1 The Idea of Evolution

Its Scope and Implications

For historians of science, the "Darwinian revolution" has always ranked alongside the "Copernican revolution" as an episode in which a new scientific theory symbolized a wholesale change in cultural values. In both cases, fundamental aspects of the traditional Christian worldview were replaced by new interpretations of nature. Medieval cosmology had pictured the earth as the center of a hierarchical cosmos stretching up through the perfect heavens to the abode of the Almighty. Because the physical universe was the stage on which the spiritual drama of humanity's creation, fall, and redemption was played out, it was natural to believe—as common sense dictated—that the earth was at the center of the whole system. Copernicus taught instead that the earth is merely the third planet orbiting around the sun. His followers realized that, by breaking down the barrier between the earth and the heavens, he had revealed a nonhierarchical universe governed by fixed laws of dynamics. The human race was not the center of everything: we are merely the inhabitants of a single planet orbiting what was soon recognized as an insignificant star lost in the immensities of space.

One could still believe that the human race had a spiritual role to play. For the Christian, humans are unique in their capacity to appreciate the moral dilemma of their existence. On the earth, at least, we are the lords of creation, the highest link in a "chain of being" that ranks all living things into a natural hierarchy. Surely no natural process could explain the existence of such an orderly system of life or of humanity's spiritual faculties. The Book of Genesis assures us that everything—including the founders of the human race, Adam and Eve—was created by divine will in a period of six days. The Darwinian revolution—which actually began before Darwin was born—undermined this belief in humanity's innate superiority over nature. Geologists showed that Genesis was not a good guide to earth history, be-

cause there were vast periods before humans appeared on the scene, when the earth was inhabited by bizarre creatures unlike any known today. Evolutionists saw the possibility that this sequence of living things might have been developed by natural laws rather than by divine miracles. And if so, the human race itself became merely another animal species, no longer the lords of creation but only superior apes.

Such changes were not accomplished without resentment. The Catholic Church resisted the new cosmology, as Galileo discovered when he was brought to trial. In this case, the opposition soon died down. Darwin's theory, however, aroused stronger passions that still generate active resistance today. If the religious controversies over Darwin's *Origin of Species* seemed to decline in the late nineteenth century, they broke out again following the emergence of twentieth-century fundamentalism, with its insistence that the Book of Genesis must be taken seriously as the history of creation. Whatever the success of evolution theory in science, the cultural phase of the Darwinian revolution has not yet reached its conclusion.

The antagonism of the creationists should not blind us to the fact that science and religion have sometimes been able to work in harmony. The history of evolutionism reveals many attempts to see the development of life on earth as the unfolding of a divine plan. There have certainly been some scientists who would adopt a more militant posture, arguing that humanity simply has to come to terms with the unpleasant fact that it is the product of a purposeless sequence of natural events. Efforts to apply the resulting theories to human affairs have, however, sparked opposition from moralists and philosophers, who may not be religious in the conventional sense. They point out that what the biologists have claimed to be "natural" human behavior all too often turns out to reflect the prejudices of a particular interest group within our society. The term *social Darwinism* has been coined to denote the illegitimate use of scientific arguments to bolster harsh or discriminatory social policies. When pushed to its logical conclusion, this critique threatens the objectivity of science itself by suggesting that no interpretation of nature can be completely free from the values of those who articulate it.

Because evolution theory so directly affects our views on human nature and the relationship between humans and the natural world, it continues to provide a focus for debate. The issues raised by Darwin and his followers are still alive today, and a study of the history of evolutionism provides invaluable background for anyone interested in how the various positions—scientific, religious, or ideological—came into existence. Much can be gained from the lessons of history, especially an awareness of the dangers of over-

simplification. Before we can undertake such a study, however, we must establish a framework for understanding the rise of modern evolutionism. We must identify the full range of issues over which evolutionism has challenged the traditional worldview. We must appreciate how aspects of the old view can be modernized to fit in with certain kinds of evolutionary thought. The basic idea of evolution can be developed in many different ways, each with its own broader implications. We must also look more closely at the problems facing the historian who has to seek a balance between the conventional image of science as the objective evaluation of factual data and the suspicion of many critics that scientific theories are value-laden contributions to philosophical and ideological debates.

THE OLD WORLDVIEW AND THE NEW

The theory of biological evolution is only one part of a new approach to the study of the earth's past that has been developed over the last few centuries. Long before Darwin tackled the question of the origin of species, geologists had challenged the literal interpretation of the Genesis creation story by showing that the earth and its inhabitants have changed significantly over a vast period of time. Only within this new vision of an evolving physical universe did it become possible to imagine that living things might also be subject to natural change. Once that possibility had been confronted, religious thinkers had to ask if the Creator might have structured the universe through the operations of the laws He established, rather than by supernatural fiat. Some scientists began to doubt that any kind of divine providence was visible in the operations of nature. Thus we can distinguish several steps in the process by which the old worldview was challenged.

The existence of a series of intermediate positions between biblical creationism and materialistic evolutionism forces us to recognize the complexity of the relationship between science and religion. All too often this relationship has been depicted as a state of open warfare. But the scholars who first wrote on the war between science and religion, such as J. W. Draper (1875) and Andrew White (in 1896), were part of a secularist movement that rejoiced in sweeping away what was regarded as outdated superstition. Modern creationists also have much to gain from depicting all evolutionism as an outgrowth of militant atheism. To construct a more balanced picture, historians have had to adopt a more flexible view of the interaction between science and religion (for recent surveys, see Brooke 1991; and Lindberg and Numbers 1986). Moore (1979) has criticized Draper's and White's analyses

of the Darwinian debates, pointing out that some religious thinkers were able to exploit the idea of evolution as part of their campaign to liberalize Christian theology. Many scientists too were deeply concerned over the religious implications of what they were doing. Both scientists and religious thinkers had to accommodate themselves to the new ideas being advanced to explain the history of life on earth.

The Expansion of the Time Scale

In the Judeo-Christian worldview, the universe was extremely short-lived, since the six days of creation were supposed to have occurred only a few thousand years ago. James Ussher, archbishop of Armagh in the mid–seventeenth century, has become notorious for his estimate (based on a sophisticated analysis of the generations of Hebrew patriarchs) that the creation took place in 4004 B.C. By 1800, geologists had shown that the earth must be far older than this estimate, and, by the time Darwin published his book, all educated persons accepted that the biblical timescale was untenable (Toulmin and Goodfield 1965). There were still debates over exactly how old the planet is, some of which affected evolutionary theory, but by the early twentieth century, radioactive dating techniques were beginning to suggest that the earth had been formed several billions of years ago. Ironically, Darwin himself did not have to respond to claims that the true age is only a few thousand years: not until the mid–twentieth century did creationists begin to revive Ussher's timescale.

The Concept of a Changing Universe

Ussher saw no reason to posit a time before the human race appeared, but the geological evidence suggested that during vast periods of time the earth had been inhabited by creatures unlike those we see today. The whole of human history formed merely the most recent episode in the development of life. It became clear that a sequence of populations of animals and plants had appeared and disappeared one after the other. The idea of divine creation could be defended only by abandoning the biblical model of a single episode of creation and invoking a succession of creative acts spread over eons. But an alternative became conceivable: the possibility that the successive populations were linked by a process of gradual change leading to the eventual appearance of the human race.

The theory of a sequence of miraculous creations spread through geological time represents the first and simplest attempt to work out a compromise that would preserve at least some aspects of the traditional worldview. One aspect of ancient Greek natural philosophy that had fitted neatly into

the Christian view of divine creation was the belief that each species of animal and plant is based on a fixed pattern. Casual observation suggests that we can assign each individual animal to a particular species. The simplest explanation of this fact is that species have a real existence; they are fixed groupings into which individual animals *must* fall, like prearranged pigeonholes into which mail is sorted (on the emergence of biological concepts from folk belief, see Atran 1990). The Greek philosopher Plato saw individual animals as being patterned on a fixed plan or type which exists eternally at a level of reality transcending the physical universe. The Christian could believe that the pattern existed in the mind of God. According to the evolutionist Ernst Mayr (1964, 1991), the great triumph of modern Darwinism is the elimination of this ancient typological view of nature. Darwinism denies the existence of these fixed types: the species is merely a breeding population. If the average nature of the individuals in the population changes, then the species itself has changed.

If species are miraculously created, then the design of each is established by God and remains constant throughout the generations of animals. This would be true even if the species first appeared at some point in the earth's history and then disappeared (became extinct) at a later date. While it exists, the type remains fixed, and thus the idea of a sequence of creations preserves the fixity of species. At first sight it might seem that any theory of evolution must break down this element of fixity: if species change, how can they be fixed? Fixity is certainly impossible in Darwinism and in any theory which supposes that species change gradually. But some theories have been based on the assumption that transmutation occurs suddenly by saltations (from the Latin *saltus*, a leap). For example, occasionally individuals may be born so different from their parents that they count as a new species—critics call this possibility the theory of the "hopeful monster." If it is assumed that significant change occurs only through saltations, the species remain fixed between the jumps. This theory preserves the typological view of species even while accepting a form of natural transmutation.

The Elimination of Design

In the old worldview, the pattern of each species is designed by its creator. The whole point of the theory of miraculous creations is to insist that only supernatural design can explain the complex and orderly structure of each animal's body. The laws of nature can perpetuate existing designs but cannot create new ones. The "argument from design" popular among the exponents of natural theology holds that the perfection of each design, and the adaptation of each species to a particular way of life, confirms the wisdom

and benevolence of God. This offers what is known as a teleological explanation of organic structures (from the Greek *telos*, purpose, and *logos*, reason). The species is constructed that way for the purpose of enabling the organisms to function in their environment. It is also possible to argue that the relationships between species exhibit a rational order or pattern that can be explained only as part of the divine plan.

The theory of a sequence of miraculous creations can preserve the notion of a pattern of creation, even if only part of the pattern exists at any one time. But what would be the consequence of denying miracles and asserting that new species can actually be formed by the operation of natural laws that presumably act to modify existing species? The most radical extension of this belief would be to argue that, since the laws of nature act blindly, the production of new species cannot be an expression of divine providence. In the Darwinian theory of natural selection, evolution exploits individual variations that are purposeless (although not absolutely random, as is popularly supposed) by simply eliminating those that confer no benefit to the organism. Evolution becomes a process of trial and error based on massive wastage and the death of vast numbers of unfit creatures. On such a model, it is difficult to see how the structure of any particular species, or the overall distribution of species, can be the product of divine forethought. There can be no goal toward which evolution is striving, only a multitude of different species each responding to local environmental challenges in an ad hoc way.

If this were the only version of evolutionism, then a war between science and religion might be inevitable. In fact, however, there are again a series of intermediate positions which allow the naturalist to view the production of new species as an expression of God's handiwork. After all, any religious thinker must accept that the laws of nature were established or instituted by the Creator. It has even been argued that Christianity fostered the rise of science precisely because it encouraged the belief in a universe governed by a divine lawgiver (Jaki 1978a). If those laws govern processes that can change species, are not the changes therefore part of the divine plan? Many efforts were made to show that the radical materialism of Darwin's theory was not the only explanation of evolutionary change. Evolution must somehow represent the unfolding of the divine plan. Some nonreligious thinkers, frightened by the haphazard and open-ended nature of evolution according to the Darwinian system, also argue that there must be orderly patterns built into the history of life on earth.

The most obvious way of retaining an element of design is to suggest that the steady progress of evolution up to the human species is itself a sign

of divine purpose, a position revived in the mid–twentieth century by Pierre Teilhard de Chardin (1959). Some biologists now argue that it is difficult to see such a progressive trajectory in evolution; progress is difficult to define except by imposing human values onto nature and even then does not occur all the time. All attempts to see evidence of purpose at a more detailed level are dismissed as illusory because the laws of nature, as understood by science, cannot be programmed to work toward the fulfillment of a future goal. Other evolutionists accept a long-range and nondeterministic progressive trend without feeling any need to ascribe this to the action of a supernatural creator.

The Inclusion of Humankind within Nature

The Bible tells us that the human race was formed in the image of the Creator and given dominion over the rest of nature. Christianity (unlike some other religions) insists that only humans have a spiritual component to their existence; the other animals are "the brutes that perish." Evolutionism states that the human race must have evolved from the lower animals and cannot have this unique status. In this view, we are part of nature, and our higher faculties cannot stem from a spiritual factor with which we alone are endowed. Even our moral or ethical feelings (our conscience) must be seen as an extension of animal social instincts produced by the laws of natural evolution. This prospect created perhaps the greatest barrier to the acceptance of Darwin's theory, and it still horrifies many people today. It was overcome in Darwin's time by invoking the idea of progress: if nature was intended to progress toward evolving these higher mental faculties, then we retain our position as the goal of creation. But critics still maintain that it is precisely in the reduction of humanity to the status of beasts that we see the true materialism of the evolutionary worldview. Social scientists also prefer to believe that some aspects of human behavior cannot be explained in purely biological terms. They warn that biologists are constantly tempted to see behavioral differences between humans as innate and hence unchangeable products of the evolutionary past. In fact, the differences may be the products of education and culture.

THE POSSIBILITIES OF CHANGE

In trying to specify the range of positions intermediate between biblical creationism and the Darwinian theory of evolution, we have already been forced to confront the fact that there are different ways of understanding

how the natural world could change through time. There is no single theory of evolution, only an array of rival depictions of how new forms of life originate. Over the last century or more, biologists have tried out many different ideas, and nonscientists have expressed passionate support for some of the alternatives. In scientific biology, the Darwinian theory of natural selection has achieved dominant status following its synthesis with genetics in the mid–twentieth century. But some biologists continue to challenge the Darwinian orthodoxy, and many nonscientists advocate less materialistic theories of the kind that biologists themselves once took seriously. Modern debates often revive issues that once were thought to have been settled, suggesting that the basic alternatives have a fascination that transcends the factual evidence (the "eternal metaphors" of Gould 1977a).

The word *evolution* itself has been applied to different concepts of change (Bowler 1975). The Latin *evolutio* means "to unroll," implying no more than the unpacking of a structure already present in a more compact form. Its first use in biology was to describe the development of the embryo, a process sometimes thought to offer a speeded-up model of the history of life on earth. Early embryologists believed that the growth of the organism was no more than the expansion of a preexisting miniature, a process which fits the literal meaning of *evolution*. Biologists soon came to believe that the development of the embryo was the classic example of a purposeful process moving from the simple to the complex. When the philosopher Herbert Spencer popularized the term *evolution* to denote the natural development of life on earth, he certainly intended to convey the impression of a necessary progress toward higher states. Most people still think that evolution is progressive, but Darwin (who seldom used the term *evolution*) pioneered a rival model in which it is by no means clear that life must advance toward higher levels.

Development or Steady State?

The assumption that evolution is necessarily progressive reflects the more general view that there must be an "arrow of time" defining the direction of history. It has been argued that the idea of the universe itself having a history was impressed on Western culture by the biblical story of the creation and the threatened end of the world. A classic scientific expression of this view is big bang cosmology, in which all matter in the universe is held to be flying outward from a gigantic explosion which marks the beginning of time. Geologists take it for granted that the earth had a beginning and has changed significantly since its origin. Even those biologists who say that

evolution is not *necessarily* progressive admit that life has occasionally moved onto a new plane of structural complexity.

If this assumption that there is a direction to history seems self-evident, it must be noted that an alternative position is tenable. Many non-Western cultures have no sense of universal history running from beginning to end: rather, everything repeats itself in an endlessly repetitive cycle (Eliade 1951). In modern science, an analogous view is expressed in steady state cosmology. Here, all change is seen to be self-correcting: if the galaxies move farther apart, new ones are formed in the intervening space so that the density remains constant. In such a model there can be no origin—or at least we can never hope to see any evidence of a starting point, since, however far back in time we look, more or less the same state of affairs will always obtain. Such a view was applied to the history of the earth by the geologist Charles Lyell, who exerted great influence on Darwin. Lyell's uniformitarian geology supposed that the erosion of mountains exactly compensated for uplift, so the earth's surface would have looked more or less the same at any point in its history. Again, Lyell insisted that we could never hope to see evidence of an original state from which the earth began, however ancient the rocks we study. Lyell's viewpoint was overthrown, not least by the evidence for the development of life on earth, but the modern Darwinians' insistence that evolution has no built-in direction of change may be a legacy of the steady state model.

Continuity or Catastrophe?

Why would Lyell advance such an apparently bizarre view of earth history? He began from the assumption that scientific geology can use only observable causes to explain the past. To invoke a state of affairs different from what we observe is to speculate and hence to become unscientific. Since we observe only slow, gradual changes, every structure on the earth's surface must have been built gradually over a long period—and this must apply even to the oldest rocks left intact. Lyell's steady state worldview was thus a by-product of his desire to uphold the "principle of continuity," according to which there are no breaks or sudden steps in the sequence of events, no causes outside the everyday range of experience (Gould 1987; Hooykaas 1959). This aspect of his geology impressed Darwin, and Darwin's theory of evolution is a classic expression of the principle of continuity in biology. It uses only processes that can be observed at work in modern populations to explain changes in the past. Since we see no evidence of species being

formed by sudden saltations today, we may not invoke such discontinuities in the past.

Lyell developed his position because he was annoyed by the tendency of the rival catastrophist school to propose massive upheavals to explain any large-scale structure, such as a mountain range. Curiously, the catastrophists accepted the progressive development of life on earth, since they were quite willing to admit that things were very different "in the beginning." Modern evolutionism has managed to combine the elements of continuity and cumulative change that were polarized in Lyell's time. Yet discontinuity continued to play a role in biology long after Darwin tried to eliminate it. The concept of saltative evolution depends on the assumption that normal, continuous processes break down at the point when a new species is formed: the radically new individual is the product of causes not normally observed in the reproductive process. This position has been largely abandoned today, but the catastrophist form of discontinuity has reemerged in the theory that the history of life has been punctuated by mass extinctions caused by asteroid impacts.

Exponents of the typological view of species outlined above often were drawn to the idea of saltation. They distrusted the theory of continuous evolution because it seemed to blur the sharp distinctions between the specific types. Darwinism shows that distinct (but not, of course, fixed) species can exist even though all change is gradual. If a population is divided in two by a geographical barrier, the two halves evolve in different directions and end up significantly different from one another, even though every step in the separation has been gradual.

Internal and External Control

The possibility that dramatic geological changes may have profound effects on the earth's inhabitants is the most extreme manifestation of a more general belief that the chief agent driving biological evolution is the external environment. Darwin's theory of natural selection builds on the same assumption but concentrates on the steady pressure of the environment when changes are very slow. In this theory, there can be no direction imposed on evolution by factors internal to the organisms, because the variation upon which selection acts is random in the sense that it is composed of many different and apparently purposeless modifications of structure. The environment determines which shall live and reproduce, and which shall die, thus defining the direction in which the population evolves. Evolution is essentially a process by which species adapt to their environment. Any other trend, for example, a progress toward more complex structures, can at best

be only a by-product of the ceaseless pressure to find a better way of coping with the demands of the external world. In such a theory, the course of evolution is open-ended and unpredictable, because each population is subject to changes in its local environment or may encounter entirely new environments through migration.

Opposed to this philosophy of environmental determinism is a range of theories based on the assumption that evolution is controlled by something other than the demands of adaptation. If one assumes that variation is not random, that something in the genetic or physical constitution of the organisms directs the production of variant characters along certain predetermined lines, then the evolution of the species would be forced to move in the direction defined by this trend. This is the theory of orthogenesis, once popular among anti-Darwinian biologists. Advocates of evolution by saltation would also argue that the production of new characters in this way is controlled by internal forces. Such theories are based on the assumption that the environment does not exert an unremitting pressure on the organisms. Nonadaptive trends can be sustained because natural selection is powerless to prevent the appearance of the predetermined characters.

Individuals and Populations

A related distinction insisted on by Richard C. Lewontin (1983) centers on the role played by the individual organism in evolution. In Darwin's theory, only populations evolve: changes which affect the individual in the course of its lifetime cannot become part of the evolutionary process. This is because, in the model of heredity confirmed by modern genetics, the only characters that can be transmitted to the next generation are those the individual was born with. Selection merely picks out the genetic characters transmitted to future generations, thus shaping the gene pool of the population. This rigid model of heredity is not accepted by what was once the great rival of Darwinism, the theory of the inheritance of acquired characteristics, usually identified with the French biologist J. B. Lamarck (see chap. 3). Lamarck believed that characters acquired by the organism in the course of its life can be transmitted to future generations. Acquired characters include the effects of use and disuse on organs: the weightlifter's muscles will be inherited by his children. On such a model, evolution is the sum total of individual acts of self-development. The individual can be said to evolve, or at least to provide some fraction of the effect that accumulates to create evolution in the population. Modern genetics denies the validity of the Lamarckian effect: acquired characters and other modifications of individual development cannot be imprinted on the genes and thus cannot participate in evolution.

Ladders and Trees

Our last important distinction relates to the way the evolutionary process is depicted visually. Stephen Jay Gould (1989) warned of the dangers implicit in different forms of diagrammatic representations of evolution. Each kind of representation has hidden assumptions built into it, and the reader must be aware of the values being projected. The simplest distinction is that between ladders and trees or bushes. The simplest idea of progress presupposes a ladderlike scale of organization, from simple to complex, which serves as the pattern of evolutionary progress. Many popular accounts of the animal kingdom are still based on the idea of an evolutionary hierarchy which concludes by presenting the human species as the pinnacle of development.

Biologists have long known that they cannot in fact arrange the various forms of life into a ladderlike pattern. There are many differences in structure that do not correspond to an increase or decrease in complexity. Evolution must be represented as a tree, with the branches diverging and rediverging in various different directions. Yet in the heyday of progressionism in the late nineteenth century, evolutionary trees were often drawn with a central trunk running to the human species at the top. Lower forms of life were depicted either as steps on the sequence leading up to humanity or as the products of side branches that split off without advancing any farther up the scale. Thus the essence of the ladder model was retained, and the human species was still seen as the goal of creation.

The idealized evolutionary tree in Darwin's *Origin of Species* has no central trunk and thus prevents the reader from imagining that the end product of one branch can somehow be the goal toward which all the others are striving. Although Darwin never completely shook off the legacy of progressionism, he realized that, in an evolutionary process governed solely by the response of the species to its environment, there was no force that could be imagined to drive species in a certain direction, and no goal toward which all life could be said to strive. Evolution is a bush rather than a tree: each branch has moved in its own direction, and we cannot present lower forms of life as merely relics of early stages in the ascent toward humankind. On this model, humans cannot have evolved from chimpanzees, because chimpanzees have evolved in their own direction at the same time that we have evolved toward our current state. The common ancestor from which we both diverged existed only in the past, and we must look for it in the fossil record, not in any living species of ape. Some modern evolutionists regard the diversity of living forms as so great that we can establish no reliable

scale of progress against which to measure their degree of evolutionary development.

Given the wide range of different positions which have been explored by evolutionary biologists, it should come as no surprise that the history of the field (like the Darwinian model of evolution) cannot be represented as a step-by-step process by which the modern theory was assembled. In the last few centuries, scientists have tried out many different theoretical models in their efforts to make sense of the bewildering array of evidence presented by the natural world. Our task is to outline not only the acquisition of factual knowledge but also the factors that have led scientists to prefer one model to another. Given the fact that some issues are still debated today, we must be careful not to assume that the Darwinian orthodoxy preferred by the majority of biologists is a goal toward which biology has been striving throughout its history. Even those who do accept modern Darwinism as the best possible explanation of the evolutionary process would do well to take account of the forces which have led biologists of previous generations to prefer rival theories. This leads us to the question of the scientific method itself and historians' efforts to understand how new theories are introduced.

THE NATURE OF SCIENCE

Historians have become involved in a more general process by which the nature of science has been questioned. Traditionally, scientists have presented themselves as disinterested providers of factual information. The scientific method was supposed to guarantee total freedom from the influence of subjective factors such as religion, philosophy, and moral values. It has now become apparent even to most scientists that this was an inadequate model of how science actually functions. Historians dealing with the development of evolution theory are in an excellent position to see why the traditional image of objectivity has broken down. Here is a theory which, even in its most basic form, begins to challenge a worldview that was deeply rooted in Western culture. Any theory advanced to explain the facts of nature had implications for these deeply rooted beliefs, and history suggests that the scientists' behavior often reflected the positions they took up on the broader issues.

The Scientific Method

The simplest model of science represents it as a process of factual discovery, the piling up of brute facts one upon another. A moment's reflection shows

that such a model is inadequate. Scientists are interested not in single facts but in universal generalizations abstracted from the facts, what we call laws of nature. At one time it was thought that the method of induction allowed scientists to recognize a law on the basis of a large number of factual instances of the law's operation. But it is impossible to perceive generalizations in a barrage of unclassified facts which might or might not be relevant. Philosophers of science have long recognized that any investigation starts not from mere fact collecting but from a hypothesis proposed to explain how the phenomenon under investigation *might* operate. The hypothesis is tested against the facts by observation and experiment: this is the hypothetico-deductive method (Hempel 1966). The most basic kind of hypotheses might eventually be accepted as laws of nature; more general hypotheses which link many related phenomena together yield theories. If a hypothesis is successful in passing the experimental tests to which it is subjected, we might be tempted to regard it as an established truth about how nature works. One who makes such a move would commit the logical fallacy of affirming the consequent: although false, a hypothesis might nevertheless pass some early tests by luck. Only when exposed to more rigorous testing would its inadequacy be revealed. In principle, all scientific knowledge must be treated as provisional, because we can never be sure that currently accepted laws and theories will not turn out to be false when exposed to future tests.

If scientific knowledge is only provisional, why should it be given higher status than other forms of knowledge? Scientists argue that their laws and theories are more objective because they have been formulated and tested in such a way as to rapidly expose any weaknesses. A scientific hypothesis is constructed to maximize its testability—or, since any test may potentially refute it, its degree of "falsifiability" (Popper 1959, 1974). By formulating their statements in a way that leaves them open to rigorous testing, scientists ensure that their kind of knowledge can be distinguished from nonscience and from pseudosciences, such as astrology, which offer vague generalizations that can never be falsified by any empirical test. Karl Popper argues that scientists have consistently been guided in their choice of hypotheses by the criterion of which is the more falsifiable.

Most scientists have been prepared to endorse Popper's definition of their objectivity because it preserves a line of demarcation between science and nonscience. If this position is ascribed to the scientists of previous generations as well, we could retain the conventional image of science as an essentially progressive force that steadily expands our knowledge of the external

world. Yet this image of steady progress seems inadequate to deal with those episodes conventionally known as scientific revolutions, where a theory that has long been accepted as valid is suddenly exposed as inadequate and replaced by something different. In principle, revolutions are not ruled out in the hypothetico-deductive system: all hypotheses, however fundamental and well tested, may eventually turn out to be false. But the prospect of scientists having to reconstruct the foundations of the way they think about nature seems to violate any impression of continuity in the development of knowledge. New theories ought to explain more facts than the old ones they replace, so there is still a sense in which science increases our level of understanding—but the increase is not brought about by a continuous development at the level of theoretical principles.

According to Popper, as soon as a theory fails an experimental test, it should be abandoned by the scientific community. But the analysis of scientific revolutions by Thomas S. Kuhn (1962) suggests that the replacement of theories is a much more complex affair (for a comparison of the Popperian and Kuhnian views of science, see Lakatos and Musgrave 1970). Kuhn used history to show that successful theories establish themselves as the paradigm for scientific activity in the field: they define not only acceptable techniques for tackling problems but also which problems are relevant for investigation. Not surprisingly, the cards are stacked in favor of the theory, because the chance of falsification is minimized by working in "safe" areas. Science done under the influence of a dominant paradigm is what Kuhn calls "normal science." Even when anomalies begin to appear, the scientific community has become so loyal to the paradigm that older scientists refuse to admit the significance of facts that falsify it and continue as though it were still functioning smoothly. Only when the number of anomalies becomes unbearable will a crisis state emerge, as younger and more radical scientists begin to look around for a new theory. When a new theory is found which deals with the outstanding problems, it soon establishes itself as the new paradigm, and another period of unadventurous normal science begins.

Kuhn's approach treats science as a social activity: scientists develop professional loyalties to their paradigm which restrict their ability to challenge the status quo. If this interpretation is valid, there are episodes in which science is anything but objective. On the contrary, scientists will do anything to defend the theory upon which their careers were founded. Objectivity may seem to be restored at the time of a revolution, but this is soon lost. And although the new paradigm seems to expand our range of knowledge

by dealing with facts that could not be fitted into the old theory, Kuhn notes that there are cases in which successful lines of investigation under the old paradigm were abandoned under the new.

Science and Society

Whether Kuhn's scheme applies to the Darwinian revolution is a topic we shall return to. But we must also consider the broader implications of the claim that science cannot be defined by a method of objective study but can be understood only as a social process subject to the same rules as any other human activity. There is one level at which even the Popperian scheme accepts that the scientist constantly must go beyond the facts. A hypothesis cannot simply emerge in the scientist's mind as a mechanical response to the facts. It goes beyond the available facts and thus represents a leap of the imagination, an act as creative as that of any artist. If we admit that any theory is only an approximate model of the real world, it is possible that at any one point in time several different hypotheses might act as useful guides to research. Only time and testing will determine which is most successful, but in the meantime we can ask why particular scientists conceive or accept the theory they choose to work with. Theories often have philosophical or ideological implications, so it is not unreasonable to suppose that scientists may be influenced in their choice of hypothesis by their feelings on these wider issues.

Science thus has to be understood in the context of the "sociology of knowledge" (Barnes, Bloor, and Henry 1996; Mulkay 1979). Sociologists accept that other areas of knowledge are shaped by social and cultural factors; what is acceptable as knowledge of God (theology) clearly has varied from society to society and from time to time. Science may have to be treated in the same way: although science increases our ability to manipulate nature, its underlying theoretical perspectives may nevertheless reflect social values. Historians of science obviously must take this possibility on board, because they must be on the lookout for the effect of these subjective factors in any past debate—especially when the theories involved are intrinsically more likely to affect sensitive issues (Barnes and Shapin 1979; Shapin 1982). Evolution theory provides a fertile field of study for historians to debate the relative significance of objective and subjective factors in determining the success or failure of theories.

Traditionally, historians of science were divided into two camps: internalists, who studied purely scientific factors in the development of knowledge, and externalists, who concerned themselves with the practical applications of