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THE STRUCTURE OF SCIENCE

Problems in the Logic of Scientific Explanation

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Preface

Science as an institutionalized art of inquiry has yielded varied fruit. Its currently best-publicized products are undoubtedly the technological skills that have been transforming traditional forms of human economy at an accelerating rate. It is also responsible for many other things not at the focus of present public attention, though some of them have been, and continue to be, frequently prized as the most precious harvest of the scientific enterprise. Foremost among these are: the achievement of generalized theoretical knowledge concerning fundamental determining conditions for the occurrence of various types of events and processes; the emancipation of men's minds from ancient superstitions in which barbarous practices and oppressive fears are often rooted; the undermining of the intellectual foundations for moral and religious dogmas, with a resultant weakening in the protective cover that the hard crust of unreasoned custom provides for the continuation of social injustices; and, more generally, the gradual development among increasing numbers of a questioning intellectual temper toward traditional beliefs, a development frequently accompanied by the adoption in domains previously closed to systematic critical thought of logical methods for assessing, on the basis of reliable data of observation, the merits of alternative assumptions concerning matters of fact or of desirable policy.

Despite the brevity of this partial list, it suffices to make evident how much the scientific enterprise has contributed to the articulation as well as to the realization of aspirations generally associated with the idea of a liberal civilization. For this reason alone, it is not astonishing that sciquiry and its significance for human life goes back to the beginnings of theoretical science in Greek antiquity; and there are few notable figures in the history of Western philosophy who have not given serious thought to problems raised by the sciences of their day.

In consequence, although the use of the term 'philosophy of science' as the name for a special branch of study is relatively recent, the name designates investigations continuous with those that have been pursued for centuries under such headings for traditional divisions of philosophy as 'logic,' 'theory of knowledge,' 'metaphysics,' and 'moral and social philosophy.' Moreover, despite the impression sometimes created by the wide currency of the term in titles given to books, courses of instruction, and learned societies that it denotes a clearly delimited discipline which deals with a group of closely interrelated questions, the philosophy of science as currently cultivated is not a well-defined area of analysis. On the contrary, contributors to the area often manifest sharply contrasting aims and methods; and the discussions commonly classified as belonging to it collectively range over most of the heterogeneous set of problems that have been the traditional concern of philosophy.

The present book, although an essay in the philosophy of science, nevertheless deals with a more integrated group of questions, and its scope is controlled by the objective of analyzing the logic of scientific inquiry and the logical structure of its intellectual products. It is primarily an examination of logical patterns exhibited in the organization of scientific knowledge as well as of the logical methods whose use (despite frequent changes in special techniques and revolutions in substantive theory) is the most enduring feature of modern science. The book accordingly ignores many issues, often discussed at length in standard works and courses on the philosophy of science, that do not seem to me relevant to its objective—for example, issues in the epistemology of sense perception, or in proposed cosmic syntheses purporting to make "intelligible" the totality of specialized scientific findings. On the other hand, I have not hesitated to consider issues that may appear to be only remotely related to the actual practice of science, if their discussion might contribute to a clarified understanding of scientific method and its fruits —for example, questions dealing with the translatability of scientific theories into statements about data of sensory observation, or with the import of the belief in universal determinism for ascriptions of moral responsibility.

The order in which problems are discussed in this book reflects in part the stress I place upon the achievement of encompassing well-grounded explanations as a major and distinctive scientific ideal. But irrespective of scientific explanations: with their logical structures, their mutual relations, their functions in inquiry, and their devices for systematizing knowledge. The second division concentrates on questions concerned with the logical structure of scientific concepts: with their articulation by way of diverse techniques of definition and measurement, their linkages to data of observation, and the conditions under which they are scientifically meaningful. The third division is directed to problems dealing with the evaluation of claims to knowledge in various sciences: with the structure of probable inference, the principles employed in weighing evidence, and the validation of inductive arguments. These three partly overlapping groups of problems constitute the scope of a systematically unified study of the logic of science; nevertheless, each group of questions can be explored with only occasional reference to issues subsumed under the others. Accordingly, although the present volume is devoted mainly to questions falling into the first of the above tripartite divisions—the problems in the other two are reserved for detailed discussion in a volume in active preparation—the volume is fully self-contained; and issues central to the other divisions but requiring immediate notice in the present volume receive at least brief attention in it.

I have tried to write this book for a wider audience than that of professional students of philosophy, in the conviction that even if some questions discussed in it are perhaps of little interest to anyone else the book as a whole deals with matters which are of more than narrowly limited professional concern. I have therefore avoided highly formalized presentations of analyses or the use of the special symbolic notation of modern formal logic, however valuable a precise formalism may be for the resolution of certain technical problems. It would have been inconsistent with the central aim of the book to exclude all mention of difficult technical notions employed in special branches of science; on the other hand, the book attempts to explain such notions when they are not likely to be familiar to many readers whom I would like to reach. I have also sought to exhibit the character of scientific method in a variety of concrete domains—in the social and biological sciences as well as in physics. I have sought to do this, even though with the omission of several other special disciplines I had originally intended to canvass, partly in order to make clear to a varied audience that despite important differences there is a basic logical continuity in the operations of scientific intelligence, and partly to provide for members of such an audience a broad foundation for assessing in a judicious spirit the current tide of criticism directed (frequently on behalf of some "higher wisdom") against the works of scientific reason.

book: "The Causal Character of Modern Physical Theory," in *Freedom and Reason* (ed. by S. Baron, E. Nagel, and K. S. Pinson), The Free Press, Glencoe, Ill., 1951; "The Meaning of Reduction in the Natural Sciences," in *Science and Civilization* (ed. R. C. Stauffer), The University of Wisconsin Press, 1949, by permission of the Regents of the University of Wisconsin; "Teleological Explanation and Teleological Systems," in *Vision and Action* (ed. by S. Ratner), Rutgers University Press, 1953; "Science, With and Without Wisdom," *The Saturday Review of Literature*, 1945; "Wholes, Sums and Organic Unities," *Philosophical Studies*, 1952; "Mechanistic Explanation and Organismic Biology" and "Determinism in History," *Philosophy and Phenomenological Research*, 1951 and 1960; and "Some Issues in the Logic of Historical Analysis," *Scientific Monthly*, 1952, by permission of the American Association for the Advancement of Science.

It is an author's privilege to acknowledge the personal debts he has incurred in writing his book, and although it is not possible for me to list them all I record with pleasure my chief creditors. My interest in the philosophy of science was first aroused by my teacher, the late Morris R. Cohen, and I remain grateful to him for the direction he gave to my thinking as well as for the continuing stimulus of his teachings. Neither Rudolf Carnap nor Philipp Frank have been formally my teachers, but I have profited greatly from the numerous conversations I have had with them since 1934 on the logic of science; and I have obtained equally invaluable instruction on the methodological problems of empirical social research from the enlightening talks I have had with Paul F. Lazarsfeld for many years. I have also received much help and encouragement from other friends: from Abraham Edel, Albert Hofstadter, and Sidney Hook, with each of whom I have enjoyed high philosophical discourse since all of us were young men, and who gave me the benefit of their criticisms on various portions of the manuscript at various stages of its completion; from John C. Cooley, Paul Edwards, Herbert Feigl, Charles Frankel, John Gregg, Carl G. Hempel, Sidney Morgenbesser, Meyer Schapiro, and Patrick Suppes, who have contributed heavily to the clarification of my ideas during the many discussions I have had with them; and from my wife, to whom the volume is dedicated, who has served patiently as a touchstone for the intelligibility of most of the things said in it. I am deeply grateful to the John Simon Guggenheim Memorial Foundation, the Rockefeller Foundation, and the Center for Advanced Study in the Behavioral Sciences for the leisure to study and write which they made possible.

E. N.

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1 Introduction: Science and Common Sense

Long before the beginnings of modern civilization, men acquired vast funds of information about their environment. They learned to recognize substances which nourished their bodies. They discovered the uses of fire and developed skills for transforming raw materials into shelters, clothing, and utensils. They invented arts of tilling the soil, communicating, and governing themselves. Some of them discovered that objects are moved more easily when placed on carts with wheels, that the sizes of fields are more reliably compared when standard schemes of measurement are employed, and that the seasons of the year as well as many phenomena of the heavens succeed each other with a certain regularity. John Locke's quip at Aristotle—that God was not so sparing to men as to make them merely two-legged creatures, leaving it to Aristotle to make them rational—seems obviously applicable to modern science. The acquisition of reliable knowledge concerning many aspects of the world certainly did not wait upon the advent of modern science and the self-conscious use of its methods. Indeed, in this respect, many men in every generation repeat in their own lives the history of the race: they manage to secure for themselves skills and competent information, without benefit of training in the sciences and without the calculated adoption of scientific modes of procedure.

If so much in the way of knowledge can be achieved by the shrewd and physical tools contribute to the acquisition of knowledge? The question requires a careful answer if a definite meaning is to be associated with the word 'science.'

The word and its linguistic variants are certainly not always employed with discrimination, and they are frequently used merely to confer an honorific distinction on something or other. Many men take pride in being "scientific" in their beliefs and in living in an "age of science." However, quite often the sole discoverable ground for their pride is a conviction that, unlike their ancestors or their neighbors, they are in possession of some alleged final truth. It is in this spirit that currently accepted theories in physics or biology are sometimes described as scientific, while all previously held but no longer accredited theories in those domains are firmly refused that label. Similarly, types of practice that are highly successful under prevailing physical and social conditions, such as certain techniques of farming or industry, are occasionally contrasted with the allegedly "unscientific" practices of other times and places. Perhaps an extreme form of the tendency to rob the term 'scientific' of all definite content is illustrated by the earnest use that advertisers sometimes make of such phrases as 'scientific haircutting,' 'scientific rug cleaning,' and even 'scientific astrology.' It will be clear, however, that in none of the above examples is a readily identifiable and differentiating characteristic of beliefs or practices associated with the word. It would certainly be ill-advised to adopt the suggestion, implicit in the first example, to limit the application of the adjective 'scientific' to beliefs that are indefeasibly true—if only because infallible guaranties of truth are lacking in most if not all areas of inquiry, so that the adoption of such a suggestion would in effect deprive the adjective of any proper use.

The words 'science' and 'scientific' are nevertheless not quite so empty of a determinate content as their frequently debased uses might indicate. For in fact the words are labels either for an identifiable, continuing enterprise of inquiry or for its intellectual products, and they are often employed to signify traits that distinguish those products from other things. In the present chapter we shall therefore survey briefly some of the ways in which "prescientific" or "common-sense" knowledge differs from the intellectual products of modern science. To be sure, no sharp line separates beliefs generally subsumed under the familiar but vague rubric of "common sense" from those cognitive claims recognized as "scientific." Nevertheless, as in the case of other words whose fields of intended application have notoriously hazy boundaries (such as the term 'democracy'), absence of precise dividing lines is not incompatible with the presence of at least a core of firm meaning for each of these words. In their more sober uses, at any rate, these words do in fact connote important and recognizable differences. It is these differences that

we must attempt to identify, even if we are compelled to sharpen some of them for the sake of expository emphasis and clarity.

1. No one seriously disputes that many of the existing special sciences have grown out of the practical concerns of daily living: geometry out of problems of measuring and surveying fields, mechanics out of problems raised by the architectural and military arts, biology out of problems of human health and animal husbandry, chemistry out of problems raised by metallurgical and dyeing industries, economics out of problems of household and political management, and so on. To be sure, there have been other stimuli to the development of the sciences than those provided by problems of the practical arts; nevertheless, these latter have had, and still continue to have, important roles in the history of scientific inquiry. In any case, commentators on the nature of science who have been impressed by the historical continuity of common-sense convictions and scientific conclusions have sometimes proposed to differentiate between them by the formula that the sciences are simply "organized" or "classified" common sense.

It is undoubtedly the case that the sciences are organized bodies of knowledge and that in all of them a classification of their materials into significant types or kinds (as in biology, the classification of living things into species) is an indispensable task. It is clear, nonetheless, that the proposed formula does not adequately express the characteristic differences between science and common sense. A lecturer's notes on his travels in Africa may be very well organized for the purposes of communicating information interestingly and efficiently, without thereby converting that information into what has historically been called a science. A librarian's card catalogue represents an invaluable classification of books, but no one with a sense for the historical association of the word would say that the catalogue is a science. The obvious difficulty is that the proposed formula does not specify what *kind* of organization or classification is characteristic of the sciences.

Let us therefore turn to this question. A marked feature of much information acquired in the course of ordinary experience is that, although this information may be accurate enough within certain limits, it is seldom accompanied by any explanation of why the facts are as alleged. Thus societies which have discovered the uses of the wheel usually know nothing of frictional forces, nor of any reasons why goods loaded on vehicles with wheels are easier to move than goods dragged on the ground. Many peoples have learned the advisability of manuring their agricultural fields, but only a few have concerned themselves with the reasons for so acting. The medicinal properties of herbs like the foxglove have been recognized for centuries, though usually no account was given of the grounds for their beneficent virtues. Moreover, when "common sense" does attempt to give explanations for its facts—as when the value of the foxglove as a cardiac stimulant is explained in terms of the similarity in shape of the flower and the human heart—the explanations are frequently accepted without critical tests of their relevance to the facts. Common sense is often eligible to receive the well-known advice Lord Mansfield gave to a newly appointed governor of a colony who was unversed in the law: "There is no difficulty in deciding a case—only hear both sides patiently, then consider what you think justice requires, and decide accordingly; but never give your reasons, for your judgment will probably be right, but your reasons will certainly be wrong."

It is the desire for explanations which are at once systematic and controllable by factual evidence that generates science; and it is the organization and classification of knowledge on the basis of explanatory principles that is the distinctive goal of the sciences. More specifically, the sciences seek to discover and to formulate in general terms the conditions under which events of various sorts occur, the statements of such determining conditions being the explanations of the corresponding happenings. This goal can be achieved only by distinguishing or isolating certain properties in the subject matter studied and by ascertaining the repeatable patterns of dependence in which these properties stand to one another. In consequence, when the inquiry is successful, propositions that hitherto appeared to be quite unrelated are exhibited as linked to each other in determinate ways by virtue of their place in a system of explanations. In some cases, indeed, the inquiry can be carried to remarkable lengths. Patterns of relations may be discovered that are pervasive in vast ranges of fact, so that with the help of a small number of explanatory principles an indefinitely large number of propositions about these facts can be shown to constitute a logically unified body of knowledge. The unification sometimes takes the form of a deductive system, as in the case of demonstrative geometry or the science of mechanics. Thus a few principles, such as those formulated by Newton, suffice to show that propositions concerning the moon's motion, the behavior of the tides, the paths of projectiles, and the rise of liquids in thin tubes are intimately related, and that all these propositions can be rigorously deduced from those principles conjoined with various special assumptions of fact. In this way a systematic explanation is achieved for the diverse phenomena which the logically derived propositions report.

Not all the existing sciences present the highly integrated form of systematic explanation which the science of mechanics exhibits, though for many of the sciences—in domains of social inquiry as well as in the various divisions of natural science—the idea of such a rigorous logical systematization continues to function as an ideal. But even in those branches of departmentalized inquiry in which this ideal is not generally pursued, as in much historical research, the goal of finding explanations for facts is usually always present. Men seek to know why the thirteen American colonies rebelled from England while Canada did not, why the ancient Greeks were able to repel the Persians but succumbed to the Roman armies, or why urban and commercial activity developed in medieval Europe in the tenth century and not before. To explain, to establish some relation of dependence between propositions superficially unrelated, to exhibit systematically connections between apparently miscellaneous items of information are distinctive marks of scientific inquiry.

2. A number of further differences between common sense and scientific knowledge are almost direct consequences of the systematic character of the latter. A well-recognized feature of common sense is that, though the knowledge it claims may be accurate, it seldom is aware of the limits within which its beliefs are valid or its practices successful. A community, acting on the rule that spreading manure preserves the fertility of the soil, may in many cases continue its mode of agriculture successfully. However, it may continue to follow the rule blindly, in spite of the manifest deterioration of the soil, and it may therefore be helpless in the face of a critical problem of food supply. On the other hand, when the reasons for the efficacy of manure as a fertilizer are understood, so that the rule is connected with principles of biology and soil chemistry, the rule comes to be recognized as only of restricted validity, since the efficiency of manure is seen to depend on the persistence of conditions of which common sense is usually unaware. Few who know them are capable of withholding admiration for the sturdy independence of those farmers who, without much formal education, are equipped with an almost endless variety of skills and sound information in matters affecting their immediate environment. Nevertheless, the traditional resourcefulness of the farmer is narrowly circumscribed: he often becomes ineffective when some break occurs in the continuity of his daily round of living, for his skills are usually products of tradition and routine habit and are not informed by an understanding of the reasons for their successful operation. More generally, common-sense knowledge is most adequate in situations in which a certain number of factors remain practically unchanged. But since it is normally not recognized that this adequacy does depend on the constancy of such factors—indeed, the very existence of the pertinent factors may not be recognized—common-sense knowledge suffers from a serious incompleteness. It is the aim of systematic science to remove this incompleteness, even if it is an aim which frequently is only partially realized.

The sciences thus introduce refinements into ordinary conceptions by the very process of exhibiting the systematic connections of propositions about matters of common knowledge. Not only are familiar practices thereby shown to be explicable in terms of principles formulating relations between items in wide areas of fact; those principles also provide clues for altering and correcting habitual modes of behavior, so as to make them more effective in familiar contexts and more adaptable to novel ones. This is not to say, however, that common beliefs are necessarily mistaken, or even that they are inherently more subject to change under the pressure of experience than are the propositions of science. Indeed, the age-long and warranted stability of common-sense convictions, such as that oaks do not develop overnight from acorns or that water solidifies on sufficient cooling, compares favorably with the relatively short life span of many theories of science. The essential point to be observed is that, since common sense shows little interest in systematically explaining the facts it notes, the range of valid application of its beliefs, though in fact narrowly circumscribed, is not of serious concern to it.

3. The ease with which the plain man as well as the man of affairs entertains incompatible and even inconsistent beliefs has often been the subject for ironic commentary. Thus, men will sometimes argue for sharply increasing the quantity of money and also demand a stable currency; they will insist upon the repayment of foreign debts and also take steps to prevent the importation of foreign goods; and they will make inconsistent judgments on the effects of the foods they consume, on the size of bodies they see, on the temperature of liquids, and the violence of noises. Such conflicting judgments are often the result of an almost exclusive preoccupation with the immediate consequences and qualities of observed events. Much that passes as common-sense knowledge certainly is about the effects familiar things have upon matters that men happen to value; the relations of events to one another, independent of their incidence upon specific human concerns, are not systematically noticed and explored.

The occurrence of conflicts between judgments is one of the stimuli to the development of science. By introducing a systematic explanation of facts, by ascertaining the conditions and consequences of events, by exhibiting the logical relations of propositions to one another, the sciences strike at the sources of such conflicts. Indeed, a large number of extraordinarily able minds have traced out the logical consequences of basic principles in various sciences; and an even larger number of investigators have repeatedly checked such consequences with other propositions obtained as a result of critical observation and experiment. There

is no iron-clad guaranty that, in spite of this care, serious inconsistencies in these sciences have been eliminated. On the contrary, mutually incompatible assumptions sometimes serve as the bases for inquiries in different branches of the same science. For example, in certain parts of physics atoms were at one time assumed to be perfectly elastic bodies, although in other branches of physical science perfect elasticity was not ascribed to atoms. However, such inconsistencies are sometimes only apparent ones, the impression of inconsistency arising from a failure to note that different assumptions are being employed for the solution of quite different classes of problems. Moreover, even when the inconsistencies are genuine, they are often only temporary, since incompatible assumptions may be employed only because a logically coherent theory is not yet available to do the complex job for which those assumptions were originally introduced. In any event, the flagrant inconsistencies that so frequently mark common beliefs are notably absent from those sciences in which the pursuit of unified systems of explanation has made considerable headway.

4. As has already been noted, many everyday beliefs have survived centuries of experience, in contradistinction to the relatively short life span that is so often the fate of conclusions advanced in various branches of modern science. One partial reason for this circumstance merits attention. Consider some instance of common-sense beliefs, such as that water solidifies when it is sufficiently cooled; and let us ask what is signified by the terms 'water' and 'sufficiently' in that assertion. It is a familiar fact that the word 'water,' when used by those unacquainted with modern science, generally has no clear-cut meaning. It is then frequently employed as a name for a variety of liquids despite important physicochemical differences between them, but is frequently rejected as a label for other liquids even though these latter liquids do not differ among themselves in their essential physicochemical characteristics to a greater extent than do the former fluids. Thus, the word may perhaps be used to designate the liquids falling from the sky as rain, emerging from the ground in springs, flowing in rivers and roadside ditches, and constituting the seas and oceans; but the word may be employed less frequently if at all for liquids pressed out of fruits, contained in soups and other beverages, or evacuated through the pores of the human skin. Similarly, the word 'sufficiently' when used to characterize a cooling process may sometimes signify a difference as great as that between the maximum temperature on a midsummer day and the minimum temperature of a day in midwinter; at other times, the word may signify a difference no greater than that between the noon and the twilight temperatures on a day in winter. In short, in its common-sense use for characterizing tem-

perature changes, the word 'sufficiently' is not associated with a precise specification of their extent.

If this example can be taken as typical, the language in which common-sense knowledge is formulated and transmitted may exhibit two important kinds of indeterminacy. In the first place, the terms of ordinary speech may be quite vague, in the sense that the class of things designated by a term is not sharply and clearly demarcated from (and may in fact overlap to a considerable extent with) the class of things not so designated. Accordingly, the range of presumed validity for statements employing such terms has no determinate limits. In the second place, the terms of ordinary speech may lack a relevant degree of specificity, in the sense that the broad distinctions signified by the terms do not suffice to characterize more narrowly drawn but important differences between the things denoted by the terms. Accordingly, relations of dependence between occurrences are not formulated in a precisely determinate manner by statements containing such terms.

As a consequence of these features of ordinary speech, experimental control of common-sense beliefs is frequently difficult, since the distinction between confirming and contradicting evidence for such beliefs cannot be easily drawn. Thus, the belief that "in general" water solidifies when sufficiently cooled may answer the needs of men whose interest in the phenomenon of freezing is circumscribed by their concern to achieve the routine objectives of their daily lives, despite the fact that the language employed in codifying this belief is vague and lacks specificity. Such men may therefore see no reason for modifying their belief, even if they should note that ocean water fails to freeze although its temperature is sensibly the same as that of well water when the latter begins to solidify, or that some liquids must be cooled to a greater extent than others before changing into the solid state. If pressed to justify their belief in the face of such facts, these men may perhaps arbitrarily exclude the oceans from the class of things they denominate as water; or, alternatively, they may express renewed confidence in their belief, irrespective of the extent of cooling that may be required, on the ground that liquids classified as water do indeed solidify when cooled.

In their quest for systematic explanations, on the other hand, the sciences must mitigate the indicated indeterminacy of ordinary language by refashioning it. For example, physical chemistry is not content with the loosely formulated generalization that water solidifies if it is sufficiently cooled, for the aim of that discipline is to explain, among other things, why drinking water and milk freeze at certain temperatures although at those temperatures ocean water does not. To achieve this aim, physical chemistry must therefore introduce clear distinctions between various kinds of water and between various amounts of cooling. Several devices

reduce the vagueness and increase the specificity of linguistic expressions. Counting and measuring are for many purposes the most effective of these techniques, and are perhaps the most familiar ones. Poets may sing of the infinity of stars which stud the visible heavens, but the astronomer will want to specify their exact number. The artisan in metals may be content with knowing that iron is harder than lead, but the physicist who wishes to explain this fact will require a precise measure of the difference in hardness. Accordingly, an obvious but important consequence of the precision thus introduced is that statements become capable of more thorough and critical testing by experience. Prescientific beliefs are frequently incapable of being put to definite experiential tests, simply because those beliefs may be vaguely compatible with an indeterminate class of unanalyzed facts. Scientific statements, because they are required to be in agreement with more closely specified materials of observation, face greater risks of being refuted by such data.

This difference between common and scientific knowledge is roughly analogous to differences in standards of excellence which may be set up for handling firearms. Most men would qualify as expert shots if the standard of expertness were the ability to hit the side of a barn from a distance of a hundred feet. But only a much smaller number of individuals could meet the more rigorous requirement of consistently centering their shots upon a three-inch target at twice that distance. Similarly, a prediction that the sun will be eclipsed during the autumn months is more likely to be fulfilled than a prediction that the eclipse will occur at a specific moment on a given day in the fall of the year. The first prediction will be confirmed should the eclipse take place during any one of something like one hundred days; the second prediction will be refuted if the eclipse does not occur within something like a small fraction of a minute from the time given. The latter prediction could be false without the former being so, but not conversely; and the latter prediction must therefore satisfy more rigorous standards of experiential control than are assumed for the former.

This greater determinacy of scientific language helps to make clear why so many common-sense beliefs have a stability, often lasting for many centuries, that few theories of science possess. It is more difficult to devise a theory that remains unshaken by repeated confrontation with the outcome of painstaking experimental observation, when the standards are high for the agreement that must obtain between such experimental data and the predictions derived from the theory, than when such standards are lax and the admissible experimental evidence is not required to be established by carefully controlled procedures. The more advanced sciences do in fact specify almost invariably the extent to which predictions based on a theory may deviate from the results of experiment without invalidating the theory. The limits of such permissible deviations are usually quite narrow, so that discrepancies between theory and experiment which common sense would ordinarily regard as insignificant are often judged to be fatal to the adequacy of the theory.

On the other hand, although the greater determinacy of scientific statements exposes them to greater risks of being found in error than are faced by the less precisely stated common-sense beliefs, the former have an important advantage over the latter. They have a greater capacity for incorporation into comprehensive but clearly articulated systems of explanation. When such systems are adequately confirmed by experimental data, they codify frequently unsuspected relations of dependence between many varieties of experimentally identifiable but distinct kinds of fact. In consequence, confirmatory evidence for statements belonging to such a system can often be accumulated more rapidly and in larger quantities than for statements (such as those expressing common-sense beliefs) not belonging to such a system. This is so because evidence for statements in such a system may be obtainable by observations of an extensive class of events, many of which may not be explicitly mentioned by those statements but which are nevertheless relevant sources of evidence for the statements in question, in view of the relations of dependence asserted by the system to hold between the events in that class. For example, the data of spectroscopic analysis are employed in modern physics to test assumptions concerning the chemical structure of various substances; and experiments on thermal properties of solids are used to support theories of light. In brief, by increasing the determinacy of statements and incorporating them into logically integrated systems of explanation, modern science sharpens the discriminating powers of its testing procedure and augments the sources of relevant evidence for its conclusions.

5. It has already been mentioned in passing that, while common-sense knowledge is largely concerned with the impact of events upon matters of special value to men, theoretical science is in general not so provincial. The quest for systematic explanations requires that inquiry be directed to the relations of dependence between things irrespective of their bearing upon human values. Thus, to take an extreme case, astrology is concerned with the relative positions of stars and planets in order to determine the import of such conjunctions for the destinies of men; in contrast, astronomy studies the relative positions and motions of celestial bodies without reference to the fortunes of human beings. Similarly, breeders of horses and of other animals have acquired much skill and knowledge relating to the problem of developing breeds that will implement certain human purposes; theoretical biologists, on the other hand,

are only incidentally concerned with such problems, and are interested in analyzing among other things the mechanisms of heredity and in obtaining laws of genetic development.

One important consequence of this difference in orientation between theoretical and common-sense knowledge, however, is that theoretical science deliberately neglects the immediate values of things, so that the statements of science often appear to be only tenuously relevant to the familiar events and qualities of daily life. To many people, for example, an unbridgeable chasm seems to separate electromagnetic theory, which provides a systematic account of optical phenomena, and the brilliant colors one may see at sunset; and the chemistry of colloids, which contributes to an understanding of the organization of living bodies, appears to be an equally impossible distance from the manifold traits of personality exhibited by human beings.

It must certainly be admitted that scientific statements make use of highly abstract concepts, whose pertinence to the familiar qualities which things manifest in their customary settings is by no means obvious. Nevertheless, the relevance of such statements to matters encountered in the ordinary business of life is also indisputable. It is well to bear in mind that the unusually abstract character of scientific notions, as well as their alleged "remoteness" from the traits of things found in customary experience, are inevitable concomitants of the quest for systematic and comprehensive explanations. Such explanations can be constructed only if the familiar qualities and relations of things, in terms of which individual objects and events are usually identified and differentiated, can be shown to depend for their occurrence on the presence of certain other pervasive relational or structural properties that characterize in various ways an extensive class of objects and processes. Accordingly, to achieve generality of explanation for qualitatively diverse things, those structural properties must be formulated without reference to, and in abstraction from, the individualizing qualities and relations of familiar experience. It is for the sake of achieving such generality that, for example, the temperature of bodies is defined in physics not in terms of directly felt differences in warmth, but in terms of certain abstractly formulated relations characterizing an extensive class of reversible thermal cycles.

However, although abstractness in formulation is an undoubted feature in scientific knowledge, it would be an obvious error to suppose that common-sense knowledge does not involve the use of abstract conceptions. Everyone who believes that man is a mortal creature certainly employs the abstract notions of humanity and mortality. The conceptions of science do not differ from those of common sense merely in being abstract. They differ in being formulations of pervasive structural properties, abstracted from familiar traits manifested by limited classes of things usually only under highly specialized conditions, related to matters open to direct observation only by way of complex logical and experimental procedures, and articulated with a view to developing systematic explanations for extensive ranges of diverse phenomena.

6. Implicit in the contrasts between modern science and common sense already noted is the important difference that derives from the deliberate policy of science to expose its cognitive claims to the repeated challenge of critically probative observational data, procured under carefully controlled conditions. As we had occasion to mention previously, however, this does not mean that common-sense beliefs are invariably erroneous or that they have no foundations in empirically verifiable fact. It does mean that common-sense beliefs are not subjected, as a matter of established principle, to systematic scrutiny in the light of data secured for the sake of determining the accuracy of those beliefs and the range of their validity. It also means that evidence admitted as competent in science must be obtained by procedures instituted with a view to eliminating known sources of error; and it means, furthermore, that the weight of the available evidence for any hypothesis proposed as an answer to the problem under inquiry is assessed with the help of canons of evaluation whose authority is itself based on the performance of those canons in an extensive class of inquiries. Accordingly, the quest for explanation in science is not simply a search for any *prima facie* plausible "first principles" that might account in a vague way for the familiar "facts" of conventional experience. On the contrary, it is a quest for explanatory hypotheses that are genuinely testable, because they are required to have logical consequences precise enough not to be compatible with almost every conceivable state of affairs. The hypotheses sought must therefore be subject to the possibility of rejection, which will depend on the outcome of critical procedures, integral to the scientific quest, for determining what the actual facts are.

The difference just described can be expressed by the dictum that the conclusions of science, unlike common-sense beliefs, are the products of scientific method. However, this brief formula should not be misconstrued. It must not be understood to assert, for example, that the practice of scientific method consists in following prescribed rules for making experimental discoveries or for finding satisfactory explanations for matters of established fact. There are no rules of discovery and invention in science, any more than there are such rules in the arts. Nor must the formula be construed as maintaining that the practice of scientific method consists in the use in all inquiries of some special set of techniques (such as the techniques of measurement employed in physical science), irrespective of the subject matter or the problem under investigation. Such

an interpretation of the dictum is a caricature of its intent; and in any event the dictum on that interpretation is preposterous. Nor, finally, should the formula be read as claiming that the practice of scientific method effectively eliminates every form of personal bias or source of error which might otherwise impair the outcome of the inquiry, and more generally that it assures the truth of every conclusion reached by inquiries employing the method. But no such assurances can in fact be given; and no antecedently fixed set of rules can serve as automatic safeguards against unsuspected prejudices and other causes of error that might adversely affect the course of an investigation.

The practice of scientific method is the persistent critique of arguments, in the light of tried canons for judging the reliability of the procedures by which evidential data are obtained, and for assessing the probative force of the evidence on which conclusions are based. As estimated by standards prescribed by those canons, a given hypothesis may be strongly supported by stated evidence. But this fact does not guarantee the truth of the hypothesis, even if the evidential statements are admitted to be true—unless, contrary to standards usually assumed for observational data in the empirical sciences, the degree of support is that which the premises of a valid deductive argument give to its conclusion. Accordingly, the difference between the cognitive claims of science and common sense, which stems from the fact that the former are the products of scientific method, does not connote that the former are invariably true. It does imply that, while common-sense beliefs are usually accepted without a critical evaluation of the evidence available, the evidence for the conclusions of science conforms to standards such that a significant proportion of conclusions supported by similarly structured evidence remains in good agreement with additional factual data when fresh data are obtained.

Further discussion of these considerations must be postponed. However, one brief addendum is required at this point. If the conclusions of science are the products of inquiries conducted in accordance with a definite policy for obtaining and assessing evidence, the rationale for confidence in those conclusions as warranted must be based on the merits of that policy. It must be admitted that the canons for assessing evidence which define the policy have, at best, been explicitly codified only in part, and operate in the main only as intellectual habits manifested by competent investigators in the conduct of their inquiries. But despite this fact the historical record of what has been achieved by this policy in the way of dependable and systematically ordered knowledge leaves little room for serious doubt concerning the superiority of the policy over alternatives to it.

This brief survey of features that distinguish in a general way the cognitive claims and the logical method of modern science suggests a variety of questions for detailed study. The conclusions of science are the fruits of an institutionalized system of inquiry which plays an increasingly important role in the lives of men. Accordingly, the organization of that social institution, the circumstances and stages of its development and influence, and the consequences of its expansion have been repeatedly explored by sociologists, economists, historians, and moralists. However, if the nature of the scientific enterprise and its place in contemporary society are to be properly understood, the types and the articulation of scientific statements, as well as the logic by which scientific conclusions are established, also require careful analysis. This is a task—a major if not exclusive task—that the philosophy of science undertakes to execute. Three broad areas for such an analysis are in fact suggested by the survey just concluded: the logical patterns exhibited by explanations in the sciences; the construction of scientific concepts; and the validation of scientific conclusions. The chapters that follow deal largely though not exclusively with problems concerning the structure of scientific explanations.

2 Patterns of Scientific Explanation

The preceding chapter has argued that the distinctive aim of the scientific enterprise is to provide systematic and responsibly supported explanations. As we shall see, such explanations may be offered for individual occurrences, for recurring processes, or for invariable as well as statistical regularities. This task is not the sole preoccupation of the sciences, if only because much of their effort goes into ascertaining what the facts are in fresh areas of experience for which explanations may be subsequently sought. It is indeed patent that at any given time the various sciences differ in the emphasis they place upon developing systematic explanations, and also in the degree of completeness with which they achieve such explanatory systems. Nevertheless, the quest for systematic explanations is never totally absent from any of the recognized scientific disciplines. To understand the requirements for, and structure of, scientific explanations is therefore to understand a pervasive feature of the scientific enterprise. The present chapter seeks to prepare the ground for such an understanding, by noting in a preliminary way ostensibly different forms of explanations encountered in the various sciences.

I. *Illustrations of Scientific Explanation*

Explanations are answers to the question 'Why?' However, very little reflection is needed to reveal that the word 'why' is not unambiguous