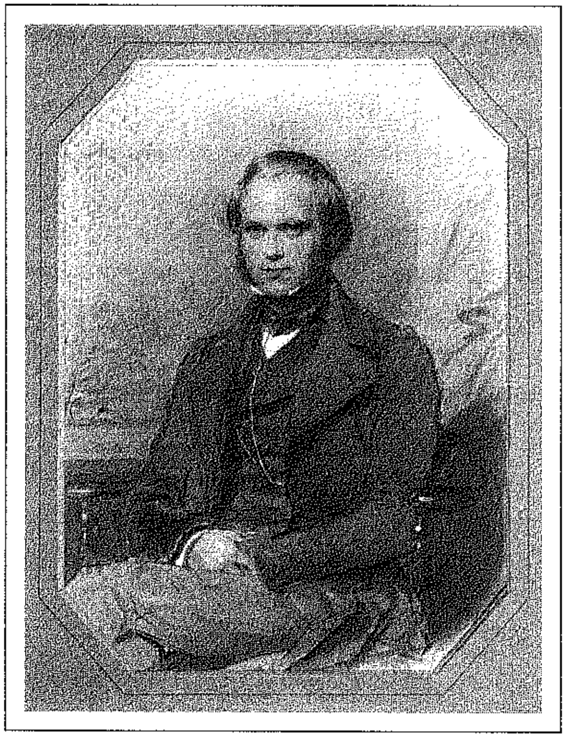

Charles Darwin at 31 years of age. Modified from painting by George Richmond.

Four

What Is Science?

WHAT IS THIS grand enterprise called *science* that has lit up heaven and earth and empowered humanity? It is organized, testable knowledge of the real world, of everything around us as well as ourselves, as opposed to the endlessly varied beliefs people hold from myth and superstition. It is the combination of physical and mental operations that have become increasingly the habit of educated peoples, a culture of illuminations dedicated to the most effective way ever conceived of acquiring factual knowledge.

You will have heard the words "fact," "hypothesis," and "theory" used constantly in the conduct of scientific research. When separated from experience and spoken of as abstract ideas they are easily misunderstood and misapplied. Only in case histories of research, by others and soon by you, will their full meaning become clear.

I'll give you an example of my own to show you what I mean. I started with a simple observation: ants remove their dead from the nests. Those of some species just dump the corpses at random outside, while those of other species place them on piles of refuse that might be called "cemeteries." The problem I saw in this behavior was simple but interesting: How does an ant know when another ant is dead? It was obvious to me that the recognition was not by sight. Ants recognize a corpse even in the complete darkness of the underground nest chambers. Furthermore, when the body is fresh and in a lighted area, and even when it is lying on its back with its legs in the air, others ignore it. Only after a day or two of decomposition does a body become a corpse to another ant. I guessed (made a hypothesis) that the undertaker ants were using the odor of decomposition to recognize death. I further thought it likely (second hypothesis) that their response was triggered by only a few of the substances exuded from the body of the corpse. The inspiration for the second hypothesis was an established principle of evolution: animals with small brains, which are the vast majority of animals on Earth, tend to use the simplest set of available cues to guide them through life. A dead body offers dozens or hundreds of chemical cues from which to choose.

Human beings can sort out these components. But ants, with brains one-millionth the size of our own, cannot.

So if the hypotheses are true, which of these substances might trigger the undertaker response—all of them, a few of them, or none? From chemical suppliers I obtained pure synthetic samples of various decomposition substances, including skatole, the essence of feces; trimethylamine, the dominant odor of rotting fish; and various fatty acids and their esters of a kind found in dead insects. For a while my laboratory smelled like a combination of charnel house and sewer. I put minute amounts on dummy ant corpses made of paper and inserted them into ant colonies. After a lot of smelly trial and error I found that oleic acid and one of its oleates trigger the response. The other substances were either ignored or caused alarm.

To repeat the experiment another way (and admittedly for my and others' amusement), I dabbed tiny amounts of oleic acid on the bodies of living worker ants. Would they become the living dead? Sure enough, they did become zombies, at least broadly defined. They were picked up by nestmates, their legs kicking, carried to the cemetery, and dumped. After they had cleaned themselves awhile, they were permitted to rejoin the colony.

I then came up with another idea: insects of all kinds that scavenge for a living, such as blowflies and scarab beetles, find their way to dead animals or dung by homing in on the scent. And they do so by using a very small number of the decomposition chemicals present. A generalization of this kind, widely applied, with at least a few facts here and there and some logical reasoning behind it, is a theory. Many more experiments, applied to other species, would be required to turn it into what can be confidently called a fact.

What, then, in broadest terms is the scientific method? The method starts with the discovery of a phenomenon, such as a mysterious ant behavior, or a previously unknown class of organic compounds, or a newly discovered genus of plants, or a mysterious water current in the ocean's abyss. The scientist asks: What is the full nature of this phenomenon? What are its causes, its origin, its consequence? Each of these queries poses a problem within the ambit of science. How do scientists proceed to find solutions? Always there are clues, and opinions are quickly formed from them concerning the solutions. These opinions, or just logical guesses as they often are, are the hypotheses. It is wise at the outset to figure out as many different solutions as seem possible, then test the whole, either one at a time or in bunches, eliminating all but one. This is called the method of multiple competing hypotheses. If something like this analysis is not followed—and, frankly, it often is not—individual scientists tend to fixate on one

alternative or another, especially if they authored it. After all, scientists are human.

Only rarely does an initial investigation result in a clear delineation of all possible competing hypotheses. This is especially the case in biology, in which multiple factors are the rule. Some factors remain undiscovered, and those that have been discovered commonly overlap and interact with one another and with forces in the environment in ways difficult to detect and measure. The classic example in medicine is cancer. The classic example in ecology is the stabilization of ecosystems.

So scientists shuffle along as best they can, intuiting, guessing, tinkering, gaining more information along the way. They persist until solid explanations can be put together and a consensus emerges, sometimes quickly but at other times only after a long period.

When a phenomenon displays invariable properties under clearly defined conditions, then and only then can a scientific explanation be declared to be a scientific fact. The recognition that hydrogen is one of the elements, incapable of being divided into other substances, is a fact. That an excess of mercury in the diet causes one disease or another can, after enough clinical studies are conducted, be declared a fact. It may be widely believed that mercury causes an entire class of similar maladies, due to the one or two known chemical reactions in cells of the body. This idea may or may not be confirmed by further studies on diseases believed affected in this manner by mercury. Meanwhile, however, when research is still incomplete, the idea is a theory. If the theory is proved wrong, it was not necessarily also altogether a bad theory. At least it will have stimulated new research, which adds to knowledge. That is why many theories, even if they fail, are said to be "heuristic"—they are good for the promotion of discovery. Incidentally, the source of the word *eureka*—"I have found it!"—descends from the legend of the Greek scientist Archimedes, who, while sitting in a public bath, imagined how to measure the density of an object regardless of its shape. Put it in water, measure its volume by the rise in the water level, and its weight by how fast it sinks in the water. The density is the amount of weight divided by the amount of volume. Archimedes is said to have then left the bath, running through the streets, hopefully in his robe, while shouting, *Heurika!* Specifically, he'd found how to determine whether a crown was pure gold. The pure substance has a higher density than gold mixed with silver, the lesser of the two noble metals. But of far greater importance, Archimedes had discovered how to measure the density of all solids regardless of their shape or composition.

Now consider a much grander example of the

scientific method. It has been commonly said, all the way back to the publication of Charles Darwin's *On the Origin of Species* in 1859, that the evolution of living forms is just a theory, not a fact. What could have been said already from evidence in Darwin's time, however, was that evolution is a fact, that it has occurred in at least some kinds of organisms some of the time. Today the evidence for evolution has been so convincingly documented in so many kinds of plants, fungi, animals, and microorganisms, and in such a great array of their hereditary traits, coming from every discipline of biology, all interlocking in their explanations and with no exception yet discovered, that evolution can be called confidently a fact. In Darwin's time, the idea that the human species descended from early primate ancestors was a hypothesis. With massive fossil and genetic evidence behind it, that can now also be called a fact. What remains a theory still is that evolution occurs universally by natural selection, the differential survival and successful reproduction of some combinations of hereditary traits over others in breeding populations. This proposition has been tested so many times and in so many ways, it also is now close to deserved recognition as an established fact. Its implication has been and remains of enormous importance throughout biology.

When a well-defined and precisely consistent process is observed, such as ions flowing in a magnetic field, a body moving in airless space, and the volume of a gas changing with temperature, the behavior can be precisely measured and mathematically defined as a law. Laws are more confidently sought in physics and chemistry, where they can be most easily extended and deepened by mathematical reasoning. Does biology also have laws?

I have been so bold in recent years as to suggest that, yes, biology is ruled by two laws. The first is that all entities and processes of life are obedient to the laws of physics and chemistry. Although biologists themselves seldom speak of the connection, at least in such a manner, those working at the level of the molecule and the cell assume it to be true. No scientist of my acquaintance believes it worthwhile to search for what used to be called the élan vital, a physical force or energy unique to living organisms.

The second law of biology, more tentative than the first, is that all evolution, beyond minor random perturbations due to high mutation rates and random fluctuations in the number of competing genes, is due to natural selection.

A source of the ground strength of science are the connections made not only variously *within* physics, chemistry, and biology, but also *among* these primary disciplines. A very large question remains in science and philosophy. It is as follows: Can this

consilience—connections made between widely separated bodies of knowledge—be extended to the social sciences and humanities, including even the creative arts? I think it can, and further I believe that the attempt to make such linkages will be a key part of intellectual life in the remainder of the twenty-first century.

Why do I and others think in this controversial manner? Because science is the wellspring of modern civilization. It is not just "another way of knowing," to be equated with religion or transcendental meditation. It takes nothing away from the genius of the humanities, including the creative arts. Instead it offers ways to add to their content. The scientific method has been consistently better than religious beliefs in explaining the origin and meaning of humanity. The creation stories of organized religions, like science, propose to explain the origin of the world, the content of the celestial sphere, and even the nature of time and space. These mythic accounts, based mostly on the dreams and epiphanies of ancient prophets, vary from one religion's belief to another. Colorful they are, and comforting to the minds of believers, but each contradicts all the others. And when tested in the real world they have so far proved wrong, always wrong.

The failure of the creation stories is further evidence that the mysteries of the universe and the human mind cannot be solved by unaided intuition. The scientific method alone has liberated humanity from the narrow sensory world bequeathed it by our prehuman ancestors. Once upon a time humans believed that light allowed them to see everything. Now we know that the visual spectrum, which activates the visual cortex of the brain, is only a sliver of the electromagnetic spectrum, where the frequencies range across many orders of magnitude, from those of extreme high-frequency gamma rays at one end to those at the extreme low-frequency radiation at the other. The analysis of the electromagnetic spectrum has led to an understanding of the true nature of light. Knowledge of its totality has made possible countless advances in science and technology.

Once people thought that Earth was the center of the universe and lay flat and unmoving while the sun rotated around it. Now we know that the sun is a star, one of two hundred million in the Milky Way galaxy alone. Most hold planets in their gravitational thrall, and many of these almost certainly resemble Earth. Do the Earthlike planets also harbor life? Probably, in my opinion, and, thanks to the scientific method, furnished with improved optics and spectroscopic analyses, we will know in a short time.

Once it was believed that the human race arose full-blown in its present form as a supernatural

event. Now we understand, in sharp contrast, that our species descended over six million years from African apes that were also the ancestors of modern chimpanzees.

As Freud once remarked, Copernicus demonstrated that Earth is not at the center of the universe, Darwin that we are not the center of life, and he, Freud, that we are not even in control of our own minds. Of course, the great psychoanalyst must share credit with Darwin, among others, but the point is correct that the conscious mind is only part of the thinking process.

Overall, through science we have begun to answer in a more consistent and convincing way two of the great and simple questions of religion and philosophy: Where do we come from? and, What are we? Of course, organized religion claims to have answered these questions long ago, using supernatural creation stories. You might then well ask, can a religious believer who accepts one such story still do good science? Of course he can. But he will be forced to split his worldview into two domains, one secular and the other supernatural, and stay within the secular domain as he works. It would not be difficult for him to find endeavors in scientific research that have no immediate relation to theology. This suggestion is not meant to be cynical, nor does it imply a closing of the scientific mind.

If proof were found of a supernatural entity or force that affects the real world, the claim all organized religions make, it would change everything. Science is not inherently against such a possibility. Researchers in fact have every reason to make such a discovery, if any such is feasible. The scientist who achieved it would be hailed as the Newton, Darwin, and Einstein, all put together, of a new era in history. In fact, countless reports have been made throughout the history of science that claim evidence of the supernatural. All, however, have been based on attempts to prove a negative proposition. It usually goes something like this: "We haven't been able to find an explanation for such-and-such a phenomenon; therefore it must have been created by God." Present-day versions still circulating include the argument that because science cannot yet provide a convincing account of the origin of the universe and of the setting of the universal physical constants, there must be a divine Creator. A second argument heard is that because some molecular structures and reactions in the cell seem too complex (to the author of the argument, at least) to have been assembled by natural selection, they must have been designed by a higher intelligence. And one more: because the human mind, and especially free will as a key part of it, appear beyond the capability of the material cause and effect, they must have been inserted by God.

The difficulty with reliance on negative hypotheses to support faith-based science is that if they are wrong, they are also very vulnerable to decisive disproof. Just one testable proof of a real, physical cause destroys the argument for a supernatural cause. And precisely this in fact has been a large part of the history of science, as it has unfolded, phenomenon by phenomenon. The world rotates around the sun, the sun is one star out of two hundred million or more in one galaxy out of hundreds of billions of galaxies, humanity descended from African apes, genes change by random mutations, the mind is a physical process in a physical organ. Yielding to naturalistic, real-world understanding, the divine hand has withdrawn bit by bit from almost all of space and time. The remaining opportunities to find evidence of the supernatural are closing fast.

As a scientist, keep your mind open to any possible phenomenon remaining in the great unknown. But never forget that your profession is exploration of the real world, with no preconceptions or idols of the mind accepted, and testable truth the only coin of the realm.