Chapter 1: How Science Makes Progress

Humans are born on a planet that serves as a relatively serene, nurturing island in an otherwise vast, hostile universe. The human brain is capable of contemplating the nature of the Earth and the cosmos in which it exists. But the brain is also complex, and has several different ways of learning about the world and of expressing its knowledge. Science is the process by which humans use their creative, logical, and calculational abilities to develop and test their guesses about the nature of the universe and everything in it. In this chapter, we will discuss both the formal structure of the scientific method and some thoughts on how the scientific process actually works in practice. We will also compare science with other manners of expressing humanity's impressions of the universe: philosophy, theology, and art.

Goals of the Scientist

The basic goal of a scientist is to describe the universe and its contents in terms of models that are based on a (preferably small) set of principles. Scientists want to describe nature as simply and completely as possible. There is a potential contradiction here: can a *complete* description also be *simple*? The answer can only be "yes" if the universe contains a high degree of order, *i.e.*, if it is based on a relatively small number of basic "laws" that govern both its structure and its behavior. If scientists did not believe this to be the case, then they would have no confidence that their endeavor is worthwhile. So, it seems that the scientist must accept on *faith* that: the universe is built on a foundation of order, which can be described through one or more underlying logical principles. The only justification for faith in this assumption is that the methods of science have led to an extraordinary increase in our understanding – and ability to make reliable predictions – of natural phenomena; or, in colloquial terms, "don't argue with success!"

Scientists have other, more specific goals as well. For a long time, it was thought that the universe as a whole probably did not change with time. In the 20th century, however, astronomers have found evidence that the universe is in fact expanding. (We will discuss this in full later in the book.) In addition, geologists have determined that the Earth has changed since its formation. Many scientists are therefore interested not only in the structure of the universe, but also in its development over time. Another concern, mostly of "applied" scientists such as engineers and medical researchers, is the adaptation of scientific knowledge to practical uses.

The Scientific Method

The basic procedure used by scientists is called the scientific method, summarized in Figure 1. It consists of a small number of steps that are repeated:

1. Observe a natural phenomenon. We often discover new phenomena by exploration with new instruments or sending probes into realms (*e.g.*, other planets) where none have been before. These activities often lead to discoveries that broaden our view of the natural world.

2. Develop hypotheses that might be able to explain the phenomenon. Use deductive reasoning (see below) as much as possible, based on previously developed theories and mathematics, if appropriate. It is, however, often necessary for the scientist to use imagination: the development of hypotheses is

usually the most creative part of the scientific process. The scientist usually starts with a model, which is an idealized or simplified description that explains the basic properties of the phenomenon.

3. Make predictions for each of the hypotheses. That is, if the hypothesis is true, what should be the properties of the phenomenon? Again, mathematics and previously developed theories can be used, although the scientist must keep in mind that the previous theories are also part of the hypothesis that will be tested in the next step.

4. Experiment with or re-observe the phenomenon in different ways that test the hypotheses. This step requires that new experiments be devised or that the phenomenon be observed in a different way if it is not possible to perform an experiment. This step often requires imagination and the development of new instrumentation.

5. Compare the results of the tests in step (4) with the predictions of step (3).

6. Return to step (2) and repeat the cycle.

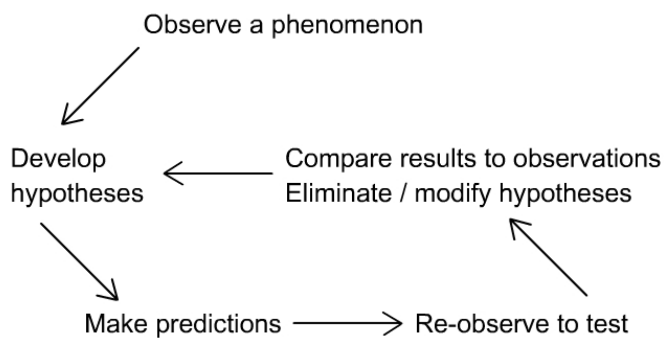

Figure 1-1. The steps of the scientific method. The loop at the bottom is never-ending.

Step (6) highlights an important aspect of the scientific method: It is never-ending. A theory[1] can *never* be considered final, no matter how well its predictions agree with observations. Rather, any theory remains subject to future rejection or modification (1) should new evidence emerge that decisively contradicts it or (2) if a new model explains a wider range of phenomena than the previous theory does. Therefore, science possesses the important property of self-correction.

Deductive reasoning, mentioned in step 2 above, corresponds to logical consequences of a hypothesis or theory. For example, if we hypothesize that planets are spheres and we know that a sphere appears as a filled circle when viewed from a distance, we can state that the spherical planet hypothesis predicts that all planets should appear as circles when viewed through a telescope. Inductive reasoning, on the other hand, draws general conclusions from limited observations. For example, if three asteroids are observed to be spherical, one might conclude that all asteroids are spherical. This is not necessarily true – it may be that only the largest asteroids are spherical, and only the largest ones could have their shapes measured by currently available telescope. But it can be a good starting point for developing hypotheses.

[1] "Theory" is a term sometimes given to an explanation that is well supported by data, but a word that scientists often use more loosely to include any model or hypothesis. A "law," on the other hand, is often used to refer to a concise summary of the observed behavior of nature. Laws describe this behavior while theories explain it.

What We Gain from Science

Science, therefore, is *not* a process in which "correct" theories are *proved*, but rather one in which invalid hypotheses are disproved. In fact, the 20th-century philosopher of science Karl Popper specified that a scientific theory should be falsifiable. Although this seems a very negative statement, it is this property of the scientific method that guarantees progress toward understanding nature. Just as Arthur Conan Doyle's fictional detective Sherlock Holmes solves perplexing crimes by eliminating possibilities that are contradicted by the evidence, scientists eliminate hypotheses about natural phenomena that cannot be true. One must be careful, though, to examine assumptions behind predictions that a theory fails to fulfill: it may be an assumption that is wrong rather than the theory. For example, the planet Uranus, discovered in 1781, its orbit was found to deviate from the predictions of Newton's laws of gravity and motion (which are discussed in Ch. 4). But Newton's laws were in fact quite accurate. It was the assumption that there are no other major planets beyond Uranus that was incorrect. In fact, the adherence to Newton's laws led to the prediction and discovery of the presence of another large planet, Neptune.

Another quality of a successful theory is that it should lead toward a comprehensive understanding of a number of natural phenomena, rather than just an explanation of a specific observation. Science seeks a unified view of the world, not one that offers a different theory for each phenomenon.

But does the scientific process lead to the *truth*? The answer to this depends on how we define the word "truth." In the author's copy of *Webster's New Collegiate Dictionary*, "truth" has two relevant meanings: (1) "the state of being the case," and (2) "the property…of being in accord with fact or reality." Although these may at first appear to be the same, there is an important philosophical difference. The first definition implies that the truth is the way things actually are, while the second merely requires that the truth describe observed events. It is this second interpretation that is relevant to science: The scientific method leads (in the long term) to an increasingly accurate description of nature. By "increasingly accurate," we mean that, over time, the predictions of scientific theories correspond more closely to observations of natural phenomena. That is, science makes progress toward describing nature more accurately.

In summary, rather than "proving" that "true" theories are correct, science produces evidence in support of descriptions of nature that are better than previous versions because they provide more accurate predictions of natural phenomena.

Does this mean that the process of science always leads toward a refinement of our understanding of nature? In the long-term, the answer seems to be "yes!" But over short periods of time, the intermediate results of the scientific method can be misleading and can even take us farther from the "truth." Many hypotheses are not good descriptions of nature, yet for some time they may be consistent with the available data. Even when they are not consistent, the hypotheses may be modified so that their adjusted predictions conform with the data. Eventually, however, false hypotheses will be found to conflict with the characteristics of observed phenomena and will be discarded by the scientific community.

One example of the long-term progress of science is the discovery that we are not at the center of the universe, which is discussed more thoroughly later in the book. Until the early part of the 20th century, it appeared that the Milky Way galaxy in which we live was the entire universe, that the Sun was at the center of this universe, and that spiral "nebulae" (clouds in space) were probably swirling clouds of gas. However, during a 9-year period starting in 1918, astronomers first found evidence that the Sun is not at the center of the Milky Way and then discovered that the spiral "nebulae" were entire galaxies of stars, similar to the Milky Way but very distant. This radical change in our picture of the universe took place because of the availability of convincing new evidence (in the case of the spiral nebulae, obtained using the newly constructed 100-inch telescope on Mt. Wilson near Los Angeles). However, a short time before these observations were made, faulty measurements by a respected astronomer seemed to show that spiral nebulae rotate, which would not be observable over human lifetimes if the nebulae were really distant galaxies. For a while, this caused most astronomers to reject the correct hypothesis that the Milky Way is just one example of a multitude of galaxies.

Does Science Provide Absolute, Objective Truth?

We have already asserted that the scientific method, in the long run, leads to the truth, as long as we define "truth" as an accurate description of nature. But does it result in *absolute, objective* truth? As emphasized by the 20th-century philosopher of science, Thomas Kuhn, it appears that science cannot claim that it produces "absolute truth." A good example cited by Kuhn is the theory of gravity. Newton's Law of Universal Gravitation (discussed in Chapter 4) provides a very accurate mathematical description of the mutual attraction of two massive bodies. But it is valid only if we do not consider the region very close to an object as massive as the Sun. In this case Einstein's more accurate Theory of General Relativity (presented in Chapter 9) must be used. We might then expect that Newton's theory would be *qualitatively* similar to Einstein's as well. It is not. While Newton's explanation of gravity was that the force occurs through a rather mysterious "action at a distance," in Einstein's theory the presence of a massive object curves space (and time) such that the motions of all other bodies – and even of light – through space are affected. And, while we know that Einstein's theory provides a mathematical description that agrees with the most precise measurements that we are able to make at the present time, it is possible that future observations will require a new theory that again uses a qualitatively different physical picture of how gravity works.

Science, it seems, does not provide absolute truth, but, rather, tentative descriptions of natural phenomena. These descriptions become more refined with time, in that they predict the behavior of natural phenomena more accurately, but history has shown that we should not consider even the most respected theories to represent "absolute truth."

But is science at least objective? This claim has been called into question by a number of social theorists who argue that science, like any other human endeavor, is affected by cultural and other biases. Indeed, the formation of hypotheses is an inherently subjective process, since it represents the creative aspect of science. (The design of new instrumentation and development of new predictions are also creative, although more concrete and therefore less subjective.) We can never be certain that the "correct" hypothesis to explain a given observation has been proposed yet. Even the phenomena that scientists study depend to a large extent on what problems are considered by the scientific community to be important at the time. However, this criticism, often directed at the applied science of medicine, neglects that science eventually eliminates hypotheses that do not describe nature well. At any given time, the current body of scientific knowledge consists of theories whose predictions have passed a number of observational tests. Any of those "accepted" theories is subject to falsification should reliable evidence later contradict it. Particularly vulnerable are the recently developed theories – which abound in medical science, for example – that have not yet been in place long enough to test thoroughly. While the current body of accepted scientific knowledge has some subjective aspects, the elimination of invalid hypotheses and the evidence in support of favored theories over very long periods of time are quite objective.

Beauty and the Formation of Hypotheses

Since it is the most creative step in the scientific method, the process of hypothesis formation is interesting to examine. Let us imagine that a scientist has just observed a new phenomenon. How would he/she try to explain it? It would make little sense to start "from scratch." It is likely that the phenomenon is related to, or even a previously unobserved aspect of, other better-studied phenomena. Hence, the scientist would probably first assume that the currently accepted theories that seem to explain the other phenomena probably also apply to the new phenomenon as well. If the new observation is not fully explained by the current theories, then the new hypothesis would probably involve a mathematical and/or logical extension of the existing models.

However, the scientist must guard against building overly complex theories in this manner. History has demonstrated that successful hypotheses usually possess the properties of simplicity, order, and symmetry, which together are often referred to as beauty. If the new hypothesis adds an additional layer of complexity to the previous theories, one should suspect that it will not lead to an advance in our understanding of nature. The 20th-century physicist Paul Dirac asserted that "It is more important to have beauty in one's equations than to have them fit experiments…because the discrepancy may be due to minor features that are not properly taken into account and that will get cleared up with further developments of the theory" [*Scientific American*, May 1963]. On the other hand, if a "beautiful" model agrees with experimental data only if it is modified so much that it loses its simplicity, it will be considered by most scientists to have been falsified. Thomas Huxley once said, "The great tragedy of science is the slaying of a beautiful hypothesis by an ugly fact" [in his essay "Biogenesis & Abiogenesis, 1870]. Perhaps all good theories are beautiful, but not all beautiful theories are good!

Why should we require that only "beautiful" theories take part in our description of nature? There are three basic reasons. (1) There are countless numbers of extremely complex models that could describe nature. But each of these would probably only describe a single phenomenon well. In other words, in this case, science would be unable to make much progress in understanding nature, since for each phenomenon there would be a separate explanation that might be unrelated to the explanations for other phenomena. (2) Science has indeed made great progress in explaining a host of observed phenomena, including some that appear quite complex, using beauty as a guide in the development of hypotheses. (3) The third reason, which is a conjecture, is that, since we are creations of this universe, we see as "beautiful" the foundation upon which the universe is constructed. The most successful hypotheses then appear beautiful to us since they describe the characteristics of the universe from which our sense of beauty is derived.

"Normal" Science and "Revolutions"

In the mid-20th century, Thomas Kuhn surprised the scientific community with his book *The Structure of Scientific Revolutions*. It describes a process of development of scientific thought that seems less systematic than had been supposed. According to Kuhn, the progress of science can be separated roughly into two different phases: the "normal" science of puzzle solving and periods of upheaval that he termed "scientific revolutions." Normal science is characterized by attempts to explain phenomena within the context of the currently accepted set of paradigms. By "paradigm," he meant a way of picturing a phenomenon based on a theoretical description. For example, the current paradigm for an orbit of a planet around the Sun is an ellipse with the Sun at a focus (see Chapter 3). This is strictly an idealization that could be realized only if the Sun and planet were the only objects in the universe, but it is still a useful way for scientists to think about orbits in order to consider related phenomena. This elliptical orbit is described mathematically using geometry and Newton's equations (see Chapter 4).

Kuhn provides evidence that phenomena that do not fit into the current paradigms are often completely overlooked or ignored as unimportant. For example, guided by Aristotle's paradigm that heavenly bodies (beyond the Moon) do not change, Europeans in the Middle Ages dismissed the appearance of comets and exploding stars as atmospheric phenomena of little interest, and paid them little attention. Chinese astronomers, however, regarded them as important occurrences and meticulously recorded these "guest stars." Another example is the discovery of the planet Uranus. It is visible to the naked eye from a dark site, yet was not discovered as an object that moves relative to the background stars until after Copernicus's and Kepler's models of the solar system allowed for the possible existence of undiscovered planets. Experiments or observations that do not fit into the paradigm generally are not undertaken. For example, Aristotle viewed a swinging pendulum as no more than a falling stone, while Galileo studied its periodic motion as an interesting phenomenon.

This adherence to the current set of paradigms can impede the progress of science for some time. After all, appointments of professors at universities and funding of scientific research are usually decided by established scientists who often insist that the current paradigms be followed. Still, in the long run, invalid theories will lead to conflicts with observations, and such paradoxes serve to advance our understanding by stimulating changes in the accepted set of paradigms.

A "scientific revolution" occurs when there is such a change in a major paradigm, usually to explain (often new) data that conflict with the old paradigm, creating a "crisis" in science. One example that we will study (Chapter 3) is Kepler's model of elliptical orbits of planets around the Sun, which overturned a two-millennium-old belief that all motions in the heavens are circular. The changed paradigm often leads to a period during which there are a number of changes to other paradigms and new modes of thought are developed. Thus, Copernicus's switch from Earth-centered to Sun-centered orbits inspired further major advances in our understanding of nature by Descartes, Galileo, Kepler, and Newton.

A curious property of these revolutions is that the new paradigms often do not at first explain the existing data better, but are more "beautiful" or apply to more phenomena. Copernicus's model provided considerably worse fits to the positions of planets on the sky as a function of time than did the complex Earth-centered model of Ptolemy because Copernicus still erroneously used circular rather than elliptical motions. However, it was appealing because it placed the biggest object in the solar system (the Sun) at the center, which made sense to many thinkers of that era.

Kuhn's analysis of the scientific process has been criticized on the grounds that it oversimplifies the way that scientists approach problems. Nevertheless, his work remains an important milestone because it altered the erroneous view that science progresses slowly and systematically through strict adherence to the scientific method. Major advances often occur when a genius like Newton or Einstein provides major new insights that radically change our view of nature.

Comparison of Science with Philosophy and Theology

In what ways is science similar to and different from other methodologies by which humans have attempted to understand the universe? Philosophy draws logical conclusions based on a set of what seem to be reasonable assumptions. There are ways of determining whether the logic of a complex series of philosophical steps is self-consistent, and the original set of assumptions can be determined to be invalid if the conclusions drawn conflict with observations. Hence, philosophical theories can be falsified, just as scientific hypotheses can. The most fundamental difference seems to be that philosophy is concerned mainly with questions about existence, the ultimate nature of reality, morality, ethics, and other non-physical subjects, while science addresses questions of a more direct physical nature. Theology is the study of the nature of the presumed creator of the universe. (Theology should be distinguished from religion, which is basically a social and cultural adaptation of human behavior centered on the belief in a specific theology.)

As intelligent beings living inside the universe, humans can make great progress toward understanding natural phenomena, but it is unclear whether we can ever gain the perspective needed to determine the origin of the universe using observations, experiments, and logic. The problem is two-fold: (1) Human logic may be a construct only of this universe, so applying logic to something beyond the universe (*e.g.*, God) may not be valid; and (2) we cannot remove ourselves from the universe to observe it objectively as a whole and therefore test our hypotheses.

Pseudoscience

Many people interpret phenomena in a different way than through the scientific method. Pseudoscience includes such activities as astrology (fortune-telling based on positions of stars and planets), belief in extra-sensory perception (ESP), explaining unidentified flying objects (UFOs) as alien spaceships, and using divining rods to find underground water. It is characterized by the lack of theoretical explanations consistent with theories of other natural phenomena, and often appeals to supernatural forces. Pseudo-science therefore possesses no explanatory power and provides no help in our attempts to understand nature. That is, it is worse than useless: Pseudoscience deceives people into false notions about the world. Scientists object to belief in pseudoscience for this reason and because it is essentially untestable. The claims made by pseudoscience are either very difficult to study in a controlled way or, when they are, the proponents insist that the experimental set-up interferes with the phenomenon in question.
Most scientists follow a principle called "Occam's Razor," which states that one should describe a phenomenon in the simplest possible way that is consistent with the data. It would be an unnecessary complication to add pseudoscientific theories that explain particular controversial phenomena - and only those phenomena - to the network of models developed through the scientific method.

Science and Reality

In its description of nature, science presents a theoretical picture of the world filled with objects that we easily detect in our everyday life – for example, rocks and trees – that are composed of tiny "particles" like electrons and protons. These particles, as well as the rocks and trees, react to "invisible" forces like electricity, magnetism, and gravity. Together, we can consider everything that has a detectable effect on the world to correspond to our **reality**. But philosophers over the years have proposed a number of different concepts of reality.

The ancient Greek philosopher Plato proposed a layered view of reality, often called "idealism." He raised geometry almost to a theology. His diagram called the Divided Line separates reality into four aspects: forms (true concepts, the highest level of reality), the intellect (including hypotheses and deductions), physical objects, and images (including reflections and shadows, the lowest level). Hence, Plato placed forms at the highest level of existence. This philosophical scheme is striking in that physical objects and how we detect them in the physical world (images, reflections, and shadows) are considered less fundamentally "real" than abstract concepts. In this sense, it is similar to most major modern theologies, in which the manifestation of ultimate reality (God, usually) does not have a physical form.

An alternative view is "empiricism," which holds that all of our knowledge about the world derives from our observations of it. If this is true, use of logic to figure out the nature of reality beyond what can be detected, as in Plato's philosophy, would yield conclusions that cannot be verified. An extreme version of empiricism, popular in the 20th century, denies that there is any reality beyond that which can be detected by scientific means. This means that interpretations of unobserved events – e.g., where a particle was during the time between two detections of its location – are meaningless. In contrast, a currently popular view among philosophers of science is "realism," which holds that science describes the world as it actually is, even if that description is currently incomplete.

The success of a scientific theory is judged by how well it:

1. explains observed phenomena.
2. predicts phenomena that are later observed and events that later take place.
3. unifies phenomena that had appeared to be different in character.
4. fits in with other theories that explain related phenomena and are well supported by observational or experimental data. (Note: Sometimes this suggests a need to modify or discard the other theories. However, scientists seek a unified picture of nature, so a model that only explains a single phenomenon while "unexplaining" others is not usually considered seriously.)
5. allows manipulations of the "real" world. (This is a positive attribute but is <u>not</u> required.)

The claim that science describes reality is based on its ability to predict events in the world, to construct physical objects based on the principles found through science, and to guide us in our activities. So, it has practical value. This is the characteristic of science that has led to its prominence in modern civilization. From a more philosophical point of view, however, the contribution of science is more esoteric: scientific theories *offer explanations* of natural phenomena in terms that humans can understand, and make verifiable predictions in those terms.

It seems accurate to say that scientists draw a picture that interprets nature, much in the same way that an artist might paint a scene that he/she views. The painting of the scene seems inherently subjective. But the fact that many people visit galleries to view such works of art suggests that it is not only the artist who can appreciate his/her perspective. So, in some sense there is a limited objectivity involved. Perhaps we can say the same about science, that it represents humanity's subjective view of the universe. It is possible that some day we will be able to communicate with non-humans with whom we can compare views to determine just how parochial this view is!

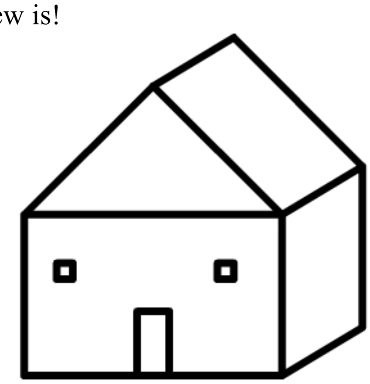

Figure 1-2. What is this?

As an exercise to illustrate the problem with the concepts of truth and reality, consider the drawing in Figure 1-2. What is it? If you answered "a house," you have given the most common response. But is it *really* a house? Of course not: it's only a crude drawing of a house! So, think more deeply now, what is it? A pattern of lines, perhaps. Or, ink on a section of paper (if you printed it out) in the form of a pattern of lines. Or, the organic molecules that compose the ink and paper. Or, the atoms that compose the molecules. Or, the electrons, protons, and neutrons that compose the atoms. Or, electrons plus the quarks that compose the protons and neutrons and the bosons that cause the forces by which the particles interact with each other. We can go on in this vein, which is an example of a <u>reductionistic</u> approach, but we have reached the limit of our understanding of particle physics. Which of these descriptions is the truth? In some respects, all of them! In other respects, none of them! Which describes reality? That depends on what layer of reality is being referred to. To our senses, the reality is that it is ink on a sheet of paper or a pattern of light from pixels on a screen. But is there an ultimate reality, for example a set of elementary particles upon which the entire macroscopic universe that we observe is based? That is a very interesting question, and the unfinished quest to answer it is one of the topics of this book.

Summary

Science is an attempt to describe natural phenomena through an iterative process that involves observations or experiments and development of hypotheses. Hypotheses whose predictions are not supported by the data are discarded, leaving only those models that agree with the evidence. Even well-established theories are subject to modification or complete invalidation if the data do not agree with their predictions. This scientific method has led, over the long term, to a progressively more accurate description of the natural world over the past four centuries. Our scientific description of nature changes with time, often in a qualitative as well as quantitative sense.

A scientific theory is successful if it explains and predicts observed phenomena and events. It is even better if it leads to practical applications. This general requirement means that the theory is connected with the "real world" experienced by humans. Still, we cannot claim that the scientific description of the universe corresponds to some absolute truth. Science provides human-originated theories supported by evidence. We cannot *prove* these theories to be correct. We can, however, prove models contradicted by the evidence to be *wrong*. Whether the concept of the world developed by science corresponds to an objective reality is a question that has caused much debate, with no general agreement on the answer.

Important Concepts

Goal of science: To describe nature as simply and completely as possible.

Faith of the scientist: That there is order to the universe such that logic can be applied to describe it.

The scientific method: An iterative procedure of creating hypotheses to explain phenomena, making predictions, and carrying out observations and/or experiments to verify (or not) the predictions.

Desired outcome of the scientific method: To falsify incorrect hypotheses and approach a more accurate description of nature.

A scientific theory must be falsifiable – Untestable hypotheses are not scientific.

Science neither proves theories true nor establishes absolute truth. Rather, it provides an increasingly accurate description of natural phenomena and finds evidence in support of this description or evidence that indicates that the description needs to be modified.

The formation of hypotheses is a somewhat subjective process, but the overall scientific method provides an objective means to eliminate invalid hypotheses. The scientific method works best over long time periods since incorrect hypotheses can be temporarily supported by data. Over such long periods, science is self-correcting.

"Beauty" (simplicity and symmetry) is a general characteristic of successful hypotheses.

The success of a scientific theory depends on how well it (1) explains observed phenomena, (2) predicts phenomena later observed, (3) unifies phenomena that had seemed different in character, (4) conforms with other successful theories (violated by some revolutionary theories), and (5) has practical applications (not required).

Glossary

Hypothesis: An "educated guess" at an explanation for an observed phenomenon.

Model: A tentative description of an observed phenomenon, often involving simplifications that allow one to visualize or calculate how to apply a hypothesis to the phenomenon.

Theory: An explanation of natural phenomena that is so successful that it is accepted by the scientific community as an accurate description of nature (*e.g.*, the Theory of Evolution). Can also be used more loosely as a general term for any description of nature (*e.g.*, "my theory predicts that a drop of water will rise when injected into liquid nitrogen").

Deductive Reasoning: Process of drawing conclusions based on the logical consequences of a hypothesis. For example, if one hypothesizes that the Earth is a sphere, then one should be able to return to the same point on its surface by traveling around a great circle in any direction.

Inductive Reasoning: Process of drawing conclusions based on examples of observations. While such conclusions are often correct, they cannot be guaranteed to be valid, since a limited number of examples may not include all of the possibilities.

Iterative Process: A set of procedures that is repeated over and over again.

Quantitative: Based on numbers from a calculation. (For example, "the model makes quantitative predictions of the values of the masses of different particles. The values are...")

Qualitative: General but not so precise as to provide, or be based on, accurate numbers. (For example, "The early models of gravity qualitatively predicted that planets farther away from the Sun have slower velocities, but they did not give a precise formula.") To say that one theory is "qualitatively different" from another means that the explanations that the theories offer are based on different principles.

Paradigm: A mental or actual picture of a phenomenon that may only be an idealization. For example, the paradigm of a ball thrown into the air is that it will follow a trajectory that has the shape of a parabola.

Pseudoscience: Descriptions of phenomena – the reality of which is considered highly doubtful by scientists – that have been developed by other means than the scientific method. Examples: astrology, UFOs as alien spacecraft, extra-sensory perception (ESP).

Divided Line: Plato's philosophical theory in which reality is classified into four aspects: forms (true concepts, the highest level of reality), the intellect (including hypotheses and deductions), physical objects, and images (including reflections and shadows, the lowest level of reality in the theory).

Idealism: Philosophy holding that the underlying basis of reality is non-physical. Plato's Divided Line is an example.

Empiricism: Philosophy holding that there is no reality beyond what can be detected.

Realism: Philosophy holding that reality consists of physical objects and the descriptions of nature that can (at least potentially) be deduced by science.

Questions for Discussion

A. What implicit (unstated) assumption does a scientist make when he or she uses the scientific method to investigate nature? What is the justification for this assumption? Would it be possible for science to appear to describe phenomena in the universe if this assumption were invalid?

B. What features of the scientific method cause it to be self-correcting? Why does this *not* imply that a model must be correct if it is the best current explanation of a phenomenon?

C. What factors can cause scientists to consider incorrect models to be valid over relatively short periods of time? What danger is there in this, *e.g.*, in medical science?

D. Some scientists call well-established theories, such as the concept that matter is composed of atoms, "true" or "a fact." To what extent is this valid, that is, is there a limit to its validity?

E. Does the vulnerability of scientific theories to falsifying evidence mean that one should not believe a scientific idea if it conflicts with ones religious or philosophical beliefs?

F. Science has been under attack by intellectual movements that assert that it is dominated by the sensibilities mainly of Western scholars, most of them male. These detractors insist that our description of nature would be quite different, although still compatible with observations, if it had been developed by non-Western or predominately female practitioners. Do you think that this is possible? If so, how different might the descriptions be, radical or subtle?

G. What qualities does a "beautiful" scientific hypothesis possess? Why should this be a guideline for the development of hypotheses? Can this be misleading, i.e., could the "beauty" of an idea be too subtle to see based on scientists' prejudices?

H. Compare and contrast the approaches toward enlightenment followed by science, philosophy, and religion. Can each of these disciplines lead to a progression toward deeper understanding of the world? Has this progression actually happened in each of these disciplines?

I. What does it mean to say that a theoretical description of a natural phenomenon is "true"? Does this mean that there is only one valid way of viewing the phenomenon?

J. In what way is the reductionistic approach useful in describing a phenomenon? Can all the aspects of a phenomenon be understood through a reductionistic approach? Think of some examples of everyday things or events that can be partly understood in this manner but which also contain aspects that can only be understood at a higher level.

K. In what ways does science resemble art? In what ways are they different?

L. As far as scientists can determine, our universe operates according to natural laws that do not vary with time or space. What are some examples of laws that you use or take for granted in your everyday life? How would your life be different if these laws were not constant in time or space?

M. What does it mean to assign a higher level of reality to abstract ideas like truth and deductions than to objects and our method of detecting objects in Plato's "Divided Line" philosophy? Can this be related to modern science?

N. What is implied by a world in which only detectable physical objects can be considered to be real?

O. Can the philosophy of realism potentially become a scientific principle, i.e., could there be scientific evidence that it is correct so that are no non-physical aspects to reality?

Exercise for In-class Discussion

a. Imagine that, after falling asleep, you wake up to find yourself sitting on a chair in a completely dark place with a hard floor. You have a small rubber ball in your pocket that is tied to a long string so that you can retrieve it after throwing it. Describe how you could estimate the following properties of the room using the ball as well as your senses, but without getting off the chair or moving the chair:

i. The dimensions of the room.
ii. The number of objects in the room.
iii. The locations of objects in the room.
iv. The hardness/softness of the objects in the room.
v. The shapes of the objects in the room.

b. For each of your answers to part (a), describe a measurement (with any instrument you choose but no light) that you could make to falsify/support your conclusion that was based on your initial measurement.

c. Can you make a measurement of objects in the room without affecting those objects? Will the next measurement necessarily find the same result?

d. What assumptions do you need to make in order to draw valid conclusions from your measurements?