CHAPTER 1

What Is Science?

WHY LEARN SCIENCE?

The purpose of this book is to explain scientific method; the person we have written for is the average educated person rather than the professional scientist. We hope, however, that the scientist might find the book valuable in providing an opportunity to look at scientific method from a broader point of view than is usually done in the practice of one's own professional specialty. We have written it because we believe that anyone living in an age when science plays so important a role needs to know something about the method of science: how scientific discoveries are made, how theories come into being, how they are tested, and why they are believed or discarded.

There are several reasons why knowledge of the method of science is important.

The first is a cultural one. Such concepts as Darwin's theory of evolution, the second law of thermodynamics, and the uncertainty principle in physics have influenced the intellectual climate of our time through impacts on such fields as philosophy, literature, and theology. But perhaps more influential than these specific examples of scientific discovery is the concept of science itself as a way of viewing the world, understanding it, and changing it.

There are many today who regard science as harmful and destructive, and not just because of the harmful and destructive uses to which modern technology, derived from scientific discovery, has been put. It is the scientific spirit itself that is under attack, for providing a mechanical and dehumanizing picture of the world. The understanding provided by science is felt to be limited and narrow, ignoring the deeper questions of the meaning of life and the values that make it worth living. In this book we do not try to answer these criticisms. They may well be true, but we intend to leave that conclusion to the reader. All we will claim is that knowledge of the scientific approach is not of itself corrupting, that it is better to have that knowledge than not to; one is still left free to reject science if one chooses, but on the basis of a real understanding of it.

We will say, however, that one of our objectives here is to convince the reader that science is not a dry, orderly compilation of useful facts, although some of those who hold the negative view of science may think that it is. Science is an activity of creative and imaginative human beings, not of computers or other machines. The creativity and imagination must be controlled by discipline and self-criticism, but that is equally true of other kinds of creative activity such as the writing of poetry. And because it is a creative and imaginative activity, there are satisfactions in engaging in it no different from those felt by creative artists in their work, and there is a beauty in the results that can be enjoyed by others in the same way that poems, pictures, and symphonies are.

In fact, the term *scientific method* is misleading. It may suggest that there is a precisely formulated set of procedures that if followed will lead automatically to scientific discoveries. There is no such "scientific method" in that sense at all, and one of the important things we want to convey in this book is the intuitive and unpredictable way scientists actually work. The *American Heritage Dictionary* gives as one sense of the word *art* the following: "A specific skill in adept performance, conceived as requiring the exercise of intuitive faculties that cannot be learned solely by study." Scientific research is, in this sense, an art.

Other reasons for having an understanding of scientific method are more immediately practical. Many decisions that we as citizens—or those whom we allow to act for us—have to make require some specific scientific knowledge—some facts about chemistry, physics, biology, and so forth. What would be the risk to human beings of an accidental explosion in a nearby nuclear power plant? How should the government decide which type of research to support to find a cure for cancer or a new source of energy? Although this book is not meant to provide that kind of specific information, it can provide an understanding of how the knowledge in question has been acquired and how sure we are of its truth. Scientists called in as experts on matters like this often disagree profoundly. Whom should we believe and why? To a great extent we have no choice but to rely on experts in these matters, but we should understand something about the sources and limitations of even expert knowledge. Further, most people, in the course of making the various choices and decisions of daily life—whom to vote for, what to buy,

where to live, what to eat—apply some features of scientific method in an intuitive way. They usually do not think of what they do as being an application of scientific method, nor do they use it to the maximum extent. But a clearer concept of some of the basic procedures of scientific thinking could be useful even in such ordinary activities. And, in turn, the fact that most people have some intuitive concept of scientific thinking gives us hope that they can acquire a more detailed understanding if it is explained properly.

We have not yet said what we mean by the term *science*, and indeed there are many definitions of it. For some, the term applies only to the "exact" sciences, such as physics, which are characterized by laws of great generality and scope, from which numerically precise predictions can be made. Isaac Newton, for example, discovered a way of describing motion in a few simple mathematical equations which could be used to describe all the different forms of motion in the then-known universe—the motion of planets around the sun, the fall of an apple, the tides and waves of the ocean, and the vibration of a violin string. These motions can be described with great precision: for example, eclipses of the sun hundreds of years in the future can be predicted to within a few seconds. If laws of great generality and accurate predictive power are taken as essential to what we define as a science, then none of the social or behavioral sciences satisfies the criterion. Such "laws" as have been found in psychology or sociology are of very limited scope, are imprecise in prediction, and are often quite controversial within the field, unlike the laws of physics.

For others, the term *science* implies the ability to do controlled experiments to test theories. A controlled experiment is one in which some property or quantity believed to be the cause of a phenomenon can be controlled; the experimenter can have it present in one trial and absent in another and can compare the results in the two cases. When a television repairman wants to find out why a set is not functioning properly, he can try replacing the suspect parts—transistors, condensers, tubes—with new ones, one at a time. A psychologist testing whether the race of the teacher makes a difference to how well black children learn may compare the performance of black children in classes with white teachers to their performance in classes with black teachers. Both the repairman and the psychologist are doing controlled experiments.

But accepting this definition of science would exclude from science many of what we are used to thinking of as the greatest of scientific achievements. In astronomy, one of the most exact of the exact sciences, for example, we cannot control any quantities whatever: we cannot move Mars closer to the sun to see how the length of the Martian year would change. In geology we interpret many of the geological features of the North American continent as the result of the action of glaciers during an "ice age" 25,000 years ago, but we have no way of making glaciers appear or disappear to see if they really produce the features observed. The experiments we can do in a biology laboratory provide only a small part of the evidence for the theory of evolution; most of the evidence is "out there," in nature, already.

OUR DEFINITION OF SCIENCE

We choose to define *science* very broadly—as an activity characterized by three features:

1. It is a search for understanding, for a sense of having found a satisfying explanation of some aspect of reality.
2. The understanding is achieved by means of statements of general laws or principles—laws applicable to the widest possible variety of phenomena.
3. The laws or principles can be tested experimentally.

Understanding

A search for understanding, for the revelation of an underlying pattern in some complex and confusing aspect of reality, is a major goal of science. But it is hard to specify precisely what constitutes understanding. It is clearly subjective: what satisfies one person doesn't satisfy another; different cultures have different standards of what is a good explanation; what satisfied people 100 years ago may not work today. As vague and ill-defined as the concept is, however, the subjective sense of gratification on gaining an understanding of some aspect of reality is strong, and it is one of the important reasons for doing science in the first place.

Generality

The understanding we look for from science is expressed in the form of laws or principles that enable us to predict what will happen and to see why it happened. By *generality* we mean the property of being applicable to the widest possible variety of phenomena. We want fewer laws, but we want them to cover more cases.

In a subsequent chapter we will give some examples from the history of science to show how, as sciences develop, they proceed from having a large number of laws each applicable to a narrow range of phenomena to having a smaller number of more general laws that apply over a much broader range. The previous large number of apparently independent laws is seen to represent special cases of a single general law. The outstanding example of this is the laws of motion discovered by Isaac Newton, which we referred to earlier in this chapter.

Science is a search for unity in diversity, for common patterns in what seem like quite unlike events. The more general our laws, the more unity we have uncovered.

Experimental Test

The requirement that we be willing to subject our explanations to experimental test is the distinguishing feature of science.

Ways of understanding the world other than the scientific way also have as their goal a sense of subjective satisfaction with the explanations found, and they too express the desire for generality. It is the possibility of experimental test, the recognition that we may have to change our minds if the facts force us to, that is unique to science.

In order for the facts to force us to change our minds, there must first of all *be* facts: interested observers must be able to agree on what is a fact and what isn't (a problem that is not so simple as it sounds; in the next chapter we will spend some time on it). Further, the facts must make a difference to our belief in the theory. We will show at length why experimental facts that agree with a theory don't really "prove" it correct, and why even if they disagree they don't always "prove" it wrong. The testing of theories is often a delicate and subtle business, and we never reach absolute certainty in science about their rightness or wrongness. But for an experimental test to be worth doing it must be able, depending on its outcome, to change our degree of belief in the theory.

Unless our belief in our theories can be changed by an experiment, the theories are not part of science.

SCIENCE VERSUS THE HUMANITIES

The concept of an experimental test does seem to distinguish science sharply from other types of scholarly disciplines, such as literary criticism.

A new interpretation of *Hamlet* may or may not be convincing, but one cannot conceive of Shakespearean scholars agreeing on some precise experimental procedure whose outcome can prove it right or wrong. Rather than to the experimental test, one appeals to the consensus of informed practitioners in the field, who judge by subjective criteria: Is it a good explanation? Does it bring into a coherent picture a large number of what were previously thought to be unrelated facts? Is it fruitful in the sense of suggesting new directions of research that were not previously thought of?

We do not minimize the gap between the use of such criteria to judge a theory and the criterion of a precise experimental test, but we do want to point out three factors that make the differences less sharp than they might seem.

First, research in the humanities is as relentlessly grounded on facts as is research in the "exact" sciences. For example, no interpretation of a Shakespeare play is likely to be worth much if the person proposing it does not really understand the precise meaning of the words of the text. Research is necessary: to know what a word means in one scene of *Hamlet*, one may have to examine carefully how it is used not only in the rest of Shakespeare's plays but also throughout Elizabethan literature. Understanding it may also depend on knowledge of some political crisis in the court of Queen Elizabeth that occurred while the play was being written.

Second, decisions between rival scientific theories, even in physics and chemistry, have not always been based on experiment alone, at least not in the idealized sense in which experimental testing is understood. Of course, if two theories agree in many areas but disagree in some, and if experiments show that where they disagree, one theory *always* gives the right answer and the other theory *always* the wrong answer, it is easy to decide in favor of the first one. In reality, however, no theories explain every possible experimental fact, and there is always considerable leeway in judging what experiments are relevant for testing the theories. Major scientific controversies have raged over competing theories, each of which had some area of application where it did better than its competitor. The disputes have been resolved by the same appeal to a consensus of informed practitioners we described as the court of last resort in the humanities, using criteria of explanatory power, coherence, and fruitfulness.

Third, both science and the humanities demand the constant operation of the critical faculty. The criterion of the experimental test in science is a reflection of a permanent obligation to be critical of one's beliefs, to be always asking, How do we know? Why are we sure? Could we be wrong? If we were wrong, how would we know? While in nonscientific disciplines the criterion for whether we are right or wrong

is not experimental testing but rather a vaguer, less easily formulated standard, the same questions need always to be asked. We are committed in both science and the humanities to constant critical examination and to the search for better and deeper insights.

We are not making any exaggerated claim that historical or literary studies could be made into "sciences" if historians or professors of literature would only make the effort. We are saying that there are some things the physicist and historian do that are similar, similar enough so that each can develop some appreciation and respect for the work of the other, and the person who is neither can appreciate and understand the common features of the work of both.

We will give some brief examples later of research in literature and history that illustrate these common features.

THE CASE HISTORIES

In Part II of the book we give detailed examples of how the scientific method has worked in three different fields of science. One example is chosen from physics, one from medical research, and one from abnormal psychology. While the scientific method has shown its greatest success in the physical sciences, and many scientists feel it can best be demonstrated by examples from physics, we have chosen to give only one example from this field. One reason is that we want to bring out more clearly the parallels between the processes of research and discovery in diverse fields of study. Another reason is that physics has a formidable reputation as a difficult subject; this is made worse by the fact that mathematics plays such a significant role in physics, and mathematics is regarded as even more formidable. We believe that science needs mathematics, and we will spend some time in this book trying to convince the reader of this. But we are sadly aware that there is something about physics and mathematics that frightens many people—so much that if they were required to study physics and mathematics to understand science as a whole, they would prefer to give up entirely. This book is written for these people, too.

Still another reason is that most people have more direct experience of and more intuitive feeling for the topics studied in psychology, medical research, and the social sciences than they do for the topics in the physical sciences. Since we wish to build as much as possible on common sense and common experience, we have weighted our choice of examples accordingly.

The first case study describes the discovery by John Snow of the mode of transmission of cholera in nineteenth-century London. It provides us with a particularly beautiful example of how a controlled experiment is done, and how it can make an overwhelming case for a theory. We will also learn that even a correct theory does not agree with every experimental fact and that even incorrect theories may explain many facts and have useful applications to real problems. We will learn also how great a variety of different kinds of facts can be relevant to a theory: Snow's keen observation of life-styles—the behavior of people of different occupations and social classes—helped him establish his theory of how cholera is spread.

The second case study is an example from the history of physics concerning the conflict between the theory that heat is a substance and the theory that it is the motion of the atoms of matter. This example will teach us something about the value of replacing qualitative impressions with quantitative measurements, which is what has given the physical sciences their power and authority. It also provides us with another example of a situation where for a time the wrong theory could explain things better than the correct one, and may give us a more sympathetic understanding of why scientists sometimes seem too conservative in their rejection of new ideas.

The third case study deals with mental disorders. The field is one where behavioral science—the study of the psychology of the individual—and social science—the study of people in groups—both play a part. We will learn something about the role of classification in science: that it is not a simple mechanical arrangement of facts to suit our convenience but rather is involved in a dynamic interaction with the theories we hold, and changes as theory changes. We will learn sometimes to be skeptical of "facts," and to check them when necessary. Most important, we will learn how difficult it is to be scientific and objective where human beings are concerned.

THE GENERAL PRINCIPLES

Part III of the book deals with some of the general features of scientific method. There is some recapitulation of points made earlier in the case studies, and some discussion of subjects not dealt with adequately there.

We had hoped that the case histories would illustrate all the important features of the scientific process. Instead, we found that no one of them, or even all three taken together, could cover everything. If we had included additional case histories to cover the features missed, it would

have led to considerable repetition of some other features of scientific method. We decided therefore that we would limit the number of case histories at the price of having to make some of our points without the support of detailed examples.

The last chapter in this section is called "The Cultural Roots of Science." It deals with a difficult but important problem: the relation of scientific beliefs to the culture in which they occur. We contrast the beliefs of a primitive African tribe, the Azande, with our own. We find that their beliefs fulfill for them the same function that our scientific understanding of the world fulfills for us. The chapter attempts to make the reader consciously aware of the body of concepts and modes of thought—taken for granted and therefore never recognized or analyzed—that are shared by all members of a culture, and that limit and shape the beliefs that can be held.

MATHEMATICS AND SCIENCE

In Part IV of the book we discuss some mathematical questions. Our main purpose is not to teach mathematics but rather to justify it: to explain, using a minimal amount of it, why it is important in science and how it is used.

The section includes chapters on probability and statistics. These two fields of mathematics are so important to all of science that we felt it was necessary to explain some of their basic concepts. However, these chapters are not the equivalent of even elementary courses in either subject. If they whet the appetite of the reader for more, they will have served their purpose.

SUGGESTED READING

The books listed below are those we have found most helpful to us in clarifying our own understanding of science and its methods.

Morris R. Cohen and Ernest Nagel, *An Introduction to Logic and Scientific Method*, Harcourt Brace Jovanovich, New York, 1934

James B. Conant, Ed., *Harvard Case Histories in Experimental Science*, Harvard University Press, Cambridge, Mass., 1948.

Thomas S. Kuhn, *The Structure of Scientific Revolutions*, 2nd ed., University of Chicago Press, Chicago, 1970.

Ernest Nagel, *The Structure of Science*, Harcourt Brace Jovanovich, New York, 1961.

W. V. Quine and J. S. Ullian, *The Web of Belief*, Random House, New York, 1970.