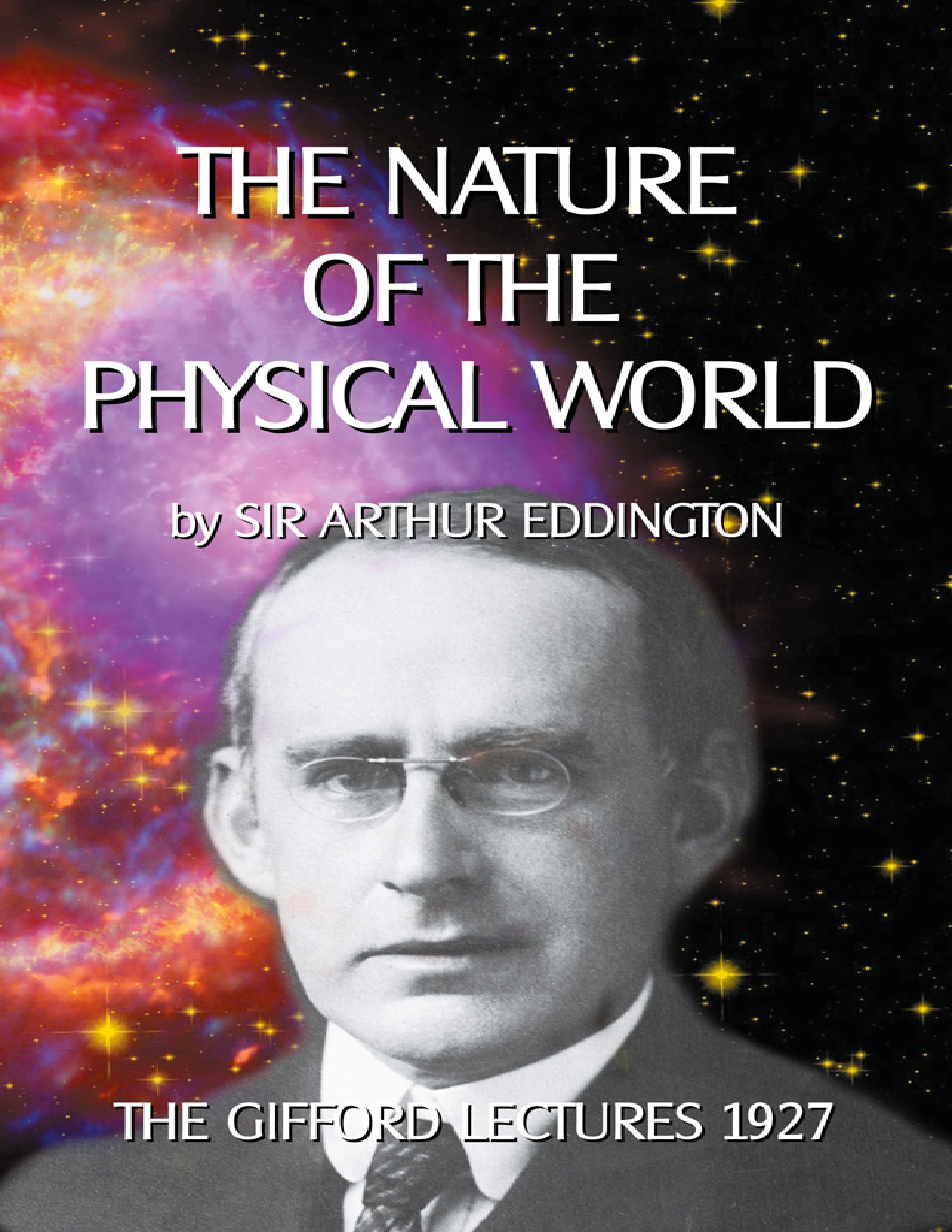

THE NATURE OF THE PHYSICAL WORLD

by SIR ARTHUR EDDINGTON

THE GIFFORD LECTURES 1927

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PREFACE

This book is substantially the course of Gifford Lectures which I delivered in the University of Edinburgh in January to March 1927. It treats of the philosophical outcome of the great changes of scientific thought which have recently come about. The theory of relativity and the quantum theory have led to strange new conceptions of the physical world; the progress of the principles of thermodynamics has wrought more gradual but no less profound change. The first eleven chapters are for the most part occupied with the new physical theories, with the reasons which have led to their adoption, and especially with the conceptions which seem to underlie them. The aim is to make clear the scientific view of the world as it stands at the present day, and, where it is incomplete, to judge the direction in which modern ideas appear to be tending. In the last four chapters I consider the position which this scientific view should occupy in relation to the wider aspects of human experience, including religion. The general spirit of the inquiry followed in the lectures is stated in the concluding paragraph of the Introduction (p. 7).

I hope that the scientific chapters may be read with interest apart from the later applications in the book; but they are not written quite on the lines that would have been adopted had they been wholly independent. It would not serve my purpose to give an easy introduction to the rudiments of the relativity and quantum theories; it was essential to reach the later and more recondite developments in which the conceptions of greatest philosophical significance are to be found. Whilst much of the book should prove fairly easy reading, arguments of considerable difficulty have to be taken in their turn.

My principal aim has been to show that these scientific developments provide new material for the philosopher. I have, however, gone beyond this and indicated how I myself think the material might be used. I realise that the philosophical views here put forward can only claim attention in so far as they are the direct outcome of a study and apprehension of modern scientific work. General ideas of the nature of things which I may have formed apart from this particular stimulus from science are of little moment to anyone but myself. But although the two sources of ideas were fairly distinct in my mind when I began to prepare these lectures they have become inextricably combined in the effort to reach a coherent outlook and to defend it from probable criticism. For that reason I would like to recall that the idealistic tinge in my conception of the physical world arose out of mathematical researches on the relativity theory. In so far as I had any earlier philosophic - al views, they were of an entirely different complexion.

From the beginning I have been doubtful whether it was desirable for a scientist to venture so far into extra-scientific territory. The primary justification for such an expedition is that it may afford a better view of his own scientific domain. In the oral lectures it did not seem a grave indiscretion to speak freely of the various suggestions I had to offer. But whether they should be recorded permanently and given a more finished appearance has been difficult to decide. I have much to fear from the expert philosophical critic, but I am filled with even more apprehension at the thought of readers who may look to see whether the book is "on the side of the angels" and judge its trustworthiness accordingly. During the year which has elapsed since the delivery of the lectures I have made many efforts to shape this and other parts of the book into something with which I might feel better content. I release it now with more diffidence than I have felt with regard to former books.

The conversational style of the lecture-room is generally considered rather unsuitable for a long book, but I decided not to modify it. A scientific writer, in forgoing the mathematical formulae which are his natural and clearest medium of expression, may perhaps claim some concession from the reader in return. Many parts of the subject are intrinsically so difficult that my only hope of being understood is to explain the points as I would were I face to face with an inquirer.

It may be necessary to remind the American reader that our nomenclature for large numbers differs from his, so that a billion here means a million million.

A. S. E.

August 1928

INTRODUCTION

I have settled down to the task of writing these lectures and have drawn up my chairs to my two tables. Two tables! Yes; there are duplicates of every object about me—two tables, two chairs, two pens.

This is not a very profound beginning to a course which ought to reach transcendent levels of scientific philosophy. But we cannot touch bedrock immediately; we must scratch a bit at the surface of things first. And whenever I begin to scratch the first thing I strike is— my two tables.

One of them has been familiar to me from earliest years. It is a commonplace object of that environment which I call the world. How shall I describe it? It has extension; it is comparatively permanent; it is coloured; above all it is *substantial.* By substantial I do not merely mean that it does not collapse when I lean upon it; I mean that it is constituted of "substance" and by that word I am trying to convey to you some conception of its intrinsic nature. It is a *thing;* not like space, which is a mere negation; nor like time, which is —Heaven knows what! But that will not help you to my meaning because it is the distinctive characteristic of a "thing" to have this substantiality, and I do not think substantiality can be described better than by saying that it is the kind of nature exemplified by an ordinary table. And so we go round in circles.^ After all if you are a plain commonsense man, not too much worried with scientific scruples, you will be confident that you understand the nature of an ordinary table. I have even heard of plain men who had the idea that they could better understand the mystery of their own nature if scientists would discover a way of explaining it in terms of the easily comprehensible nature of a table.

Table No. 2 is my scientific table. It is a more recent acquaintance and I do not feel so familiar with it. It does not belong to the world previously mentioned— that world which spontaneously appears around me when I open my eyes, though how much of it is objective and how much subjective I do not here consider. It is part of a world which in more devious ways has forced itself on my attention. My scientific table is mostly emptiness. Sparsely scattered in that emptiness are[1] numerous electric charges rushing about with great speed; but their combined bulk amounts to less than a billionth of the bulk of the table itself. Notwithstanding its strange construction it turns out to be an entirely efficient table. It supports my writing paper as satisfactorily as table No. 1; for when I lay the paper on it the little electric particles with their headlong speed keep on hitting the underside, so that the paper is maintained in shuttlecock fashion at a nearly steady level. If I lean upon this table I shall not go through; or, to be strictly accurate, the chance of my scientific elbow going through my scientific table is so excessively small that it can be neglected in practical life. Reviewing their properties one by one, there seems to be nothing to choose between the two tables for ordinary purposes; but when abnormal circumstances befall, then my scientific table shows to advantage. If the house catches fire my scientific table will dissolve quite naturally into scientific smoke, whereas my familiar table undergoes a metamorphosis of its substantial nature which I can only regard as miraculous.

There is nothing *substantial* about my second table. It is nearly all empty space—space pervaded, it is true, by fields of force, but these are assigned to the category of "influences", not of "things". Even in the minute part which is not empty we must not transfer the old notion of substance. In dissecting matter into electric charges we have travelled far from that picture of it which first gave rise to the conception of substance, and the meaning of that conception—if it ever had any— has been lost by the way. The whole trend of modern scientific views is to break down the separate categories of "things", "influences", "forms", etc., and to substitute a common background of all experience. Whether we are studying a material object, a magnetic field, a geometrical figure, or a duration of time, our scientific information is summed up in measures; neither the apparatus of measurement nor the mode of using it suggests that there is anything essentially different in these problems. The measures themselves afford no ground for a classification by categories. We feel it necessary to concede some background to the measures—an external world; but the attributes of this world, except in so far as they are reflected in the measures, are outside scientific scrutiny. Science has at last revolted against attaching the exact knowledge contained in these measurements to a traditional picture-gallery of conceptions which convey no authentic information of the background and obtrude irrelevancies into the scheme of knowledge.

I will not here stress .further the non-substantiality of electrons, since it is scarcely necessary to the present line of thought. Conceive them as substantially as you will, there is a vast difference between my scientific table with its substance (if any) thinly scattered in specks in a region mostly empty and the table of everyday conception which we regard as the type of solid reality—an incarnate protest against Berkleian subjectivism. It makes all the difference in the world whether the paper before me is poised as it were on a swarm of flies and sustained in shuttlecock fashion by a series of tiny blows from the swarm underneath, or whether it is supported because there is substance below it, it being the intrinsic nature of substance to occupy space to the exclusion of other substance; all the difference in conception at least, but no difference to my practical task of writing on the paper.

I need not tell you that modern physics has by delicate test and remorseless logic assured me that my second scientific table is the only one which is really there—wherever "there" may be. On the other hand I need not tell you that modern physics will never succeed in exorcising that first table— strange compound of external nature, mental imagery and inherited prejudice—which lies visible to my eyes and tangible to my grasp. We must bid good-bye to it for the present for we are about to turn from the familiar world to the scientific world revealed by physics. This is, or is intended to be, a wholly external world.

"You speak paradoxically of two worlds. Are they not really two aspects or two interpretations of one and the same world?"

Yes, no doubt they are ultimately to be identified after some fashion. But the process by which the external world of physics is transformed into a world of familiar acquaintance in human consciousness is outside the scope of physics. And so the world "studied according to the methods of physics remains detached from the world familiar to consciousness, until after the physicist has finished his labours upon it. Provisionally, therefore, we regard the table which is the subject of physical research as altogether separate from the familiar table, without prejudging the question of their ultimate identification. It is true that the whole scientific inquiry starts from the familiar world and in the end it must return to the familiar world; but the part of the journey over which the physicist has charge is in foreign territory.

Until recently there was a much closer linkage; the physicist used to borrow the raw material of his world from the familiar world, but he does so no longer. His raw materials are aether, electrons, quanta, potentials, Hamiltonian functions, etc., and he is nowadays scrupulously careful to guard these from contamination by conceptions borrowed from the other world. There is a familiar table parallel to the scientific table, but there is no familiar electron, quantum or potential parallel to the scientific electron, quantum or potential. We do not even desire to manufacture a familiar counterpart to these things or, as we should commonly say, to "explain" the electron. After the physicist has quite finished his world-building a linkage or identification is allowed; but premature attempts at linkage have been found to be entirely mischievous.

Science aims at constructing a world which shall be symbolic of the world of commonplace experience. It is not at all necessary that every individual symbol that is used should represent something in common experience or even something explicable in terms of common experience. The man in the street is always making this demand for concrete explanation of the things referred to in science; but of necessity he must be disappointed. It is like our experience in learning to read. That which is written in a book is symbolic of a story in real life. The whole intention of the book is that ultimately a reader will identify some symbol, say BREAD, with one of the conceptions of familiar life. But it is mischievous to attempt such identifications prematurely, before the letters are strung into words and the words into sentences. The symbol *A* is not the counterpart of anything in familiar life. To the child the letter *A* would seem horribly abstract; so we give him a familiar conception along with it. "*A* was an Archer who shot at a frog." This tides over his immediate difficulty; but he cannot make serious progress with word-building so long as Archers, Butchers, Captains, dance round the letters. The letters are abstract, and sooner or later he has to realise it. In physics we have outgrown archer and apple-pie definitions of the fundamental symbols. To a request to explain what an electron really is supposed to be we can only answer, "It is part of the A BC of physics".

The external world of physics has thus become a world of shadows. In removing our illusions we have removed the substance, for indeed we have seen that substance is one of the greatest of our illusions. Later perhaps we may inquire whether in our zeal to cut out all that is unreal we may not have used the knife too ruthlessly. Perhaps, indeed, reality is a child which cannot survive without its nurse illusion. But if so, that is of little concern to the scientist, who has good and sufficient reasons for pursuing his investigations in the world of shadows and is content to leave to the philosopher the determination of its exact status in regard to reality. In the world of physics we watch a shadowgraph performance of the drama of familiar life. The shadow of my elbow rests on the shadow table as the shadow ink flows over the shadow paper. It is all symbolic, and as a symbol the physicist leaves it. Then comes the alchemist Mind who transmutes the symbols. The sparsely spread nuclei of electric force become a tangible solid; their restless agitation becomes the warmth of summer; the octave of aethereal vibrations becomes a gorgeous rainbow. Nor does the alchemy stop here. In the transmuted world new significances arise which are scarcely to be traced in the world of symbols; so that it becomes a world of beauty and purpose— and, alas, suffering and evil.

The frank realisation that physical science is concerned with a world of shadows is one of the most significant of recent advances. I do not mean that physicists are to any extent preoccupied with the philosophical implications of this. From their point of view it is not so much a withdrawal of untenable claims as an assertion of freedom for autonomous development. At the moment I am not insisting on the shadowy and symbolic character of the world of physics because of its bearing on philosophy, but because the aloofness from familiar conceptions will be apparent in the scientific theories I have to describe. If you are not prepared for this aloofness you are likely to be out of sympathy with modern scientific theories, and may even think them ridiculous—as, I daresay, many people do.

It is difficult to school ourselves to treat the physical world as purely symbolic. We are always relapsing and mixing with the symbols incongruous conceptions taken from the world of consciousness. Untaught by long experience we stretch a hand to grasp the shadow, instead of accepting its shadowy nature. Indeed, unless we confine ourselves altogether to mathematical symbolism it is hard to avoid dressing our symbols in deceitful clothing. When I think of an electron there rises to my mind a hard, red, tiny ball; the proton similarly is neutral grey. Of course the colour is absurd—perhaps not more absurd than the rest of the conception—but I am incorrigible. I can well understand that the younger minds are finding these pictures too concrete and are striving to construct the world out of Hamiltonian functions and symbols so far removed from human preconception that they do not even obey the laws of orthodox arithmetic. For myself I find some difficulty in rising to that plane of thought; but I am convinced that it has got to come.

In these lectures I propose to discuss some of the results of modern study of the physical world which give most food for philosophic thought. This will include new conceptions in science and also new knowledge. In both respects we are led to think of the material universe in a way very different from that prevailing at the end of the last century. I shall not leave out of sight the ulterior object which must be in the mind of a Gifford Lecturer, the problem of relating these purely physical discoveries to the wider aspects and interests of our human nature. These relations cannot but have undergone change, since our whole conception of the physical world has radically changed. I am convinced that a just appreciation of the physical world as it is understood to-day carries with it a feeling of open-mindedness towards a wider significance transcending scientific measurement, which might have seemed illogical a generation ago; and in the later lectures I shall try to focus that feeling and make inexpert efforts to find where it leads. But I should be untrue to science if I did not insist that its study is an end in itself. The path of science must be pursued for its own sake, irrespective of the views it may afford of a wider landscape; in this spirit we must follow the path whether it leads to the hill of vision or the tunnel of obscurity. Therefore till the last stage of the course is reached you must be content to follow with me the beaten track of science, nor scold me too severely for loitering among its wayside flowers. That is to be the understanding between us. Shall we set forth?

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Chapter I

THE DOWNFALL OF CLASSICAL PHYSICS

The Structure of the Atom.

Between 1905 and 1908 Einstein and Minkowski introduced fundamental changes in our ideas of time and space. In 1911 Rutherford introduced the greatest change in our idea of matter since the time of Democritus. The reception of these two changes was curiously different. The new ideas of space and time were regarded on all sides as revolutionary; they were received with the greatest enthusiasm by some and the keenest opposition by others. The new idea of matter underwent the ordinary experience of scientific discovery; it gradually proved its worth, and when the evidence became overwhelmingly convincing it quietly supplanted previous theories. No great shock was felt. And yet when I hear to-day protests against the Bolshevism of modern science and regrets for the old-established order, I am inclined to think that Rutherford, not Einstein, is the real villain of the piece. When we compare the universe as it is now supposed to be with the universe as we had ordinarily preconceived it, the most arresting change is not the rearrangement of space and time by Einstein but the dissolution of all that we regard as most solid into tiny specks floating in void. That gives an abrupt jar to those who think that things are more or less what they seem. The revelation by modern physics of the void within the atom is more disturbing than the revelation by astronomy of the immense void of interstellar space.

The atom is as porous as the solar system. If we eliminated all the unfilled space in a man's body and collected his protons and electrons into one mass, the man would be reduced to a speck just visible with a magnifying glass.

This porosity of matter was not foreshadowed in the atomic theory. Certainly it was known that in a gas like air the atoms are far separated, leaving a great deal of empty space; but it was only to be expected that material with the characteristics of air should have relatively little substance in it, and "airy nothing" is a common phrase for the insubstantial. In solids the atoms are packed tightly in contact, so that the old atomic theory agreed with our preconceptions in regarding solid bodies as mainly substantial without much interstice.

The electrical theory of matter which arose towards the end of the nineteenth century did not at first alter this view. It was known that the negative electricity was concentrated into unit charges of very small bulk; but the other constituent of matter, the positive electricity, was pictured as a sphere of jelly of the same dimensions as the atom and having the tiny negative charges embedded in it. Thus the space inside a solid was still for the most part well filled.

But in 1911 Rutherford showed that the positive electricity was also concentrated into tiny specks. His scattering experiments proved that the atom was able to exert large electrical forces which would be impossible unless the positive charge acted as a highly concentrated source of attraction; it must be contained in a nucleus minute in comparison with the dimensions of the atom. Thus for the first time the main volume of the atom was entirely evacuated, and a "solar system" type of atom was substituted for a substantial "billiard-ball". Two years later Niels Bohr developed his famous theory on the basis of the Rutherford atom, and since then rapid progress has been made. Whatever further changes of view are in prospect, a reversion to the old substantial atoms is unthinkable.

The accepted conclusion at the present day is that all varieties of matter are ultimately composed of two elementary constituents—protons and electrons. Electrically these are the exact opposites of one another, the proton being a charge of positive electricity and the electron a charge of negative electricity. But in other respects their properties are very different. The proton has 1840 times the mass of the electron, so that nearly all the mass of matter is due to its constituent protons. The proton is not found unadulterated except in hydrogen, which seems to be the most primitive form of matter, its atom consisting of one proton and one electron. In other atoms a number of protons and a lesser number of electrons are cemented together to form a nucleus; the electrons required to make up the balance are scattered like remote satellites of the nucleus, and can even escape from the atom and wander freely through the material. The diameter of an electron is about 1/50,000 of the diameter of an atom; that of the nucleus is not very much larger; an isolated proton is supposed to be much smaller still.

Thirty years ago there was much debate over the question of aether-drag —whether the earth moving round the sun drags the aether with it. At that time the solidity of the atom was unquestioned, and it was difficult to believe that matter could push its way through the aether without disturbing it. It was surprising and perplexing to find as the result of experiments that no convection of the aether occurred. But we now realise that the aether can slip through the atoms as easily as through the solar system, and our expectation is all the other way.

We shall return to the "solar system" atom in later chapters. For the present the two things which concern us are (1) its extreme emptiness, and (2) the fact that it is made up of electrical charges.

Rutherford's nuclear theory of the atom is not usually counted as one of the scientific revolutions of the present century. It was a far-reaching discovery, but a discovery falling within the classical scheme of physics. The nature and significance of the discovery could be stated in plain terms, i.e. in terms of conceptions already current in science. The epithet "revolutionary'' is usually reserved for two great modern developments—the Relativity Theory and the Quantum Theory. These are not merely new discoveries as to the content of the world; they involve changes in our mode of thought about the world. They cannot be stated immediately in plain terms because we have first to grasp new conceptions undreamed of in the classical scheme of physics.

I am not sure that the phrase "classical physics" has ever been closely defined. But the general idea is that the scheme of natural law developed by Newton in the *Principia* provided a pattern which all subsequent developments might be expected to follow. Within the four corners of the scheme great changes of outlook were possible; the wave-theory of light supplanted the corpuscular theory; heat was changed from substance (caloric) to energy of motion; electricity from continuous fluid to nuclei of strain in the aether. But this was all allowed for in the elasticity of the original scheme. Waves, kinetic energy, and strain already had their place in the scheme; and the application of the same conceptions to account for a wider range of phenomena was a tribute to the comprehensiveness of Newton's original outlook.

We have now to see how the classical scheme broke down.

The FitzGerald Contraction.

We can best start from the following fact. Suppose that you have a rod moving at very high speed. Let it first be pointing transverse to its line of motion. Now turn it through a right angle so that it is along the line of motion. The rod contracts. It is shorter when it is along the line of motion than when it is across the line of motion.

This contraction, known as the FitzGerald contraction, is exceedingly small in all ordinary circumstances. It does not depend at all on the material of the rod but only on the speed. For example, if the speed is 19 miles a second—the speed of the earth round the sun—the contraction of length is 1 part in 200,000,000, or 21/^{2} inches in the diameter of the earth.

This is demonstrated by a number of experiments of different kinds of which the earliest and best known is the Michelson-Morley experiment first performed in 1887, repeated more accurately by Morley and Miller in 1905, and again by several observers within the last year or two. I am not going to describe these experiments except to mention that the convenient way of giving your rod a large velocity is to carry it on the earth which moves at high speed round the sun. Nor shall I discuss here how complete is the proof afforded by these experiments. It is much more important that you should realise that the contraction is just what would be expected from our current knowledge of a material rod.

You are surprised that the dimensions of a moving, rod can be altered merely by pointing it different ways. You expect them to remain unchanged. But which rod are you thinking of? (You remember my two tables.) If you are thinking of continuous substance, extending in space because it is the nature of substance to occupy space, then there seems to be no valid cause for a change of dimensions. But the scientific rod is a swarm of electrical particles rushing about and widely separated from one another. The marvel is that such a swarm should tend to preserve any definite extension. The particles, however, keep a certain average spacing so that the whole volume remains practically steady; they exert electrical forces on one another, and the volume which they fill corresponds to a balance between the forces drawing them together and the diverse motions tending to spread them apart. When the rod is set in motion these electrical forces change. Electricity in motion constitutes an electric current. But electric currents give rise to forces of a different type from those due to electricity at rest, viz. magnetic forces. Moreover these forces arising from the motion of electric charges will naturally be of different intensity in the directions along and across the line of motion.

By setting in motion the rod with all the little electric charges contained in it we introduce new magnetic forces between the particles. Clearly the original balance is upset, and the average spacing between the particles must alter until a new balance is found. And so the extension of the swarm of particles—the length of the rod—alters.

There is really nothing mysterious about the Fitz-Gerald contraction. It would be an unnatural property of a rod pictured in the old way as continuous substance occupying space in virtue of its substantiality; but it is an entirely natural property of a swarm of particles held in delicate balance by electromagnetic forces, and occupying space by buffeting away anything that tries to enter. Or you may look at it this way: your expectation that the rod will keep its original length presupposes, of course, that it receives fair treatment and is not subjected to any new stresses. But a rod in motion is subjected to a new magnetic stress, arising not from unfair outside tampering but as a necessary consequence of its own electrical constitution; and under this stress the contraction occurs. Perhaps you will think that if the rod were rigid enough it might be able to resist the compressing force. That is not so; the FitzGerald contraction is the same for a rod of steel and for a rod of India-rubber; the rigidity and the compressing stress are bound up with the constitution in such a way that if one is large so also is the other. It is necessary to rid our minds of the idea that this failure to keep a constant length is an imperfection of the rod; it is only imperfect as compared with an imaginary "something" which has not this electrical constitution—and therefore is not material at all. The FitzGerald contraction is not an imperfection but a fixed and characteristic property of matter, like inertia.

We have here drawn a qualitative inference from the electrical structure of matter; we must leave it to the mathematician to calculate the quantitative effect. The problem was worked out by Lorentz and Larmor about 1900. They calculated the change in the average spacing of the particles required to restore the balance after it had been upset by the new forces due to the change of motion of the charges. This calculation was found to give precisely the FitzGerald contraction, i.e. the amount already inferred from the experiments above mentioned.

Thus we have two legs to stand on. Some will prefer to trust the results because they seem to be well established by experiment; others will be more easily persuaded by the knowledge that the FitzGerald contraction is a necessary consequence of the scheme of electromagnetic laws universally accepted since the time of Maxwell. Both experiments and theories sometimes go wrong; so it is just as well to have both alternatives.

Consequences of the Contraction.

This result alone, although it may not quite lead you to the theory of relativity, ought to make you uneasy about classical physics. The physicist when he wishes to measure a length— and he cannot get far in any experiment without measuring a length—takes a scale and turns it in the direction needed. It never occurred to him that in spite of all precautions the scale would change length when he did this; but unless the earth happens to be at rest a change must occur. The constancy of a measuring scale is the rock on which the whole structure of physics has been reared; and that rock has crumbled away. You may think that this assumption cannot have betrayed the physicist very badly; the changes of length cannot be serious or they would have been noticed. Wait and see.

Let us look at some of the consequences of the FitzGerald contraction. First take what may seem to be a rather fantastic case. Imagine you are on a planet moving very fast indeed, say 161,000 miles a second. For this speed the contraction is one-half. Any solid contracts to half its original length when turned from across to along the line of motion. A railway journey between two towns which was 100 miles at noon is shortened to 50 miles at 6 p.m. when the planet has turned through a right angle. The inhabitants copy Alice in Wonderland; they pull out and shut up like a telescope.

I do not know of a planet moving at 161,000 miles a second, but I could point to a spiral nebula far away in space which is moving at 1000 miles a second. This may well contain a planet and (speaking unprofessionally) perhaps I shall not be taking too much licence if I place intelligent beings on it. At 1000 miles a second the contraction is not large enough to be appreciable in ordinary affairs; but it is quite large enough to be appreciable in measurements of scientific or even of engineering accuracy. One of the most fundamental procedures in physics is to measure lengths with a scale moved about in any way. Imagine the consternation of the physicists on this planet when they learn that they have made a mistake in supposing that their scale is a constant measure of length. What a business to go back over all the experiments ever performed, apply the corrections for orientation of the scale at the time, and then consider *de novo* the inferences and system of physical laws to be deduced from the amended data! How thankful our own physicists ought to be that they are not in this runaway nebula but on a decently slow moving planet like the earth!

But stay a moment. Is it so certain that we are on a slow-moving planet? I can imagine the astronomers in that nebula observing far away in space an insignificant star attended by an -insignificant planet called Earth. They observe too that it is moving with the huge velocity of 1000 miles a second; because naturally if we see them receding from us at 1000 miles a second they will see us receding from them at 1000 miles a second. "A thousand miles a second!" exclaim the nebular physicists, "How unfortunate for the poor physicists on the Earth! The FitzGerald contraction will be quite appreciable, and all their measures with scales will be seriously wrong. What a weird system of laws of Nature they will have deduced, if they have overlooked this correction!"

There is no means of deciding which is right—to which of us the observed relative velocity of 1000 miles a second *really* belongs. Astronomically the galaxy of which the earth is a member does not seem to be more important, more central, than the nebula. The presumption that it is we who are the more nearly at rest has no serious foundation; it is mere selfflattery.

"But", you will say, "surely if these appreciable changes of length occurred on the earth, we should detect them by our measurements." That brings me to the interesting point. We could not detect them by any measurement; they may occur and yet pass quite unnoticed. Let me try to show how this happens.

This room, we will say, is travelling at 161,000 miles a second vertically upwards. That is my statement, and it is up to you to prove it wrong. I turn my arm from horizontal to vertical and it contracts to half its original length. You don't believe me? Then bring a yard-measure and measure it. First, horizontally, the result is 30 inches; now vertically, the result is 30 half-inches. You must allow for the fact that an inch-division of the scale contracts to half an inch when the yard-measure is turned vertically.

"But we can see that your arm does not become shorter; can we not trust our own eyes?"

Certainly not, unless you remember that when you got up this morning your retina contracted to half its original width in the vertical direction; consequently it is now exaggerating vertical distances to twice the scale of horizontal distances.

"Very well", you reply, "I will not get up. I will lie in bed and watch you go through your performance in an inclined mirror. Then my retina will be all right, but I know I shall still see no contraction."

But a moving mirror does not give an undistorted image of what is happening. The angle of reflection of light is altered by motion of a mirror, just as the angle of reflection of a billiard-ball would be altered if the cushion were moving. If you will work out by the ordinary laws of optics the effect of moving a mirror at 161,000 miles a second, you will find that it introduces a distortion which just conceals the contraction of my arm.

And so on for every proposed test. You cannot disprove my assertion, and, of course, I cannot prove it; I might equally well have chosen and defended any other velocity. At first this seems to contradict what I told you earlier—that the contraction had been proved and measured by the Michelson-Morley and other experiments—but there is really no contradiction. They were all *null* experiments, just as your experiment of watching my arm in an inclined mirror was a null experiment. Certain optical or electrical consequences of the earth's motion were looked for of the same type as the distortion of images by a moving mirror; these would have been observed unless a contraction occurred of just the right amount to compensate them. They were not observed; therefore the compensating contraction had occurred. There was just one alternative; the earth's true velocity through space might happen to have been nil. This was ruled out by repeating the experiment six months later, since the earth's motion could not be nil on both occasions. Thus the contraction was demonstrated and its law of dependence on velocity verified. But the actual amount of contraction on either occasion was unknown, since the earth's true velocity |(as distinct from its orbital velocity with respect to the sun) was unknown. It remains unknown because the optical and electrical effects by which we might hope to measure it are always compensated by the contraction. I have said that the constancy of a measuring scale is the rock on which the structure of physics has been reared. The structure has also been supported by supplementary props because optical and electrical devices can often be used instead of material scales to ascertain lengths and distances. But we find that all these are united in a conspiracy not to give one another away. The rock has crumbled and simultaneously all the other supports have collapsed.

Frames of Space.

We can now return to the quarrel between the nebular physicists and ourselves. One of us has a large velocity and his scientific measurements are seriously affected by the contraction of his scales. Each has hitherto taken it for granted that it is the other fellow who is making the mistake. We cannot settle the dispute by appeal to experiment because in every *experiment* the mistake introduces two errors which just compensate one another.

It is a curious sort of mistake which always carries with it its own compensation. But remember that the compensation only applies to phenomena actually observed or capable of observation. The compensation does not apply to the intermediate part of our deduction—that system of inference from observation which forms the classical physical theory of the universe.

Suppose that we and the nebular physicists survey the world, that is to say we allocate the surrounding objects to their respective positions in space. One party, say the nebular physicists, has a large velocity; their yard-measures will contract and become less than a yard when they measure distances in a certain direction; consequently they will reckon distances in that direction too great. It does not matter whether they use a yard-measure, or a theodolite, or merely judge distances with the eye; all methods of measurement must agree. If motion caused a disagreement of any kind, we should be able to determine the motion by observing the amount of disagreement; but, as we have already seen, both theory and observation indicate that there is complete compensation. If the nebular physicists try to construct a square they will construct an oblong. No test can ever reveal to them that it is not a square; the greatest advance they can make is to recognise that there are people in another world who have got it into their heads that it is an oblong, and they may be broadminded enough to admit that this point of view, absurd as it seems, is really as defensible as their own. It is clear that their whole conception of space is distorted as compared with ours, and ours is distorted as compared with theirs. We are regarding the same universe, but we have arranged it in different spaces. The original quarrel as to whether they or we are moving with the speed of 1000 miles a second has made so deep a cleavage between us that we cannot even use the same space.

Space and time are words conveying more than one meaning. Space is an empty void; or it is such and such a number of inches, acres, pints. Time is an ever-rolling stream; or it is something signalled to us by wireless. The physicist has no use for vague conceptions; he often has them, alas! but he cannot make real use of them. So when he speaks of space it is always the inches or pints that he should have in mind. It is from this point of view that our space and the space of the nebular physicists are different spaces; the reckoning of inches and pints is different. To avoid possible misunderstanding it is perhaps better to say that we have different *frames of space*— different frames to which we refer the location of objects. Do not, however, think of a frame of space as something consciously artificial; the frame of space comes into our minds with our first perception of space. Consider, for example, the more extreme case when the FitzGerald contraction is onehalf. If a man takes a rectangle 2" x 1" to be a square it is clear that space must have dawned on his intelligence in a way very different from that in which we have apprehended it.

The frame of space used by an observer depends only on his motion. Observers on different planets with the same velocity (i.e. having zero relative velocity) will agree as to the location of the objects of the universe; but observers on planets with different velocities have different frames of location. You may ask, How can I be so confident as to the way in which these imaginary beings will interpret their observations? If that objection is pressed I shall not defend myself; but those who dislike my imaginary beings must face the alternative of following the argument with mathematical symbols. Our purpose has been to express in a conveniently apprehensible form certain results which follow from terrestrial experiments and calculations as to the effect of motion on electrical, optical and metrical phenomena. So much careful work has been done on this subject that science is in a position to state what will be the consequence of making measurements with instruments travelling at high speed—whether instruments of a technical kind or, for example, a human retina. In only one respect do I treat my nebular observer as more than a piece of registering apparatus; I assume that he is subject to a common failing of human nature, viz. he takes it for granted that it was his planet that God chiefly had in mind when the universe was created. Hence he is (like my reader perhaps?) disinclined to take seriously the views of location of those people who are so misguided as to move at 1000 miles a second relatively to his parish pump.

An exceptionally modest observer might take some other planet than his own as the standard of rest. Then he would have to correct all his measurements for the FitzGerald contraction due to his own motion with respect to the standard, and the corrected measures would give the space-frame belonging to the standard planet as the original measures gave the space-frame of his own planet. For him the dilemma is even more pressing, for there is nothing to guide him as to the planet to be selected for the standard of rest. Once he gives up the naive assumption that his own frame is the one and only right frame the question arises, Which then of the innumerable other frames is right? There is no answer, and so far as we can see no possibility of an answer. Meanwhile all his experimental measurements are waiting unreduced, because the corrections to be applied to them depend on the answer. I am afraid our modest observer will get rather left behind by his less humble colleagues.

The trouble that arises is not that we have found anything necessarily wrong with the frame of location that has been employed in our system of physics; it has not led to experimental contradictions. The only thing known to be "wrong" with it is that it is not unique. If we had found that