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[25]
THE THEORY OF SPECIAL RELATIVITY

[26] THE previous considerations concerning the configuration of rigid bodies have been founded, irrespective of the assumption as to the validity of the Euclidean geometry, upon the hypothesis that all directions in space, or all configurations of Cartesian systems of co-ordinates, are physically equivalent. We may express this as the "principle of relativity with respect to direction," and it has been shown how equations (laws of nature) may be found, in accord with this principle, by the aid of the calculus of tensors. We now inquire whether there is a relativity with respect to the state of motion of the space
[27] of reference; in other words, whether there are spaces of reference in motion relatively to each other which are physically equivalent. From the standpoint of mechanics it appears that equivalent spaces of reference do exist. For experiments upon the earth tell us nothing of the fact that we are moving about the sun with a velocity of approximately 30 kilometres a second. On the other hand, this physical equivalence does not seem to hold for spaces of reference in arbitrary motion; for mechanical effects do not seem to be subject to the same laws in a jolting railway train as in one moving with uniform velocity; the rotation of the earth must be considered in writing down the equations of motion relatively to the earth. It appears, therefore, as if there were Cartesian systems of co-ordinates, the so-called inertial systems, with reference

to which the laws of mechanics (more generally the laws of physics) are expressed in the simplest form. We may surmise the validity of the following proposition: If K is an inertial system, then every other system K' which moves uniformly and without rotation relatively to K, is also an inertial system; the laws of nature are in concordance for all inertial systems. This statement we shall call the "principle of special relativity." We shall draw certain conclusions from this principle of "relativity of translation" just as we have already done for relativity of direction.

In order to be able to do this, we must first solve the following problem. If we are given the Cartesian co-ordinates, x_ν, and the time t, of an event relatively to one inertial system, K, how can we calculate the co-ordinates, x'_ν, and the time, t', of the same event relatively to an inertial system K' which moves with uniform translation relatively to K? In the pre-relativity physics this problem was solved by making unconsciously two hypotheses:—

1. Time is absolute; the time of an event, t', relatively to K' is the same as the time relatively to K. If instantaneous signals could be sent to a distance, and if one knew that the state of motion of a clock had no influence on its rate, then this assumption would be physically validated. For then clocks, similar to one another, and regulated alike, could be distributed over the systems K and K', at rest relatively to them, and their indications would be independent of the state of motion of the systems; the time of an event would then be given by the clock in its immediate neighbourhood.

2. Length is absolute; if an interval, at rest relatively to K, has a length s, then it has the same length s, relatively to a system K' which is in motion relatively to K.

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If the axes of K and K' are parallel to each other, a simple calculation based on these two assumptions, gives the equations of transformation

$$(21) \qquad \begin{cases} x'_\nu = x_\nu - a_\nu - b_\nu t \\ t' = t - b \end{cases}$$

This transformation is known as the "Galilean Transformation." Differentiating twice by the time, we get

$$\frac{d^2 x'_\nu}{dt^2} = \frac{d^2 x_\nu}{dt^2}.$$

Further, it follows that for two simultaneous events,

$$x'^{(1)}_\nu - x'^{(2)}_\nu = x^{(1)}_\nu - x^{(2)}_\nu.$$

The invariance of the distance between the two points results from squaring and adding. From this easily follows the co-variance of Newton's equations of motion with respect to the Galilean transformation (21). Hence it follows that classical mechanics is in accord with the principle of special relativity if the two hypotheses respecting scales and clocks are made.

But this attempt to found relativity of translation upon the Galilean transformation fails when applied to electro-magnetic phenomena. The Maxwell-Lorentz electro-magnetic equations are not co-variant with respect to the Galilean transformation. In particular, we note, by (21), that a ray of light which referred to K has a velocity c, has a different velocity referred to K', depending upon its direction. The space of reference of K is therefore distinguished, with respect to its physical properties, from all spaces of reference which are in motion relatively to it (quiescent ether). But all experiments have shown that electro-magnetic and optical phenomena, relatively to the

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earth as the body of reference, are not influenced by the translational velocity of the earth. The most important of these experiments are those of Michelson and Morley, [28] which I shall assume are known. The validity of the principle of special relativity also with respect to electro-magnetic phenomena can therefore hardly be doubted.

On the other hand, the Maxwell-Lorentz equations have proved their validity in the treatment of optical problems in moving bodies. No other theory has satisfactorily explained the facts of aberration, the propagation of light in moving bodies (Fizeau), and phenomena observed in double stars (De Sitter). The consequence of [29] the Maxwell-Lorentz equations that in a vacuum light is propagated with the velocity c, at least with respect to a definite inertial system K, must therefore be regarded as proved. According to the principle of special relativity, we must also assume the truth of this principle for every other inertial system.

Before we draw any conclusions from these two principles we must first review the physical significance of the concepts "time" and "velocity." It follows from what has gone before, that co-ordinates with respect to an inertial system are physically defined by means of measurements and constructions with the aid of rigid bodies. In order to measure time, we have supposed a clock, U, present somewhere, at rest relatively to K. But we cannot fix the time, by means of this clock, of an event whose distance from the clock is not negligible; for there are no "instantaneous signals" that we can use in order to compare the time of the event with that of the clock. In order to complete the definition of time we may employ the principle of the constancy of the velocity of light in a vacuum. Let us suppose that we place similar clocks at points of the