Bertrand

Russell

Human Knowledge

Its Scope and Limits

With an introduction by John G. Slater

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Introduction by John G. Slater

In his private correspondence Russell was fond of referring to some of his philosophical projects as aiming at the writing of a "big" book. *Human Knowledge: Its Scope and Limits* is Russell's last big book, and its topic—the problem of non-demonstrative inference—has been of central concern to philosophers ever since Hume undermined inductive arguments. At the beginning of his career Russell focused his interest, his talent, and his energies on trying to determine whether there was any certain knowledge. Since nobody claimed that either inductive arguments or any other non-demonstrative arguments, for that matter, yielded certain knowledge, he paid little or no attention to these arguments. Beginning with its use in mathematics, he studied demonstrative inference as the likeliest source of knowledge with any claim to certainty. But the mathematics he had been taught, he soon discovered, was built on fallacious proofs, so he was forced back to logic for his starting point.

A logic freed of hidden assumptions would be a useful tool by which to establish mathematical proof on a firm basis. To his great delight he found that many others shared his belief about the importance of a new logic for mathematics; he avidly studied their works and he was soon ready to make original contributions to the development of symbolic logic. As his work proceeded he gradually became convinced that the new logic was not just a tool to be used in improving mathematical proofs, but was itself the very foundation of mathematics. His conviction, and that of Alfred North Whitehead, who had been one of his teachers at Cambridge, that much of mathematics is a branch of symbolic logic, led them to devote a decade of their lives to developing a proof of their thesis. *Principia Mathematica*, published in three large volumes between 1910 and 1913, reports the results of their research in elaborate detail.

When *Principia Mathematica* was finished Russell turned his attention to exploiting what he had learned during its production. He was convinced that a similar method could be applied to other realms of human knowledge with the result that their a priori (certain) and empirical (merely probable) parts could be disentangled. Physics was his first candidate for analysis using the new method. Through a careful study of the writings of physicists, he hoped to discover the minimum vocabulary required in physics, and to state, using only that minimum vocabulary and purely logical terms, the basic relationships of these terms to each other. The model he had in mind is nicely exhibited by the Peano postulates for arithmetic. Using only "zero", "number" and "successor" as undefined mathematical terms, and logical terms, Peano stated five axioms from which, using only logical rules of inference, the ordinary truths of arithmetic are deducible. An important feature of *Principia Mathematica* is the set of definitions that Whitehead and Russell provided for Peano's undefined terms. These definitions are written in purely logical notation, allowing each of them, and, therefore, each of Peano's postulates, to find its proper place in the logical and mathematical system being developed in that book.

Russell expended much thought on this problem of providing a foundation for physics; he called it "the problem of matter". But he did not succeed in cracking it. In the course of his work, he found that progress on the problem of matter required the solution to certain problems in the theory of knowledge, more specifically, the problem of our knowledge of the external world. So he turned his attention in that direction and began to write a "big" book on the theory of knowledge. Wittgenstein turned up during this period and Russell showed him some of his manuscript. The severity of Wittgenstein's criticism led Russell to abandon the book. *Theory of Knowledge: The 1913 Manuscript* was only published in 1984 as Volume 7 of *The Collected Papers of Bertrand Russell*. Although he abandoned one book he soon wrote another dealing with some of the same topics. *Our Knowledge of the External World* was written to be read to a Boston audience during his visit to Harvard in the spring of 1914. Russell had just begun to bring the ideas in that book to bear on the problem of matter, most notably in "The Relation of Sense-Data to Physics" (1914), when the First World War shattered his world.

When he returned to philosophical work after the war his thinking was still dominated by the axiomatic model of *Principia Mathematica*. While studying William James with the intention of refuting him, Russell persuaded himself that James's theory of neutral monism—that both mind and matter are constituted of entities of only one sort, for James it was "experience", for Russell, "events"—was correct. Mind and matter were merely different configurations of the same basic stuff. With somewhat less persistence than he had shown in mathematics, Russell attempted during the 1920s to discover minimum vocabularies for discussing mind and matter and to propose analyses of some, at least, of these terms in the language of events. Two books, *The Analysis of Mind* (1921) and *The Analysis of Matter* (1927), serve to record his achievements in these projects.

Throughout these studies Russell tended to push questions of empirical knowledge aside. The real gold was a priori knowledge; on such a rock one could build one's philosophy. Empirical knowledge had its uses, but, since it could never be certain, it was outranked by the a priori kind. The axiomatic method, therefore, tended to dominate his thinking. Whenever he tackled a problem, he tried, first of all, to discover its minimum vocabulary, and then, when he experienced some success on that front, he would attempt to formulate the basic propositions linking the various terms of the minimum vocabulary with one another. Success in such an enterprise provides one with a starting point, a set of axioms, from which other truths can be deduced. One's knowledge of the subject being investigated derives from the small set of propositions which serve as premisses in every demonstration. This set of propositions is, in effect, a hostage for the truth of the derived propositions. If a derived proposition is found to be in error, one knows where to look for the source of the error. For most of his life, Russell, like Plato and many later philosophers, fell under the seductive charms of this model of human knowledge.

During the Second World War, which he spent in the United States, Russell came to the conclusion that he could no longer put off dealing with the problem of empirical knowledge. One reason for this change had been simmering in his mind for a long time. During the period he was working on deductive logic he was convinced that the propositions of logic were not only true but also significant. Mathematics was true of the world. His faith in this position had been undermined by Wittgenstein who argued very strenuously that the propositions of logic and mathematics were tautologies, merely formal truths, and, therefore, told us nothing about the world. For a man of Russell's philosophical disposition this was a bitter pill to swallow, and it is doubtful that he ever did swallow it. One immediate consequence of regarding formal truths as tautologies is to increase the importance of contingent truths, for they do refer to the world, and hence are significant.

A second reason has to do with scepticism. Although Russell always prized a sceptical frame of mind, he was not a sceptic in the philosophical sense. Pyrrhonian or Humean scepticism was an insincere philosophy, he believed, because its partisans always preferred bread to stones at meal time. Application of the scientific method has resulted in knowledge about which only theoretical doubt is possible, but Hume's doubts about induction appeared at first glance to taint these results. Since everybody uses induction and other forms of non-demonstrative inference, and everyone has beliefs about the future, what is needed is a canon of non-demonstrative inference; such a canon would serve as a justification for our faith in non-demonstrative inference. In 1943, in an outline which he entitled “Project of Future Work”, Russell raised what he regarded as the “main question”: “In what circumstances does scientific method allow us to infer the existence of something unobserved from what is observed?” Such an inference is never legitimate in deductive, or demonstrative, logic, but it is in science and in everyday life. A careful analytical study of the actual use of scientific method ought to lead to the formulation of a set of principles which would, collectively, serve as a canon to justify our use of non-demonstrative inference.

Closely related to the second reason is a third: it concerns empiricism as a philosophy. After about 1912 Russell regarded himself as carrying on the work of the great British empiricists, Locke, Berkeley, Hume and Mill, but most of his philosophical work, as we have seen, had to do with the problem of a priori knowledge. The rise of the logical positivists in the 1930s forced him to reconsider his position. They claimed him, along with Hume and Mach and Wittgenstein, as their philosophical ancestor, but, after reading a number of their works and finding some of their positions too extreme for his taste, Russell realized that he had work to do to distinguish his position from logical positivism. The unifying thread he hit upon was an examination of all of those arguments whose conclusions are never certain, given the truth of the premisses, but only probable.

At the end of a long study of the use of non-demonstrative arguments in both science and ordinary life, Russell concluded that five postulates are required to validate arguments of this sort. They are brought together at the end of the book and the justification for including each of them is summarized. What surprised Russell, and will astonish some readers, is that the principle of induction is not a member of this set of postulates. Russell came to the conclusion, after an extensive study of the role of probability theory in scientific method, that the form of induction used there is demonstrable in probability theory. Therefore, it is unnecessary to assume it as a postulate.

Although the argument of this book proceeds in much the same way as the arguments to be found in his earlier philosophical works, there is one statement in the Preface which seems to call into question the philosophical method which he advocated in “Scientific Method in Philosophy” (1914), written in the flush of the success of *Principia Mathematica*. In that essay, after arguing that “philosophy is the science of the possible”, he went on to amplify: “Philosophy, if what has been said is correct, becomes indistinguishable from logic as that word has now come to be used.” And there can be no doubt that by “logic” he meant the logic developed in *Principia Mathematica*. It is, therefore, astonishing to find, in the first paragraph of his Preface to *Human Knowledge: Its Scope and Limits*, this long-standing position unceremoniously abandoned: "Logic, it must be admitted, is technical in the same way as mathematics is, but logic, I maintain, is not part of philosophy. Philosophy proper deals with matters of interest to the general educated public, and loses much of its value if only a few professionals can understand what is said." His style of writing often leads him into making statements with more sweep than he probably intends, and in this case he probably intends less than meets the eye. Whatever the truth is on this point, the reader of this book will soon discover that Russell has not abandoned logical analysis as his preferred method, for one finds it used on every page, although, in consideration of those readers unacquainted with modern symbolic logic, he does keep the use of special symbols to a bare minimum. A member of "the general educated public" should, therefore, be able to follow his argument and learn a great deal about the many problems upon which Russell turns his formidable philosophical talent in this important book.

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Preface

The following pages are addressed, not only or primarily to professional philosophers, but to that much larger public which is interested in philosophical questions without being willing or able to devote more than a limited amount of time to considering them. Descartes, Leibniz, Locke, Berkeley, and Hume wrote for a public of this sort, and I think it is unfortunate that during the last hundred and sixty years or so philosophy has come to be regarded as almost as technical as mathematics. Logic, it must be admitted, is technical in the same way as mathematics is, but logic, I maintain, is not part of philosophy. Philosophy proper deals with matters of interest to the general educated public, and loses much of its value if only a few professionals can understand what is said.

In this book I have sought to deal, as comprehensively as I am able, with a very large question: how comes it that human beings, whose contacts with the world are brief and personal and limited, are nevertheless able to know as much as they do know? Is the belief in our knowledge partly illusory? And, if not, what must we know otherwise than through the senses? Since I have dealt in earlier books with some parts of this problem, I am compelled to repeat, in a larger context, discussions of certain matters which I have considered elsewhere, but I have reduced such repetition to the minimum compatible with my purpose.

One of the difficulties of the subject with which I am concerned is that we must employ words which are common in ordinary speech, such as "belief", "truth", "knowledge", and "perception". Since these words, in their everyday uses, are vague and unprecise, and since no precise words are ready to hand by which to replace them, it is inevitable that everything said in the earlier stages of our inquiry should be unsatisfactory from the point of view that we hope to arrive at in the end. Our increase of knowledge, assuming that we are successful, is like that of a traveller approaching a mountain through a haze: at first only certain large features are discernible, and even they have indistinct boundaries, but gradually more detail becomes visible and edges become sharper. So, in our discussions, it is impossible first to clear up one problem and then proceed to another, for the intervening haze envelops all alike. At every stage, though one part of our problem may be in the focus of attention, all parts are more or less relevant. The different key words that we must use are all interconnected, and so long as some remain vague, others must, more or less, share this defect. It follows that what is said at first is liable to require emendation later. The Prophet announced that if two texts of the Koran appeared inconsistent, the later text was to be taken as authoritative, and I should wish the reader to apply a similar principle in interpreting what is said in this book.

The book has been read in typescript by my friend and pupil Mr. C. K. Hill, and I am indebted to him for many valuable criticisms, suggestions, and emendations. Large parts of the typescript have also been read by Mr. Hiram J. McLendon, who has made a number of useful suggestions.

Part III, Chapter 4, on "Physics and Experience", is a reprint, with few alterations, of a little book with the above title, published by the Cambridge University Press, to whom I owe thanks for permission to reprint it.

INTRODUCTION

The central purpose of this book is to examine the relation between individual experience and the general body of scientific knowledge. It is taken for granted that scientific knowledge, in its broad outlines, is to be accepted. Scepticism, while logically impeccable, is psychologically impossible, and there is an element of frivolous insincerity in any philosophy which pretends to accept it. Moreover, if scepticism is to be theoretically defensible it must reject *all* inferences from what is experienced; a partial scepticism, such as the denial of physical events experienced by no one, or a solipsism which allows events in my future or in my unremembered past, has no logical justification, since it must admit principles of inference which lead to beliefs that it rejects.

Ever since Kant, or perhaps it would be more just to say ever since Berkeley, there has been what I regard as a mistaken tendency among philosophers to allow the description of the world to be influenced unduly by considerations derived from the nature of human knowledge. To scientific common sense (which I accept) it is plain that only an infinitesimal part of the universe is known, that there were countless ages during which there was no knowledge, and that there probably will be countless ages without knowledge in the future. Cosmically and causally, knowledge is an unimportant feature of the universe; a science which omitted to mention its occurrence might, from an impersonal point of view, suffer only from a very trivial imperfection. In describing the world, subjectivity is a vice. Kant spoke of himself as having effected a "Copernican revolution", but he would have been more accurate if he had spoken of a "Ptolemaic counter-revolution", since he put Man back at the centre from which Copernicus had dethroned him.

But when we ask, not "what sort of world do we live in?" but "how do we come by our knowledge about the world?" subjectivity is in order. What each man knows is, in an important sense, dependent upon his own individual experience: he knows what he has seen and heard, what he has read and what he has been told, and also what, from these data, he has been able to infer. It is individual, not collective, experience that is here in question, for an inference is required to pass from my data to the acceptance of testimony. If I believe that there is such a place as Semipalatinsk, I believe it because of things that have happened to *me*; and unless certain substantial principles of inference are accepted, I shall have to admit that all these things might have happened to me without there being any such place.

The desire to escape from subjectivity in the description of the world (which I share) has led some modern philosophers astray—at least so it seems to me—in relation to theory of knowledge. Finding its problems distasteful, they have tried to deny that these problems exist. That data are private and individual is a thesis which has been familiar since the time of Protagoras. This thesis has been denied because it has been thought, as Protagoras thought, that, if admitted, it must lead to the conclusion that all knowledge is private and individual. For my part, while I admit the thesis, I deny the conclusion; how and why, the following pages are intended to show.

In virtue of certain events in my own life, I have a number of beliefs about events that I do not experience—the thoughts and feelings of other people, the physical objects that surround me, the historical and geological past of the earth, and the remote regions of the universe that are studied in astronomy. For my part, I accept these beliefs as valid, apart from errors of detail. By this acceptance I commit myself to the view that there are valid processes of inference from events to other events—more particularly, from events of which I am aware without inference to events of which I have no such awareness. To discover what these processes are is a matter of analysis of scientific and common-sense procedure, in so far as such procedure is generally accepted as scientifically valid.

Inference from a group of events to other events can only be justified if the world has certain characteristics which are not logically necessary. So far as deductive logic can show, any collection of events might be the whole universe; if, then, I am ever to be able to infer events, I must accept principles of inference which lie outside deductive logic. All inference from events to events demands some kind of interconnection between different occurrences. Such interconnection is traditionally asserted in the principle of causality or natural law. It is implied, as we shall find, in whatever limited validity may be assigned to induction by simple enumeration. But the traditional ways of formulating the kind of interconnection that must be postulated are in many ways defective, some being too stringent and some not sufficiently so. To discover the minimum principles required to justify scientific inferences is one of the main purposes of this book.

It is a commonplace to say that the substantial inferences of science, as opposed to those of logic and mathematics, are only *probable*—that is to say, when the premisses are true and the inference correct, the conclusion is only *likely* to be true. It is therefore necessary to examine what is meant by "probability". It will be found that there are two different concepts that may be meant. On the one hand, there is mathematical probability: if a class has n members, and m of them have a certain characteristic, the mathematical probability that an unspecified member of this class will have the characteristic in question is m/n. On the other hand, there is a wider and vaguer concept, which I call "degree of credibility", which is the amount of credence that it is rational to assign to a more or less uncertain proposition. Both kinds of probability are involved in stating the principles of scientific inference.

The course of our inquiry, in broad outline, will be as follows.

Part I, on the world of science, describes some of the main features of the universe which scientific investigation has made probable. This Part may be taken as setting the goal which inference must be able to reach, if our data and our principles of inference are to justify scientific practice.

Part II, on language, is still concerned with preliminaries. These are mainly of two sorts. On the one hand, it is important to make clear the meanings of certain fundamental terms, such as "fact" and "truth". On the other hand, it is necessary to examine the relation of sensible experience to empirical concepts such as "red", "hard", "metre", or "second". In addition, we shall examine the relation of words having an essential reference to the speaker, such as "here" and "now", to impersonal words, such as those assigning latitude, longitude, and date. This raises problems, of considerable importance and some difficulty, which are concerned with the relation of individual experience to the socially recognized body of general knowledge.

In Part III, on Science and Perception, we begin our main inquiry. We are concerned, here, to disentangle data from inferences in what ordinarily passes for empirical knowledge. We are not yet concerned to justify inferences, or to investigate the principles according to which they are made, but we are concerned to show that inferences (as opposed to logical constructions) are necessary to science. We are concerned also to distinguish between two kinds of space and time, one subjective and appertaining to data, the other objective and inferred. Incidentally we shall contend that solipsism, except in an extreme form in which it has never been entertained, is an illogical halfway house between the fragmentary world of data and the complete world of science.

Part IV, on scientific concepts, is concerned to analyse the fundamental concepts of the inferred scientific world, more especially physical space, historical time, and causal laws. The terms employed in mathematical physics are required to fulfil two kinds of conditions: on the one hand, they must satisfy certain formulae; on the other hand, they must be so interpreted as to yield results that can be confirmed or confuted by observation. Through the latter condition they are linked to data, though somewhat loosely; through the former they become determinate as regards certain structural properties. But considerable latitude of interpretation remains. It is prudent to use this latitude in such a way as to minimize the part played by inference as opposed to construction; on this ground, for example, point-instants in space–time are constructed as groups of events or of qualities. Throughout this Part the two concepts of space–time structure and causal chains assume a gradually increasing importance. As Part III was concerned to discover what can be counted as data, so Part IV is concerned to set forth, in a general way, what, if science is to be justified, we must be able to infer from our data.

Since it is admitted that scientific inferences, as a rule, only confer probability on their conclusions, Part V proceeds to the examination of Probability. This term is capable of various interpretations, and has been differently defined by different authors. These interpretations and definitions are examined, and so are the attempts to connect induction with probability. In this matter the conclusion reached is, in the main, that advocated by Keynes: that inductions do not make their conclusions probable unless certain conditions are fulfilled, and that experience alone can never prove that these conditions are fulfilled.

Part VI, on the postulates of scientific inference, endeavours to discover what are the minimum assumptions, anterior to experience, that are required to justify us in inferring laws from a collection of data; and further, to inquire in what sense, if any, we can be said to know that these assumptions are valid. The main logical function that the assumptions have to fulfil is that of conferring a high probability on the conclusions of inductions that satisfy certain conditions. For this purpose, since only probability is in question, we do not need to assume that such-and-such a connection of events occurs always, but only that it occurs frequently. For example, one of the assumptions that appear necessary is that of separable causal chains, such as are exhibited by light-rays or sound-waves. This assumption can be stated as follows: when an event having a complex space–time structure occurs, it frequently happens that it is one of a train of events having the same or a very similar structure. (A more exact statement will be found in Chapter 6 of this Part.) This is part of a wider assumption of regularity, or natural law, which, however, requires to be stated in more specific forms than is usual, for in its usual form it turns out to be a tautology.

That scientific inference requires, for its validity, principles which experience cannot render even probable, is, I believe, an inescapable conclusion from the logic of probability. For empiricism, it is an awkward conclusion.

But I think it can be rendered somewhat more palatable by the analysis of the concept of "knowledge" undertaken in Part II. "Knowledge", in my opinion, is a much less precise concept than is generally thought, and has its roots more deeply embedded in unverbalized animal behaviour than most philosophers have been willing to admit. The logically basic assumptions to which our analysis leads us are psychologically the end of a long series of refinements which start from habits of expectation in animals, such as that what has a certain kind of smell will be good to eat. To ask, therefore, whether we "know" the postulates of scientific inference, is not so definite a question as it seems. The answer must be: in one sense, yes, in another sense, no; but in the sense in which "no" is the right answer we know nothing whatever, and "knowledge" in this sense is a delusive vision. The perplexities of philosophers are due, in a large measure, to their unwillingness to awaken from this blissful dream.

Part I

The World of Science

1

INDIVIDUAL AND SOCIAL KNOWLEDGE

Scientific knowledge aims at being wholly impersonal, and tries to state what has been discovered by the collective intellect of mankind. In this chapter I shall consider how far it succeeds in this aim, and what elements of individual knowledge have to be sacrificed in order to achieve the measure of success that is possible.

The community knows both more and less than the individual: it knows, in its collective capacity, all the contents of the Encyclopaedia and all the contributions to the Proceedings of learned bodies, but it does not know the warm and intimate things that make up the colour and texture of an individual life. When a man says "I can never convey the horror I felt on seeing Buchenwald" or "no words can express my joy at seeing the sea again after years in a prison camp", he is saying something which is strictly and precisely true: he possesses, through his experience, knowledge not possessed by those whose experience has been different, and not completely capable of verbal expression. If he is a superb literary artist he may create in sensitive readers a state of mind not wholly unlike his own, but if he tries scientific methods the stream of his experience will be lost and dissipated in a dusty desert.

Language, our sole means of communicating *scientific* knowledge, is essentially social in its origin and in its main functions. It is true that, if a mathematician were wrecked on a desert island with a note-book and a pencil, he would, in all likelihood, seek to make his solitude endurable by calculations using the language of mathematics; it is true also that a man may keep a diary which he intends to conceal from all eyes but his own. On a more everyday plane, most of us use words in solitary thinking. Nevertheless the chief purpose of language is communication, and to serve this purpose it must be public, not a private dialect invented by the speaker. It follows that what is most personal in each individual's experience tends to evaporate during the process of translation into language. What is more, the very publicity of language is in large part a delusion. A given form of words will usually be interpreted by competent hearers in such a way as to be true for all of them or false for all of them, but in spite of this it will not have the same meaning for all of them. Differences which do not affect the truth or falsehood of a statement are usually of little practical importance, and are therefore ignored, with the result that we all believe our private world to be much more like the public world than it really is.

This is easily proved by considering the process of learning to understand language. There are two ways of getting to know what a word means: one is by a definition in terms of other words, which is called *verbal* definition; the other is by frequently hearing the word when the object which it denotes is present, which is called *ostensive* definition. It is obvious that ostensive definition is alone possible in the beginning, since verbal definition presupposes a knowledge of the words used in the *definiens*. You can learn by a verbal definition that a pentagon is a plane figure with five sides, but a child does not learn in this way the meaning of every-day words such as "rain", "sun", "dinner", or "bed". These are taught by using the appropriate word emphatically while the child is noticing the object concerned. Consequently the meaning that the child comes to attach to the word is a product of his personal experience, and varies according to his circumstances and his sensorium. A child who frequently experiences a mild drizzle will attach a different idea to the word "rain" from that formed by a child who has only experienced tropical torrents. A short-sighted and a long-sighted child will connect different images with the word "bed".

It is true that education tries to depersonalize language, and with a certain measure of success. "Rain" is no longer the familiar phenomenon, but "drops of water falling from clouds towards the earth", and "water" is no longer what makes you wet, but H_2O. As for hydrogen and oxygen, they have verbal definitions which have to be learnt by heart; whether you understand them does not matter. And so, as your instruction proceeds, the world of words becomes more and more separated from the world of the senses; you acquire the art of using words correctly, as you might acquire the art of playing the fiddle; in the end you become such a virtuoso in the manipulation of phrases that you need hardly ever remember that words have meanings. You have then become completely a public character, and even your inmost thoughts are suitable for the Encyclopaedia. But you can no longer hope to be a poet, and if you try to be a lover you will find your depersonalized language not very successful in generating the desired emotions. You have sacrificed expression to communication, and what you can communicate turns out to be abstract and dry.

It is an important fact that the nearer we come to the complete abstractness of logic, the less is the unavoidable difference between different people in the meaning attached to a word. I see no reason why there should be any difference at all between two suitably educated persons in the idea conveyed to them by the word "3481". The words "or" and "not" are capable of having exactly the same meaning for two different logicians. Pure mathematics, throughout, works with concepts which are capable of being completely public and impersonal. The reason is that they derive nothing from the senses, and that the senses are the source of privacy. The body is a sensitive recording instrument, constantly transmitting messages from the outside world; the messages reaching one body are never quite the same as those reaching another, though practical and social exigencies have taught us ways of disregarding the differences between the percepts of neighbouring persons. In constructing physics we have emphasized the spatio-temporal aspect of our perceptions, which is the aspect that is most abstract and most nearly akin to logic and mathematics. This we have done in the pursuit of publicity, in order to communicate what is communicable and to cover up the rest in a dark mantle of oblivion.

Space and time, however, as human beings know them, are not in reality so impersonal as science pretends. Theologians conceive God as viewing both space and time from without, impartially, and with a uniform awareness of the whole; science tries to imitate this impartiality with some apparent success, but the success is in part illusory. Human beings differ from the theologians' God in the fact that their space and time have a *here* and *now*. What is here and now is vivid, what is remote has a gradually increasing dimness. All our knowledge of events radiates from a space–time centre, which is the little region that we are occupying at the moment. "Here" is a vague term: in astronomical cosmology the Milky Way may count as "here", in the study of the Milky Way "here" is the solar system, in the study of the solar system "here" is the earth, in geography it is the town or district in which we live, in physiological studies of sensation it is the brain as opposed to the rest of the body. Larger "heres" always contain smaller ones as parts; all "heres" contain the brain of the speaker, or part of it. Similar considerations apply to "now".

Science professes to eliminate "here" and "now". When some event occurs on the earth's surface, we give its position in the space–time manifold by assigning latitude, longitude, and date. We have developed a technique which insures that all accurate observers with accurate instruments will arrive at the same estimate of latitude, longitude, and date. Consequently there is no longer anything personal in these estimates, in so far as we are content with numerical statements of which the meaning is not too closely investigated. Having arbitrarily decided that the longitude of Greenwich and the latitude of the equator are to be zero, other latitudes and longitudes follow. But what is "Greenwich"? This is hardly the sort of term that ought to occur in an impartial survey of the universe, and its definition is not mathematical. The best way to define "Greenwich" is to take a man to it and say: "Here is Greenwich." If some one else has already determined the latitude and longitude of the place where you are, "Greenwich" can be defined by its latitude and longitude relative to that place; it is, for example, so many degrees east and so many degrees north of New York. But this does not get rid of "here", which is now New York instead of Greenwich.

Moreover it is absurd to *define* either Greenwich or New York by its latitude and longitude. Greenwich is an actual place, inhabited by actual people, and containing buildings which antedate its longitudinal pre-eminence. You can, of course, describe Greenwich, but there always might be another town with the same characteristics. If you want to be *sure* that your description applies to no other place, the only way is to mention its relation to some other place, for instance, by saying that it is so many miles down the Thames from London Bridge. But then you will have to define "London Bridge". Sooner or later you are faced with the necessity of defining some place as "here", and this is an egocentric definition, since the place in question is not "here" for everybody. There may be a way of escape from this conclusion; at a later stage, we will resume the question. But there is no obvious or easy way of escape, and until one is found all determinations of latitude and longitude are infected with the subjectivity of "here". This means that, although different people assign the same latitude and longitude to a place, they do not, in ultimate analysis, attach the same meaning to the figures at which they arrive.

The common world in which we believe ourselves to live is a construction, partly scientific, partly pre-scientific. We perceive tables as circular or rectangular, in spite of the fact that a painter, to reproduce their appearance, has to paint ellipses or non-rectangular quadrilaterals. We see a person as of about the same size whether he is two feet from us or twelve. Until our attention is drawn to the facts, we are quite unconscious of the corrections that experience has led us to make in interpreting sensible appearances. There is a long journey from the child who draws two eyes in a profile to the physicist who talks of electrons and protons, but throughout this journey there is one constant purpose: to eliminate the subjectivity of sensation, and substitute a kind of knowledge which can be the same for all percipients. Gradually the difference between what is sensed and what is believed to be objective grows greater; the child's profile with two eyes is still very like what is seen, but the electrons and protons have only a remote resemblance of logical structure. The electrons and protons, however, have the merit that they *may* be what actually exists where there are no sense-organs, whereas our immediate visual data, owing to their subjectivity, are almost certainly not what takes place in the physical objects that we are said to see.

The electrons and protons—assuming it scientifically correct to believe in them—do not depend for their existence upon being perceived; on the contrary, there is every reason to believe that they existed for countless ages before there were any percipients in the universe. But although perception is not needed for their existence, it is needed to give us a reason for believing in their existence. Hundreds of thousands of years ago, a vast and remote region emitted incredible numbers of photons, which wandered through the universe in all directions. At last a very few of them hit a photographic plate, in which they caused chemical changes which made parts of the plate look black instead of white when examined by an astronomer. This tiny effect upon a minute but highly educated organism is our only reason for believing in the existence of a nebula comparable in size with the Milky Way. The order for knowledge is the inverse of the causal order. In the order for knowledge, what comes first is the brief subjective experience of the astronomer looking at a pattern of black and white, and what comes last is the nebula, vast, remote, and belonging to the distant past.

In considering the reasons for believing in any empirical statement, we cannot escape from perception with all its personal limitations. How far the information which we obtain from this tainted source can be purified in the filter of scientific method, and emerge resplendently godlike in its impartiality, is a difficult question, with which we shall be much concerned. But there is one thing that is obvious from the start: only in so far as the initial perceptual datum is trustworthy can there be any reason for accepting the vast cosmic edifice of inference which is based upon it.

I am not suggesting that the initial perceptual datum must be accepted as indubitable; that is by no means the case. There are well-known methods of strengthening or weakening the force of individual testimony; certain methods are used in the law courts, somewhat different ones are used in science. But all depend upon the principle that *some* weight is to be attached to every piece of testimony, for it is only in virtue of this principle that a number of concordant testimonies are held to give a high probability. Individual percepts are the basis of all our knowledge, and no method exists by which we can begin with data which are public to many observers.

2

THE UNIVERSE OF ASTRONOMY

Astronomy is the oldest of the sciences, and the contemplation of the heavens, with their periodic regularities, gave men their first conceptions of natural law. But in spite of its age, astronomy is as vigorous as at any former time, and as important in helping us to form a just estimate of man's position in the universe.

When the Greeks began inventing astronomical hypotheses, the apparent motions of the sun and moon and planets among the fixed stars had already been observed for thousands of years by the Babylonians and Egyptians, who had also learned to predict lunar eclipses with certainty and solar eclipses with a considerable risk of error. The Greeks, like other ancient nations, believed the heavenly bodies to be gods, or at any rate each closely controlled by its own god or goddess. Some, it is true, questioned this opinion: Anaxagoras, in the time of Pericles, maintained that the sun was a red-hot stone and that the moon was made of earth. But for this opinion he was prosecuted and compelled to fly from Athens. It is very questionable whether either Plato or Aristotle was equally rationalistic. But it was not the most rationalistic among the Greeks who were the best astronomers; it was the Pythagoreans, to whom superstition suggested what happened to be good hypotheses.

The Pythagoreans, towards the end of the fifth century B.C., discovered that the earth is spherical; about a hundred years later, Eratosthenes estimated the earth's diameter correctly within about fifty miles. Heraclides of Pontus, during the fourth century, maintained that the earth rotates once a day and that Venus and Mercury describe orbits about the sun. Aristarchus of Samos, in the third century, advocated the complete Copernican system, and worked out a theoretically correct method of estimating the distances of the sun and moon. As regards the sun this result, it is true, was wildly wrong, owing to inaccuracy in his data; but a hundred years later Posidonius made an estimate which was about half of the correct figure. This extraordinarily vigorous advance, however, did not continue, and much of it was forgotten in the general decay of intellectual energy during later antiquity.

The cosmos, as it appears, for instance, in Plotinus, was a cosy and human little abode in comparison with what it has since become. The supreme deity regulated the whole, but each star was a subordinate deity, similar to a human being but in every way nobler and wiser. Plotinus finds fault with the Gnostics for believing that, in the created universe, there is nothing more worthy of admiration than the human soul. The beauty of the heavens, to him, is not only visual, but also moral and intellectual. The sun and moon and planets are exalted spirits, actuated by such motives as appeal to the philosopher in his best moments. He rejects with indignation the morose view of the Gnostics (and later of the Manicheans) that the visible world was created by a wicked Demiurge and must be despised by every aspirant to true virtue. On the contrary, the bright beings that adorn the sky are wise and good, and such as to console the philosopher amid the welter of folly and disaster that was overtaking the Roman Empire.

The medieval Christian cosmos, though less austere than that of the Manicheans, was shorn of some elements of poetic fancy that paganism had preserved to the end. The change, however, was not very great, for angels and archangels more or less took the place of the polytheists' celestial divinities. Both the scientific and the poetic elements of the medieval cosmos are set forth in Dante's *Paradiso*; the scientific elements are derived from Aristotle and Ptolemy. The earth is spherical, and at the centre of the universe; Satan is at the centre of the earth, and hell is an inverted cone of which he forms the apex. At the antipodes of Jerusalem is the Mount of Purgatory, at whose summit is the earthly paradise, which is just in contact with the sphere of the moon.

The heavens consist of ten concentric spheres, that of the moon being the lowest. Everything below the moon is subject to corruption and decay; everything from the moon upwards is indestructible. Above the moon, the spheres in their order are those of Mercury, Venus, the Sun, Mars, Jupiter, Saturn and the fixed stars, beyond which is the Primum Mobile. Last of all, above the Primum Mobile, is the Empyrean, which has no motion, and in which there are no times or places. God, the Aristotelian Unmoved Mover, causes the rotation of the Primum Mobile, which, in turn, communicates its motion to the sphere of the fixed stars, and so on downwards to the sphere of the moon. Nothing is said in Dante as to the sizes of the various spheres, but he is able to traverse them all in the space of twenty-four hours. Clearly the universe as he conceived it was somewhat minute by modern standards; it was also very recent, having been created a few thousand years ago. The spheres, which all had the earth at the centre, afforded the eternal abodes of the elect. The elect consisted of those baptized persons who had reached the required standard both in faith and works, together with the patriarchs and prophets who had foreseen the coming of Christ, and a very few pagans who, while on earth, had been miraculously enlightened.

It was against this picture of the universe that the pioneers of modern astronomy had to contend. It is interesting to contrast the commotion about Copernicus with the almost complete oblivion that befell Aristarchus. Cleanthes the Stoic had urged that Aristarchus should be prosecuted for impiety, but the Government was apathetic; perhaps if he had been persecuted, like Galileo, his theories might have won wider publicity. There were, however, other more important reasons for the difference between the posthumous fame of Aristarchus and that of Copernicus. In Greek times astronomy was an amusement of the idle rich—a very dignified amusement, it is true, but not an integrated part of the life of the community. By the sixteenth century, science had invented gunpowder and the mariner's compass, the discovery of America had shown the limitations of ancient geognosis, Catholic orthodoxy had begun to seem an obstacle to material progress, and the fury of obscurantist theologians made the men of science appear as heroic champions of a new wisdom. The seventeenth century, with the telescope, the science of dynamics, and the law of gravitation, completed the triumph of the scientific outlook, not only as the key to pure knowledge, but as a powerful means of economic progress. From this time onwards, science was recognized as a matter of social and not merely individual interest.

The theory of the sun and planets as a finished system was practically completed by Newton. As against Aristotle and the medieval philosophers it appeared that the sun, not the earth, is the centre of the solar system; that the heavenly bodies, left to themselves, would move in straight lines, not in circles; that in fact they move neither in straight lines nor in circles, but in ellipses; and that no action from outside is necessary to preserve their motion. But as regards the origin of the system Newton had nothing scientific to say; he supposed that at the Creation the planets had been hurled by the hand of God in a tangential direction, and had then been left by Him to the operation of the law of gravitation. Before Newton, Descartes had attempted a theory of the origin of the solar system, but his theory proved untenable. Kant and Laplace invented the nebular hypothesis, according to which the sun was formed by the condensation of a primitive nebula, and threw off the planets successively as a result of increasingly rapid rotation. This theory also proved defective, and modern astronomers incline to the view that the planets were caused by the passage of another star through the near neighbourhood of the sun. The subject remains obscure, but no one doubts that, by some mechanism, the planets came out of the sun.

The most remarkable astronomical progress in recent times has been in relation to the stars and the nebulae. The nearest of the fixed stars, Alpha Centauri, is at a distance of about 25×10^{12} miles, or 4.2 light-years. (Light travels 186,000 miles a second; a light-year is the distance it travels in a year.) The first determination of the distance of a star was in 1835; since then, by various ingenious methods, greater and greater distances have been computed. It is believed that the most distant object that can be detected with the most powerful telescope now in existence is about 500 million light-years away.

Something is now known of the general structure of the universe. The sun is a star in the galaxy, which is an assembly of about 300,000 million stars, about 150,000 light-years across and between 25,000 and 40,000 light-years thick. The total mass of the galaxy is about 160,000 million times the mass of the sun; the mass of the sun is about 2×10^{27} tons. The whole of this system is slowly rotating about its centre of gravity; the sun takes about 225 million years to complete its orbit round the milky way.

In the space beyond the milky way, other systems of stars, of approximately the same size as the milky way, are scattered at fairly regular intervals throughout the space that our telescopes can explore. These systems are called extra-galactic nebulae; it is thought that about 30 millions of them are visible, but the census is not yet complete. The average distance between two nebulae is about 2 million light-years. (Most of these facts are taken from Hubble, *The Realm of the Nebulae*, 1936.)

One of the oddest facts about the nebulae is that the lines in their spectra, with very few exceptions, are shifted towards the red, and that the amount of the shift is proportional to their distance of the nebula. The only plausible explanation is that the nebulae are moving away from us, and that the most distant ones are receding most quickly. At a distance of 135 million light-years, this velocity amounts to 14,300 miles per second (Hubble, Plate VIII, p. 118). At a certain distance, the velocity would become equal to the velocity of light, and the nebulae would therefore be invisible however powerful our telescopes might be.

The general theory of relativity has an explanation to offer of this curious phenomenon. The theory maintains that the universe is of finite size—not that it has an edge, outside which there is something which is not part of the universe, but that it is a three-dimensional sphere, in which the straightest possible lines return in time to their starting-point, as on the surface of the earth. The theory goes on to predict that the universe must be either contracting or expanding; it then uses the observed facts about the nebulae to decide for expansion. According to Eddington, the universe doubles in size every

1,300 million years or so. (*New Pathways in Science*, p. 210.) If this is true, the universe was once quite small, but will in time become rather large.

This brings us to the question of the ages of the earth and the stars and the nebulae. On grounds that are largely geological, the age of the earth is estimated at about 3,000 million years. The age of the sun and the other stars is still a matter of controversy. If, in the interior of a star, matter can be annihilated by transforming an electron and a proton into radiation, the stars may be several million million years old; if not, only a few thousand million. (H. Spencer Jones, *Worlds Without End*, p. 231.) On the whole, the latter view seems to be prevailing.

There is even some reason to think that the universe had a beginning in time; Eddington used to maintain that it began in about 90,000 million B.C. This is certainly more than the 4,004 in which our great-grandfathers believed, but it is still a finite period, and raises all the old puzzles as to what was going on before that date.

The net result of this summary survey of the astronomical world is that, while it is certainly very large and very ancient, there are grounds—though as yet they are very speculative—for thinking that it is neither infinitely large nor infinitely old. The general theory of relativity professes to be able to tell us things about the universe as a whole, by means of an ingenious mixture of observation and reasoning. If this is valid—and I am by no means persuaded that it is—the increase of scale, both in space and time, which has hitherto characterized astronomy, has a limit, and one which we are within measurable distance of reaching. Eddington maintains that the circumference of the universe is of the order of 6,000 million light-years. (*New Pathways in Science*, p. 218.) If so, somewhat better telescopes should enable us to "grasp this sorry scheme of things entire". As we are beginning to see, we may before long be also able to "shatter it to bits". But I do not think we shall be able to "remould it nearer to the heart's desire".

3

THE WORLD OF PHYSICS

The most advanced science in the present day, and the one which seems to throw the most light on the structure of the world, is physics. This science virtually begins with Galileo, but in order to appreciate his work it will be well to glance briefly at what was thought before his time.

The scholastics, whose views were in the main derived from Aristotle, thought that there were different laws for celestial and terrestrial bodies, and also for living and dead matter. They held that dead matter, left to itself, would gradually lose any motion it might have, at any rate in the terrestrial sphere. Everything living, according to Aristotle, had some kind of soul. The vegetable soul, possessed by all plants and animals, was only concerned with growth; the animal soul was concerned to cause movements. There were four elements, earth, water, air, and fire, of which earth and water were heavy, while air and fire were light. Earth and water had a natural downward motion, air and fire a natural upward motion. There was also, in the highest heavens, a fifth element, a kind of sublimated fire. There was no suggestion of one set of laws for all kinds of matter, and there was no science of changes in the movements of bodies.

Galileo—and in a lesser degree Descartes—introduced the fundamental concepts and principles which sufficed for physics until the present century. It appeared that the laws of motion are the same for all kinds of dead matter, and probably for living matter also. Descartes held that animals are automata, and that their movements could theoretically be calculated by using the same principles that govern a falling lump of lead. The view that all matter is homogeneous, and that its only scientifically important property is position in space, prevailed practically among physicists, at any rate as a working hypothesis. For theological reasons, human bodies were often (though not always) exempted from the rigid determinism to which physical laws seemed to lead. With this possible exception, scientific orthodoxy came to endorse Laplace's view, that a calculator possessed of sufficient mathematical ability, given the position and velocity and mass of every particle in the universe at a given instant, could calculate the whole past and future of the physical world. If, as some thought, miracles occasionally intervened, these lay outside the purview of science, since they were in their very nature not subject to law. For this reason, even those who believed in miracles had no occasion to lapse from scientific rigour in their calculations.

Galileo introduced the two principles that did most to make mathematical physics possible: the law of inertia, and the parallelogram law. Something must be said about each of these.

The law of inertia, familiar as Newton's first law of motion, states, in Newton's language, that:

"Every body perseveres in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed thereon."

The conception of "force", which was prominent in the work of Galileo and Newton, turned out to be superfluous, and was eliminated from classical dynamics during the nineteenth century. This necessitated a re-statement of the law of inertia. But let us first consider the law in relation to the beliefs prevailing before Galileo.

All terrestrial motions tend to slacken and finally stop. Bowls on even the smoothest bowling-green come to rest after a while; a stone thrown onto ice does not go on sliding for ever. The heavenly bodies, it is true, persist in their orbits, without any discoverable loss of velocity; but their motions are not rectilinear. According to the law of inertia, the retardation of the stone on ice, and the curvilinear orbits of the planets, are not to be explained by anything intrinsic in their own natures, but by the action of the environment.

This principle led to the possibility of regarding the physical world as a causally self-contained system. It soon appeared that in any dynamically independent system—such as the sun and planets are to a very near approximation—the amount of motion, or momentum, in every direction is constant. Thus a universe once in motion will remain in motion for ever, unless stopped by a miracle. Aristotle had thought that the planets needed gods to push them round their orbits, and that movements on earth could be spontaneously initiated by animals. The motions of matter, on this view, could only be accounted for by taking account of non-material causes. The law of inertia changed this, and made it possible to calculate the motions of matter by means of the laws of dynamics alone.

Technically, the principle of inertia meant that the causal laws of physics should be stated in terms of *acceleration*, i.e. a change of velocity in amount or direction or both. Uniform motion in a circle, which the ancients and the scholastics regarded as "natural" for the heavenly bodies, ceased to be so, since it required a continual change in the direction of motion. The departure from a straight line required a cause, which was found in Newton's law of gravitation.

Acceleration being the second differential of position with respect to time, it followed from the law of inertia that the causal laws of dynamics must be differential equations of the second order, though this form of statement could not be made until Newton and Leibniz had invented the infinitesimal calculus. Throughout all the modern changes in theoretical physics, this consequence of the law of inertia has stood firm. The fundamental importance of *acceleration* is perhaps the most permanent and the most enlightening of all Galileo's discoveries.

The parallelogram law, in Newtonian language, is concerned with what happens when a body is subject to two forces at once. It says that if a body is subject to two forces, one of which is measured, in direction and magnitude, by a line AB, and the other by a line BC, then the effect of their both acting at once is measured by the line AC. This amounts, roughly speaking, to saying that when two forces act simultaneously the effect is the same as if they acted successively. In technical language it means that the equations are linear, which greatly facilitates mathematical calculation.

The law may be interpreted as asserting the mutual independence of different causes acting simultaneously. Take, for example, the question of projectiles, in which Galileo was professionally interested. If the earth did not attract a projectile, it would, according to the law of inertia, continue to move horizontally with uniform velocity (neglecting the resistance of the air). If the projectile had no initial velocity, it would fall vertically with uniform acceleration. To determine where it will in fact be after (say) a second, we may suppose that it first moves horizontally with uniform velocity for a second, and then, starting from rest, falls vertically with uniform acceleration for a second.

When the forces to which a body is subject are not constant, the principle does not allow us to take each separately for a finite time, but if the finite time is short the result of taking each separately will be approximately right, and the shorter the time the more nearly right it will be, approaching complete rightness as a limit.

It must be understood that this law is purely empirical; there is no mathematical reason for its truth. It is to be believed in so far as there is evidence for it, and no further. In quantum mechanics it is not assumed, and there are phenomena which seem to show that it is not true in atomic occurrences. But in the physics of large-scale occurrences it remains true, and in classical physics it played a very important role.

From Newton to the end of the nineteenth century, the progress of physics involved no basically new principles. The first revolutionary novelty was Planck's introduction of the quantum constant *h* in the year 1900. But before considering quantum theory, which is chiefly important in connection with the structure and behaviour of atoms, a few words must be said about relativity, which involved a departure from Newtonian principles much slighter than that of quantum theory.

Newton believed that, in addition to matter, there is absolute space and absolute time. That is to say, there is a three-dimensional manifold of points and a one-dimensional manifold of instants, and there is a three-term relation involving matter, space, and time, namely the relation of "occupying" a point at an instant. In this view Newton agreed with Democritus and the other atomists of antiquity, who believed in "atoms and the void". Other philosophers had maintained that empty space is nothing, and that there must be matter everywhere. This was Descartes' opinion, and also that of Leibniz, with whom Newton (using Dr. Clarke as his mouthpiece) had a controversy on the subject.

Whatever physicists might hold as a matter of philosophy, Newton's view was implicit in the technique of dynamics, and there were, as he pointed out, empirical reasons for preferring it. If water in a bucket is rotated, it climbs up the sides, but if the bucket is rotated while the water is kept still, the surface of the water remains flat. We can therefore distinguish between rotation of the water and rotation of the bucket, which we ought not to be able to do if rotation were merely relative. Since Newton's time other arguments of the same sort have accumulated. Foucault's pendulum, the flattening of the earth at the poles, and the fact that bodies weigh less in low latitudes than in high ones, would enable us to infer that the earth rotates even if the sky were always covered with clouds; in fact, on Newtonian principles we can say that the rotation of the earth, not the revolution of the heavens, causes the succession of night and day and the rising and setting of the stars. But if space is purely relative, the difference between the statements "the earth rotates" and "the heavens revolve" is purely verbal: both must be ways of describing the same phenomena.

Einstein showed how to avoid Newton's conclusions, and make spatio-temporal position purely relative. But his theory of relativity did much more than this. In the special theory of relativity he showed that between two events there is a relation, which may be called "interval", which can be divided in many different ways into what we should regard as a spatial distance and what we should regard as a lapse of time. All these different ways are equally legitimate; there is not one way which is more "right" than the others. The choice between them is a matter of pure convention, like the choice between the metric system and the system of feet and inches.

It follows from this that the fundamental manifold of physics cannot consist of persistent particles in motion, but must consist of a four-dimensional manifold of "events". There will be three co-ordinates to fix the position of the event in space, and one to fix its position in time, but a change of co-ordinates may alter the time co-ordinate as well as the space co-ordinates, and not only, as before, by a constant amount, the same for all events—as, for example, when dating is altered from the Mohammedan era to the Christian.

The general theory of relativity—published in 1915, ten years after the special theory—was primarily a geometrical theory of gravitation. This part of the theory may be considered firmly established. But it has also more speculative features. It contains, in its equations, what is called the "cosmical constant", which determines the size of the universe at any time. This part of the theory, as I mentioned before, is held to show that the universe is growing either continually larger or continually smaller. The shift towards the red in the spectra of distant nebulae is held to show that they are moving away from us with a velocity proportional to their distance from us. This leads to the conclusion that the universe is expanding, not contracting. It must be understood that, according to this theory, the universe is finite but unbounded, like the surface of a sphere, but in three dimensions. All this involves non-Euclidean geometry, and is apt to seem mysterious to those whose imagination is obstinately Euclidean.

Two kinds of departure from Euclidean space are involved in the general theory of relativity. On the one hand, there are what may be called the small-scale departures (where the solar system, e.g., is regarded as "small"), and on the other hand the large-scale departure of the universe as a whole. The small-scale departures occur in the neighbourhood of matter, and account for gravitation. They may be compared to hills and valleys on the surface of the earth. The large-scale departure may be compared with the fact that the earth is round and not flat. If you start from any point on the earth's surface and travel as straight as you can, you will ultimately return to your starting-point. So, it is held, the straightest line possible in the universe will ultimately return into itself. The analogy with the surface of the earth fails in that the earth's surface is two-dimensional and has regions outside it, whereas the spherical space of the universe is three-dimensional and has nothing outside it. The present circumference of the universe is between 6,000 and 60,000 million light-years, but the size of the universe is doubled about every 1,300 million years. All this, however, must still be regarded as open to doubt.

According to Professor E. A. Milne,[1] there is a great deal more that is questionable in Einstein's theory. Professor Milne holds that there is no need to regard space as non-Euclidean, and that the geometry we adopt can be decided entirely by motives of convenience. The difference between different geometries, according to him, is a difference in language, not in what is described. Where physicists disagree it is rash for an outsider to have an opinion, but I incline to think that Professor Milne is very likely to be in the right.

Quantum theory, in contrast to the theory of relativity, is mainly concerned with the smallest things about which knowledge is possible, namely atoms and their structure. During the nineteenth century the atomic constitution of matter became well established, and it was found that the different elements could be placed in a series starting with hydrogen and ending with uranium. The place of an element in this series is called its "atomic number". Hydrogen has the atomic number 1, and uranium 92. There are two gaps in the series at present, so that the number of known elements is 90, not 92; but the gaps may be filled any day, as a number of previously existing gaps have been. In general, but not always, the atomic number increases with the atomic weight. Before Rutherford, there was no plausible theory as to the structure of atoms, or as to the physical properties which caused them to fall into a series. The series was determined by their chemical properties alone, and of these properties no physical explanation existed.

The Rutherford–Bohr atom, as it is called after its two inventors, had a beautiful simplicity, now, alas, lost. But although it has become only a pictorial approximation to the truth, it can still be used when extreme accuracy is not required, and without it the modern quantum theory could never have arisen. It is therefore still necessary to say something about it.

Rutherford gave experimental reasons for regarding an atom as composed of a nucleus carrying positive electricity surrounded by very much lighter bodies, called "electrons", which carried negative electricity, and revolved, like planets, in orbits about the nucleus. When the atom is not electrified, the number of planetary electrons is the atomic number of the element concerned; at all times, the atomic number measures the net positive electricity carried by the nucleus. The hydrogen atom consists of a nucleus and one planetary electron; the nucleus of the hydrogen atom is called a "proton". It was found that the nuclei of other elements could be regarded as composed of protons and electrons, the number of protons being greater than that of the electrons by the atomic number of the element. Thus helium, which is number 2, has a nucleus consisting of four protons and two electrons. The atomic weight is practically determined by the number of protons, since a proton has about 1,850 times the mass of an electron, so that the contribution of the electrons to the total mass is almost negligible.

It has been found that, in addition to electrons and protons, there are two other constituents of atoms, which are called "positrons" and "neutrons". A position is just like an electron, except that it carries positive instead of negative electricity; it has the same mass as an electron, and probably the same size, in so far as either can be said to have a size. The neutron has no electricity, but has approximately the same mass as a proton. It seems not unlikely that a proton consists of a positron and a neutron. If so, there are three ultimate kinds of constituents in the perfected Rutherford–Bohr atom: the neutron, which has mass but no electricity, the positron, carrying positive electricity, and the electron, carrying an equal amount of negative electricity.

But we must now return to theories which ante-date the discovery of neutrons and positrons.

Bohr added to the Rutherford picture a theory as to the possible orbits of electrons, which, for the first time, explained the lines in the spectrum of an element. This mathematical explanation was almost, but not quite, perfect in the cases of hydrogen and positively electrified helium; in other cases the mathematics was too difficult, but no reason appeared to suppose that the theory would give wrong results if the mathematics could be worked out. His theory made use of Planck's quantum constant h, concerning which a few words must be said.

Planck, by studying radiation, proved that in a light or heat wave of frequency v the energy must be $h.v$ or $2h.v$ or $3h.v$ or some other integral multiple of $h.v$, where h is "Planck's constant", of which the value in C.G.S. units is about 6.55×10^{-27}, and the dimensions are those of action, i.e. energy $\times$ time. Before Planck, it had been supposed that the energy of a wave could vary continuously, but he showed conclusively that this could not be the case. The frequency of waves is the number that pass a given point in a second. In the case of light, the frequency determines the colour; violet light has the highest frequency, red light the lowest. There are other waves of just the same kind as light-waves, but not having the frequencies that cause visual sensations of colour. Higher frequencies than those of violet light are, in order, ultra-violet, X-rays and γ-rays; lower frequencies, infra-red and those used in wireless telegraphy.

When an atom emits light, it does so because it has parted with an amount of energy equal to that in the light-wave. If it emits light of frequency v, it must, according to Planck's theory, have parted with an amount of energy measured by $h.v$ or some integral multiple of $h.v$. Bohr supposed that this happened through a planetary electron jumping from a larger to a smaller orbit; consequently the change of orbit must be such as to involve a loss of energy $h.v$ or some integral multiple of this amount. It followed that only certain orbits could be possible. In the hydrogen atom, there would be a smallest possible orbit, and the other possible ones would have 4, 9, 16, . . . times the radius of the minimum orbit. This theory, first propounded in 1913, was found to agree well with observation, and for a time won general acceptance. Gradually, however, it was found that there were facts which it could not explain, so that, though clearly a step on the way to the truth, it could no longer be accepted as it stood. The new and more radical quantum theory, which dates from 1925, is due in the main to two men, Heisenberg and Schrödinger.

In the modern theory there is no longer any attempt to make an imaginative picture of the atom. An atom only gives evidence of its existence when it emits energy, and therefore experimental evidence can only be of changes of energy. The new theory takes over from Bohr the doctrine that the energy in an atom must have one of a discrete series of values involving h; each of these is called an "energy level". But as to what gives the atom its energy the theory is prudently silent.

One of the oddest things about the theory is that it has abolished the distinction between waves and particles. Newton thought that light consisted of particles emitted by the source of the light; Huygens thought that it consisted of waves. The view of Huygens prevailed, and until recently was thought to be definitely established. But new experimental facts seemed to demand that light should consist of particles, which were called "photons". Per contra, De Broglie suggested that matter consists of waves. In the end it was shown that everything in physics can be explained either on the particle hypothesis or on the wave hypothesis. There is therefore no physical difference between them, and either may be adopted in any problem as may suit our convenience. But whichever is adopted, it must be adhered to; we must not mix the two hypotheses in one calculation.

In quantum theory, individual atomic occurrences are not determined by the equations; these suffice only to show that the possibilities form a discrete series, and that there are rules determining how often each possibility will be realized in a large number of cases. There are reasons for believing that this absence of complete determinism is not due to any incompleteness in the theory, but is a genuine characteristic of small-scale occurrences. The regularity which is found in macroscopic phenomena is a statistical regularity. Phenomena involving large numbers of atoms remain deterministic, but what an individual atom may do in given circumstances is uncertain, not only because our knowledge is limited, but because there are no physical laws giving a determinate result.

There is another result of quantum theory, about which, in my opinion, too much fuss has been made, namely what is called Heisenberg's uncertainty-principle. According to this there is a theoretical limit to the accuracy with which certain connected quantities can be simultaneously measured. In specifying the state of a physical system, there are certain pairs of connected quantities; one such pair is position and momentum (or velocity, so long as the mass is constant), another is energy and time. It is of course a commonplace that no physical quantity can be measured with complete accuracy, but it had always been supposed that there was no theoretical limit to the increase of accuracy obtainable by improved technique. According to Heisenberg's principle this is not the case. If we try to measure simultaneously two connected quantities of the above sort, any increase of accuracy in the measurement of one of them (beyond a certain point) involves a decrease in the accuracy of the measurement of the other. In fact, there will be errors in both measurements, and the product of these two errors can never be less than $h/2\pi$. This means that, if one could be completely accurate, the error in the other would have to be infinite. Suppose, for instance, that you wish to determine the position and velocity of a particle at a certain time: if you get the position very nearly right, there will be a large error in the velocity, and if you get the velocity very nearly right, there will be a large error as to the position. Similarly as regards energy and time: if you measure the energy very accurately, the time when the system has this energy will have a large margin of uncertainty, while if you fix the time very accurately the energy will become uncertain within wide limits. This is not a question of imperfection in our measuring apparatus, but is an essential principle of physics.

There are physical considerations which make this principle less surprising. It will be observed that h is a very small quantity, since it is of the order of 10^{-27}. Therefore wherever h is relevant we are concerned with matters involving very great minuteness. When an astronomer observes the sun, the sun preserves a lordly indifference to his proceedings. But when a physicist tries to find out what is happening to an atom, the apparatus by means of which he makes his observations is likely to have an effect upon the atom. Detailed considerations show that the sort of apparatus best suited for determining the position of an atom is likely to affect its velocity, while the sort of apparatus best suited for determining its velocity is likely to alter its position. Similar arguments apply to other pairs of related quantities. I do not think, therefore, that the uncertainty principle has the kind of philosophical importance that is sometimes attributed to it.

Quantum equations differ from those of classical physics in a very important respect, namely that they are not "linear". This means that when you have discovered the effect of one cause alone, and then the effect of another cause alone, you cannot find the effect of both together by adding the two previous effects. This has very odd results. Suppose, for instance, that you have a screen with a small slit, and you bombard it with particles; some of these will get through the slit. Suppose now you close the first slit and make a second; then some will get through the second slit. Now open both slits at once. You would think that the number getting through both slits would be the sum of the previous numbers, but this turns out not to be the case. The behaviour of the particles at one slit seems to be affected by the existence of the other slit. The equations are such as to predict this result, but it remains surprising.

In quantum mechanics there is less independence of causes than in classical physics, and this adds greatly to the difficulty of the calculations.

Both relativity and quantum theory have had the effect of replacing the old conception of "mass" by that of "energy". "Mass" used to be defined as "quantity of matter"; "matter" was, on the one hand "substance" in the metaphysical sense, and on the other hand the technical form of the common-sense notion of "thing". "Energy" was, in its early stages, a state of "matter". It consisted of two parts, kinetic and potential. The kinetic energy of a particle is half the product of the mass and the square of the velocity. The potential energy is measured by the work that would have to be done to bring the particle to its present position from some standard position. (This leaves a constant undetermined, but that is of no consequence.) If you carry a stone from the ground to the top of a tower, it acquires potential energy in the process; if you drop it from the top, the potential energy is gradually transformed into kinetic energy during the fall. In any self-contained system, the total energy is constant. There are various forms of energy, of which heat is one; there is a tendency for more and more of the energy in the universe to take the form of heat. The conservation of energy first became a well-grounded scientific generalization when Joule measured the mechanical equivalent of heat.

Relativity theory and experiment both showed that mass is not constant, as had been held, but is increased by rapid motion; if a particle could move as fast as light, its mass would become infinite. Since all motion is relative, the different estimates of mass formed by different observers, according to their motion relative to the particle in question, are all equally legitimate. So far as this theory is concerned, however, there is still one estimate of mass which may be considered fundamental, namely the estimate made by an observer who is at rest relatively to the body whose mass is to be measured. Since the increase of mass with velocity is only appreciable for velocities comparable with that of light, this case covers practically all observations except those of α and β particles ejected from radio-active bodies.

Quantum theory has made a greater inroad upon the concept of "mass". It now appears that whenever energy is lost by radiation there is a corresponding loss of mass. The sun is held to be losing mass at the rate of four million tons a second. To take another instance: a helium atom, unelectrified, consists (in the language of Bohr's theory) of four protons and four electrons, while a hydrogen atom consists of one proton and one electron. It might have been supposed that, assuming this to be the case, the mass of a helium atom would be four times that of a hydrogen atom. This, however, is not the case: taking the mass of the helium atom as 4, that of the hydrogen atom is not 1, but 1.008. The reason is that energy is lost (by radiation) when four hydrogen atoms combine to form one helium atom—at least so we must suppose, for the process is not one which has ever been observed.

It is thought that the combination of four hydrogen atoms to form one atom of helium occurs in the interior of stars, and could be made to occur in terrestrial laboratories if we could produce temperatures comparable to those in the interior of stars. Almost all the loss of energy involved in building up elements other than hydrogen occurs in the transition to helium; in later stages the loss of energy is small. If helium, or any element other than hydrogen, could be artificially manufactured out of hydrogen, there would be in the process an enormous liberation of energy in the form of light and heat. This suggests the possibility of atomic bombs more destructive than the present ones, which are made by means of uranium. There would be a further advantage: the supply of uranium in the planet is very limited, and it is feared that it may be used up before the human race is exterminated, but if the practically unlimited supply of hydrogen in the sea could be utilized there would be considerable reason to hope that *homo sapiens* might put an end to himself, to the great advantage of the other less ferocious animals.

But it is time to return to less cheerful topics.

The language of Bohr's theory is still adequate for many purposes, but not for stating the fundamental principles of quantum physics. To state these principles, we must avoid all pictures of what goes on in an atom, and must abandon attempts to say what energy is. We must say simply: there is something quantitative, to which we give the name "energy"; this something is very unevenly distributed in space; there are small regions in which there is a great deal of it, which are called "atoms", and are those in which, according to older conceptions, there was matter; these regions are perpetually absorbing or emitting energy in forms that have a periodic "frequency". Quantum equations give rules determining the possible forms of energy emitted by a given atom, and the proportion of cases (out of a large number) in which each of the possibilities will be realized. Everything here is abstract and mathematical except the sensations of colour, heat, etc., produced by the radiant energy in the observing physicist.

Mathematical physics contains such an immense superstructure of theory that its basis in observation tends to be obscured. It is, however, an empirical study, and its empirical character appears most unequivocally where the physical constants are concerned. Eddington (*New Pathways in Science*, p. 230) gives the following list of the primitive constants of physics:

e, The charge of an electron,
m, The mass of an electron,
M, The mass of a proton,
h, Planck's constant,

c, The velocity of light,
G, The constant of gravitation,
λ, The cosmical constant.

These constants appear in the fundamental equations of physics, and it is usually (though not always) held that no one of them can be inferred from the others. Other constants, it is held, are theoretically deducible from these; sometimes the calculation can be actually made, sometimes it is as yet too difficult for the mathematicians. They represent the residuum of brute fact after as much as possible has been reduced to equations. (I am not including brute facts which are merely geographical.)

It should be observed that we are much more certain of the importance of these constants than we are of this or that interpretation of them. Planck's constant, in its brief history since 1900, has been represented verbally in various ways, but its numerical value has not been affected by such changes. Whatever may happen to quantum theory in the future, it is virtually certain that the constant h will remain important. Similarly as regards e and m, the charge and mass of an electron. Electrons may disappear completely from the fundamental principles of physics, but e and m are pretty certain to survive. In a sense it may be said that the discovery and measurement of these constants is what is most solid in modern physics.

NOTE

1 *Relativity, Gravitation and World Structure*. By E. A. Milne. Oxford, 1935.