# EINSTEIN AND THE UNIVERSE

# EINSTEIN AND THE UNIVERSE

*A Popular Exposition of the Famous Theory*

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*With a Preface by the Rt. Hon.*

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# PREFACE

A DISTINGUISHED German authority on mathematical physics, writing recently on the theory of Relativity, declared that if his publishers had been willing to allow him sufficient paper and print he could have explained what he wished to convey without using a single mathematical formula. Such success is conceivable. Mathematical methods present, however, two advantages. Their terminology is precise and concentrated, in a fashion which ordinary language cannot afford to adopt. Further, the symbols which result from their employment have implications which, when brought to light, yield new knowledge. This is deductively reached, but it is none the less new knowledge. With greater precision than is usual, ordinary language may be made to do some, if not a great deal, of this work for which mathematical methods are alone quite appropriate. If ordinary language can do part of it an advantage may be gained. The difficulty that attends mathematical symbolism is the accompanying tendency to take the symbol as exhaustively descriptive of reality. Now it is not so descriptive. It always embodies an abstraction. It accordingly leads to the use of metaphors which are inadequate and generally untrue. It is only qualification by descriptive language of a wider range that can keep this tendency in check. A new school of mathematical physicists,

still, however, small in number, is beginning to appreciate this.

But for English and German writers the new task is very difficult. Neither Anglo-Saxon nor Saxon genius lends itself readily in this direction. Nor has the task as yet been taken in hand completely, so far as I am aware, in France. Still, in France there is a spirit and a gift of expression which makes the approach to it easier than either for us or for the Germans. Lucidity in expression is an endowment which the best French writers possess in a higher degree than we do. Some of us have accordingly awaited with deep interest French renderings of the difficult doctrine of Einstein.

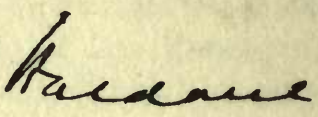
M. Nordmann, in addition to being a highly qualified astronomer and mathematical-physicist, possesses the gift of his race. The Latin capacity for eliminating abstractness from the description of facts is everywhere apparent in his writing. Individual facts take the places of general conceptions, of *Begriffe*. The language is that of the *Vorstellung*, in a way that would hardly be practicable in German. Nor is our own language equal to that of France in delicacy of distinctive description. This book could hardly have been written by an Englishman. But the difficulty in his way would have been one as much of spirit as of letter. It is the lucidity of the French author, in combination with his own gift of expression, that has made it possible for the translator to succeed so well in overcoming the obstacles to giving the exposition in our own tongue this book contains. The rendering seems to me, after reading the book both in French and in English, admirable.

M. Nordmann has presented Einstein's principle in

words which lift the average reader over many of the difficulties he must encounter in trying to take it in. Remembering Goethe's maxim that he who would accomplish anything must limit himself, he has not aimed at covering the full field to which Einstein's teaching is directed. But he succeeds in making many abstruse things intelligible to the layman. Perhaps the most brilliant of his efforts in this direction are Chapters V and VI, in which he explains with extraordinary lucidity the new theory of gravitation and of its relation to inertia. I think that M. Nordmann is perhaps less successful in the courageous attack he makes in his third chapter on the obscurity which attends the notion of the "Interval." But that is because the four-dimensional world, which is the basis of experience of space and time for Einstein and Minkowski, is in itself an obscure conception. Mathematicians talk about it gaily and throw its qualities into equations, despite the essential exclusion from it of the measurement and shape which actual experience always in some form involves. They lapse on that account into unconscious metaphysics of a dubious character. This does not destroy the practical value of their equations, but it does make them very unreliable as guides to the character of reality in the meaning which the plain man attaches to it. Here, accordingly, we find the author of this little treatise to be a good man struggling with adversity. If he could make the topic clear he would. But then no one has made it clear excepting as an abstraction which works, but which, despite suggestions made to the contrary, cannot be clothed for us in images.

This, however, is the fault, not of M. Nordmann himself, but of a phase of the subject. With the

subject in its other aspects he deals with the incomparable lucidity of a Frenchman. I know no book better adapted than the one now translated to give the average English reader some understanding of a principle, still in its infancy, but destined, as I believe, to transform opinion in more regions of knowledge than those merely of mathematical physics.



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# INTRODUCTION

THIS book is not a romance. Nevertheless. . . . If love is, as Plato says, a soaring toward the infinite, where shall we find more love than in the impassioned curiosity which impels us, with bowed heads and beating hearts, against the wall of mystery that environs our material world ? Behind that wall, we feel, there is something sublime. What is it ? Science is the outcome of the search for that mysterious something.

A giant blow has recently been struck, by a man of consummate ability, Albert Einstein, upon this wall which conceals reality from us. A little of the light from beyond now comes to us through the breach he has made, and our eyes are enchanted, almost dazzled, by the rays. I propose here to give, as simply and clearly as is possible, some faint reflex of the impression it has made upon us.

Einstein's theories have brought about a profound revolution in science. In their light the world seems simpler, more co-ordinated, more in unison. We shall henceforward realise better how grandiose and coherent it is, how it is ruled by an inflexible harmony. A little of the ineffable will become clearer to us.

Men, as they pass through the universe, are like those specks of dust which dance for a moment in the golden rays of the sun, then sink into the darkness. Is there a finer or nobler way of spending this life than to fill

one's eyes, one's mind, one's heart with the immortal, yet so elusive, rays ? What higher pleasure can there be than to contemplate, to seek, to understand, the magnificent and astounding spectacle of the universe ?

There is in reality more of the marvellous and the romantic than there is in all our poor dreams. In the thirst for knowledge, in the mystic impulse which urges us toward the deep heart of the Unknown, there is more passion and more sweetness than in all the trivialities which sustain so many literatures. I may be wrong, after all, in saying that this book is not a romance.

I will endeavour in these pages to make the reader understand, accurately, yet without the aid of the esoteric apparatus of the technical writer, the revolution brought about by Einstein. I will try also to fix its limits ; to state precisely what, at the most, we can really know to-day about the external world when we regard it through the translucent screen of science.

Every revolution is followed by a reaction, in virtue of the rhythm which seems to be an inherent and eternal law of the mind of man. Einstein is at once the Sieyès, the Mirabeau, and the Danton of the new revolution. But the revolution has already produced its fanatical Marats, who would say to science : " Thus far and no farther."

Hence we find some resistance to the pretensions of over-zealous apostles of the new scientific gospel. In the Academy of Sciences M. Paul Painlevé takes his place, with all the strength of a vigorous mathematical genius, between Newton, who was supposed to be overthrown, and Einstein. In my final pages I will examine the penetrating criticisms of the great French

geometrician. They will help me to fix the precise position, in the evolution of our ideas, of Einstein's magnificent synthesis. But I would first expound the synthesis itself with all the affection which one must bestow upon things that one would understand.

Science has not completed its task with the work of Einstein. There remains many a depth that is for us unfathomable, waiting for some genius of to-morrow to throw light into it. It is the very essence of the august and lofty grandeur of science that it is perpetually advancing. It is like a torch in the sombre forest of mystery. Man enlarges every day the circle of light which spreads round him, but at the same time, and in virtue of his very advance, he finds himself confronting, at an increasing number of points, the darkness of the Unknown. Few men have borne the shaft of light so deeply into the forest as has Einstein. In spite of the sordid cares which harass us to-day, amid so many grave contingencies, his system reveals to us an element of grandeur.

Our age is like the noisy and unsubstantial froth that crowns, and hides for a moment, the gold of some generous wine. When all the transitory murmur that now fills our ears is over, Einstein's theory will rise before us as the great lighthouse on the brink of this sad and petty twentieth century of ours.

CHARLES NORDMANN.

# EINSTEIN AND THE UNIVERSE

## CHAPTER I

### THE METAMORPHOSES OF SPACE AND TIME

*Removing the mathematical difficulties—The pillars of knowledge—Absolute time and space, from Aristotle to Newton—Relative time and space, from Epicurus to Poincaré and Einstein—Classical Relativity—Antinomy of stellar aberration and the Michelson experiment.*

"HAVE you read Baruch?" La Fontaine used to cry, enthusiastically. To-day he would have troubled his friends with the question "Have you read Einstein?"

But, whereas one needs only a little Latin to gain access to Spinoza, frightful monsters keep guard before Einstein, and their horrible grimaces seem to forbid us to approach him. They stand behind strange moving bars, sometimes rectangular and sometimes curvilinear, which are known as "co-ordinates." They bear names as frightful as themselves—"contravariant and covariant vectors, tensors, scalars, determinants, orthogonal vectors, generalised symbols of three signs," and so on.

These strange beings, brought from the wildest depths of the mathematical jungle, join together or part from each other with a remarkable promiscuity, by means of some astonishing surgery which is called *integration* and *differentiation*.

In a word, Einstein may be a treasure, but there is

a fearsome troop of mathematical reptiles keeping inquisitive folk away from it; though there can be no doubt that they have, like our Gothic gargoyles, a hidden beauty of their own. Let us, however, drive them off with the whip of simple terminology, and approach the splendour of Einstein's theory.

Who is this physicist Einstein? That is a question of no importance here. It is enough to know that he refused to sign the infamous manifesto of the professors, and thus brought upon himself persecution from the Pan-Germanists.[1] Mathematical truths and scientific discoveries have an intrinsic value, and this must be judged and appreciated impartially, whoever their author may chance to be. Had Pythagoras been the lowest of criminals, the fact would not in the least detract from the validity of the square of the hypotenuse. A theory is either true or false, whether the nose of its author has the aquiline contour of the nose of the children of Sem, or the flattened shape of that of the children of Cham, or the straightness of that of the children of Japhet. Do we feel that humanity is perfect when we hear it said occasionally: "Tell me what church you frequent, and I will tell you if your geometry is sound." Truth has no need of a civil status. Let us get on.

. . . . .

All our ideas, all science, and even the whole of our practical life, are based upon the way in which we picture

[1] [Albert Einstein, born in 1879, is a German Jew of Würtemberg. He studied in Switzerland, and was an engineer there until 1909, when he became professor at Zurich University. In 1911 he passed to Prague University, in 1912 to the Zurich Polytechnic, and in 1914 to the Prussian Academy of Science. He refused to give his name to the manifesto in which ninety-three professors of Germany and Austria defended Germany's war-action.—Trans.]

to ourselves the successive aspects of things. Our mind, with the aid of our senses, chiefly ranges these under the headings of time and space, which thus become the two frames in which we dispose all that is apparent to us of the material world. When we write a letter, we put at the head of it the name of the place and the date. When we open a newspaper, we find the same indications at the beginning of each piece of telegraphic news. It is the same in everything and for everything. Time and space, the situation and the period of things, are thus seen to be the twin pillars of all knowledge, the two columns which sustain the edifice of men's understanding.

So felt Leconte de Lisle when, addressing himself to "divine death," he wrote, in his profound, philosophic way:

> Free us from time, number, and space:
> Grant us the rest that life hath spoiled.

He inserts the word "number" only in order to define time and space quantitatively. What he has finely expressed in these famous and superb lines is the fact that all that there is for us in this vast universe, all that we know and see, all the ineffable and agitated flow of phenomena, presents to us no definite aspect, no precise form, until it has passed through those two filters which are interposed by the mind, time and space.

The work of Einstein derives its importance from the fact that he has shown, as we shall see, that we have entirely to revise our ideas of time and space. If that is so, the whole of science, including psychology, will have to be reconstructed. That is the first part of Einstein's work, but it goes further. If that were the whole of his work it would be merely negative.

Once he had removed from the structure of human knowledge what had been regarded as an indispensable wall of it, though it was really only a frail scaffolding that hid the harmony of its proportions, he began to reconstruct. He made in the structure large windows which allow us now to see the treasures it contains. In a word, Einstein showed, on the one hand, with astonishing acuteness and depth, that the foundation of our knowledge seems to be different from what we had thought, and that it needs repairing with a new kind of cement. On the other hand, he has reconstructed the edifice on this new basis, and he has given it a bold and remarkably beautiful and harmonious form.

I have now to show in detail, concretely, and as accurately as possible, the meaning of these generalities. But I must first insist on a point which is of considerable importance: if Einstein had confined himself to the first part of his work, as I have described it, the part which shatters the classical ideas of time and space, he would never have attained the fame which now makes his name great in the world of thought.

The point is important because most of those—apart from experts—who have written on Einstein have chiefly, often exclusively, emphasised this more or less "destructive" side of his work. But, as we shall see, from this point of view Einstein was not the first, and he is not alone. All that he has done is to sharpen, and press a little deeper between the badly joined stones of classical science, a chisel which others, especially the great Henri Poincaré, had used long before him. My next point is to explain, if I can, the real, the immortal, title of Einstein to the gratitude of men: to

show how he has by his own powers rebuilt the structure in a new and magnificent form after his critical work. In this he shares his glory with none.

. . . . .

The whole of science, from the days of Aristotle until our own, has been based upon the hypothesis—properly speaking, the hypotheses—that there is an absolute time and an absolute space. In other words, our ideas rested upon the supposition that an interval of time and an interval of space between two given phenomena are always the same, for every observer whatsoever, and whatever the conditions of observation may be. For instance, it would never have occurred to anybody as long as classical science was predominant, that the interval of time, the number of seconds, which lies between two successive eclipses of the sun, may not be the fixed and identically same number of seconds for an observer on the earth as for an observer in Sirius (assuming that the second is defined for both by the same chronometer). Similarly, no one would have imagined that the distance in metres between two objects, for instance the distance of the earth from the sun at a given moment, measured by trigonometry, may not be the same for an observer on the earth as for an observer in Sirius (the metre being defined for both by the same rule).

"There is," says Aristotle, "one single and invariable time, which flows in two movements in an identical and simultaneous manner; and if these two sorts of time were not simultaneous, they would nevertheless be of the same nature. . . . Thus, in regard to movements which take place simultaneously, there is one and the same time, whether or no the movements are equal in rapidity; and this is true even if one of them

is a local movement and the other an alteration. . . . It follows that even if the movements differ from each other, and arise independently, the time is absolutely the same for both." [1] This Aristotelic definition of physical time is more than two thousand years old, yet it clearly represents the idea of time which has been used in classic science, especially in the mechanics of Galileo and Newton, until quite recent years.

It seems, however, that in spite of Aristotle, Epicurus outlined the position which Einstein would later adopt in antagonism to Newton. To translate liberally the words in which Lucretius expounds the teaching of Epicurus:

"Time has no existence of itself, but only in material objects, from which we get the idea of past, present, and future. It is impossible to conceive time in itself independently of the movement or rest of things." [2]

Both space and time have been regarded by science ever since Aristotle as invariable, fixed, rigid, absolute data. Newton thought that he was saying something obvious, a platitude, when he wrote in his celebrated Scholion: "Absolute, true, and mathematical time, taken in itself and without relation to any material object, flows uniformly of its own nature. . . . Absolute space, on the other hand, independent by its own nature of any relation to external objects, remains always unchangeable and immovable."

The whole of science, the whole of physics and mechanics, as they are still taught in our colleges and in most of our universities, are based entirely upon these propositions, these ideas of an absolute time and space, taken by themselves and without any reference

[1] *Physics*, bk. iv, ch. xiv.
[2] *De Natura Rerum*, bk. i, vv. 460 ff.

to an external object, independent by their very nature.

In a word—if I may venture to use this figure—time in classical science was like a river bearing phenomena as a stream bears boats, flowing on just the same whether there were phenomena or not. Space, similarly, was rather like the bank of the river, indifferent to the ships that passed.

From the time of Newton, however, if not from the time of Aristotle, any thoughtful metaphysician might have noticed that there was something wrong in these definitions. Absolute time and absolute space are "things in themselves," and these the human mind has always regarded as not directly accessible to it. The specifications of space and time, those numbered labels which we attach to objects of the material world, as we put labels on parcels at the station so that they may not be lost (a precaution that does not always suffice), are given us by our senses, whether aided by instruments or not, only when we receive concrete impressions. Should we have any idea of them if there were no bodies attached to them, or rather to which we attach the labels? To answer this in the affirmative, as Aristotle, Newton, and classical science do, is to make a very bold assumption, and one that is not obviously justified.

The only time of which we have any idea apart from all objects is the psychological time so luminously studied by M. Bergson: a time which has nothing except the name in common with the time of physicists, of science.

It is really to Henri Poincaré, the great Frenchman whose death has left a void that will never be filled, that we must accord the merit of having first proved,

with the greatest lucidity and the most prudent audacity, that time and space, as we know them, can only be relative. A few quotations from his works will not be out of place. They will show that the credit for most of the things which are currently attributed to Einstein is, in reality, due to Poincaré. To prove this is not in any way to detract from the merit of Einstein, for that is, as we shall see, in other fields.

This is how Poincaré, whose ideas still dominate the minds of thoughtful men, though his mortal frame perished years ago, expressed himself, the triumphant sweep of his wings reaching further every day:

"One cannot form any idea of empty space. . . . From that follows the undeniable relativity of space. Any man who talks of absolute space uses words which have no meaning. I am at a particular spot in Paris—the Place du Panthéon, let us suppose—and I say: 'I will come back *here* to-morrow.' If anyone asks me whether I mean that I will return to the same point in space, I am tempted to reply, 'Yes.' I should, however, be wrong, because between this and to-morrow the earth will have travelled, taking the Place du Panthéon with it, so that to-morrow the square will be more than 2,000,000 kilometres away from where it is now. And it would be no use my attempting to use precise language, because these 2,000,000 kilometres are part of our earth's journey round the sun, but the sun itself has moved in relation to the Milky Way, and the Milky Way in turn is doubtless moving at a speed which we cannot learn. Thus we are entirely ignorant, and always will be ignorant, how far the Place du Panthéon shifts its position in space in a single day. What I really meant to say was: 'To-morrow I shall again see the dome and façade of

the Panthéon.' If there were no Panthéon, there would be no meaning in my words, and space would disappear."

Poincaré works out his idea in this way:

"Suppose all the dimensions of the universe were increased a thousandfold in a night. The world would remain the same, giving the word 'same' the meaning it has in the third book of geometry. Nevertheless, an object that had measured a metre in length will henceforward be a kilometre in length; a thing that had measured a millimetre will now measure a metre. The bed on which I lie and the body which lies on it will increase in size to exactly the same extent. What sort of feelings will I have when I awake in the morning, in face of such an amazing transformation? Well, I shall know nothing about it. The most precise measurements would tell me nothing about the revolution, because the tape I use for measuring will have changed to the same extent as the objects I wish to measure. As a matter of fact, there would be no revolution except in the mind of those who reason as if space were absolute. If I have argued for a moment as they do, it was only in order to show more clearly that their position is contradictory."

It would be easy to develop Poincaré's argument. If all the objects in the universe were to become, for instance, a thousand times taller, a thousand times broader, we should be quite unable to detect it, because we ourselves—our retina and our measuring rod—would be transformed to the same extent at the same time. Indeed, if all the things in the universe were to experience an absolutely irregular spatial deformation—if some invisible and all-powerful spirit were to distort the universe in any fashion, drawing it out as

if it were rubber—we should have no means of knowing the fact. There could be no better proof that space is relative, and that we cannot conceive space apart from the things which we use to measure it. When there is no measuring rod, there is no space.

Poincaré pushed his reasoning on this subject so far that he came to say that even the revolution of the earth round the sun is merely a more convenient hypothesis than the contrary supposition, but not a truer hypothesis, unless we imply the existence of absolute space.

It may be remembered that certain unwary controversialists have tried to infer from Poincaré's argument that the condemnation of Galileo was justified. Nothing could be more amusing than the way in which the distinguished mathematician–philosopher defended himself against this interpretation, though one must admit that his defence was not wholly convincing. He did not take sufficiently into account the agnostic element.

Poincaré, in any case, is the leader of those who regard space as a mere property which we ascribe to objects. In this view our idea of it is only, so to say, the hereditary outcome of those efforts of our senses by means of which we strive to embrace the material world at a given moment.

It is the same with time. Here again the objections of philosophic Relativists were raised long ago, but it was Poincaré who gave them their definitive shape. His luminous demonstrations are, however, well known, and we need not reproduce them here. It is enough to observe that, in regard to time as well as space, it is possible to imagine either a contraction or an enlargement of the scale which would be completely

imperceptible to us ; and this seems to show that man cannot conceive an absolute time. If some malicious spirit were to amuse itself some night by making all the phenomena of the universe a thousand times slower, we should not, when we awake, have any means of detecting the change. The world would seem to us unchanged. Yet every hour recorded by our watches would be a thousand times longer than hours had previously been. Men would live a thousand times as long, yet they would be unaware of the fact, as their sensations would be slower in the same proportion.

When Lamartine appealed to time to "suspend its flight," he said a very charming, but perhaps meaningless, thing. If time had obeyed his passionate appeal, neither Lamartine nor Elvire would have known and rejoiced over the fact. The boatman who conducted the lovers on the Lac du Bourget would not have asked payment for a single additional hour ; yet he would have dipped his oars into the pleasant waters for a far longer time.

I venture to sum up all this in a sentence which will at first sight seem a paradox : in the opinion of the Relativists it is the measuring rods which create space, the clocks which create time. All this was maintained by Poincaré and others long before the time of Einstein, and one does injustice to truth in ascribing the discovery to him. I am quite aware that one lends only to the rich, but one does an injustice to the wealthy themselves in attributing to them what does not belong to them, and what they need not in order to be rich.

There is, moreover, one point at which Galileo and Newton, for all their belief in the existence of absolute space and time, admitted a certain relativity. They recognised that it is impossible to distinguish between

uniform movements of translation. They thus admitted the equivalence of all such movements, and therefore the impossibility of proving an absolute movement of translation.

That is what is called the Principle of Classic Relativity.

. . . . .

An unexpected fact served to bring these questions upon a new plane, and led Einstein to give a remarkable extension to the Principle of Relativity of classic mechanics. This was the issue of a famous experiment by Michelson, of which we must give a brief description.

It is well known that rays of light travel across empty space from star to star, otherwise we should be unable to see the stars. From this physicists long ago concluded that the rays travelled in a medium that is devoid of mass and inertia, is infinitely elastic, and offers no resistance to the movement of material bodies, into which it penetrates. This medium has been named ether. Light travels through it as waves spread over the surface of water at a speed of something like 186,000 miles a second: a velocity which we will express by the letter V.

The earth revolves round the sun in a veritable ocean of ether, at a speed of about 18 miles a second. In this respect the rotation of the earth on its axis need not be noticed, as it pushes the surface of the globe through the ether at a speed of less than two miles a second. Now the question had often been asked: Does the earth, in its orbital movement round the sun, take with it the ether which is in contact with it, as a sponge thrown out of a window takes with it the water which it has absorbed? Experiment—or rather, experiments, for many have been tried with

the same result—has shown that the question must be answered in the negative.

This was first established by astronomical observation. There is in astronomy a well-known phenomenon discovered by Bradley which is called aberration. It consists in this: when we observe a star with a telescope, the image of the star is not precisely in the direct line of vision. The reason is that, while the luminous rays of the star which have entered the telescope are passing down the length of the tube, the instrument has been slightly displaced, as it shares the movement of the earth. On the other hand, the luminous ray in the tube does not share the earth's motion, and this gives rise to the very slight deviation which we call aberration. This proves that the medium in which light travels, the ether which fills the instrument and surrounds the earth, does not share the earth's motion.

Many other experiments have settled beyond question that the ether, which is the vehicle of the waves of light, is not borne along by the earth as it travels. Now, since the earth moves through the ether as a ship moves over a stationary lake (not like one floating on a moving stream), it ought to be possible to detect some evidence of this speed of the earth in relation to the ether.

One of the devices that may be imagined for the purpose is the following. We know that the earth turns on itself from west to east, and travels round the sun in the same way. It follows that in the middle of the night the revolution of the earth round the sun means that Paris will be displaced, in the direction from Auteuil toward Charenton, at a speed of about thirty kilometres a second. During the day, of course, it is precisely the opposite. Paris changes its place round the sun in the direction from Charenton toward

Auteuil. Well, let us suppose that at midnight a physicist at Auteuil sends a luminous signal. A physicist receiving this ray of light at Charenton, and measuring its velocity, ought to find that the latter is V + 30 kilometres. We know that, as a result of the earth's motion, Charenton recedes before the ray of light. Consequently, since light travels in a medium, the ether, which does not share the earth's motion, the observer at Charenton ought to find that the ray reaches him at a less speed than it would if the earth were stationary. It is much the same as if an observer were travelling on a bicycle in front of an express train. If the express travels at thirty metres a second and the cyclist at three metres a second, the speed of the train in relation to the cyclist will be 30—3 = 27 metres a second. It would be *nil* if the train and the cyclist were travelling at the same rate.

On the other hand, if the cyclist were going toward the train, the speed of the train in relation to him would be 30 + 3 = 33 metres a second. Similarly, when the physicist at Charenton sends out a luminous message at midnight, and the physicist of Auteuil receives it, the latter ought to find that the ray of light has a velocity of V + 30 kilometres.

All this may be put in a different way. Suppose the distance between the observer at Auteuil and the man at Charenton were exactly twelve kilometres. While the ray of light emitted at Auteuil speeds toward Charenton, that town is receding before it to a small extent. It follows that the ray will have to travel a little more than twelve kilometres before it reaches the man of science at Charenton. It will travel a little less than that distance if we imagine it proceeding in the opposite direction.

Now the American physicist Michelson, borrowing an ingenious idea from the French physicist Fizeau, succeeded, with a high degree of accuracy, in measuring distances by means of the interference-bands of light. Every variation in the distance measured betrays itself by the displacement of a certain number of these bands, and this may easily be detected by a microscope.

Let us next suppose that our two physicists work in a laboratory instead of between Charenton and Auteuil. Let us suppose that they are, by means of the interference-bands, measuring the space traversed by a ray of light produced in the laboratory, according as it travels in the same direction as the earth or in the opposite direction. That is Michelson's famous experiment, reduced to its essential elements and simplified for the purpose of this essay. In those circumstances Michelson's delicate apparatus ought to reveal a distinctly measurable difference according as the light travels with the earth or in the opposite direction.

But no such difference was found. Contrary to all expectation, and to the profound astonishment of physicists, it was found that light travels at precisely the same speed whether the man who receives it is receding before it with the velocity of the earth or is approaching it at the same velocity. It is an undeniable consequence of this that *the ether shares the motion of the earth.* We have, however, seen that other experiments, not less precise, had settled that *the ether does not share the motion of the earth.*

Out of this contradiction, this conflict of two irreconcilable yet indubitable facts, Einstein's splendid synthesis, like a spark of light issuing from the clash of flint and steel, came into being.

## CHAPTER II

### SCIENCE IN A NO-THOROUGHFARE

*Scientific truth and mathematics—The precise function of Einstein—Michelson's experiment, the Gordian knot of science—The hesitations of Poincaré—The strange, but necessary, Fitzgerald-Lorentz hypothesis—The contraction of moving bodies—Philosophical and physical difficulties.*

It would be foolish to pretend that we can penetrate the most obscure corners of Einstein's theories without the aid of mathematics. I believe, however, that we can give in ordinary language—that is to say, by means of illustrations and analogies—a fairly satisfactory idea of these things, the intricacy of which is usually due to the infinitely subtle and supple play of mathematical formulæ and equations.

After all, mathematics is not, never was, and never will be, anything more than a particular kind of language, a sort of shorthand of thought and reasoning. The purpose of it is to cut across the complicated meanderings of long trains of reasoning with a bold rapidity that is unknown to the mediæval slowness of the syllogisms expressed in our words.

However paradoxical this may seem to people who regard mathematics as *of itself* a means of discovery, the truth is that we can never get from it anything that was not implicitly inherent in the data which were thrust between the jaws of its equations. If I may use a somewhat trivial illustration, mathematical

reasoning is very like certain machines which are seen in Chicago—so bold explorers in the United States tell us—into which one puts living animals that emerge at the other end in the shape of appetising prepared meats. No spectator could have, or would wish to have, eaten the animal alive, but in the form in which it issues from the machine it can at once be digested and assimilated. Yet the meat is merely the animal conveniently prepared. That is what mathematics does. By means of a marvellous machinery the mathematician extracts the valuable marrow from the *given facts*. It is a machinery that is particularly useful in cases where the wheels of verbal argument, the chain of syllogisms, would soon be brought to a halt.

Does it follow that, properly speaking, mathematics is not a science? Does it follow at least that it is only a science in so far as it is based upon reality, and fed with experimental data, since "experience is the sole source of truth." I refrain from answering the question, as I am one of those who believe that everything is material for science. Still, it was worth while to raise the question because many are too much disposed to regard a purely mathematical education as a scientific education. Nothing could be further from the truth. Pure mathematics is, in itself, merely an abbreviated form of language and of logical thought. It cannot, of its own nature, teach us anything about the external world; it can do so only in proportion as it enters into contact with the world. It is of mathematics in particular that we may say: *Naturæ non imperatur nisi parendo.*

Are not Einstein's theories, as some imperfectly informed writers have suggested, only a play of mathematical formulæ (taking the word in the meaning given

to it by both mathematicians and philosophers) ? If they were only a towering mathematical structure in which the $x$'s shoot out their volutes in bewildering arabesques, with swan-neck integrals describing Louis XV patterns, they would have no interest whatever for the physicist, for the man who has to examine the nature of things before he talks about it. They would, like all coherent schemes of metaphysics, be merely a more or less agreeable system of thought, the truth or falseness of which could never be demonstrated.

Einstein's theory is very different from that, and very much more than that. It is based upon facts. It also leads to facts—new facts. No philosophical doctrine or purely formal mathematical construction ever enabled us to discover new phenomena. It is precisely because it has led to such discovery that Einstein's theory is neither the one nor the other. That is the difference between a scientific theory and a pure speculation, and it is that which, I venture to say, makes the former so superior.

Like some suspension bridge boldly thrown across an abyss, Einstein's theory rests, on the one side, on experimental phenomena, and it leads, at the other side, to other, and hitherto unsuspected, phenomena, which it has enabled us to discover. Between these two solid experimental columns the mathematical reasoning is like the marvellous network of thousands of steel bars which represent the elegant and translucent structure of the bridge. It is that, and nothing but that. But the arrangement of the beams and bars might have been different, and the bridge—though less light and graceful, perhaps—still have been able to join together the two sets of facts on which it rests.

In a word, mathematical reasoning is only a kind of reasoning in a special language, from experimental premises to conclusions which are verifiable by experience. Now there is no language which cannot in some degree be translated into another language. Even the hieroglyphics of Egypt had to give way before Champollion. I am therefore convinced that the mathematical difficulties of Einstein's theories will some day be replaced by simpler and more accessible formulæ. I believe, indeed, that it is even now possible to give by means of ordinary speech an idea, rather superficial perhaps, but accurate and substantially complete, of this wonderful Einsteinian structure which ranges all the conquests of science, as in some well-ordered museum, in a new and superb unity. Let us try.

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We may resume in the few following words the story of the origin, the starting-point, of Einstein's system. 1. Observation of the stars proves that interplanetary space is not empty, but is filled with a special medium, ether, in which the waves of light travel. 2. The fact of aberration and other phenomena seems to prove that the ether is not displaced by the earth during its course round the sun. 3. Michelson's experiment seems to prove, on the contrary, that the earth bears the ether with it in its movement.

This contradiction between facts of equal authority was for years the despair and the wonder of physicists. It was the Gordian knot of science. Long and fruitless efforts were made to untie it until at last Einstein cut it with a single blow of his remarkably acute intelligence.

In order to understand how that was done—which is the vital point of the whole system—we must retrace

our steps a little and examine the precise conditions of Michelson's famous experiment.

I pointed out in the preceding chapter that Michelson proposed to study the speed of a ray of light produced in the laboratory and directed either from east to west or west to east: that is to say, in the direction in which the earth itself moves, at a speed of about eighteen miles a second, as it travels round the sun, or in the opposite direction. As a matter of fact, Michelson's experiment was rather more complicated than that, and we must return to it.

Four mirrors are placed at an equal distance from each other in the laboratory, in pairs which face each other. Two of the opposing mirrors are arranged in the direction east–west, the direction in which the earth moves in consequence of its revolution round the sun. The other two are arranged in a plane perpendicular to the preceding, the direction north–south. Two rays of light are then started in the respective directions of the two pairs of mirrors. The ray coming from the mirror to the east goes to the mirror in the west, is reflected therefrom, and returns to the first mirror. This ray is so arranged that it crosses the path of the light which goes from north to south and back. It interferes with the latter light, causing "fringes of interference" which, as I said, enable us to learn the exact distance traversed by the rays of light reflected between the pairs of mirrors. If anything brought about a difference between the length of the two distances, we should at once see the displacement of a certain number of interference-fringes, and this would give us the magnitude of the difference.

An analogy will help us to understand the matter. Suppose a violent steady east wind blew across London,

and an aviator proposed to cross the city about twelve miles from extreme west to east and back: that is to say, going with the wind on his outward journey and against it on the return journey. Suppose another aviator, of equal speed, proposed at the same time to fly from the same starting-point to a point twelve miles to the north and back, the second aviator will fly both ways at right angles to the direction of the wind. If the two start at the same time, and are imagined as turning round instantaneously, will they both reach the starting-point together? And, if not, which of them will have completed his double journey first?

It is clear that if there were no wind, they would get back together, as we suppose that they both do twenty-four miles at the same speed, which we may roughly state to be 200 yards a second.

But it will be different if, as I postulated, there is a wind blowing from east to west. It is easy to see that in such circumstances the man who flies east to west will take longer to complete the journey. In order to get it quite clearly, let us suppose that the wind is travelling at the same speed as the aviator (200 yards a second). The man who flies at right angles to the wind will be blown twelve miles to the west while he is doing his twelve miles from south to north. He will therefore have traversed *in the wind* a real distance equal to the diagonal of a square measuring twelve miles on each side. Instead of flying twenty-four miles, he will really have flown thirty-four in the wind, the medium in relation to which he has any velocity.

On the other hand, the aviator who flies eastward will never reach his destination, because in each second

of time he is driven westward to precisely the same extent as he is travelling eastward. He will remain stationary. To accomplish his journey he would need to cover *in the wind* an infinite distance.

If, instead of imagining a wind equal in velocity to the aviator (an extreme supposition in order to make the demonstration clearer), I had thought of it as less rapid, we should again find, by a very simple calculation, that the man who flies north and south has less distance to cover in the wind than the man who flies east and west.

Now take rays of light instead of aviators, the ether instead of the wind, and we have very nearly the conditions of the Michelson experiment. A current or wind of ether—since the ether has been already shown to be stationary in relation to the earth's movement—proceeds from one to the other of our east–west mirrors. Therefore the ray of light which travels between these two mirrors, forth and back, must cover a longer distance in ether than the ray which goes from the south mirror to the north and back. But how are we to detect this difference? It is certainly very minute, because the speed of the earth is ten thousand times less than the velocity of light.

There is a very simple means of doing this: one of those ingenious devices which physicists love, a differential device so elegant and precise that we have entire confidence in the result.

Let us suppose that our four mirrors are fixed rigidly in a sort of square frame, something like those "wheels of fortune" with numbers on them that one sees in country fairs. Let us suppose that we can turn this frame round as we wish, without jerking or displacing it, which is not difficult if it floats in a bath of mercury.

I then take a lens and observe the permanent interference-fringes which define the difference between the paths traversed by my two rays of light, north–south and east–west. Then, without losing sight of the bands or fringes, I turn the frame round a quarter of a circle. Owing to this rotation the mirrors which were east–west now become north–south, and *vice versa*. The double journey made by the north–south ray of light has now taken the direction east–west, and has therefore suddenly been lengthened; the double journey of the east–west ray has become north–south, and has been suddenly shortened. The interference-fringes, which indicate the difference in length between the two paths, which has suddenly changed, must necessarily be displaced, and that, as we can calculate, to no slight extent.

Well, we find no change whatever! The fringes remain unaltered. They are as stationary as stumps of trees. It is bewildering, one would almost say revolting, because the delicacy of the apparatus is such that, even if the earth moved through the ether at a rate of only three kilometres a second (or ten times less than its actual velocity), the displacement of the fringes would be sufficient to indicate the speed.

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When the negative result of this experiment was announced, there was something like consternation amongst the physicists of the world. Since the ether was not borne along by the earth, as observation had established, how could it possibly behave as if it did share the earth's motion? It was a Chinese puzzle. More than one venerable grey head was in despair over it.

It was absolutely necessary to find a way out of this

inexplicable contradiction, to end this paradoxical mockery which the facts seemed to oppose to the most rigorous results of calculation. This the men of science succeeded in doing. How? By the method which is generally used in such circumstances—by means of supplementary hypotheses. Hypotheses in science are a kind of soft cement which hardens rapidly in the open air, thus enabling us to join together the separate blocks of the structure, and to fill up the breaches made in the wall by projectiles, with artificial stuff which the superficial observer presently mistakes for stone. It is because hypotheses are something like that in science that the best scientific theories are those which include least hypotheses.

But I am wrong in using the plural in this connection. In the end it was found that one single hypothesis conveniently explained the negative result of the Michelson experiment. That is, by the way, a rare and remarkable experience. Hypotheses usually spring up like mushrooms in every dark corner of science. You get a score of them to explain the slightest obscurity.

This single hypothesis, which seemed to be capable of extricating physicists from the dilemma into which Michelson had put them, was first advanced by the distinguished Irish mathematician Fitzgerald, then taken up and developed by the celebrated Dutch physicist Lorentz, the Poincaré of Holland, one of the most brilliant thinkers of our time. Einstein would no more have attained fame without him than Kepler would without Copernicus and Tycho Brahe.

Let us now see what this Fitzgerald–Lorentz hypothesis, as strange as it is simple, really is.

But we must first glance at a preliminary matter of some importance. A number of able men have

declared—after the issue, let it be said—that the result of the Michelson experiment could only be negative *a priori*. In point of fact, they argue (more or less), the Classic Principle of Relativity, the principle known to Galileo and Newton, implies that it is impossible for an observer who shares the motion of a vehicle to detect the motion of that vehicle by any facts he observes while he is in it. Thus, when two ships or two trains pass each other,[1] it is impossible for the passengers to say which of the two is moving, or moving the more rapidly. All that they can perceive is the relative speed of the trains or ships.

The men of science to whom I have referred say that, if Michelson's experiment had had a positive result, it would have given us the absolute velocity of the earth in space. This result would have been contrary to the Principle of Relativity of classical philosophy and mechanics, which is a self-evident truth. Therefore the result could only be negative.

This is, as we shall see, ambiguous. There is, if I may say so, a flaw in the argument which has escaped the notice even of distinguished men of science like Professor Eddington, the most erudite of the English Einsteinians. It was he who organised the observations of the solar eclipse of May 29, 1919, which have, as we shall see, furnished the most striking verification of Einstein's deductions.

In the first place, if Michelson's experiment had had a positive result, what it would have indicated is the velocity of the earth in relation to the ether. But, for this to be an absolute velocity, the ether would have to be identical with space. This is so far from being

[1] It is assumed that the ship is not rolling or pitching, and that there is no vibration in the train.

necessary that we can easily conceive a space—to put it better, a discontinuity—between two stars that contains no ether and across which neither light nor any other known form of energy would travel.

When Eddington says that "it is legitimate and reasonable," that it is "inherent in the fundamental laws of nature," that we cannot detect any movement of bodies in relation to ether, and that this is certain "even if the experimental evidence is inadequate," he affirms something which would be evident only if space and ether were evidently identical. But this is far from being the case. If Michelson's experiment had had a positive result, if we had detected a velocity on the part of the earth, should we have discovered a velocity in relation to an absolute standard? Certainly not. It is quite possible that the stellar universe which is known to us, with its hundreds of thousands of galaxies which it takes light millions of years to cross, may be contained in a sphere of ether that rolls in an abyss which is devoid of ether, and is sown here and there with other universes, other giant drops of ether, from which no ray of light or anything else may ever reach us. It is, at all events, not inconceivable. And in that case, assuming that the ether has the properties attributed to it by classic physics, even if we had detected the movement of the earth in relation to it, we should not have discovered an absolute movement, but at the most a movement in relation to the centre of gravity of our particular universe, a standard which we could not refer to some other which would be absolutely stationary. The Classical Principle of Relativity would not be violated.

Hence, whatever may have been said to the contrary, the issue of Michelson's experiment might, in these

hypotheses, be either positive or negative without any detriment to Classical Relativism. As a matter of fact, it was negative, so nothing further need be said. Experiment has pronounced, and it alone had the right to pronounce.

These distinctions were not unknown to Poincaré, and he wrote: "By the real velocity of the earth I understand, not its absolute velocity, which is meaningless, but its velocity in relation to the ether." Therefore the possibility of the existence of a velocity discoverable in relation to the ether was not regarded as an absurdity by Poincaré. He said: "Any man who speaks of absolute space uses a word that has no meaning."

It is worth while noticing that in all this the development of Poincaré's ideas betrays a certain hesitation. Speaking of experiments analogous to those of Michelson, he said: "I know that it will be said that we are not measuring its absolute velocity, but its velocity in relation to the ether. That is scarcely satisfactory. Is it not clear that, if we conceive the principle in this fashion, we can make no deductions whatever from it?" From this it is evident that Poincaré, in spite of himself and all his efforts to avoid it, was disposed to find the distinction between space and ether "scarcely satisfactory."

I must admit that Poincaré's own argument seems to me not wholly satisfactory, or at least not convincing. "Nature," says Fresnel, "cares nothing about analytical difficulties." I imagine that it cares just as little about philosophical or purely physical difficulties. It is hardly an incontestable criterion to suppose that a conception of phenomena is so much nearer to reality the more "satisfactory" it is to us, or the better

it is found adapted to the weakness of the human mind. Otherwise we should have to hold, whether we liked or no, that the universe is necessarily adapted to the categories of the mind; that it is constituted with a view to giving us the least possible intellectual trouble. That would be a strange return to anthropocentric finalism and conceit! The fact that vehicles do not pass there, and that pedestrians have to turn back, does not prove that there are no such things as no-thoroughfares in our towns. It is possible, even probable, that the universe also, considered as an object of science, has its no-thoroughfare.

Clearly one may reply to me that it is not the universe that is adapted to our mind, but the mind that has become adapted to the universe in the evolutionary course of their relations to each other. The mind needs in its evolution to adapt itself to the universe, in conformity with the principle of minimum action formulated by Fermat: perhaps the most profound principle of the physical, biological, and moral world. In that respect the simplest and most economical ideas are the nearest to reality.

Yes, but what proof is there that our mental evolution is complete and perfect, especially when we are dealing with phenomena of which our organism is insensible?

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Experiment alone has proved, and had the right to prove, that it is impossible to measure the velocity of an object relatively to the ether. At all events, this is now settled. After all, since it is evidently in the very nature of things that we cannot detect an absolute movement, is it not because the velocity of the earth in relation to the ether is an absolute

velocity that we have been unable to detect it? Possibly; but it cannot be proved. If it is so—which is not at all certain—it is in the last resort *experience*, the one source of truth, which thus tends to prove, indirectly, that the ether is really identical with space. In that case, however, a space devoid of ether, or one containing spheres of ether, would no longer be conceivable, and there can be nothing but a single mass of ether with stars floating in it. In a word, the negative result of Michelson's experiment could not be deduced *a priori* from the problematical identity of absolute space and the ether; but this negative result does not justify us in denying the identity *a posteriori*.

Let us return to our proper subject, the Fitzgerald–Lorentz hypothesis which explains the issue of the Michelson experiment, and which was in a sense the spring-board for Einstein's leap. The hypothesis is as follows.

The result of the experiment is that, whereas when the path of a ray of light between two mirrors is transverse to the earth's motion through ether, and it is then made parallel to the earth's motion, the path ought to be longer, we actually find no such lengthening. According to Fitzgerald and Lorentz, *this is because the two mirrors approached each other in the second part of the experiment.* To put it differently, *the frame in which the mirrors were fixed contracted in the direction of the earth's motion, and the contraction was such in magnitude as to compensate exactly for the lengthening of the path of the ray of light which we ought to have detected.*

When we repeat the experiment with all kinds of different apparatus, we find that the result is always

the same (no displacement of the fringes). It follows that the character of the material of which the instrument is made—metal, glass, stone, wood, etc.—has nothing to do with the result. Therefore all bodies undergo an equal and similar contraction in the direction of their velocity relatively to the ether. This contraction is such that it exactly compensates for the lengthening of the path of the rays of light between two points of the apparatus. In other words, the contraction is greater in proportion as the velocity of bodies relatively to the ether becomes greater.

That is the explanation proposed by Fitzgerald. At first it seemed to be very strange and arbitrary, yet there was, apparently, no other way of explaining the result of Michelson's experiment.

Moreover, when you reflect on it this contraction is found to be less extraordinary, less startling, than one's common sense at first pronounces it. If we throw some non-rigid object, such as one of those little balls with which children play, quickly against an obstacle, we see that it is slightly pushed in at the surface by the obstacle, precisely in the same sense as the Fitzgerald–Lorentz contraction. The ball is no longer round. It is a little flattened, so that its diameter is shortened in the direction of the obstacle. We have much the same phenomenon, though in a more violent form, when a bullet is flattened against a target. Therefore, if solid bodies are thus capable of deformation—as they are, for cold is sufficient of itself to concentrate their molecules more closely—there is nothing absurd or impossible in supposing that a violent wind of ether may press them out of shape.

But it is far less easy to admit that this alteration may be exactly the same, in the given conditions, for

all bodies, whatever be the material of which they are composed. The little ball we referred to would by no means be flattened so much if it were made of steel instead of rubber.

Moreover, there is in this explanation something quite improbable, something that shocks both our good sense and that caricature of it which we call common sense. Is it possible to admit that the contraction of bodies always exactly compensates for the optic effect which we seek, whatever be the conditions of the experiment (and they have been greatly varied)? Is it possible to admit that nature acts as if it were playing hide-and-seek with us? By what mysterious chance can there be a special circumstance, providentially and exactly compensating for every phenomenon?

Clearly there must be some affinity, some hidden connection, between this mysterious material contraction of Fitzgerald and the lengthening of the light path for which it compensates. We shall see presently how Einstein has illumined the mystery, revealed the mechanism which connects the two phenomena, and thrown a broad and brilliant light upon the whole subject. But we must not anticipate.

The contraction of the apparatus in Michelson's experiment is extremely slight. It is so slight that if the length of the instrument were equal to the diameter of the earth—that is to say, 8,000 miles—it would be shortened in the direction of the earth's motion by only six and a half centimetres! In other words, the contraction would be far too small to be in any way measurable in the laboratory.

There is a further reason for this. Even if Michelson's apparatus were shortened by several inches—

that is to say, if the earth travelled thousands of times as rapidly as it does round the sun—we could not detect and measure it. The measuring rods which we would use for the purpose would contract in the same proportion. The deformation of any object by a Fitz-gerald–Lorentz contraction could not be established by any observer on the earth. It could be discovered only by an observer who did not share the movement of the earth: an observer on the sun, for instance, or on a slow-moving planet like Jupiter or Saturn.

Micromegas would, before he left his planet to visit us, have been able to discover, by optical means, that our globe is shortened by several inches in the direction of its orbital movement; supposing that Voltaire's genial hero were provided with trigonometrical apparatus infinitely more delicate than that used by our surveyors and astronomers. But when he reached the earth, Micromegas, with all his precise apparatus, would have found it impossible to detect the contraction. He would have been greatly surprised—until he met Einstein and heard, as we shall hear, the explanation of the mystery.

I have, unfortunately, neither the time nor the space—it is here, especially, that space is relative, and is constantly shortened by the flow of the pen—to give the dialogue which would have taken place between Micromegas and Einstein. Perhaps, indeed, if we are to be faithful to the Voltairean original, the dialogue would have been very superficial, for—to speak confidentially—I believe that Voltaire never quite understood Newton, though he wrote much about him, and Newton was less difficult to understand than Einstein is. Neither did Mme. du Châtelet, for all the praise that has been lavished upon her translation

of the immortal *Principia*. It swarms with meaningless passages which show that, whether she knew Latin or no, she did not understand Newton. But all this is another story, as Kipling would say.

The movement of the apparatus in the ether varies in speed according to the hour and the month in which the Michelson and similar experiments are made. As the compensation is always precise, we may try to calculate the exact law which governs the contraction as a function of velocities, and makes it, as we find, a precise compensation for the latter. Lorentz has done this. Taking V as the velocity of light and $v$ as the velocity of the body moving in ether, Lorentz found that, in order to have compensation in all cases, the length of the moving body must be shortened, in the plane of its progress, in the proportion of 1 to $\sqrt{1-\frac{v^2}{V^2}}$. If we take by way of illustration the case of the orbital movement of the earth, where $v$ is equal to thirty kilometres, we find that the earth contracts in the plane of its orbit in the proportion $\sqrt{1-\frac{1}{100,000,000}}$. The difference between these two numbers is $\frac{1}{200,000,000}$, and the two hundred millionth part of the earth's diameter is equal to $6\frac{1}{2}$ centimetres. It is the figure we had already found.

This formula, which gives the value of the contraction in all cases, is elementary. Even the inexpert can easily see the meaning of it. It enables us to calculate the extent of contraction for every rate of velocity We can easily deduce from it that if the earth's orbital motion were, not 30 kilometres, but 260,000 kilometres a second, it would be shortened by one-half its diameter in the plane of its motion (without any change in its dimensions in the perpendicular). At that speed a

sphere becomes a flattened ellipsoid, of which the small axis is only half the length of the larger axis; a square becomes a rectangle, of which the side parallel to the motion is twice as small as the other.

These deformations would be visible to a stationary spectator, but they would be imperceptible to an observer who shares the movement, for the reason already given. The measuring rods and instruments, and even the eye of the observer, would be equally and simultaneously altered.

Think of the distorting mirrors which one sees at times in places of amusement. Some show you a greatly elongated picture of yourself, without altering your breadth. Others show you of your normal height, but grotesquely enlarged in width. Try, now, to measure your height and breadth with a rule, as they are given in these deformed reflections in the mirror. If your real height is 5 feet 6 inches, and your real width 2 feet, the rule will, when you apply it to the strange reflection of yourself in the glass, merely tell you that this figure is 5 feet 6 inches in height and 2 feet in breadth. The rule as seen in the mirror undergoes the same distortion as yourself.

Hence it is that, even if the globe of the earth had the fantastic speed which we suggested above, its inhabitants would have no means of discovering that they and it were shortened by one-half in the plane east to west. A man 5 feet 6 inches in height, lying in a large square bed in the direction north–south, then changing his position to east–west, would, quite unknown to himself, have his length reduced to 2 feet 9 inches. At the same time he would become twice as stout as before, because previously his breadth was orientated from east to west. But the earth travels

at the rate of only thirty kilometres a second, and its entire contraction is only a matter of a few centimetres.

In contrast with the earth's velocity, the speed of our most rapid means of transport is only a small fraction of a kilometre a second. An aeroplane going at 360 kilometres an hour has a speed of only 100 metres a second. Hence the maximum Fitzgerald–Lorentz contraction of our speediest machines can only be such an infinitesimal fraction of an inch that it is entirely imperceptible to us. That is why—that is the only reason why—the solid objects with which we are familiar seem to keep a constant shape, at whatever speed they pass before our eyes. It would be quite otherwise if their speed were hundreds of thousands of times greater.

All this is very strange, very surprising, very fantastic, very difficult to admit. Yet it is a fact, if there really is this Fitzgerald–Lorentz contraction, which has so far proved the only possible explanation of the Michelson experiment. But we have already seen some of the difficulties that we find in entertaining the existence of this contraction.

There are others. If all that we have just said is true, only objects which are stationary in the ether would retain their true shapes, for the shape is altered as soon as there is movement through the ether. Hence, amongst the objects which we think spherical in the material world (planets, stars, projectiles, drops of water, and so on), there would be some that really are spheres, whilst others would, on account of the speed or slowness of their movements, be merely elongated or flattened ellipsoids, altered in shape by their velocity. Amongst the various square objects, some would be really square, while others, travelling

at different speeds relatively to the ether, would be rather rectangles, shortened on their longer sides owing to their velocity. And it is supposed that we would have no means of knowing which of these objects moving at different speeds are really shaped as we think and which are shaped otherwise, because, as the Michelson experiment proves, we cannot detect a velocity relatively to the ether.

This we utterly decline to believe, say the Relativists. There are too many difficulties about the matter. Why speak persistently, as Lorentz does, of velocities in relation to the ether, when no experiment can detect such a velocity, yet experiment is the sole source of scientific truth ? Why, on the other hand, admit that some of the objects we perceive have the privilege of appearing to us in their real shape, without alteration, while others do not ? Why admit such a thing when it is, of its very nature, repugnant to the spirit of science, which is always opposed to exceptions in nature —science deals only with general laws—especially when the exceptions are imperceptible ?

That was the state of affairs—very advanced from the point of view of the mathematical expression of phenomena, but very confused, deceptive, contradictory, and troublesome from the physical point of view —when "at length Malherbe arrived" . . . I mean Einstein.

## CHAPTER III

### EINSTEIN'S SOLUTION

*Provisional rejection of ether—Relativist interpretation of Michelson's experiment—New aspect of the speed of light—Explanation of the contraction of moving bodies—Time and the four dimensions of space—Einstein's "Interval" the only material reality.*

EINSTEIN'S first act of intelligent audacity was that, without relegating the ether to the category of those obsolete fluids, such as phlogiston and animal spirits, which obstructed the avenues of science until Lavoisier appeared—without denying all reality to ether, for there must be some sort of support for the rays which reach us from the sun—he observed that, in all that we have as yet seen, there is always question of velocities relatively to the ether.

We have no means whatever of establishing such velocities, and perhaps it would be simpler to leave out of our arguments this entity, real or otherwise, which is inaccessible and merely plays the futile and troublesome part of fifth wheel to the electromagnetic chariot in the progress of physicists along the ruts of their difficulties.

The first point is then: Einstein begins, provisionally, by omitting the ether from his line of reasoning. He neither denies nor affirms its existence. He begins by ignoring it.

We will now follow his example. We shall no longer, in the course of our demonstration, speak about the

medium in which light travels. We shall consider light only in relation to the beings or material objects which emit or receive it. We shall find that our progress becomes at once much easier. For the moment we will relegate the ether of the physicists to the store of useless accessories, along with the suave, formless, vague—but so precious artistically—ether of the poets.

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Shortly, what does Michelson's experiment prove? Only that a ray of light travels at the surface of the earth from west to east at exactly the same speed as from east to west. Let us imagine two similar guns in the middle of a plain, both firing at the same moment, in calm weather, and discharging their shells with the same initial velocity, but one toward the west and the other toward the east. It is clear that the two shells will take the same time to traverse an equal amount of space, one going toward the west and the other toward the east. The rays of light which we produce on the earth behave in this respect, as regards their progress, exactly as the shells do. There would therefore be nothing surprising in the result of the Michelson experiment, if we knew only what experience tells us about the luminous rays.

But let us push the comparison further. Let us consider the shell fired by one of the guns, and imagine that it hits a target at a certain spot, and that, when it reaches the target, the residual velocity of the shell is, let us say, fifty metres a second. I imagine the target mounted on a motor tractor. If the latter is stationary the velocity of the shell in relation to the target will be, as we said, fifty metres a second at the point of impact. But let us suppose that the tractor and the target are moving at a speed of, for instance, ten metres

a second toward the gun, so that the target passes to its preceding position exactly at the moment when the shell strikes it. It is clear that the velocity of the shell relatively to the target at the moment of impact will not now be fifty metres, but 50 + 10 = 60 metres a second. It is equally evident that the speed will fall to 50 — 10 = 40 metres a second if (other things being equal) the target is travelling away from the gun, instead of toward it. If, in the latter case, the velocity of the target were equal to that of the shell, it is clear that the relative velocity of the shell would now be *nil*.

So much is clear enough. That is how jugglers in the music-halls can catch eggs falling from a height on plates without breaking them. It is enough to give the plate, at the moment of contact, a slight downward velocity, which lessens by so much the velocity of the shock. That is also how skilled boxers make a movement backward before a blow, and thus lessen its effective force, whereas the blow is all the harder if they advance to meet it.

If the luminous rays behaved in all respects like the shells, as they do in the Michelson experiment, what would be the result ? When one advances very rapidly to meet a ray of light, one ought to find its velocity increased relatively to the observer, and lessened if the observer recedes before it. If this were the case, all would be simple ; the laws of optics would be the same as those of mechanics ; there would be no contradiction to sow discord in the peaceful army of our physicists, and Einstein would have had to spend the resources of his genius on other matters.

Unfortunately—perhaps we ought to say fortunately, because, after all, it is the unforeseen and the

mysterious that lend some charm to the way of the world—this is not the case. Both physical and astronomical observation show that, under all conditions, when an observer advances rapidly toward luminous waves or recedes rapidly from them, they still show always the same velocity relatively to him. To take a particular case, there are in the heavens stars which recede from us and stars which approach us; that is to say, stars from which we recede, or which we approach, at a speed of tens, and in some cases hundreds, of miles a second. But an astronomer, de Sitter, has proved that the velocity of the light which reaches us is, for us, always exactly the same.

Thus, up to the present it has proved quite impossible for us, by any device or movement, to add to or lessen in the least the velocity with which a ray of light reaches us. The observer finds that the rate of speed of the light is always exactly the same relatively to himself, whether the light comes from a source which rapidly approaches or recedes from him, whether he is advancing toward it or retreating before it. The observer can always increase or lessen, relatively to himself, the speed of a shell, a wave of sound, or any moving object, by pushing toward or moving away from the object. When the moving object is a ray of light, he can do nothing of the kind. The speed of a vehicle cannot in any case be added to that of the light it receives or emits, or be subtracted from it.

This fixed speed of about 186,000 miles a second, which we find always in the case of light, is in many respects analogous to the temperature of 273° below zero which is known as "absolute zero." This also is, in nature, an impassable limit.

All this proves that the laws which govern optical

phenomena are not the same as the classic laws of mechanical phenomena. It was for the purpose of reconciling these apparently contradictory laws that Lorentz, following Fitzgerald, gave us the strange hypothesis of contraction.

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But we shall now find Einstein showing us, in luminous fashion, that this contraction is seen to be perfectly natural when we abandon certain conceptions —perhaps erroneous, though classical—which ruled our habitual and traditional way of estimating lengths of space and periods of time.

Take any object—a measuring rod, for instance. What is it that settles for us the apparent length of the rod? It is the image made upon our retina by the two rays that come from the two ends of the rod, and which reach our eye *simultaneously*.

I italicise the word, because it is the key of the whole matter. If the rod is stationary before us, the case is simple. But if it is moved while we are looking at it, the case is less simple. It is so much less simple that before the work of Einstein most of our learned men and the whole of classic science thought that the instantaneous image of an object that was not subject to change of shape was necessarily and always identical, and independent of the velocities of the object and the observer. The whole of classical science argued as if the spread of light was itself instantaneous—as if it had an infinite velocity—which is not the case.

I stand on the bank by the side of a railway. On the line is a handsome Pullman car, in which it is so pleasant to think that space is relative, in the Galileian sense of the word. Close to the line I have two pegs fixed,

one blue, the other red, and they exactly mark the ends of the coach and indicate its length. Then, without leaving my observation-post on the bank, my face turned towards the middle of the coach, I give orders for the coach to be drawn back and coupled to a locomotive of unheard-of power, which is to carry the coach past me at a fantastic speed, millions of times faster than the speed any mere engineer could provide. Such is the potential superiority of the imagination over sober reality! I assume further that my retina is perfect, and is so constituted that the visual impressions will remain on it only as long as the light which causes them. These somewhat arbitrary suppositions count for nothing in the essence of the demonstration. They are only for the sake of convenience.

Now for the question. Will the coach (which I assume to be of some rigid metal), as it passes before me at full speed, seem to me to be exactly the same length as it did when it was at rest? To put it differently, at the moment when I see its front end coincide with the blue peg I had planted, shall I see its back end coincide at the same time with the red peg? To this question Galileo, Newton, and all the supporters of classic science would reply *yes*. Yet according to Einstein the answer is *no*.

Here is the simple proof, as we deduce it from Einstein's general idea.

I am, recollect, on the edge of the track, at an equal distance from both pegs. When the front end of the coach coincides with the blue peg, it sends toward my eye a certain ray of light (which, for convenience, we will call the front ray), and this coincides with the luminous ray coming to me from the blue peg. This

front ray reaches my eye *at the same time* as a certain ray that comes from the back end of the coach (which we will call the back ray). Does the back ray coincide with the ray which comes to me from the red peg? Clearly not. The front ray leaves the front end of the coach at the same speed as the back ray leaves the back end; as any observer in the coach would find who cared to try the Michelson experiment on them. But the front end of the coach is receding from me while the back end is approaching me. Hence the front ray travels toward my eye more slowly than the back ray, though I cannot perceive this, as, when they reach me, I find that they both have the same velocity. Hence the back ray, which reaches my eye at the same time as the front ray, must have left the back end of the coach later than the front ray left the front end of the coach. Therefore, when I see the front end of the coach coincide with the blue peg, I at the same time see the back end of the carriage *after* it has passed the red peg. Therefore the length of a coach travelling at full speed, and such as it appears to me, is shorter than the distance between the two pegs, which indicated the length of the coach at rest. Q.E.D.

Very little attention is needed for any person to understand this argument, though its elementary simplicity has not been attained without difficulty. It is part of Einstein's mathematical argument and of his conception of simultaneity.

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It follows that the coach, or, in general, any object, seems to be contracted in virtue of its velocity, and in the direction of that velocity, relatively to the spectator. The same thing happens, obviously, if the

observer moves in relation to the object, because we can know only relative velocities, in virtue of the Classical Principle of Relativity of Newton and Galileo.

In this new light the Lorentz–Fitzgerald contraction becomes intelligible, or at least admissible. The contraction, thus considered, is not the cause of the negative result of the Michelson experiment: it is an effect of it. It is now quite clear, and we see that there was something wrong with the classical way of estimating the instantaneous dimension of objects.

Certainly the fact that luminous rays, starting out from their sources at different speeds, should have the same speed when they reach our eye, is strange. It upsets our habitual way of looking at things. If I may venture to use a comparison simply for the purpose of provoking reflection, not at all in the way of explanation, we have here something analogous to what happens with the bombs of aviators. Bombs of a given type, whether released at a height of 5,000 or of 10,000 metres, which therefore have very different downward velocities at 5,000 metres from the ground, have always the same residual velocity when they reach the ground. This is due to the moderating and equalising influence of the atmospheric resistance, which prevents the speed from increasing indefinitely, and makes it constant when it has attained a certain value.

Must we suppose that there is round our eye and round objects a sort of field of resistance which sets a similar limit to the light ? Who knows ? But perhaps such questions have no meaning for the physicist. He can know nothing about the behaviour of light except when it leaves its source or when it reaches the eye, whether armed with instruments or no.

He cannot learn how it behaves during its passage across the intermediate space, in which there is no matter.

Indeed, the more deeply we study the new physics, the more we see that it derives almost all its strength from its systematic disdain of all that is beyond phenomena, all that cannot fall under experimental observation. It is because it is solely based upon facts (however contradictory they may be) that our proof of the necessary contraction of objects owing to their velocity relatively to the observer is so strong.

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We must understand the profound significance of the Fitzgerald–Lorentz contraction. This apparent contraction is by no means due to the movement of objects relatively to the ether. It is essentially the effect of the movements of objects and observers relatively to each other, or relative movements in the sense of the older mechanics.

The greatest relative velocities to which we are accustomed in our daily life are less than a few kilometres a second. The initial velocity of the shell fired by "Bertha" was only about 1,300 metres a second. For movements so slow as this the Relativist contraction is entirely negligible. Hence, as the classical mechanics had never observed such contraction, it regarded the shapes and dimensions of rigid objects as independent of systems of reference.

It was very nearly true; and that makes all the difference between true and false. To say that 999,990 + 9 = 1,000,000, is to say something that is very nearly true, and is therefore false. When it was discovered that the earth was round no change was made in their procedure by architects. They

continued to build as if the direction indicated by the plumb-line was always parallel to itself. In the same way those who make our locomotives and aeroplanes will not have to consider the forms of the machines as dependent on their velocities. What does it matter? The practical point of view is not, and cannot be, that of science except indirectly. So much the worse if there is no indirect influence, or if it is slow in coming.

Some years ago, however, we discovered things which move at speeds, relatively to us, of tens or hundreds of thousands of kilometres a second; the projectiles of the cathode rays and of radium. In this case the Relativist contraction is very considerable. We shall see how it has been observed.

But let us first recapitulate what we have seen. Objects seem to alter their shape in the direction of their movement and not in the direction perpendicular to this. Therefore their forms, even if they be composed of an ideal and perfectly rigid material, depend on their velocity relatively to the observer. This is the essentially new point of view which Einstein's "Special Relativity" superimposes upon the Relativity of classical mechanics and philosophers. For these the absolute dimensions of a rigid object or a geometrical figure were not absolute; it was only the *relations* of these dimensions which were real.

The new point of view is that these relations are themselves relative, because they are a function of the velocity of the observer. It is a sort of Relativity in the second degree, of which neither the philosophers nor the classic physicists had dreamed.

Spatial relations themselves are relative, in a space which is already relative.

In the case of our Pullman car and the two pegs

which mark its length when it is stationary, an observer situated in the carriage would find the distance between the two pegs shortened as he passes them. The coach would seem to him longer than the distance between the pegs. I who remain beside the pegs observe the contrary. Yet I have no means of proving to the passenger that he is wrong. I see quite plainly that the ray of light which comes from the back peg runs behind the coach, and has therefore, relatively to it, a speed of less than 186,000 miles a second. I know that this is the reason for the passenger's error, but I have no means of convincing him that he is wrong. He will always say, and rightly: "I have measured the speed at which this ray reaches me, and I have found it 186,000 miles a second." Each of us is really right.

In very rapid motion a square would seem to the observer a rectangle; a circle would appear to be an ellipse. If the earth travelled some thousands of times faster round the sun, we should see it elongated, like a giant lemon suspended in the heavens. If an aviator could fly at a fantastic speed over Trafalgar Square, in the direction of the Strand—and if the impressions on his retina were instantaneous—he would see the Square as a very flattened rectangle. If he flew in a diagonal line about it, he would find it shaped like a lozenge. If the same aviator flew across a road on which fat cattle were being driven to the slaughter-house, he would be astonished, for the beasts would seem to him extraordinarily lean, while there would be no change in their length.

The fact that these alterations of shape owing to velocity are reciprocal is one of the most curious consequences of all this. A man who could pass in

every direction amongst his fellows at the fantastic speed of one of Shakespeare's spirits—let us put it at about 170,000 miles an hour, though there would be no limit—would find that his fellows had become dwarfs only half as large as himself. Would he have become a giant, a sort of Gulliver amongst the Lilliputians? Not in the least. Such is the justice of the scheme of earthly things that he himself would seem a dwarf to the people whom he thought smaller than himself, and who are quite sure of the contrary.

Which is right, and which wrong? Both. Each point of view is accurate, but there are only personal points of view.

Again, any observer whatever will only see things that are not connected with him as smaller—never larger—than the things which are connected with his movement. If I might venture to relieve this sober exposition by a reflexion rather less austere than is usual in physics, I would say that the new system affords a supreme justification of egoism, or, rather, of egocentricism.

It is the same with time as with space. By similar reasoning to that which has shown us how the distance of things in space is connected with their velocity relatively to the observer, it can be shown that their distance in time likewise depends upon this.

It would be useless to reproduce here the whole of the Einsteinian argument as to duration. It is analogous to that which we have used in regard to length, and even simpler. The result is as follows. The time expressed in seconds which a train takes to pass from one station to another is shorter for the passengers on the train than for us who watch it pass, though our

watches may be just the same as theirs.[1] Similarly, all the gestures of men who are on moving vehicles will seem to a stationary observer slowed down, and therefore prolonged, and vice versa. But the velocity would, as in the case of variation in length, have to be fantastic to make these variations in time perceptible.

It is not less true that the time between the birth and the death of any creature, its life, will seem longer if the creature moves rapidly and fantastically relatively to the observer. In this world, where appearance is almost everything, this is not without importance, and it follows that, philosophically speaking, to move on is to last longer; but for others, not for oneself; just as others may seem to me to last longer. A striking, a profound, an unforeseen justification of the words of the sage: immobility is death!

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Formerly, before the Einsteinian *hegira*, before the Relativist Era opened, everybody was convinced that the portion of *space* occupied by an object was sufficiently and explicitly defined by its dimensions—length, breadth, and height. These are what are called the three *dimensions* of an object; just as we speak, to use a different expression, of the longitude, latitude, and altitude of each of its points, or as we speak in astronomy of its right ascension, declination, and distance.

It was quite understood that we had, in addition,

[1] The best definition of the second that can be given is the following: it is the time which light takes to cover 186,000 miles in empty space and far from any strong gravitational field. This definition, the only strict definition, is further justified by the fact that there is no better means of regulating clocks than luminous or Hertzian (which have the same speed) signals.

to indicate the epoch, the moment, to which these data correspond. If I define the position of an aeroplane by its longitude, latitude, and altitude, these indications are only correct for a certain moment, because the aeroplane is moving relatively to the observer, and the moment also must be indicated. In this sense it has long been known that space depends upon time.

But the Relativist theory shows that it depends upon time in a much more intimate and deeper manner, and that time and space are as closely connected as those twin monsters which the surgeon cannot separate without killing both.

The dimensions of an object, its shape, the apparent *space* occupied by it, depend upon its velocity : that is to say, upon the *time* which the observer takes to traverse a certain distance relatively to the object. Here we have *space* already depending upon *time*. In addition, the observer measures the time with a chronometer, the seconds of which are more or less accelerated according to his velocity.

Hence it is impossible to define space without time. That is why we now say that time is the fourth dimension of space, or that the space in which we live has four dimensions. It is remarkable that there were able men in the past who had a more or less clear intuition of this. Thus we find Diderot, in 1777, writing in the *Encyclopédie*, in the article " Dimension " :

" I have already said that it is impossible to conceive more than three dimensions. A learned man of my acquaintance, however, believes that one might regard duration as a fourth dimension, and that the product of time by solidity would be, in a sense, a product of four dimensions. The idea may not be admitted, but

it seems to be not without merit, if it be only the merit of originality."

It was algebra, undoubtedly, that gave rise to the idea of a space with more than three dimensions. Since, in point of fact, lines or spaces of one dimension are represented by algebraical expressions of the first degree, surfaces or spaces of two dimensions by formulæ of the second degree, and volumes or spaces of three dimensions by expressions of the third degree, it was natural to ask oneself if formulæ of the fourth and higher degrees are not also the algebraical representation of some form of space with four or more dimensions.

The four-dimensional space of the Relativists is, however, not quite what Diderot imagined. It is not the product of time by extension, for a diminution of time is not compensated in it by an increase of space. Quite the contrary. Take two events, such as the successive passage of our Pullman car through two stations. For a passenger in the car the distance between the two stations, measured by the length of the track covered, is, as we saw, shorter than for a person who is standing stationary beside the line. The time between passing through the two stations is likewise less for the first observer. The number of seconds and fractions of seconds marked by his chronometer is smaller for him, as we saw.

In a word, distance in time and distance in space diminish simultaneously when the velocity of the observer increases, and both increase when the velocity of the observer lessens.

Thus velocity (velocity relatively to the things observed, we must always remember) acts in a sense as a double brake lessening durations and shortening

lengths. If a different illustration be preferred, velocity enables us to see both spaces and times more obliquely, at an increasingly sharp angle. Space and time are therefore only changing effects of perspective.

Can we conceive space of four dimensions? That is to say, can we imagine or visualise it? Even if we cannot, it proves nothing as regards the reality of such space. During ages no one conceived such a thing as the Hertzian waves, and even to-day we have no direct sense-impression of them. They exist none the less. As a matter of fact, we find it difficult to conceive space of three dimensions. If it were not for our muscular changes, we should know nothing about it. A paralysed and one-eyed man, that is to say, a man without the sensation of relief which we get from binocular vision—and even this is, in the first place, a muscular sensation—would, with his single eye, see all objects on the same plane, as on the drop-scene of a theatre. He could have no perception of three-dimensional space.

I believe there are people who can form an idea of four-dimensional space. The successive appearances of a flower in its various phases of growth, from the day when it is but a frail green bud until the time when its exhausted petals fall sadly to the ground, and the successive changes of its corolla under the influence of the wind, give us a globular image of the flower in four-dimensional space.

Are there any who can see all this together? I believe that there are, especially amongst good chess-players. When a skilful player plays well, it is because he can take in with a single glance of his mental eye the whole chronological and spatial series of moves

that may follow the first move, with all their effects on the board. He *sees the whole series simultaneously.*

The words I have italicised look contradictory. That is because we are in a province where it is all but impossible to express the fine shades of things in words. One might just as well attempt to define verbally all that there is in a symphony of Beethoven. "The translator is a traitor." If there is any truth in the proverb, it is because words are the organ of translation.

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We have reached a point in our gradual progress into Relativist physics where we have before our eyes merely a battlefield strewn with corpses and ruins.

We had regarded time and space as hooks solidly fastened to the wall behind which lurks reality, and on these we hang our floating ideas of the material world, just as we hang our coats on the rack. Now they lie, torn down and crumpled, amongst the rubbish of ancient theories, victims of the hammer-blows of the new physics.

We knew quite well, of course, that the souls of men were inscrutable to us, but we did think that we saw their faces. Now, as we approach them, we find that it is only masks we saw. The material world, as Einstein shows it to us, is a sort of masked ball, and, by a deceptive irony, it is we ourselves who have made the black velvet masks and the gay costumes.

Instead of revealing reality to us, space and time are, according to Einstein, only moving veils, woven by ourselves, which hide it from us. Yet—strange and melancholy reflection—we can no more conceive the world without space and time than we can observe

certain microbes under the microscope without first injecting colouring matter into them.

Are time and space, then, merely hallucinations? And, if so, what *is* real?

No. Once the Relativist has thrown down the tottering ruins, he begins to reconstruct. Behind the veils, now torn down and trodden under foot, a new and more subtle reality is about to appear.

If we describe the universe in the usual way, in separate categories of space and time, we see that its aspect depends upon the observer. Happily, it is not the same when we describe it in the unique category of the four-dimensional continuum in which Einstein locates phenomena, and in which space and time are inseparably united.

If I may venture to use this illustration, time and space are like two mirrors, one convex, the other concave, the curvature of which is accentuated in proportion to the velocity of the observer. Each of these mirrors gives us, separately, a distorted picture of the succession of things. But this is fortunately compensated for by the fact that, when we combine the two mirrors so that one reflects the rays received by the other, the picture of the succession of things is restored in its unaltered reality.

The distance in time and the distance in space of two given events which are close to each other both increase or decrease when the velocity of the observer decreases or increases. We have shown that. But an easy calculation—easy on account of the formula given previously to express the Lorentz–Fitzgerald contraction—shows that there is a constant relation between these concomitant variations of time and space. To be precise, the distance in time and the

distance in space between two contiguous events are numerically to each other as the hypotenuse and another side of a rectangular triangle are to the third side, which remains invariable.[1]

Taking this third side for base, the other two will describe, above it, a triangle more or less elevated according as the velocity of the observer is more or less reduced. This fixed base of the triangle, of which the other two sides—the spatial distance and the chronological distance—vary simultaneously with the velocity of the observer, is, therefore, a quantity independent of the velocity.

It is this quantity which Einstein has called the *Interval* of events. This "Interval" of things in four-dimensional space-time is a sort of conglomerate of space and time, an amalgam of the two. Its components may vary, but it remains itself invariable. It is the constant resultant of two changing vectors. The "Interval" of events, thus defined, gives us for the first time, according to Relativist physics, an impersonal representation of the universe. In the striking words of Minkowski, "space and time are mere phantoms. All that exists in reality is a sort of intimate union of these entities."

The sole reality accessible to man in the external world, the one really objective and impersonal thing which is comprehensible, is the Einsteinian *Interval* as we have defined it. The *Interval* of events is to Relativists the sole perceptible part of the real. Apart from that there is something, perhaps, but nothing that we can know.

[1] In the geometrical calculus or representation that may be substituted for this the hypotenuse of the triangle is the distance in time, each second being represented by 300,000 kilometres.

Strange destiny of human thought! The principle of relativity has, in virtue of the discoveries of modern physics, spread its wings much farther than it did before, and has reached summits which were thought beyond the range of its soaring flight. Yet it is to this we owe, perhaps, our first real perception of our weakness in regard to the world of sense, in regard to reality.

Einstein's system, of which we have now to see the constructive part, will disappear some day like the others, for in science there are merely theories with "provisional titles," never theories with "definitive titles." Possibly that is the reason of its many victories. The idea of the *Interval* of things will, no doubt, survive all these changes. The science of the future must be built upon it. The bold structure of the science of our time rises upon it daily.

It must, in fine, be clearly understood that the *Einsteinian Interval* tells us nothing about the absolute, about things in themselves. It, like all others, shows us only relations between things. But the relations which it discloses seem to be real and unvarying. They share the degree of objective truth which classic science attributed, with, perhaps, unfounded assurance, to the chronological and spatial relations of phenomena. In the view of the new physics these were but false scales. The Einsteinian Interval alone shows us what can be known of reality.

Einstein's system, therefore, takes pride in having lifted for all future time a corner of the veil which conceals from us the sacred nudity of nature.

## CHAPTER IV

### EINSTEIN'S MECHANICS

*The mechanical foundation of all the sciences—Ascending the stream of time—The speed of light an impassable limit—The addition of speeds and Fizeau's experiment—Variability of mass—The ballistics of electrons—Gravitation and light as atomic microcosms—Matter and energy—The death of the sun.*

When Baudelaire wrote:

> I hate the movement that displaces lines,

he thought only, like the physicists of his time, of the static deformations which have been known as long as there have been men to observe them. What we have seen about Einsteinian time and space has taught us that there must be, in addition to these, kinematic deformations, to which every material object, however rigid it seems, is liable.

Movement, therefore, displaces lines much more than Baudelaire supposed, even the lines of the hardest of marble statues. This kind of deformation, which is pleasant rather than hateful, since it brings us nearer to the heart of things, has upset the whole of mechanics.

Mechanics is at the foundation of all the experimental sciences, because it is the simplest, and because the phenomena it studies are always present—if not exclusively present—amongst the phenomenal objects of the other sciences, such as physics, chemistry, and biology.

The converse of this is not true. For instance,

there is not a single phenomenon in chemistry or biology in which one has not to study bodies in movement, objects endowed with mass and giving out or absorbing energy. On the other hand, the peculiar aspects of a biological, chemical, or physical phenomenon, such as the existence of a difference of potential, an oxidation, or an osmotic pressure, are not always found in the study of the movements of a ponderable mass and of the forces which act upon and through it.

Compared with mechanics, the sciences of physics, chemistry, and biology have, in the order in which we name them, objects of increasing complexity and generality, or, to put it better, of decreasing universality. These sciences are mutually dependent in the way that the trunk, branches, leaves, and flowers of a tree are. They are to some extent related to each other as are the various parts of the jointed masts on which military telegraphists fix their antennæ. The lower part of the mast, the larger part, sustains the whole ; but it is the upper parts which bear the delicate and complicated organs.

The object of the great synthetists in science has always been, and is, to reduce all phenomena to mechanical phenomena, as Descartes attempted. Whether these attempts are well-grounded or no, whether they will some day succeed or are condemned *a priori* to failure because physico-biological phenomena involve elements that are essentially incapable of reduction to mechanical elements, is a question that has been, and will continue to be, much discussed. But, however thinkers may differ on that point, they are agreed on this : in all natural phenomena, in all phenomena that are objects of science, there is the

mechanical element—exclusive in some, the principal element in others.

All this leads to the conclusion that whatever modifies mechanics, modifies at the same time the whole structure of ideas founded thereon—that is to say, the other sciences, the whole of science, our entire conception of the universe. But we are now going to see that Einstein's theory, as a direct effect of what it teaches in regard to space and time, completely upsets the classical mechanics. It is in this way, particularly, that it has shaken the rather somnolent frame of traditional science, and the vibration is not yet over.

In approaching the Einsteinian mechanics we shall have the pleasure of passing from ideas of time and space that are rather too exclusively geometrical and psychological to the direct study of material realities, of *bodies*. Here we can compare theory and reality, the mathematical premises and the substantial verifications ; and we shall be pleased to see what the facts, given in experience, have to say on the matter. We shall be able to make our choice, with informed minds and sound criteria, between the old and the new ideas.

In a word, if I may use this illustration, as long as we were dealing with ideas of space and time—which are empty frames in themselves, vases that would interest us chiefly by the liquids they contain—we were rather like the young men who have to choose a *fiancée* solely by the description of her which has been given them. We are now going to see with our own eyes, and see at work the two aspirants to our affection : classical science and Einstein's theory. We shall see both of them take up the paste of facts, and we shall be able to compare the delicious dishes which they

respectively make from it for the nourishment of the mind.

Theories have no value except as functions of facts. Those which, like so many in metaphysics, have no real criterion by which we may test them, are all of the same value. Experience, the sole source of truth of which Lucretius said long ago :

unde omnia credita pendent,

or the material facts, is going to judge Einstein's system for us.

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The result of the Michelson experiment, the impossibility of proving any velocity of the earth in relation to the medium in which light is propagated, amounts to this : we have no means whatever of detecting a speed higher than that of light. This consequence of the Michelson experiment will be better understood, perhaps, if we put it in a tangible form. Here is an illustration that will serve our purpose.

In some astronomical novel an imaginary observer is supposed to recede from the earth at a speed greater than that of light—at 300,000 miles a second, let us say —yet to keep his eyes (armed with prodigious glasses) steadily fixed on this little globe of ours.

What will happen ? Evidently, our observer will see the train of earthly events in inverse order, because in the course of his voyage he will catch up in succession the luminous waves which left the earth before him. The farther away they are, the longer it must be since they left the earth. After a time our man, or our superman, will witness the Battle of the

Marne. He will first see the field strewn with the dead. Gradually the dead men will rise and join their regiments, and presently they will be seen in groups in Gallieni's taxis, which will travel backwards at full speed to Paris, arriving in the midst of a population that is extremely anxious about the issue of the struggle, and the soldiers will, naturally, be unable to give them any news. In a word, our observer will, if he recedes from the earth at a speed greater than that of light, see terrestrial events happening as if he were *ascending* the stream of time.

It would be very different if the observer remained stationary, and the earth receded from him at a speed of 300,000 miles a second. What would happen then ? It is clear that in this case our observer will see terrestrial events, not in inverse order, but as they are: except that they would seem to him to take place with majestic slowness, because the rays of light which leave the earth at the end of some particular event will take a much longer time to reach him than the rays which left the earth at the beginning of the event.

In sum, the phenomena observed by him being essentially different in the two cases, our imaginary observer would be able to say whether it is he who is receding from the earth or the earth that is receding from him ; to detect the real movement of the event through space. This means, of course, movement relatively to the medium of the propagation of light, not necessarily, as we saw, movement in relation to absolute space.

The experiment we have imagined could not very well be carried out with the actual resources of our laboratories. We cannot attain these fantastic speeds,

and even if we could the observer would not distinguish much. But we have chosen a colossal instance, and the results of it would be colossal, as there would be question of nothing less than a reversal of the order of time.

If we were to use more modest means, the results will be more modest, but according to the older theories they ought to be recorded in our instruments. But the Michelson experiment—a miniature version of what we have just described—shows that the differences we should expect are not observed. Therefore the premise we laid down—that there can be velocities greater than that of light in empty space—does not harmonise with reality. Hence this velocity of light is a wall, a limit that cannot be passed.

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Now let us see what follows. There is at the base of classical mechanics, as it was founded by Galileo, Huyghens, and Newton, and as it is taught everywhere, a principle which is in the long run, like all the principles of mechanics, grounded upon experience. It is the principle of the composition of velocities. If a boat, which makes ten miles an hour in smooth water, sails down a river which flows at five miles an hour, the speed of the boat in relation to the bank will be, as we may find by actual measuring, equal to the sum of the two speeds, or fifteen miles an hour. This is the rule of the addition of velocities.

In a more general way, if a body starts from a state of rest, and under the action of some force takes on in a second the velocity V, what will it do if the action of the force is prolonged for another second? According to classical mechanics it will take on the

velocity 2V.[1] Let us imagine an observer who is travelling at the velocity V, yet thinks he is at rest. It will seem to him, at the end of the first second, that the body is at rest (because it has the same velocity as the observer). In virtue of the Classical Principle of Relativity, the apparent movement of the body must be the same for our observer as if the rest were real. This means that at the end of the second second the relative velocity of the body in reference to the observer will be V, and, as the observer already has the velocity V, the absolute velocity of the body will be 2V. In the same way it will be 3V at the end of three seconds, 4V at the end of four seconds, and so on. Could it increase indefinitely if the force continues to act long enough ? Classical mechanics says " yes." Einstein says " no," because there cannot be a greater velocity than that of light.

We have imagined an observer who has the velocity V relatively to us, and who believes that he is at rest. For him the body observed was likewise at rest at the beginning of the second second, because its velocity was the same as that of the observer. From the fact that the apparent movement of the body is for the observer, during the second second, the same as it was for us during the first, classical mechanics concluded that its velocity doubles during the second second. It did not know what Einstein has now taught us : that the time and space of this observer are different from ours.

[1] As an example of an identical force acting during periods of time successively equal to 1, 2, or 3, we may take three guns of the same calibre, but of lengths equal to 1, 2, and 3, and of which the charges, or rather, their propulsive forces, are identical and constant. It is found that the initial velocities of the shells are, in relation to each other, 1, 2, and 3.

What is a velocity? It is the space traversed in the course of a second. But the space thus measured by our moving observer, which he believes to be of a certain length, is in reality, for us who are stationary, smaller than he thinks, because the rules he uses are, as Einstein has shown, shortened by velocity without his perceiving it. Therefore the velocities are not added together in equal proportions and indefinitely for a given observer, as classical mechanics maintained.

Under the action of the same force, the old mechanics said, a body will always experience the same acclera-tion, whatever be the velocity already acquired. Under the action of the same force, the new mechanics says, the motion of the body will be accelerated less and less in proportion to its velocity.

Take, for instance, some movable object having, relatively to me, a velocity of 200,000 kilometres a second. Let us place an observer on this object. The observer will then start, in the same direction and under the same conditions as we have done, a second movable object, which will thus have, *re-latively to him*, a speed of 200,000 kilometres. The Relativist says that the resultant velocity of the second object relatively to us will not be, as the classical addition of velocities would make it, 200,000 + 200,000 = 400,000 kilometres a second. It will be only 277,000 kilometres a second. What the second moving observer took to be 200,000 kilometres (because his measuring rod was shortened owing to velocity) was really only 77,000 of our kilometres. How is it possible to calculate that? Simply by using the formula of Lorentz which I gave in Chapter II, which gives us the value of the contraction due to velocity. We then easily find that, if we have two

velocities, $v_1$ and $v_2$, and if we call the resultant $w$, classical mechanics stated that

$$w = v_1 + v_2$$

The Einstein mechanics says that this is not correct, and that what we really have (C being the velocity of light) is

$$w = \frac{v_1 + v_2}{1 + \frac{v_1 v_2}{C^2}}$$

I apologise for again introducing—it shall be the last time—an algebraical formula into my work. But it spares me a large number of words, and it is so simple that every reader who has even a tincture of elementary mathematics will at once see its great significance and the consequences of it.

The formula expresses in the first place the fact that the resultant of the velocities, however great it may be, cannot be greater than the speed of light. It conveys also that, if one of the component velocities is that of light, the resultant velocity must have the same value. It means, in fine, that in the case of the slight velocities we have to do with in actual life (that is to say, when the component velocities are much smaller than that of light) the resultant is very nearly equal to the sum of the two components, as the classical mechanics says.

The classical mechanics was, we must remember, founded upon experience. We understand how, in those circumstances, Galileo and his successors, dealing only with relatively slowly moving bodies, reached a principle which seemed to be true for them, but is only a first approximation.

For instance, the resultant of two velocities, each equal to a hundred kilometres a second (which is far higher than any velocities obtainable by Galileo and Newton), amounts to, not 200 kilometres, but 199·999978 kilometres. The difference is scarcely twenty-two millimetres in 200 kilometres! We can quite understand that the earlier experimenters could not detect differences even less minute than that.

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Amongst the verifications of the new law of composition of velocities we may quote one, the outcome of an early experiment of the great Fizeau, which is very striking.

Imagine a pipe full of some liquid, such as water, and a ray of light travelling along it. We know the speed of light in water: it is much lower than in air or in empty space. Suppose, further, that the water is not stationary, but flows through the pipe at a certain speed. What will be the velocity of the ray of light when it leaves the pipe after traversing the moving liquid? That was what Fizeau, with many variations of the conditions of the experiment, tried to ascertain.

The velocity of light in water is about 220,000 kilometres a second. There is question here of so rapid a propagation that there is a great difference between the law of addition of the old classical mechanics and of Einsteinian mechanics. Now the results of Fizeau's experiment are in complete harmony with Einstein's formula, and are not in harmony with that of the older mechanics. Many observers, including, recently, the Dutch physicist Zeeman, have repeated Fizeau's experiment with the greatest care, but the result was the same.

When Fizeau made the experiment in the last

century, attempts were made to interpret his results in the light of the older theories. This, however, led to very improbable hypotheses. Fresnel, for instance, trying to explain Fizeau's results, had been compelled to admit that the ether is partially borne along by the water as it flows, and that this partial displacement varies with the length of the luminous waves sent through, or that it is not the same for the blue as for the red waves! A very startling deduction, and one very difficult to admit.

The new law of composition of velocities given to us by Einstein, on the other hand, immediately and with perfect accuracy explains Fizeau's results. They are opposed to the classical law.

The facts, the sovereign judges and criteria, show in this case that the new mechanics corresponds to reality; the earlier mechanics does not, at least in its traditional form. Here is something, therefore, which enables us to see at once the profound truth (scientific truth being what is verifiable), the beauty, of the doctrine of Einstein: something which shows us, superbly, how a scientific, a physical, theory differs from an arbitrary and more or less consistent philosophical system.

Experience, the supreme judge, decides in favour of the Einsteinian mechanics against the older mechanics. We shall see further examples; and we shall not find a single case in which the verdict is the other way.

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Let us turn now to a different matter. The new law of composition of velocities and the resistance of a velocity-limit equal to that of light may be expressed in a different language from that we have hitherto used.

Up to this we have spoken only of velocities and movements. Let us see how these things look when we at the same time examine the particular qualities of the moving objects, of bodies, of matter.

Everybody knows that the characteristic feature of matter is what we call inertia. If matter is at rest, a force is needed to set it in motion. If it is in motion, it needs a force to stop it. It needs one to accelerate the movement and one to alter the direction. This resistance which matter offers to the forces which tend to modify its condition of rest or movement is what we call *inertia*. But different bodies may offer a different degree of resistance to these forces. If a force is applied to an object, it will give it a certain acceleration. But the same force applied to another object will, as a rule, give it a different acceleration. A race-horse making a supreme effort will get along much more quickly under a small jockey than under a man of fifteen stone. A draught-horse will run more quickly if the cart it draws is empty than if it is full of goods. You can start a perambulator with a push that would be useless in the case of a heavy truck.

When a locomotive with a few coaches suddenly starts, the velocity imparted to the train during the first second is what we call its acceleration. If the same locomotive starts, in the same conditions, with a much longer train, we see that the acceleration is less. Hence the idea, introduced into science by Newton, of the *mass* of bodies, which is the measure of their inertia.

If in our example the locomotive produces in the second case an acceleration only half as great, we express this by saying that the mass of the second

train is double that of the first. If we find that the acceleration produced by the locomotive is the same for three trucks loaded with wheat as for a single truck loaded with metal, we see that the two trains are equal in mass.

In a word, the masses of bodies are conventional data defined by the fact that they are proportional to the accelerations caused by one and the same force. To put it differently, the mass of a body is the quotient of the force which acts upon it by the acceleration given to it. Poincaré used to say picturesquely: "Masses are coefficients which it is convenient to use in calculations."

If there is one property of bodies which comes within the range of our senses, a property of which every man has some sort of instinct or intuition, it is *mass*. Yet careful analysis shows us that we are unable to define it otherwise than by disguised conventions. Poincaré's definition seems paradoxical in its admission of powerlessness. But it is correct. Mass is only a "coefficient," a conventional outcome of our weakness!

Nevertheless, something remained upon which we thought we could base, if not our craving for certainty —genuine men of science gave up the idea of certainty long ago—at least our desire for accuracy of deduction in our classification of phenomena. We believed in the constancy of mass, of this convenient and so clearly defined *coefficient*.

Here again, unfortunately, we have to recant—or, perhaps, we should say fortunately, as there is no pleasure like that of novelty.

The older mechanics taught us that mass is constant in one and the same body, and is therefore independent of the velocity which the body acquires. From which

it followed, as we have already explained, that, if a force continues to act, the velocity acquired at the end of a second will be doubled at the end of two seconds, tripled at the end of three seconds, and so on indefinitely.

But we have just seen that the velocity increases less during the second second than during the first, and so on, continuously diminishing until, when the velocity of light is attained, that of the moving body can increase no further, whatever force may act upon it.

What does that mean ? If the velocity of a body increases less during the second second, it must be because it offers an increasing resistance to the accelerating force. Everything happens as if its inertia, its mass, had changed ! Which amounts to saying that *the mass of bodies is not constant : it depends upon their velocity, and increases with an increase of velocity.*

In the case of feeble velocities this influence is imperceptible. It was because the founders of classical mechanics, an experimental science, had experience only of relatively feeble velocities that they found that mass was *perceptibly* constant, and believed they might conclude that it was *absolutely* constant. In the case of greater velocities that is not so.

Similarly, in the case of feeble velocities, in the new mechanics as well as the old, bodies perceptibly oppose the same resistance of inertia to the forces which tend to accelerate their movement as to those which tend to alter the direction, to give a curve to their trajectories. In the case of great velocities that is not so.

Mass, therefore, increases rapidly with velocity. It becomes infinite when the velocity equals that of light. No body whatever can attain or surpass the velocity of

light, because, in order to pass that limit, it would need to overcome an infinite resistance.

In order to make it quite clear, let us give certain figures which show how mass varies with velocity. The calculation is easy, thanks to the formula which we have previously seen, giving the values of the Fitzgerald–Lorentz construction.

A mass of 1,000 grammes will weigh an additional two grammes at the velocity of 1,000 kilometres a second. It will weigh 1,060 grammes at the velocity of 100,000 kilometres a second; 1,341 grammes at the velocity of 200,000 kilometres a second; 2,000 grammes (or double) at the velocity of 259,806 kilometres a second; 3,905 grammes at the velocity of 290,000 kilometres a second.

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That is what the new theory tells us. But how can we verify it? It would have been impossible only fifty years ago, when the only velocities known were those of our vehicles and projectiles, which then did not rise, even in the case of shells, above one kilometre a second. The planets themselves are far too slow for the purpose of verification. Mercury, for instance, the swiftest of them, travels at a speed of only a hundred kilometres a second, which is not enough.

If we had at our disposal no higher velocities than these, we should have no means of settling which was right, the classical mechanics with its constancy of mass or the new mechanics with its assertion of variability.

It is the cathode rays and the Beta rays of radium which have provided us with velocities great enough for the purpose of verification. These rays consist of an uninterrupted bombardment by small and very rapid

projectiles, each of a mass less than the two-thousandth part that of an atom of hydrogen, and charged with negative electricity. They are the *electrons*.

The cathode tubes of radium give out a continuous bombardment of these minute projectiles, charged, not with melinite, but electricity : far smaller than the shells of our artillery, but animated with infinitely greater initial speeds. The velocity of "Bertha's" shells is contemptible in comparison.

But how was it possible to measure the speed of these projectiles ?

We know that electrified bodies act upon each other. They attract or repel each other. Now our electrons are charged with electricity. If, therefore, we put them in an electric field, between two plates connected at the edges by an electrical machine or an induction coil, they will be subjected to a force that will cause them to change their direction. The cathode rays, in other words, will change their direction under the influence of an electric field. The amount of diversion will depend upon the speed of the projectiles and upon their mass ; that is to say, upon the resistance of inertia which the mass opposes to the causes which tend to divert it.

But this is not all. The electric charges borne by the projectiles are in movement, even rapid movement. Now, electricity in movement is an electric current, and we know that currents are diverted by magnets or magnetic fields. Therefore the cathode rays will be diverted by the magnet. This diversion will, like the former, depend upon the velocity and the mass of the projectile ; but not quite in the same way. Other things being equal, the magnetic diversion will

be greater than the electrical diversion, if the velocity is high. As a matter of fact, the magnetic diversion is due to the action of the magnet on the current. It will be greater in proportion to the intensity of the current; and the current will be more intense in proportion to the height of the velocity, since it is the movement of the projectile which causes the current. On the other hand, the trajectory of our little projectiles will be less influenced by the electrical attraction in proportion as the velocity of the projectile is great.

Hence it is easy to see that when we subject a cathode ray to the action of an electric field, then to that of a magnetic field, we may, by comparing the two deviations, measure at one and the same time the velocity of the projectile and its mass (related to the known electric charge of the electron).

In this way we find enormous velocities, rising from a few tens of kilometres to 150,000 kilometres a second, and even more. As to the Beta rays of radium, they are still more rapid. In cases they attain velocities not far short of that of light, and higher than 290,000 kilometres a second. Here are just the velocities we need in order to test whether or no mass increases with them.

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In order to understand clearly the progress of the experiments, it remains to say a few words about the curious phenomenon of electrical inertia which is called *self-induction*. When we want to set up an electric current, we find a certain initial resistance which ceases as soon as the current begins. If afterwards we want to break the current, it tends to maintain itself, and we have just the same trouble to stop it as to stop a vehicle in motion. It is a matter of daily experience.

Sometimes the trolley of a tramcar leaves for a moment the wire which conducts the current, and we then see sparks. Why? There was a current passing from the wire to the trolley, and if the trolley breaks away from the wire for a moment, leaving an interval of air which obstructs the passage of electricity, the current will not stop. It has been set going, as it were, and it leaps the obstacle in the form of a spark. This phenomenon is what we call self-induction.

Self-induction—or "self" as the electrical workers call it—is a real inertia. The surrounding medium offers resistance to the force which tends to establish an electric current, and to that which tends to stop a current already set up; just as matter resists the force which tends to cause it to pass from rest to movement, or from movement to rest. There is, therefore, a real electrical inertia as well as mechanical inertia.

But our cathodic projectiles, our electrons, are charged. When they begin to move, they start an electric current; when they come to rest, the current ceases. Besides mechanical inertia, then, they must also have electrical inertia. *They have, so to speak, two inertias; that is to say, two inert masses, a real and mechanical mass, and an apparent mass due to the phenomena of electro-magnetic self-induction.* By studying the two deviations, electric and magnetic, of the Beta rays of radium or of the cathode rays, it is possible to determine the respective parts of each of these masses in the total mass of the electron. The electro-magnetic mass due to the causes which we have explained varies with the velocity, according to certain laws which we gather from the theory of electricity. Hence, by observing the relation between

the total mass and the velocity, we can see what part belongs to the real and invariable mass and what to the apparent mass of electro-magnetic origin.

The experiment has been made repeatedly by physicists of distinction. The result of it is surprising: the real mass is *nil*, and the whole mass of the particle is of electro-magnetic origin. Here is something that is calculated to modify entirely our ideas of the essence of what we call matter. But that is another story.

Physicists then asked themselves—this is what we were coming to, after clearing the way of various difficulties—whether the relation between the mass and the velocity of the cathodic projectiles was the same as that which we found in virtue of the Principle of Relativity.

The result of the experiments is absolutely clear and consistent, and some of them have dealt with Beta rays corresponding to a mass-value ten times greater than the original mass. This result is: mass varies with velocity, and in exact accord with the numerical laws of Einstein's dynamics.

Here is a new and valuable experimental confirmation. This in turn tends to show that classical mechanics was merely a rough approximation, valid at the most only for the comparatively slight velocities with which we have to deal in the very restricted course of daily life.

Thus the mass of bodies, the Newtonian property which was believed to be the very symbol of constancy, the equivalent of what loyalty to treaties is in the moral order of things, is now merely a small coefficient, variable, undulating, and relative to the point of view. In virtue of the reciprocity which we have described, when there is question of contraction due to velocity,

the mass of an object increases in the same way, not only if the object is displaced, but if the observer is displaced, and without any other observer, connected with the object, being able to detect the difference.

For instance, a measuring rod that moves at a velocity of about 260,000 kilometres a second will not only have its length shortened by one-half, but will have its mass doubled at the same time. Hence its density, which is the relation of its mass to its volume, will be quadrupled.

The physical ideas which were believed to be most solidly established, most constant, most unshakeable, have been uprooted by the storm of the new mechanics. They have become soft and plastic things moulded by velocity.

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Further confirmations of the new formula, quite independent of the one we have just described, have recently been provided by physicists. One of the most astonishing of these is given in spectroscopy.

As is well known, when we cause a ray of sunlight, admitted through a narrow slit, to pass through the edge of a glass prism, the ray expands, as it issues from the prism, like a beautiful fan, the successive blades of which consist of the different colours of the rainbow. When we examine closely this coloured fan, we notice certain fine discontinuities, narrow lines or gaps, in which there is no light. They look like cuts made with a pair of scissors in our polychrome fan. They are the dark lines of the solar spectrum. Each of these lines, or each group of them, corresponds to a special chemical element, and serves to identify this, whether in our laboratories or in the sun and the stars.

It was explained long ago that these lines are due to electrons which revolve rapidly round the nuclei of the atoms. Their sudden changes of velocity give rise to a wave (like those caused in water when you drop a pebble into it) in the surrounding medium, and this is one of the characteristic luminous waves of the atom. It reveals itself in one of the lines of the spectrum. The Danish physicist Bohr has recently developed this theory in detail, and has shown that it accurately explains the various spectral lines of the different chemical elements. These, I may note, differ from each other in the number and arrangement of the electrons which revolve within their atoms.

Now Sommerfeld has argued as follows. The electrons which gravitate near the centre of an atom must have a higher velocity than those which revolve in its outer part; just as the smaller planets, Mercury and Venus, revolve round the sun far more rapidly than the larger planets, Jupiter and Saturn. It follows if Lorentz and Einstein are right that the mass of the interior electrons of the atoms must be greater than that of the exterior electrons: appreciably greater, as the former revolve with enormous velocities. We can calculate that, in those conditions, each line in the spectrum of a chemical element must in reality consist of a number of fine lines joined together. This is precisely what Paschen afterwards (1916) found. He discovered that the structure of the fine lines is strictly such as Sommerfeld had predicted. It was an astonishing confirmation of an hypothesis: a proof of the soundness of the new mechanics.

But that is not all. We know that the X-rays are vibrations analogous to light, the same in origin, but consisting of much shorter waves, or waves with a far

higher frequency. Hence, while light comes from the external electrons of the miniature solar system which we call an atom, the X-rays come from the most rapid electrons—those nearest to the centre. It follows that the special structure of the fine lines, due to the variation of the mass of the electron with its velocity, must be much more marked in the case of the X-rays than in the case of the spectral lines of light. This, again, was confirmed by experiment. The figures expressing the observed facts correspond exactly with the calculations of the new mechanics, as regards the predicted variation of mass with velocity.

It is therefore settled that the phenomena which take place in the microcosm of each atom are subject to the laws of the new mechanics, not the old, and that, in particular, masses in motion vary as the new mechanics demands.

Experience, "sole source of truth," has given its verdict.

We are now very far from the ideas which were once prevalent. Lavoisier taught us that matter can neither be created nor destroyed. It remains always the same. What he meant was that mass is invariable, as he proved by means of scales. Now it appears that, perhaps, bodies have no mass at all—if it is entirely of electro-magnetic origin—and that, in any case, mass is not invariable. This does not mean that Lavoisier's law has now no meaning. There remains something that corresponds to mass at low velocities. Our idea of matter is, however, revolutionised. By matter we particularly meant mass, which seemed to us to be at once the most tangible and most enduring of its properties. Now this "mass" has no more reality than the time and space in which we

thought we located it! Our solid realities were but phantoms.

The reader must pardon me for whatever difficulties he finds in this exposition. The new mechanics opens out to us such strange new horizons that it is worth far more than a rapid and superficial glance. If you want to see a vast prospect in an unexplored world, you must not hesitate to do some rough climbing, however breathless it may leave you for the time.

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There is, in fine, another fundamental idea of mechanics, that of *energy*, which takes on a new aspect in the light of Einstein's theory: an aspect which, in turn, is largely justified by experiment.

We saw that a body charged with electricity and in motion makes a certain resistance to interference, on account of the electrical inertia which is known as self-induction. Calculation and experiment show that, if we reduce the dimensions of a body that is charged with a certain quantity of electricity, without altering the charge, the electrical inertia increases. As a matter of fact, in our hypotheses, and if the inertia is entirely electro-magnetic in origin, the electrons are now merely a sort of electric trails moving in the propagating medium of electrical and luminous waves which we call ether.

The electrons are no longer anything in themselves. They are merely, in the words of Poincaré, a sort of "holes in ether," round which the ether presses much as a lake makes eddies which check the progress of a boat.

In that case, however, the smaller the holes in the ether are, the more important will be the agitation of the ether round them; and, consequently, the greater

will be the inertia of the "hole in ether" which represents the corpuscle under investigation. What will follow? We know from measurements we have made that the mass of the tiny sun of each atom, the *positive nucleus*, round which the planet-electrons revolve, is greater than that of an electron. If this mass and the corresponding inertia are electro-magnetic in origin, it follows that the positive nucleus of the atom is much smaller than the electron.

Let us consider the atom of hydrogen, the lightest and simplest of the gases. We know that it consists of one planet only, one single negative electron revolving round the minute central sun, the positive nucleus. We know also that the mass of the electron is two thousand times as small as that of the hydrogen atom. It follows, as we can calculate, that the *positive nucleus* must have a radius two thousand times smaller than that of the electron. Now, the experiments of the English physicists have proved that the large Alpha particles of the radium-emanation can pass through hundreds of thousands of atoms without being appreciably diverted by the positive nucleus. We conclude that the latter is in reality much smaller than the electron, as theory predicted.

All this irresistibly compels us to think that the inertia of the various component parts of atoms—that is to say, of all matter—is exclusively electro-magnetic in origin. There is now no matter. There is only electrical energy, which, by the reactions of the surrounding medium upon it, leads us to the fallacious belief in the existence of this substantial and massive something which hundreds of generations have been wont to call "matter."

And from all this it also follows, by calculation and by

the simple and elegant reasoning of Einstein, of which I here convey only the faintest adumbration, that mass and energy are the same thing, or are at least the two different sides of one and the same coin. There is, then, no longer a material mass. There is nothing but energy in the external universe. A strange—in a sense, an almost spiritual—turn for modern physics to take!

According to all this the greater part of the "mass" of bodies must be due to a considerable and concealed internal energy. It is this energy which we find gradually dissipated in radio-active bodies, the only reservoirs of atomic energy which have as yet opened externally.

If this is true, if energy and mass are synonymous, if mass is merely energy, it follows that free energy must possess the property of mass. As a matter of fact, light, for instance, has mass. Careful experiments have shown that when a ray of light strikes a material object, it exerts upon it a pressure which has been measured. Light has mass; therefore it has weight, like all masses. When we come to consider the new form given by Einstein to the problem of gravitation, we shall see a further and beautiful proof that light has weight.

We can calculate that the light received from the sun by the earth in the space of a year is rather more than 58,000 tons. It seems very little when one thinks of the formidable weight of coal that would be needed to maintain our globe at the temperature at which the sun keeps it—in the event of a sudden extinction of our luminary.

The reason for the difference is that, when we produce heat from a certain amount of coal, we use only a small proportion of its total energy, its chemical

energy. Its intra-atomic energy is inaccessible to us. It is a pity, as otherwise we should need only a few ounces of coal to supply heat for a whole year to all the towns and workshops of England! How many problems that would simplify! When humanity emerges from the ignorance and the clumsy barbarism in which it lives to-day—that is to say, in some hundreds of centuries—this will be accomplished. Yes, it will one day be done. It will be a glorious spectacle, one in which we may justly rejoice in advance.

Meantime, our sun, like all the other stars, like every incandescent body, loses its weight in proportion as it radiates. But this happens so slowly that we need not fear to see it disappear at some early date, like the ephemeral things which die because they gave themselves too freely.

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To finish with Einstein's mechanics, let me reproduce a very suggestive application of these ideas about the identity of energy and mass.

There is in chemistry a well-known elementary law which is called "Prout's Law." It states that the atomic masses of all the elements must be whole multiples of the mass of hydrogen. Since hydrogen has the lightest atoms amongst all known bodies Prout's Law started from the hypothesis that all the atoms are built up of a fundamental element, the atom of hydrogen. This supposed unity of matter seems to be more and more confirmed by the facts. On the one hand, it is proved that the electrons which come from different chemical elements are identical. On the other hand, in the transformation of radio-active bodies we find heavy atoms simplifying themselves by successively emitting atoms of helium gas. Lastly,

the great British physicist Sir Ernest Rutherford showed in 1919 that by bombarding the atoms of nitrogen gas, in certain circumstances, by means of radium emanation, we can detach hydrogen atoms from them. This experiment, the importance of which has not been fully realised—it is the first instance of transmutation really effected by man—also tends to prove the soundness of Prout's hypothesis.

Yet, when we accurately measure and compare the atomic masses of the various chemical elements, we find that they do not strictly conform to Prout's Law. For instance, while the atomic mass of hydrogen is 1, that of chlorium is 35·46, which is not a whole multiple of 1.

But we can calculate that, if the formation of complex atoms from hydrogen upwards is accompanied, as is probable, by variations of internal energy, as a consequence of the radiation of a certain amount of energy during the combination, it necessarily follows (since the lost energy has weight) that there will be variations in the mass of the body composed, and these will explain the known departures from Prout's Law.

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In our somewhat hurried and informal excursion into the bush of the new facts which confirm the mechanics outlined by Lorentz and completed by Einstein our progress has been rather difficult. It is because, since we could not use terminology and technical formulæ which would be unsuitable in this work, we have had to be content with bold and rapid moves into the districts we wished to reconnoitre. Perhaps they have sufficed to enable the reader to understand what a revolution in the very bases of science, what an explosion amidst its age-old foundations, the

brilliant synthesis of Einstein has caused. New light now streams upon all who slowly climb the slopes of knowledge : upon all who, wisely renouncing the desire to know " why," would at least learn the " how " in many things.

A little before his death, foreseeing, with the intuition of genius, that a new era opened in mechanics, Poincaré advised professors not to teach the new truths to the young until they were steeped to the very marrow of their bones in the older mechanics.

" It is," he added, " with ordinary mechanics that their life is concerned : it is that alone that they will ever have to apply. Whatever speed our motor-cars may attain, they will never reach a speed at which the old mechanics ceases to be true. The new is a luxury, and we must think of luxuries only when it can be done without injury to necessaries."

I would appeal from Poincaré's text to the man himself. For him this luxury, the truth, was a necessary. On the day in question, it is true, he thought of the young. But do men ever cease to be children ? To that the master, too early taken from us, would have replied, in his grave, smiling manner : " Yes—at all events, it is better to suppose so."

# CHAPTER V

## GENERALISED RELATIVITY

*Weight and inertia—Ambiguity of the Newtonian law—Equivalence of gravitation and accelerated movement—Jules Verne's projectile and the principle of inertia—Why rays of light are subject to gravitation—How light from the stars is weighed—An eclipse as a source of light.*

We are now on the threshold of the great mystery of gravitation.

In the preceding chapter we saw how Einstein brought under one magnificent law both the slow movements of massive objects and the far more rapid movements of light. They had hitherto been separate and anarchic provinces of the universe. We now know that the same laws govern mechanics and optics. If for a time it appeared otherwise, it was because at velocities which approach that of light the lengths and masses of objects experience in the eyes of the observer an alteration which is imperceptible at familiar speeds. It is in its power of synthesis that Einstein's mechanics is so splendid. Thanks to it, we perceive more unity, more harmony, more beauty, than formerly in this astounding universe, in which our thoughts and our anxieties are so ephemeral.

The theory of Relativity, however, has up to the present not touched a phenomenon that is fundamental, essential, ubiquitous in our cosmos. I mean gravitation, the mysterious property of bodies which

rules the tiny atom no less than the most gigantic star, and directs their paths in majestic curves.

The universal attraction which, as far as earth is concerned, we call weight was a kind of steep-cliffed island in the sea of phenomena, something unrelated to the rest of natural philosophy.

The Einsteinian mechanism, as we have described it up to now, passed by this island, taking no notice of it. For that reason it was, in this form, known as "the theory of Special Relativity." In order to convert it into a perfect instrument of synthesis, the phenomenon of gravitation had to be introduced. It is thus that Einstein crowned his work, and his system assumed the form which is well called "the theory of General Relativity."

Einstein has drawn gravitation from its "splendid isolation," and has annexed it, docile and vanquished, to the triumphal chariot of his mechanics. He has, moreover, given Newton's famous law a more correct form, and experiment, the supreme judge, has declared this the only just form.

How he did this, by what subtle and powerful chain of reasoning, by what calculations based upon facts, I will now endeavour to tell; and I will again do my best to avoid the network of barbed wire of mathematical terminology.

Why did Newton, followed by the whole of classical science, believe that gravitation, the fall of bodies, did not belong to the mechanics of which he formulated the laws? Why, in a word, did he regard gravitation as a force or—to use a vaguer but more general term—an action which prevents heavy bodies from changing their positions *freely* in space?

*Because of the principle of inertia.* This principle,

the foundation of the whole Newtonian mechanics, may be expressed thus : a body which is not acted upon by any force maintains its velocity and direction unchanged.

Why do we equip steam-engines with the heavy wheels which we call " fly-wheels," which work nothing? Because the principle of inertia is certainly nearly true. When the engine experiences a sudden and sharp check, or an acceleration, the fly-wheel serves to keep it steady. Driven by the speed it has acquired, and driving the engine in its turn, it tends to preserve its velocity, and it prevents or modifies accidental checks or accelerations. The principle is therefore based upon experience, especially on the experiments of Galileo, who verified it by rolling balls down planes inclined at different angles.

For instance, we find that a ball set in motion on a highly polished horizontal plane keeps its direction, and would preserve its velocity if the resistance of the atmosphere and the friction of the plane did not gradually reduce it to zero. We find that, in proportion as we reduce the friction, the ball tends to maintain its speed so much the longer.

Newton's principle of inertia is based upon a number of these experiments. It is by no means in the nature of a self-evident mathematical truth. This is so true that ancient thinkers believed, contrary to classical mechanics, that the movement ceases as soon as the cause of it is removed. Certain of the Greek philosophers even thought that all bodies travel in a circle, if nothing interferes with them, because the circular is the noblest of all movements.

We shall see later how the principle of inertia of Einstein's generalised mechanics has a strange affinity

to this idea, and at the same time to the curious declination, the *clinamen*, which the great and profound Lucretius attributed to the free path of the atoms. But we must not anticipate.

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This belief, that an object left freely to itself and not acted upon by any force preserves its velocity and direction, cannot pretend to be more than an experimental truth. But the observations on which it is based, especially those of Galileo, but any that may be imagined by physicists, could not possibly be conclusive, because in practice it is impossible to protect a moving body from every external force, such as atmospheric resistance, friction, or other.

I am aware that Newton grounded his principle on astronomical as well as terrestrial observations. He noticed that, *apart from any attraction by other celestial bodies*, and as far as we can see, the planets seem to maintain their direction and velocity relatively to the vault of heaven. But Relativists think that the words I have italicised in the preceding sentence, which reflect Newton's idea, really beg the question. His argument assumes that the planets do not circulate *freely*; that they are governed in their motions by a force which he called universal attraction.

We shall see how Einstein came to think that this is not a force, and in that case the issue of the argument is very different. However that may be, the classical principle of inertia is a truth based upon (imperfect) experience, and it is therefore subject to the constant control of facts. All that we can say about it is that practically—that is to say, approximately—it harmonises with what we find.

Newton did not regard it as such, not as a more or

less precise approximation, but as a strict truth. That is why, when he saw that the planets do not travel in straight lines but in curved orbits, he concluded—which is a *petitio principii*—that they were subject to a central force, gravitation. That is why heavy bodies did not seem to him amenable to the mechanical laws which he had formulated for bodies left freely to themselves. That is why, in a word, Newton's law of gravitation and his laws of dynamics are two distinct and separate things.

The great genius, the mind which had no equal, was nevertheless human. The immortal Descartes put forward strange statements and very occult hypotheses (about the pineal gland and animal spirits), after he had expressly resolved to affirm nothing that he did not perceive clearly and distinctly. In the same way Newton, after laying down as his principle *Hypotheses non fingo*, put the hypotheses of absolute time and space at the very basis of his mechanics. At the basis of his masterly theory of gravitation he put the hypothesis —which is *a priori* easier to admit—that there is a special force of gravitation.

These are weaknesses which the greatest of men do not escape. They ought to make us admire all the more the finer aspects of their work. So deep is the furrow ploughed by these great students of the unknown that, even when it is not straight, it takes two centuries and a half before men dream of inquiring afresh whether Newton's distinction between purely mechanical and gravitational phenomena was just.

It is the signal distinction of Einstein that he successfully accomplished this: that, after erasing many things which were supposed to be finally settled, he blended mechanics and gravitation in a superb syn-

thesis, and enabled us to see more clearly the sublime unity of the world.

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To tell the truth—let us premise this before we go further into the profound and marvellous truths of General Relativity—it is *a priori* evident that Newton's law of universal attraction can no longer be considered satisfactory.

It says : *Bodies attract each other in direct proportion to their masses and in inverse proportion to the square of their distances.* What does that mean ? We saw that the mass of a body varies with its velocity. When, for instance, we introduce the mass of our planet into calculations which involve Newton's law, what precisely do we mean ? Do we mean the mass which the earth would have if it did not revolve round the sun ? Or do we mean the larger mass which it has in virtue of its motion ? This motion, however, is not always of the same speed, because the earth travels in an ellipse, not a circle. What value shall we give to this variable mass in the calculation ? That which corresponds to perihelion or aphelion, the period when the earth travels most rapidly or most slowly ? Moreover, ought we not also to take into account the velocity of translation of the solar system, which in turn increases or diminishes according to the season ?

Again, under Newton's law what shall we make the distance from the earth to the sun ? Is it to be the distance relatively to an observer on the earth or on the sun, or to a stationary observer in the middle of the Milky Way who does not share the motion of our system across it ? Here again we shall have different values in each case, because spatial distances vary,

as we saw with Einstein, according to the relative velocity of the observer.

Hence Newton's law is, in spite of its simple and artistic form, ambiguous and far from clear. I am aware that the differences I have just noted are not very important, but our calculations show that they are by no means negligible. Einsteinians therefore regard it as indisputable, apart from the considerations which we shall see presently, that Newton's law, in its classical form, is obscure, and must be modified and completed.

These preliminary remarks will serve to at least put us in the frame of mind that is required of iconoclasts ; and in science the iconoclasts are often the makers of progress. The particular idols at which we are preparing to deal a few audacious blows are the conception of the Newtonian law and gravitation.

Laplace wrote, in his *Exposition du Système du Monde*: "It is impossible to deny that nothing is more fully proved in natural philosophy than the principle of universal gravitation in virtue of mass and in inverse proportion to the square of the distance." Nothing can better show us than this sentence of the great mathematician the importance of the step taken by Einstein when he, as we shall see, improved what had been regarded as the very type, the most perfect example, of scientific truth : the famous Newtonian law.

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Gravitation, or weight, has this in common with inertia, that it is a quite general phenomenon. All material objects, whatever may be their physical and chemical condition, are both inert (that is to say, according to their mass they resist forces which tend to displace them) and heavy (they fall when they are

left to themselves). But it is a strange thing, noted by Newton, though he did not realise the significance of it—he regarded it merely as an extraordinary coincidence—that the same figure which defines the inertia of a body also defines its weight. This figure is the mass of the body.

Let us return to the illustration which I used in a previous chapter in dealing with Einstein's mechanics. If two trains drawn by two similar locomotives start in the same conditions, and if the velocity communicated to the first train at the end of a second is double that communicated to the second, we conclude that the inertia, the inert mass, of the second train (leaving out of account the friction with the rails) is twice as great as that of the first. If we afterwards weigh our two trains, we find that the weight of the second is similarly twice as great as that of the first.

This experiment, though crude enough in our illustration, has been made with great precision by physicists, who used delicate methods which we need not describe here. The result was the same. The inert mass and the weight of bodies are exactly expressed by the same figures. Newton saw in this a mere coincidence. Einstein found in it the key to the hermetically sealed and inviolate dungeon in which gravitation was isolated from the rest of nature. Let us see how.

There is one remarkable feature of weight or gravitation: whatever be the nature of the objects, they always fall at the same speed (apart from atmospheric resistance). This is easily proved by causing a number of different objects to fall, in the same period of time, down a long tube in which a vacuum has been created. They all reach the bottom of the tube at the same time. A ton of lead and a sheet of paper will, if they are

launched into the void simultaneously from the summit of a tower, reach the ground simultaneously, with a velocity the acceleration of which is, near the ground, 981 centimetres a second. This fact was known to Lucretius. Two thousand years ago that profound and immortal poet wrote :

> Nulli, de nulla parte, neque ullo
> Tempore, inane potest vacuum subsistere rei,
> Quin sua quod natura petit concedere pergat.
> Omnia quapropter debent per inane quietum
> Æque ponderibus non æquis concita ferri.[1]

Now if weight were a *force* analogous to electrical attraction, to the propulsion of a locomotive, or even to the propulsive action of a charge of powder, this ought not to be the case. The velocities which it communicates to different masses ought to be different from each other. The two trains of unequal mass in our illustration receive unequal accelerations from the same locomotive. Nevertheless, if a great trench suddenly opened before them, they would fall into it with the same velocity.

From this it is only one step to conclude that gravitation is not a force, as Newton thought, but simply a property of space in which bodies move freely. Einstein took this step without hesitation.

Imagine the cable of the lift in some colossal skyscraper suddenly breaking. The lift will fall with an accelerated movement, though less rapidly than it would in a vacuum, on account of the atmospheric resistance and the friction of the cage of the apparatus. But let us suppose, further, that the electrical engine which works the lift has its commutator reversed at the

[1] *De Natura Rerum*, bk. ii, vv. 235–40.

same time, and this accelerates the fall to such an extent that the velocity of the descent increases 981 centimetres in every second. It would be quite easy for our engineers to carry out this experiment, though the interest of it has not up to the present seemed great enough to justify it. But we have the right, when it is necessary to make a subject clear, to say with the poet:

An thou wilt, let us dream a dream.

Let us suppose our dream fulfilled. The lift falls from above with precisely the accelerated velocity of an object falling in a vacuum.

If the passengers have kept cool enough in their giddy rush downward to observe what happens, they will notice that their feet cease to press against the floor of the lift. They can imagine themselves like La Fontaine's charming and poetic princess:

No blade of grass had felt
The light traces of her steps.

Our passengers' purses will, even if they are full of gold, no longer be heavy in their pockets—which may give them a momentary anxiety. If their hats are released from their hands, they will remain suspended in the air beside them. If they happen to have scales with them, they will notice that the pans remain poised at equal height, even if various weights are put in one pan. All this is because the objects, as a natural effect of their weight, fall toward the ground with the same velocity as the lift itself. Their weight has disappeared.

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Jules Verne described this state of things in the

projectile which he imagined taking his heroes from the earth to the moon, at the moment when the romantic projectile reaches the "neutral point": that is to say, the point where it leaves the earth's sphere of gravitation, but has not yet entered that of the moon. We might add that Jules Verne perpetrated a few little scientific heresies in connection with his projectile. In particular, he forgot that, in compliance with what is most conspicuously evident in the principle of inertia, the unfortunate passengers ought to have been flattened like pancakes against the bottom of the projectile when the charge was fired. He also wrongly supposed that objects ceased to have weight in the projectile only at the point where it was exactly between the two spheres of attraction, that of the earth and that of the moon.

But let us overlook these trifles and return to the admirable illustration he has prophetically provided for our convenience in explaining Einstein's system.

Let us take the projectile when it begins to fall freely toward the moon.[1] It is evident that from this point onward, until it lands on the moon, it will behave exactly like the lift which we have described.

During this fall upon the moon the passengers, if they have miraculously escaped being flattened at the start, will see the various objects about them suddenly deprived of their weight, floating in the air, and, at the slightest shake, adhering to the walls or the vaulted roof of the projectile. They will feel themselves extraordinarily light, and they will be able to make

[1] It is obvious that we assume the projectile to be without rotation: that is to say, the Columbia cannon must not, in our hypotheses, be rifled. This is indispensable, for if the projectile turned, there would be centrifugal effects which would greatly complicate both the phenomena and our argument.

prodigious leaps without any effort. This is because they and all the objects about them fall toward the moon with the same velocity as the projectile. Hence the disappearance of weight or gravitation, which vanish as if spirited away by some magician. The magician is the properly accelerated movement, the unimpeded fall of the observers.

In a word, to get rid of the apparent effects of gravitation in any place whatever it is enough for the observer to acquire a properly accelerated velocity. That is what Einstein calls the "principle of equivalence": equivalence of the effects of weight and of an accelerated movement. The one cannot be distinguished from the other.

Let us imagine Jules Verne's projectile and its unfortunate passengers transported a long distance from the moon, the earth, and the sun, to some deserted and glacial region of the Milky Way where there is no matter, and so remote from the stars that there is no longer any weight or attraction. Let us suppose that our projectile is abandoned there, and motionless. It is clear that in these circumstances there will be no such thing as high or low—no such thing as weight—for the passengers. They will find themselves relieved of every inconvenience of weight. They may, if they choose, stand on the inner wall of the upper part of the projectile or on the floor, as it was when they were falling upon the moon.

Now let us suppose that the wizard Merlin quietly approaches and, fastening a cord to the ring on the top of the projectile, begins to drag it with a uniformly accelerated movement. What will happen to the passengers? They will notice that they have suddenly recovered their weight, and that they are riveted

to the floor of the projectile, much as they were drawn to the surface of our planet before they left it. Indeed, if the motion of Merlin is accelerated 981 centimetres a second, they will have exactly the same sensations of weight as they had on the earth.

They will notice that if they throw a plate into the air at a given moment, it will fall upon the floor and be broken. "This is," they will think, "because we are again subject to weight. The plate falls in virtue of its weight, its inert mass." But Merlin will say: "The plate falls because, on account of its inertia, it has retained the increasing velocity which it had at the moment when it was thrown. Immediately afterwards, as I drew the projectile with an accelerated movement, the ascending velocity of the projectile was greater than that of the plate. That is why the bottom of the projectile, in its accelerated ascending course, knocked against the plate and broke it."

This proves that the weight or gravitation of a body is indistinguishable from its inertia. Inert mass and heavy mass are not, as Newton supposed, two things which happen by some extraordinary coincidence to be equal; they are identical and inseparable. The two things are really one.

And we are thus led to believe that the laws of weight and the laws of inertia, the laws of gravitation and those of mechanics, must be identical, or must at least be two modalities of one and the same thing: much as the full face and the profile of the same man are the same face seen under two different angles.

Even if the travellers in the projectile—who look rather like guinea-pigs—peep out of the window and see the cord that is drawing them, it will not alter their illusion. They will believe that they are at rest

and floating at a point of space where weight has been restored: that is to say, in the language of the experts, at a point of space where there is a "gravitational field." This phrase is analogous to the familiar "magnetic field," which refers to a part of space in which there is magnetic action, a part in which the needle of the compass has a definite direction imposed upon it.

In sum, we can at any point replace a gravitational field, or the effects of weight, by a properly accelerated movement of the observer, and vice versa. There is a complete equivalence between the effects of weight and those of an appropriate movement.

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This now enables us to establish very simply the following fundamental fact, unknown only a few years ago, but now brilliantly proved by experiment: *Light does not travel in a straight line in those parts of the universe where there is gravitation, but its path is curved like that of heavy objects.*

We showed in one of the preceding chapters that in the four-dimensional continuum in which we live, which we might call "space-time" but which we more simply call the universe, there is something that remains constant, identical for observers who move at given and different velocities. It is the "Interval" of events.

It is natural to suppose that this "Interval" will remain identical even if the velocity of the observers changes—even if it is accelerated like the velocity of the lift in our illustration, or of Jules Verne's projectile, during their fall.

In point of fact, if something in the universe is an *invariant*, as physicists say, or invariable, for the observers who move at different speeds, this something

must *naturally* remain the same for a third observer whose velocity changes gradually from that of the first to that of the second observer, and who is therefore in a state of uniformly accelerated movement. From this we deduce certain consequences of a fundamental character.

In the first place, one thing is evident, and is unanimously admitted by physicists: in a vacuum, and in a region of space where there is no force acting and no such thing as weight, light travels in a straight line. That is certain for many reasons—in the first place, on the mere ground of symmetry, because in a region of isotropic vacuum a ray which is uninfluenced will not depart from its rectilinear path in any direction whatever. That is evident, whatever hypothesis we adopt as to the nature of light, and even if, like Newton, we suppose that it consists of ponderable particles.

Admitting that, let us now suppose that at some point in the universe where there is weight—at the moon's surface, for instance—there is a remarkable gun which can fire a ball that has and retains (along its whole path) the velocity of light.

The trajectory of this ball will be very extensive, on account of its great velocity, yet curved toward the surface of the moon on account of its weight. As we may make our choice in the field of hypotheses, there is nothing to prevent us from supposing that the ball is of such a nature as to disclose its path by a faint luminous trail. There were projectiles of this character during the Great War.

As the ball advances, it also falls every second toward the moon's surface, to the same extent as any other projectile would which was fired at any velocity

whatever, or had no velocity. All objects near the surface of the ground (in a vacuum) fall at the same vertical velocity, and this is independent of their motion in the horizontal direction. That is, in fact, the reason why the paths of projectiles are the more curved the less initial speed they have.

Seen from the windows of Jules Verne's projectile (which is itself falling toward the moon), the trajectory of the ball will seem to the passengers to be a straight line, because it falls with the same velocity as they.

Now let us suppose that a luminous ray, from the flame of the gun, starts at the same time and in the same direction as the ball. This luminous ray will obviously be rectilinear for the passengers in the projectile, because light travels in a straight line when there is no weight. Consequently, since it has the same form, direction, and velocity as the luminous ball, the passengers will see the ray of light coincide in its whole course with the trajectory of the ball.

It further follows that the "Interval" (both in time and space) of the luminous ray and of the ball is, and remains, zero. Now this "Interval" must remain the same, whatever be the velocity of the observer. Hence, if Jules Verne's projectile ceases to fall, and is stopped at the moon's surface, its passengers will continue to see the luminous ray coincide at every point with the trajectory of the ball. This trajectory is, as they now notice, curved on account of weight. Therefore, the luminous ray is similarly curved in its path on account of weight.

This shows that light does not travel in a straight line, but falls, under the influence of gravitation, like all other objects. The reason why this was never known before, and it was always thought that light

travels in a straight line, is that on account of the enormous velocity of light its trajectory is only very slightly curved by weight.

That is easy to understand. At the earth's surface, for instance, light must fall (like all other objects) with a velocity equal to 981 centimetres at the end of a second. Now by the end of a second a luminous ray has travelled 300,000 kilometres. Suppose we could observe a horizontal luminous ray 300 kilometres long near the earth's surface—a very far-fetched supposition—during the thousandth part of a second, which it will take the ray to pass from one observer to the other, it will fall to the extent of only about the five-thousandth of a millimetre.

We can understand how it was that a luminous ray that deviates only to this imperceptible extent from its initial direction in the course of three hundred kilometres was always considered rectilinear.

Is there no means of verifying whether light is or is not bent out of its path by gravitation ? There is such a means in astronomy, as we shall now see.

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It is impossible to detect the curvature of a luminous ray travelling from one point to another on the earth's surface, mainly because weight on the earth is too slight to bend the ray much. A further reason is that our planet is so ridiculously small that we cannot follow the light over a sufficient distance.

But what cannot be done on this little globule of ours, the entire diameter of which light can cover in the twenty-fifth of a second, may possibly be done in the gigantic laboratory of celestial space. We have, almost within our reach—a mere matter of 93,000,000 miles away, that is to say—a star on which weight is

twenty-seven times greater than on the earth. We mean the sun. On the sun a body left to itself falls 132 metres in the first second. Its fall is twenty-seven times as rapid as on the earth.

Hence, near the sun, light will be much more bent out of its path by gravitation. The deviation will be all the greater from the fact that the sun is 800,000 miles in diameter, and a luminous ray needs a much longer time to cover this distance than to travel the length of the earth's diameter. Hence gravitation acts upon the ray of light during a much longer time than upon a ray that reaches the earth, and it will be all the more curved.

Take a luminous ray that comes from a star at a great distance behind the sun. If it reaches us after passing near to the sun, it will behave like a projectile. Its path will no longer be rectilinear. It will be slightly curved toward the sun. In other words, the ray will deviate from a straight line, and the direction it has when our eyes receive it on the earth is a little different from the direction it had when it left the star. It has been diverted.

Calculation shows that this deviation, though very slight, can be measured. It is equal to an angle of a second and three quarters : an angle which the delicate methods of our astronomers are able to measure.

Certainly such an angle is very far from considerable, for it takes 324,000 angles of one second to make a right angle. In other words, an angle of one second is that at which we should see the two ends of a rod, a metre in length, fixed in the ground, at a distance of 206 kilometres. If our eyes were sharp enough to see a man of normal height standing 200 kilometres away from us, our glance, in passing from his head to his feet,

would have a very small angle of deviation. Well, this angle accurately represents the deviation experienced by the light that comes to us from a star when it has passed close to the golden globe of the sun.

Minute as this angle is, the methods of the astronomer are so delicate and precise that he can determine it. The tiny measurement is by no means to be despised. Disdain of the men who devote themselves to such refined subtleties is very much out of place, because our modern science has been revolutionised by this measurement. Einstein is right, and Newton wrong, because we have been able to measure this minute angle and establish the curvature of light.

A great difficulty arose when we wished to verify this. How can we observe in full daylight a ray of light that comes to us from a star and passes close to the sun? It cannot be done. Even if we use the most powerful glasses the stars on the farther side of the sun are completely drowned in its blaze—to speak more correctly, in the light which is diffused by our atmosphere.

To say the truth—if we may venture upon a parenthetic remark at this juncture—night has taught us much more than day about the mysteries of the universe. In literary symbolism, in politics, the light of day is the very symbol of progress and knowledge: night is the symbol of ignorance. What folly! It is a blasphemy against night, the sweetness of which we ought rather to venerate. I do not refer to its romantic charm, but to the mighty progress in knowledge which it has enabled us to make.

Midnight is not merely the hour of crime. It is also the hour of prodigious flight toward remote worlds. During the day we see only one sun: by night we see millions of suns. The blinding veil which the sunlight

draws across the heavens may be woven of the most brilliant rays, but it is none the less a veil, for it makes us as blind as the moths which, in a strong light, can see no further than the tips of their wings.

In order to solve our problem, therefore, we have to observe in complete darkness stars which are nevertheless near the edge of the sun's disk. Is that impossible? No. Nature has met our need by providing total eclipses of the sun which may at times be seen from various stations on the earth. At those times the bright disk is hidden for a few minutes behind the disk of the moon. Midday is turned into midnight. We see stars shine out close to the masked face of the sun.

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Fortunately, a total eclipse, visible in Africa and South America, was due on May 29, 1919, shortly after Einstein had, on the strength of an argument like that we have just expounded, announced the deviation of the light of the stars when it passed the sun.

Two expeditions were organised by the astronomers of Greenwich and Oxford. One proceeded to Sobral, in Brazil, the other to the small Portuguese island Principe, in the Gulf of Guinea. Some of the English astronomers were rather sceptical about the issue. How could we, until it was proved, admit that Newton was wrong, or had at least failed to formulate a perfect law? But this *was* proved, and very decisively, by the observations.

These observations consisted in taking a certain number of photographs during the few minutes of total eclipse of the stars near the sun. They had been photographed with the same instruments some weeks before, at a time when the region of the sky in which they shine was visible at night and far from the sun.

As everybody knows, the sun passes successively, in its annual course, through the different constellations of the zodiac.

If the light of the stars which were photographed were not bent out of its path in passing the sun, it is clear that their distances ought to be the same on the plates exposed during the eclipse as on the negatives taken during the night some time previously. But if the light from them were bent out of its course during the eclipse by the gravitational influence of the sun, it would be quite otherwise. The reason is as follows. When the moon rises on one of our plains, it is not round, as everybody will have noticed, but flattened at top and bottom, somewhat like a giant tangerine lifted above the horizon for some magic supper. The moon has, of course, not ceased to be round. It merely seems to be flattened because the rays which come from its lower edge, and have to pass through a thick stratum of the atmosphere before they reach us, are bent toward the ground by the refraction of the denser atmosphere much more than are the rays coming from the moon's upper edge, which pass through a less dense mass of air. Our eyes see the edge of the moon in the direction from which its rays come to us, not in the direction from which they started. That is why the lower edge of the moon seems to us to be raised higher above the horizon than it really is. This deviation is due to refraction.

In the same way a star situated a little to the east of the sun (the rays in this case being curved by weight, not by refraction) will seem to us further away from it. It will look as if it were further east than it really is. Similarly, a star to the west of the sun will seem to us still further from the sun's western edge.

Hence the stars on either side of the sun will, if Einstein is right, be more widely separated from each other in the negatives taken during the eclipse. In their normal position, on the photographs taken during the night, they will seem nearer to each other.

This is precisely what was found when the photographs taken at Sobral and Principe were studied with the aid of the micrometer. Not only was it thus proved that the light of the stars is bent out of its path by the sun, but it was found that the deviation had exactly the extent which had been predicted by Einstein. It amounts to an angle of one second and three-quarters (1″·75) in the case of a star that is quite close to the sun's disk, and the angle decreases rapidly in proportion to the distance of stars from the sun. It was a great triumph for the theory of Einstein, and for the first time it gave us some connecting link between light and gravitation.

On the preceding page I compared the curvature of light owing to its weight with the deviation that is caused by atmospheric refraction. As a matter of fact, there were astronomers who wondered whether the agreement between Einstein's theory and the results obtained during the eclipse was not merely a coincidence: whether the deviation that was recorded was not due to refractive action by the sun's atmosphere.

It seems impossible to admit this. Sometimes we see comets passing quite close to the surface of the sun during their journey through space. Their movement would be considerably disturbed if the sun's atmosphere were refractive enough to account for the deviations observed at Sobral and Principe. Perturbations of cometary orbits of this nature, near the sun, have never been recorded. The only possible interpretation,

therefore, is that the phenomena are due to the effect of weight upon light.

Thus the light of the stars, weighed in a balance of the most exquisite delicacy, has given us a decisive confirmation of Einstein's theoretical deductions. By its fruit we know the tree.

## CHAPTER VI

### THE NEW CONCEPTION OF GRAVITATION

*Geometry and reality—Euclid's geometry and others—Contingency of Poincaré's criterion—The real universe is not Euclidean but Riemannian—The avatars of the number π—The point of view of the drunken man—Straight and geodetic lines—The new law of universal attraction—Explanation of the anomaly of the planet Mercury—Einstein's theory of gravitation.*

DOES the universe conform to the laws of geometry? It is a question that has been much discussed by philosophers and scholars, but the deviation of light owing to its weight now enables us to approach it with confidence.

In our schools we are taught a magnificent series of geometrical theorems, all solidly interconnected, the principal of which were created by the great Greek genius, Euclid. That is why classical geometry is known as Euclidean geometry. Its theorems are based upon a certain number of axioms and postulates, though these are really only affirmations or definitions.

The most important of these definitions is: "A straight line is the shortest distance between two points." That seems to schoolboys quite simple, because they know that the youth who amuses himself by running in a zigzag on the racing track will be the last to reach the tape; and at the sports ground one is not in a mood or has not time to bother about the validity of the axioms of geometry. What is the precise meaning of this definition of a straight line? There

has been a great deal of discussion of that point. Henri Poincaré has written a number of fine and profound pages on it, yet his conclusions are not entirely without an element of uncertainty.

In practice we all know what we mean by a straight line: it is the line that we make by means of a good ruler. But how do we know that a ruler is good and correct? By holding it up before the eye, and seeing that both ends of it and all the intermediate points in its edge merge together when we look along it. That is how a carpenter tells if a board is smoothly planed. In a word, in practice we mean by a straight line the line which is taken by the eye of the rifleman looking along his sights.

All this amounts to saying that a straight line is the direction in which a ray of light travels. However we look at the matter, we always come back to the same point—to say that the edge of an object is straight means that the delimiting line coincides in its whole length with a ray of light.[1] We may therefore say that practically a straight line is the path followed by light in a homogeneous medium.

And that gives rise to a question. Is the world in which we live, the universe, in conformity with Euclid's geometry? Is it Euclidean?

It must be understood that Euclid's geometry is not the only one that has been created. In the nineteenth century there were bold and profound mathematicians —Riemann, Bolyay, Lobatchewski, even Poincaré— who founded new and different and rather strange geometries. They are just as logical and coherent as the classical geometry of Euclid, but they are based

[1] It goes without saying that in all this we assume that the luminous ray travels in a homogeneous medium.

upon different axioms and postulates—in a word, different definitions.

For instance, "parallels" are said to be two straight lines, being in the same plane, which can never meet. The geometry which we learned in our boyhood says: "Through a given point there can be only one straight line parallel to a given straight line." This is said to be Euclid's postulate. Riemann, however, does not admit this and wishes to replace it by: "Through a given point there cannot be any straight line parallel to a given straight line"—that is to say, any line which never meets it. Upon this Riemann founds a quite consistent system of geometry.

Who will venture to say that Euclid's geometry is true and that of Riemann false? As theoretical ideal constructions they are both equally true.

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A question that we may legitimately ask is: Does the real universe correspond to the classical geometry of Euclid or to that of Riemann?

It was long believed that it corresponded to Euclid's geometry. Poincaré himself, speaking of Euclid's system, said: "It is, and will remain, the most convenient, (1) because it is the simplest; (2) because it agrees very well with the properties of natural solids, the bodies with which our limbs and our eyes are concerned, and out of which we make our measuring instruments."

When people used to say in earlier ages that the earth is flat, they argued pretty much as Poincaré does: "This theory is the most convenient, (1) because it is the simplest; (2) because it agrees very well with the properties of the natural objects with which we are in contact." But when men came into touch

with more remote objects, when navigators and astronomers multiplied these remote objects, the idea of a flat earth ceased to be the most convenient, the simplest, and the best suited to the facts of experience. Then appeared the idea that the earth is round, and this was found infinitely more convenient, simpler, and better adapted to the material universe.

"Convenience," which Poincaré makes a criterion of scientific truth, is a contingent and elastic thing. A point of view may be convenient in London and not in Bedford. A theory may be convenient in an area of a hundred yards and no longer convenient for an area of a hundred million miles.

The hypothesis of a flat earth has been replaced by the theory of the earth's rotundity. The stationary earth has been replaced by a revolving globe. In the same way, it seems that in our time Euclid's geometry must give way to another as a *convenient* representation of the real world.

Can there be, in our universe, our space, a parallel to a straight line ? That is to say, is it true that two straight lines being in the same plane will never meet ? The real meaning of the question is : Is it impossible for two luminous rays, travelling in empty space and being in what (for each fraction of the rays) we will call the same plane, ever to meet ? *The answer to this question is in the negative.*

As these two luminous rays are bent out of their paths in space by the gravitation of the stars, and as they are differently affected in this way because they are at different distances from the stars, it follows necessarily that they will cease to be parallel (in the Euclidean sense of the word) and will finally meet ; or at least that they cease to realise the first condition

of parallelism — coexistence — in the same local plane.

In a word, if we consider the matter, not within the ridiculously limited field of experiment in the laboratory, but in the vast field of celestial space, the real universe is not Euclidean, because in it light does not travel in a straight line.

Kant regarded the truths—to be accurate, the deductive affirmations—of the Euclidean geometry as "synthetic judgments *a priori*," or self-evident propositions. As we have seen, Kant was wrong, not only from the point of view of theoretical geometry, but also from the point of view of real geometry. The etymology of the word "geometry" (which means "measuring the earth") is enough of itself to show that it was originally, and chiefly, a practical science. That is a sufficient justification for our asking which geometry is most in accord with the real universe.

Gauss, a profound thinker, asked the question long ago, in the last century, and he made certain delicate experiments to measure if the sum of the angles of a triangle is really equal to two right angles, as the Euclidean geometry says. With this view he took a vast triangle, the apices of which were formed by the highest peaks of three widely separated mountains. One of them was the famous Brocken. With his assistants he took simultaneous sights of each peak in relation to the other two, and he found that the sum of the three angles of the triangle only differed from 180 degrees to an extent that might be put down to error in observation.

There were many philosophers who ridiculed Gauss and his experiments. With the *a priori* dogmatism that one so often encounters amongst these people

they said that his measurements, even if they had had a different result, would have proved nothing to the detriment of Euclid's theorems, but would merely have shown that some disturbing cause bent the luminous rays between the three apices of the trangle. This is true, but it does not matter.

If Gauss had found that the sum of the angles of the triangle in question was larger than two right angles, it would have proved that real geometry is not the geometry of Euclid. The question which Gauss asked was profound and reasonable. The philosophers who ridiculed it might have been challenged to define real straight lines, natural straight lines, in any other terms than those of the passage of light.

Gauss did not find the sum of the angles different from two right angles because his measurements were not sufficiently precise. If they had been much more rigorous, or if he could have used a much larger triangle —with the earth, Jupiter in opposition, and another planet as its apices—he would have found a considerable difference.

The real universe is not Euclidean. It is only approximately Euclidean in those parts of space where light travels in a straight line: that is to say, in the parts which are far from any gravitational mass, such as that in which, on an earlier page, we left Jules Verne's projectile.

There are many other reasons why the universe, in consequence of gravitation, does not conform to the laws of Euclid's geometry.

For instance, in the Euclidean geometry the extent of the circumference has a well-known proportion to its diameter, and this is indicated by the Greek letter $\pi$. This proportion, expressing how many times the

diameter is contained in the circumference, is equal to 3·14159265 . . . etc., but I pass over the rest, as $\pi$ has an infinite number of decimals. We then ask: In practice is the proportion of circumferences to their diameters really equal to the classic value of $\pi$? For instance, is this precisely the proportion of the earth's circumference to its diameter? [1] Einstein says that it is not, and he gives us the following proof. Imagine two very clever and quick and wizard-like surveyors setting out to measure the circumference and diameter of the earth at the Equator. They both use the same scales of measurement. They begin measuring at the same moment, and they start from the same point on the Equator. But one goes westward and the other eastward, and their speeds are equal, and such that the one who goes westward keeps up with the earth's rotation, and thus sees the sun all day long stationary at the same height above the horizon. In music-halls, for instance, one sometimes sees an acrobat walking on a rolling ball and keeping to the top of the ball, because the pace of his steps is exactly equal and contrary to the displacement of the spherical surface.

A stationary observer in space—on the sun, let us say—would thus see our surveyor who is going westward, stationary right opposite to him. On the other hand, the surveyor who goes eastward will seem to him to go round the earth, and twice as quickly as if he had remained at the starting-point.

When each of our surveyors, both going at the same speed, has finished his task of measuring the round of the earth, will they both have the same result? Evidently not. As the super-observer in the sun will

[1] We are, of course, imagining the earth as perfectly circular, without irregularities.

see, the yard of the surveyor who travels eastward is shortened by velocity in virtue of the Fitzgerald–Lorentz contraction. On the other hand, the yard of the surveyor who travels westward does not experience this contraction, as the super-observer on the sun, in reference to whom he remains stationary, would see.

Consequently the two surveyors reach different figures for the earth's circumference, the one who travels westward finding a result a few yards less than that of the other. Yet it is obvious that when they proceed to measure the earth's diameter, travelling at the same speed, the two observers will reach the same figure for it.

Hence the $\pi$ which expresses the proportion of the earth's circumference to its diameter on the ground of actual measurement differs according as the measurer travels in the direction of the earth's rotation or in the opposite direction. Therefore, as the *real* values of $\pi$ are different, they cannot be the unique and quite definite figure of classical geometry. Therefore the real universe does not conform to this geometry.

These differences, in the illustration we have given, are due to the earth's rotation. From the standpoint of gravitation the earth's rotation has centrifugal effects which modify the centripetal influence of weight. We have seen, moreover, that for the surveyor whose speed equals that of the earth's rotation the value of $\pi$ is smaller than for the observer whose speed seems to be double that of the rotation. Thus the effects of weight being the reverse of those of rotation, or of centrifugal force, it follows (it would be just as easy to prove this as the preceding) that the effect of weight is to give $\pi$ something less than its classical value.

In a word, in the universe real circumferences traced upon gravitating masses, such as stars, are, in proportion to their diameters, less than they are in the Euclidean geometry.

The difference is generally very slight, it is true. But there *is* a difference. If we put a mass of a thousand kilogrammes in the centre of a circle that is ten metres in diameter, the figure $\pi$ will differ in reality from its Euclidean value by less than one-thousand-million-billionth.

In the neighbourhood of such formidable masses of matter as the stars are, the difference may be far greater, as we shall see. This is the origin of the divergences between Newton's law of gravitation and that of Einstein: divergences which observation has settled in favour of the latter. But we will not anticipate.

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We showed in a previous chapter that the real universe of the Relativists is a four-dimensional continuum —not three-dimensional, as classic science thought— and that in this continuum distances in time and space are relative. The only thing that has a value independent of the conditions of observation—that has an absolute, or at least objective, value—is what we called the "Interval" of events, the synthesis of the spatial and chronological data.

Yet, in spite of its four dimensions, the universe, as we discussed it in connection with the Michelson experiment and the Special Relativity which this discloses, was nevertheless a Euclidean continuum, in which the classical geometry was verified, and light travelled in a straight line. As we have just seen, we have to recant this. The universe not only has four dimensions, but it is not Euclidean.

With what geometry does the universe accord best—or most conveniently, to use the language of Poincaré? Probably that of Riemann. When we take the compasses and draw a small circle on a sheet of paper spread on the table, the radius of the circle is found by the distance between the points of the compasses, and the circle is Euclidean. But if we draw the circle on an egg, the fixed point of the compasses being stuck in the top of the egg, and again get the radius by the distance between the points, the circle we have now drawn is not Euclidean. The proportion of the circumference to the radius as thus defined is smaller than $\pi$, just as it is smaller than $\pi$ when the circle is traced round a massive star.

Well, there is the same difference between the non-Euclidean real universe and a Euclidean continuum as there is between our flat sheet of paper and the surface of the egg, taking into account the fact that these surfaces have only two dimensions while the universe has four.

Two-dimensional space may be flat like the sheet of paper or curved like the surface of the egg. By leaving the sheet of paper flat or rolling it up we can make the geometry of the figures drawn on it correspond with or differ from the Euclidean geometry. In just the same way space with more than two dimensions may or may not be Euclidean.

As a matter of fact, the universe is, as we saw, only approximatively Euclidean in those regions which are remote from all heavy masses. It is not Euclidean, but curved or warped in the vicinity of the stars; and the curvature is the greater in proportion as we approach the stars.

Hence the geometry of curved space, as founded by

Riemann, seems to be the best adapted to the real universe. It is the one used by Einstein in his calculations.

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When we sought to prove, on a previous page, that rays of light fall just as projectiles of the same velocity would, we used the following argument:

Since the "Interval" of two events is the same for two observers moving at uniform and different velocities, it is *natural* to think that it will be the same for a third observer whose velocity increases from that of the first to that of the second—that is to say, whose velocity is uniformly accelerated.

There is, in fact, no reason why the passengers in a train which runs at a uniform speed of sixty miles an hour should observe an "invariant" element in phenomena just as do those in another train moving at half the speed, yet this "invariant" should cease to be such for the passengers in a third train which passes gradually from the velocity of the first train to that of the second. To admit the contrary would be to grant a privileged position in the universe to the first two and others like them. If there is any estate in the world that has had its unjust privileges suppressed by the new physics, it is the study of the material world.

This privilege of observers moving at a uniform velocity would be the less justified as, if we go to the root of the matter, it is very difficult to say exactly what a uniform movement is.

What do we mean when we say that a train has a uniform velocity of sixty miles an hour? We mean that the train has this velocity in reference to the rails or the ground. But in reference to an observer in a

balloon, or who passes in another train, the velocity has not the same value, and it may cease to be a uniform velocity. We know only relative movements, or, to be quite accurate, movements relative to some material object or other. According to our choice of this object, this standard of comparison, the same velocity may be uniform or accelerated. In the long run, it is clear, we should have to have recourse to Newton's hypothesis of absolute space to be able to say whether a given velocity is really uniform or accelerated.

That is the profound reason why the Einsteinian "Interval" of things, the invariable quantity or "Invariant," must be the same for all observers whatever be their velocity, and in particular for observers moving at velocities equivalent, in a given place, to the effects of gravitation.

But in that case the inferences we draw from the Michelson experiment, in regard to the aspect of phenomena for observers in uniform different movements of translation, no longer suffice to explain to us the whole of reality. They need to be completed in such fashion that the universal invariant, the "Interval" of things, remains the same for an observer who is moving in any way whatever.

If I pass along a street at some unheard-of speed, but with a uniform motion, its general aspect may, on account of the contraction caused by my velocity, be a little different from what it would seem to me if I were stationary.[1] The houses, for instance, will seem narrower in proportion to their height. Nevertheless the general aspect and proportions of objects

[1] It goes without saying that we assume the observer to have a retina with instantaneous impressions.

will be much the same in both cases, and they will have something in common. Thus the gas-lights will seem to me thinner, but they will be straight.

It will be quite otherwise if the observer's movements are varied : if, for instance, we imagine him a drunken giant, reeling about at a prodigious speed. For such an observer the street will have quite a new aspect. The gas-jets will no longer be straight, but zigzag, reproducing in an inverse way the zigzags which he himself makes as he reels along. This is so true that caricaturists generally represent the trees and lamp-posts and houses seen by a drunken man by ridiculously waving lines.

Our observer will be convinced that objects really have the zigzag forms which he sees, and that the forms change at every step he takes. Try to tell him that it is he who is dancing, not the objects ; that it is he who is not walking straight, not the dog he has on leash. He will not believe it—and from the point of view of General Relativity he is neither more nor less right than you.

Yet there is something in the aspect of the world that must be common to the drunkard and the drinker of water.

If the whole universe were suddenly plunged in a mass of gelatine which has set, and one were to squeeze or alter the shape in any way of this gelatinous mass, there would still be something unchanged in the coagulated stuff. What is this something ? And what is the calculus to use for it ? The answer to these questions was the last stage for Einstein to cover in order to establish the equations of gravitation and General Relativity.

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Here it was the penetrating genius of Henri Poincaré that indicated the path. It is very necessary to insist on this, as justice has not been done in the matter to the great French mathematician.

If all the bodies in the universe were to be simultaneously dilated, and to an identical extent, we should have no means of knowing it. Our instruments and our own bodies being similarly dilated, we should not perceive this formidable historical and cosmic event. It would not distract us for a moment from the trivialities of the hour.

What is more, not only will it be unrecognisable if worlds are modified in such a fashion as to alter the scale of lengths and time, but it would be impossible to distinguish between two worlds, if one single point of the first corresponds to each point of the second; if to each object or event of the one world there corresponds one of the same character, placed exactly in the same position, in the other. Now the successive and diverse deformations which we impose upon the gelatinous mass in which we metaphorically enclosed our entire universe in an earlier paragraph give us precisely indistinguishable worlds from this point of view. Poincaré has the distinction of first calling our attention to this and proving that the relativity of things must be understood in this very broad sense.

The amorphous and plastic continuum in which we place the universe has a certain number of properties which are exempt from all idea of measurement. The study of these properties is the work of a special geometry, a qualitative geometry. The theorems of this geometry have this peculiarity, that they would still be true even if the figures were copied by a clumsy draughtsman who made gross errors in the proportions

and substituted irregular and wavy lines for straight lines.

This is the geometry which, as Poincaré ably indicated, must be used for the four-dimensional and, according to its regions, more or less Euclidean continuum which is the Einsteinian universe. It is precisely this geometry which states what there is in common between the forms of objects seen by the drunken man and those seen by the water-drinker.

It is along this route, or a route analogous to this, that Einstein at last reached success. The universe being a more or less warped continuum, he proposed to apply to it the geometry created by Gauss for the study of surfaces of variable curvature: a geometry generalised by Riemann. It is by means of this special geometry that we express the fact that the "Interval" of events is an invariant.

Here is an illustration which will, I think, lead us to the heart of the problem of gravitation and to the solution of it.

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Let us consider a surface of variable curvature—for instance, the surface of any large district with its hills, mountains, and valleys. When we travel in this region, we can proceed in a straight line as long as we are on the level plain. A straight line on a level plain has the remarkable feature of being the shortest distance between two points. It has also this peculiarity, that it is the only one of its kind and its length, whereas we may draw a great number of lines that are not straight uniting the two points, longer than the straight line but all of equal length.

But we have reached the hilly district. It is now impossible for us to follow a straight line from one

point to another if there is a hill between them. Whatever path we take, it will be curved. But amongst the various possible paths which lead from one point to the other on the farther side of the hill, there is one —and only one, as a rule—which is shorter than any of the others, as we could prove by means of a tape. This shortest path, the only one of its kind, is what is called the *geodetical* of the surface covered.

In the same way no vessel can go in a straight line if it is sailing from Lisbon to New York. It must follow a curved path, because the earth is round. But amongst the possible curved paths there is a privileged one which is shorter than the others: the one which follows the direction of the great circle of the earth. In going from Lisbon to New York, though they are nearly in the same latitude, vessels are careful not to head straight westward, in the direction of the parallels. They sail a little to the north-west, so that when they reach New York they come from the north-east, having followed pretty closely a terrestrial great circle. On our globe, as on all spheres, the *geodetical*, the shortest route between two points, is the arc of a great circle passing through the two points.

Now the "Interval" of two points in the four-dimensional universe precisely represents the geodetical, the minimum path of progress between the two points traced in the universe. Where the universe is curved, the geodetic is a curved line. Where the universe is approximately Euclidean, it is a straight line.

I may be told that it is very difficult to imagine as curved a three-dimensional space, and still more a four-dimensional. I agree. We have already seen that it is difficult enough to imagine four-dimensional space even when it is not curved.

But what does that prove? There are many other things in nature which we cannot visualise or form a mental picture of. The Hertz waves, the X-rays, and the ultra-violet waves exist all the same, though we cannot imagine them, or at least only by giving them a visible form which does not belong to them. It is just one of our human infirmities that we cannot conceive what we cannot picture to ourselves. Hence our tendency to—if one may use an inelegant but expressive word—visualise everything.

Let us therefore return to our geodetics. These we can very well picture to ourselves, because in the universe, in spite of its four dimensions, they are lines of only one dimension, like all other lines that we know.

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The existence of geodetics, of shortest-distance lines, will now beautifully explain to us the connection between inertia and weight, which did not appear in the Euclidean world of classic science. Hence the Newtonian distinction between the principle of inertia and the force of gravitation.

We Relativists find this distinction no longer necessary. Material masses, like light, travel in a straight line when they are far from a gravitational field, and in a curved line when they are near gravitational masses. In virtue of symmetry a free material point can only follow a geodetic in the universe.

If we now reflect that the force of gravitation introduced by Newton does not exist—such action at a distance is very problematical—and that in empty space there are only objects freely left to themselves, we are driven to the following conclusion, which unites in a simple way the previously separated sisters, inertia

and weight: *Every moving body freely left to itself in the universe describes a geodetic.*

Far from the massive stars this geodetic is a straight line, because there the universe is almost Euclidean. Near the stars it is a curved line, because there the universe is not Euclidean. A fine conception, combining in a single rule the principle of inertia and the law of gravitation! A brilliant synthesis of mechanics and gravitation, putting an end to the schism which so long kept them separate and non-corresponding sciences!

In this bold and simple theory gravitation is not a force. The planets have curved paths because near the sun, just as in the neighbourhood of every concentration of matter the universe is curved or warped. The shortest path from one point to another is a line that only seems straight to us—poor pygmies that we are—because we measure it with very small rods and over small distances. If we could follow the line over millions of miles, and during a sufficient period, we should find it curved.

In a word—to use an illustration that must be regarded only as an analogy—the planets describe curved paths because they follow the shortest path in a curved universe, just as at a sports ground cyclists have no need to turn the handles when they reach the corner, but pedal straight on, because the slope of the ground compels them of itself to turn. In the sports ground, as in the solar system, the curvature is greater in proportion as the machine is nearer to the inner edge of the track.

All that now remains is to assign to the universe, to space-time, such a curvature at its various points that the geodetics will exactly represent the paths of the planets and of falling bodies, admitting that the

curvature of the universe is caused at each point by the presence or vicinity of material masses.

In this calculation we have to take into account the fact that the "Interval"—that is to say, the part of the geodetic between two points that are very near each other—must be an invariant whoever may be the observer. In this way the same geodetic will be a curved or even wavy line for the drunken man we introduced and a straight line for a stationary observer. The length of the line is the same, whether it appears straight or curved.

Taking all this into account, and doing prodigies of mathematical skill of which we have sufficiently indicated the object, Einstein has succeeded in expressing the law of gravitation in a completely invariant form.

In calculating, on the ground of Newton's law, the "Interval" of two astronomical events—for instance, the successive falls of two meteorites into the sun—we should find that the "Interval" has not precisely the same value for observers who are moving at different velocities.

With the new form given to the law by Einstein the difference disappears. The two laws, however, differ little from each other, as was to be expected in view of the accuracy with which astronomers found Newton's law verified during a couple of centuries. The improvement made in Newton's law by Einstein means, in a word (and to use the old language of the Euclidean universe), that we consider the law accurate with the reserve that the distances of the planets from the sun are measured by a scale which decreases slightly in length as the sun is approached.

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It is surprising that Newton and Einstein agree in expressing the movements of gravitating stars in an *almost* identical form, because their starting-points are very different.

Newton starts from the hypothesis of absolute space, the empirical laws of the motions of the planets expressed in Kepler's laws, and the belief that gravitational attraction is a force proportional to mass. Einstein, on the other hand, in making his calculations starts from the conditions of invariance which we indicated. He starts, in a sense, from the philosophical principle or postulate or impulse to hold that the laws of nature are invariant and independent of the point of view—irrelative, if I may use the word.

Einstein even abandons the hypothesis which ascribed the curving of gravitational paths to a distinct force of attraction. Yet, starting from a point of view so different from that of Newton, and one that seems at first less overloaded with hypotheses, Einstein reaches a law of gravitation which is *almost* identical with Newton's.

This "almost" is of immense interest, because it enables us to test which is the accurate law, that of Newton or that of Einstein. They give the same results when there is question of velocities that are feeble in comparison with that of light, but their results differ a little when there is question of very high velocities. We have already seen that, near the sun, light itself is bent out of its course in exact conformity with Einstein's law, and in a way that Newton's law did not predict as such.

But there is another divergence between the two laws. According to the Newtonian law the planets revolving round the sun describe ellipses which—

neglecting the small perturbations due to the other planets—have a rigorously fixed position.

Suppose we put on a table a slice of lemon cut through the longer diameter of the fruit, and imagine that the chief stars, the northern constellations, are painted on the vaulted roof of the vast hemispherical room in the middle of which we place our table. The slice of lemon has very nearly the form of an ellipse, and, if we take one of the pips to represent the sun, it will stand for the orbit of one of our planets. Newton's law says that—after making due corrections—the planetary orbit keeps a fixed position relatively to the stars as long as the planet continues to revolve. This means that the slice of lemon remains stationary.

Einstein's law says, on the contrary, that the orbital ellipse turns very slowly amongst the stars while the planet traverses it. This means that our slice of lemon must turn slightly on the table, in such wise that the two ends of the lemon do not remain opposite the same stars painted on the wall.

If we calculate, in virtue of Einstein's law, the extent to which the elliptical orbits of the planets must thus turn, we find it so small as to be impossible of observation except in the case of one planet, the swiftest of all, Mercury.

Mercury revolves completely round the sun in about eighty-eight days, and Einstein's law shows that its orbit must at the same time turn by a small angle which amounts to forty-three seconds of an arc (43″) at the end of a century. Small as this quantity is, the refined methods of the modern astronomer can easily measure it.

As a matter of fact, it had been noticed during the

last century that Mercury was the only one of the planets to show a slight anomaly in its movements, which could not be explained by Newton's law. Le Verrier made prodigious calculations in connection with it, as he thought that the anomaly might be due to the attraction of an unknown body lying between Mercury and the sun. He hoped that he would thus discover, by calculation, an intra-Mercurial planet, just as he had discovered the trans-Uranian planet Neptune.

But no one ever observed his planet, and the anomaly of Mercury continued to be the despair of astronomers. Now, in what did the anomaly consist ? Precisely in an abnormal rotation of the planetary orbit ; a rotation which Le Verrier's calculations showed to be forty-three seconds of an arc in a century. That is exactly the figure that we deduce, without using any hypothesis, from Einstein's law of gravitation !

It is true that, according to the recent calculations of Grossmann, the astronomical observations collected by Newcomb give as the recorded value of the secular displacement of the perihelion of Mercury, not 43″ as Le Verrier believed, but 38″ at the most. The agreement with Einstein's theoretical result is, therefore, not perfect (which would have been extraordinary), but it is striking, and is within the limits of possible error of observation.

Einstein's law is just as exact as Newton's for the slower planets. For faster bodies, the motion of which can be observed with a higher degree of precision, Newton's law is wrong, and Einstein's triumphs once more.

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This improvement of what had been considered per-

fect—the work of Newton—is a great victory for the human mind. Astronomy and celestial mechanics derive additional precision and power of forecast from it. We can now follow the golden orbs, on the triumphal wings of calculation, better than we could before, or antedate their movements by centuries.

But there is another test of Einstein's law of gravitation. If it is sound, the duration of a phenomenon increases, according to Einstein, when the gravitational field becomes more intense. It follows that the duration of the vibration of a given atom must be longer on the sun than on the earth. The wave-lengths of the spectral lines of the same chemical element ought to be a little greater in sunlight than in light which originates on the earth. Recent observations tend to confirm this, but the verification is less satisfactory than in the case of Mercury because other causes may intervene to modify the wave-lengths.

On the whole, the powerful synthesis which Einstein calls the theory of General Relativity, which we have here rapidly outlined, is a lofty and beautiful mental construction as well as a superb instrument of exploration.

To know is to forecast. This theory forecasts, and better than its predecessors did. For the first time it combines gravitation and mechanics. It shows how matter imposes upon the external world a curvature or warping of which gravitation is but a symptom: just as the weeds one sees floating on the sea are but indications of the current which bears them along.

Whatever modifications it may undergo in the future—for everything in science is open to improve-

ment—it has shown us a little more of the harmony that is born of unity in the laws of nature.

But I have sufficiently shown that if I have succeeded in enabling the reader to understand—to feel, at least—these matters without invoking the aid of the pure light which geometry pours upon the invisible.

## CHAPTER VII

### IS THE UNIVERSE INFINITE ?

*Kant and the number of the stars—Extinct stars and dark nebulæ—Extent and aspect of the astronomical universe—Different kinds of universes—Poincaré's calculation—Physical definition of the infinite—The infinite and the unlimited—Stability and curvature of cosmic space-time—Real and virtual stars—Diameter of the Einsteinian universe—The hypothesis of globes of ether.*

Is the universe infinite ? It is a question that men have asked in all ages, though they have not defined its meaning very accurately. The theory of Relativity enables us to approach it from a new and subtle point of view.

Kant—the genial grumbler who found it so horribly monotonous to see the same sun shining, and the same spring blossoming, every year—took his stand on metaphysical considerations when he affirmed that space is infinite, and is sown with similar stars in all parts.

It is, perhaps, better to confine ourselves in such a matter to the results of recent observation, and close the doors of our debating-room against the fog of metaphysics. Indeed, the latter would compel us to define pure space, about which we know nothing—not even if there is such a thing.

The proof that we know little about it is the fact that the Newtonians believe in it, while the Einsteinians regard it merely as an inseparable attribute of material things. They define space by matter ; and they then have to define the latter. Descartes,

on the contrary, defined matter in terms of extension, which is the same thing as space. It is a vicious circle. It is therefore better to leave Kant's metaphysical arguments out of our discussion, and adhere strictly to experience, to what is measurable.

To simplify matters, we will admit the reality of this continuum in which the stars float, which is traversed by their radiations, which common sense calls space. If there were stars everywhere—if they were infinite in number—there would also be space and matter everywhere. Newtonians might find this a triumph equally with Einsteinians. Those who believe in absolute space and those who deny it—Absolutists and Relativists—would equally rejoice.

It would be fortunate if astronomical observation were to show that the number of the stars is infinite, and thus the holders of contrary opinions could both chant a victory in their writings. But what does astronomical observation actually report?

There are those who deny *a priori* that the number of the stars can be infinite. That number, they said, is capable of increase; it is therefore not infinite, because nothing can be added to the infinite. The argument is specious, but unsound; although Voltaire himself was seduced by it. One need not be a great mathematician to see that it is always possible to add to an infinite number, and that there are infinite quantities which are themselves infinitely small in comparison with others. Let us get on to the facts.

If the stellar universe has no limits, there is no visual line drawn from the earth to the heavens which will not encounter one of the stars. The astronomer Olbers has said that the whole nocturnal sky would in that case shine with the brilliance of the sun. But

the total brilliance of all the stars put together is only three thousand times greater than that of a star of the first magnitude, or thirty million times less than the light of the sun.

But that proves nothing, as Olbers' argument is wrong, for two reasons. On the one hand, there are necessarily a good many extinct or dark stars in the heavens. Some of them have been closely studied, even weighed. They betray their existence by periodically eclipsing brighter stars, with which they revolve. On the other hand, it was discovered some time ago that celestial space is occupied over large stretches by dark gaseous masses and clouds of cosmic dust, which absorb the light of more distant stars. We thus see that the existence of an infinite number of stars is quite compatible with the poorness of the light of the heavens at night.

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Now let us put on our spectacles—our telescopes, I mean—and turn from the province of possibility to that of reality, and we shall see that recent astronomical observation has yielded a number of remarkable facts which lead irresistibly to the following conclusions.

The number of the stars is not, as was long supposed, limited by the range of our telescopes alone. As we get further away from the sun, the number of stars contained in a unity of space, the frequence of the stars, the density of the stellar population, do not remain uniform, but decrease in proportion as we approach the limits of the Milky Way.

The Milky Way is a vast archipelago of stars, our sun lying in its central region. This mass of stars, to which we belong, has, roughly, the shape of a watch-case, the thickness being only about half the width

of the structure. Light, which travels from the earth to the moon in little over a second, from the earth to the sun in eight minutes, and from the earth to the nearest star in three years, needs at least 30,000 years—three hundred centuries—to pass from end to end of the Milky Way.

The number of stars in the Milky Way is something between 500 and 1,500 millions. It is a small number: scarcely equal to the human population of the earth, much smaller than the number of molecules of iron in a pin's head.

In addition to these we have discovered dense masses of stars, such as the Magellanic Clouds, the cluster in Hercules, and so on, which seem to belong to the fringes of our Milky Way—to be suburbs of it, so to say. These suburbs seem to stretch a considerable distance, particularly on one side of the Milky Way. The furthest away is, perhaps, not less than 200,000 light-years from us.

Beyond these space seems to be deserted, devoid of stars over expanses which are enormous in comparison with the dimensions of our galactic universe as we have described it. What is beyond this?

Well, beyond this we find those strange bodies, the spiral nebulæ, lying like silver snails in the garden of the stars. We have discovered several hundred thousand of them. Some astronomers believe that these spiral masses of stars may be annexes of the Milky Way, reduced models of it. Most astronomers incline to think, for very good reason, that the spiral nebulæ are systems like the Milky Way, and comparable to it in their dimensions. If the former view is correct, the entire system of stars accessible to our telescopes could be traversed by light in some hundreds

of thousands of years. On the second hypothesis the dimensions of the stellar universe to which we belong must be multiplied by ten, and light would take at least millions of years to traverse it.

On the first view the entire stellar universe, in so far as it is accessible to us, consists of the Milky Way and its annexes: that is to say, a local concentration of stars, beyond which we can see nothing. The stellar universe is, in other words, practically limited, or at least finite.

On the second view our Milky Way is simply one of the myriads of spiral universes we see. The spiral nebula (with its hundreds of millions of stars) plays the same part in this vaster universe that a star has in the Milky Way. We have the same problem as before, but on a vaster scale: if the Milky Way consists of a concentration of a finite number of stars, as observation proves, does the accessible universe consist of a finite number of spiral nebulæ?

Experience has as yet not pronounced on this point. But in my opinion it is probable that, when our instruments are powerful enough to tackle such a problem —in several centuries, perhaps—science will answer "yes."

If it were otherwise, if the spiral nebulæ were fairly evenly distributed as we go outward, we can show by calculation that, attraction being in inverse proportion to the square of the distance, gravitation would have an infinite intensity in such a universe, even in the part in which we live. But this is not the case. It follows that, either the attraction of two masses decreases at great distances rather more rapidly than in inverse proportion to the square of the distance (which is not wholly impossible), or that the number of stellar

systems and stars is finite. Personally I favour the second hypothesis, but it is incapable of proof. In such matters there is always an alternative, always a way of escaping in accordance with one's bias, and there is really nothing that compels us to say that the stars are finite in number.

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Starting from the mean value, as it has been observed, of the proper motions of the nearer stars, Henri Poincaré has calculated that the total number of stars in the Milky Way must be about one thousand million. The figure agrees fairly well with the results of the star-gauges effected by astronomers by means of photographic plates.

He has also shown that the proper motions of stars would be greater if there were many more stars than those which we see. Thus Poincaré's calculations are opposed to the hypothesis of an indefinite extension of the stellar universe, as the number of stars "counted" agrees fairly closely with the number "calculated." We should add, however, that these calculations prove nothing if the law of attraction is not quite the inverse proportion of the square at enormous distances.

On the other hand, if the universe is finite in space as it is conceived in classic science, the light of the stars, and isolated stars themselves, would gradually drift away into the infinite, and the cosmos would disappear. Our mind resents this consequence, and astronomical observation discovers no trace whatever of such a dislocation.

In a word, in the space of the "Absolutists" the stellar universe can only be infinite if the law of the square of distances is not quite exact for very remote

masses ; and it cannot be finite except on the condition that it is ephemeral in point of time.

For Newton, indeed, the *stellar* universe might be finite within an infinite universe, because in his view there can be space without matter. For Einstein, on the contrary, the universe and the material or stellar universe are one and the same thing, because there is no space without matter or energy.

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These difficulties and obscurities disappear in great part when we consider space, or space-time, from the Einsteinian standpoint of General Relativity.

What is the meaning of the sentence, " The universe is infinite " ? From either the Einsteinian, the Newtonian, or the Pragmatist point of view it means : If I go straight ahead, going on eternally, I shall never get back to my starting-point.

Is it possible ? Newton is compelled to say yes, because in his view space stretches out indefinitely, independent of the bodies that occupy part of it, whether the number of the stars is or is not limited.

But Einstein says no. For the Relativist the universe is not necessarily infinite. Is it therefore limited, fenced in by some sort of railings ? No. It is not limited.

A thing may be unlimited without being infinite. For instance, a man who moves on the surface of the earth may travel over it indefinitely in every direction without ever reaching a limit. The surface of the earth, thus regarded, or the surface of any sphere whatsoever, is therefore both finite and unlimited. Well, we have only to apply to space of three dimensions what we find in two-dimensional space (a spherical

surface), to see how the universe may be at one and the same time finite and unlimited.

We saw that, in consequence of gravitation, the Einsteinian universe is not Euclidean, but curved. It is, as we said, difficult, if not impossible, to visualise a curvature of space. But the difficulty exists only for our imagination, which is restricted by our life of sense, not for our reason, which goes farther and higher. It is one of the commonest of errors to suppose that the wings of the imagination are more powerful than those of reason. If one wants proof of the contrary, one has only to compare what the most poetic of ancient thinkers made of the starry heavens with what modern science tells about the universe.

Here is the way to approach our problem. Let us not notice for the moment the rather irregular distribution of stars in our stellar system, and take it as fairly homogeneous. What is the condition required for this distribution of the stars under the influence of gravitation to remain stable? Calculation gives us this reply: The curvature of space must be constant, and such that space is bent like a spherical surface.

Rays of light from the stars may travel eternally, indefinitely, round this unlimited, yet finite, universe. If the cosmos is spherical in this way, we can even imagine the rays which emanate from a star—the sun, for instance—crossing the universe and converging at the diametrically opposite point of it.

In such case we might expect to see stars at opposite points in the heavens, of which one would be the image, the spectre, the "double" of the other—in the sense which the ancient Egyptians gave to the word. Properly speaking, this "double" would represent, not the generating star as it is, but as it was at the time

when it emitted the rays which form the double, or millions of years earlier.

If we observe the original and the double star, the reality and the mirage, simultaneously from some remote part of the stellar system, such as our planet, we shall see a great difference between them, since the " copy " will show us the original as it was thousands of centuries before. It may, in fact, happen that the second star is more brilliant than the first, because in the meantime the first has gradually cooled, and may even be extinct.

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It is improbable that we should find many of these phantom-stars, or virtual stars, luminous and unreal daughters of heavy suns. The reason is that the rays in their passage through the universe will generally be diverted by the stars near which they pass. Concentration or convergence of them at the antipodes of the real star must be rare. Moreover, the rays are to some extent absorbed by the cosmic stuff they meet in space. It is, however, not impossible that the astronomers of the future may discover such phenomena. It is, in fact, not impossible that we have already observed such things without knowing it.

In any case, what observers have not done in the past they may very well do in the future, thanks to the suggestions of the new science. Possibly it is going to have a great effect on observational astronomy and induce it to furnish brilliant new verifications of theory. There may be astonishing results, unforeseen by our folly, of the new conceptions, surpassing in their fantastic poetry the most romantic constructions of the imagination. Reality, or at least the possible, is

rising to giddy heights that were far beyond the reach of the golden wings of fantasy.

I spoke on a previous page of the millions of years which light takes to travel round our curved universe. Starting from the fairly well-ascertained value of the quantity of matter comprised in the Milky Way, it is possible to calculate the curvature of the world and its radius. We find that the radius has a value equal to at least 150,000,000 light-years.

It therefore takes light at least 900,000,000 years, at a speed of 186,000 miles a second, to travel round the universe, assuming that it consists only of the Milky Way and its annexes. The figure is quite consistent with the figures we get from astronomical observation for the dimensions of the galactic system, and also with the much larger figures which we find if we regard the spiral nebulæ as Milky Ways.

Thus for the Relativist the universe may be unlimited without being infinite. As to the Pragmatist, who goes straight ahead—who follows what he calls a straight line, or the path of light—he will get back in the end to the body from which he started, provided that he has time enough at his disposal. He will then say that, if that is the nature of things, the universe is not infinite.

Hence the question of the infinity or finiteness of the universe can be controlled by experience, and some day it will be possible to prove whether the whole cosmos and space are Newtonian or Einsteinian. Unfortunately, it will have to be a very long experience, with various little practical difficulties to overcome.

We may therefore prefer not to commit ourselves without further instructions. We may not feel ourselves obliged to choose between the two conceptions,

and we may leave the benefit of the doubt to whichever of the two is false.

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Moreover, there is perhaps a third issue: if not for the Pragmatist, at least for the philosopher—I mean, seeing that in England physics comes under the head of "Natural Philosophy," for the physicist.

Here it is. If all the heavenly bodies we know belong to the Milky Way. other and very remote universes may be inaccessible to us because they are optically isolated from us; possibly by the phenomena of the cosmic absorption of light, to which we have already referred.

But this might also be due to something else which will, perhaps, shock Relativists, but will seem to Newtonians quite possible. The ether, the medium that transmits the luminous waves, and which Einstein has ended by admitting once more (refusing, however, to give it its familiar kinematic properties), and matter seem more and more to be merely modalities. We explained this, on the strength of the most recent physical discoveries, in a previous chapter. There is nothing to prove that these two forms of substance are not always associated.

Does this not give me the right to think that perhaps our whole visible universe, our local concentration of matter, is only an isolated clump or sphere of ether? If there is such a thing as absolute space (which does not mean that it is accessible to us), it is independent of ether as well as matter. In that case there would be vast empty spaces, devoid of ether, all round our universe. Possibly other universes palpitate beyond these; and for us such worlds would be for ever as if they did not exist. No ray of knowledge would ever

reach us from them. Nothing could cross the black, dumb abysses which environ our stellar island. Our glances are confined for ever within this giant—yet too small—monad.

"Are there, then," some will cry in astonishment, "things which exist, yet we will never know them ?" Naive pretension—to want to embrace everything in a few cubic centimetres of grey brain-stuff !

## CHAPTER VIII

### SCIENCE AND REALITY

*The Einsteinian absolute—Revelation by science—Discussion of the experimental bases of Relativity—Other possible explanations—Arguments in favour of Lorentz's real contraction—Newtonian space may be distinct from absolute space—The real is a privileged form of the possible—Two attitudes in face of the unknown.*

We approach the end of our work. Has reality, seen through the prism of science, changed its aspect with the new theories? Yes, certainly. The Relativist theory claims to have improved the achromatism of the prism and by this means improved the picture it gives us of the world.

Time and space, the two poles upon which the sphere of empirical data turned, which were believed to be unshakeable, have been dislodged from their strong positions. Instead of them Einstein offers us the continuum in which beings and phenomena float: four-dimensional space-time, in which space and time are yoked together.

But this continuum is itself only a flabby form. It has no rigidity. It adapts itself docilely to everything. There is nothing fixed, because there is no definite point of reference by means of which we could distribute phenomena; because on the shores of this great ocean in which things float there are none left of those solid rings to which mariners once fastened their vessels.

Up to this point the theory of Relativity well deserves its name. But now, in spite of it and its very name,

there rises something which seems to have an independent and determined existence in the external world, an objectivity, an *absolute* reality. This is the "Interval" of events, which remains constant and invariable through all the fluctuations of things, however infinitely varied may be the points of view and standards of reference.

From this datum, which, speaking philosophically, strangely shares the intrinsic qualities with which the older absolute time and absolute space were so much reproached, the whole constructive part of Relativity, the part which leads to the splendid verifications we described, is derived.

Thus the theory of Relativity seems to deny its origin, even its very name, in all that makes it a useful monument of science, a constructive tool, an instrument of discovery. It is a theory of a new absolute: the Interval represented by the geodetics of the quadridimensional universe. It is a new absolute theory. So true is it that even in science you can build nothing on pure negation. For creation you need affirmation.

The theory of Relativity has won brilliant victories, crowned by the decisive sanction of facts. We have given some astonishing instances of these in our earlier chapters. But to say that the theory is true because it has predicted phenomena that were afterwards verified would be to judge it from too narrowly Pragmatist a standpoint. It would also—there is real danger in this—be to close against the mind other paths where there are still flowers to cull. We will not do that.

It is therefore important, in spite of its successes—nay, on account of them—to turn the light of criticism upon the foundations of the new doctrine. Even

Cæsar, as he mounted the Capitol, had to listen to the jokes of the soldiers round his chariot and lower his pride. The theory of Relativity also, as it advances in all its magnificence along the Triumphal Way, must learn that it has its limits, perhaps its weaknesses.

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But before we go further into it, before we turn the raw light upon it, let us make one observation.

Whatever be the obscurities of physical theories, whatever be the eternal and fated imperfection of science, one thing may be positively laid down here: scientific truths are the best established, the most certain, the least doubtful of all the truths we can know in regard to the external world. If science cannot reveal to us the nature of things in its entirety, there is nothing else that can do it as well. The truths of sentiment, of faith, of intuition, have nothing to do with those of science as long as they remain strictly truths of the interior world. They are on another plane. But the moment they claim to be measures of the external world—which would be their only cause of weakness—they subject themselves to the material reality, to the scientific investigation of the truth.

It is therefore nonsense to speak of a "bankruptcy of science" as contrasted with the certainty which other disciplines may give us respecting the external world. The bankruptcy of one would make all the others bankrupt. When it is not a question of the intimate oasis in which the serene realities of sentiment flourish, but of the arid and imperfectly explored desert of the material world, the scientific facts are the basis of all constructions. Destroy those and you destroy everything. If you ram the ground floor of a house

and bring it down, you bring down also the upper stories.

To say the truth, it would seem that nothing here below so much reveals the mystic presence of the divine as does the eternal and inflexible harmony that unites phenomena, and that finds expression in the laws of science.

Is not this science which shows us the vast universe well ordered, coherent, harmonious, mysteriously united, organised like a great mute symphony, dominated by law instead of caprice, by irrefragable rules instead of individual wills—is this not a revelation ?

There you have the only means of reconciling the minds which are devoted to external realities and those which bow to metaphysical mystery. To talk of bankruptcy of science—if it means anything more than to point out human weakness, which is, alas ! obvious enough—is really to calumniate that part of the divine which is accessible to our senses, the part which science reveals.

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In sum, the whole Einsteinian synthesis flows from the issue of the Michelson experiment, or at least from a particular interpretation of that issue.

The phenomenon of stellar aberration proves that the medium which transmits the light of the stars to our eyes does not share the motion of the earth as it revolves round the sun. This medium is known to physicists as ether. Lord Kelvin, who was honoured by being buried in Westminster Abbey not far from the tomb of Newton, rightly regarded the existence of interstellar ether as proved as fully as the existence of the air we breathe ; for without this medium the

heat of the sun, mother and nurse of all terrestrial life, would never reach us.

In his theory of Special Relativity, Einstein, as we saw, interprets phenomena without introducing the ether, or at least without introducing the kinematic properties which are usually attributed to it. In other words, Special Relativity neither affirms nor denies the existence of the classic ether. It ignores it.

But this indifference to or disdain of the ether disappears in the theory of General Relativity. We saw in a previous chapter that the trajectories of gravitating bodies and of light are directly due, on this theory, to a special curvature and the non-Euclidean character of the medium which lies close to massive bodies in the void—that is to say, ether. This, therefore, though Einstein does not give it the same kinematic properties as classic science did, becomes the substratum of all the events in the universe. It resumes its importance, its objective reality. It is the continuous medium in which spatio-temporal facts evolve.

Hence in its general form, and in spite of the new kinematic attitude which is ascribed to it, Einstein's general theory admits the objective existence of ether.

Stellar aberration shows that this medium is stationary relatively to the orbital motion of the earth. The negative result of Michelson's experiment tends, on the contrary, to prove that it shares the earth's motion. The Fitzgerald–Lorentz hypothesis solves this antinomy by admitting that the ether does not really share the earth's motion, but saying that all bodies suddenly displaced in it are contracted in the direction of the movement. This contraction increases with their

velocity in the ether, which explains the negative result of the Michelson experiment.

Lorentz's explanation seemed to Einstein inadmissible on account of certain improbabilities which we pointed out, and especially because it assumes that there is in the universe a system of privileged references which recalls Newton's "absolute space." Einstein, taking his stand on the principle that all points of view are equally relative, does not admit that there are in the universe privileged spectators—spectators who are stationary in the ether—who could see things as they are, whereas these things would be deformed for every other observer.

Then, while preserving the Lorentz contraction and the formulæ in which it is expressed, Einstein says that this contraction, while it really exists, is only an appearance, a sort of optical illusion, due to the fact that the light which shows us objects does not travel instantaneously, but with a finite velocity. This spread of light follows laws of such a nature that apparent space and time are changed in precise accordance with the formulæ of Lorentz. That is the foundation of Einstein's Special Relativity.

Hence the two immediate possible explanations of the negative result of the Michelson experiment are :

1. Moving objects are contracted in the stationary ether, the fixed substratum of all phenomena. This contraction is real, and it increases with the velocity of the body relatively to the ether. That is Lorentz's explanation.

2. Moving objects are contracted relatively to any observer whatsoever. This contraction is only apparent, and is due to the laws of the propagation of light. It increases with the velocity of the moving

body relatively to the observer. That is Einstein's explanation.

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But there is at least one other possible explanation. It introduces new and strange hypotheses, but they are by no means absurd. Indeed, it is especially in physics that truth may at times seem improbable. This explanation will show how we may account for the result of the Michelson experiment apart from either Lorentz or Einstein.

This third explanatory hypothesis is as follows. Every material body bears along with it, as a sort of atmosphere, the ether that is bound up with it. There is, in addition, a stationary ether in the interstellar spaces; an ether insensible to the motion of the material bodies that move in it, and which we may, to distinguish it from the ether bound up with bodies, call the "super-ether." This super-ether occupies the whole of interstellar space, and near the heavenly bodies it is superimposed upon the ether which they bear along. The ether and the super-ether interpenetrate each other just as they penetrate matter, and the vibrations they transmit spread independently. When a material body sends out series of waves in the ether which surrounds it, these move relatively to it with the constant velocity of light. But when they have traversed the relatively thin stratum of ether bound up with the material body, which merges gradually in the super-ether, they spread in the latter, and it is relatively to this that they progressively take their velocity.

It is like a boat crossing the Lake of Geneva at a certain speed. About the middle of the lake it has

this speed relatively to the narrow current which the River Rhone makes there, and then it resumes it relatively to the stationary lake.

In the same way the luminous rays of the stars, although they come from bodies which are approaching or receding from us, have the same velocity when they reach us, and this will be the common velocity which the super-ether imposes upon them. Thus also, on the other hand, the stellar rays that reach our telescopes will be transmitted to us by the super-ether, without the very thin stratum of mobile ether bound up with the earth being able to disturb their propagation.

These hypotheses explain and reconcile all the facts: (1) the fact of stellar aberration, because the rays which reach us from the stars are transmitted to us unaltered by the super-ether; (2) the negative result of the Michelson experiment, because the light which we produce in the laboratory travels in the ether that is borne along by the earth, where it originates; (3) the fact that, in spite of the approach or recession of the stars, their light reaches us with the common velocity which it had acquired in the super-ether, shortly after it started.

However strange this explanation may seem, it is not absurd, and it raises no insurmountable difficulty. It shows that, if the result of the Michelson experiment is a sort of no-thoroughfare, there are other ways out of it besides Einstein's theory.

To resume the matter, we have offered to us three different ways of escaping the difficulties, the apparent contradictions, involved in our experience—the antinomy arising from aberration and the Michelson result—and they are reduced to these alternatives:

1. The contraction of bodies by velocity is real (Lorentz).

2. The contraction of bodies by velocity is only an appearance due to the laws of the propagation of light (Einstein).

3. The contraction of bodies by velocity is neither real nor apparent: there is no such thing (hypothesis of super-ether connected with ether).

This shows that the Einsteinian explanation of phenomena is by no means imposed upon us by the facts, or is at least not absolutely imposed by them to the exclusion of any other explanation.

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Is it at least imposed by reason, by principles, by the evidential character of its rational premises, or because it does not conflict with our good sense and mental habits as the others do?

One would suppose this at first, when one compares it with the teaching of Lorentz; and, in order to relieve this discussion, I will for the moment leave out of account the third theory which I sketched, that of a super-ether.

What seemed most difficult to admit in Lorentz's hypothesis of real contraction was that the contraction of bodies was supposed to depend entirely upon their velocity, not in any way upon their nature; that it was supposed to be the same for all bodies, no matter what was their chemical composition or physical condition.

A little reflexion shows that this strange suggestion is not so clearly inadmissible. We know that the atoms are all formed of the same electrons, and they differ, and differentiate bodies, only in their number and arrangement. If, then, the electrons common to all matter and their relative distances experience simul-

taneously a contraction due to velocity, it is natural enough to suppose that the result may be the same for all objects. When an iron grating of a given length is dilated by heat, the extent to which a temperature of a hundred degrees dilates it will be the same whether it counts ten or a hundred steel bars to the square yard, provided they are identical.

Hence it is not really here that we find the improbability which caused Relativists to reject the Lorentz theory. It is in the principles of the theory. It is because the theory admits in nature a system of privileged reference—the stationary ether relatively to which bodies move.

Let us examine this more closely. It has been said that Lorentz's stationary ether is merely a resuscitation of Newton's absolute space, which the Relativists have so vigorously attacked. That is very far from the truth. If, as we supposed in the preceding chapter, our stellar universe is only a giant globe of ether rolling in a space that is devoid of ether—one of many such globes that will remain for ever unknowable to man—it is obvious that the drop of ether which represents our universe may very well be moving in the environing space, which would then be the real "absolute space."

From this standpoint the Lorentzian ether cannot be identified with absolute space. To do so amounts to saying that the space called "absolute" by Newton does not deserve the name. If Newtonian space is only the physical continuum in which the events of our universe happen, it is anything but stationary.

In that case the whole fault one has to find with Newton is that he used a wrong expression: that he called something absolute which is merely privileged for a given universe. It would be a quarrel about

grammar; and such things have never succeeded in revolutionising science.

But the Relativists—at least those impenitent Relativists, the Einsteinians—will not be content with that. It is not enough for them that the Newtonian space with all its privileges may not be absolute space.

Our conception of the universe, as a moving island of ether, is well calculated to reconcile the pre-eminence of Newtonian space with that agnosticism which forbids us to hope to attain the absolute. But this again is not enough for the Einsteinians. What they mean to do is to strip of all its privileges the Newtonian space on which the structure of classical mechanics has been reared. They mean to reduce this space to the ranks, to make it no more than analogous to any other spaces that can be imagined and which move arbitrarily in reference to it.

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From the agnostic, the sceptical, point of view this is a fine and strong attitude. But in the course of this volume we have so much admired Einstein's powerful theoretical synthesis and the surprising verifications to which it led that we are now entitled to make some reserves. It is legitimate to call into question even the denials of doubters, because, after all, they are really themselves affirmations.

We believe that in face of this philosophic attitude of the Einsteinians—in face of what I should like to call their absolute relativism—we are justified in rebelling a little and saying something like this:

"Yes, everything is possible; or, rather, many things are possible, but all things are not. Yes, if I go into a strange house, the drawing-room clock may be round, square, or octagonal. But once I have entered the

house and seen that the clock is square, I have a right to say: 'The clock is square. It has the privilege of being square. It is a fact that it is neither round nor octagonal.'

"It is the same in nature. The physical continuum which contains, like a vase, all the phenomena of the universe, might have, relatively to me—and as long as I have not observed it—any forms or movements whatever. But as a matter of fact, it is what it is. It cannot be different things at the same time. The drawing-room clock cannot at one and the same time be composed entirely of gold and entirely of silver.

"There is therefore one privileged possibility amongst the various possibilities which we imagine in the external world. It is that which has been effectively realised: that which exists."

The complete relativism of the Einsteinians amounts to making the universe external to us to such an extent that we have no means of distinguishing between what is real and what is possible in it, as far as space and time are concerned. The Newtonians, on the other hand, say that we can recognise real space and real time by special signs. We will analyse these signs later.

In a word, the pure Relativists have tried to escape the necessity of supposing that reality is inaccessible. It is a point of view that is at once more modest and much more presumptuous than that of the Newtonians, the Absolutists.

It is more modest because according to the Einsteinian we cannot know certain things which the Absolutist regards as accessible: real time and space. It is more presumptuous because the Relativist says that there is no reality except that which comes under observation. For him the unknowable and non-

existent are the same thing. That is why Henri Poincaré, who was the most profound of Relativists before the days of Einstein, used to repeat constantly that questions about absolute space and time have " no meaning."

One might sum it up by saying that the Einsteinians have taken as their motto the words of Auguste Comte : " Everything is relative, and that is the only absolute."

Newton, whose spatio-temporal premises Henri Poincaré vigorously refused to admit, and classical science take up an attitude, on the contrary, which Newton himself well described when he wrote : " I am but a child playing on the shore, rejoicing that I find at times a well-polished pebble or an unusually fine shell, while the great ocean of truth lies unexplored before me." Newton says that the ocean is unexplored, but he says that it exists ; and from the features of the shells he found he deduced certain qualities of the ocean, especially those properties which he calls absolute time and space.

Einsteinians and Newtonians are agreed in thinking that the external world is not in our time entirely amenable to scientific research. But their agnosticism differs in its limits. The Newtonians believe that, however external to us the world may be, it is not to such an extent as to make " real time and space inaccessible to us." The Einsteinians hold a different opinion. What separates them is only a question of degree of scepticism. The whole controversy is reduced to a frontier quarrel between two agnosticisms.

# CHAPTER IX

## EINSTEIN OR NEWTON ?

*Recent discussion of Relativism at the Academy of Sciences—Traces of the privileged space of Newton—The principle of causality the basis of science—Examination of M. Painlevé's objections—Newtonian arguments and Relativist replies—M. Painlevé's formulæ of gravitation—Fecundity of Einstein's theory—Two conceptions of the world—Conclusion.*

WHAT are these " special signs " by which the Newtonian conception of nature recognises that we are in touch with the privileged space which Newton called absolute space, and which seemed to him the real, intrinsic, exclusive frame of phenomena ?

These signs or criteria are implicitly at the root of the development of classic science, but they for a time remained in the shades of the discussions provoked by Einstein's theory. Leaving aside for a moment other, and perhaps less noble, cares, M. Paul Painlevé, addressing the Academy of Sciences at Paris, has with brilliant success drawn attention to the arguments, ancient yet ever robust, which constitute the strength of the Newtonian conception of the world.

Let us from this point speak of the absolute time and space of Newton and of Galileo as privileged space and privileged time, in order not to expose our flanks further to the metaphysical objections—not without justification—which the qualification " absolute " provokes.

Why is classical science, the mechanics of Galileo and

Newton, founded upon privileged space and privileged time? Why do they refer all phenomena to these unique standards, and consider them adequate to reality? It is on account of the principle of causality.

The principle may be formulated thus: Identical causes produce identical effects. That means that the initial conditions of a phenomenon determine its ulterior modalities. It is briefly a statement of the determinism of phenomena, and without that science is impossible.

It is, of course, possible to be captious on the point. Conditions entirely identical with given initial conditions can never be reproduced or discovered at a different time or in a different place. There is always some circumstance that will be different; for instance, the fact that in the interval between the two experiments the Nebula in Andromeda will have come several thousand miles nearer to us. And we have no influence on the Nebula in Andromeda.

Happily—this saves the situation—distant bodies have, it seems, only a negligible influence on our experiments. That is why we can repeat them. For instance, if we to-day put a gramme of sulphuric acid in ten grammes of soda-solution (one-tenth), they will in the same period of time produce the same quantity of sulphate of sodium that they would have done a year previously in the same conditions of temperature and pressure; in spite of the fact that meantime Marshal Foch sailed for the United States.

Thus the principle of causality (like causes, like effects) is always verified, and never found at fault. It is therefore an empirical truth, but in addition to this it imposes itself on our mind with irresistible force. It even imposes itself upon animals. "The scalded

cat avoids hot water," is proof enough. In any case, not science only but the whole life of man and animals is based upon it.

It is a consequence of the principle that if the initial conditions of a movement present a symmetry, this will appear again in the movement. M. Paul Painlevé insisted strongly on this in the course of the recent discussion of Relativism at the Academy of Sciences. The principle of inertia in particular follows from this statement : a body left to itself far from any material mass will, by reason of symmetry, remain at rest or travel in a straight line.

It will certainly follow a straight line for a given observer (or for observers moving with uniform velocities relatively to the first). The Newtonians say that the space of these observers is privileged.

On the other hand, for another observer who is, relatively to them, moving at an accelerated velocity, the path of the moving body will be a parabola, and will no longer be symmetrical. Therefore the space of this new observer is not privileged space.

It seems to me that the Relativists might reply to this as follows. You have no right to define the initial conditions for a given observer, then the subsequent movement for another observer who is moving with accelerated velocity. If you thus define your initial conditions relatively to the latter, the moving body at the moment when it is released is not free for this observer, but falls in a gravitational field. It is therefore not surprising that the motion produced seems to him accelerated and dissymmetrical. The principle of causality is not wrong for either observer.

One might also give a different definition of the privileged system, saying : it is that relatively to which

light travels in a straight line in an isotropic medium. But in that case the rays from the stars travel in a spiral for an observer fixed on a turning earth, and the Newtonians would infer from this that the earth turns relatively to their privileged space. Einsteinians will reply that the space in which the rays travel is not isotropic, and that they are diverted from the straight line in it by the turning gravitational field which causes the centrifugal force of the earth's rotation. They will always find an escape which will leave the principle of causality intact.

It seems difficult, therefore, to give unanswerable proof of the existence of the privileged system when we start from the principle of causality. Each party retains its position.

. . . . .

On the other hand, there is evidential value, a keen and convincing penetration, in the second part of the criticism which M. Painlevé directs against the principles of Einstein's theory.

Let us sum up the argument of the distinguished geometrician. You, he says to the Einsteinians, deny all privilege to any system of reference whatever. But when you want to deduce, by calculation, the law of gravity from your general equations, you cannot do it, and you really do not do it, except by introducing scarcely disguised Newtonian hypotheses and privileged axes of reference. You only reach the result of your calculation by sharply separating time and space as Newton does, and by referring your gravitating moving objects to purely Newtonian privileged axes, in the case of which certain conditions of symmetry are realised.

To this fine and profound criticism which M. Pain-

levé raises may be added that of Wiechert, who has pointed out various other hypotheses introduced by Einstein in the course of his calculations.

In a word, Einstein seems not to have kept entirely clear of the Newtonian premises which he repudiates. He has not the disdain for them that one would suppose, and he does not hesitate to have recourse to them occasionally for the purpose of helping out his calculations. That is rather to pay a little reverence to the idols you have burned.

In reply the Einsteinians will doubtless say that, if they introduce Newtonian axes in the course of their arguments, it is to make the results of calculation comparable to the result of experimental measurements. The axes introduced into their equations have for the Relativists the sole privilege of being those to which experimenters refer their measurements. But we must admit that that is no small privilege.

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That is not all. The principle of General Relativity amounts to this: All systems of reference are equivalent for expressing natural laws, and these laws are invariant to any system of reference to which they are related. That means in effect: There are relations between objects of the material world which are independent of the one who observes them, and particularly of his velocity. Thus, when a triangle is drawn on paper, there is something in the triangle which characterises it and which is identical, whether the observer passes very quickly or very slowly, or at any speed and in any direction whatever, beside the paper.

M. Painlevé observes, with some reason, that in this form the principle is a sort of truism. It is a severe

verdict, yet it expresses a certain fact. The real relations of external objects cannot be altered by the standpoint of the observer.

Einstein replies that it is at all events something to have provided a sieve by which we may sift the laws and formulæ which serve to represent the phenomena that have been empirically observed: a criterion which they must pass before they are recognised as correct. This is true. Newton's law, in its classic form, did not meet this criterion. This proves that it was not quite so obvious. A truth that was unknown yesterday has become to-day a truism. So much the better.

In expressing one of the conditions which must be satisfied by natural laws the theory of Relativity at least has what is called in philosophical jargon a "heuristic" value. But it is none the less true, as M. Painlevé points out with great force and clearness, that the principle of General Relativity, considered in this light, would be unable to provide precise laws. It would be quite consistent with a law of gravity in which the attraction would be in inverse proportion, not to the square, but to the seventeenth or hundredth power, or any power whatever, of the distance.

In order to extract the correct law of gravitation from the principle of General Relativity we have to add to it the Einsteinian interpretation of the result of the Michelson experiment—to wit, that relatively to any observer whatsoever light travels locally with the same velocity in every direction. We have also to add various hypotheses which M. Painlevé regards as Newtonian.

To the critical discussion of Relativity which he so brilliantly presented at the Academy of Sciences

M. Paul Painlevé added a valuable mathematical contribution of which the chief result is the following: It is possible to excogitate other laws of gravitation than that offered by Einstein, and all of them will fulfil the Einsteinian conditions.

The learned French geometrician indicated several of these, especially one of which the formula differs considerably from that of Einstein, yet equally and precisely explains the motions of the planets, the displacement of the perihelion of Mercury, and the deviation of rays of light near the sun.

This new formula corresponds to a space that is independent of time, and it does not involve the consequence that Einstein's formula does in regard to the shifting toward the red of all the lines in the solar spectrum. The verification or non-verification of this consequence of Einstein's equation, of which we pointed out the difficulties (perhaps insurmountable) in a previous chapter, thus acquires a new importance.

It is a remarkable thing that many of the formulæ of gravitation given by M. Painlevé lead to the conclusion, differently from that of Einstein, that space remains Euclidean even near the sun, in the sense that measures are not necessarily contracted.

All this light on the astronomical horizon seems like the dawn of a new era in which observations of unprecedented delicacy will provide tests that are calculated to give a more precise and less ambiguous form to the law of gravitation. There are great days—or, rather, great nights—in store for the astronomer.

. . . . .

As far as the principles are concerned, the controversy will go on. It must end in something like the following dialogue:

*The Newtonian:* Do you admit that at a point in the universe that is far away from all material masses a moving object left to itself must follow a straight line? If so, you recognise the existence of privileged observers—those for whom the line is straight. For another observer the line is a parabola. Therefore his point of view is wrong.

*The Relativist:* Yes, I grant it; but in point of fact there is no point in the universe where there is no influence of distant material masses. Therefore your moving object left to itself is a mere fiction, and I am not going to base science upon an unverifiable piece of imagination. The whole aim of the Relativist is to rid science of everything that has no experimental significance. As to the observer who sees the moving object in question describe a parabola, he will interpret his observation to mean that the object is in a gravitational field.

*The Newtonian:* You are therefore compelled to admit that far away from all matter, far from all heavenly bodies, there can be what you call a gravitational field, that it varies according to the velocity of the observer, and that it can be very intense in spite of the distance of the heavenly bodies, and even, at times, increase with that distance. These are strange and absurd hypotheses.

*The Relativist:* They are strange, but I defy you to prove that they are absurd. They are less absurd than to localise and set in motion a point that is isolated and independent of any material mass.

*The Newtonian:* For my part, I can easily imagine a single material point in the universe having a certain position and a certain velocity in it.

*The Relativist:* For my part, on the contrary, if

such a material point existed, it would be absurd and impossible to speak of its position and its motion. It would have neither position nor motion nor rest. Such things can exist only with reference to other material points.

*The Newtonian :* That is not my opinion.

*The Impartial Spectator :* In order to know which of you is right we should need to try an experiment on a material point that is withdrawn from the influence of the rest of the universe. Can you try this experiment ?

*The Newtonian and the Relativist* (together) : No, unhappily.

*The Metaphysician* (coming up like the third thief in the fable) : Then, gentlemen, I advise you to return to your telescopes, your laboratories, and your tables of logarithms. The rest is my affair.

*The Newtonian and the Relativist* (together) : In that case we are quite sure we shall never learn anything further about it than we know or believe now.

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Meantime, it is impossible to exaggerate the importance of the new light thrown on the question of Relativity by the intervention of M. Paul Painlevé at the Academy of Sciences. It will have a lasting and prodigious echo.

Will Einstein's fine synthesis be defeated ? Shall we see it sink in the controversies, doubts, and obscurities of which we have given a short account ? I think not.

When Christopher Columbus discovered America, it was all very well to tell him that his premises were wrong, and that if he had not believed that he was sailing for the Indies he would never have reached a

new continent. He might have replied, after the style of Galileo: "I discovered it, for all that." The method that gives good results is always a good method.

When we have to plunge into the depths of the unknown to discover something new, when we have to learn more and better, the end justifies the means. When he reminds us of optics, mechanics, and gravitation, now bound up together in a new sheaf, of the deviation of light by gravity which he foretold against all expectation, of the anomalies of Mercury which he was the first to explain, and of his improvement of the Newtonian law, Einstein has the right to say, with some pride: "There is what I have done."

It is said that the paths by which he attained all these fine results are not devoid of unpleasant false turns and quagmires. Well, there are many ways to Rome and to truth, and some of them are not perfect. The main thing is to get there. And in this case the truth means ancient facts brought into a new harmony, and new facts set forth in prophetic equations and verified in the most surprising manner.

If discussion of principles—if theory, which is only the servant of knowledge—shrugs its servile and disloyal shoulders a little over Einstein's work, at all events experience, the sole source of truth, has justified him. Brilliant formulæ that Einstein had not foreseen are now discovered to explain the anomaly of Mercury and the deviation of light. It is good: but we must not forget that the first of these correct formulæ, that of Einstein, went boldly in advance of the verification.

New trenches have been won in the war against the eternal enemy, the unknown. Certainly we have now to organise them and create more direct roads to them.

But to-morrow we shall have to advance again, to gain more ground. We shall have, by any theoretical device that we can, to state other new facts, unknown but verifiable facts. That is what Einstein did.

If it is a weakness of Einstein's teaching to deny all objectivity, all privilege, to any system of reference whatever, while utilising such a system for the necessities of calculation, it was at all events a weakness shared by the great Poincaré. To the day of his death he rebelled energetically against the Newtonian conception. The support of such a genius, whom one finds involved in all our modern discoveries, is enough to secure some respect for the Relativist theory.

If we have on the one side Newton and his ardent and persuasive apologist, equipped with a fine mathematical genius, Paul Painlevé, we have on the other side Einstein and Henri Poincaré. Even in earlier history we have Aristotle against Epicurus, Copernicus against the Scholastics, at the same barricade. It is an eternal war of ideas, and it may be endless if, as Poincaré believed, the Principle of Relativity is at the bottom only a convention with which experience cannot quarrel because, when we apply it to the entire universe, it is incapable of verification.

It is the fertility of the Einsteinian system which proves that it is strong and sound. Are the new beings with which it has peopled science—the discoveries predicted by it—legitimate children? The Newtonians say that they are not. But in properly ordered science, as in an ideal State, it is the children that matter, not their legitimacy.

At all events the vigorous counter-offensive of M. Painlevé has driven back to their lines the over-zealous apostles of the new gospel, who thought that they had

pulverised classic science beyond hope of recovery. Each side now remains in its positions. There is no longer any question of regarding the Newtonian conception of the world as a piece of childlike barbarism. A different conception is now opposed to it—that is all. The war between them is as yet undecided, and may remain for ever undecided, as the weapons with which it might be possible to bring it to an issue are sealed up for ever in the arsenal of metaphysics.

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Whatever may happen, Einstein's teaching has a power of synthesis and prediction which will inevitably incorporate its majestic system of equations in the science of the future.

M. Émile Picard, perpetual secretary of the Academy of Sciences, and one of the luminous and profound thinkers of our time, has asked if it is an advance "to try, as Einstein has done, to reduce physics to geometry." Without lingering over this question, which may be insoluble, like all speculative questions, we will conclude with the distinguished mathematician that the only things which matter are the agreement of the final formulæ with the facts and the analytic mould in which the theory casts the phenomena.

Considered from this angle, Einstein's theory has the solidity of bronze. Its correctness consists in its explanatory force and in the experimental discoveries predicted by it and at once verified.

What changes in theories are the pictures we form of the objects between which science discovers and establishes relations. Sometimes we alter these pictures, but the relations remain true, if they are based upon observed facts. Thanks to this common fund of truth, even the most ephemeral theories do

not wholly die. They pass on to each other, like the ancient runners with their torch, the one accessible reality: the laws that express the relations of things.

To-day it happens that two theories together clasp the sacred torch. The Einsteinian and the Newtonian vision of the world are two faithful reflections of it: just as the two images, polarised in opposite directions, which Iceland spar shows us in its strange crystal both share the light of the same object.

Tragically isolated, imprisoned in his own "self," man has made a desperate effort to "leap beyond his shadow," to embrace the external world. From this effort was born science, and its marvellous antennæ subtly prolong our sensations. Thus we have in places approached the brilliant raiment of reality. But in comparison with the mystery that remains the things we know are as small as are the stars of heaven compared with the abyss in which they float.

Einstein has discovered new light for us in the depths of the unknown. He is, and will remain, one of the light-houses of human thought.

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