Science and Hypothesis

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1 Scientific Explanation

To learn the truth about the world, the world must be studied scientifically. However, individual truths do not take us very far; a mere collection of facts no more constitutes a science than a collection of stones constitutes a house. The aim of science is to discover general truths with which the facts we encounter can be *explained*.

What is an explanation? Every explanation gives an account, a set of statements from which the thing to be explained can be logically inferred. The best account will be the one that most reduces the problematic aspects of what was to be explained. Such an account will comprise a coherent set of general truths, or a theory. To explain some serious disease, for example, we need a coherent account of what causes that disease and how it can be treated. Is the presence or absence of some particular substance the key to the disorder? The theory explaining diabetes, for example, is a coherent account of the use of sugars by the human body and the central role, in that use, of a protein hormone called *insulin*, produced by certain special cells within the body. According to this theory, it is a deficiency of insulin (or the inability of the body to use the insulin it produces) that explains the resulting disorder in the absorption of sugars from the blood. An account of this kind (here greatly oversimplified, of course) gives a **scientific explanation** of this serious disease. Patients suffer from diabetes *because* of their insulin deficiency.

When we say "*Q* because *P*," that may express either an explanation or an argument. It expresses an argument when we are inferring the conclusion, *Q*, from the premises, *P*. It expresses an explanation when, facing the *fact* of *Q*, our reasoning moves back from that fact to discover the circumstances that led to it. Diabetes—excess sugar in the blood—is a cruel fact in the lives of many patients. We *explain* their diabetes by calling attention to the insulin deficiency that has that result. The account of the interrelated set of circumstances in which the insulin deficiency, *P*, accounts for the sugar excess, *Q*, is thus an *explanation* of that disease.

Scientific explanation
A theoretical account of some fact or event, predicated upon empirical evidence and subject to revision in the light of new information.

A good explanation must offer truths that are *relevant* to the fact explained. If I seek to explain my being late to work on some occasion by calling attention to the rising birth rate in Brazil, the fact thus introduced may be correct, but it is not relevant, and it therefore cannot be a satisfactory explanation of my absence, the event in question. In this trivial example, an explanation is sought for a single event. In science we seek explanations that are not only true and relevant, but also general. The explanations we aim for will provide an understanding of all the events of some given *kind*—say, all the occurrences of diabetes, for example.

The more facts for which a scientific theory accounts, the more powerful it is. Some theories are magnificent in their range and power. Here, for example, is a short statement of Isaac Newton's law of universal gravitation:

> Every particle of matter in the universe attracts every other particle with a force that is directly proportional to the product of the masses of the particles and inversely proportional to the square of the distance between them.

An explanation may be relevant and general, and yet not scientific. The regular motions of the planets were long thought to be accounted for by the "intelligence" that was held to reside in each planet. In some cultures, disease is "explained" as the work of an evil spirit that has invaded the body. These are certainly unscientific accounts, although the explanations they offer are general and are relevant to the facts of interest. What, then, distinguishes genuinely scientific from unscientific explanations?

There are two chief differences. The first is *attitude*. An **unscientific explanation** is presented dogmatically; the account that it gives is regarded as being unquestionably true and not improvable. The opinions of Aristotle were accepted for centuries as the ultimate authority on matters of fact. Aristotle himself appears to have been open-minded, but his views were adopted by some medieval scholars in a rigid and unscientific spirit. One of the scholars to whom Galileo offered his telescope to view the newly discovered moons of Jupiter declined to look, expressing his certainty that no real moons could possibly be seen because no mention of them could be found in Aristotle's treatise on astronomy! In contrast, the attitude of a serious scientist is undogmatic; explanations are put forward provisionally; hypotheses may be thought highly probable, but they are regarded as subject to alteration in the light of the evidence.

The vocabulary of science is sometimes misleading on this point. When what is first suggested as a "hypothesis" is well confirmed, its status may be elevated to that of a "theory"; after universal acceptance, it may be further elevated to that of a "law." However, the use of these terms is not consistent. Newton's discovery is still called the "law of gravitation," while Einstein's contribution, which improved and superseded it, is referred to as the "theory of relativity." Whatever the terms used, the attitude of genuine scientists is not dogmatic. The general propositions of science are all in essence hypotheses, never absolutely certain.

Unscientific explanation
An explanation that is asserted dogmatically and regarded as unquestionable.

In everyday speech the word *theory* is often used to refer to a hunch, or a mere opinion. Scientists use the word differently. In physics and chemistry we refer—not dogmatically, but nevertheless with great confidence—to "quantum theory" and to the "molecular theory of matter"; in biology we rightly rely upon the "cellular theory" and the "germ theory of disease." These are sets of very well-established truths, not ungrounded speculations.

Evolution—the "theory of evolution"—is also an established fact; doubts about evolution expressed because it is "only a theory" are the result of this semantic misunderstanding.

The second difference concerns the *basis* for accepting the account in question. In science a hypothesis is worthy of acceptance only to the extent that there is good evidence for it. An unscientific belief may be held independently of what we should regard as evidence in its favor; the explanation is taken as simply true—perhaps because "everyone knows" that it is so, or perhaps because it is thought to have been revealed from on high. There is no reliable test of such claims, whereas in genuine science the claims for truth can be tested, and those tests lie in our experience. Thus we say that genuine science is *empirical*.

To say that a hypothesis is *testable* is at least to say that some prediction made on the basis of that hypothesis may confirm or disconfirm it. Science demands evidence. But, of course, the evidence accumulated that could confirm the hypothesis in question can never be complete, as we have earlier emphasized; *all* the evidence is never in hand. Therefore, even when that supporting evidence is very strong, some doubt must remain, and certainty is unattainable. On the negative side, however, if the evidence shows indisputably that the predictions made on the basis of that hypothesis are false, our confidence that the hypothesis must be rejected may be total. Although we cannot complete the verification of a hypothesis, we can, with closure, establish that it has been falsified. For reasons of this kind, some philosophers have held that to say of a scientific hypothesis that it is testable is also to say that it is, at least in principle, falsifiable.

The test of truth may be direct or indirect. To determine whether it is raining outside, I need only glance out the window. In general, however, the propositions offered as explanatory hypotheses are not directly testable. If my lateness at work had been explained by my claim about some traffic accident, my employer, if suspicious, might test that explanation indirectly by seeking the police accident report. An indirect test deduces, from the proposition to be tested (for example, that I was involved in an accident), some other proposition (for example, that an accident report had been submitted) capable of being tested directly. If that deduced proposition is false, the explanation that implied it is very likely to be false. If the deduced proposition is true, that provides some evidence (but not conclusive evidence) that the explanation is true, having been indirectly confirmed.

Indirect testing is never certain. It always relies on some additional premises, such as the premise that accidents of the sort I described to my employer are invariably reported to the police. But the accident report that should have been submitted in my case may not have been, so its absence does not *prove* my explanation false. Even the truth of some added premises does not render my explanation *certain*—although the successful testing of the conclusion deduced (the reality of the accident report, in this example) does corroborate the premises from which it was deduced.

Even an unscientific explanation has *some* evidence in its favor, namely, the very fact it is held to explain. The unscientific theory that the planets are inhabited by "intelligences" that cause them to move in their observed orbits can claim, as evidence, the fact that the planets do move in those orbits. However, the great difference between that hypothesis and the reliable astronomical explanation of planetary movement lies in this: For the unscientific hypothesis there is no other directly testable proposition that can be deduced from it. Any scientific explanation of a given phenomenon, on the other hand, will have directly testable propositions deducible from it *other than the proposition stating the fact to be explained*. This is what we mean when we say that an explanation is *empirically verifiable*, and such verifiability is the most essential mark of a scientific explanation.*

2 Scientific Inquiry: Hypothesis and Confirmation

We seek scientific explanations that are correct, and whose correctness may be empirically verified. How can we obtain these explanations? No formulas for doing science can be given, but there are stages, or distinct phases, in most scientific investigations. By identifying and describing seven such stages we may come to understand more fully how good science advances.

A. Identifying the Problem

Scientific investigation begins with a problem of some kind. By *problem* is meant only some fact, or group of facts, for which no acceptable explanation is at that time available. The sociologist confronts a puzzling trend in work or play; what accounts for it? The medical investigator confronts a puzzling disease; what causes it? The economist observes different patterns of spending or saving; what explains the variations? Some problems are quite sharply identified, as when a detective confronts a specific crime and asks: Who is the perpetrator? Some problems may arise from a gap in current understanding. Eratosthenes, librarian at Alexandria in the third century BCE, believed correctly that the Earth was a sphere, but its size was unknown. His problem was to determine the circumference of the sphere we call Earth. Reflective thinking—whether in sociology or medicine or law enforcement or physics, or any other realm—is *problem-solving* activity, as John Dewey and other modern philosophers have repeatedly emphasized. The recognition of some problem is the trigger for the science that ensues.

B. Devising Preliminary Hypotheses

Preliminary speculation is the second step—some very tentative explanation of the problem identified. Long before a full solution is in sight, some theorizing is needed to indicate the kind of evidence needed, and perhaps to indicate where such evi-

*This general conception of "scientific explanation" rightly applies outside the realm of what is normally thought of as the sciences, such as physics or psychology. Thus, the explanation of an event such as my lateness to work as a consequence of a traffic accident, in being indirectly testable in various ways, is in this wide sense "scientific."

dence might best be sought. The detective examines the scene of the crime, interviews suspects, seeks clues. The physician examines the patient, records data, notes irregularities. Bare facts are accumulated; they become usable clues or revealing symptoms only when they are fitted into some coherent pattern, even if that pattern is speculative and incomplete. To illustrate: Thomas Malthus had shown, in "An Essay on the Principle of Population" (1798), that the tendency of population to grow faster than the food supply keeps most people at the edge of starvation. Charles Darwin, reading this while speculating about the origin of species many years later, hit upon an exceedingly fruitful notion. He wrote:

> It at once struck me that under these circumstances favourable variations would tend to be preserved, and unfavourable ones to be destroyed. . . . Here then I had at last got a theory by which to work" (*Autobiography*, 1881).

There are too many possibly relevant facts—too much data in the world—for the scientist to collect them all. The most thorough investigator must select some facts for further study and put other facts aside as not relevant. If the Earth is a sphere, the rays of the sun will fall (at any given time) upon different points of that sphere at different angles. Might geometry help us to calculate the size of the Earth? The outline of a theory is essential because, without that, the investigator cannot decide which facts to select and pursue from the totality of facts. However incomplete or tentative, a preliminary hypothesis of some kind is needed before serious inquiry can get under way.

C. Collecting Additional Facts

The preliminary hypothesis serves to guide the search for relevant facts. As a preliminary matter, the patient is thought to have some infection, and that hypothesis puts the physician on the trail of certain kinds of data that are normally associated with infection: temperature irregularities, patterns of inflammation, and the like. The preliminary supposition that the crime was committed by a member of the household will cause the detective to inquire into the conduct of persons residing there, and so on. If the angle at which the sun's rays strike the Earth must differ at different points on the Earth's surface, one must seek, in order to apply geometric principles, at least one point at which the sun is known to be *directly* overhead at a given time. Where might that be?

The second and third steps are not fully separable, of course; in real life they are interconnected and mutually suggestive. New facts found may cause an adjustment of the preliminary hypothesis; that adjustment may lead to facts earlier not noted. The process of gathering evidence by using the preliminary hypothesis merges with the process of refining that hypothesis, leading to new findings, and so on and on.

D. Formulating the Explanatory Hypothesis

Eventually, the investigator—the scientist, or detective, or ordinary person—may come to believe that all the facts needed for solving the original problem are in hand. The task then becomes that of assembling the pieces of the puzzle in a way that makes sense of the whole. If that synthesis is successful, a hypothesis will emerge that accounts for all the data—the original set of facts that gave rise to the problem, as well as the additional facts to which earlier hypotheses had pointed. A surge in unemployment is explained by some larger theory of the labor market. The patient is found to be suffering from an identifiable infectious agent known to cause the symptoms noted in this patient's condition. An identifiable member of the household is charged by the state as the perpetrator of the crime and the case against him is formulated.

There is no mechanical way to find some overarching theory. The actual discovery, or invention, of a successful explanatory hypothesis is a process of creation, in which imagination as well as knowledge is involved. That is why those who make important scientific discoveries are so widely honored and so much admired.

What *is* the circumference of the globe? Eratosthenes learned that in the Egyptian town of Syene (now called Aswan), the sun's rays shine directly down a deep well at a given time on a particular day each year. At that same time he could measure the sun's shadows (and therefore the angle of its rays) in Alexandria; he found that the rays there deviated from the vertical by 7°. That is about one-fiftieth of the 360° of the sphere's circumference. The distance between Syene and Alexandria was known. The circumference of the entire sphere of Earth must therefore be about fifty times that distance. Eratosthenes' subsequent calculation of the Earth's circumference ("250,000 *stadia*") is believed (we are unsure of the length of a *stadium*) to have an error of less than 5 percent. He had no way to confirm that calculation, but it was impressive science for his time. Truly great scientists—such as Einstein or Newton—are understandably viewed as creative geniuses.

E. Deducing Further Consequences

A good explanatory hypothesis will be fruitful; that is, it will explain not only the facts that provoked the inquiry but many other facts as well. It is likely to suggest some facts that had not even been thought of earlier. Verification of these additional facts may strongly confirm (but, of course, cannot prove with certainty) the hypothesis that led to them.

To illustrate, the cosmological theory known as the *Big Bang* hypothesizes that the present universe began with one singular explosive event. The initial fireball would have been smooth and homogenous, lacking structure. But the universe today exhibits a great deal of structure; its visible matter is clumped into galaxies, clusters of galaxies, and so on. If the Big Bang theory is correct, the seeds of the present structure of the universe must in principle be identifiable. We need to be able to look back in time—and by observing the most distant objects in an expanding universe, astronomers actually can, in effect, look back in time, since the light being received must have left its sources billions of years ago. If, in these observations, early structures were not detectable by the most sensitive instruments, the Big Bang theory would be seriously undermined. But if such structure were detectable, the Big Bang theory would be significantly confirmed.

F. Testing the Consequences

Critical for the evaluation of every explanatory hypothesis is the accuracy of its predictions. Can the facts to which the theory points be ascertained? Often they can. If there was structure in the universe early in its expansion, as the Big Bang theory predicts, there would have to be irregularities, unevenness, that may be found in background radiation and traced to that early time. Happily, it is possible to measure that background radiation and thus to determine now, indirectly, that there were structural irregularities very shortly after the supposed Big Bang. To detect those predicted radiation irregularities, a special satellite was designed—the Cosmic Background Explorer (COBE). Using this satellite, the predicted irregularities have indeed been detected, giving very important confirmatory evidence for the truth of the Big Bang hypothesis.

Consider prediction in another context. In biology we may come to formulate the hypothesis that a particular protein is produced in mammals as a reaction to a particular enzyme, and that that enzyme is produced under the direction of a specifically identified gene. From this hypothesis we may deduce the further consequence that when that gene is absent there will be an absence, or a deficiency, of the protein in question.

To test that hypothesis we construct an experiment in which the effect of the identified gene may be measured. This can sometimes be done by breeding mice in which the critical gene has been deleted—"knockout mice." If, in such mice, the enzyme in question and the protein associated with it are indeed also absent, our hypothesis will have been strongly confirmed.* Much information that proves very valuable in medicine is acquired in just this way. We devise the experiment to determine whether what we thought to be true (if such-and-such were the case) really is true. To do that we must often *construct* the very special circumstances in which such-and-such has been made the case. "An experiment," as the great physicist Max Planck said, "is a question that science poses to Nature; a measurement is the recording of Nature's answer."

It is not always feasible to construct the circumstances needed to perform a test. We must then seek the circumstances needed for testing in some natural setting. That was the case in the effort to test the general theory of relativity.† Einstein's theory proposed that gravitation is not a force (as Newton had thought) but a curved field in the space–time continuum, created by the presence of mass. This might be proved (or disproved), Einstein suggested, by measuring the de-

*Testing of this kind relies on what we call the method of difference. The many methods discussed there (Mill's methods) are intellectual tools used to confirm (or disconfirm) hypotheses.

†"The Foundation of the General Theory of Relativity" was published in 1916, in *Annalen der Physik.*

flection of starlight as it traveled close by the mass of the sun; the starlight needed would be visible only during a total eclipse of the sun. The testing of this prediction had to await the solar eclipse of 1919, when the sun would be silhouetted against the Hyades star cluster, for which the positions were known exactly. During that eclipse, physicist Sir Arthur Eddington stationed himself on an island off the western coast of Africa; another group of British scientists went to Brazil. The two teams measured accurately the apparent position of several of the stars in the cluster; their measurements plainly showed that light from these stars was indeed bent as it grazed the sun, and that it was bent by the exact amount of Einstein's prediction. The general theory of relativity had been very solidly confirmed.

This theory showed that space, time, and gravity are so entwined that to speak sensibly about one there must be reference to the others. Einstein struggled to go further, to develop a theory in which all of nature's forces are merged into one single, overarching theory. In this effort he did not succeed, and neither has anyone else so far.

A new approach—to construct a complete and unified theory of natural forces called *string theory*—now has many adherents. It offers a theoretical account that may unify gravity, quantum mechanics, and nature's other forces, and solve some earlier mathematical problems as well. String theory, which is based on a new conception of matter's fundamental constituents, is free of mathematical contradictions but it has not yet been confirmed.

What predictions does string theory make that might confirm it by experimental test? It may become possible to confirm the theory's predictions regarding new kinds of particles; it may become possible to test the prediction that highly energetic particle collisions will produce microscopic black holes. As this is being written, a gigantic particle accelerator, the Large Hadron Collider, is performing its first set of high-energy collisions. In a few years we may have empirical evidence to confirm the explanations given by string theory, or to disconfirm them.[*]

Evolutionary theory, as presented by Darwin in *The Origin of Species* (1859) and by very many of his successors, is now almost universally accepted as a correct explanation of the development of species of animals and plants. Predictions that can test this theory prospectively (rather than retrospectively) are difficult to devise because the natural selection hypothesized seems to require the passage of many generations. Very recently, a Harvard professor of evolutionary biology, Jonathan Losos, devised an experiment that makes speedy testing feasible. On some tiny cays in the Bahamas, where the brown lizard *Anolis sagrei* lives free of predators and reproduces rapidly, he introduced a predator whose activity would quickly result in the development (in those islands as compared to other, similar islands left unperturbed) of a lizard population with longer legs, much

[*]Some scientists contend that string theory makes no predictions whose testing will truly confirm or disconfirm it. See L. Smolin, *The Trouble with Physics* (Boston: Houghton Mifflin, 2006); and P. Woit, *Not Even Wrong: The Failure of String Theory* (New York: Basic Books, 2006). It may be that the theory makes predictions that are testable in principle, but not testable in practice given current technological limitations. This heated controversy is likely to continue.

better suited to running away. Selective forces operated as expected; long legs came to predominate. However, when continually preyed upon, the *Anolis* lizard climbs into trees and bushes, where short legs are much more advantageous. The further prediction was that natural selection would produce a reversal and that short legs would eventually predominate—and six months later that prediction also was confirmed. Evolution has been first manipulated and then deliberately reversed. Said Prof. Losos:

> Evolutionary biology is often caricatured as incompatible with controlled experimentation. Recent work has shown, however, that evolutionary biology can be studied on short time scales and that predictions about it can be tested experimentally. We predicted, and then demonstrated, a reversal in the direction of natural selection acting on limb length in a population of lizards. We did a controlled, replicable experiment in nature. It illustrates that evolutionary biology at its heart is no different from any other science.[1]

G. Applying the Theory

When a phenomenon is encountered, one goal is to explain it; however, people also strive to *control* those phenomena to their advantage. Not only do the theories of Newton and Einstein and their successors play a central role in our understanding of celestial phenomena, but they are also critical in our actual exploration of the solar system, and outer space beyond. Nuclear fusion is now well understood as a process; we seek to apply this understanding in producing energy on a scale we can control. Disease and disorder are understood as never before, incorporating the well-tested explanations of genetic theory and our grasp of the human genome; now we seek to put this understanding to use in clinical medicine by eliminating genetic disorders, and even by regenerating organic tissue. In this twenty-first century it is probably biological science, more than any other field, whose explanations will enhance the quality and the length of ordinary human lives.

Good practice in every sphere must be guided by good theory. Good theory must pass the test of empirical verification. Theory and practice are not two realms; they are equally critical aspects of every genuinely scientific undertaking. More than two centuries ago, Immanuel Kant wrote an incisive little book explaining why it makes no good sense to say, "that may be right in theory but it won't work in practice."[2] What is right in theory *does* work in practice, and for everything that does work in practice we may reasonably hope to discover the explanatory theory that underlies its success.

3 Evaluating Scientific Explanations

The same phenomenon may receive different explanations, all scientific in the sense we have described, and yet some of them may not be true. Conflicting explanations of some physical or economic phenomenon may be offered. In a criminal investigation we may hypothesize that the perpetrator was X, or was Y.

More than one hypothesis may account for the facts neatly, but not all can be true. How shall we choose among alternative scientific explanations?

Let us assume that all the alternatives are relevant and testable. How ought we determine which of the available hypotheses is the best? There are standards—going beyond relevance and testability—to which acceptable hypotheses may be expected to conform. Three criteria are most commonly used in judging the merit of competing hypotheses.

1. ***Compatibility* with previously well-established hypotheses.** Science aims at achieving a *system* of explanatory hypotheses. A satisfactory system must be internally consistent, of course. A satisfactory explanatory system cannot contain contradictory elements; if it did, the full set of propositions could not possibly be true. We progress by gradually expanding hypotheses to comprehend more and more facts, but each new hypothesis brought into the set must be compatible with those already confirmed.

   Sometimes the expansion involves only one new hypothesis, as when the aberrations in the orbit of Uranus were explained by the hypothesis that there was some other planet, uncharted at that time, whose mass was creating the aberrations. That supposition was perfectly consistent with the main body of astronomical theory at the time. A search for the mysterious object resulted in the discovery of the planet Neptune in 1846. The theory that led to that discovery *fit* very nicely with all the other theories concerning planetary movements generally accepted at that time.

   Although theoretical knowledge grows gradually, it does not always grow by adding just one new hypothesis after another in orderly fashion. Clumps of theory may be introduced; new hypotheses that are flatly inconsistent with older theories sometimes replace their predecessors outright, rather than being fitted in with them. Einstein's theory of relativity was of that sort: It shattered many of the preconceptions of the older, Newtonian theory of gravitation. In another branch of physics, it was discovered that radium atoms undergo spontaneous disintegration, and this well-confirmed fact was simply inconsistent with an older principle that matter could neither be created nor destroyed. To maintain a consistent set of hypotheses, the older principle had to be relinquished.

   The consistency of the set of scientific theories in a given field is thus achieved in different ways. However, apart from those cases in which some revolutionary theory upsets long-established principles, the first criterion for an acceptable new hypothesis is that it retain the existing consistency, be compatible with what is already known, or be reasonably believed.

   When old and new collide, the established scientific theories will not be abandoned quickly in favor of some that are shinier or more trendy. The older body of theory will be adjusted to accommodate the new if that is possible. Large-scale change will be resisted. Einstein himself always insisted that his own work was a modification of Newton's, not a rejection of it. The principle of the conservation of matter was modified by being absorbed into the more comprehensive principle of the conservation of mass–energy. An established theory has the support that it does because it explains a considerable mass of data, so it cannot be dethroned by some new hypothesis unless the new hypothesis accounts for the same facts as well as (or better than) the older one, and accounts for other known facts also.

Science advances as its theories give more comprehensive explanations, more adequate accounts of the world we encounter. When inconsistencies arise, the greater age of one hypothesis does not automatically prove it correct. If the older view has been extensively confirmed, presumption will support it. When the newer, competing view has also received extensive confirmation, mere age and priority cease to be relevant. We must then decide between the competitors on the basis of something we learn about the observable facts. The ultimate court of appeal is always experience.

2. ***Predictive power.*** As we have seen, every scientific hypothesis must be testable, and testability requires that some observable fact or facts be deducible from it. Alternative hypotheses will differ in the nature and extent of their predictions, and we seek the theoretical explanation that has the greater predictive power.

   To illustrate: The behavior of bodies near the surface of the Earth was explained by Galileo Galilei (1564–1642) with his laws of falling bodies. The behavior of bodies far off in the solar system was explained at about that same time by the German astronomer Johannes Kepler (1571–1630), who formulated the laws of planetary motion. Using the data that had been collected by Denmark's Tycho Brahe, Kepler could account for the motions of the planets on the basis of the elliptical orbits they travel around the sun. Galileo gave a theoretically powerful account of the various phenomena of terrestrial mechanics. Kepler gave a theoretically powerful account of celestial mechanics. But the two accounts were isolated from one another. Their unification was needed; it came with Isaac Newton's theory of universal gravitation, and his three laws of motion. All the phenomena explained by Galileo and by Kepler, and many more facts besides, were explained by Newton's account of universal gravitation.

   A fact that can be deduced from a given hypothesis is said to be explained by it, and may also be said to be *predicted* by it. Newton's theories had enormous predictive power. The greater the predictive power of any hypothesis, the better it contributes to our understanding of the phenomena with which it is concerned.

Earlier we described the great predictive power of Einstein's general theory of relativity, which accounts for the admiration given to it and to its creator. We also pointed out that his enterprise—the development of an overarching theory of natural forces—is held by some to approach success now in the form of what is called string theory; some predictions of great interest are claimed to be deducible from this theory. If those predictions are one day confirmed, the predictive power of string theory will elevate it to a position of the very first importance in physics and cosmology.

However, the criterion of predictive power also has a negative side. If the hypothesis predicts what does not take place, or is in some other way shown to be inconsistent with well-attested observations, that hypothesis has been *falsified* and must be rejected. A meaningful scientific hypothesis must be at least falsifiable—that is, we must know what would or might show it to be false. If there is no set of observable outcomes that will lead us to conclude that the hypothesis is false, we may seriously doubt if the hypothesis has any predictive power whatever.

Suppose we confront two different hypotheses, both of which fully explain some set of facts, both of which are testable, and both of which are compatible with the body of already established scientific theory. In such a case, it may be possible to devise a *crucial experiment* to decide between the conflicting theories. If the first hypothesis entails that, under a given set of circumstances, a specified result will occur, and the second entails that it will not, we may decide between the competitors by observing the presence or absence of that predicted result. Its appearance falsifies the second hypothesis; its nonappearance falsifies the first.

The experiment described earlier, in which the general theory of relativity was tested by making exact measurements of the starlight that passed closely by the mass of sun, was crucial in just this way. The theory of Newton and the theory of Einstein cannot both be correct. If the bending of the light is as Einstein's theory predicted, the Newtonian view is disconfirmed; if the bending of light is not observed, the general theory of relativity is disconfirmed. With good cameras, very careful observers, and a solar eclipse in which the three bodies (sun, moon, and Earth) were correctly lined up, the crucial experiment might be made. Those ideal circumstances arose on 29 May 1919. Photographs proved that Einstein was right; we do live in a curved, four-dimensional space–time continuum. Einstein became a worldwide sensation overnight.

3. ***Simplicity.*** Two rival hypotheses may fit equally well with established theory, and they may also have predictive power that is roughly equal. In such circumstances we are likely to favor the simpler of the two. The conflict between the Ptolemaic (Earth-centered) and the Copernican (sun-centered) theories of celestial motion was like that. Both fit well with earlier theory, and they predicted celestial movements about equally

> well. Both hypotheses relied on a clumsy (and, as we now know, mistaken) device, hypothesized epicycles (smaller circles of movement on the larger orbits), in order to explain some well-established astronomical observations. But the Copernican system relied on many fewer such epicycles and was therefore much simpler. This greater simplicity contributed substantially to its acceptance by later astronomers.
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> Simplicity seems to be a "natural" criterion to invoke. In ordinary life also, we are inclined to accept the simplest theory that fits all the facts. Two theories about a crime may be presented at a trial; the verdict is likely to be given—perhaps ought to be given—in favor of the hypothesis that seems simpler, more natural.
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> "Simplicity," however, is a tricky notion. That one of the competing theories will involve a smaller number of some troubling entity (such as the epicycles in the case of Copernican astronomy) is a rare situation. Each of two theories may be simpler than the other in different ways. One may rely on a smaller number of entities, while the other may rely on simpler mathematical equations. Even "naturalness" may prove to be deceptive. Many find it more "natural" to believe that the Earth, which does not seem to be moving, really is not moving, and that the Sun, which appears to move around us, is doing just that. The lesson here is that simplicity is a criterion that is difficult to formulate and not always easy to apply.

Progress in science is never easy and rarely straightforward. No one supposes that simply by applying the seven steps of the hypothetico-deductive method (recounted in Section 2) to some problem he will find its solution. Correct explanatory hypotheses are often obscure and may require very elaborate theoretical machinery. Devising a final, presumably correct theory may be exceedingly difficult. Far from being mechanical, the process commonly requires, in addition to laborious observation and measurement, insight and creative imagination.

When some hypothesis already in hand is widely believed to explain the phenomena in question, a replacement for it encounters very high hurdles. The new hypothesis is likely to encounter ridicule and disdain. The new hypothesis is very probably inconsistent with the previously accepted theory, and the established view always has the upper hand. A crucial experiment, of the sort described earlier in the case of the general theory of relativity, is possible only in rare circumstances.

Contemporary physics faces a major conflict of just this kind. Between its two most powerful general theories there is an apparent conflict that cannot presently be resolved. The general theory of relativity is well confirmed. From its laws (describing gravity and how it shapes space and time), it is an apparently inevitable consequence that some collapsing, massive stars will form "black holes" from which escape would require a speed faster than light, which is impossible. The laws of quantum mechanics are also well confirmed, and they entail that information cannot ever be permanently lost, even if drawn into a black hole. Therefore, either there is some property of space and time, not now understood, that can account for the retention of that information, or there is some lawlessness in physics that can account for the permanent loss of that information. One of the two theories must need at least an amendment, but we do not yet know which one, and we do not have the means to construct an experiment that would enable us to decide between them.*

Confronted by such conflicts we will seek to apply the criteria of good scientific explanations we set forth earlier: Which of the competing theories is *simpler*? Which of the two has greater *compatibility* with previously established hypotheses? Finally, above all, which has the greater explanatory or *predictive power*? So long as definitive answers to these questions are lacking, the intellectual controversy is likely to continue unresolved.

It does happen in the history of scientific progress that such conflicts are sometimes resolved. There is no better way to exhibit the methods of science, and to exemplify the application of the criteria described here, than by recounting the observational confirmation by Galileo of the heliocentric account of the solar system—and the resulting replacement of the geocentric account that had been accepted as true for more than a thousand years.

By the early 1600s, the movement of the planets against the backdrop of the fixed stars had been so carefully studied that their apparent movements were quite accurately predictable. The Moon, also much studied, was believed by theologians to be a perfect sphere. The heavenly bodies, deemed flawless in shape and movement, were widely believed to travel in perfect circles around the Earth, which was the center of the world God had created. By 1609, Galileo had devised a telescope with 20-power magnification, its chief uses being thought at first to be maritime, or as a spyglass that could provide military advantage. With this instrument he observed the heavens, almost by accident, in January 1610. On the 7th of that month he began a long letter, reporting in detail his observations of the moon and other bodies. He wrote:

> I have observed with one of my telescopes. . . the face of the Moon, which I have been able to see very near. . . . [W]hat is there can be discerned with great distinctness, and in fact it is seen that the Moon is most evidently not at all of an even, smooth and regular surface, as a great many people believe of it and of the other heavenly bodies, but on the contrary it is rough and unequal. In short, it is shown to be such that sane reasoning cannot conclude otherwise than that it is full of prominences and cavities similar, but much larger, to the mountains and valleys spread over the Earth's surface.[3]

*A hypothetical experiment has been proposed: Throw a volume of the *Encyclopaedia Britannica* into a black hole. Will the information it contains be forever lost? Is such a total loss impossible? A wager, lighthearted but serious, between two distinguished Caltech physicists has been placed on the outcome. Prof. Kip Thorne bets on relativity, whose equations describe space and time and predict that from the singularity of a black hole there could *never* be any recovery. Prof. John Preskill bets on quantum mechanics, whose equations precisely describe the lives of minuscule elementary particles and predict that the information can never be *totally* lost. The stakes of the wager are a set of encyclopedias. Payoff is unlikely to come soon. Says their equally distinguished colleague, Prof. Stephen Hawking of Cambridge University, who originally was in on the bet, "In my opinion it could go either way." Hawking, but not Thorne, conceded the bet in 2004. [*Science News*, 25 September 2004]

To save the hypothesis that the Moon was indeed a perfect sphere, and thus to retain the coherence of the theological account of the heavenly bodies of which that perfection was one element, some of Galileo's critics later proposed the hypothesis—outrageously *ad hoc*—that the apparent cavities and irregularities on the surface of the Moon were, in fact, filled in by a celestial substance that was flawless and crystalline, and thus invisible through Galileo's telescope!

More than the Moon was examined by Galileo. His letter continued:

> And besides the observations of the Moon. . . many fixed stars are seen with the telescope that are not [otherwise] discerned; and only this evening I have seen Jupiter accompanied by three fixed stars, totally invisible [to the naked eye] by their smallness, and the configuration was in this form:[4]

At that point Galileo inserted a sketch that appears here as Figure 1, showing the three stars in a straight line, two to the east and one to the west of Jupiter; he reported that they did not extend more than one degree of longitude, but since at that time he supposed them to be fixed stars, their distances from Jupiter and from one another were indicated only very roughly.

On the following day, 8 January 1610, "led by I know not what," Galileo happened to observe Jupiter once again; the earlier positions of those "fixed stars" had fortunately been written down. His letter remained unsent; at the bottom of the sheet he wrote the following note:

> On the 8th thus: [He inserts a sketch showing Jupiter and three stars now closer to one another and nearly equidistant from one another, and *all three to the west of Jupiter*!]

This created a serious theoretical problem for Galileo, because at this time the assumption that the newly discovered stars were fixed had not been seriously doubted. Therefore their appearance on the other side of Jupiter had to be accounted for by Jupiter's movements. On the 8th he added the note:

> It [Jupiter's movement] was therefore direct and not retrograde.

If, on the 8th, Jupiter was to the east of all three stars, and the day before Jupiter had been to the west of two of them, Jupiter must have moved, and moved in a way that was *contrary* to reliable astronomical calculations! One can imagine Galileo's agitation as he waited for the observations of the following night; could his direct observations and his calculations remain so sharply inconsistent? On the 9th it was too cloudy to observe, but he was able to resume his observations the following night and to record the new pattern. On 11 January a similar pattern was observed, but on this night Galileo later wrote:

> The star nearer Jupiter was half the size of the other, and very close to the other, whereas the other evenings all three of the said stars appeared of equal size and equally far apart.

On the 12th, Jupiter apparently had moved back to the west, and two of the new "stars" were again observed to the east of the planet! Clearly, something had to give. From the accepted theories and beliefs a prediction confidently could be drawn, a deduction concerning the movements of Jupiter, which—if those three

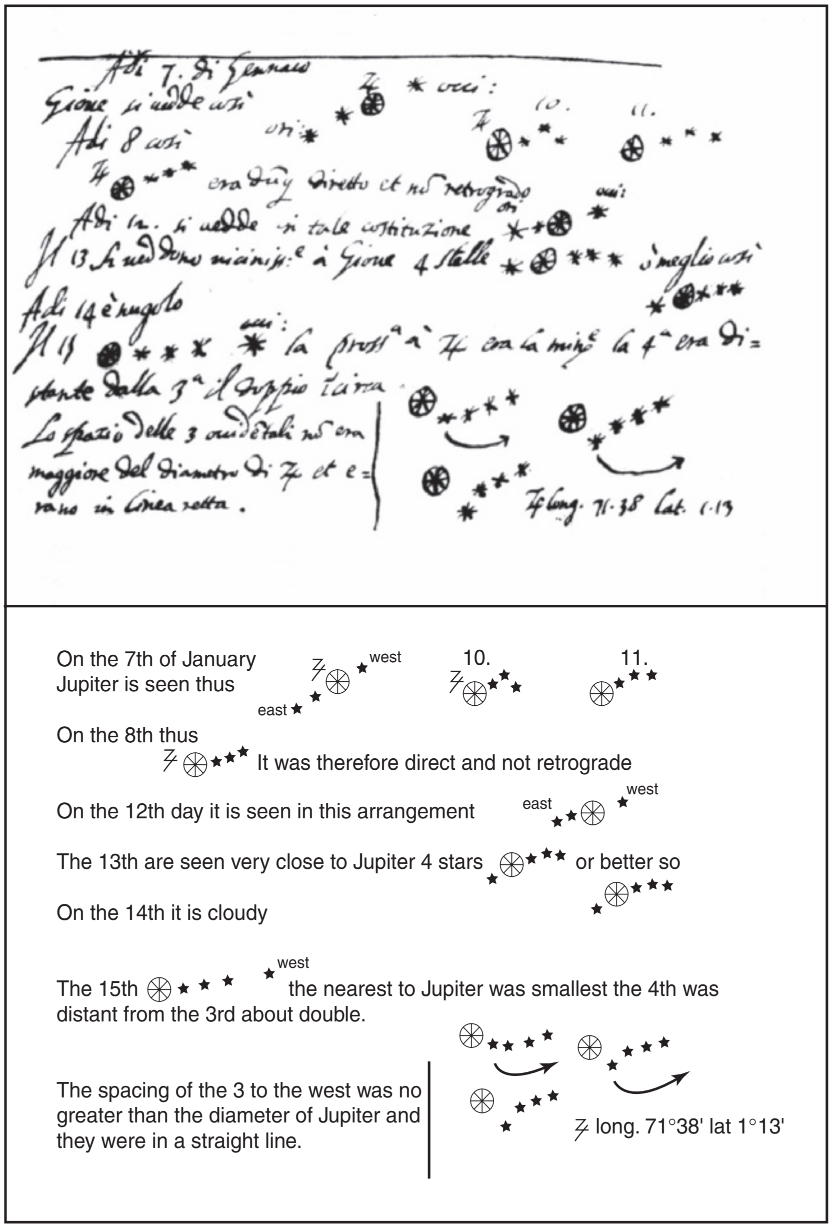

Figure 1 A photograph of the letter begun by Galileo on 7 January 1610, on which are recorded his first monumental observations of the four major satellites of Jupiter, thus confirming the Copernican account of the movement of the celestial bodies. The letter itself was to be sent to the Doge in Venice, and included a telescope with which Galileo intended to present him. On a draft of that letter which he happened to have in hand, Galileo made the critical notes of his observations, which appear on the bottom half of the sheet. The translation of the bottom half into English appears below. Courtesy of the Special Collections Library, University of Michigan.

new stars were fixed, and Galileo's observations were accurate—did not take place. One could save the belief that those new stars were fixed by somehow revamping the entire set of astronomical calculations, but these were not in serious doubt; or, one could challenge the accuracy of Galileo's observations—which is what some of his critics later sought to do, calling his telescope an instrument of the devil. Galileo himself had no doubt about what he had seen, and he grasped quickly which element in the set of accepted hypotheses had to be relinquished, to the great distress of his dogmatic opponents. His note on the observation of the 11th continued:

> . . . from which it appears that around Jupiter there are three moving stars invisible to everyone to this time.

And these three moving stars, he later wrote,

> . . . revolved round Jupiter in the same manner as Venus and Mercury revolved round the sun.

The observations of the following nights confirmed this revolutionary conclusion, which, together with his earlier observations of the moon, cast serious doubt on the account of celestial bodies that had been widely and dogmatically affirmed for many centuries.

On 13 January 1610, Galileo observed a fourth "star," and the four major satellites of Jupiter had been discovered. These observations provided very strong confirmation of the Copernican hypothesis—an account of the celestial bodies that was difficult to reconcile with the established theological doctrine of Galileo's time. Many moons of Jupiter have been discovered since, but these four moons—Ganymede, Io, Europa, and Callisto—are appropriately called "the Galilean satellites." On a clear night, when Jupiter is visible in the sky, the revolutions of the Galilean satellites around the planet may be readily confirmed with no more than an ordinary pair of binoculars.

The ultimate success of the Copernican account of the solar system was due not merely to its greater simplicity, but to its correctness, made manifest in the much larger body of facts it was able to account for, and the remarkable predictions deducible from the theory that were very soon confirmed beyond reasonable doubt.

4 Classification as Hypothesis

It is a mistake to suppose that hypotheses are important only in the advanced sciences, such as physics and chemistry, but play no role in the so-called descriptive sciences, such as botany or history. In fact, description itself is based on, or embodies, hypotheses. Hypotheses are as critical to the various systems of classification in biology as they are to interpretation in history, and as they are to all knowledge in the social sciences.

In the science of history the importance of hypotheses is easily shown. Many historians seek explanations of past events that can account for them and that can be confirmed by other recorded events. For some it is some larger purpose or pattern, religious or naturalistic, that explains the entire course of recorded history. For others, who reject such cosmic designs, the study of the past nevertheless reveals some historical laws that explain some past sequences and can then be used to predict some future events. Both of these two groups conceive of history as a theoretical science, not one that is merely descriptive; for both the role of hypothesis is central to the historian's enterprise.

A third group sets a more modest goal. For them the task of historians is simply to chronicle the past, to present an accurate description of past events in chronological order. Their concern is with the facts themselves, rather than with theories about the facts, so it might seem that they have no need of hypotheses.

However, past events are not so easily chronicled as this view would have us believe. The past itself simply is not available for this kind of bare description. What is available are records of the past and traces of the past. We have government archives, epic poems, the writings of earlier historians, the artifacts unearthed by archeological excavations, and so on. It is from a great variety of facts like these that historians must infer the nature of the past events they aim to describe. They cannot do this without some hypotheses. Not all hypotheses are general; some are particular, and with particular hypotheses historians seek to convert the data at hand into evidence for their account of the events in question.

Historians are detectives on a grand scale. Their methods are the same, and their difficulties too. The evidence is scanty, and much of it has been destroyed by intervening wars or natural disasters. False or misleading clues throw detectives off the scent, and similarly, many existing "records" are falsifications of the past, perhaps unintentional, such as the writings of earlier, uncritical historians. The methods of science must be used by good detectives and good historians both, and even those historians who seek to limit themselves to the bare description of past events must work from some hypotheses. They are theorists in spite of themselves.

Biologists are in a more favorable position. The facts with which they deal are present and available for inspection. To describe the flora and fauna of a region, biologists are not obliged to draw elaborate inferences, as historians are, because they can perceive the data directly. Their descriptions are not casual or random, but highly systematic. They *classify* plants and animals, and do not merely describe them. But classification and description are, at bottom, the same process. To describe an animal as carnivorous is to classify it as a carnivore; to classify it as a reptile is to describe it as reptilian. To describe any object as having a certain attribute is to classify it as a member of the class of objects having that attribute.

Scientific **classification** involves not merely a single division of objects into groups, but further subdivision of each group into subgroups and subclasses, and so on. Classification is also the tool of our inquiry when we play "Twenty Questions"—but it is a nearly universal tool, because it answers an almost universal need. Primitive people needed to sort the poisonous from the edible, the dangerous from the harmless, and so forth. We all draw distinctions, and we do so more meticulously with respect to the matters that chiefly concern us. The farmer's vegetables he will classify with greatest care, while treating all the flowers, in which he has no interest, as weeds. The florist will give delicate care to the classification of flowers, but may treat all the farmer's crops merely as "produce."

Classification
The organization and division of large collections of things into an ordered system of groups and subgroups, often used in the construction of scientific hypotheses.

Two basic motives lead us to classify things. One is practical, the other theoretical. In any library, with many thousands of volumes, books could not be found if they were not shelved according to some system of classification. The larger the number of objects with which we deal, the greater is the need to classify them. In museums, libraries, large department stores, this practical need is plain.

The theoretical object of classification is less obvious. Alternative schemes of classification are neither true nor false. Objects may be described in different ways, from different points of view. The system of classification adopted will depend on the purpose or interest of the classifier. A librarian will classify books according to their subject matter; a bookbinder according to the material of their leaves and bindings; a bibliophile by date of publication and perhaps by rarity; a shipper by weight and size—and there will be other schemes of classification as well.

What is the special interest of scientists, leading them to prefer one scheme of classification over another? The scientist seeks knowledge, not merely of this or that particular fact, but of the general laws to which the facts conform, and of their causal interrelations. One scheme of classification is better than another, from the scientific point of view, to the extent that it is more fruitful in suggesting scientific laws, and more helpful in the formulation of explanatory hypotheses.

The theoretical, or scientific, motivation for classifying objects is the desire to increase our knowledge of them, to achieve insight into their attributes, their similarities and differences, and their interrelations. Classification with a narrowly practical purpose—dangerous and harmless, or flying and swimming—will not much advance that understanding. The rattlesnake and the wild boar will go into one class, the grass snake and the domestic pig into the other; the bats and the birds will go into one class, the whales and the fishes into another. However, snakes and boars are profoundly different, whereas whales and bats are profoundly like one another. Being warm-blooded or not, bearing young alive or laying eggs, are much more important characteristics than dangerousness on which to base a system of classification.

A characteristic is important when it indicates the presence of other characteristics. When an attribute is causally connected with many other attributes, it can serve in the framing of a greater number of causal laws and of more general explanatory hypotheses. That classification scheme is best which is based on the most important characteristics of the objects to be classified. We cannot know in advance which these are, because we cannot know in advance the causal connections we aim to learn. So scientists classify *hypothetically*. Different classification schemes are tried, with the understanding that later they may be improved on or rejected. Later investigations may reveal other characteristics that are involved in a greater number of causal laws and explanatory hypotheses, and we will then revise the classification scheme so as to base our categories on it.

It is true that classification tends to be more important in the early or less developed stages of a science, but it need not diminish in importance as that science develops. Taxonomy is a legitimate, important, and still growing branch of biology, in which earlier systems of classification have been abandoned in favor of others that prove more productive. Some classificatory tools—such as the periodic table of the elements—remain valuable to the chemist.

Hypotheses in history are illuminated by these biological considerations. Historians, too, focus on what they find to be most important in increasing our understanding of past events. Life is too short to permit the description of past events in *complete* detail, so every description by a historian must be selective, recording only some features. How may that selection be made? Of course historians want to focus on what is important, ignoring the insignificant. Historians, like biologists and other scientists, regard those aspects of events as important that enter most widely into the formulation of causal laws and explanatory hypotheses—always subject to correction in the light of further research, of course. Early historians emphasized the political and military aspects of events, ignoring other attributes we now think to be important. The turn to economic and social attributes brought enormous changes in the work and the products of historians; today we go beyond economic and social issues to attend to cultural and other characteristics that are now thought to be causally related to a maximum number of others. So the decision to focus on one rather than another set of attributes embodies some hypothesis about which characteristics really are important. Some such hypotheses are required before historians can even begin to do any systematic describing of the past. It is this *hypothetical* character of classification and description that leads us to regard hypothesis as the all-pervasive method of scientific inquiry.

EXERCISES

In each of the following passages,

a. What data are to be explained?

b. What hypotheses are proposed to explain them?

c. Evaluate the hypotheses in terms of the criteria presented in Section 3.

1. In an unusual logjam of contradictory claims, a revolutionary new model of the universe, as a soccer ball, arrived on astronomers' desks in October of 2003—at least slightly deflated.

Based on an analysis of maps of the Big Bang, Dr. Jeffrey Weeks and colleagues, from Canton, NY, suggest that space is a kind of 12-sided hall of mirrors, in which the illusion of infinity is created by looking out and seeing multiple copies of the same stars.

If his model is correct, Dr. Weeks said, it would rule out one variant of the Big Bang theory that asserts that our own observable universe is just a bubble among others in a realm of vastly larger extent. "It means we can just about see the whole universe now," Dr. Weeks said.

Other astronomers, led by Dr. David Spergel of Princeton, said that their analysis of the same data had probably already ruled out the soccer-ball universe. The two groups of scientists, who have been in intense communication in recent days, disagree about whether the soccer ball universe has been refuted. But they all agree that what is amazing about this debate is that the controversy will actually be settled soon, underscoring the power of modern data to resolve issues that were once considered almost metaphysical.

In the scientific journal *Nature* Dr. Weeks wrote: "Since antiquity our ancestors have wondered whether our universe is finite or infinite. Now, after more than two millennia of speculation, observational data might finally settle this ancient question."

Dr. Weeks and his colleagues propose that the universe is 12-sided, a dodecahedron. The waves appearing in a radio map of the universe when it was very young indicate, he argues, that if you go far enough in one direction you would find yourself back where you started, like a cursor disappearing off the left side of a computer screen and reappearing on the right. Thus when cosmic radiation intersects the edges of the universe it would make identical circles on opposite sides of the sky—six pairs of circles, 35 degrees in diameter, in the case of Dr. Weeks's dodecahedron.

Dr. Max Tegmark, a cosmologist at the University of Pennsylvania, observed: "What's nice is that this is so testable. It's the truth or it's dead. The data are actually already out there; it's just a question of sifting through them. We ought to have seen those circles." So far the circles have not showed up. "Is space infinite or is it not?" Dr. Tegmark asked. "This is what got Giordano Bruno burned at the stake!"

—Reported in *Nature*, 9 October 2003

2. Population clusters—groups of persons who are found to buy the same things, get their entertainment from the same sources, exhibit similar voting patterns, and generally behave in quite similar ways—are of growing interest. Michael J. Weiss has distinguished some 62 of these clusters, which he calls "distinctive lifestyle types." He also names them and highlights some of their peculiarities.

In the *Towns and Gowns* cluster, for example, tequila is far more popular than elsewhere, and twice as many people watch the soap opera "Another World" there than do people elsewhere. In the *Military Quarters* cluster people are four times as likely to watch the TV show "Hard Copy" as the average American. Among the young, middle-class Americans in suburbia, furniture refinishing, downhill skiing, and cats are abnormally popular, while chess and tractor pulls are abnormally unpopular.

Lifestyle clusters are found useful by businesses seeking customers, by candidates seeking votes, by nonprofit organizations seeking new contributors, and so on. What may appear trivial can be very revealing. In Washington, DC, Weiss observes, "there is a fault line between the fans of Brie cheese, who tend to hold down executive jobs and write the laws, and those of Kraft Velveeta, who maintain the service economy." He asks: "What prompts some of us to eat Brie and others to devour Velveeta cheese?"

—Michael J. Weiss, *The Clustered World* (Boston: Little, Brown, 2000)

3. Monkeypox, a viral disease related to smallpox but less infectious and less deadly, was detected for the first time in the Americas in 2003. At least 20 cases have been reported, in three Midwestern states, Wisconsin, Illinois and Indiana, according to the Centers for Disease Control and Prevention.

The patients ranged in age from 4 to 48, and became ill between 15 May and 3 June, 2003. All had direct or close contact with ill prairie dogs, which have become common household pets, and which might have caught monkeypox from another species, possibly Gambian giant pouched rats, which are imported as pets from West or Central Africa, where the disease had long occurred. Monkeypox in Africa is carried mainly by squirrels but is named after monkeys because it often kills them.

Several patients in the American outbreak work for veterinarians or pet stores that sold prairie dogs and Gambian rats. By quickly identifying the animals that can be infected with monkeypox, health officials hope to eliminate them before the disease becomes endemic in the Americas.

—Reported in the *The New York Times*, 9 June 2003

4. A small study of heart-disease patients testing a hypothesis so improbable that its principal investigator says he gave it a one-in-10,000 chance of succeeding has found that just a few treatments with an experimental drug, developed by Esperion Therapeutics of Ann Arbor, Michigan, reversed what may be the equivalent of years' worth of plaque in coronary arteries.

Forty-seven heart attack patients were randomly assigned to be infused with either a concentration of a substance that mimics high density lipoprotein (or HDL, the substance that removes cholesterol from arteries) or to be infused with an inactive saline solution, which served as a control.

After 5 weekly infusions those who got the experimental drug had a 4.2-percent decrease in the volume of plaque in their coronary arteries, while those who had saline infusions had, if anything, a slight increase in their plaque.

"Until now," said Dr. Steven Nissen, a cardiologist at the Cleveland Clinic who directed the study, "the paradigm has been to prevent disease by lowering bad cholesterol (LDL). If you get the bad cholesterol low enough, the plaques don't build up in the artery walls. This experiment says you can also remove the disease in the wall of the artery."

—Reported in the *Journal of the American Medical Association*, 5 November 2003

5. Boy babies tend to be about 100 grams heavier on average than girl babies, but it has never been explained, until recently, why that is so. Investigators were unsure whether the increased weight was to be explained by the fact that mothers of boys took in more energy, or because (when the fetus was male) those mothers used the energy taken in more efficiently.

Dr. Rulla M. Tamimi, of the Harvard School of Public Health, sought to resolve this uncertainty by measuring the intake of calories. During the second trimester of their pregnancy, 244 women in Boston were asked to record their dietary intake in full detail. The data collected were later correlated with the resultant births. Women carrying boys, Dr. Tamimi found, took in (as carbohydrates, fats, or proteins) about 10 percent more calories than women carrying girls. It is intake, and not efficiency of use, that makes the difference.

But what accounts for that difference of intake? Dr. Tamimi speculated that it may be triggered by some signal from the testosterone given off by the male fetuses.

—Reported in the *British Medical Journal*, June 2003

6. Humans, apes, and dolphins are highly social animals with large brains; they have been shown to be aware of themselves by recognizing themselves in a mirror. Most animals pay very little attention to their reflections in a mirror. Elephants are like humans in being large-brained and empathic, but they don't share a relatively recent common ancestor with humans, like apes do. Might they also recognize an image of themselves?

Yes, they do. Elephants at the Bronx Zoo, in New York City, inspected themselves with their trunks while staring at their reflections in a huge mirror. One of the elephants (but only one) completed the highest level of self-recognition, called the "mark test." Researchers placed a white X above one eye of each elephant. After approaching the mirror, this elephant touched the mark with her trunk 12 times in 90 seconds—confirmation that she believed that what she saw in the mirror was indeed herself.

—Reported by Diana Reiss, of the Wildlife Conservation Society and Columbia University, in *Proceedings of the National Academy of Sciences*, November 7, 2006

7. The Nobel Prize for chemistry for 2003 was shared by Dr. Peter Agre, who encountered a new protein by serendipity. He had been studying a particular protein found in blood when he found another protein contaminating his sample. Trying to develop an antibody that would hook on to the protein he was studying, Dr. Agre found that the antibody hooked on to the contaminating protein instead—which turned out to be one of the most abundant proteins found in blood samples, although no one had identified it before.

But what did it do? He looked for similar proteins and found some—whose functions also were not known—in the roots of plants. The situation grew "curiouser and curiouser," Dr. Agre said. Finally he tried testing whether the new protein could be a water channel. That such channels might exist had been suggested long ago—but diffusion had then seemed to explain water movement, and specific channels had never been discovered.

To test the water channel hypothesis, Dr. Agre added the gene that produced the mystery protein to the eggs of frogs. The modified eggs, placed in fresh water, quickly swelled and burst, strongly confirming that theory. "The eggs exploded like popcorn," Dr. Agre said. The newly discovered proteins, called "aquaporins," have a channel just a little wider than a water molecule, and have recently been found also in human kidneys, where water is extracted from urine and recycled.

"This really fell into our laps," Dr. Agre said when his Nobel Prize was announced. "Being lucky is an important ingredient in scientific success."

8. Early in the eighteenth century Edmund Halley asked: "Why is the sky dark at night?" This apparently naive question is not easy to answer, because if the universe had the simplest imaginable structure on the largest possible scale, the background radiation of the sky would be intense. Imagine a static infinite universe—that is, a universe of infinite size in which the stars and galaxies are stationary with respect to one another. A line of sight in any direction will ultimately cross the surface of a star, and the sky should appear to be made up of overlapping stellar disks. The apparent brightness of a star's surface is independent of its distance, so that everywhere the sky should be as bright as the surface of an average star. Since the sun is an average star, the entire sky, day and night, should be about as bright as the surface of the sun. The fact that it is not was later characterized as Olbers' paradox (after the eighteenth-century German astronomer Heinrich Olbers). The paradox applies not only to starlight but also to all other regions of the electromagnetic spectrum. It indicates that there is something fundamentally wrong with the model of a static infinite universe, but it does not specify what.

—Adrian Webster, "The Cosmic Radiation Background,"
Scientific American, August 1974

9. Swedish researchers, collaborating with colleagues in South Africa, found that dung beetles active during the day detect polarity patterns in sunlight and rely on those patterns to find their way out of great masses of elephant dung. Dr. Marie Dacke, of the University of Lund, noticed subsequently that on moonlit nights one beetle species worked (rolling dung) particularly late. Could they have been relying upon the polarization of moonlight?

Researchers set up polarizing filters to shift the moonbeams—and sure enough, the African beetle, *Scarabaeus zambesianus*, changed direction to compensate. When the polarization of the moonlight under the filter was rotated by 90 degrees, they found that beetles under that filter deviated from their course by almost exactly 90 degrees. "This is the first proof," writes Dr. Dacke in her report in *Nature* of 3 July 2003, "that any animal can use polarized moonlight for orientation."

10. For centuries (since the 1500s in Scandinavia) people have puzzled over lemmings, northern rodents whose populations surge and crash so quickly and so regularly that they inspired an enduring myth: that lemmings commit mass suicide when their numbers grow too large, pitching themselves off cliffs to their deaths in a foamy sea.

Scientists debunked that notion decades ago, but have never been certain what causes the rapid boom-and-bust population cycles—a mystery in ecology that has been hotly debated. "There have been several dozen hypotheses," said Dr. Oliver Gilg, an ecologist at the University of Helsinki in Finland, "and scientists were sticking so closely to their hypotheses that they were almost killing each other." But Dr. Gilg, the author of a recent study published in the journal *Science*, provides a single hypothesis that his team of researchers claims provides the entire explanation.

The rapid population cycles have nothing to do with self-annihilation, they contend, but everything to do with hungry predators. After 15 years of research they have discovered that the actions of four predator species—snowy owls, arctic foxes, seabirds called long-tailed skuas, and the weasel-like stoats—account for the four-year cycles during which lemming populations rapidly explode and then nearly disappear. After creating a model based only on those four predators, they found that the model predicted precisely the numerical fluctuation of lemming populations in nature.

—Reported in *Science*, 31 October 2003

chapter Summary

In this chapter we explored the principles that underlie the methods of science.

In Section 1, we distinguished scientific from unscientific explanations, the former being always hypothetical and empirically verifiable, the latter dogmatic in spirit and not testable by propositions that can be deduced from them.

In Section 2, we examined the method of science, relying on the confirmation of hypotheses. We identified the seven stages that may be distinguished in any scientific inquiry:

1. The identification of some problem
2. The construction of some preliminary hypothesis
3. The collection of additional data in the light of that preliminary hypothesis
4. The formulation of a fully explanatory hypothesis supported by the data collected

5. The deduction of further consequences from the explanatory hypothesis
6. The testing of the consequences deduced
7. The application of the theory developed

In Section 3, we explored the evaluation of alternative scientific hypotheses. We identified criteria with which we might choose between competing hypotheses:

1. The compatibility of a theory with the body of theory previously established
2. The degree of predictive or explanatory power that a new theory manifests
3. The relative simplicity of competing theories

We illustrated these criteria with events in the history of science—most notably, the replacement of the geocentric (or Ptolemaic) theory of the solar system with the heliocentric (or Copernican) theory, confirmed by the remarkable observations of Galileo Galilei.

In Section 4, we discussed classification, an intellectual instrument that is greatly valued in the social and biological sciences as well as in the physical sciences, noting that every classificatory scheme suggests general truths and invites the formation of explanatory hypotheses.

END NOTES

[1]D. Biello, "Island Lizards Morph in Evolutionary Experiment," *Scientific American*, 17 November 2006.

[2]*On the Old Saying: "That Might Be Right in Theory"* [*Uber den Gemeinspruch: Das mag in der Theorie richtig sein*], 1793, translated by E. B. Ashton (Philadelphia: University of Pennsylvania Press, 1974).

[3]This letter, dated 7 January 1610, apparently was written over a period of many days. It, and other notes taken by Galileo during these momentous days, are discussed in detail in Jean Meeus, "Galileo's First Records of Jupiter's Satellites," *Sky and Telescope,* February 1964; in Stillman Drake, "Galileo's First Telescopic Observations," *Journal of the History of Astronomy,* 1976, p. 153; and in Dale P. Cruikshank and David Morrison, "The Galilean Satellites of Jupiter," *Scientific American*, May 1976. A photocopy of the original sketch Galileo made to record his observations, his notes appearing on it in Italian, is reproduced in Figure 1, through the courtesy of the library of the University of Michigan, Ann Arbor, in whose rare-book room that precious manuscript is held.

[4]That Galileo began this letter on 7 January 1610 is clear; the exact days of that month on which he continued it, with sketches and notes, are a matter about which scholars disagree.

Logic Overview—The Seven Stages of Scientific Investigation: The Scientific Method

1. Identify the problem
2. Devise preliminary hypotheses
3. Collect additional facts
4. Formulate a refined explanatory hypothesis
5. Deduce consequences from the refined hypothesis
6. Test the consequences deduced
7. Apply the theory