58. "King's College Lecture"

[before 13 June 1921][1]

[p. 1] It is a special joy for me to be able to speak in the capital of the country from where the most important basic ideas of theoretical physics were brought into the world.[2] I think of the theories of the motion of masses and of gravitation, which Newton gave us,[3] and of the concept of the electromagnetic field by Faraday and Maxwell, which provided physics with a new foundation. One may well say that the theory of relativity brought a kind of conclusion to Maxwell's and Lorentz's grand framework of ideas by trying to extend the physics of fields to all of its phenomena, gravitation included.[4]

Turning to the subject of the theory of relativity, I want to emphasize that this theory has no speculative origin, it rather owes its discovery only to the desire to adapt theoretical physics to observable facts as closely as possible. This is by no means a revolutionary process but merely the natural development of a trail that can be traced through the centuries.[5] The abandonment of certain concepts of space, time and motion, treated up to now as fundamental, must not be perceived as voluntary, but only as enforced by observed facts.

The law of the constancy of the speed of light, corroborated through the development of electrodynamics and optics, combined with Michelson's famous experiment that decisively demonstrated the equality of all inertial systems (principle of [p. 2] special relativity), relativized the concept of time, where every inertial system had to be given its own special time. During the development of this idea it became obvious that the previous connection between the immediate experience, on the one hand, and the combination of coordinates and time, on the other, had not been analyzed with sufficient rigor.—It is, by the way, an essential trait of the theory of relativity to more rigorously clarify the relation between the general concepts and the experienced facts. The valid principle is here to base the justification of physical concepts exclusively upon their clear and unique relation to experienced facts. According to the theory of special relativity, spatial coordinates and time have an absolute character only insofar as they can be directly measured by means of rigid bodies and clocks.—But they are relative insofar as they depend upon the state of motion of the selected inertial system. According to the theory of special relativity, the four-dimensional continuum, formed by the union of space and time, retains that kind of absolute character that in previous theories space and time held separately (Minkowski). From an interpretation of the coordinates and time through measurements, one finds what influence motion (relative to the coordinate system) has upon the shape of bodies and upon the rate of clocks; also the equivalence of energy and inertial mass.

The theory of general relativity owes its origin primarily to the experimental fact of the numerical equality of inertial and gravitational mass of a body, a fundamental fact for which classical mechanics has given no interpretation. Such interpretation is obtained by extending the principle of relativity to inertial systems that are accelerated relative to each other. The introduction of coordinate systems that are accelerated relative to inertial systems causes the appearance of gravitational fields relative to these coordinate systems. This is the reason why the theory of general [p. 3] relativity, based upon the equality of inertia and gravity, also provides a theory of the gravitational field.

The introduction of coordinate systems that are accelerated relative to each other as equally admissible coordinate systems—as it is implied by the identity of inertia and gravity—leads in combination with the results of the theory of special relativity to the conclusion that the laws of positioning rigid bodies in the presence of gravitational fields do not obey the laws of Euclidean geometry. An analogous result follows with respect to the rate of clocks. From this arises the need for a second generalization of the theory of space and time, because the immediate interpretation of space and time coordinates as measurements with rods and clocks breaks down. This generalization of metric—already worked out in the field of pure mathematics by the researches of Gauss and Riemann—is essentially based upon the fact that the metric of the theory of special relativity is still valid for the general case, provided it is confined to small domains.

The course of development that we described here deprives the space-time coordinate system of all independent reality. Now the metric reality is only defined when the space-time coordinates are combined with the mathematical quantities that describe the gravitational field.

There is a second root to the basic ideas of the theory of general relativity. As Ernst Mach has already emphasized, there is the following unsatisfying point in Newton's theory. When motion is not viewed from a causal but rather from a purely [p. 4] descriptive point of view, then there is a relative motion[6] of things against each other. But the acceleration in Newton's laws of motion cannot be understood in the concept of relative motion. This forced Newton to hypothetically imagine a physical space relative to which an acceleration should exist. This concept of absolute space, introduced ad hoc, is admittedly logically correct, but it is not satisfying. Therefore, Mach looks for a modification of the equations of mechanics such that the inertia of bodies is not derived from their motion against absolute space but rather against the totality of all the other gravitating bodies. Given the state of the art as it existed then, his attempts had to fail.

But it seems very reasonable to pose the problem at all. This train of thought presses itself with even stronger intensity upon the theory of general relativity, because according to this theory the physical properties of space are influenced by ponderable matter. This speaker is convinced that the theory of general relativity can solve this problem in a satisfactory manner only by viewing the world as spatially closed. The mathematical results of the theory lead to this view if one assumes that the mean density of ponderable matter in the universe has finite value, no matter how small this value.[7]