snow produced a famous map,²⁸ which graphically illustrated how the disease was focused around a particular well. The handle to the pump was immediately removed and the spread of the disease declined dramatically.

Snow's technique was to demonstrate many examples of a correlation between exposure to polluted water and the incidence of cholera. Not everyone



Map of cholera outbreak distribution.

who drank the water died and many people who did not drink from the polluted water did get cholera. Nevertheless, using the map, Snow was able to show a strong correlation between the polluted drinking water and the incidence of cholera. (As discussed in Chapter 5, a correlation exists when two factors such as polluted water and cholera vary together, or co-vary.)

Unfortunately, Snow did not have a biological explanation of how the polluted water caused the spread of cholera because his work preceded that of Pasteur and the development of the germ theory of illness. Snow's polluted water theory was also up against the dominant and long-standing theory of miasmas, noxious forms of "bad air." (The miasma theory has since, of course, been supplanted by the germ theory of disease.)

As a result, despite his continued effort to collect evidence of a causal link, his theory did not receive widespread acceptance until after his death. In 1866, eight years after Snow's death, Farr wrote a report supporting Snow's theory with extensive statistical information. Farr and others, informed by the development of the germ theory of disease, had come to see that Snow's theory was the best explanation for the spread of the disease. Snow is credited with being the father of modern epidemiology because of his pioneering work and the statistical and mapping methods he used.²⁹

The Structure of Inquiry: Snow and the Search for the Cause of Cholera

What Is the Issue? What Kinds of Claims and Judgments Are at Issue? This is a very useful question in the context of statistical research. Basically there are two possibilities: the researchers may only be claiming a correlation, or they may be making a causal claim based in part on evidence of a correlation. (See the section on causal arguments in Chapter 5, pages 117–24 for a discussion of causal explanations and correlation.)

What Do You Think?

Was Snow only claiming a correlation between cholera and consumption of polluted water or was he making a causal claim?

Snow believed that the correlation between cholera and the consumption of polluted water revealed that something in the polluted water was the cause of cholera.

What Are the Relevant Reasons and Arguments on Various Sides of the Issue? Snow's pollution theory and the alternative miasma view are reviewed above. In fairness to his critics, there were cases of the disease in which the linkage to polluted waters did not appear to exist. In addition, the miasma theory did have some correlational evidence to support it, although it was weaker than the correlational evidence supporting the polluted water theory. Crucially, there was no biological explanation, no established theory of microorganisms that could explain the linkage. Snow has been vindicated, but it was not obvious at first because of the arguments and information of the day.

What Is the Context of the Issue? In scientific inquiry, one important aspect of context is the history of inquiry of the question being investigated. In this regard, it is important to ask whether the current study is consistent with or contrary to previous studies. We also want to know whether this claim has been extensively or only minimally studied. For this reason, we need to know the context of Snow's research. Snow had some evidence from the previous cholera epidemic that made him suspect that polluted water was the source of the epidemic. He was prepared when the epidemic hit again and, therefore, he was able to collect very convincing data confirming the correlation between polluted water consumption and cholera. He was also in a position to alter the situation by having the pump handle removed, and the immediate decline in the incidence of cholera gave him additional grounds for believing that the polluted water was the cause of cholera. Unfortunately for Snow, the context was one in which there was a dominant alternative view, and the germ theory of disease was not yet available.

How Do We Comparatively Evaluate the Various Reasons and Arguments to Reach a Reasoned Judgment?

What Do You Think?

How reasonable was it to accept Snow's theory?

At the time, Snow had grounds for making a causal claim because of the decline in cholera resulting from the removal of the well handle. But his lack of an explanatory model was a reasonable limit to the acceptance of his view. His method of collecting data to establish a causal claim was, however, an insight of great fruitfulness and has become a backbone of most scientific inquiry.

Applying Statistical Techniques in the Physical Sciences: Climate Change

One of the most important recent uses of statistics in the physical sciences is its application to the issue of climate change. An enormous massing of data from a variety of sources has shown that the world's global average temperature is increasing at a precipitous rate. While there had been some debate about this claim, there is now no question about the increasing temperature. The remaining controversy is over the cause or causes of this increase. Let's see how our students can address this question.

"Global Warming"

Winnie, Phil, and Nancy have just been watching a program on climate change.

Winnie: Wow. What a depressing show. From what they say, it appears we're headed for a disastrous change in the weather.

Phil: Wait a minute. That was just one show and one opinion. There are some scientists who point out that there are problems with these theories. And many people, especially some politicians, reject global warming.

Nancy: That's terrible. How can they do that? The world is clearly suffering and yet other people go around trying to protect their interests with lobbying and propaganda. They're incredibly selfish. I think we have a duty to the world and future generations to protect the Earth from human activity.

Phil: Wait a minute. The weather people can't even predict the weather for tomorrow so why should anyone think they could predict the climate ten, twenty, or fifty years from now?

Winnie: Nice try, Phil, but that's a faulty analogy. The next day's weather is hard to predict because it's affected by many local factors. But climate is different. We know the climate is warmer in Hawaii than Alaska. And January is colder than July—in the Northern Hemisphere anyway. Individual days might be hard to predict, but the overall climate is actually easier to predict.

Phil: I never thought of it that way. I see your point. Got to be careful with my analogies, I guess. But aren't you suspicious of these climate change types? Don't you think it's a sort of left-wing conspiracy to justify government interference in our lives?

Winnie: No, I don't, and before you buy that line, we'd better do an inquiry and find out just what the science really says and how well it's supported.

Inquiry into Climate Change

What Is the Issue? What Kinds of Claims and Judgments Are at Issue?

Nancy: Before we do that, we'd better get clear on the issue.

Phil: Good point. I know that I used to think the controversial issue was whether the world is getting warmer. But apparently that's no longer the focus of the argument. The issue is whether the warming is the result of human activity. We know that the climate changes naturally from time to time—look at the ice ages. But the real question is whether the current change is caused by humans.

Nancy: In that case, I think that the question is: are humans causing the current climate change?

Phil: Sounds good. Before we do any research, though, let's get clear on what we know, or think we know.

Winnie: We all know the theory, but just to be sure, it goes like this. As humans use fossil fuels and engage in other activities like agriculture, they emit certain gases which stay in the atmosphere for quite a long time. And these gases act like a kind of insulation, keeping the heat from the sun from escaping the atmosphere. And because these gases last a long time, continued emissions will have an added effect on climate change.

The issue around climate change has often been called "global warming." But this is a bit misleading. Climate scientists prefer the term "climate change" since the effect of the increased greenhouse gases is to warm some places and chill others. The issue of whether the climate is changing dramatically is often confused with the issue of what is causing the change.

What Is the Context of the Issue?

Phil: We know that the debate has been going on for some time. We know that various interests have opposed the claim that climate change is caused by humans and that many American politicians challenge the claim. They believe that the claim is sponsored by some left-wing movement which includes Al Gore. We know, though, that the majority of people, including the Obama administration, now agree that there is a problem. On the other hand, I just looked up a recent vote in the U.S. Senate,

and about half the senators (virtually all Republicans) don't believe that humans are contributing to climate change.³⁰

Nancy: Well, we all know that a lot of the controversy is politically and economically motivated. I think most of these critics realize that addressing the problem of greenhouse gas emissions means a significant change to their financial positions.

Phil: That may be. In any case, I think it's pretty clear that what should be a judgment of fact is treated as a political question. But like it or not, that's the context of this issue.

Nancy: Well, that pretty much fits with what I know.

Winnie: Me too. But I think we should also check into some of the history of the issue.

The history of this issue, though short, is very relevant because of the profound political and economic implications of the theory.

Winnie: I didn't realize it, but the topic was brought up at an international conference of the World Meteorological Organization as early as the late 1970s and the International Panel on Climate Change (IPCC) was formed in 1988. So scientists have been concerned about this issue for at least forty years. The United Nations created the IPCC to provide a credible source of information since everyone knew this was going to be a big political issue. What's also interesting is that the role of the IPCC is not to do research, but, like us, to come to a reasoned judgment based on all the research they can find. The panel actually was given three responsibilities: assess the climate change science, assess the impact of climate change, and suggest what should be done.

What Are the Relevant Reasons and Arguments on Various Sides of the Issue?

Phil: So what's the position of the IPCC?

Winnie: Here's the central claim from their latest report of 2014:

The evidence for human influence on the climate system has grown since the IPCC Fourth Assessment Report (AR4). It is *extremely likely* that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in GHG concentrations and other anthropogenic forcings together. The best estimate of the human-induced contribution to warming is similar to the observed warming over this period (Figure SPM.3). Anthropogenic forcings have *likely* made a substantial contribution to surface temperature increases since the mid-20th century over every continental region except Antarctica. Anthropogenic influences have *likely* affected the global water cycle since 1960 and contributed to the retreat of glaciers since the 1960s and to the increased surface melting of the Greenland ice sheet since 1993. Anthropogenic influences have very likely contributed to Arctic sea-ice loss since 1979 and have *very likely* made a substantial contribution to increases in global upper ocean heat content (0–700 m) and to global mean sea level rise observed since the 1970s.³¹

And here's what they mean by their confidence terms. They're a lot like the ones we've learned to use.

Phil: I admit that IPCC is the best source of climate change information, and their views are widely supported by other scientific organizations.³³ So finding credible objectors was actually quite difficult. Many of the objectors have been discredited for working for the oil companies. But there are still objections that are probably worth considering.³⁴ The trouble is that the details of the debate are overwhelming and beyond anything I had the time or ability to look into. One of the disturbing aspects of the information on the Web is that most of the critical stuff is not by scientists, to say nothing of climate scientists.

One of the most common objections—though not by scientists—is that the whole thing is a hoax created by scientists to promote government control of the economy. The chair of the Environment and Public Works Committee, Senator Inhofe, has even written a book titled *The Greatest Hoax: How the Global Warming Conspiracy Threatens Your Future*.

Winnie: I sure hope you're not falling for that conspiracy nonsense. Thousands of scientists perpetuating a hoax? I don't have much tolerance for this whole conspiracy business, but that's a topic for another day.

Phil: Actually, I agree. I found that theory just too politically motivated to spend any time on. But before I review the objections, we should remember that, given the current scientific consensus, the critics bear a strong burden of proof. I found three objections that were either popular or might have some scientific plausibility:

1. The graphs showing a dramatic increase in global warming were misleading and erroneous.
2. The claims about human "forcing" are based on computer models, not "hard science." Or, to put it another way, there isn't a really well-established causal connection between human greenhouse gas emissions and the change in the climate.
3. There's an alternative mechanism that is correlated with warming—solar activity.³⁵

Nancy: So how do the supporters of the theory that global warming is humanly caused respond?

Phil: The first objection is to the so-called hockey stick graph by a scientist named Mann. It's a version of the global warming graph we see in Al Gore's movie.³⁶ The claim is that it exaggerates the amount of global warming. I used the National Academy of Science report that reviewed Mann's graph at the request of the U.S. Congress.

Likelihood Scale	
Term	Likelihood of the Outcome
Virtually certain	99–100% probability
Very likely	90–100% probability
Likely	66–100% probability
About as likely as not	33–66% probability
Unlikely	0–33% probability
Very unlikely	0–10% probability
Exceptionally unlikely	0–1% probability

Characterizations of levels of confidence expressed in terms of the odds of being correct.³²

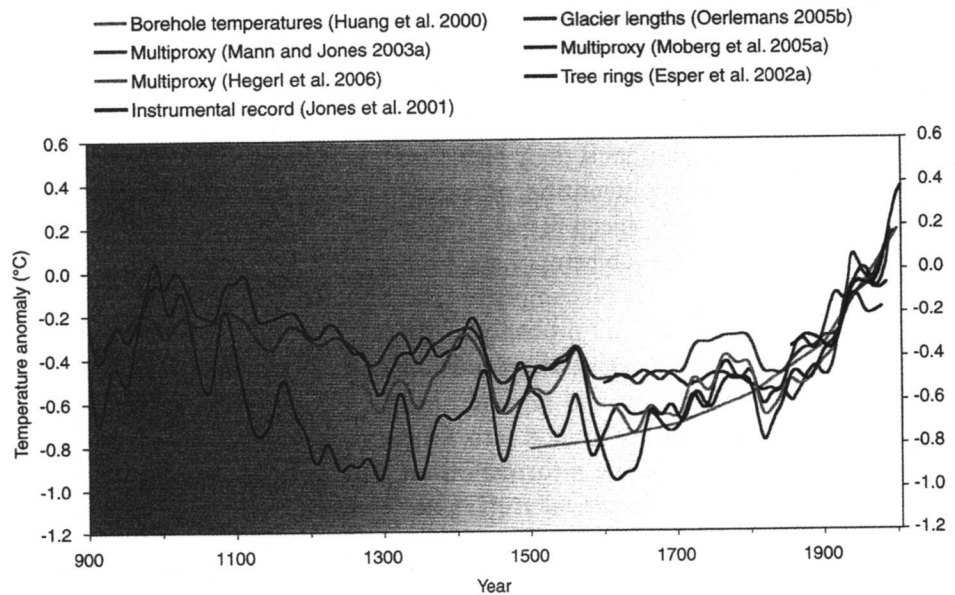


FIGURE S-1 Smoothed reconstructions of large-scale (Northern Hemisphere mean or global mean) surface temperature variations from six different research teams are shown along with the instrumental record of global mean surface temperature. Each curve portrays a somewhat different history of temperature variations and is subject to a somewhat different set of uncertainties that generally increase going backward in time (as indicated by the gray shading). This set of reconstructions conveys a qualitatively consistent picture of temperature changes over the last 1,100 years and especially over the last 400.

They said basically that, while the early temperature data is obviously weak (e.g., data about temperatures in the middle ages), the recent data is credible. Have a look at this awesome graph.³⁷

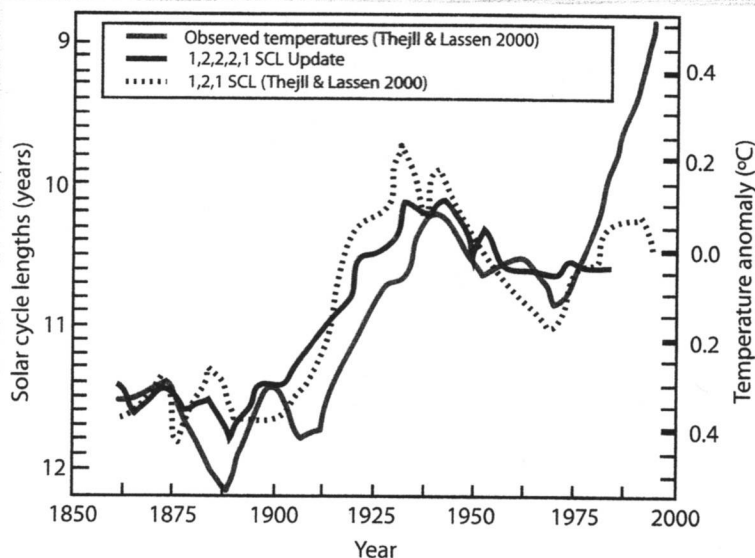
Winnie: It's interesting—just about all researchers using all sorts of different approaches get a similar curve.

Phil: As for the second objection, my first reaction to the idea that the computer models weren't a good tool was to wonder how you would theorize about global climate without these kinds of models. Making models is one of the main things that scientists do. Of course, the models in this case are really complex and there's a lot of uncertainty. But after all, we're talking about the whole planet. I looked at the IPCC site for some response to this objection. The IPCC points out that these models have been consistently revised and improved over the past thirty years as more historical and current data are collected. They claim that the only way to get the model to have outputs that fit the data is to factor in greenhouse gas data. They don't deny the effect of other factors such as solar cycles on climate (and things like volcanoes and human dust production, which slow global warming because the dust reflects sunlight back). But the key claim is, if you don't factor in what we know about greenhouse gases in the atmosphere, you don't get a temperature curve that fits the data.

Winnie: But what about solar activity as an explanation?

One thing to note about this graph is the different methods that scientists use to establish past temperatures. These methods, which do not directly measure the temperature but are seen as good indicators of the temperature, are called proxies.





Observed temperatures (red solid line) and 1,2,1-filtered solar cycle lengths (black dotted line) as shown in Thejll and Lassen, 2000. 1,2,2,2,1-filtered solar cycle lengths as shown in Friis-Christensen and Lassen, 1991, with four updated points (blue solid line).

Phil: The story is interesting and brief. Here's a graph that tells it all:³⁸

As you can see, up to about 1990, the fit looks pretty good and people could plausibly argue that there was some relationship between the solar cycle and global temperature variation. But after 1990, they parted ways dramatically. And now, even the leading theorist of the solar argument has abandoned his position, saying that the correlation between global warming and solar activity has not been maintained since the 1990s.³⁹

Nancy: But aren't all those objectors just a bunch of paid hacks for the oil companies?

Phil: Some of the opponents of the greenhouse gas theory were in fact supported by oil companies and car companies. Of course, I don't want to be accused of committing an ad hominem, but it does seem to give some reasonable grounds for suspicion.⁴⁰

How Do We Comparatively Evaluate the Various Reasons and Arguments to Reach a Reasoned Judgment?

Winnie: The impression I got is that there are a few credible scientist out there who have reservations, but their reservations are about how confident we can be in the predictions, especially given the effect that unpredictable human behavior has on the results. It's the old confounding factor problem. For example, the recent financial crisis slowed economic activity and resulted in lower greenhouse gas outputs for a little while.

One of the scientists argued that there is correlation but no causation. Using graphs like the above graph is used to illustrate an apparent correlation between solar cycle length and temperature. But without a causal mechanism to explain the relationship, this theory faces the same problems that Sn faced. When the correlation disappeared in 1990, the other scientists who had put forward the theory abandoned their claim of correlation although they still often cite less responsible opponents.

Phil: True, but overall the convergence of scientific opinion is very real and very strong. The skeptics don't really seem to have very credible objections. But the problem is that politically motivated critics know that they can skew the debate just by saying there's some uncertainty.

Winnie: I remember that also came up when we were discussing evolution. Religiously motivated folks try to use anomalies to suggest that the theory is uncertain.

Phil: Naturally people like to have certainty before they act, especially if they're going to make major changes. We'd all like certainty. But we have to realize that the "very likely" level of confidence, which is, after all, 90 to 100 percent probability, is as close to certainty as we're going to get.

Winnie: Good point, Phil. Given our inquiry, it seems that the crucial investigation should be about what we should do now. Should we be reducing GHG emissions or preparing for the inevitable problems this warming is going to produce?

Nancy: False dilemma, Winnie. Surely we should be doing both.

Winnie: Good point, Nancy.

Nancy: I really feel that putting all these gases into the atmosphere is just wrong. Humans just can't be messing with the environment on this scale. It's got to be a disaster.

Winnie: I appreciate your feelings, Nancy. But we don't need to just rely on feelings. We have good solid evidence that this is a problem. I think that most people do care about the environment and future generations. It's just a question of figuring out what to do and, of course, weighing the tradeoffs between all the different approaches.

Phil: That's a whole other inquiry, and a really important one.

The issue of climate change is complex, but overwhelming scientific consensus, together with a lack of credible objections, make it clear that humans are making an immense contribution to climate change. There is, of course, the very major problem of what to do about it. We leave the reader to continue this inquiry, using the references suggested below, by exploring more of the evidence, arguments, and objections. Time is always a precious commodity and some research is almost always better than none despite the cliché "a little bit of knowledge is a dangerous thing." That cliché assumes that the people with little knowledge will not realize how little they know. The problem facing the citizen dealing with the climate change issue is the profound economic and social significance of the issue and the complexity of the science involved. Without doing an extremely comprehensive inquiry, the average citizen can sensibly rely on experts consensus, with an appropriate review of the critics.

We have tried to illustrate such an inquiry above. While not the last word, it is more than most citizens probably have done or even could be expected to do. But with the concepts learned from this text, students should be able to undertake such an inquiry. As the dialogue illustrates, with a basic understanding of science, the role that graphs play in illustrating and arguing for a correlation, the appropriate ways

to express or illustrate statistical uncertainty, and the appropriate use of information about the credibility of sources, one can make a reasoned judgment. The issue of climate change also illustrates the frequent need to evaluate information in the context of decision making. Climate science cannot tell us how to act in the face of the strong possibility of disastrous negative consequences. But as noted, the IPCC has a third working group that does have information on strategies for both mitigation (how to reduce GHG emissions) and adaptation (what to do about the consequences of global climate change, such as sea level rises).⁴¹

**Apply Your
Understanding
Exercises 8, 9**

Scientific Inquiry: A Final Note

You may have noted that we have not used traditional experimental sciences such as physics and chemistry to illustrate scientific inquiry. Rather, we have illustrated scientific inquiry by looking at what are called “observational sciences.” Learning only about experimental sciences gives a limited impression of the breadth, complexity, and challenges of scientific evidence and argument. In experimental sciences such as physics and chemistry, researchers often have the enviable luxury of being able to control virtually every factor when doing their investigation. When these researchers manipulate something, like adding a chemical or increasing a force, for example, they can be reasonably confident that the result is caused by the factor they changed—not by some other confounding factor. Because experiments provide a high level of control, the experimental sciences usually have more straightforward arguments for what constitutes the best explanation of their results.

Observational sciences, on the other hand, face special challenges. In the sciences we have alluded to in this chapter, the observations are often very remote in time from the phenomena being investigated. As we saw, this creates an additional challenge for the task of identifying the best explanation. You should note that one way that this problem is addressed is by analogy. Geologists theorize about glacial activity in part by noticing how current glaciers behave. Biologists can run experiments to show how species, such as fruit flies, evolve in the lab, but they must argue by analogy, as Darwin did, that this process is mimicked in the field.

We also do not wish to leave readers with the impression that all debate in science is about large and profound theories such as evolution and climate change. Most debates are about much more particular topics. Sometimes, the debates are about very esoteric topics such as the accuracy of carbon dating, and sometimes, scientists debate better known topics, such as what accounts for the disappearance of the dinosaurs and many other species some 65 million years ago. Science progresses because of debate and because scientists continue to search for new evidence and the best explanation for the phenomenon at issue.⁴²

In the next chapter, we will study in more detail the use of statistics in science, with a focus on social science. We will look at the scientific investigation of human behavior and the special challenges human behavior presents for inquiry.

**Apply Your
Understanding
Exercises
10, 11, 12**