The Theory Of Relativity

and its

Influence on Scientific Thought

Arthur Stanley Eddington

THE ROMANES LECTURE

1922

The Theory of Relativity and its Influence on Scientific Thought

BY

ARTHUR STANLEY EDDINGTON

M.A, F.R.S.

Plumian Professor of Astronomy, Cambridge

President of the Royal Astronomical Society

DELIVERED

IN THE SHELDONIAN THEATRE

24 MAY 1922

Has not a deeper meditation taught certain of every climate and age,

that the where and the when so mysteriously inseparable

from all our thoughts, are but superficial terrestrial adhesions to thought?

CARLYLE, *Sartor Resartus.*

The Theory Of Relativity

In the days before Copernicus the earth was, so it seemed, an immovable foundation on which the whole structure of the heavens was reared. Man, favourably situated at the hub of the universe, might well expect that to him the scheme of nature would unfold itself in its simplest aspect. But the behaviour of the heavenly bodies was not at all simple; and the planets literally looped the loop in fantastic curves called epicycles. The cosmogonist had to fill the skies with spheres revolving upon spheres to bear the planets in their appointed orbits; and wheels were added to wheels until the music of the spheres seemed wellnigh drowned in a discord of whirling machinery. Then came one of the great revolutions of scientific thought, which swept aside the Ptolemaic system of spheres and epicycles, and revealed the simple plan of the solar system which has endured to this day.

The revolution consisted in changing the view-point from which the phenomena were regarded. As presented to the earth the track of a planet is an elaborate epicycle; but Copernicus bade us transfer ourselves to the sun and look again. Instead of a path with loops and nodes, the orbit is now seen to be one of the most elementary curves—an ellipse. We have to realize that the little planet on which we stand is of no great account in the general scheme of nature; to unravel that scheme we must first disembarrass nature of the distortions arising from the local point of view from which we observe it. The sun, not the earth, is the real centre of the scheme of things—at least of those things in which astronomers at that time had interested themselves—and by transferring our view-point to the sun the simplicity of the planetary system becomes apparent. The need for a cumbrous machinery of spheres and wheels has disappeared.

Every one now admits that the Ptolemaic system, which regarded the earth as the centre of all things, belongs to the dark ages. But to our dismay we have discovered that the same geocentric outlook still permeates modern physics through and through, unsuspected until recently. It has been left to Einstein to carry forward the revolution begun by Copernicus—to free our conception of nature from the terrestrial bias imported into it by the limitations of our earthbound experience. To achieve a more neutral point of view we have to imagine a visit to some other heavenly body. That is a theme which has attracted the popular novelist, and we often smile at his mistakes when sooner or later he forgets where he is supposed to be and endows his voyagers with some purely terrestrial appanage impossible on the star they are visiting. But scientific men, who have not the novelist's licence, have made the same blunder. When, following Copernicus, they station themselves on the sun, they do not realize that they must leave behind a certain purely terrestrial appanage, namely, the frame of space and time in which men on this earth are accustomed to locate the events that happen. It is true that the observer on the sun will still locate his experiences in a frame of space and time, if he uses the same faculties of perception and the same methods of scientific measurements on the earth; but the solar frame of space and time is not precisely the same as the terrestrial frame, as we shall presently see.

I think you will readily understand what is meant by a frame of space and time. It is the system of location to which we appeal when we state, for example, that one event is 100 miles distant from and 10 hours later than another. The terms space and time have not only a vague descriptive reference to a boundless void and an ever-rolling stream, but denote an exact quantitative system of reckoning distances and time-intervals. Einstein's first great discovery was that there are many such systems of reckoning— many possible frames of space and time—exactly on all fours with one another. No one of these can be distinguished as more fundamental than the rest; no one frame rather than another can be identified as the scaffolding used in the construction of the world. And yet one of them does present itself to us as being the actual space and time of our experience; and we recoil from the other equivalent frames which seem to us artificial systems in which distance and duration are mixed up in an extraordinary way. What is the cause of this invidious selection? It is not determined by anything distinctive in the frame; it is determined by something distinctive in us—by the fact that our existence is bound to a particular planet and our motion is the motion of that planet. Nature offers an infinite choice of frames; we select the one in which we and our petty terrestrial concerns take the most distinguished position. Our mischievous geocentric outlook has cropped out again unsuspected, persuading us to insist on this terrestrial space-time frame which in the general scheme of nature is in no way superior to other frames.

The more closely we examine the processes by which events are assigned to their positions in space and time, the more clearly do we see that our local circumstances play a considerable part in it. We have no more right to expect that the space-time frame on the sun will be identical with our frame on the earth than to expect that the force of gravity will be the same there as here. If there were no experimental evidence in support of Einstein's theory, it would nevertheless have made a notable advance by exposing a fallacy underlying the older mode of thought—the fallacy of attributing unquestioningly a more than local significance to our terrestrial reckoning of space and time. But there is abundant experimental evidence for detecting and determining the difference between the frames of differently circumstanced observers. Much of the evidence is too technical to be discussed here, and I can only refer to the Michelson-Morley experiment. I fear that some of you must be getting rather tired of the Michelson-Morley experiment; but those who go to a performance of Hamlet have to put up with the Prince of Denmark.

This famous experiment is a simple test whether light travels at the same speed in two different directions. For this purpose an apparatus is constructed with two equal arms at right angles, providing two equal tracks for the light. A beam of light is divided into two parts so that one part travels along one arm and back, and the other along the other arm and back. The two rays then re-unite, and by delicate interference tests it is possible to tell if one has been delayed more than the other; a delay of less than a thousand-billionth of a second could be detected. The experiment is simply a race between two light-rays with equal tracks, but pointing in different directions; the result turns out to be a dead-heat. At first sight this is just what would be expected; and one almost wonders why it should have been thought worth while to try the experiment. But Michelson, like a good Copernican, had stationed himself on the sun to watch the race; accordingly he realized that the apparatus was being borne along by the earth's orbital motion with a speed of 20 miles a second. Consequently the light does not travel exactly the double length of the arm; starting at one end it has to go to the turning-mark at the other end which has moved on a little in the meantime; then it returns to the place which the starting-mark has travelled to whilst the race is in progress. That does not add up to exactly the double-length of the arm. Making the calculations we easily find that, although the two arms are equal, the two light-journeys are unequal; the competitor whose track lies in the line of the earth's motion has the longer journey, and is at a disadvantage. And yet according to the experiment he does not suffer the expected delay. From our standpoint on the sun, the experiment seems to have gone wrong; Copernicus has met with a rebuff, and Ptolemy is triumphant.

But that is because we have not admitted the full consequences of transferring our standpoint to the sun. We have all the while been keeping one foot on earth. Of course, the whole experiment turns on the two arms having been first adjusted to perfect equality. This could only be ascertained by experiment; and the test applied was to rotate the apparatus through a right angle, so that if, for example, the journey in the line of the earth's motion had had the advantage of the shorter arm on one occasion, the transverse journey would have had it on the repetition. That is a perfectly satisfactory test for a terrestrial observer; to turn a rod from one direction to another is the simple and direct way of marking out equal lengths. But the test is not satisfactory to an observer on the sun; he would not think of attempting to partition equal lengths of space by means of rods travelling at 20 miles a second. His frame of space —the space not only of refined measurement, but also of the cruder measurements made with the sense-organs of his body which determine his perception of space— is partitioned by appliances at rest relatively to him, e. g. his own eyes and limbs. Lengths of objects carried on the earth must be judged by him according to the room they occupy in his own frame. In the space of the terrestrial observer the two arms of the apparatus were adjusted to equal length; but in the re-partitioned space of the solar observer they may quite well occupy unequal lengths, and when we take the view-point of an observer on the sun we must not overlook this inequality. This inequality is not so much an hypothesis proposed to account for Michelson's result as a direct deduction from it. The two light-journeys were found to occupy equal times; this clearly shows that the arm in the less favoured direction is shorter than the other so as to counterbalance the handicap to which I have referred.

When the apparatus is turned through a right angle, the experiment still gives the same result. It does not matter which of the two arms we place in the line of the earth's motion; that arm must be shorter than the other. In other words each arm must automatically contract when it is turned from the transverse to the longitudinal position with respect to its line of motion. This is the famous FitzGerald contraction of a moving rod. It is of the same amount whatever the material of the rod, and depends only on the speed of its motion. For the earth's orbital motion the contraction amounts to one part in 200 million; in fact the earth's diameter in the direction of its motion is always shortened by 2 1/2 inches, the transverse diameter being unaffected.

This contraction of a moving material object was first revealed to us by the Michelson-Morley experiment; but it is not at all disagreeable to theoretical anticipations. We have to remember that a rod consists of a large number of molecules kept in position by their mutual forces. The chief force is the force of cohesion, and there is little doubt that this is of electrical nature. But when the rod is set in motion, the electrical forces inside it must change. For example, each electric charge when put in motion becomes an electric current) and the currents will exert magnetic attractions on each other which did not occur in the system at rest. Under the new system of forces the molecules will have to find new positions of equilibrium; they become differently spaced; and it is therefore not surprising that the form of the rod changes. Without going beyond the classical laws of Maxwell we can anticipate theoretically what will be the new equilibrium state of the rod, and it turns out to be contracted to the exact amount required by the Michelson-Morley result.

The contraction of the moving rod ought not to surprise us; it would be much more surprising if the rod were to maintain the same form in spite of the alteration of the electrical forces which determine the spacing of the molecules. But the remarkable thing is that the contraction is only apparent according to the outlook of the solar observer; and we on the earth, who travel with the rod, cannot appreciate it. The fact that the contraction happens to be very small is irrelevant. For convenience suppose that the earth's velocity is 8,000 times faster, so that the contraction amounts to something like a half the original length. We should still fail to notice it in everyday life.

Let us say that the direction of the earth's motion is vertically upwards. I turn my arm from horizontal to vertical and it contracts to half its length. No, you cannot convince me I am wrong; I am not afraid of a yard-measure. Bring one and measure my arm; first horizontally, the result is 30 inches; now vertically, the result is 30 half-inches! Because you must remember that you have turned the scale into the line of the earth's motion so that each inch-division contracts to half an inch.' But we can see that your arm does not contract. Are we not to trust our eyes ?' Certainly not, unless you first correct your visual impressions for the contraction of the retina in the vertical direction, and for the effect of our rapid motion on the apparent direction of propagation of the waves of light. You will find, when you calculate these corrections, that they just conceal the contraction. 'But if the contraction takes place, ought one not to feel it happening to the arm?' Not necessarily; I am an observer on the earth, and my feelings like other sense-impressions belong to the geocentric outlook on nature, which Copernicus has persuaded us to abandon.

Take a pair of compasses and twiddle them on a sheet of paper. Is the resulting curve a circle or an ellipse? Copernicus from his standpoint on the sun declares that owing to the FitzGerald contraction the two points drew nearer together when turned in the direction of the earth's orbital motion; hence the curve is flattened into an ellipse. But here I think Ptolemy has a right to be heard; he points out that from the beginning of geometry circles have always been drawn with compasses in this way, and that when the word 'circle' is mentioned every intelligent person understands that this is the curve meant. The same pencil line is in fact a circle in the space of the terrestrial observer and an ellipse in the space of a solar observer. It is at the same time a moving ellipse and a stationary circle. I think that illustrates as well as possible what we mean by the relativity of space.

It is sometimes complained that Einstein's conclusion that the frame of space and time is different for observers with different motions tends to make a mystery of a phenomenon which is not after all intrinsically strange. We have seen that it depends on a contraction of moving objects which turns out to be quite in accordance with Maxwell's classical theory. But even if we have succeeded in explaining it to ourselves intelligibly, that does not make the statement any the less true! A new result may often be expressed in various ways; one mode of statement may sound less mysterious; but another mode may show more clearly what will be the consequences in amending and extending our knowledge. It is for the latter reason that we emphasize the relativity of space—that lengths and distances differ according to the observer implied.

Distance and duration are the most fundamental terms in physics; velocity, acceleration, force, energy, and so on, all depend on them; and we can scarcely make any statement in physics without direct or indirect reference to them. Surely then we can best indicate the revolutionary consequences of what we have learnt by the statement that distance and duration, and all the physical quantities derived from them, do not as hitherto supposed refer to anything absolute in the external world, but are relative quantities which alter when we pass from one observer to another with different motion. The consequence in physics of the discovery that a yard is not an absolute chunk of space, and that what is a yard for one observer may be eighteen inches for another observer, may be compared with the consequences in economics of the discovery that a pound sterling is not an absolute quantity of wealth, and in certain circumstances may 'really' be seven and sixpence. The theorist may complain that this last statement tends to make a mystery of phenomena of currency which have really an intelligible explanation; but it is a statement which commends itself to the man who has an eye to the practical applications of currency.

Ptolemy on the earth and Copernicus on the sun are both contemplating the same external universe. But their experiences are different, and it is in the process of experiencing events that they become fitted into the frame of space and time—the frame being different according to the local circumstances of the observer who is experiencing them. That, I take it, is Kant's doctrine, 'Space and time are forms of experience.' The frame then is not in the world; it is supplied by the observer and depends on him. And those relations of simplicity, which we seek when we try to obtain a comprehension of how the universe functions, must lie in the events themselves before they have been arbitrarily fitted into the frame. The most we can hope for from any frame is that it will not have distorted the simplicity which was originally present; whilst an ill-chosen frame may play havoc with the natural simplicity of things. We have seen that the simplicity of planetary motions was obscured in Ptolemy's frame, and became apparent in Copernicus's frame. But for ordinary terrestrial phenomena the position is reversed and Ptolemy's frame allows their natural simplicity to become apparent. In Copernicus's frame the most simple phenomena are brought about by highly complicated processes which mutually cancel one another. Ordinary objects contract and expand as they are moved about, and the changes are concealed by an elaborate conspiracy in which all the quantities of nature—electrical, optical, mechanical, gravitational—have joined. In Copernicus's frame we have a great complication of description which has no counterpart in anything occurring in the external world; because the terms of our description refer to the irrelevant process of fitting into the selected frame of space and time. This elaborate Copernican scheme rather reminds one of the schemes of the White Knight:

But I was thinking of a plan
To dye one's whiskers green,
And always use so large a fan
That they could not be seen.

We do not deny the subtlety and the remarkable efficiency of the plan; but we may be allowed to question whether it is the simplest interpretation of the drab monotony of the face of nature presented to us. The simple fact is that a terrestrial or Ptolemaic frame fits naturally the terrestrial phenomena, and a solar or Copernican frame fits the phenomena ofthe solar system; but we cannot make one frame serve for both without introducing irrelevant complications.

We go beyond Copernicus nowadays, and are not content with a visit to the sun. Why choose the sun rather than some other star in order to obtain an undistorted view of things? The astronomer now places himself so as to travel with the centre of gravity of the stellar universe, and is not even then quite satisfied. The physicist dreams of a land of Weissnichtwo, which shall be truly at rest in the ether. We realize the distortion imported into the world of nature by the parochial standpoint from which we observe it, and we try to place ourselves so as to eliminate this distortion—so as to observe that which actually is. But it is a vain pursuit. Wherever we pitch our camera, the photograph is necessarily a two-dimensional picture distorted according to the laws of perspective; it is never a true semblance of the building itself.

We must try another plan. I do not think we can ever eliminate altogether the human element in our conception of nature; but we can eliminate a particular human element, namely, this framework of space and time. If our thought must be anthropocentric,it need not be geocentric. Nor are we permanently better off if we merely substitute the space-time frame of some other star or standard of motion. We must leave the frame entirely indeterminate. When we do that, we find that the world common to all observers—in which each observer traces a different space-time frame according to his own outlook—is a world of four dimensions.

When we look at any object, say a chair, the impression on our eyes is a two-dimensional picture depending on the position from which we are looking; but we have no difficulty in conceiving of the chair as a solid object, not to be identified with any one of our two-dimensional pictures of it, but giving rise to them all as the position of the observer is varied. We must now realize that this solid chair in three dimensions is itself only an appearance, which changes according to the motion of the observer, and that there is a super-object in four-dimensions, not to be identified with the three-dimensional chair in Ptolemy's scheme, or the same chair in Copernicus's scheme, but giving rise to both these appearances. The synthesis of a three-dimensional chair from a number of flat pictures is easy to us because we are accustomed to assume different positions in rapid succession; indeed our two eyes give us slightly different points of view simultaneously. By sheer necessity four brains have been forced to construct the conception of the solid chair to combine these changing appearances. But we do not vary our motion to any appreciable extent and our brains have not hitherto been called upon to combine the appearances for different motions; thus the effort which we now ask the brain to make is a novel one. That explains why the result seems to transcend our ordinary mode of thought.

The discovery, or one should rather say the rediscovery, of the world of four dimensions is due to Minkowski. Einstein had worked out fully the relations between the frames of space and time for observers with different motions. To the genius of Minkowski we owe the realization that these frames are merely systems of partitions arbitrarily drawn across a four-dimensional world which is common to all observers.

There is a strange delusion that the fourth dimension must be something wholly beyond the conception of the ordinary man, and that only the mathematician can be initiated into its mysteries. It is true that the mathematician has the advantage of understanding the technical machinery for solving the problems which may arise in studying the world of four dimensions; but as regards the conception of the four dimensions of the world his point of view is the same as that of anybody else. Is it supposed that by intense thought he throws himself into some state of trance in which he perceives some hitherto unsuspected direction stretching away at right angles to length, breadth, and thickness? That would not be much use. The world of four dimensions, of which we are now speaking, is perfectly familiar to everybody. It is obvious to every one—even to the mathematician—that the world of solid and permanent objects has three dimensions and no more; that objects are arranged in a threefold order, which for any particular individual may be analysed into right-and-left, backwards-and-forwards, up-and-down. But it is no less obvious to every one that the world of events is of four dimensions; that events are arranged in a fourfold order, which in the experience of any particular individual will be analysed into right-and-left, backwards-and-forwards, up-and-down, sooner-and-later. The subject of our study is external nature, which is a world of events, common to all observers but represented by them differently in their parochial frames of space and time; it is obvious to the most commonplace experience that this absolute world contains a fourfold order.

The news that the events around us form a world of four dimensions is as stale as the news that Queen Anne is dead. The reason why the relativist resurrects this ancient truism is because it is only in this undissected combination of four dimensions that the experiences of all observers meet. In our own experience one dimension is sharply separated from the other three and is distinguished as time; but our experience is solely terrestrial, and if we insist on building the scheme of nature on purely terrestrial experience we are limiting ourselves to the mediaeval geocentric system of the world.

We have been accustomed to regard the enduring world as composed of a continuous succession of instantaneous states, as though the world of events were stratified. Each event is supposed to lie in a definite instant or stratum, and the orderly succession of these strata makes up the whole of reality. The instant 'now' represents one such stratum running throughout the universe. Indeed we are accustomed to extend it beyond the universe, and we even use the word 'now' with reference to the existence of those who have passed away from the material world. The investigations of the relativity theory show incontrovertibly that this supposed stratification is an illusion; there is not the slightest evidence for such a view of world-structure. The instantaneous state, which we have hitherto taken to be a natural stratum in the four-dimensional world of events, is merely an arbitrary partition created by ourselves to correspond with our geocentric outlook. We can take a differently inclined partition, that is to say, a section which includes on the one side of us events which happened a little while ago and on the other side of us events which have not yet happened; such a farcical combination is in every way equivalent to our so-called instantaneous state, and indeed it is an instantaneous state according to the outlook of some non-terrestrial observer with suitably assigned motion.

It is so contrary to our natural prejudices to recognize that the world-wide instant now is created by ourselves and has no existence apart from our geocentric outlook, that I will spend a few moments trying to show its artificiality. When I say that I am conscious of an instant now, I am only conscious of it in so far as it is here—inside me. What then has led me to imagine that there exists a continuation of it outside me? It is because I look out on the world and see various events happening 'now', so that I jump to the conclusion that this instant of which I am conscious has to be extended to include them. But that idea is another inheritance from the dark ages, overthrown by Romer in 1675. It is not the events themselves but the sense-impressions to which they give rise which are happening in the instant now. So my justification for placing the events outside me in the instants of which I am conscious has entirely disappeared.

Unfortunately, however, the crude outlook was not abolished, but patched up; it was found that the immediate difficulties could be met by locating the external events not in the instant of our visual perception of them but in an instant which we had experienced a little time back—allowing, as we say, for the time of propagation of light. Thus our instants were still made to extend through space; but they were carried like partitions among the events by an artificial process of computation, and no longer by immediate intuition. The relativity theory recognizes these worldwide instants for what they are—artificial partitions constructed for purposes of calculation. I may add that it in no way tampers with the local instants which form the stream of our consciousness; it fully recognizes that the chain of events in such a time-succession is a series of an entirely distinctive character from the succession of points along a line in space. Those who suspect that Einstein's theory is playing unjustifiable tricks with time should realize that it leaves entirely untouched that time-succession of which we have intuitive knowledge, and confines itself to overhauling the artificial scheme of time which Romer first introduced into physics.

The study of the four-dimensional world of events gives us a new insight into the processes of nature because it removes the irrelevant stratification in a particular direction—the instantaneous states—which we have so unnecessarily introduced in our customary outlook. When this stratification is ignored we are enabled to see the processes in their simplest aspect, though not, of course, in their most familiar aspect. We must distinguish between 'simplicity and familiarity; a pig may be most familiar to us in the form of rashers, but the unstratified pig is a simpler object of study to the biologist who wishes to understand how the animal functions.

I will conclude this part of the argument with an experimental application which illustrates the power of Einstein's method. Much study has of late been given to electrons moving with very high speeds; for example, the beta particles shot off from radioactive substances are negative electrons which sometimes attain speeds of 100,000 miles a second. It is found by experiment that the rapid motion produces an increase of mass of these particles. I want to show that the theory of relativity gives a very simple explanation of just how this increase of mass occurs. But I must first remark that an explanation had been previously given which had generally been accepted as satisfactory. The phenomenon was actually predicted by J. J. Thomson before relativity was thought of; because, assuming that the mass of a beta particle is of electrical origin, an application of Maxwell's equations shows that it ought to increase with velocity. But the precise law of increase cannot be predicted on this basis, since various plausible assumptions lead to slightly different results. Moreover, Maxwell's equations are after all only empirical laws, with a mystery of their own; it was a notable advance to connect the change of mass at high speeds with other phenomena whose strangeness has disappeared by long familiarity, but there is still scope for a more far-reaching explanation. Einstein takes us straight to the root of the mystery, and he clears up one point which was misleading, if not actually wrong, in the older explanation. The change of mass does not in any way depend on whether the mass is of electrical origin or not; it arises simply from the fact that mass is a relative quantity, depending by its definition on the relative quantities length and time.

Let us look at the beta particle from its own point of view; it is just an ordinary electron in no way different from any other. 'But it is traveling unusually rapidly?' 'That', says the electron, 'is a matter of opinion. So far as I am aware I am at rest, if the word "rest" has any meaning. In fact I was just contemplating with amazement your extraordinary speed of 100,000 miles a second with which you are shooting past me.' Of course our motion is of no particular concern to the electron, and it will not modify its constitution on our account; so it keeps its mass, radius, electric field, &c, equal to the standard constants applying to electrons in general. These terms are relative, and refer therefore to some particular frame of space and time—clearly the frame appropriate to an electron in self-contemplation, viz. the one with respect to which it is at rest. But this frame is not the usual geocentric frame to which we refer quantities such as length, time, and mass; there is a difference of 100,000 miles a second between our station of observation and that of the beta particle in self-contemplation. It is a mere matter of geometry to discover what the beta particle's lengths and times become when referred to the partitions which we have drawn across the world. But when we calculate the consequential change of mass resulting from the changes of length and time, we find that it should be increased in precisely the proportion indicated by the most refined experiments.

The point is that every electron, at rest or in motion, is a perfectly constant structure; but we distort it by fitting it into the space-time frame appropriate to our own motion with which the electron has no concern. The greater our motion with respect to the electron, the greater will be the distortion. The distortion is not produced by any physical agency at work in the electron; it is a purely subjective distortion depending on our transformation of the reference frame of space and time. This distortion involves a change in our physical description of the electron in terms of mass, shape, size; and in particular the change of mass agrees precisely with that found experimentally.

You see that it is not altogether idle discussing the natural space-time frames for observers moving with huge velocities. We know of no animate observers with these speeds; but we do know of inanimate material objects. Their common resemblance is obscured when we refer them indiscriminately to our irrelevant geocentric frame; we think they have altered their properties, varied in mass, and so on; but the resemblance is restored when we refer each individual to the frame appropriate to it, and so describe them all in comparable terms.

Our measurements of distance in space are found to be subject to certain laws—the laws of geometry. But it has now become impossible to regard the subject of space-geometry as complete in itself. Consider a triangle formed by three points (or events) in the four-dimensional world; if we happen to have drawn our instantaneous strata so that the three points lie in one stratum, then the triangle is a space-triangle and its properties fall within the scope of our classical geometry. But another observer will draw his strata in a different direction, and for him the triangle would be partly in space and partly in time, so that it would not be a fit subject for space-geometry. The subject of geometry is in a desperate condition, because Copernicus and Ptolemy not merely disagree as to the geometry of a configuration; they even disagree as to whether a given configuration is one to which space-geometry is applicable. It is clear that to save it we must extend our geometry so as to include time as well as space.

Let me give an illustration of this extension. The terrestrial observer can have a space-triangle (formed by three points or events at the same instant) whose sides he can measure with scales; he can also have a 'time-triangle', formed by three events on different dates, whose sides he must measure with clocks. You all know the law of the space-triangle—that if you measure with a scale from A to B and from B to C the sum of the readings is always greater than the measure from A to C. It is not so well known that there is a precisely analogous law for the time-triangle—that if you measure with a clock from A to B and from B to C the sum of the readings is always less than the reading of a clock measuring directly from A to C. In the space-triangle any two sides are together greater than the third side; in the time-triangle two sides are together less than the third side. Both these laws must be combined in our general geometry of four dimensions, so that it will not be quite so simple a geometry as that to which we are accustomed.

But the point to which I would especially direct attention is this. Evidently the proposition which I have given you about time-triangles cannot be dissociated from the corresponding proposition about space-triangles. When we give up the mediaeval geocentric standpoint, we must recognize that they belong to one geometry, of which our ordinary space-geometry is only a part or projection. But if you examine the proposition about time-triangles, you will see that it is a statement about the behaviour of clocks when they move about, a subject which obviously comes under the heading of mechanics, When we deal with the four-dimensional world we can no longer distinguish between geometry and mechanics. They become the same subject. When we have completely mastered the geometry of the world of events, we shall have inevitably learnt the mechanics of it. That is why Einstein, studying the geometry of the world and discovering that it was strictly non-Euclidean, found that he was at the same time studying the mechanical force of gravitation. And when he had made up his mind which of the possible varieties of non-Euclidean geometry was obeyed, and so settled the laws of the new geometry, the same decision settled the law of gravitation—a law approximating to, but not identical with, the law which Newton had given.

Here a wide vista opens before us. We see that two great divisions of mathematical physics, viz. geometry and mechanics, have met in the four-dimensional world. It is not merely that mechanical problems can be treated by formulae originally belonging to pure geometry; that device has long been in use. Experimental geometry and mechanics actually relate to the same subject-matter; and the young student who discovers experimental laws with ruler and compasses and cardboard figures, and later goes on to pendulums and spring-balances, is developing a single subject which cannot be divided any more than the subject of magnetism can be divided from electricity.

It is through this unification of geometry and mechanics that I should like to approach the problem of gravitation, showing that a field of force is a manifestation of the geometry of space and time. But I fear that that would be too technical; so we will approach it from a different angle.

We have shown that the contemplation of the world from the standpoint of a single observer is liable to distort its simplicity, and we have tried to obtain a juster idea by taking into account and combining other points of view. The more standpoints the better. Let us now consider another point of view, which we have not previously thought about—the point of view of an observer who has tumbled out of an aeroplane and is falling headlong. In many respects his is an ideal situation —temporarily. Unfortunately on terrafirma we are continually subjected to a very disturbing influence; we undergo a terrific bombardment by the molecules of the ground, which are hammering on the soles of our boots with a total force of some ten stone weight pressing us upwards. Now our bodies are the scientific appliances which we use to make our common observations of the world. I am sure that no physicist would permit any one to enter his laboratory and hammer on his clocks and galvanometers whilst he was observing with them; at any rate he would think it necessary to apply some corrections for the effect of the disturbance. Let us then allow ourselves to fall freely in vacuo; then we shall be free from this disturbing bombardment and able to take a much more natural view of what is going on around us.

Whilst falling, we perform the experiment of letting go an apple held in the hand. The apple is now free, but it cannot fall any more than it was falling already; consequently it remains poised in contact with our hand. In our new outlook—in our new frame of space and time—an apple does not drop. There is no mysterious force accelerating it. And remember that this new frame of space and time is the natural frame of a free observer; whereas the old frame, in which the mysterious accelerating force occurred, was the frame of a very much disturbed observer. It is true that when we look down at the earth we see trees and houses rushing up to meet us; but there is no mystery about that. There is an obvious cause for it; plainly they are being propelled upwards from below by that molecular bombardment which I have mentioned. You see that the apple's view of things is simpler than Newton's. Newton had to invent a mysterious force dragging the apple down; the apple observes only a familiar physical agency propelling Newton up.

It is not my purpose to emphasize unduly the superiority of the apple's view over Newton's, but rather to regard both on an equal footing. I have perhaps been a little unfair to Newton. His position on the surface of the earth was unfortunate, but he would have been perfectly content to be at the centre of the earth, where he could have remained without support, i.e. without disturbance by molecular bombardment. From there he would still have observed the well-known acceleration of the apple; and the apple would have observed a corresponding acceleration of Newton without any molecular bombardment causing it. From either point of view there is a mysterious agent at work. How shall we picture to ourselves this agent? Shall we picture it as a force—a tug of some kind? But if so, to which of them is the tug applied? If we take the standpoint of Newton the tug is applied to the apple, if the standpoint of the apple the tug is applied to Newton; so that in our synthesis of all standpoints we cannot decide which is being tugged, and the picture of gravitation as a tugging agent becomes impossible. Einstein replaces it by a different picture, which we shall perhaps better understand if we compare it with a very similar revolution of scientific thought which occurred long ago.

The ancients believed that the earth was flat. The small portion of its surface with which they were chiefly concerned could be represented without serious distortion on a flat map. As more distant countries were added, it would be natural to think that they also could be included in the flat map. You have all seen such maps of the world, e.g. Mercator's projection, and you will remember how Greenland appears enormously exaggerated in size. Now those who adhered to the flat-earth theory must hold that the flat map gives the true size of Greenland. How then would they explain that travellers in that country reported that the distances were much shorter? They would, I suppose, invent a theory that a demon resided in -that country who helped travellers on their way, making the journeys appear much shorter than they 'really' were. No doubt the scientists would preserve their self-respect by using some Graeco-Latin polysyllable instead of the word 'demon', but that must not disguise from us the fact that they were appealing to a deus ex machina. The name demon is rather suitable, however, because he has the impish characteristic that we cannot pin him down to any particular locality. We might equally well start our flat map with its centre in Greenland; then it would be found that journeys there were quite normal, and that the activities of the demon were disturbing travellers in Europe. We now recognize that the true explanation is that the earth's surface is curved; and the demoniacal complications appeared because we were forcing the earth's surface into an inappropriate flat frame which distorts the simplicity of things.

What has happened in the case of the earth has happened also in the case of the world, and a similar revolution of thought is needed. An observer, say at the centre of the earth, finds that there is a frame of space and time—a flat or Euclidean frame—in which he can locate things happening in his neighbourhood without distorting their natural simplicity. There is no gravitation, no tendency of bodies to fall, so long as the observer confines his observations to his immediate neighbourhood. He extends this frame of space and time to greater distances, and ultimately to the earth's surface where he encounters the phenomenon of falling apples. This new phenomenon must be accounted for, so he invents a deus ex machina which he calls gravitation to whose activities the disturbance is attributed. But we have seen that we may just as well start with the falling apple. It has a flat frame of space and time into which phenomena in its neighbourhood fit without distortion ; and from its point of view bodies near it do not undergo any acceleration. But when it extends this frame farther afield, the simplicity is lost; and it too has to postulate the demon force of gravitation existing in distant parts, and for example causing undisturbed objects at the centre of the earth to fall towards it. As we change from one observer to another—from one flat space-time frame to another—so we have to change the region of activity of this demon. Is not the solution now apparent? The demon is simply the complication which arises when we force the world into a flat Euclidean space-time frame into which it does not fit without distortion. It does not fit the frame, because it is not a Euclidean or flat world. Admit a curvature of the world and the mysterious disturbance disappears. Einstein has exorcized the demon.

Einstein, recognizing that in the phenomena of gravitation he was not dealing with a 'tug' but with a curvature of the world, had to reconsider the law of gravitation. He could not make any possible law of curvature correspond exactly with the previously assumed law of tugging. Thus he was led to propound a new law of gravitation—a law which in most practical cases differs very little from that of Newton, although it has an essentially different foundation. I need not here dwell on the very remarkable way in which Einstein's emendation of the law of gravitation has been confirmed both by the anomalous secular change in the orbit of the planet Mercury, and by the observed displacement of the stars near the sun during the total eclipse of 1919. I might, however, remind you that in the latter observation the point at issue between Newton's and Einstein's theory was not the existence of a deflection of light-rays passing near the sun but the amount of the deflection, Einstein predicting twice the deflection possible on the Newtonian theory. The larger deflection was quantitatively confirmed by the eclipse observations.

Einstein's main achievement is a new law, not a new explanation, of gravitation. He attributes the gravitation of massive bodies to a curvature of the world in the region surrounding them and so throws a flood of light on the whole problem; but he is not primarily concerned to explain how material bodies produce (or are associated with) this curvature of the world around them, nor how this curvature is made subject to a law. Although it would be an entire misunderstanding of Einstein's attitude in propounding the general relativity theory to regard it as a search for an explanation of gravitation, nevertheless I think that the further following up of his ideas has led to a genuine explanation as complete as could be desired. But I am not going to give you the explanation in this lecture; sometimes an explanation requires a great deal of explaining.

I think that we can without mathematics form a general idea of why Einstein found it necessary to amend Newton's law of gravitation. Let us return to the illustration of the pig, and imagine that we wish to discover the law governing the distribution of fat and lean in the animal. From the breakfast-table standpoint a plausible type of law would be that half of each rasher is fat and the other half lean ; and if this turned out to to be confirmed very approximately by observation we might well imagine that we had discovered the exact law of porcine structure. But the case is altered if we give up the breakfast-table standpoint and contemplate the animal in a more general way, remembering that he has not been designed with any particular reference to the series of rashers into which our grocer has chosen to slice him.

We must now look for a different type of law altogether. Two possibilities may arise. We may find that our proposed law, although expressed in breakfast-table parlance, is nevertheless equivalent to a possible biological law; it may be immediately capable of translation into a more general statement which makes no reference to a particular stratification. But on the other hand, it may happen that the suggested law cannot be freed from this reference to a particular system of slicing. In that case we can only regard it as approximate, perhaps holding fairly well for the slices of which we have most experience but becoming less and less accurate in the more tortuous parts of the animal. Both these cases are illustrated in Einstein's modifications of classical theory. Newton's law of gravitation explicitly refers to a space-time frame and therefore to a world stratified into instantaneous states. It proves to be impossible to free it from this reference to a particular stratification without modifying it. In fact if the crucial astronomical observations had shown that Newton's law and not Einstein's was the exact law of gravitation, this would have been evidence of a real stratification of the structure of the world—a stratification revealed by no other phenomena. Einstein's law is the simpler law because it is consistent with what we now know of the general plan of world-structure; Newton's law could only be made possible by introducing a novel and specialized feature—a stratified arrangement of structure—which is not revealed in any other phenomena.

Maxwell's laws of electromagnetism afford an example of the other type. These, it is true, are stated as relating to the particular slices of the world of events, which are served up to us like rashers instant by instant. But they can be restated, without alteration of effect, in a form making no reference to slices. This is a very remarkable property of Maxwell's equations which was quite unknown at the time they were first put forward. It was brought to light much later by the researches of Larmor and Lorentz. In consequence of this Einstein is able to take over the whole classical theory of electromagnetism unaltered; he restates it so as to show how it applies generally and is not bound up with the purely terrestrial point of view, but he does not amend the laws. He metes out different treatment to the gravitational laws and electromagnetic laws, because he finds the latter already adapted to his scheme.

If I have succeeded in my object, you will have realized that the present revolution of scientific thought follows in natural sequence on the great revolutions at earlier epochs in the history of science. Einstein's special theory of relativity, which explains the indeterminateness of the frame of space and time, crowns the work of Copernicus who first led us to give up our insistence on a geocentric outlook on nature; Einstein's general theory of relativity, which reveals the curvature or non-Euclidean geometry of space and time, carries forward the rudimentary thought of those earlier astronomers who first contemplated the possibility that their existence lay on something which was not flat. These earlier revolutions are still a source of perplexity in childhood, which we soon outgrow; and a time will come when Einstein's amazing revelations have likewise sunk into the commonplaces of educated thought.

To free our thought from the fetters of space and time is an aspiration of the poet and the mystic, viewed somewhat coldly by the scientist who has too good reason to fear the confusion of loose ideas likely to ensue. If others have had a suspicion of the end to be desired, it has been left to Einstein to show the way to rid ourselves of these 'terrestrial adhesions to thought'. And in removing our fetters he leaves us, not (as might have been feared) vague generalities for the ecstatic contemplation of the mystic, but a precise scheme of world-structure to engage the mathematical physicist.