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WHAT DOES EINSTEIN MEAN?[1]

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I AM not sure that I shall fully succeed in explaining during this hour what relativity is, but I shall be satisfied if I succeed in at least removing some of the prejudices which have arisen in connection with this question. Relativity is so simple that the greatest difficulty in understanding it lies in getting rid of one's prejudices. It is really remarkable that Einstein, who is certainly the most popular scientist in the world, is the author of the most unpopular theory in the world. I think a greater harmony should prevail in the popular mind between the man and his work.

One of the common prejudices concerning the theory of relativity is the idea that according to it everything is relative. Nothing could be more incorrect than this assumption. The theory of Einstein states that many things, many notions, many qualities which we thought absolute are actually relative, but on the other hand it destroys the old absolutes only to build up new ones. It could be called, with better right perhaps, the theory of the absolute and not the theory of relativity. It introduces relative quantities only in order to build up absolute quantities out of them and to build up rules for connecting them which will be absolute and which will express physical laws. Maybe if the theory of relativity were called the theory of the absolute it would not appeal so much to the present sophisticated generation, and there would be less talk about it.

Another prejudice is the idea that the theory of relativity was entirely created by Einstein. It was prepared for by the work of Newton. The relativity of space was incorporated in Newton's work; Einstein extended this so as to include the relativity of time.

In his celebrated "Principia" Newton started by saying that space is absolute and that space is at rest: also, he added that time is absolute and flowing uniformly without any connection with other events. Let us leave time alone for a while, and consider what

[1] Address before the Minnesota Chapter of Sigma Xi.

Newton meant when he said that space is absolute and at rest.

I have heard that Ibsen was asked once as to what he meant by one of his plays, and he answered that when he wrote it only God and himself knew what he meant: but since then he had forgotten! I think Newton would say the same thing about his absolute space which is at rest, because from the results established by Newton himself it followed that it is physically impossible to discover and furthermore to determine what this "rest" meant. If some frame of reference is supposed to be at rest, and then another frame of reference is introduced which moves uniformly and in a straight line with respect to the first, then all the events will take place in exactly the same way with respect to the second "moving" frame as with respect to the first, which was supposed to be at rest, and therefore, so far as we can judge from physical phenomena, there is no difference whatever between the two systems of reference—both of them could, with equal right, be supposed to be at rest.

This statement expresses an experience which is very familiar to all who have had the opportunity of riding in a car, ship or train. You feel just as comfortable on a uniformly moving train or ship as you do in a room in a house. One does not notice the uniform motion. All events that happen on a uniformly moving car will take place in exactly the same manner as they take place with respect to the earth, and therefore we do not have any reason to say the earth is at rest and the car is moving.

The same result can be derived mathematically from the fundamental laws of motion established by Newton, thus disproving his original assertion that one can talk about an absolute space that is at rest. The first relativistic idea which we have to introduce is the relativity of uniform rectilinear motion. Given two systems moving with respect to each other uniformly and in a straight line, either of them can be considered as being at rest. From this relativity of motion, or more exactly of uniform motion, there follows the relativity of distances between points in space, so far, at least, as these points refer to events taking place at *different times.*

Let us speak more concretely. Suppose you are riding on a train and let us say are walking forward to the diner: you start at one moment and you arrive a few minutes later at the diner. What is the distance you have moved? It depends on how you measure it. If you measure it relative to the train it will be a rather short distance, perhaps 200 or 500 feet. If you measure the distance traveled with respect to the earth it would be an entirely different quantity, which depends upon the speed of the train. It is not necessary, however, to confine yourselves to the earth: you could take into account the motion of the earth in space. You could, for example, refer the motion of the earth to a frame of reference which is fixed at the center of gravity of the solar system, and then it would turn out that the distance you had moved was not 500 feet or the few miles that the train moved during this time with respect to the earth, but it was perhaps a few hundred or a few thousand miles, since the earth has moved with respect to this frame of reference fixed at the center of gravity of the solar system. And there is also no reason to use that particular system of reference. You could refer the motion of the solar system to any other coordinate system, and then it would turn out that the distance through which you moved was perfectly indefinite: it may have been 100 yards, or 100 miles or a million miles.

Now, this indefiniteness is the result of the fact that one can not define in an unambiguous way a point in empty space. It can be defined only with reference to some coordinate system. If you take two coordinate systems which move with respect to each other, then the distance between the point from which you started and the point to which you have arrived will be different for the two systems. Take, for example, a coordinate system which is moving with you. With respect to this system you will always be at rest, the distance traveled being in this case zero.

So the distance between two points is a perfectly relative quantity, at least so far as these two points relate to events corresponding to different instants of time. You can say, for example, that I have been staying at the same place from the beginning of my talk, which will be true if you consider the room and earth at rest. If you take into account the motion of the earth with respect to the center of gravity of the solar system, all of us have traveled quite a long distance during the ten minutes that I have been talking.

So you see, if uniform motion is a relative motion, then distance in space is also relative or, rather, indefinite. To this principle, however, an important amendment would be made by one adept in the old Newtonian theory, namely: That it is true if you consider the distance between points referring to events which take place at *different times, not simultaneously.* The distance between two points, considered at the same instant of time, was assumed to be absolute, *i.e.,* independent of the choice of the coordinate system which was supposed to be at rest. The definition of "rest" would be immaterial in this case, because so long as the notion of simultaneity is considered as absolute, *i.e.,* independent of the definition of rest or motion, the latter can not affect our estimate of the distance between two points visualized at the same time, the distance traveled by ourselves (or our system of reference) in no time being zero.

Here, then, I must warn you against a misunderstanding. When I am talking about the distance between two objects, I am thinking of the points of space with which these two objects coincide at their respective instants of time. When I am thus thinking of two objects at the same instant of time, then the distance between these two objects or the points of space which they occupy at the same instant of time will be independent according to Newton's theory of which coordinate system we assume to be at rest. So you see that the distance between two points is relative so far as they refer to non-simultaneous events, but it is absolute if they refer to simultaneous events.

This absolute character of the distance between points referring to simultaneous events was connected in the Newtonian theory with an absolute character of simultaneity. It was thought in the Newtonian theory that the notion of simultaneity was an absolute notion, that the notion of the interval of time between two events was unambiguous, in contradistinction to the notion of their distance in space. We thought that we could talk of a definite instant of time for the whole universe and could accordingly define a lapse of time as something definite for all the universe, irrespective of the coordinate system supposed to be at rest and to which we refer the places of all the events observed.

Thus the Newtonian theory was only semi-relativistic. It was relativistic with respect to space and distances in space so far as time was not concerned. Considering different points at the same instant of time one admitted that the distances between them also become absolute, because simultaneity was thought of as an absolute notion.

Now let us inquire why it was that the Newtonian theory admitted the possibility of defining an instant of time unambiguously for all the universe. I am sure that in this respect you all or most of you are the faithful followers of the Newtonian theory, and you probably also think there is no reason why you should not be able to define simultaneity in this absolute way. Now, if you think about it you will see that there was a physical reason which seemed to justify the assumption as to the possibility of defining simultaneity unambiguously (*i.e.,* independently of the coordinate system) for the whole world. This physical reason lies in the Newtonian conception of *force* or *action.* After all, how can you ascertain that two events taking place in different places, on different planets, for instance, are simultaneous? Only through some action coming from these two planets, and such action need not be the action of light: it is sufficient to assume that there is *some* action which can be transmitted from these two planets to the earth instantaneously. If such action existed we should theoretically be able to justify the notion of simultaneity as applied to events in different points of space.

Now, this was exactly the Newtonian and post-Newtonian notion about the transmission of forces through space. It was thought until the second half of the nineteenth century that forces could be transmitted instantaneously through space. We are so used to this notion that we don't even notice how it slips into our arguments. When a physicist talks about the force of interaction between two bodies, as determined by the relative position of these bodies, he fails even to mention that he thinks of the simultaneous position. He considers this simultaneity as something self-understood.

When he thinks, for instance, of the action which the earth experiences from the sun, the moon and the other planets, he usually assumes that this action depends upon the simultaneous position of all the other celestial bodies. He thus assumes that this action is propagated through all space instantaneously. It is this idea of the action at a distance which is propagated through space with infinite velocity that forms the basis of the assumption that simultaneity can be unambiguously defined. If you can theoretically imagine that the whole world can be embraced by some sort of action at a certain instant of time, then it is reasonable to talk of simultaneity as of something definite, which is independent of the choice of the frame of reference.

This idea of force, as propagated instantly through space, was developed with the Newtonian theory of gravitation as a model for forces of all other kinds. It was assumed that gravity was a force acting at a distance through empty space and transmitted with infinite velocity. Newton did not attempt to understand the nature of gravitation. He was satisfied with the recognition of the fundamental fact that gravitational forces were very similar to the forces of inertia connected with accelerated motion, both being proportional to the quantity which is defined as the mass of the body. Newton did not go beyond that, and further, in the Newtonian theory, the relativity of motion could not be generalized for non-uniform motion, *i.e.,* for motion which is connected with acceleration. It was supposed that acceleration, *i.e.,* the rate of change of velocity, was absolute and that relativity suffered a breakdown when applied to accelerated motion.

So you see that there was already a relativistic theory in the old physics created by Newton, but it was limited to space, it did not affect time, and further it was limited to uniform motion. Now let us see what Einstein changed in this situation, and what was the basis of this change.

Einstein's theory did not come just like a "Deus ex machina," that is, completely unexpected. It was prepared for also by the development of physics in the second half of the nineteenth century. The fundamental results of this development consisted in the following facts (1) that all physical forces with the exception of gravity were reduced to electrical forces due to the invariable electrical charges of the elemental particles of matter, namely, the electrons and protons: and (2) that electrical forces are propagated through empty space with a finite velocity, whereas gravitational forces formerly were supposed to be transmitted through empty space with infinite velocity.

Now, this velocity with which all physical forces, so far as they are of electrical origin, are propagated is equal to the velocity of light. This coincidence is due to the simple reason that light is itself an electric phenomenon. In the present era of radio everybody knows that electrical vibrations generate electromagnetic forces, which are propagated through space in the form of "electro-magnetic waves" with the same speed as light, light vibrations differing from these radio vibrations in frequency or wave-length only. In the case of light, the wave-length is about one billion times shorter than in the case of radio waves, this difference being due to the minute dimensions of the atoms of matter which act like broadcasting stations in the case of light waves.

Therefore, the coincidence of the velocity of light with the velocity of propagation of electrical forces is simply the expression of the fact that light is one of the manifestations of electricity. If in the sequel I refer to this velocity as the velocity of light don't think that I am particularly stressing the optical side of physical phenomena.

Now, leaving aside for a while the forces of gravity, let us assume that all physical forces are propagated with a finite velocity—the velocity of light. What is the implication of this principle with respect to the definition of simultaneity? I mentioned before that the absolute character of simultaneity in Newton's theory was justified by the idea that one could embrace all space at a single instant of time by a physical force emanating from some material body. We now see that this is wrong. A physical force produced by any material body will spread in space with a finite velocity, and thus we lose our solid foundation when we speak of simultaneity as something absolute. This is the real physical basis for the "relativation," so to speak, of time.

The relativity of time follows from the impossibility of combining (by means of a physical action) what is separate in space. This principle could be the starting point of Einstein's theory. The path which is pursued by pioneers of scientific discovery is often more complicated than that which we can follow when we know the goal at which we must arrive. Einstein's path was more complicated than the one which I am indicating now—but let us continue on along this straightforward path. I shall at the conclusion of my lecture come back to the more sinuous path which was followed by Einstein, a path that was obstructed by a lot of prejudices which had to be destroyed.

There is no reason whatever, therefore, for assuming that events, separate in space, can be unified in time. There is no reason why the distance in time between two events taking place on different planets should be a perfectly definite quantity (*i.e.*, independent of the choice of the frame of reference supposed to be at rest). It may be just as indefinite as the distance between the points of space where these two planets were at the initial moment. It may be perfectly possible that the distance in time between two events taking place in Jupiter and Mars will appear different to an observer on the earth and one on another planet, if there were any such.

We are left now, so to say, with no criterion for the comparison of the intervals of time between two events as they must be determined by observers connected with two different systems. I must again warn you against a prejudice. It is sometimes admitted that the Einstein theory changes our ideas of time and space, time particularly, in a very fundamental way. Now, so far as we are considering events with reference to one particular frame (supposed to be at rest) relative to this room for instance or the earth, etc.—Einstein's theory does not change anything about our notions of time and space. Einstein's theory refers to the comparison of space and time intervals between given events as measured or determined with reference to different coordinate systems, which are moving uniformly with respect to each other and in a straight line, either of which may be assumed to be at rest.

Now, how shall we correlate the determinations of the time interval between two definite events by two observers, which are connected with different systems, moving with respect to each other? This question can be solved with the help of that very fundamental principle that is bringing us to the relativity of time, namely, the finite speed of the propagation of physical action. Here is a very delicate point which also gives rise to considerable confusion and which we must carefully elucidate.

Einstein's original (restricted) theory is based on the relativity of space so far as it depends upon the relativity of uniform rectilinear motion (*i.e.*, motion with a constant velocity). Now, if motion is relative, then velocity must be relative also: the velocity with which something is moving, with which, for instance, force is propagated. This velocity should therefore be a quantity, which depends upon the choice of the system of reference supposed to be at rest. This seems perfectly natural: if motion is relative, velocity also is relative. We have just said on the other hand that physical actions are propagated through empty space with a definite velocity equal to that of light, *i.e.,* 187,000 miles per second. This velocity being relative, *i.e.,* being definable only with respect to some frame of reference supposed to be at rest, must at the same time be definite, *i.e.,* independent of the choice of this system. Now this looks like a contradiction. It seems to follow from the relativity of velocity that it also should be indefinite, *i.e.,* that its value should depend upon the choice of the "resting" frame of reference, and it seems impossible to make an exception in the case of any particular velocity, that of light, for example.

If it were so, however, the propagation of light and of physical forces in general would be a physical phenomenon which would enable us to discriminate between two systems of reference moving with respect to each other. If light were propagated in a different way with respect to two such systems then we certainly could say that the systems have different states of motion, *i.e.,* different velocities with respect to "empty space." That coordinate system with respect to which light is speeding with the same standard velocity 187,000 miles a second in all directions could be defined as being truly at rest and all the other systems with respect to which the velocity of light would be different, say in different directions, could be defined as truly moving. But the notions "true" motion, "true" rest, "true" velocity mean that rest, motion and velocity can be defined in an absolute sense with respect to empty state as the fundamental frame of reference supposed to be at rest. This would mean that one must give up the idea of relativity of motion.

But how can we give it up if space is actually void, if it does not contain anything? How can we speak of motion in an absolute sense? When Newton said space is absolute and at rest he did not seriously mean what he said, and we can not seriously mean to say that we can define the real or true velocity of a body with respect to empty space.

If therefore there is a relativity of motion then all velocities must be relative including of course the velocity of light, which, however, must be absolute in the sense that it must be the same whatever the system of reference, supposed to be at rest, with respect to which it is measured. Is it really a contradiction to assume that the velocity is relative in the sense that it can be defined only with respect to a coordinate system which is arbitrarily supposed to be at rest and that at the same time it is absolute in the sense that it is independent of the choice of this system? There is no contradiction between the two statements because the words "relative" (in the former) and "absolute" (in the latter) are used in entirely different senses. I should prefer, in order to escape confusion, to use two different words in the two cases. The term "relative" should be used with respect to velocity in the sense that velocity acquires a definite magnitude only with respect to some coordinate system which is assumed to be at rest: the velocity of light is no exception to this principle—it acquires a definite value only with respect to a system which is supposed to be at rest. As far, however, as any other velocity is concerned not only its definition but also its magnitude depends upon the choice of the "resting" coordinate system. Such velocities are therefore variable or indefinite. The velocity of light, or more exactly the velocity of propagation of all physical actions, enjoys an exceptional position in the sense that being relative it is at the same time definite, invariable or as they usually say in mathematics "invariant" (which does not mean that it is absolute). The invariant character of the velocity of light was established experimentally by Michelson, who tried without success to detect a difference in the velocity of propagation of light rays with respect to the earth (assumed to be moving in space) in different directions. Without by any means questioning the historic importance of Michelson's experiments we can say at present that these experiments were actually useless. If physicists were not prejudiced by the idea of the ether, a material medium in which light vibrations were supposed to be propagated, they would have come to the fundamental ideas of the theory without any experiments on the propagation of light relatively to the earth. For we know now, after the ether theory has been done away with, that if it turned out that light were propagated with different velocities in different directions with respect to the earth then there would be a meaning in talking about the absolute velocity of the earth with respect to empty space, but we have too much confidence in our intelligence to assume that such a notion has any physical meaning.

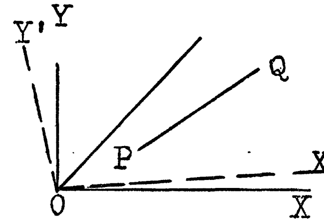
Let us now see what are the consequences of the two principles, that every velocity is relative, and that the velocity of light being relative is invariant (while all the other velocities do depend upon the choice of the coordinate system). Let us consider, for example, the propagation of a radio signal from one ship to another ship, the first one being anchored and the second moving with respect to it. Let us suppose that the anchored ship is sending a radio signal to the moving ship. What is the distance traveled by the signal and the time which it used to travel this distance? The distance between the point of space from which the radio signal issued and the point of space where it arrived will depend upon the choice of the frame of reference which is supposed to be at rest. If this frame is connected with the anchored ship, then the point of arrival will be that point of space where the other ship is located at the moment of arrival, this point being displaced with respect to its position at the moment when the signal was emitted by the first ship by the distance the second ship is supposed to move while the signal is speeding towards it. If, on the other hand, the frame of reference is connected with the second ship, which is thus supposed to be at rest, while the anchored ship moves with the earth in the opposite direction, then the point of issuance will be that point of space where the anchored ship was at the moment of sending the signal, and the point of arrival can be identified with that point of space where the second ship was situated at the same moment, since it is assumed that it remains at rest. Thus the distance traveled by the radio signal must be different from the points of view of the first and of the second ship.

Now what about the time? Will the time elapsed between the sending of the signal and the receiving also depend upon the choice of the frame of reference supposed to be at rest? Not according to the old theory, which says that this time is a perfectly definite thing and that it must be the same for any reference system. This would imply that the velocity of propagation of the radio signal is indefinite—that it should depend upon the choice of the coordinate system supposed to be at rest.

Now we can say that this is not true. The velocity of light or radio waves must be the same with respect to any frame of reference. Since, on the other hand, the distance must be different for frames of reference moving with respect to each other we are forced to the conclusion that the interval of time between two definite events, between emission and receipt of radio signals in our example will be also different. We are thus forced to abandon the old dogma of the absoluteness and invariance of time. It would be considered as a big sacrifice if we persisted in thinking that we could define time in an absolute manner for the whole of space, that we could grasp the whole of space at a definite instant of time by means of some instantly transmitted physical action. Now we know that this was a wrong pretense, that what is separate in space can not be united in time, and there is therefore no obstacle whatever to giving up the idea that "duration," the time interval between two events, must be the same as estimated by two different observers moving with respect to each other. We shall willingly give it up, but how shall we get the correlation between the different times as determined by different observers? Now it can be easily seen that it is just this invariance of the velocity of light, for the sake of which the absoluteness of time has to be sacrificed, which enables one to establish the above correlation, *i.e.,* to compare the measurements of time by different observers. We can say that the intervals of time between two definite events—the issuance of the radio signal by the first ship, and its reception by the second as determined with respect to two different frames of reference—must stand in the same ratio as the corresponding distances, so that the ratio of the distance to the time, equal to the velocity of light, should be the same in both cases.

If we did not have this principle of the invariancy of the velocity of light we would have absolutely no way of comparing the determinations of time by different observers. It is only this principle that allows us to compare the estimations of time. An important point that should be mentioned here is that the theory of relativity allows the invariance of one velocity only (that of light). It would be impossible to build up a consistent theory of time and space if we had to insure the invariance of two or more different velocities. Thus Einstein's relativity theory is based on the unique character of the velocity of light.

The preceding results can be illustrated in a graphical way which I think will help one to understand them. We physicists are used to represent motion graphically. I hope all are acquanited with the principle of this representation. We draw two (usually) perpendicular axes OX and OY. Let distances be represented along the first and times along the second. A point P on this diagram represents an event

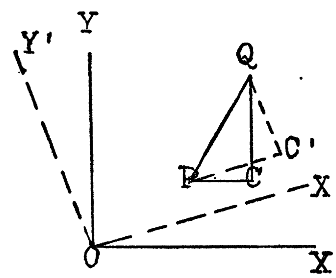


whose place is given by its distance along X and whose time is indicated by its distance along Y. The projections of the line PQ where the points P and Q represent two definite events represent the space and time distance between these events. A succession of points, *i.e.,* a line, represents motion. Straight line corresponds to uniform motion (taking place in a definite direction). A vertical line represents motion with zero velocity, *i.e.,* motion "in time" (without any change of position). So we can say a vertical line represents rest while an inclined line represents motion, the angle of inclination being a measure of the velocity of this motion.

Relativity of motion on this diagram can be interpreted as relativity of direction of inclination. We can just as well assume that the line OY is vertical, thus representing rest, while the line OY′ is inclined and thus represents a point in motion, or that OY′ is vertical and OY inclined and representing motion in the opposite direction. At the present time, in the twentieth century, it is very easy to realize this relativity of direction and of vertical direction in particular. The vertical direction is not the same for different points of the earth's surface, for New Yorkers or inhabitants of Paris. It is not a definite direction in space, as we imagined it to be in our childhood; it is a quite indefinite direction; so we can take any direction as vertical. Therefore the notion of inclination will also be relative. It depends upon what we take as vertical, and this relativity of inclination represents the relativity of motion or of velocity.

Now, let us take these two points, representing two events, P and Q. As has been mentioned above, the distance between the places of these two events and the distance between the times of these two events will be measured by the projections of the line PQ on the coordinate axis. They will thus be equal to PC and CQ, respectively, with respect to the coordinate system XOY (OY being the axis of time, *i.e.*, the "vertical" line representing rest).

Let us now take another system of coordinates X′OY′, with the time or "rest" axis represented by the "inclined" line OY′. The projections of PQ on this new axis will be represented by PC′ and C′Q: they will be different from PC and CQ and will thus represent a different distance in space and a different



interval of time. So far as distance in space is concerned, this is a perfectly natural thing we are already prepared to admit in the Newtonian theory. It is the difference in the estimation of time, as measured by CQ and C′Q, that constitutes a result which is characteristic of the new relativity theory.

But is there anything that remains invariant that does not change here as we pass from one set of coordinates to another that has the same value for both sets? This is the "space-time distance" PQ: It remains the same, whether we measure it in one set of coordinates or the other. We thus see that while the theory of relativity destroys the absolute character of notions which we thought absolute, it introduces instead new notions which are absolute, which do not depend upon the choice of the coordinate system which is supposed to be at rest.

I must now say a few words about the measurement of space distance between events assumed to be simultaneous, for instance, the length of a rod, moving parallel to its length. It is stated in popular presentations of relativity that such a rod should suffer a longitudinal contraction. Why should a thing contract when it is moving and how can one speak of a definite contraction if motion is relative? As a matter of fact, it does not contract at all. This belief in a contraction is a prejudice and misunderstanding. We must clearly understand what we mean when we talk about the length of a moving body. This length, *e.g.*, the length of the rod, is defined as the distance between that point of space at which one end of the rod was at a definite instant and that point of space where the other end of the rod was at the same instant. It is the distance between two different points in space with which the ends were supposed to coincide at the same instant that is to be regarded as the length of the rod.

Now what does "the same instant" mean? That is not a perfectly definite notion. What seems simultaneous in one frame of reference (supposed to be at rest) will not be simultaneous in another. The distance between two points of space where the ends of the rod were "at the same time" will be different, depending upon the choice of the coordinate system. If this distance turns out to be smaller in a frame of reference with respect to which the rod is moving than in a frame of reference with respect to which it is at rest, it does not mean a real contraction, but a perfectly natural variability of length, depending upon the relative character of the definition of simultaneity.

I can illustrate this by the following example: Suppose we want to measure the height of a tower. You could define this height by saying that it is equal to the distance from the bottom of the tower to the top. Now is this definition correct? It is certainly correct from our Minneapolis point of view, but let us be more broad-minded and let us give ourselves the point of view, say, of the New Yorker. We don't have to go to New York and look through a telescope at the tower, but we have simply to replace the Minneapolis vertical by the New York vertical. What will be the height then? It will not then be the distance from top to bottom—it will be the projection of this distance on the New York vertical line (which seems an inclined one from our point of view). So you see in Minneapolis the building has only a height, but with respect to New York it has a height which is smaller and also a length which is equal to its projection on the horizontal plane at New York. Let us now cross the Atlantic and go to Moscow, say. Then the Moscow vertical will be parallel to the Minneapolis horizontal and the Moscow horizontal to the Minneapolis vertical. Thus from the Moscow point of view the building does not have any height at all, but only length. There is no mysticism about it, there is no trick to it, it is simply the result of the definition of height. Suppose a telegraph pole just fell to the earth. What would its height be? The distance from one end to the other would be the height when the pole was standing vertically: it will be the length when it is lying on the ground. Exactly the same can be said about the estimation of distance in time and distance in space. The former or "duration" can be compared to height, while the latter to length. Both are projective quantities: they depend upon the choice of the coordinate system, which is supposed to be at rest, *i.e.*, on the definition of rest. In spite of the relativity of height and length and the possibility of assigning to the same building various heights, that height which can be identified with the distance from top to bottom and which corresponds to such a choice of coordinates with respect to which the building will be vertical and will have a length zero—that height, I say, will be justly considered if not the "true" one at least as the most "natural."

The same can be said about definition of distance in time as well as of the distance in space. If you have two different events, then usually you can do either one of the two following things. Either you can choose such a coordinate system that the two events will seem to take place at the same point of space (the corresponding points on the XOY diagram will lie on the same vertical) and the whole space-time distance will then reduce to the distance in time. This can be defined as the "true," most convenient and the most natural definition of the interval of time in the same sense as the height of the building in Minneapolis is the most convenient or natural height.

Or you can select a coordinate system with respect to which the events will appear simultaneous but taking place in different points of space: the distance between the latter can be defined as the most natural length of the line connecting the points of the two events (the ends of a rod, for example).

Lack of time does not permit my giving any further development of these considerations. I would like briefly to point out the chief importance of the relativity theory to physics. This importance does not consist only in this "relativation" of what we thought to be absolute. Much more important is the other side of the theory, which is the establishment of new absolute things or invariable quantities and invariable relations between variable quantities because physical laws must be invariable or "invariant" laws, true irrespective of the definition of rest, *i.e.*, of the choice of the coordinate system with respect to which we are considering the various physical phenomena.

As a compass is to a sailor, so relativity is to physics. It does not enable one by itself to make new discoveries, just as a compass can not be sufficient for the discovery of land. If, however, you have some idea about the direction in which the new land may lie, using the compass you may unerringly reach this land. So with the relativity theory: if a physicist has good intuition, if he knows where he wants to get, then the theory of relativity points the way. He will not err if he follows the path shown by the relativity theory. It is a most important method which has demonstrated its power in Einstein's work on the theory of gravitation (which is connected with the general theory of relativity) and lately in the development of the new quantum theory.

Beyond the "restricted" theory which refers to uniform motion, I can say only a few words. The possibility of generalizing the relativity theory for any type of motion and making relative not only velocities but also accelerations and so on is, as I mentioned at the beginning, due to the fact that forces of inertia connected with non-uniform motion can not be distinguished from forces of gravity. Suppose that a person is restricted to live all his life in an elevator which is moving up and down. How will he register his observations and interpret them? When the elevator starts up you feel heavier and while its ascending motion is being retarded you feel an unusual lightness—as is also the case when the elevator is beginning to descend. Its stopping is again accompanied by a sensation of increased weight. This change of weight is usually described as apparent, due to the addition or subtraction from the "true" weight the force of inertia which is proportional to the acceleration or retardation. Now a prisoner convicted for life to remain in the elevator and not seeing anything outside the elevator will not admit the idea that the elevator is moving up and down and will identify the apparent weight with the true one and assume that the force of gravity of the earth is being changed, that it acts sometimes with a larger, sometimes with a smaller force.

This fusion of forces of gravity with those of inertia into one single whole is the fundamental idea of Einstein's theory of gravitation and the relativity of all motion as expressed by the general relativity theory. If we assume that motion is relative, then we can consider that the elevator remains at rest and that it is the earth which is moving up and down. This is perfectly natural, though somewhat unusual. We are thinking always that it is the weaker and smaller object that must move, the bigger remaining at rest. It is neither fair not correct from the point of view of the relativity of motion. Let us thus consider that the earth is swinging up and down, the elevator remaining at rest: the result is a change in the pull of gravity due to the earth's motion. The same thing can be said about a "horizontal" motion, such as that of a car. If a car moves very roughly, when starting or stopping you are thrown back and forth; you can say, however, just as well that the car has remained at rest and it is the earth that swayed backward and forward, the gravity force of the moving earth being then directed not downwards, but along an inclined line.

Einstein's theory of gravity amounted to formulating the law of gravity in such a way that it would include the forces of inertia and that it would be valid whatever the system of reference chosen (and supposed to be at rest).

The gravitational theory of Einstein is not actually an *explanation* of gravity, it is only a *description* of gravity, but a more correct description than the theory of Newton.

This theory of Einstein has aroused a great deal of misunderstanding. I think people are especially struck by things they are unable to understand, and they think these "ununderstandable" things are the most important. Einstein's theory of gravity is, I think, associated in everybody's mind with the idea of a "curved" space.

Now what does Einstein mean when he talks about curved space? We must remember that he thinks in mathematical terms, and uses expressions which are misleading to the layman who does not understand the conventional meaning of these words.

Suppose you are on a ship and you drop a stone. As viewed by you or any other person on board it falls vertically in a straight line. As viewed by some person on the shore, the stone will move in a curved line, namely, a parabola with vertical axis. Now this does not mean that the space is curved. It means only that the notion of straightness or curvature is relative in its geometrical aspect. When Einstein talks of space he means actually not space alone but space time, and the curvature attributed to this space-time extension is simply the expression of the fact that there is a lack of uniformity of motion which is due to gravity and which can not be eliminated by a choice of a coordinate system with rectilinear axis. I can not give you the details of that theory, but only an idea of what is actually meant by curvature—it is a kinematical, not statistical or purely geometrical concept.

I can not close without a few words about the retarded propagation of physical forces, which is the corner-stone of relativity, because I have based all my conclusions on this conception, which I not only did not prove but did not explain.

It seems a difficult thing to imagine that forces should be propagated to one body from another through empty space, even if instantly: still more difficult that they are propagated with finite speed, and many people think it is impossible to imagine this and that one must therefore otherwise interpret the facts.

The propagation of light with finite velocity was explained 300 years ago by Huyghens in assuming that space was filled with an elastic medium called the luminiferous ether—a very beautiful name and a very helpful idea for the development of physics. It is queer, but it is a fact that the main merit of the ether theory has been in helping to achieve a unification of physical phenomena. In the nineteenth century Faraday, while studying experimentally electromagnetic phenomena, was biased by the idea that electric and magnetic forces can not be propagated through empty space but only through a material medium, and since it was unreasonable to fill space with another medium, when it was already supposed to be filled with ether it turned out that the ether must transmit not only light vibrations but also electric and magnetic forces. This meant obviously, on the one hand, that light was itself an electromagnetic phenomena and, on the other, that electric and magnetic forces must be propagated with a finite velocity equal to that of light. This result remained in the later development of physics, although the idea or rather the picture of the ether underlying it was destroyed. The theory of the ether had to be abandoned because it led to lots of difficulties. There was however a time—in the second half of the nineteenth century—when physicists thought ether the only thing that really existed, and that matter and all other things were simply manifestations of the motion of the ether. Lord Kelvin, for instance, set forth a theory according to which atoms were just little vortices in the ether. The noted German physicist Drude published in the year 1890 a book on electromagnetic theory which was entitled "The Physics of the Ether."

I should like to write down a translation of a part of an old ode.

> O, thou infinite in space
> And eternal in time
> Whom nobody could comprehend,
> Who fills everything, builds up everything, constitutes everything,
> Whom we call—God.

This ode was written by a Russian poet, Desjavin, 120 years ago and was dedicated to God.

You see, however, that this definition of God fully applies to the ether, and the ether actually was the god of physicists of the nineteenth century. This analogy between God and ether as a logical concept is very deep indeed. The development of the ether theory followed precisely the same lines as the development of the idea of divinity. In primitive physics ordinary crude substances forming "ponderable bodies" were distinguished from certain divine bodies, imponderable substances like the caloric, electric and magnetic fluids and finally the ether, which were responsible for all the other properties outside gravity, just as in primitive religion the ordinary mortal beings were opposed to divine or immortal beings. Then in physics we had a gradual fusion of various divine imponderable substances to one divine substance, which was the ether, just as in religion we had a fusion of small deities into one big deity, whose properties are defined in the above ode. In physics the process did not stop here but continued (as by the way it is being continued in religion). It did not stop with the electron theory of Lorentz, where the ether was actually stripped of all its physical properties and reduced to the rôle of Newton's "absolute space remaining at rest." This idea of the ether corresponds to the idea of the perfectly neutral God in modern "deistic" religions.

Finally Einstein threw the ether overboard, and through this "atheistic" act opened the way to the discovery of his relativity theory. In his revolutionary step Einstein was helped very much by Michelson's experiment. In trying to measure the velocity with which light was propagated with respect to the ether, which was supposed to fill all space and which in Lorentz's theory was supposed to be at rest, Michelson found that this velocity remains the same in all directions, irrespective of the alleged motion of the earth through the ether, and this result was the starting-point of Einstein's researches that led to getting physics freed from the ether.

We must not be overthankful to the ether, and keep it in spite of the fact that it is no longer useful. It is rather a nuisance, for it interfered with the development of the true theory. Those who were used to think of physical phenomena in terms of the ether theory, *i.e.*, of the theory that physical actions were propagated through ether, were confronted with extremely difficult problems which could not be solved.

From the point of view of the ether theory, astronomical phenomena pointed to the fact that the earth was moving with respect to the ether while terrestrial experiments pointed to the opposite fact that the ether was dragged along by the earth and physicists were at a loss how to reconcile this contradiction. This problem was, however, a purely fictitious one, like many problems discussed by medieval scholars; for instance, those referring to the properties and behavior of the devil. Some said the devil had a tail, others that he did not. Then there was the issue: if he had a tail he must show it, whereas according to the protagonists of the anti-tail theory it has never been seen. But the representatives of the other point of view retorted that the devil concealed his tail so well that it could not be seen. Exactly in the same way argued the protagonists of the ether.

If Michelson failed to discover motion of the earth through the ether, *i.e.*, the drift of the ether with respect to the earth, then said these people, this meant that the ether produced such a longitudinal contraction in the earth and all the terrestrial bodies that its drift could not be observed.

Einstein was the first to recognize that all these difficulties were fictitious, because the ether, like the devil, was not a real object but a product of human imagination which was helpful for some time in the development of physics but detrimental for further progress of science, and he accordingly threw it overboard.

PHYSIOLOGICAL TIME

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PHYSICAL time, which is measured by a clock, obviously differs from the time which we live. Time is as much a constituent of ourselves as space. Body and consciousness are a history. Existence is identical with duration. This inherent time can not be reduced to psychological time, which consists of the succession of our states of consciousness as consecutive instants. According to the Bergsonian view, these states of consciousness are only instantaneous pictures which stand out against a continuously streaming background. But our duration is certainly much more than the flux of our inner life. It comprehends the whole organism. Mind and body are two aspects of a single thing. We are composed of structural and functional, as well as of psychological changes. The time which we live includes both physiological and psychological times. It is measured in hours, days and years, and assumed to flow evenly, inexorably and at the rate of solar time. Such a supposition is convenient, but its truth should be questioned. Even at a superficial glance, physiological time does not seem to pass at a constant rate through