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MOTION, SPACE, TIME*.

Abstract. The paper discusses the properties of spacetime we study by analyzing the phenomenon of motion. Of special interest are the spacetime symmetries, the spacetime structures and the ontological status of spacetime. These problems are considered on the grounds of the classical theories of motion contained in Newtonian physics, special and general theory of relativity. The controversy between an absolute and a relational conception of motion and its ontological implications are also analyzed.

1. INTRODUCTION

Because space and time are not directly accessible to our senses, we are forced to study them indirectly through phenomena taking place in them. Such justification is needed by substantivalists, who admit that space and time exist independently of material world, but is not needed by relationists and advocates of property view[1], who deny that space and time are substances. The necessity of resorting to physical phenomena is for them a natural consequence of accepted ontological assumptions.

Motion is one of the most interesting phenomena, which can provide us with information of space and time. Searching for an adequate theory of motion helps us to understand space and time: their properties, structures they are endowed with and relations between them. In this paper I would like to analyze this problem firstly in the nonrelativistic theory and then in the relativistic theory. Last of all I would like to discuss the controversy between the absolute and the relational conception of motion and its ontological consequences.

There is, however, one problem, that will not be considered in the paper. This is the problem of time reversibility of physical phenomena. All known theories of motion are time reversible, but the problem of time reversibility of physical phenomena cannot be discussed on the sole ground of the analysis of the phenomenon of motion.

If we want to describe a motion of bodies, we must decide what this motion is related to and what properties it has. The latter question concerns the spacetime symmetries of the intended theory of motion, the former — the problem whether we want to describe the motion of bodies with respect to space and time (if necessary — spacetime) or to other bodies. Each of these choices assumes some properties of space and time and the test of adequacy of the obtained theory of motion tells us whether our assumptions are right or not (by adequacy of a theory I understand its ability to explain and predict physical phenomena).

H. Eilstein (ed.), A Collection of Polish Works on Philosophical Problems of Time and Spacetime, 1-22.

Let's consider alternative ways of building theories of motion. I will begin with the relational and the absolute conceptions of motion. The relational conception of motion can be expressed in the following way:

REL Each motion of bodies is relative to other bodies or takes place relative to a definite structure which is determined by the distribution of mass in the Universe.

According to relationists the adequate theory of motion should contain in its equations only *relative* particle quantities, such as *relative* particle distances, *relative* particle velocities, *relative* particle accelerations, etc. or should refer to some structures, e.g. the inertial or affine structures, which are determined by distribution of mass in the Universe.

The relational conception of motion (REL) gives the relationist a choice between two alternative strategies. The first one is the classical strategy. Its first consistent representative was Ch. Huygens.[2] The second one was considered by Newton in his early work *De Gravitatione* (about 1668), but he rejected it as inadequate. It was later undertaken by Berkeley (1752) and Mach (1883). According to this strategy, inertial forces are produced by relative motion of bodies with respect to the fixed stars. That strategy corresponds to the so-called Mach's principle, which says, that inertial frames are determined by distribution of mass in the Universe. It was only when the general theory of relativity (hereafter GTR) came into being that the advocates of the Mach's principle seemed to acquire a chance of realization of that strategy. I will demonstrate in my paper whether or not their hope was well-founded.

The advocates of absolute conception of motion, like Newton, would of course deny (REL), endorsing the following claim:

ABS Each adequate theory of motion should contain in its equations at least one of the absolute (that is, relating to space or spacetime, and not to other bodies) quantities, such as location, velocity, acceleration, etc.

Spacetime properties, i.e. spacetime symmetries acknowledged by a given absolutist would decide, which of these quantities are used in his theory of motion. Because the demand to construct a relational theory of motion also imposes some spacetime symmetries on the spatiotemporal quantities represented in a given theory of motion, the controversy between the relational and the absolute conception of motion is related to another problem under consideration, namely, what spacetime symmetries should have to be accepted in an adequate theory of motion.

2. THE PRERELATIVISTIC PHYSICS

The choice of spacetime symmetries accepted in Galileo's first modern theory of motion was determined by a significant discovery made by its founder:

> Shut yourself up with some friend in the main cabin below decks on some large ship, and have with you there some flies, butterflies, and other small flying animals. Have a large bowl of water with some fish in it; hang up a bottle that empties drop by drop

> into a wide vessel beneath it. With the ship standing still, observe carefully how the little animals fly with equal speed to all sides of the cabin. The fish swim indifferently in all directions; the drops fall into the vessel beneath; and, in throwing something to your friend, you need throw it no more strongly in one direction than another, the distances being equal; jumping with your feet together, you pass equal spaces in every direction. When you have observed all these things carefully (though there is no doubt that when the ship is standing still everything must happen in this way), have the ship proceed with any speed you like, so long as the motion is uniform and not fluctuating this way and that. You will discover not the least change in all the effects named, nor could you tell from any of them whether the ship was moving or standing still. (Galileo 1632, pp. 186-187)

The result of this discovery was an important physical principle called the *principle of Galilean relativity* which in its classical formulation says, that mechanical phenomena do not distinguish any of inertial frames, rectilinearly and uniformly moving relative to one another. This principle together with the requirement of absoluteness of time has led to the Galilean transformations, which correspond to the symmetry group of Newtonian dynamics:

$$x^{\alpha} \rightarrow x'^{\alpha} = R^{\alpha}{}_{\beta}\, x^{\beta} + v^{\alpha} \cdot t \ + \ constant \qquad \text{(GAL)}$$

$$t \rightarrow t' = t + constant$$

where $R^{\alpha}{}_{\beta}$ is a constant orthogonal matrix, $v^{\alpha} = const$ and $\alpha, \beta = 1,2,3$. Notation in this formula (and other ones in this text) follows Einstein's summation convention: if an index is repeated once at the lower level and once at the upper level, the summation must be carried out over the whole range of that index.
Newton's first law of dynamics, as we understand it now, says, that there exists a preferred class of motions, called free motions[3], and there exist preferred reference frames, called inertial frames, relative to which the free motions are rectilinear and uniform. Newton's laws of dynamics have the same form in each of these inertial frames. Every inertial frame is related to any other by some (GAL) transformation, passively interpreted as a coordinate transformation. The passively interpreted transformation should be understood as a change from old to new coordinates while the actively interpreted transformation means acting on a system of particles to produce, for example, a rotation or translation, or a velocity boost of the system.

The equation of motion, covariant with respect to the Galilean group (GAL), is expressed by Newton's second law:

$$F^{\alpha} = m\, d^{2}x^{\alpha}/dt^{2} \qquad (1)$$

(where m — mass of a particle, F^{α} — an impressed force, x^{α} — location of the particle).

The equation (1) says, that the acceleration $d^{2}x^{\alpha}/dt^{2}$ of a particle is directly proportional to the impressed force and inversely proportional to the mass of the particle.

In Newtonian physics there is no possibility to link up the inertial structure with the mass distribution in the Universe, so we must attribute it to space and time.

Thus, the acceleration appearing in the second law of dynamics is the absolute acceleration (acceleration relative to space) and Newtonian dynamics is an absolute theory of motion. This fact has not been noticed by Newton's opponents and some of their commentators;[4] Berkeley and Mach, criticizing Newton's absolute space, did not propose any alternative theory, which could link up the inertial structure with the distribution of mass in the Universe. The problem of the ontological consequences of the absoluteness of motion will be discussed in § 4, whereas now I would like to analyze exactly the Galilean spacetime, introduced by (GAL).

Traditionally, it was assumed that spacetime symmetries of a theory are represented by the symmetries of its equations. The symmetry mappings of the Newton's second law (1), for example, assume the form (GAL). At present we know, however, that Newtonian mechanics, like many others physical theories, can be expressed in a generally covariant form and thus we cannot identify symmetries of theory's equations with the symmetry of that theory[5]. E.g. Newton's second law assumes the following generally covariant form:

$$F^{i}=m\,[d^{2}x^{i}/dt^{2}+\Gamma^{i}_{jk}(dx^{j}/dt)(dx^{k}/dt)] \tag{2}$$

where Γ^{i}_{jk} are coefficients of a flat affine connection, that is, of a connection for which there exists a global coordinate system, in which $\Gamma^{i}_{jk}=0$ $(i,j,k=1,2,3,4)$. The coordinate systems satisfying this condition are just inertial frames. Equations of the form (2) do not change under any differentiable transformation.

To introduce the concept of spacetime symmetry of a certain theory we must distinguish between absolute and dynamical objects of that theory. The *absolute objects* A_i are those that are not affected by the interactions described in the theory. They characterize the fixed spacetime structure assumed in the theory in question and are invariant with respect to the corresponding transformations. The *dynamical objects* P_i characterize the physical content of its spacetime and can be affected by the interactions described in the theory. Examples of absolute objects are space metric and absolute time in the case of Newtonian mechanics, and the metric of special theory of relativity (hereafter STR). The metric of GTR, affected by the energy-momentum tensor, and the electromagnetic field tensor, affected by the current density four-vector, are examples of dynamical objects. Models of any physical theory T may be expressed in the following form:

$$M=\langle M, A_1, A_2 \ldots, P_1, P_2 \ldots\rangle$$

where M — differential manifold, A_i — absolute objects and P_i — dynamical objects.

We will define now the group of *spacetime symmetries* of a theory as the group of all *automorphisms* of the absolute objects A_i of the theory i.e. the group of all diffeomorphisms Ψ that map M onto M in such a way that $\Psi{*}A_i = A_i$ for all i.[6]

The group of spacetime symmetries of Newtonian mechanics is the Galilean group (GAL). We have the following absolute objects in this theory: flat affine connection Γ^{i}_{jk}, time metric t_i (representing absolute time) and Euclidean space

metric h^{ij} for the three-dimensional instantaneous spaces. The principle of Galilean relativity can now be expressed in the following form: the symmetry group of Newtonian mechanics $(M, \Gamma^i_{jk}, t_i, h^{ij})$ is the Galilean group (GAL).
The symmetries we are discussing inform us about important properties of space and time in Newtonian physics. We have the following properties: the homogeneity of space and time (expressed by the invariance of the absolute objects of Newtonian mechanics under the spatial and temporal translations), the isotropy of space (expressed by invariance of the absolute objects under the spatial rotation) and the symmetry in respect of mirror image reflection. It is worth noting that, according to Noether's theorem, every symmetry (in particular, every spacetime symmetry) corresponds with a some conservation law. And so the invariance under temporal translations corresponds with the energy conservation law, the invariance under spatial translations implies the momentum conservation law, and the invariance under the spatial rotations entails the angular momentum conservation law[7].

The replacement of the equation (1) by the more general equation (2) does not change absoluteness of Newtonian mechanics, for the affine connection appearing in this last equation can be related in the Newtonian mechanics only to spacetime. In the equation (2) we have also the absolute (relating to spacetime) acceleration d^2x^i/dt^2. The additional term $\Gamma^i_{jk}(dx^j/dt)(dx^k/dt)$ appearing in this equation describes the inertial forces acting in the noninertial reference frames. This term vanishes in the inertial frames where $\Gamma^i_{jk} = 0$.

So Newtonian mechanics is the absolute theory of motion because the acceleration appearing in its equations (1) (or (2)) relates to the inertial (or affine) structure of spacetime. However, Newton understood this absoluteness in a different way. He did not distinguish between the ontological absoluteness (the substantival character) of space and the absoluteness in the sense of the existence of an absolute (distinguished) reference frame. He thought that absoluteness of motion consists in existence of an absolute (distinguished) reference frame:

> Absolute motion is the translation of a body from one absolute place into another; and relative motion, the translation from one relative place into another. Thus in a ship under sail, the relative place of a body is that part of the ship which the body possesses; or that part of the cavity which the body fills, and which therefore moves together with the ship; and relative rest is the continuance of the body in the same part of the ship, or of its cavity. But real, absolute rest, is the continuance of the body in the same part of that immovable space, in which the ship itself, its cavity, and all that it contains, is moved. (Newton 1729, p. 7)

It is surprising that Newton believed in the existence of such a frame and in that absolute motion consist in the change of absolute position in this frame, although he realized that he could not point it out:

> And therefore as it is possible, that in the remote regions of the fixed stars, or perhaps far beyond them, there may be some body absolutely in rest; but impossible to know, from the position of bodies to one another in our regions, whether any of these do keep the same position to that remote body; it follows that absolute rest cannot be determined from the position of bodies in our regions. (Newton 1729, p. 8-9)

The introduction in Newton's *Scholium*, of a distinguished reference frame into the absolute spacetime structure means the necessity to restrict its symmetries by

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