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[after December 1916]

If you ask someone who is intelligent but not learned to define space and time, he might answer as follows: imagine the universe without matter, stars and light, then all that remains is some kind of giant vessel without walls, something we simply call "space." This space plays the same role in world affairs as the stage in a theatre performance. Inside this space, in this vessel without walls, there is an eternal uniformly continuous tick-tock. Though only spirits can hear it, they can hear it everywhere. This is "time." This conception of the nature of space and time has prevailed with most natural scientists up to now, even though they did not phrase it in such naive terms as we just did for reasons of simplicity.

Based on this conception one is inclined to attribute an immediate meaning to the following statements. Two eruptions of Mount Vesuvius occur at different times but at the same place (at the crater of Mount Vesuvius). Two distant "new stars" ignite at the same time but in different locations. It has been known for a long time that statements of the first kind (on equi-locality) are meaningless. After all, the earth rotates around its axis, orbits around the sun and, on top of everything, moves conjointly with the sun toward the constellation of Hercules. Therefore, one cannot seriously claim that the two eruptions of Mount Vesuvius occurred at the same location in the universe. This example certainly shows that we cannot attribute any meaning to statements like that about equi-locality. We can only say: Both eruptions of Mount Vesuvius occur in the same place *relative to the earth*. In this statement, earth becomes a "reference body;" statements of locality only make sense in [p. 2]
relation to a reference body.

In contrast, statements about simultaneity, or time in general, seem to make sense independently of any reference body. At first, one tends to declare anybody insane who claims that the statement about the simultaneous ignition of two stars makes no sense without a reference body to which the statement of simultaneity refers. And yet, science has been forced by the persuasive power of factual experience to state just this. How did this happen?

This strange conclusion was reached from the experiences with the propagation of light. Numerous experiments led physicists to the conviction that light propagates through empty space at a speed of c = 300,000 kilometers per second—entirely independently of the velocity of the object that emits the light. Now, imagine a ray of light emitted by the sun in a certain direction. According to the law just stated, this ray travels a distance of c per second. Now imagine the sun hurling an object after this ray of light, so that it moves through space in the same direction with a velocity of 1,000 kilometers per second. This is easy to imagine. Now we [p. 3] might as well select this ejected object as a reference body and ask: what is the velocity of propagating light when judged by an observer who does not sit on the sun, but on the ejected object? The answer seems simple. If the ejected object races behind the light with a speed of 1,000 kilometers per second, the ray of light is only able to advance against it at a rate of 299,000 kilometers per second. It would be the same if the ray of light were not emitted by the sun, but rather by the ejected object; because we know that the velocity of light does not depend on the state of motion of its source.

This conclusion makes one suspicious. Should light propagate differently when judged from the ejected object rather than from the sun? Should the laws of light propagation depend upon the state of motion of the reference body? If so, one could argue, something like absolute rest would exist in the world. Relative to arbitrarily moving bodies of reference (in this case the ejected object), light propagates with a velocity that depends upon its direction and is different from c. This would mean that there exist reference bodies with very distinct states of motion relative to which light would propagate in all directions with the same velocity c. We could justifiably describe such reference bodies as being at absolute rest (in our example, the sun). But does absolute rest really exist in a physical sense? Do the laws of nature really depend upon the observer's state of motion, or the system of reference, as the above argument about light propagation seems to prove?

Experience contradicts this. When we travel in a railroad car that is free of vi- [p. 4] bration we do not notice the motion of the car. All physics experiments succeed in this car just the same as in a house at rest with respect to the earth. No physical experiment performed on earth shows any effect of the motion of the earth with all its objects on it. In general: *the laws of nature are independent of the state of motion of the reference body.* This statement is called, in short, the "principle of relativity." But didn't we believe, as a result of our preceding argument, that the principle of relativity does *not* apply to the laws of light propagation? Now, what is the truth? More than 30 years ago, the American Michelson proved with his famous optical experiment that the principle of relativity would be valid for the propagation of light also in the case that the theory would predict an influence of the movement of the earth on the course of the experiment.[2]

Therefore the argument above had to contain an error. The law of light propagation is exactly the same, whether you choose the sun or the ejected object as a reference body. The same ray of light travels with 300,000 kilometers per second whether it is emitted by the sun or by the ejected object traveling at 1,000 kilometers per second. If this seems impossible, it is only because the hypothesis of the absolute character of time is wrong. One second judged from the sun is not one second seen from the ejected object.

There is no omnipresent tic-tac audible in the universe that we could regard as time. If physics wants to make use of time, it first has to define it. In an effort to do this, it becomes clear that a reference body is needed for this definition, and that the definition only makes sense relative to this reference body. It turns out that one can [p. 5] define time in relation to this reference body in such a way that, relative to it, the laws governing light's velocity are valid. This definition of time can be made for reference bodies in any state of velocity. However, it so happens that the times of differently moving reference bodies do not coincide. There is a more detailed proof of this matter in my popular book about the theory of relativity.[3] If two events happen simultaneously in two different locations judged from a reference body, they are not simultaneous if judged from another reference body moving relative to the first.

Before I continue this train of thought, I have to say something about the role played by the reference body in Galileo's and Newton's mechanics. Altogether, I must also mention that, in the development of science, there is only a building up and never a tearing down. If one generation were unable to build upon the edifice of an earlier one, there would be no science. It would be sad if the theory of relativity would have to overthrow mechanics, just like one tyrant overthrows another. The theory of relativity is nothing else than another step in the centuries old development of our natural sciences. It preserves and deepens previously established connections and adds new ones. The theory of relativity does not overthrow Newton's and Maxwell's theories, just as the League of Nations does not destroy the states that join it. They will have to accept some modifications of their laws, but in return they gain a higher degree of security.—

In everyday life the the earth's surface serves as a reference body whose individual points can be recognized time and again. In mathematical physics three orthogonal straight rods originating from one point are used as a reference body (coordinate system). The position of a point relative to this system of rods is described by three numbers (coordinates) that can be obtained by measurement with rigid rods (measuring rods). In this case it is assumed that Euclidean geometry correctly describes the laws of the arrangement of rigid bodies. All statements of position in [p. 6] today's physics are based on this assumption. Wherever a point may be located, the system of rods and the procedures of measurement can be thought of as complete in such a way that they lead to the point under consideration. Imagine this like a scaffolding with which one reaches every little turret and corner, no matter how large the building. In physics it is not even necessary that this scaffolding really exist, if you can imagine it built only with indirect operations (with rays of light, etc.).

Galileo's and Newton's fundamental laws of mechanics are such that they cannot claim validity relative to arbitrarily moving reference bodies, but only relative to reference bodies with appropriately chosen states of motion. These reference bodies which are admissible in mechanics are called "inertial systems." Now, a theorem in mechanics states: If the reference body *K* is an inertial system, then any other reference body moving uniformly, in a straight line and without rotation relative to *K,* is also an inertial system. Stated more simply: If the laws of mechanics apply relative to the surface of the earth as a reference body, then they also apply relative to a uniformly moving rail road car as a reference body.

With the following simple formula I would now like to summarize what has previously been said about light: Relative to every inertial system—given the correct definition of time—the theorem of the constancy of the velocity of light in empty space applies. In more general terms, the theorem that states "the laws of nature are the same in all inertial systems," is an expression of manifold experience. This theorem is called "principle of special relativity."

That this theorem incorporates a novel physical research method can be understood as follows: Assuming the universe or the individual events that constitute it have been described relative to *one* inertial system, then the course of events *seen from a different inertial system* looks different, but is, nevertheless, fully determined. The Dutch <mathematician> physicist calculated general rules that allow
[p. 7] the recalculation of position and time from one inertial system to a different one. This way, not only individual events can be recalculated, but also the mathematically formulated laws of nature. The principle of special relativity demands that these laws do not change by such a transformation. If they do not have this quality, they are to be rejected according to the principle of special relativity. The laws of nature must be adapted to the principle of special relativity.

During these investigations it first became clear that Newton's mechanics are in need of a modification when it comes to extremely rapid movements or, more precisely, movements whose velocities are not insignificantly small relative to the velocity of light. Furthermore it turned out that the inertia of a body is not a characteristic constant of that body, but dependent on the energy content. *Mass and energy are identical in nature.*