THE EVOLUTION OF SPACE AND TIME

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The attention of physicists has of late been directed back to the fundamental concepts of space and time, which they are being forced to reshape in the light of new experimental facts. Nothing demonstrates the empirical origin of these concepts more clearly than their continuing adaptation to the increasingly refined data of human experience.

I should like to show that the form in which these concepts have hitherto been presented, which as a rule is not analysed with sufficient care, was determined and conditioned by a specific and provisional synthesis of the world, namely, by the mechanistic theory. Our space and our time have in fact been those devised to suit the needs of rational mechanics.

The new and increasingly authoritative synthesis of physical phenomena that is represented by the electromagnetic theory introduces a space and a time (and particularly a time) which are different from those of mechanics and which are supported by the methods of experimental investigation now available to us. It is particularly remarkable that even today we are still being compelled by the increasing refinement of our methods of measurement, the accuracy of which has in some cases been pushed beyond one part in a thousand million, to continue the adaptation to established fact of the most fundamental categories of our thought. This surely constitutes, for the philosopher, an excellent opportunity of penetrating the innermost nature of these categories, in that he can see them still in the course of evolution, alive and changing before his very eyes.

Neither space nor time exists *a priori*: for every moment in time and for every degree of refinement of our theories about the physical world, there is a corresponding conception of space and time. The mechanistic theory introduced the old conception, and the electromagnetic theory is now demanding a new one, but there is nothing to justify our saying that this will be the definitive one.

Furthermore, it is difficult for our brain to become accustomed to these new forms of thought: their assimilation presents particular problems, and can be aided only by the formation of an adequate language.

This is the task in which, to facilitate the evolution of the human species, the philosophers and physicists of today must collaborate.

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All living beings have a capacity for internal and spontaneous expansion that increases with their degree of adaptation to the environment into which they have been born. When, as a result of this expansion, an encounter takes place between individuals or species, the outcome is either mutual adaptation or, if agreement is impossible, conflict ending in survival of the fittest, which usually assimilates the substance of the other and imposes upon it a new form that life appears to have judged to be better.

It is the same with our physical theories: some will have been particularly well formulated and will have succeeded brilliantly in the interpretation and ordering of one category of experimental facts which represent matter upon which they impose a form; they then develop spontaneously in accordance with this form and rhythm of their own, using as materials for the edifice that they construct firstly facts which are already known but not yet ordered, then facts to whose discovery they lead the way, and finally facts that have already been incorporated into syntheses in the form of other theories which the new theory absorbs after entering into conflict with them.

Just as the process of constructing living beings is aided by the organic syntheses already present in the other beings on which they feed, so the new theory retains and uses to differing degrees the orderings of facts already accomplished by the theories that it has supplanted.

At the present time, we are witnessing a conflict of this kind between two particularly important and elegant conceptions of the world, namely, the rational mechanics of Galileo and Newton and the electromagnetic theory in the mature form given it by Maxwell, Hertz and Lorentz.

Rational mechanics was created to interpret the phenomena of visible motion, and succeeds admirably in doing this. Throughout the eighteenth century and for much of the nineteenth, all scientific effort was devoted to extending this interpretative capacity to cover all physical phenomena, by applying these same laws to the invisible motions of material particles or of fluids of different kinds.

It was in this way that the doctrine known as mechanism developed, by a fusion of rational mechanics with the hypotheses of atomic theory. It was highly successful in some fields, such as the kinetic theory of fluids, for example, but less so in others, such as elasticity and optics.

It must not be forgotten that the failures of mechanism are often blamed entirely upon the atomistic conception, yet this has now been definitively established on the basis of indisputable experimental facts, and its combination with the electromagnetic theory has proved remarkably fruitful over the last fifteen years. What really seems to have been the unreliable factor involved is the application to invisible motions of the laws of mechanics, which were originally formulated for visible motions, and represent even for these nothing more than a first approximation, albeit an excellent one.

The theory of electromagnetic phenomena as we know it today is certainly independent of the laws imposed upon the motion of matter by rational mechanics, even though the latter theory appears to contribute to certain fundamental definitions. The best proof of this independence is furnished by the contradictions that are now arising between the two syntheses.

Electromagnetism is as closely adapted to its primary field as rational mechanics was to its field. With its specialized concepts of a medium which transmits actions step by step and of electric and magnetic fields which characterize the state of this medium, and with the highly specific form of the relations that it defines between the simultaneous variations of these fields in space and in time, electromagnetism constitutes a discipline or a way of thought which is quite separate and quite distinct from mechanics and possesses an astonishing capacity for expansion, in that it has effortlessly assimilated the vast field of optics and radiant heat, in the face of which mechanism remained powerless, and is constantly leading the way to new discoveries in this field. Electromagnetism has conquered the greater part of physics, invaded chemistry, and ordered a vast array of facts formerly lacking any form or coherence.

Of our two opposing theories, the first boasts the titles of an already ancient past and possesses the authority of having seen its laws verified by both the most distant stars and the most minute molecules of gases, while the second, which is younger and more alive, is infinitely better adapted to physics as a whole and possesses an internal capacity for growth that the other seems to have lost.

Maxwell believed it possible to reconcile the two theories and to show that electromagnetic phenomena allow of mechanical interpretations. However, his demonstration of this, which was anyway based on the special case of the phenomena displayed by closed currents, proves merely that the two syntheses have some features in common and share the property of giving certain integrals stationary values; they may remain irreconcilable with respect to other features.

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These divergent features have recently been emphasized by new experimental facts, namely, by the lack of success encountered in all the experiments (some of them of an extraordinary degree of refinement) that have been undertaken in an attempt to demonstrate the collective uniform translational motion of a material system by means of experiments made within this system, that is, to define absolute translational motion.

It was already known, and indeed rational mechanics accounts quite adequately for this fact, that mechanical experiments on visible motions that are carried out within a material system do not make it possible to demonstrate a collective uniform translational motion of this system, but they do make it possible to show rotational motion by means of Foucault's pendulum or the gyroscope. In other words, from the mechanics point of view collective uniform translation has no absolute meaning, whereas rotation does.

However, it is possible to carry out within a material system other experiments which involve electromagnetic or optical phenomena. In its explanations, the electromagnetic theory assumes the existence of a medium, the ether, which transmits electric and magnetic actions and in which electromagnetic perturbations, and light in particular, are propagated at a specified velocity.

It was hoped that, if a material system is moving in uniform translation relative to this medium, electromagnetic or optical experiments carried out within the system could make it possible to determine and to demonstrate this translation.

Since the Earth, in its annual motion, possesses a translational velocity that varies constantly by amounts ranging up to sixty kilometres per second for the relative velocity corresponding to two diametrically opposite positions of the globe in its orbit, it was hoped that, at least at certain moments in the year, observers and their instruments on the Earth would be moving with respect to the ether at a velocity of this order and would be able to demonstrate their motion.

The grounds for expecting this were that when the fundamental equations of electromagnetism, which are assumed to be valid for stationary observers in the ether, were combined with the ordinary concepts of space and time as stipulated by rational mechanics, it was found that these equations should undergo a change of form for observers in motion in the ether, and that the differences, for velocities of the order of that of the Earth in its orbit, should be visible in certain highly refined experiments.

The results of such experiments have, however, always been negative, and independently of any interpretation we can state as an experimental fact the content of the following principle, known as the principle of relativity:

If various groups of observers are in uniform motion relative to one another (for instance, observers on the Earth for various positions of the latter in its orbit), all mechanical and physical phenomena will obey the same laws for all of these groups of observers. None of them will be able to demonstrate, on the basis of experiments carried out within the material system to which he belongs, the collective uniform motion of this system.

From the electromagnetics point of view, it can also be said that the fundamental equations, in their ordinary form, are verified for all of these groups of observers simultaneously, and that everything happens for each of them as if he were motionless with respect to the ether.

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Thus, it is an experimental fact that the equations between physical quantities that we use to express the laws of the external world necessarily have exactly the same form for different groups of observers, or for different reference systems that are in uniform translational motion relative to one another.

This requires, in the language of mathematics, that these equations should allow of a group of transformations corresponding to the transition from one reference system to another that is in motion relative to it. The equations of physics must remain valid for all the transformations in this group. In a transformation of this kind, when a transition is made from one reference system to another, measurements of the various quantities, particularly those corresponding to space and time, are modified in a way that corresponds to the very structure of these concepts.

The equations of rational mechanics effectively allow of a group of transformations corresponding to the change of reference system, and the part of this group that concerns measurements of space and time is in agreement with the ordinary form of these concepts.

It will be Lorentz's main claim to fame that he demonstrated that the fundamental equations of electromagnetism also allow of a group of transformations that enables them to resume the same form when a transition is made from one reference system to another. *This group differs fundamentally from the above group as regards transformations of space and time.*

We have to choose. If we wish to retain an absolute value for the equations of rational mechanics, that is, for mechanism, and hence for the space and time that correspond to them, then we have to regard those of electromagnetism as false and renounce the admirable synthesis that we discussed above, returning in the field of optics, for example, to a theory of emission with all the associated difficulties that caused it to be rejected more than fifty years ago. If, on the other hand, we wish to retain electromagnetism, then we have to adapt our way of thinking to the new conceptions of space and time that it demands, and regard rational mechanics as being no more than a first approximation, although one that is more than adequate in the case of motions whose velocity does not exceed some thousands of kilometres per second. Only electromagnetism (and those laws of mechanics that allow of the same group of transformations as electromagnetism) would make it possible to go farther, and it would then assume the leading position that mechanism assigned to rational mechanics.

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To demonstrate the opposition between the two syntheses more clearly, it is simpler to fuse the two concepts of space and time together in the more general concept of world, as was suggested by Minkowski.

The world is the ensemble of all events: an event consists in something taking place or existing in a certain place at a certain moment in time. With a given reference system, that is, a system of axes associated with a certain group of observers, any event is determined from the point of view of its position in space and time by four coordinates related to this reference system, three for space and one for time.

Any two events related to any one reference system will generally differ both in space and in time, that is, they will take place at different points at different moments in time. Thus, for any pair of events there will be a corresponding distance in space (that between the points at which the two events take place) and interval in time.

Thus, time can be defined as the ensemble of events that take place successively at any one point, as, for example, in any one portion of matter related to the reference system, and space can be defined as the ensemble of simultaneous events. This definition of space is equivalent to saying that the form of a body in motion is defined by the ensemble of the simultaneous positions of the various portions of matter of which it consists, or of its various material points, and by the ensemble of events represented by the simultaneous presences of these various material points. If we follow Minkowski in calling the ensemble of events that take place successively in a portion of matter that can be in motion relative to the reference system the *world line* of this portion of matter, the form of a body at any given moment in time is determined by the ensemble of the simultaneous positions on their world lines of the various material points that make up this body.

The concept of simultaneity of events that take place at different points is therefore fundamental to the very definition of space when we are concerned with bodies in motion, and this is the general case.

In the usual conception of time, an absolute meaning is attributed to this simultaneity, that is, it is assumed to be independent of the reference system. We need, however, to analyse the content of this generally tacit assumption more closely.

Why are we usually unable to accept that two events that are simultaneous for any one group of observers may not be so for another group that is in motion relative to the first, or, what amounts to the same thing, why do we not accept that a change of reference system makes it possible for the order of succession in time of two events to be reversed?

The reason for this is, obviously, that we assume implicitly that if two events follow each other in a certain order for a given reference system, it is possible for the one that took place first to have acted as cause and altered the conditions in which the second took place, whatever the distance separating them in space.

In these conditions, it is absurd to suggest that for other observers, or for another reference system, the second event, or effect, can precede its cause.

The absolute nature that is normally attributed to the concept of simultaneity is therefore based on the implicit hypotheses of a causality that can travel at an infinite velocity, i.e. the hypothesis that an event can act instantaneously as cause at any distance.

This hypothesis conforms with the mechanistic conception and is required by it, since a perfect solid of rational mechanics, or, for example, an inelastic bell-pull stretched between the two points at which the events take place, would make it possible to signal the occurrence of the first event instantaneously at the point where the second is to occur, and would consequently make it possible to take the first into account and make it act as cause in the conditions that govern the second. There is, therefore, mutual adaptation of rational mechanics and of the normal conceptions of space and time in which the simultaneity of two events that are separated in space possesses an absolute meaning.

It is therefore in no way surprising to observe that, in the transformation group which retains the equations of mechanics, *the interval of time between two events remains constant and is measured in the same way by all groups of observers, whatever their relative motions.*

This is not so in the case of their distance in space: it is a quite plain fact, and one that is incorporated in the normal concepts, that the distance separating two events in space does not generally have an absolute meaning and varies with the reference system that is used.

A concrete example will serve to demonstrate how the distance separating any two given events in space can be different for various groups of observers that are in motion relative to one another. Suppose that two objects are dropped one after the other through a hole in the floor of a car that is in motion relative to the ground; the two events represented by the emergence of the two objects through the hole take place at one and the same point for observers in the car, but at different points for observers on the ground. The distance separating these two events in space is zero for the first group of observers, whereas for the second group it is equal to the product of the speed of the car by the interval of time separating the dropping of the two objects.

It is only in the case where the two events are simultaneous that their distance in space has an absolute meaning, that is, does not vary with the reference system. It follows directly from this that the dimensions of an object, such as the length of a ruler, have an absolute meaning and are the same for observers who are either at rest or in motion relative to this object. This is because we have observed that for all observers the length of a ruler is the distance between two simultaneous positions of the ends of the ruler, that is, the distance in space separating two simultaneous presences of the two ends of the ruler. We have just seen that simultaneity, as also the distance in space separating two simultaneous events, has an absolute meaning in the normal conceptions of time and space.

Given any two successive events, that is, two events that are separated in time, it will always be possible to find a reference system with respect to which these two events coincide in space, or observers for whom these two events take place at one and the same point. All that we need to do is to assign to these observers a motion relative to the original reference system such that, having witnessed the first event, they then witness the second, the two events thus taking place for them at any one given point near to them; we need only assign to these observers a velocity equal to the quotient of the distance in space separating the two events related to the original reference system by the interval of time between them, and this will always be possible if this interval of time is not zero, that is, if the two events are not simultaneous.

We have seen that this possibility of engineering the coincidence of two events in space by a suitable choice of reference system does not exist in the case of time, since the interval of time separating two events has an absolute meaning, that is, it is measured in the same way in all reference systems.

This constitutes a lack of symmetry between the normally accepted space and time which is eliminated in the new conceptions: with these, the interval in time, like the distance in space, becomes variable with the reference system, or with the motion of the observer.

In the new conceptions, only one case remains, and has to remain, in which the change of reference system has no effect, and this is the case in which the two events coincide both in space and in time. This double coincidence has to have an absolute meaning, since it corresponds to an encounter between the two events, and this encounter can give rise to a phenomenon, or a new event, which necessarily has an absolute meaning. Returning to the example used above, if the two objects that are dropped from the car through the same hole are dropped simultaneously, that is, if their dropping coincides both in space and in time, the result may be a collision and breakage of the objects, and this collision phenomenon has an absolute meaning. This means that in no conception of the world, whether that of electromagnetics or that of mechanics, can coincidence both in space and in time, if it exists for one group of observers, be denied by another group, whatever its motion relative to the first. Both for those who see the car going by and for those who are in the car, the two objects will have been broken reciprocally because they were dropped at the same time and at the same point.

With the exception of this very special case, it is easy to see that the electromagnetic conception requires a fundamental reshaping of the world concept. In their usual form, the equations of electromagnetism stipulate that an electromagnetic perturbation such as a light wave, for example, travels *in vacuo* at a velocity that is constant in all directions and equal to approximately three hundred thousand kilometres per second.

Since experimental facts that have recently been established have shown that, if these equations are valid for one group of observers, they must also be so for all others, whatever their motion relative to the first group, this leaves us with the paradoxical fact that any given light wave must travel at the same velocity for different groups of observers in motion relative to one another. One group of observers sees a light wave travelling in a certain direction at a velocity of three hundred thousand kilometres per second and sees a second group of observers running after this wave at a velocity that can be selected arbitrarily; notwithstanding this, for this second group of observers the light wave will still be moving with respect to them at this same velocity of three hundred thousand kilometres per second.

Einstein was the first to demonstrate how this necessary consequence of the electromagnetic theory can by itself determine the nature of the space and time that are required by the new world concept. It can be seen from what has been said above that the velocity of light must play an essential role in the new statements of physical phenomena. It is the only velocity that remains constant when there is a transition from one reference system to another, and in the universe of electromagnetics it plays the role played by infinite velocity in the universe of mechanics. This will be shown clearly by the results described below.

For any pair of events, a change of reference system modifies both the distance in space and the interval in time separating them, but from the point of view of the extent of these modifications it seems advisable to classify pairs of events into two broad categories for which space and time play symmetric roles.

The first category consists of pairs of events such that their distance in space is greater than the distance travelled by light during their interval in time, that is, such that if the occurrence of the two events is accompanied by the emission of light signals, each of them will take place *before* the arrival of the signal coming from the other. A relationship of this kind has an absolute meaning, that is, it is valid for all reference systems if it is so for one of them.

The equations of transformation that are required by the electromagnetic theory show that, in this case, the order of succession of the two events in time has no absolute meaning. If the two events follow each other in a given order for one reference system, this order will be reversed for observers moving with respect to the first group of observers at a velocity less than that of light, that is, at a physically attainable velocity.

It is obviously impossible for two events whose order of succession can be reversed in this way to be linked by a relationship of cause and effect; if a relationship of this kind existed between our two events, some observers would be seeing the cause later than the effect, which is absurd.

Given that the distance in space of our two events is greater than the distance travelled by light during their interval in time, the first could not act as cause in the occurrence of the second, and the second could be informed of the first, only if the causal link could travel at a velocity greater than that of light. On the basis of what has been said above, we have to eliminate this possibility; it must be impossible for causality, whatever its nature, to travel at a velocity greater than that of light, that is, for there to exist either a messenger or a signal that can traverse more than three hundred thousand kilometres per second.

We therefore have to accept that an event can not act instantaneously as cause at a distance, and that its repercussion can make itself felt immediately only locally, at the actual point where it occurs, and then subsequently at increasing distances which increase at most at the velocity of light. Thus, even from this point of view alone the velocity of light certainly plays, in the new conceptions, the role played in the old conceptions by infinite velocity, which in their terms represents the maximum velocity at which causality can travel.

It can be seen from this that the present antagonism between mechanism and electromagnetism merely expresses in a new form the opposition between the two conceptions which succeeded each other in the development of the electrical theories: that of instantaneous action at a distance, which was compatible with mechanism, and that of transmission via a medium by step-by-step action, which was introduced by Faraday. Nowadays, this ancient opposition is having repercussions on the most fundamental concepts themselves.

There are various inferences to be drawn from what has been said above. Firstly, it is impossible for a portion of matter to move relative to another at a velocity greater than that of light. This paradoxical result is contained in the formulae introduced by the new kinematics for the composition of velocities: the composition of any number of velocities that are less than the velocity of light always gives a velocity that is less than that of light. In the same way, the usual conception specifies that the composition of any number of finite velocities always gives a finite velocity.

Secondly, we can state that it must be impossible for any action at a distance, such as gravitation, to travel faster than light, and we know that this is in no way contradicted by the results that are now being obtained in the field of astronomy.

Lastly, the perfect solid of mechanics, which represented a means of signalling instantaneously at a distance and of establishing a causal link able to travel faster than light, has to be rejected. There is nothing in what we know of real solids to indicate otherwise than that every action or every wave must travel at a velocity less than that of light. Elastic waves in the most rigid bodies travel, in fact, at a velocity much lower than this. The important thing is that we have to reject the entire conception of the perfect solid, that is, of a body which could be set in motion simultaneously at all its points.

The reasoning given above can be summarized as follows: if there existed a signal able to travel at a velocity greater than that of light, there could be observers for whom this signal would have arrived before having been transmitted, that is, for whom the causal link that this signal makes it possible to establish would be inverted. As Einstein says, it would be possible to send a telegram into the past, and this would patently be absurd.

Thus, it is necessarily impossible for the two events of the pair in question, which have no clearly defined order of succession in time, to have any mutual influence; they are truly independent events. It is clear that, since there is no causal link between them, they can not follow each other in one and the same portion of matter, that is, they can not belong to one and the same world line or to the lifetime of one and the same being. This impossibility also conforms with the fact that, to be the site of these two events one after the other, this portion of matter would have to move at a velocity greater than that of light.

There is, therefore, no choice of reference system by which the two events can be made to coincide in space, but they can be made to coincide in time: since their order of succession can be inverted, there do exist reference systems for which the two events are simultaneous.

The pairs of events that we have just examined, whose order of succession in time has no absolute meaning but between which there is absolute separation in space, can be called *pairs in space*.

It is notable that, although the distance in space of the two events can not be reduced to zero, it passes through a minimum for those reference systems relative to which the two events are simultaneous.

This leads us to the following statement.

The distance in space of two events that are simultaneous for a given group of observers is shorter for them than for all other observers in any kind of motion relative to them.

This statement contains, as a special case, what has been named the Lorentz contraction, that is, the fact that one and the same ruler that is examined by various groups of observers, some at rest and others in motion relative to it, is shorter for those who see it pass by than for those who are attached to it. This is because, as we have seen, the length of a ruler for observers who see it pass by is defined by the distance in space of two simultaneous (for these observers) positions of the two ends of the ruler. And on the basis of what has been stated above, this distance will be shorter for these observers than for all others, and in particular shorter than for those who are attached to the ruler.

Thus, it can readily be seen how this Lorentz contraction can be reciprocal, that is, how two rulers that are of equal length when at rest relative to each other are mutually shortened when they slide against each other, with observers attached to one of the two rulers seeing the other as shorter than theirs. This reciprocity is based on the fact that the observers attached to the two rulers in motion relative to one another do not define simultaneity in the same way.

For pairs of events belonging to the second category, we find properties that are exactly correlative to those stated above if we interchange space and time. These pairs, which we shall call *pairs in time*, are defined by the following condition, which has an absolute meaning: the distance in space of the two events is smaller than the distance travelled by light during their interval in time. In other words, the second event takes place *after* the arrival of the light signal whose emission coincides in space and in time with the first event. This introduces a lack of symmetry from the point of view of time between the two events; the first occurs before the arrival of the light signal whose emission coincides in space and in time with the second event, while the second occurs after the arrival of the light signal whose emission accompanies the first event. It is possible for a link of causality to exist between the two events, at least through the agency of light, that is, for the second event to have been informed of the first, and this means that the order of succession has to have an absolute meaning and can not be reversed by any change of reference system. It can be seen immediately that such an inversion would require a velocity greater than that of light for the second reference system relative to the first.

Although two events between which there thus exists a real possibility of influence can not be made to coincide in time, they can always be made to coincide in space by a suitable choice of reference system. In particular, if the two events belong to one and the same world line, that is, follow each other in an absolute order in the lifetime of one and the same portion of matter, they coincide in space for observers attached to this portion of matter.

Correlatively to what was the case above, although the interval in time of the two events can not be reduced to zero, it passes through a minimum for that reference system relative to which the two events coincide in space.

This leads us to the following statement.

The interval of time separating two events that coincide in space, that is, *that follow each other at one and the same point for a given reference system, is smaller for this system than for all other systems in any kind of uniform translational motion relative to the first.*

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In everything that has been said above, the reference systems used are assumed to be endowed with uniform translational motions: it is only for systems of this kind that the observers attached to them are unable to detect experimentally their collective motion, and that the equations of physics necessarily retain their form when there is a transition from one to another. For systems of this kind, everything happens as if they were motionless with respect to the ether; uniform translational motion in the ether has no experimental meaning.

This, is however, no reason to conclude, as has sometimes been done prematurely, that the concept of ether should be abandoned, and that the ether is non-existent and inaccessible to experiment. It is only a velocity that is uniform with respect to the ether that can not be demonstrated; any change of velocity, or acceleration, has an absolute meaning. In particular, it is a fundamental point in the electromagnetic theory that any change of velocity or acceleration of a charged particle is accompanied by the emission of a wave that is propagated in the medium at the velocity of light, and the existence of this wave has an absolute meaning; conversely, every electromagnetic wave, such as a light wave, originates in the change of velocity of a charged particle. Thus, we have identified the ether through the intermediary of accelerations; acceleration has an absolute meaning in that it determines the production of waves from the matter which has undergone the change of velocity, and the ether demonstrates its reality as a vehicle or carrier of the energy transported by these waves.

The theory allows the possibility of demonstrating, by means of electromagnetic or optical experiments, any acceleration of the collective motion of a material system with the aid of experiments carried out within this system, even if only by verifying the emission of waves by charged bodies attached to the system and motionless with respect to it. We also know that, if the acceleration of the collective motion is communicated to the system by external forces which (as opposed to what happens in the case of gravitation) act only upon certain parts of the system, we have many other means of demonstrating it, such as deformations within the system which cause the acceleration to be transmitted from portions of the system that are subjected to the external forces to other portions that are not.

In a uniform gravitational field, in which every portion of the system would be directly subject to the external force that would communicate to it the collective acceleration, as in Jules Verne's projectile, reactions of this kind would not take place, but it would still be possible, as stated above, to carry out electromagnetic or optical experiments in order to demonstrate the change of velocity of the collective motion. The laws of electromagnetism would not be the same for axes attached to this material system as for axes in collective uniform translational motion.

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We shall now see this absolute nature of acceleration present itself in another form.

Let us consider a portion of matter in any kind of motion and the succession of events that constitute the lifetime of this portion of matter, that is, its world line.

For two of these events that are sufficiently close to each other, observers in uniform motion who witness these two events successively may be regarded as being attached to the portion of matter, since the change of velocity of this portion of matter is imperceptible in the interval separating the two events. For these observers, the interval of time between the two events, which will constitute an element of what we shall call the *proper time* of the portion of matter, will be shorter than for any other group of observers attached to a reference system that is in any kind of uniform motion.

If we now take any two events in the lifetime of our portion of matter, their interval of time as measured by observers in non-uniform motion who will have constantly followed the portion of matter will, by integration of the above result, be shorter than for the reference system in uniform motion.

In particular, this reference system can be such that the two events in question take place within it at one and the same point, and that with respect to it the portion of matter has travelled through a closed cycle, or returned to its starting point as a result of its non-uniform motion. *And we can state that, for observers attached to this portion of matter, the time that will have elapsed between the departure and the return, or the proper time of the portion of matter, will be shorter than for observers who have remained attached to the reference system in uniform motion.* In other words, the portion of matter will have aged less between its departure and its return than if it had not undergone any accelerations, but had remained fixed with respect to a reference system in uniform translational motion.

We can, in fact, say that it is sufficient to be in non-uniform motion or to undergo accelerations in order to age less quickly; we shall see in a moment just how much time can be expected to be gained in this way.

We shall take two concrete examples. Let us imagine, firstly, a laboratory attached to the Earth, whose motion can be regarded as a uniform translation, and, in this laboratory, two completely identical samples of radium. From our knowledge of the spontaneous decay of radioactive substances, we are able to state that, if these samples remain in the laboratory, they will both lose their activity at the same rate in time and will have equal activities at all times. However, if we send one of these samples out on a journey at a high enough velocity and then bring it back into the laboratory, this necessarily implies that, at certain moments in time at least, this sample has undergone accelerations. We are able to state that, on its return, since its proper time between departure and return is less than the interval of time measured between these same events by observers attached to the laboratory, it will have decayed less than the other sample and will consequently be more active; it will have aged less, since it has been subjected to more non-uniform motion. Calculation shows that, in order to obtain a difference of one part in ten thousand between the variations in activity of the two samples, it will have been necessary to maintain the travelling sample at a velocity of approximately four thousand kilometres per second during the separation.

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Before looking at a second concrete example, we shall present our result again in a different light. Let us assume that two portions of matter encounter each other a first time, separate, and then meet again. We are able to state that observers attached to one and to the other respectively during the separation will not have made the same evaluation of the duration of this separation and will not have aged to the same extent as each other. It follows from what has been said above that the ones that will have aged the least will be those whose motion during the separation has been farthest from being uniform, or who have undergone most accelerations.

In this observation there lies the means, for any one of us willing to devote two years of his life to it, of knowing what will have become of the Earth in two hundred years, of exploring the future of the Earth by taking a forward leap into its lifetime that will last two centuries for the Earth and two years for him, although it would have to be without any hope of returning or any possibility of coming back to inform us of the result of his journey, since any attempt to do this could only carry him farther and farther forward.

To do this, our traveller would need only to agree to being shut up inside a projectile that the Earth would launch at a velocity sufficiently close to that of light, but still less than it, which is physically possible, arranging for an encounter with, say, a star to take place at the end of one year in the lifetime of the traveller and to send him back towards the Earth at the same velocity. Having returned to Earth two years older, he will emerge from his ark to find that our globe has aged two hundred years, provided that his velocity has remained within the range of only one part in twenty thousand less than the velocity of light. The most reliably established experimental facts of physics enable us to state that this is indeed what would happen.

It is diverting to picture how our explorer and the Earth would watch each other living if they could keep in constant communication during their separation by means of light signals or wireless telegraphy, and to understand in this way how it is possible for there to be a lack of symmetry between the two measurements of the duration of separation.

While they are moving away from each other at a velocity close to that of light, each of them will appear to the other to be fleeing in front of the electromagnetic or light signals sent to him, so that it will take a very long time to receive the signals emitted during a given period. Calculation, in fact, shows that each of them will see the other living two hundred times more slowly than normal. During the year for which this movement apart will last for him, the traveller will receive from the Earth only news of the first two days after his departure; during this year he will have seen the Earth perform the actions of two days. In addition, for the same reason arising from the Doppler principle, the radiations that he will receive from the Earth during this time will have, for him, a wavelength two hundred times greater than for the Earth. What will appear to him as luminous radiation by which he will be able to see the Earth will have been emitted by the Earth as extreme ultra-violet radiation, possibly close to X-rays. And if we wish to maintain communication between them by Hertzian signals, that is, by wireless telegraphy, the explorer having taken with him receiving equipment having a certain antenna length, the transmitting equipment used by the Earth during these two days following his departure will need to have an antenna length two hundred times shorter than his.

During the return journey, conditions will be reversed. Each of them will see the other living at a singularly accelerated rate, two hundred times more quickly than normal, and during the year for which the return journey will last for him the explorer will see the Earth perform the actions of two centuries; it can thus be seen that on his return he will find the Earth two hundred years older. He will also be able to see it during this period with the aid of waves which for him will be light waves but which for the Earth will belong to the extreme infra-red, with the aid of the rays of approximately 100-micron wavelength that Rubens and Wood recently discovered in the emission spectrum of the Welsbach mantle. For him to continue to receive Hertzian signals from the Earth, after the first two days and throughout the following two centuries, the Earth will have to use a transmitting antenna two hundred times longer than that of the traveller, and forty thousand times longer than that used during the first two days.

To understand this lack of symmetry, it should be noted that the Earth will take two centuries to receive the signals transmitted by the explorer during his motion away from the Earth, which for him lasts for a year. During this time the Earth will see him live in his ark at a rate that is slowed down two hundred times; it will see him perform the actions of one year. During the two centuries for which the Earth will see him thus moving away, in order to receive the Hertzian signals that he emits it will need to use an antenna two hundred times longer than his. At the end of these two centuries, news will reach the Earth of the projectile's encounter with the star, which marks the start of the return journey. The traveller's arrival will then take place two days after this, and during these two days the Earth will see him live two hundred times more quickly than normal, that is, it will see him perform the actions of a second year and so find him aged by only two years on his return. During these last two days, in order to receive news of him the Earth will need to use a receiving antenna two hundred times shorter than that of the traveller.

Thus, the lack of symmetry arising from the fact that it is only the traveller who has undergone, on his journey, an acceleration that changes the direction of his velocity and brings him back to his starting point on the Earth, is reflected by the fact that the traveller sees the Earth move away from him and then approach him for periods of time that for him are each equal to one year, whereas the Earth, which is informed of this acceleration only by the arrival of light waves, sees the traveller move away from it for two centuries and then return for two days, that is, for a period of time forty thousand times shorter.

Now, if we seek to determine the conditions in which a project of this kind could be carried out in practice, we naturally find ourselves faced with enormous material difficulties.

It is possible to calculate theoretically the work that the Earth would need to expend in order to launch the projectile and communicate to it the kinetic energy corresponding to its enormously high velocity. If we assume the mass of the projectile to be only one ton, it can readily be calculated that if we wish to take only one year to launch it, by whirling it at the end of a sling before releasing it, for instance, it would be necessary to apply four hundred thousand million horse power continuously throughout this year, and to burn at least a thousand cubic kilometres of oil to produce this power.

These difficulties at the start would then be followed by difficulties that would be no less daunting at the stages of reflection and stoppage of the projectile. First of all, it would be necessary, for its reflection, to find a system capable of storing the enormous kinetic energy of the projectile and then restoring it in order to launch it back in the opposite direction at the same velocity. For stopping the projectile, it would be necessary to dissipate this same energy gradually without allowing there to occur at any time either acceleration or a rise in temperature that would be harmful to the projectile, even though the amount of heat equivalent to its kinetic energy would be sufficient to take it to a temperature of at least 10^{16} degrees.

In addition, we have good reason to think that, if a projectile arrived back at the Earth at a velocity of this order, the Earth would not even be aware of its arrival, and that the projectile would come to a stop only when it had reached a certain depth in the earth, without even leaving a hole at the point on the surface through which it would have passed. It would scarcely produce even a slight increase in the electrical conductivity of the air on its trajectory through the atmosphere. For we know from the example of the α-particles of radium that helium material atoms, whose velocity is barely twenty thousand kilometres per second, can follow a perfectly rectilinear trajectory through matter and pass through other atoms without leaving any trace of their passage other than an increase in conductivity, and our projectile would have, per unit mass, a kinetic energy one hundred thousand times greater than that of α-particles. It would constitute an extraordinarily penetrating radiation. To avoid these difficulties, it would be necessary to find a means of slowing down its motion gradually as it approached the Earth. Nor would it seem in this case possible to attempt to apply the principle of the rocket that my colleague M. Perrin has suggested should be used for interplanetary travel.

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My sole purpose in developing these speculations has been to demonstrate, with the aid of a striking example, the kind of consequences, far removed from the usual conceptions, to which the new form of the concepts of space and time leads us. It must be remembered that this represents the perfectly valid extrapolation of conclusions that are determined by indisputable experimental facts of which our forbears had no knowledge when they formulated, on the basis of their experience relating to mechanism, the categories of space and time that we have inherited from them. It is now our turn to carry on their work by pursuing, in more minute detail, and in keeping with the means that we have at our disposal, the adaptation of man's thinking to the facts.

It is not only in the field of space and time that we are being forced to reshape the most fundamental conceptions of the mechanistic synthesis. Mass, which was used to measure inertia, a prime attribute of matter, was once considered to be an essentially unvarying element characteristic of a given portion of matter. This concept is now disappearing and is being fused with that of energy: the mass of a portion of matter varies with its internal energy, increasing and decreasing with it. A portion of matter that is radiating loses its inertia in a quantity proportional to the energy being radiated. It is the energy that is inert; matter resists a change in its velocity only in proportion to the energy that it contains.

The concept of energy itself is losing its absolute meaning: its measurement varies with the reference system to which the phenomena are related, and physicists are at present seeking to determine which are the true elements in the expression of the laws of the universe which possess an absolute meaning, that is, the elements which remain constant when there is a transition from one reference system to another and which will play, in the electromagnetic conception of the universe, the part played by time, mass and energy in the mechanistic synthesis.

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