ness in the use of language. For example, the "boiling point of water" as a thermometric fixed point, like the "absolute" scale of temperature, is a loose expression, only understood by those who know; and unless some looseness be permitted the measurement of the "specific heat of copper" would have to disappear from the elementary course. With the two exceptions mentioned, the adoption of "absolute" units for atmospheric measurements, which was not "made in Germany," has been received with profound indifference in scientific circles. But the whole question of units and their nomenclature is of great importance to us at this juncture. Our practice of using one set of units in the laboratory and another set in practical life can only be described as stupid. Although the particular point raised is not a crucial one, it is much to be desired that Prof. Marvin's note may be the beginning of the serious consideration of this important subject by the exponents of the physical sciences.

GRAVITATION AND THE PRINCIPLE OF RELATIVITY.[1]

THERE were many difficulties to encounter in entering the room just now. To begin with, we had to bear the crushing load of the atmosphere, amounting to 14 lb. on every square inch. At each step forwards it was necessary to tread gingerly on a piece of ground moving at the rate of twenty miles a second on its way round the sun. We were poised precariously on a globe, apparently hanging by our feet, head outwards into space. And this acrobatic feat was performed in the face of a tremendous wind of æther, blowing at I do not know how many miles a second literally through us. We do not claim much credit for overcoming these difficulties—because we never noticed them. But I venture to remind you of them, because I am about to speak of some other extraordinary things that may be happening to us of which we are quite unconscious.

Not to go too far back in history, the present subject arises from a famous experiment performed in the year 1887, known as the Michelson-Morley experiment. The apparatus was elaborate, but the principle of the experiment is not very difficult. If you are in a river, which will be the quicker—to swim to a point fifty yards up stream and back again, or to a point fifty yards across stream and back again? Mathematically the answer is, perhaps, not immediately obvious, because the net effect of the current is a delay in both cases. But I think that anyone who has swum in a river will have no hesitation about the answer. The up-and-down journey takes longer. Now we *are* in a river—of æther. There is a swift current of æther flowing through this room; or, if we happen to be at rest in the æther at the present moment, six months hence the earth's orbital motion will be reversed, and then there must be a swift current. Michelson divided a beam of light into two parts; he sent one half swimming up the stream of æther for a certain distance, and then by a mirror back to the starting point; he sent the other half an equal distance (as he thought) across the stream and back. It was a race; and with his apparatus he could test very accurately which part got back first. To his surprise, it was a dead-heat. Clearly the two paths could not really have been equal, the along-stream path must have been a little shorter to compensate for the greater hindrance of the current. That objection was foreseen, and the apparatus, which was mounted on a stone pier floating in mercury, was rotated through a right angle, so that the arm which was formerly along the stream was now across the stream, and *vice versa*. Again the two portions of the beam arrived at the same moment; so this time the other arm had become the shorter—simply by altering its position. In fact, these supposedly rigid arms had contracted when placed in the up-and-down stream position by just the amount necessary to conceal the effect which was looked for.

That is the plain meaning of the experiment; but we might well hesitate to accept this straightforward interpretation, and try to evade it in some way, were it not for some theoretical discoveries made later. It has gradually appeared that matter is of an electrical nature, and the forces of cohesion between the particles, which give a solid its rigidity, are electrical forces. Larmor and Lorentz discovered that this property of contraction in the direction of the æther current was something actually inherent in the formulæ for electrical forces written down by Maxwell many years earlier and universally adopted; it only waited for some mathematician to recognise it. It would be going too far to say that Maxwell's equations actually prove that contraction must take place; but they are, as it were, designed to fall in line with the contraction phenomenon, and certain details left vague by Maxwell have since been found to correspond.

We are then faced with the result that a material body experiences a contraction in the direction of its motion through the æther. According both to theory and experiment the contraction is the same for all kinds of matter—a universal property. One reservation should be made; the experiment has only been tried with solids of laboratory dimensions, which are held together by *cohesion*. There is at present no experimental evidence that a body such as the earth the form of which is determined by *gravitation* will suffer the same contraction; we shall, however, assume that the contraction takes place in this case also.

I am going to ask you to suppose that we in this room are travelling through the æther at the rate of 161,000 miles a second, vertically upwards. Let us be bolder and say that that *is* our velocity through the æther—because no one will be able to contradict us. No experiment yet tried can detect or disprove that motion; because all such experiments give a null result, as the Michelson-Morley experiment did. With that speed the contraction is just one-half. This pointer, which I hold horizontally, is 8 ft. long. Now [turning it vertically] it is 4 ft. long. But, you may say, it is taller than I am, and I must be approaching 6 ft. No, if I lay down on the floor I should be, but as I am standing now I am under 3 ft. The contraction affects me just as it did the pointer. It is no use bringing a standard yard-measure to measure me, because that also will contract and represent only half a yard. "But we saw that the pointer did not change length when it turned." How did you tell that? What you perceived was an image of the pointer on the retina of your eye, and you thought the image occupied the same space of retina in both positions; but your retina has also contracted in the vertical direction without your knowing it, so that your estimates of length in that direction are double what they should be. And similarly with every test you could apply. If everything undergoes the same change, it is just as though there were no change at all.

We thus get a glimpse of what, from our present point of view, must be called the *real* world, strangely different from the world of appearance. In the real world, by changing position you extend yourself like a telescope; and the stoutest individual may regain slimness of figure by an appropriate orientation. It must be something like what we see in a distorting mirror; and you can almost see a living-picture of this real world reflected in a polished door-knob.

[1] Discourse delivered at the Royal Institution on Friday, February 1, by Prof. A. S. Eddington, F.R.S.

If our speed through the æther happens not to be so great as we have supposed, the contraction is smaller; but it escapes notice in our practical life, not because it is small, but because from its very nature it is undetectable. And because this real world is undetectable we do not as a rule attempt to describe it. Not merely in everyday life, but in scientific measurements also, we describe the world of appearance. We do this by imagining natural objects to be placed, not in the absolute space, but in a quite different framework of our own contriving—a space which corresponds with appearance. In the space of appearance a rod does not seem to change length when its direction is altered; and we use that property to block out our conventional space, counting the length occupied by the standard yard-measure as always a yard however its true length may vary. It is found also that in like manner our time is a special time of our own, different from the time we should adopt if our motion through the æther were *nil*. This is a perfectly right procedure; it introduces no scientific inexactness, and it is more in accordance with the ordinary meaning attached to space and time; the only thing to remember is that this space and time framework is something peculiar to us, defined by our motion, and it has not the metaphysical property of absoluteness, which we have often unconsciously attributed to it.

Now let us visit for a moment the star Arcturus, which is moving relatively to us with a velocity of more than 200 miles per second. Consequently its motion through the æther is different from ours, and the contraction of objects on it will be different. It follows that our conventional space would not be suitable for Arcturus, because it was specially chosen to eliminate our own contraction effects. There is a different space and a different time proper to Arcturus. We must then imagine each star carrying its own appropriate space and time according to its motion through the æther. The space and time of one star will not fit the experience of individuals on another star.

The exact relation between the appropriate space and time of one star and the space and time of another was first brought out clearly by Minkowski; it is a very remarkable one. We recognise three dimensions of space, which we may take as up-and-down, right-and-left, backwards-and-forwards. If we go over to Ireland we still have the same space, but Ireland's up-and-down no longer corresponds with ours. The directions are inclined; and what is vertical to them is partly vertical and partly horizontal to us. Now let us add a fourth dimension, imaginary[2] time, at right angles to the other three. There is no room for it in the model, but we must do our best to imagine it in four dimensions. In Ireland the three space-dimensions will have rotated, as I have said; but the time will be just the same. But if we go to Arcturus, or to any body moving with a velocity different from our own, the time-dimension also has rotated. What is time to them is partly time and partly imaginary space to us. It is a change in the space-time world of four dimensions just analogous to the change in the space-world between here and Ireland. That is Minkowski's great result; space-time is the same universally, but the orientation—the resolution into space and time separately—depends on the motion of the individual experiencing it, just as the resolution of space into horizontal and vertical depends on his situation. In Minkowski's own famous words—"Henceforth Space and Time in themselves vanish to shadows, and only a kind of union of the two preserves an independent existence."

From our original point of view it seems very remarkable that in the Michelson-Morley experiment the contraction should have been of just the right amount to annul the expected effect of our motion through the æther. Many other experiments, which seemed likely to show such an effect, have been tried since then, but in all of them the same kind of compensation takes place. It looks as though all the forces of Nature had entered on a conspiracy together with the one design of preventing us from measuring or even detecting our motion through the æther. It is still an open question whether one force, the force of gravitation, has joined the conspiracy. Hitherto gravitation has stood aloof from all the other interrelated phenomena in majestic isolation. We have become almost reconciled to leaving it outside every physical theory. A new model of the atom is put forward which accounts for a whole host of abstruse and recently discovered properties; but it would be considered unfair to suggest that it ought to account for the simple and universal property of gravitation. Dare we think that gravitation has so far forgotten its dignity as to join this conspiracy? There is certainly not enough evidence for a jury to convict; but yet I think we shall have to intern it on suspicion. Recently Sir Oliver Lodge, believing that gravitation was innocent of the conspiracy, showed that a very famous astronomical discordance in the motion of Mercury might be an effect due to the sun's motion through the æther, and might afford a means of estimating its speed. It is difficult in a brief reference to deal quite fairly with an intricate question, but it seems now that we should rather lay stress, not on this single discordance, which can perhaps be otherwise explained, but on the exact agreement of Venus and the earth with theory; for they also should show evidence of the sun's motion through the æther if gravitation had not joined in the conspiracy to conceal all such effects. It may be that the effects on Venus and the earth are not found because the sun's motion through the æther happens to be very small; but on the whole it appears more likely that the effect of the motion is null, just as in the Michelson-Morley experiment, because there is a complete compensation in the law of gravitation itself.

The great advantage of Minkowski's point of view is that it gets rid of all idea of a conspiracy. You cannot have a conspiracy of concealment when there is nothing to conceal. We cut Minkowski's space-time world in a certain direction, so as to give us separately space and time as they appear to us. We have been imagining that there exists some direction which would separate it into a real and absolute space and time. But why should there be? Why should one direction in this space-time world be more fundamental than any other? We do not attempt to cut the space-world in a particular direction so as to give us the *real* horizontal and vertical. The words "horizontal" and "vertical" have no meaning except in reference to a particular spot on the earth. So for a particular observer the space-time world falls apart into its four components, up-and-down, right-and-left, backwards-and-forwards, sooner-and-later; but no observer can say that this division is the one and only real one.

Our idea of a real space more fundamental than our own was, however, not entirely metaphysical; we had materialised it by filling it with an æther supposed to be at rest in it. We now deny the existence of any unique framework of that kind. We have failed to obtain experimental knowledge of such a framework since we cannot detect our motion relative to it. Whatever may be the nature of the æther, it is devoid of those material properties which could constitute it a

[2] Imaginary in the mathematical sense, *i.e.* involving $\sqrt{-1}$. It is much simpler to consider imaginary time; and throughout the lecture I have ventured to omit reference to the complications which arise when our results are restated in terms of real time.

framework of reference in space. We can perhaps best picture the æther as a four-dimensional fluid filling uniformly Minkowski's space-time *continuum*, not as a material three-dimensional fluid occupying space and time independently.

The position we have now reached is known as the principle of relativity. In so far as it is a physical theory, it seems to be amply confirmed by numerous experiments (except in regard to gravitation). In so far as it is a philosophical theory, it is no more than a legitimate and useful point of view. I now pass on to a generalised principle of relativity, in which we must be content at first to be guided by a natural generalisation of these results, hoping later to be able to check our tentative conclusions by experiment.

If we analyse any scientific observation, distinguishing between what we perceive and what we merely infer, it always resolves itself into a *coincidence* in space and time. A physicist states that he has observed that the current through his coil is 5 milliamperes; but what he actually saw was that the image of a wire thrown by his galvanometer *coincided* with a certain division on a scale. He measures the temperature of a liquid, but the observation is the *coincidence* of the top of the mercury with a division on the thermometer. If then we had to sum up the whole of our experimental knowledge, we should have to describe it as consisting of a large number of coincidences.

A complete history of the progress of a particle consists of a knowledge of its path and the time at which it occupied each point of the path. The time may be regarded as an extra co-ordinate corresponding with a fourth dimension, and so the whole history may be summed up by a line in four dimensions representing the particle's progress through space and time. We call this four-dimensional line the *world-line* of the particle. Imagine that we have drawn the world-lines of all the particles, light-waves, etc., in the universe: we shall then have a complete history of the universe. It will be a rather dull history-book; the Venus of Milo will be represented by an elaborate schedule of measurements, and Mona Lisa by a mathematical specification of the distribution of paint; still they are there, if only we can recognise them. I have here a history of the universe—or part of it. Unfortunately I was not able to draw it in four dimensions, and even three dimensions presented difficulties, so I have drawn the world-lines in two dimensions on the surface of a football bladder.

A great deal is shown here which, properly speaking, is not history at all, because it is necessarily outside experience. As we have seen, it is only coincidences—the intersections of the world-lines—that constitute observational knowledge; and, moreover, it is not the place of intersection, but the fact of intersection that we observe. I am afraid the two-dimensional model does not give a proper idea of this, because in two dimensions any two lines are almost bound to meet sooner or later; but in three dimensions, and still more in four dimensions, two lines can, and usually do, miss one another altogether, and the observation that they do meet is a genuine addition to knowledge.

When I squeeze the bladder the world-lines are bent about in different ways. But I have not altered the history of the universe, because no intersection is created or destroyed, and so no observable event is altered. The deformed bladder is just as true a history of Nature as the undeformed bladder. The bladder represents Minkowski's space-time world, in which the world-lines were drawn; so we can squeeze Minkowski's world in any way without altering the course of events. We do not usually use the common word "squeeze"; we call it a *mathematical transformation*, but it means the same thing.

The laws of Nature in their most general form must describe correctly the behaviour of the world-lines in either the undistorted or the distorted model, because it is indifferent which we take as the true representation of the course of Nature. That is a very important principle; but, being almost a truism, it does not in itself help us to determine the laws of Nature without making some additional hypothesis. There is one law—the law of gravitation—which especially attracts our attention at this point, and we shall look into it more closely.

We know that one particle attracts another particle, and so influences the history of its motion. This evidently means that one world-line will deflect any other world-line in its neighbourhood. Apart from this influence, the world-line runs straight, bending neither to the right nor to the left, provided the bladder is in its undistorted state, *i.e.* provided we use Minkowski's original space-time. That is not so much a matter of observation as of definition. It defines what we are to regard as the undistorted state, though it is by observation that we learn that it is possible to find a space-time in which the world-lines run straight when undisturbed by gravitational or other forces. I must own that there is a certain logical difficulty in saying that a world-line runs straight when there are no others near it; because in that case there could be no intersections, and we could learn nothing about its course by observation. However, that is not a serious difficulty, though you may be reminded of the sage remark, "If there were no matter in the universe, the law of gravitation would fall to the ground."

(*To be continued.*)

UNIVERSITY AND EDUCATIONAL INTELLIGENCE.

THE *Times* announces that Senator Dennis has given 12,000*l.* to Dalhousie University for a chair of political science in memory of his son, Capt. Eric Dennis, who was killed at Vimy Ridge; and that Major E. A. de Rothschild, who died at Cairo from wounds on November 17, aged thirty-one, has left the sum of 5000*l.* to Harrow School for a scholarship, the conditions of which are to be approved by his brother Anthony.

THE Department of Agriculture and Technical Instruction for Ireland has issued its programme of summer courses of instruction for teachers to be held this year. The courses will, with the exception of the courses of instruction in rural science (including school gardening) for National School teachers, begin on July 2, and close on July 26. The courses in rural science (including school gardening) will begin on August 6, and close on August 30. Teachers who attend the courses regularly will be allowed a sum of 3*l.* 10*s.* towards their expenses while living at the centre, and third-class railway fare for one return journey from the railway station nearest their school or centre. Among the subjects in which courses have been arranged are the chemistry of engineering materials, technology for teachers, experimental science, domestic science, and rural science. The courses are open only to those who are above twenty years of age, and, except in certain cases, only to teachers who are engaged (*a*) by local committees of technical instruction, or (*b*) in schools receiving grants either directly from the Department or under the provisions of an approved local scheme of technical instruction.

THE annual report of University College, London, shows that whereas in normal times the total number of students, day and evening, amounts to about 2200,