FROM THE EDITORS

The following article by A. A. Tyapkin contains a number of controversial premises. The editorial board discussed this article in detail and the author took into consideration some particular observations of the members of the editorial board and the reviewers. However, the final text of the article presented by the author still leaves room for general observations, which the editors thought advisable to publish at the end of the article.

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Expression of the General Properties of Physical Processes in the Space-Time Metric of the Special Theory of Relativity

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Historical references concerning the establishment of the conventional character of the concept of simultaneity of spatially separated events are cited in the article. It is shown that when the criteria for simultaneity admissible on the basis of cause-effect relations have been chosen, there appear in the general case anisotropic descriptions of the velocities of physical processes, which, owing to kinematic similitude, are impossible to distinguish from the isotropic description. It is noted that the theory constructed by Lorentz in his 1904 paper is essentially one of possible forms of presentation of the theory of relativity. The attempts to "develop" Lorentz's erroneous explanation of the relativistic effects are reviewed. The special theory of relativity is analyzed with allowance for the conventionality of the individual propositions of the traditional form of presentation of the theory. A preliminary analysis of the kinematics of physical phenomena for different reference frames in common space-time scales enabled us to establish the fact that the relativity principle is satisfied, owing to the appearance of a kinematic similitude for the corresponding processes, which proceed differently in different inertial coordinate systems. It is shown that the characteristics of the Lorentz transformations lie in just an expression for a universal difference between the velocities of propagation of physical processes in the direction of relative motion of the reference frames. The necessity of the universality requirement for the properties of motion, expressed in terms of the metric properties of space-time, is especially emphasized in the paper, and attention is drawn to a possible use of the old data on the metric of the physical space-time to uncover new properties of motion.

CONTENTS

THE special theory of relativity introduced radical changes into the most fundamental and general physical concepts about the motion of matter, changes which have found expression in the establishment of new physical properties of space and time. Signifying the beginning of a radical reconstruction of classical physics, the special theory of relativity exerted a colossal influence on the shaping of all subsequent branches of contemporary theoretical physics.

Thus, began the transformation of Newton's theory of gravitation, which was completed with the construction of the general theory of relativity, with the extension of the requirements of the special theory of relativity to gravitational interactions. The de Broglie waves and, finally, the relativistic Dirac equation in quantum mechanics were the result of the extension of the ideas of the theory.

The validity of the theory of relativity* was confirmed both by experiments which were specially set up for the verification of the theory and by the agreement of all its consequences with experiment. The laws of the theory of relativity are used in modern technology—in the construction of particle accelerators, and of diverse separators and spectrometers for relativistic particles—and are the basis of the energy computations connected with the application of nuclear technology.

Not one physical theory or scientific discovery has ever aroused such a wide interest of the public as did the theory of relativity. The unusual nature of the answers of the theory to seemingly the most simple problems of physics has invariably aroused interest in the theory far beyond the confines of scientific circles. Heated controversies arose over the physical and philosophical problems of the theory of relativity, and this happened not only in the first years of its exist- .ce.

It would seem that, several decades after the founding of the theory of relativity, its construction and elucidation through the efforts of physicists would have been completed—sufficiently not only for all arguments to have ceased, but also for the theory to have been successfully incorporated together with other branches of classical physics into the program of the school course. However, in spite of the abundance of monographs and original texts on the theory of relativity*,

*)We shall, for brevity, often omit below the term "special."

*)The world literature at present includes more than a hundred books on the theory of relativity.

the exposition and explanation of this simplest of all the modern physical theories still retain some of the defects and gaps of the original construction and exposition, which arose as a result of the fact that the transition to the new space-time transformations was made without considering the corresponding general kinematic properties of physical processes within the framework of the Galilean transformations. Moreover, the possibility of such an analysis, which will secure the development of the treatment of the physical content of the theory, follows from some not fully explained and, to a large extent, already forgotten assertions of the founders of the theory of relativity. Thus, the necessity for an analysis of the entire physical content of the special theory of relativity, with the aim of establishing objective theorems that do not depend on the conventional agreements on the accepted form of representation of the theory becomes clear, in particular, with the clarification of the validity of H. Poincaré's assertion of the arbitrariness of the concept of simultaneity of events occurring at different points in space.

I. ON THE ARBITRARINESS OF THE CONCEPT OF SIMULTANEITY

1. On the history of the conventional solution of the problem of simultaneity of spatially separated events. The postulate that the velocity of light is constant, which is the basis of the theory of relativity, includes the directly experimentally verifiable assertion that the velocity of light does not depend on the motion of the light source, and the assumption that the velocities of light in any two opposite directions are equal in each inertial coordinate system. This last assumption, which can be used directly to establish the simultaneity of spatially separated events in each reference frame, cannot at all be unequivocally confirmed experimentally and is used on the basis of a conditional agreement—convention.

As far back as in 1898 Poincaré in the article "The Measurement of Time"[1] raised a question fundamental to the future of the theory, that of the nonexistence of absolute time and a predestined simultaneity of two events. He was the first to draw attention to the dependence of the simultaneity of events on an agreement concerning the magnitude of the velocity of light in different directions. The proposition that the velocity of light does not depend on the motion of the source was, as is well known, a direct consequence of the then widespread notion that light propagated in a special light-carrying medium—the ether. Having accepted this thesis, Poincaré at the same time went substantially farther than anybody else and discovered in the proposition that "light has a constant velocity and, in particular, that this velocity is the same for all directions" ([1], p. 10), an element of a conventional agreement which falls outside the limits of experimentally established facts. He made the following categorical assertion apropos of the constancy of the velocity of light: "It is a postulate without which it will be impossible to carry out a measurement of this velocity. This postulate can never be verified directly by experiment. It could come into conflict with experiment if the results of different experiments did not agree. We should consider ourselves fortunate that this contradiction does not occur" ([1], p. 10). And although this statement was subsequently repeated by several eminent scientists, it nevertheless did not receive general recognition, and the content of the theory of relativity was never analyzed with allowance for the conventional character of the accepted definition of simultaneity.

Poincaré's assertion that the definition of simultaneity is conventional, like his firm belief in the possibility of an exact description of the results of a physical experiment with the aid of an intrinsically consistent geometry, conformed wholly to his philosophical views*. This circumstance alone eliminated the necessity for a concrete solution in the framework of physical science to the question of the validity or otherwise of Poincaré's assertions. Furthermore, it is also possible to come across in the current literature the assertion (see, for example,[3]) that the above-cited view of Poincaré, in which he negates the possibility of an experimental confirmation of the accepted postulate and at the same time acknowledges the possibility of its rejection on the basis of experiment, is intrinsically inconsistent.

In reality, however, the possibility of assuming in each reference frame the equality of the velocities of light for opposite directions indeed depends on the properties of the real world—in particular, on the fact that the instantaneous transmission of actions is not possible in nature. But one can, in the opinion of Poincaré, accept this proposition—in the event that it is admissible—only as a convention, since experiment can be adjusted to the contrary assumption to the same degree.

Let us consider the views of other authorities on the conventional character of the concept of simultaneity.

The assumption of the equality of the velocities of light in two opposite directions in a moving system was introduced by A. Einstein as a definition in his 1905 paper ([4], p. 9). However, he does not, in contrast to Poincaré, touch upon the question of the ambiguous relationship between this definition and experimental facts. Therefore, the choice of this definition was interpreted by many people as a way of constructing the theory, and the agreement of its predictions with experiment was acknowledged as experimental confirmation of the basic assumption.

In a paper read at the Zurich conference of the Society of Naturalists in 1911, Einstein speaks more definitely in favor of the arbitrariness of the accepted definition: "In order to measure the velocity of light in a definite direction, we must measure the distance between two points A and B between which the signal propagates and, then, measure the time the light is sent from A and the time it arrives at B. Consequently, it would be necessary to measure the time at different points, and this could be done if the sought-for definition of time already existed. But if velocity, in particular, the velocity of light cannot, in principle, be measured without arbitrary assumptions, then we have the right to make arbitrary assumptions about the velocity

*The fact, however, is that we must distinguish between the assertions of Poincaré apropos of specific conventions in the natural sciences and his views, expressed in the spirit of philosophical conventionalism which negates the objectivity of scientific theory[2].

of light" ([4], p. 181).

In 1917 in a popular article on the theory of relativity, Einstein repeats the assertion that the equality of the velocities of light is done on a free-choice basis, but he only puts these words in the mouth of the reader who disputes with him ([4], p. 542). In all the subsequent numerous expositions of the special theory of relativity, Einstein completely neglects this question, and his above-noted utterances remained unnoticed even by the critics of the conventional viewpoint on the concept of simultaneity of spatially separated events. But in those same years, during which Einstein clearly shared Poincaré's viewpoint on this question, he did not consistently adhere to it and did not analyze it to find out to what extent the individual assertions of the theory depended on the adopted convention.

We must note for the subsequent discussion the fact that according to Einstein the arbitrariness in the choice of the definition of simultaneity did not at all imply the possibility of choosing a common simultaneity for two reference frames moving relative to each other. He wrote, in particular: "Thus, we have no right to suppose a priori that we could adjust the clocks of the two groups in such a way that the two time coordinates of an elementary event would be the same, in other words, such that t would be equal to t'" ([4], p. 150). Thus, having recognized the arbitrariness in the choice of the definition for simultaneity, Einstein did not see in it a justification for the description of the process of light propagation in a moving coordinate system with the aid of the Galilean spatial scales and time intervals, a description which he actually used in his first paper. He also did not perceive the direct connection between the specific formulations of the relativistic effects and the accepted convention with respect to the simultaneity of spatially separated events. In a brief note to an article by V. Varičak in 1911, he disputed the view that "the Lorentz contraction has its roots exclusively in the arbitrary definition 'of the mode of comparison of clocks and the mode of measurement of lengths'" ([4], p. 187). However, to prove the error of this view, Einstein cited the example of the thought experiment in which the length of a moving rod is supposedly measured without reference to the readings of clocks fixed according to the conventionally accepted definition of simultaneity. He suggests that in this experiment the points of coincidence of the ends of two identical rods moving in opposite directions with the same speed should be recorded in the initial coordinate system. The misunderstanding is that Einstein does not notice that his obligatory condition for the coincidence of the speeds of the rods moving in opposite directions already implies the use of a definite convention concerning simultaneity; for without the acceptance of a convention it is impossible to compare experimentally, for opposite directions, not only the velocities of propagation of light but also the velocities of propagation of any physical processes. In a different convention with respect to simultaneity, the rods moving in opposition will correspond in Einstein's thought experiment to different traveling speeds and to different lengths in the initial system. Therefore, the distance between the points of coincidence of their ends will, in general, not be the length of even one of the rods in the initial coordinate system. Neither the recording of the positions of the coincident ends of the rods, nor the registration of the moments when they coincide will in fact make it possible for us to determine the length of a moving rod, or, correspondingly, determine synchronous moments of time, by-passing a convention concerning the relationship between the velocities of some physical process in the forward and backward directions.

The absence of a pertinent remark when the "Note on V. Varičak's paper" was published in the collected works of Einstein is in itself an indication of the fact that this question is not sufficiently clearly understood at present. It is also significant that W. Pauli repeats, in his splendid book "The Theory of Relativity," the same mistake by referring to Einstein's thought experiment with the two moving rods as proof of the fact that "the ascertainment of simultaneity of events occurring at different points, which is necessary for the observation of the Lorentz contraction, may be accomplished with the aid of only scales, without the use of clocks" ([5], pp. 26–27).

The arbitrariness of the accepted definition of simultaneity was also noted in the works of A. Eddington, L. I. Mandel'shtam, S. M. Rytov, and S. É. Khaĭkin. Attention should be drawn especially to the fact that Eddington quite correctly stressed the identity of the two forms of simultaneity convention—by means of the translation of the clocks, or their synchronization with the aid of light signals. Thus, he wrote in 1923: "In this way we obtain one and the same difference in the estimates of simultaneity by the observers S and S' whether we use the clock-translation or the light-signal method. A convention with respect to the computation of time differences at different points is introduced in both cases. This convention in the two methods cited takes one of the following forms:

1) The clock transported with an infinitesimally small velocity from one point to another, continue to indicate the correct time in its new position, or

2) the velocity of light in one direction along any line is equal to its velocity in the opposite direction.

Neither of the assertions is in itself an expression of an experimental fact and does not pertain to any characteristic inherent property of clocks or light; it is just a formulation of rules which we propose to be guided by in the extension of the conventional divisions of time to the whole world. But the mutual agreement of the two assertions is a fact which could be verified through observation" ([6], p. 39).

L. I. Mandel'shtam insisted on the conventional character of the concept of simultaneity in his lectures ([7], p. 190). This view was later defended by his pupils S. M. Rytov and S. É. Khaĭkin. However, no fundamental distinction is reflected in Mandel'shtam's lectures between the conventional (the simultaneity-of-events type of convention) definition and the definitions of physical quantities in terms of the specific procedures for their measurement, extensively used in his lectures ([7], pp. 180–190). These last definitions help concretize the physical meaning of quantities, but the use of them to justify the very physical concepts leads to groundless exaggeration of the importance of the operationalistic interpretation of physical theory. A convention, however, is itself a necessary prerequisite for the possibility of obtaining concrete results in specific measurements. For example, without the adoption of a definite convention on the relationship between the velocities of propagation of some physical process in opposite directions it is in general not possible to measure the velocity of propagation of any physical process and obtain an unambiguous theoretical scheme for the description of the kinematics of physical processes. These fundamentally necessary agreements are conventional, owing to the possibility of assumption of different—from the qualitative view-point—variants of the agreement. L. I. Mandel'shtam draws attention to this possibility of adoption of different definitions. However, he entrusts the task of clarification of the question as to what will be gained by the use of another definition not to theoretical analysis, but to experiment: "You cannot say that there exists some a priori concept of simultaneity. We should define it by some other method. But what the other method will demonstrate is already a question for experiment" ([7], p. 190). The fact, however, is that the distinguishing feature of a convention is that a change in the accepted convention leads only to a change in the theoretical form of the description of the same experimental facts and, therefore, the relationship between different descriptions is established from a simple theoretical analysis without actually resorting to the comparison of experiments that make use of the different conventions. If we do not answer this aspect of the question, then the emphasis on the correct assertion concerning the arbitrariness of the accepted convention, it turns out, leads only to an erroneous justification of the positivistic view of physical theory and establishes a premise for conclusions to be drawn in the spirit of philosophical conventionalism which negates the objectivity of scientific theories.

On the face of it it seems that L. I. Mandel'shtam contradicts the above-quoted assertion made by A. Eddington concerning the agreement and identity of the two forms of the simultaneity convention by attributing to the theory of relativity the following assertion: "The theory of relativity rejects this. It asserts that if you transport the clocks at one time, and you determine the synchronization with the aid of a signal at another time, then you obtain two different settings of the clocks. Clocks synchronized through transfer turn out to be nonsynchronous with respect to a radio signal" ([7], p. 190). Here, however, the confusion stems only from the fact that, in contrast to A. Eddington, Mandel'shtam does not have in mind a slow transfer of the clock. The synchronization of clocks with the aid of a signal in the case when the equality of the velocities of propagation of the signal in the forward and backward directions is accepted, is exactly equivalent to the assertion that the clocks remain synchronized during an arbitrarily slow transfer of them to different points. On the other hand, if we assume the inequality of the velocities of propagation of the signal, then we should, in the framework of this convention, inevitably admit the loss of synchronization of the clocks during an arbitrarily slow transfer of them. The simplest theoretical analysis of these two synchronization procedures leads, for a given convention concerning the relationship between the velocities of physical processes in opposite directions, to the same conclusion. Nothing depends on the choice of the measurement procedure. However, the choice of a convention concerning the relationship between the velocities of propagation of physical processes in the forward and backward directions corresponds to a definite simutaneity, which can be unambiguously established by means of any measurement procedure that takes the accepted convention into account.

The important question of the possibility, in principle, of choosing a common simultaneity in two reference frames in relative motion is also touched upon in L. I. Mandel'shtam's lectures. However, this question is discussed by him extremely inconsistently. On the one hand, we encounter in the lectures assertions, permitting the choice of a single simultaneity and, consequently, of the Galilean transformations (see[7], pp. 202–203 and 250). On the other hand, L. I. Mandel'shtam asserts that "the theory of relativity.... ... negates the validity of both Newton's equations and the Galilean transformations" ([7], p. 124), and further characterizes Einstein's view-point in these words: "How do you happen to know that the Galilean transformations, i.e., the space-time relations they express, are correct?" ([7], p. 176).

It is possible that these expressions are simply accidental reservations or the result of an inaccurate interpretation of the lectures. The fact remains, however, that L. I. Mandel'shtam did not see in the admissibility of the choice of a common simultaneity and, consequently, of the Galilean transformations, the implication that relativistic effects could in principle be described. On the contrary, he assumed that experiment would allow us to select from the many definitions the correct one. Such an interpretation of L. I. Mandel'shtam's views is corroborated by his appraisal of H. A. Lorentz's 1904 paper. The first six lectures of his course are devoted to an historical review of the shaping of the ideas of the theory of relativity*. Discussing Lorentz's paper at the end of this part of the course, he mentions as the main defect the use of a common time ([7], p. 164). L. I. Mandel'shtam does not notice that the description of the new physical theory in Lorentz's paper was given on the basis of the old simultaneity convention.

S. M. Rytov, who prepared Mandel'shtam's lectures for publication, repeated the main points of that course in the chapter "The Optics of Moving Bodies and the Special Theory of Relativity," which he wrote for the physics textbook edited by Academician N. D. Papaleksi[10]. Unfortunately, he also made the assertion that it is necessary to turn to experiment to check the agreement between different conventions.

In the second edition of the textbook "Mechanics"[11], S. É. Khaĭkin also drew attention to the arbitrariness of the equality of the velocity of light in opposite directions: "The postulate of the constancy of the velocity of light includes, as we can see, statements which bear different relationships to experiment—the assumption that the velocity of light remains the same as it propagates "back" and "forth," which cannot be experimentally verified, and the assertion—taken from observations—that the velocity of light is independent of the velocity of the source ....." ([11], p. 517). "But

*Poincaré's discussion of the main original ideas of the theory of relativity in earlier papers[1,8,9] is not, however, reflected in any way in this detailed historical review.

we cannot, for example, verify experimentally that the "back" and "forth" velocity of light is always the same—it is one and the same by definition ([11], p. 512).

2. Reasons for the negation of the arbitrariness of the definition of simultaneity. Thus, Poincaré, Einstein, Eddington, Mandel'shtam, Rytov and Khaĭkin, at different times in the period from 1898 through 1948, stuck to the view that an experimental confirmation of the equality of the velocity of light in the forward and backward directions, is impossible. However, this assertion did not at all become universally recognized, the prestige of the scientists upholding it notwithstanding*. And there is, in fact, nothing surprising in this. The other scientists did not in their utterances go further than repeat Poincaré's assertions. The specific physical assertion that it is impossible to establish experimentally the equality of the velocities of light for opposite directions was thus not rigorously and generally proved. Several motives for the negation of the validity of this assertion are quite clear for philosophical reasons. The absolutely correct thesis about the conventionality of the chosen criterion for simultaneity turned out, in fact, to have been used to support the assertion of the positivistic view of science, since the absence of an analysis of the consequences of other possible conventions on the simultaneity of events permitted an unhindered projection of the generally accepted form of presentation of the theory of relativity as the only possible correct theory. This led to a situation in which a few scientists of materialistic persuation were to some extent provoked to come out against the correct scientific assertion. Not only the publication in the physical literature of the Fifties of similar attempts at the solution of the concrete physical problem of the measurement of the velocity of light on the basis of philosophical considerations[54], but also the absence in the subsequent literature of any refutation of the criticism against the correct views concerning the conventionality, eloquently characterizes the current level of comprehension of the central points of the construction of the theory of relativity.

It is unfortunately possible to come across even in the more recent literature unfavorable appraisals of Poincaré's assertion on simultaneity. Thus, for example, in the book devoted to historical sketches on the theory of relativity, U. I. Frankfurt characterizes Poincare's and Eddington's viewpoint on the conventionality of the chosen definition of simultaneity as philosophically untenable:"'Following Poincaré, Eddington thinks that the definition of simultaneity is based on a convention on the equality of the velocity of light in opposite directions. The conventional character of this assertion is stressed by both Eddington and Poincaré.

However, many authors (A. D. Aleksandrov, V. A. Folk, and others) correctly consider Einstein's definition of simultaneity as being based on the law of constancy of the velocity of light in opposite directions. The Poincaré-Eddington conventionalistic concept was not accepted by the majority of investigators, while its philosophical untenability has been shown in many papers" ([12a], p. 90). These erroneous assertions were repeated by Frankfurt seven years later in another book[12b].

Actually, there is a brief note in V. A. Fock's book to the effect that the definition of simultaneity adopted in the theory of relativity "is not arbitrary" ([13], p. 48). The conventional character of the adopted definition of simultaneity is more firmly rebutted by A. D. Aleksandrov in a number of his papers[14]. We can only regret that the materialistic beliefs of the author were turned against the existence of conventions in the natural sciences, while he was not at all against philosophical conventionalism.

Also paradoxical is the fact that when developing a cause-effect approach similar to the chronometry succesfully analyzed earlier by the Irish physicist A. Robb in his book[15], A. D. Aleksandrov, in contrast to Robb, did not notice that the events that precede a given event at another point in space, are separated from later events by a whole temporal interval of events, for which there cannot, in principle, be any cause-effect relations with the given event.

However, the philosophers were, in fact, not united in their appraisal of the arbitrariness of the thesis concerning simultaneity of events. In papers by the well-known American philosophers H. Reichenbach[16,17] and, especially, A. Grünbaum[18,19], the arbitrariness in the choice of the criterion for simultaneity, due to the existence of a limiting velocity of transmission of interaction, is directly stressed. A similar viewpoint, but in a somewhat different formulation, has been expressed by the Soviet philosopher Yu. B. Molchanov[20]. Unfortunately, however, these authors did not go beyond the simple acknowledgement of this thesis. Having found it impossible to describe relativistic phenomena on the basis of a common simultaneity of the Galilean transformations, they did not, naturally, arrive at a more precise formulation of the most important premises of the theory.

The failure of the individual physicists and philosophers, who explained the conventional essence of the definition of simultaneity, to give a rigorous and general proof to this thesis should be considered as the main cause of the widespread underestimation of this most important question of the construction of the theory, which is most clearly manifested in the periodic appearance in the scientific press of new suggestions for accomplishing the experimental comparison of the velocities of light in opposite directions. We must call our readers' attention to such suggestions, since they should seemingly contain a direct refutation of Poincaré's assertion of the impossibility of an experimental demonstration of the equality of the velocities of light in opposite directions. We recall that S. I. Vavilov made at one time a big contribution to the critical analysis of previously suggested experiments for the demonstration of the equality of the velocities of light in opposite directions, or for the detection of a difference of first-order in v/c in these velocities. Summing up a detailed analysis of such suggestions in 1928 in his book, "The Experimental Foundations of the

*The absence of recognition of this correct physical assertion is shown, first, by the fact that this important thesis is ignored in the rest of the numerous textbooks and monographs on the theory of relativity; second, by the regular appearance in the scientific press of basically erroneous suggestions for carrying out an experimental comparison of the velocity of light in the forward and backward directions and, finally, by the fact that the groundless criticism negating the conventional character of the accepted definition of simultaneity remains thus far unrefuted[54].

Theory of Relativity," he wrote: "The projects described are in themselves correct but unfeasible under the conditions of physical measurements. A considerable number of first-order experiments, which have been performed or planned, are conceptually incorrect. We could write a long history of such errors or inexpediency of the experiments, They invariably yielded a negative result which is, however, trivial, because it follows at once from the two competing hypotheses—of a dragged and undragged ether. We cannot draw any theoretical conclusions from such experiments" ([21], pp. 24–25). However, in spite of this severe pronouncement on the examined suggestions for the so-called first-order experiments, S. I. Vavilov did not give a general proof of the untenability of all such experiments, which attempt to subject to experimental verification not the physical assertion, but the convention concerning the equality of the velocities of light in opposite directions*. For this reason, his critical analysis of previous plans for first-order experiments did not prevent repetition of similar mistakes in our time.

In an article by N. G. Basov, et al. ([24], pp. 49–53) and in a later article by G. M. Strakhovskiĭ and A. V. Uspenskiĭ in[25], first-order experiments, which were suggested and performed abroad, are described. Also described is a plan for an experiment which has been suggested by G. M. Strakhovskiĭ. These suggestions were published without any shadow of doubt on the part of the authors and without any editorial comments drawing attention to the groundlessness of such experiments. No refutation of these suggestions from the numerous readers of the journal has appeared in the past years. And yet, the proposed first-order experiments have the same false foundation as those previously analyzed by S. I. Vavilov, and differ from them only in the use of the latest techniques. We shall show the falsity of the interpretation of such experiments as the experimental demonstration of the equality of the velocities of light in opposite directions, using the proposal by G. M. Strakhovskiĭ [26] as an example. It is suggested that we measure in this experiment the difference between the phases of the oscillations of two nonsynchronous masers spaced at a certain distance apart. The observed phase difference depends on the velocity of propagation of these oscillations in one definite direction. It is further suggested that we observe the change in the measured phase difference of the oscillations when the masers interchange places. It is asserted that if the velocities of propagation of the oscillations in the forward and backward directions differ by $2v$, then the measured phase difference should change by an amount proportional to the first power of v. This conclusion, which is the justification for setting up the experiment in question, is, however, totally false. In fact, the observed phase difference of the oscillations should remain unchanged, irrespective of whether we assume the velocities of propagation of the oscillations to be the same or we take them to be $c - v$ and $c + v$ for the opposite directions. If the latter convention is adopted, then it will be necessary to take into account the desynchronization of the masers (clocks), which must arise during any arbitrarily slow transfer of them to the new positions. This desynchronization of the generators exactly cancels the phase difference of the oscillations that builds up over the distance L, because of the assumed difference in the velocities of propagation of the oscillations.

All such first-order experiments are based typically on an erroneous computation of the effect in the case when the velocities of light for opposite directions are assumed to be unequal. The curious thing about the already performed experiments of this sort is that if we drop the erroneous conclusion that equality of the velocities of light in opposite directions has been experimentally demonstrated, then it is difficult to put into them any physical meaning which allows another interpretation of the results obtained. In contrast to the first-order experiments indicated in the preceding footnote, these experiments have nothing to do with the verification of the physical assertions of the theory of relativity*.

Thus, the gap in the understanding of the central points of the traditional construction of the theory of relativity leads now to real losses, connected with the expenditure of resources and efforts on experiments based on false premises.

Of course, to eliminate this gap in the understanding of the theory it is not at all sufficient to merely recognize as a fact the arbitrariness of the simultaneity concept. Besides a rigorous proof of the impossibility of measuring the velocity of propagation of any physical process in a definite direction without a special convention concerning the relation to the velocity of the process in the opposite direction, we must clarify the dependence of the individual premises of the theory on the adopted convention and then determine that objective content of the theory which remains invariant when the chosen convention is changed.

3. On the proof of the existence of a definite arbitrariness in the choice of the simultaneity convention. We show in this section that the impossibility of establishing for spatially separated events a unique simultaneity, on the basis of the cause-effect relations which determine material processes, follows directly from the existence of a finite limiting velocity of propagation of the interaction between physical objects. Not only does absolute simultaneity of events not exist for different inertial reference frames in relative motion, but a unique simultaneity determined by the material processes themselves does not exist also for each of these coordinate systems. Therefore, it will be sufficient for the proof of the stated assertion to limit ourselves to the consideration of the cause-effect relations for events in one reference frame.

Let a real interaction be sent along the x-axis with

*)Such "experiments" should not, of course, be confused with the first-order experiments on the verification of the independence of the velocity of light of the velocity of its source[22,23], or on the verification of the relativistic effect pertaining to the addition of velocities during the measurement of the velocities of some physical process in the case when the velocities of its source are different.

*)We could speak of a search for another interpretation of such experiments if a positive result is obtained which indicates a violation of the laws of both the special theory of relativity and classical mechanics. However, such a new basis for the necessity of setting up similar first-order experiments should certainly include proof that the supposed affirmative proof of violation of the laws does not contradict the numerous experiments already performed.

the maximum possible velocity from the origin ($x = 0$) of the chosen reference frame at some moment of time $t_1(0)$ (event $E_1(0)$)*. Further, let at the moment $t_2(x)$ of arrival of the action at the point x, an action be sent also with the maximum possible velocity, but now in the opposite direction (event $E_2(x)$). The return of the action to the point $x = 0$ is recorded at the moment $t_3(0)$ (event $E_3(0)$).

It is clear that all the events at the point $x = 0$ preceding the event $E_1(0)$ took place absolutely earlier than the event $E_2(x)$, while the events following the event $E_3(0)$ occurred absolutely later than the event $E_2(x)$. The measured time interval $t_3(0) - t_1(0)$ allows us to determine only some effective value for the limiting velocity of transmission of the interaction "there" and "back," $c = 2x/(t_3 - t_1)$. This analysis does not allow us to determine the magnitude of the maximum velocity separately for each of these directions.

The finite magnitude of the maximum velocity of transmission of interactions leads to a nonvanishing measurable time interval $t_3(0) - t_1(0)$. A special distinctive feature of the set of events at the point $x = 0$ with the temporal coordinate t within the interval $t_3(0) - t_1(0)$ is that these events cannot be connected by cause-effect relations with the event E_2 at the point x**. On this basis, A. Robb[15] suggested that the entire set of events within the interval $t_3(0) - t_1(0)$ should not be considered as being in any way temporally connected with the event $E_2(x)$. The opposite viewpoint has been advanced by Yu. B. Molchanov[20]. He suggests that the entire set of moments of time within this interval should be considered as being objectively simultaneous with the event $E_2(x)$, on the basis that at the point $x = 0$ only the moments of time not entering into this set can be considered as having objectively occurred earlier or later than the event E_2 at the point x.

However, both of these extreme viewpoints are simply inadmissible, if only for reasons of a practical requirement for uniqueness of the description of physical processes. Any possible kinematic description is based on the comparison of only one moment of time at some point in space as simultaneous with some moment of time at another point. Therefore, it will be more accurate to call, following G. Whitrow ([27], p. 383), all these moments of time inside the interval $t_3(0) - t_1(0)$ potentially simultaneous with the event $E_2(x)$. We should, of course, here imply under the term "potentially" only the possibility of realizing any of these simultaneities in the chosen concrete scheme for the kinematic description of the physical processes.

*Notice that the consideration of the process of transmission of the interaction between material objects placed at different points in space corresponds directly to the study of a chain of causally related events. It is precisely this aspect of the material process which is in fact borne in mind when the process of sending a signal is analyzed in the theory of relativity, and not at all the process of transmission and reception of subjective information in the form of a signal. It should also be noted that when the model of space-time events is used, this implies the ignoring of the whole manifold of properties of the real events of the physical world, and only the objective possibility of finding these events in cause-effect relations is taken into account.

**These events are outside the light cones constructed from the point x in the positive and negative directions of the time axis.

The time of the event $E_2(x)$ can be expressed in a general form in terms of the time coordinates of the events E_1 and E_3 at the point $x = 0$ by the following simple relation:

$$t_2(x) = t_1(0) + \varepsilon\,[t_3(0) - t_1(0)],$$

where the parameter ϵ is contained in the interval $0 < \epsilon < 1$. The choice of a specific value for the parameter ϵ in the indicated interval implies the acknowledgement of the moment of time $t_2(0) = t_0(0) + \epsilon\,[t_3(0) - t_1(0)]$ at the origin as being simultaneous with the event E_2 at the point x. The value $\epsilon = 1/2$ corresponds to the assumption of equality of the maximum velocities of transmission of an interaction for opposite directions in the reference frame under consideration. In this lies, naturally, the convenience of the simultaneity in each coordinate system, chosen by Poincaré and Einstein. But we must find out whether there exist physical reasons that exclude the possibility of constructing a kinematic description of the physical processes on the basis of a simultaneity corresponding to values $\epsilon \neq 1/2$.

The foregoing analysis of the process of transmission of an interaction with the maximum possible velocity does not, in fact, allow us to single out some specific value of ϵ as corresponding to an objective simultaneity of events at different points of the system under consideration. This analysis shows that any event at one point of the system may be set in correspondence to a set of events that occur at another point at different moments of time and cannot be connected with the first event by cause-effect relations. However, this is only a necessary and not a sufficient condition for the justification of the possibility of choosing a simultaneity that does not correspond to the value $\epsilon = 1/2$*. Indeed, the choice $\epsilon \neq 1/2$ corresponds to the assumption that the velocities in the forward and backward directions are different not only for the process of light propagation, but also for all other physical processes.

Thus, for light this difference in the velocities of propagation "there" and "back" is equal to $2c(1 - 2\epsilon)$. For an arbitrary physical process the difference in the velocities of propagation in opposite directions for $\epsilon = 1/2$ will be equal to

$$2c\,(1-2\varepsilon)\,\{[(c^2/u^2)-1]\,[4\varepsilon\,(1-\varepsilon)]^{-1}+1\}^{-1},$$

where u is the velocity of the physical process in question in the isotropic description.

Although the physical processes propagating in space with a velocity less than the maximum velocity do not determine the boundaries of the set of causally

*It must be noted that H. Reichenbach[17], in complete conformity with the traditional treatment of the theory of relativity, considered only the value $\epsilon = 1/2$ as corresponding to simultaneity in a given coordinate system. The events corresponding to the rest of the values of ϵ were recognized by him as being simultaneous with a given, causally unrelated event only in appropriate definite reference frames moving relative to the initial coordinate system. On the contrary, A. Grünbaum in his recent papers[18,19] considered as sufficient for the choice, in one and the same reference frame, of different conventions on simultaneity, the establishment of the impossibility in principle of a causal relation between an event at one point in space and a whole set of events at another point.

unrelated events, it is nevertheless only by comparison with them that we could justify any thought experiment for the detection of an anisotropy in the velocity of a process propagating with the maximum velocity. The experimental detection of the difference in the velocities of propagation of processes in the forward and backward directions would certainly become possible if any change occurred in the kinematic relations for different physical processes as compared to the relations obtaining when the velocities of all processes do not depend on direction.

Therefore, to prove finally the possibility of an arbitrary choice of simultaneity within the limits of a time interval for causally unrelated events, we must show in the general case that any experimentally observable kinematic relations between the most different physical processes do not depend on the value of the parameter ϵ chosen for the description of the processes. As was shown in our paper[28], the necessary independence of all experimentally observable relations of the choice of the degree of the universal anisotropy in the kinematic description of physical processes fully guarantees the simultaneous satisfaction of the following two conditions:

(i) The arbitrarily allowable anisotropy in the kinematic description of processes should be characterized by a constant difference—for all physical processes—in the time of propagation between two definite points in space in the forward and backward directions. (The fulfilment of this condition leads to the impossibility of detecting an anisotropy in a direct comparison of the velocities of different processes for opposite directions.)

(ii) The ratio of the total times of propagation in the forward and backward directions should also remain the same for any physical processes. (The fulfilment of this condition excludes also the last possibility of an experimental detection of the asymmetry introduced into the description when the total times of propagation "there" and "back" for any physical processes are compared.)

It is perfectly clear that the choice of a value $\epsilon \neq 1/2$ within the indicated limits from 0 to 1 does not violate these conditions for processes propagating directly along the x axis. But an action can be transmitted from one point to another along any other path joining the same two points on the x axis. A more detailed analysis shows that the proposed conditions for the nonobservability in principle of the asymmetry in the kinematic description of processes are fulfilled when the choice of simultaneity is made with a certain consistency at all points in space. Thus, for example, if the parameter $\epsilon_0 \neq 1/2$ is chosen for the direction of the x axis and its deviation from $1/2$ for this direction is assumed to be maximal, then the asymmetry parameter should, for all the remaining directions in space, be equal to

$$\varepsilon(\theta)=\frac{1}{2}-\frac{1}{2}(1-2\varepsilon_0)\cos\theta\,[1-(1-2\varepsilon_0)^2\sin^2\theta]^{-1/2}.$$

If in the isotropic description, $\epsilon = 1/2$, simultaneous moments of time are represented for all directions by a plane parallel to the XY plane, then the simultaneous values for an experimentally indistinguishable anisotropic description should be represented in this space by a plane inclined to the XY plane. There appears then in the description of the velocities of propagation of each physical process a definite dependence on direction

$$u^*(\theta)^* = uf(\theta^*, u),$$

where u is the velocity of the physical process in question when the isotropic variant of the description is chosen.

It is shown in Appendix A that the dependence of the function $f(\theta^*, u)$ on the quantity u is determined uniquely from the requirement that the conditions (i) and (ii) be fulfilled:

$$f(\theta^*, u) = [\alpha(\theta)^* + u\beta(\theta)^*]^{-1}, \tag{1}$$

where the functions $\alpha(\theta^*)$ and $\beta(\theta^*)$ are necessarily general functions for all physical processes.

The specific form of these functions will be determined in the next chapter when the description of processes in two reference frames in relative motion is considered*.

In the present section, however, it was important for us to explain that the arbitrariness in the choice of the criterion for simultaneity allowed within the limits of a time interval corresponding to causally unrelated events leads to a corresponding universal anisotropy in the description of the velocities of all processes that satisfy the conservation conditions, stipulating that any kinematic relations between different processes should remain unchanged. The assumption that the velocities of propagation of light in the forward and backward directions differ by an amount less than 2c, corresponds to choosing a criterion for the simultaneity of events, for which cause-effect relations are allowable. The corresponding changes in the description of the velocities of other physical processes completely exclude any experimental effects that distinguish the adopted description from the isotropic description**. In spite of the assumption of an explicit dependence of the velocity of propagation of individual physical processes on direction, the unique kinematic similitude, which guarantees the independence of the kinematic relations between different physical processes, renders such a description totally identical to the isotropic description in respect to any observations. Any experiment that admits of an explanation on the basis of the isotropic description can always be interpreted in the framework of a kinematically similar anisotropic description of the velocities of physical processes. We cannot say that the possibility discussed by us of an anisotropic description of the entire set of physical processes should be rejected because the anisotropy cannot be observed, since the isotropy of the generally used description is unobservable to the same extent.

*)Notice that the determination of the angle-dependent function in the description of the velocities of a specific physical process, e.g., of the propagation of light, allows us to find the function $\alpha(\theta^*)$ and $\beta(\theta^*)$ and to determine according to (1) the angular dependence in the description of any physical process.

**)Therefore, there is not, and there can never be, an experiment which proves the equality of the velocities of propagation of light in two opposite directions. Analysis of suggestions of similar experiments makes sense only if it is done with the aim of determining the specific mistakes in the computations carried out to justify the suggestions.

It will be more accurate to say that experiment does not permit us in principle to distinguish the isotropic description from the description that admits of a definite form of a universal anisotropy in the velocities of physical processes. Of course, there is a whole set of strong reasons for preferring the isotropic variant of the description. However, it is important for us to emphasize here that the choice of the isotropic description is made not on the basis of a unique interpretation of the experimental data, but on the basis of a definite convention—of an agreement. The arbitrariness that obtains pertains only to the choice of the form of the kinematic description of physical phenomena, with respect to which experimental facts emerge as unique "objective invariants"*. Therefore, the admissibility of different conventions in the present case characterizes only an ample opportunity for choosing the forms of description of the same experimental facts, and cannot serve as a basis for positivistic conclusions.

The choice of a definite convention on the simultaneity of events at different points in space leads not only to the appearance of the corresponding universal anisotropy in the description of the kinematics of physical processes, but also to a corresponding change in the spatial and temporal scales. For example, two lengths, which are differently oriented in space and which correspond to the same total time of propagation of some physical process in the forward and backward directions, are assumed to be equal only in the case of the isotropic version of the description. The same segments are expressed with different lengths in accordance with the adopted anisotropy function for the velocities of the physical processes. In other words, the congruence (identity-condition) problem for lengths differently oriented in space, which also allows a solution on the basis of an arbitrary choice, should, in the present case, be solved in accordance with the already chosen criterion for simultaneity. It can be shown that the relation between the spatial scales of the anisotropic and the isotropic descriptions is proportional to the function $\alpha^{-1}(\theta^*)$:

$$l^*(\theta^*)/l' = \gamma\alpha^{-1}(\theta^*),$$

where the quantity γ does not depend on the angle θ^*. In particular, in this case a circle transforms into an ellipse, while the sum of the angles of a triangle remains invariant.

This interrelationship between the anisotropy of the kinematic description and of the magnitudes of the spatial scales on the one hand, and the choice of a definite convention about the simultaneity of events at different points in space, on the other, is easily established from theoretical considerations without recourse to an analysis of any experiments. In practice, however, to realize the simultaneity corresponding to the anisotropic description we must in synchronizing the clocks proceed from the assumption that there is a corresponding dependence of the velocities of the process on the direction of propagation. In doing this not only the propagation of light, but any of the physical processes can be used to determine the time at each point in space (from the events corresponding to the moment a signal is sent and the moment it returns) and to establish simultaneity at different points of the reference frame.

It should be noted that the elucidation of all these questions requires the consideration of the physical processes in only one coordinate system, and, consequently, the existence of a definite arbitrariness in the choice of the description could be established long before the appearance of the theory of relativity from the analysis of the assumption of the absence in nature of instantaneous transmission of interaction between spatially separated objects.

And, in fact, this problem was formulated and solved in 1898 in Poincaré's paper "The Measurement of Time," before the theory of relativity was founded. This paper contains the correct conclusion that in view of the impossibility of an experimental confirmation of the equality of the velocities of light for different directions, the problem of the determination of the simultaneity of events should be solved on the basis of the adoption of a convention: "The simultaneity of two events or their sequential order, and the equality of two durations should be determined in such a way that the formulation of the natural laws would be as simple as possible. In other words, all these rules and all these definitions are just the result of an inexplicable convention" ([1], p. 13).

We presented in the present section only a more comprehensive justification of this thesis and we considered in detail the consequences of the choice of the convention, which led to an inconvenient description of phenomena in one coordinate system. However, as will subsequently become clear, this case turns out to be useful for the important comparison of the descriptions of physical processes in reference frames moving relative to each other, in unified space-time scales.

II. FURTHER REFINEMENT OF THE INTERPRETATION OF THE SPECIAL THEORY OF RELATIVITY

1. Formulation of the principle of relativity. It is possible to encounter in the literature several formulations of the relativity principle. In some formulations attention is drawn to the fact that it is impossible to detect by means of any physical experiments, conducted in one inertial frame of reference, motion with respect to another inertial frame. In other formulations of the relativity principle the equivalence of different inertial coordinate systems and the possibility of choosing the same description of physical phenomena are stressed*.

However, these precise formulations of the relativity principle are not so concrete as to make it clear whether we are dealing with a complete coincidence or with just a similitude of physical phenomena which pro-

*)The concept of "objective invariants" was introduced by Poincaré to designate the assertions of a physical theory which do not depend on the chosen scheme of description. As was noted in "The Philosophical Encyclopaedia"[29], a distinct materialistic tendency in the development of Poincaré's views was manifest in this.

*)Less definite versions of these two types of formulation of the relativity principle are also encountered. It is thus asserted, for example, that all physical phenomena take place in the same manner in inertial reference frames moving with respect to each other. We shall see below that this version of the formulation does not, strictly speaking, correspond to the true content of the relativity principle which has been established by relativistic theory.

ceed in different ways. To clarify the fundamental difference between these two possibilities of realizing in nature the relativity principle, let us consider two inertial coordinate systems in relative motion.

Let us choose in one of these coordinate systems the simultaneity corresponding to the convenient isotropic description of physical processes and let us call this coordinate system K the initial system. We use the simultaneity coinciding with the simultaneity of the initial system K in the coordinate system moving relative to the system K. Let us denote such a reference frame by the letter K*. The coordinates of the reference frames K and K* are naturally related by the Galilean transformations.

If the classical Galilean principle of relativity were valid for all the physical phenomena in nature. Hertz's hypothesis that the ether is totally dragged along by moving bodies and Ritz's ballistic hypothesis for optical phenomena would be valid. We should have observed in that case that all physical processes also receive an isotropic description in the system K* in terms of space-time scales which are chosen to coincide with the scales of the initial system K. Furthermore, there would have been for the corresponding physical processes a complete coincidence of the kinematic descriptions in the two systems*. It would have been natural to identify the identity in these systems of the physical laws, expressing the relations among the various characteristics of physical processes, with invariance with respect to the Galilean transformations. We would in that case have had every reason not to return to the abstract possibility, discussed in the preceding section, of choosing essentially inconvenient anisotropic versions of the description of the kinematics of physical processes.

However, the extension of the Galilean principle of relativity not only to mechanical, but also to all other physical phenomena would have implied, for example, the existence of a direct dependence of the velocity of light on the motion of its source. And for α particles emitted by nuclei which are at rest in the system K*, the velocity with respect to the initial reference frame would have been expressed directly by the vector sum of the velocity of the system K* and the velocity of the α particle with respect of the system K*. But the first-order experiments in which the independence of the velocity of light of the motion of the source is investigated, or in which the relativistic formula for the addition of velocities is verified, directly negate precisely such a possibility of realization of the generalized Galilean principle of relativity in nature. At the same time either of the above-enumerated formulations of the relativity principle is compatible with such a generalized Galilean principle of relativity.

)We have in mind here the comparison of the same physical processes under identical conditions in the corresponding reference frames. For example, if we consider in the system K the process of emission of α particles by nuclei which are at rest in this system, then we must consider in the system K the analogous process of α particle emission by the same nuclei, which are, however, at rest in the system K*. This applies to the process of light propagation, in which the source of the light should also be chosen so as to be at rest in the appropriate reference frames. The terms "corresponding quantities" and "corresponding states" were used by Lorentz[30].

The well-known difficulties of classical physics in the solution of the problem of combining the relativity principle with the postulate that the velocity of light is independent of the motion of the source, arose exactly because of the inadmissibility of a simple generalization of the Galilean principle of relativity to electromagnetic and optical phenomena. The solution to this problem was the establishment of the completely different form of realization of the relativity principle in nature, a form which is the basis of the new physical ideas about space and time. In order to clearly and directly elucidate the fundamental difference between the relativity principle that is realized in nature and the foregoing generalized Galilean principle of relativity, we must use the same coordinate systems K and K*, in which a single simultaneity and the same spatial and time scales are used. With that end in view, we must clarify the possibility of realization in the moving coordinate system K* the principle of relativity, which agrees with the fact that the velocity of light is independent of the motion of its source.

The view that it is impossible to combine the two basic principles of the theory of relativity and not give up using the Galilean transformations is widespread in the physical literature**. In particular, the difficulties of classical physics in the solution of this problem are usually explained by using a single simultaneity in two reference frames that are in a state of translational motion with respect to each other. We will subsequently understand that this view does not at all correspond to the facts and that its popularization in the literature was made possible only by the somewhat limited nature of the generally accepted treatment of the theory of relativity. The Galilean principle of relativity is indeed not realized in nature at high velocities of motion, and physical phenomena, including the mechanical ones, are not invariant with respect to the space-time Galilean transformations. However, it does not at all follow from this that it is impossible to use these transformations and the single simultaneity, that is the basis of these transformations, to describe physical phenomena in two inertial coordinate systems moving relative to each other. To the contrary, it is only by using the identical space-time scales in the different reference frames that one is able to determine the difference that exists in the course of physical processes and does not violate the principle of relativity. The assertion, however, that the properties of nature exclude the possibility of choosing the Galilean group for the description of physical phenomena turns out from the fundamental point of view to be equivalent to the absurd assertion that the properties of nature exclude feasibility of measuring length in inches but allows measurement in centimeters*. Notice also that no practical difficulties are encountered in the determination in the spatial and time scales of the reference frame K* of the units

*)See, for example, L. I. Mandel'shtam's lectures ([7], p. 164).

**)Criticizing the assertion that it is possible to choose for the description of experimental data only a certain geometry, Poincaré wrote with reference to the formulation of this question: "From my standpoint, it is entirely equivalent to the following question, the absurdity of which will be conspicuous to anybody: do lengths exist which can be expressed in meters and centimeters, but which cannot be measured in yards, feet and inches?" ([9b], p. 86).

of scale that coincide with the units of the initial system K.

Thus, in conformity with the chosen definition of simultaneity, all physical processes in the initial system K receive the convenient isotropic description. In particular, we obtain in the system K for the process of light propagation a velocity which is independent of direction. In order to establish on the basis of the same simultaneity the description of the velocities of different processes in the moving coordinate system K*, we must first consider in the system K* the light-propagation process, since the information needed for this follows from the independence of the velocity of light of the motion of its source. Indeed, light emitted by a source at rest in the system K* will propagate in the initial system K with a constant velocity c that is independent of direction. At the same time, in the reference frame K*, moving with velocity v relative to the initial system K, the velocity of propagation of the light should necessarily be described by the following function of the angle θ^*:

$$u_c^* (\theta^*) = (c^2 - v^2 \sin^2 \theta^*)^{1/2} - v \cos \theta^*, \qquad (2)$$

where θ^* is the angle measured in the system K* between the direction of propagation of the light and the x* axis, which is chosen to be in the direction opposite to the direction of the relative motion of the system K.

In particular, the velocity of light is equal to c-v along the x* axis and to c + v in the opposite direction. It would appear that this noninvariance of the process of light propagation with respect to the Galilean transformations should manifest itself directly in experiments as a violation of the relativity principle. However, this conclusion will be incorrect if the noninvariance is of a universal character, such that in the description of the velocities of all other processes, performed in the reference frame K*, there arises an anisotropy analogous to the relation (2) and satisfying the similitude requirement for kinematic characteristics. And this will mean that a new version of the relativity principle is realized in nature, which we cannot, of course, distinguish from the classical Galilean principle of relativity by means of any experiments in the moving system K*. Only when the phenomena produced in the reference frame K* are considered relative to the other inertial system will a violation of the classical principle of relativity manifest itself.

Thus, the relativity principle can be compatible with the independence of the velocity of light of the motion of the course only in the case when all other physical processes occur in such a way that a dependence on direction, which satisfies the conditions of indistinguishability from the isotropic version of the description, is detected in the description of their velocities in the system K*. By using the relations obtained in the Appendix A, we can, on the basis of the function (2), which describes the dependence of the velocity of light on the angle θ^* in the system K*, determined for the velocity of an arbitrary physical process the angular dependence satisfying the similitude condition. For this purpose we substitute into the relations (A.1) and and (A.2) of the Appendix the function $f_c(\theta^*)$, which for light is known and which is, according to (2), equal to

$$f_c (\theta^*) = u_c (\theta^*)/c = [1 - (v^2/c^2) \sin^2 \theta^*]^{1/2} - (v/c) \cos \theta^*.$$

We obtain as a result

$$\alpha (\theta^*) = [1 - (v^2/c^2) \sin^2 \theta^*]^{1/2}/[1 - (v^2/c^2)],$$
$$\beta (\theta^*) = (v/c^2) \cos \theta^*/[1 - (v^2/c^2)].$$

Consequently, the angular-asymmetry function for the velocity of an arbitrary physical process in the system K* will, according to the relation (1), be of the form

$$f_u (\theta^*) = [1 - (v^2/c^2)]/\{[1 - (v^2/c^2) \sin^2 \theta^*]^{1/2} + (uv/c^2) \cos \theta^*\},$$

while the magnitude of the absolute velocity $u^*(\theta^*)$ of an arbitrary physical process for the direction inclined at an angle θ^* to the x* axis in the system K* will be expressed in terms of the magnitude of the velocity u of the corresponding physical process in the initial system K by the following relation:

$$u^* (\theta^*) = u [1 - (v^2/c^2)]/\{[1 - (v^2/c^2) \sin^2 \theta^*]^{1/2} + (uv/c^2) \cos \theta^*\}, \qquad (3)$$

where $v < c$ and $u < c$.

In particular, we obtain for the magnitude of the velocities of propagation of an arbitrary process in the direction of the x axis and in the opposite direction

$$u^* (0) = u [1 - (v^2/c^2)]/[1 + (uv/c^2)],$$
$$u^* (\pi) = u [1 - (v^2/c^2)]/[1 - (uv/c^2)]. \qquad (4)$$

respectively. From these relations for light (u = c), we obtain in accordance with (2), the velocities c − v and c + v.

We must especially draw attention to the fact that in contrast to the kinematic-similitude conditions, considered in the preceding chapter and pertaining to the different possible descriptions of the same physical processes in the same coordinate system, we are dealing here with the kinematic similitude of the isotropic description of physical processes in the initial reference frame K to the anisotropic description of the corresponding physical processes, reproduced under the same conditions in the moving system K*. The fundamental difference is the fact that the proof of the possibility of transforming the isotropic description into the anisotropic in the same coordinate system did not require any experimental facts or theoretical assumptions besides the negation of the possibility of instantaneous transmission of interactions, and the transition from one description to the other can be accomplished only by adopting appropriate convention. The proof, however, of the possibility of obtaining analogous kinematically similar relations for the corresponding physical processes, reproduced in the other inertial reference frame, is based on new facts about the fulfilment of the relativity principle for all physical phenomena and the existence in nature of a process whose velocity of propagation does not depend upon the motion of the source. These basic postulates of the theory of relativity directly embrace the general data on the properties of the real world, which we used to establish the fact that physical processes proceed differently in inertial coordinate systems moving relative to each other, but preserve the kinematic similitude in the relations among the characteristics of the various physical processes. Only the specific expression of this fact is conventional: an isotropic description of the velocities of processes in the initial coordinate system K and an anisotropic description in the system K^*.

Actually, the appearance of the anisotropic description of the velocities of physical processes in the moving system K^* was not the result of the adopted special convention, directly concerning this reference frame. We merely chose the natural convention on simultaneity which corresponds to the isotropic description of the velocities of processes in the initial system K, and then adopted this simultaneity and the corresponding spatial and time scales for the description of the processes in all other inertial reference frames moving relative to the initial system with a velocity less than the velocity of light. This may, of course, be objected to by pointing out that this last condition about the use in different inertial coordinate systems of a single simultaneity and the same scales is the special convention which predetermined the appearance of the anisotropic description of velocities in the coordinate system K^*. This assertion is, of course, true. But the condition in question was not at all adopted specifically for the derivation of the anisotropic description of the velocities of processes in the system K^*, but as a necessary condition for the identity of the difference in the corresponding physical processes, reproduced in different inertial coordinate system, to be uncovered. Readers familiar with only prerelativistic mechanics know firmly that the agreement of the numerical values of the velocities implies their equality only in the case if the same units are chosen for the measurement of the spatial and time intervals, or when the spatial and time units differ by the same factor. For those people, however, who have formally assimilated the orthodox treatment of relativistic kinematics, we need to prove that the equality of light in different inertial system has a completely different meaning, not pertaining to the comparison of these quantities, since the proper space-time scales used in the measurement of these quantities do not coincide with each other.

The use of the same spatial and time scales is thus a necessary condition for directly uncovering a difference in the kinematics of corresponding processes reproduced under identical conditions in different inertial reference frames. This difference in the kinematics is universal in character and does not violate the principle of relativity and the equivalence of inertial reference frames in a state of relative motion. We can, in fact, choose in a moving reference frame the simultaneity corresponding to the convenient isotropic description of the velocities of processes in this coordinate system (we shall designate such a reference frame by the letter K'). But the choice of this convention does not at all eliminate the uncovered difference in the kinematics of processes. The use of the proper spatial and time scales of the reference frame K' for the description of physical processes, relative to the system which was originally taken as the initial system, will lead to the appearance in the description of their velocities of an anisotropy which is opposite to that obtaining in the system K^*. In other words, the dependence of the velocities of processes on the direction of processes on the direction of propagation in the former initial coordinate system is described by the same relations (3) after changing the sign of the velocity v in it.

It is precisely the transition to the consideration of physical processes in both reference frames in the so-called proper space-time scales of the moving system K' which demonstrates that the previously uncovered difference in the kinematics of processes cannot be explained by the absolute motion of the system K^* (K') relative to some preferred coordinate system. The complete equivalence of inertial coordinate systems implies that their relative motion is the cause of the difference in the kinematics of processes in these systems. The initially adopted division of the reference frames into initial (fixed) and moving systems is therefore arbitrary. We can choose in any of the inertial coordinate systems the natural and convenient isotropic description for the kinematics of the processes occurring in the system, i.e., in this sense any inertial coordinate system can in our treatment occupy the place of an initial system. The difference in the kinematics of processes, which exists objectively, then manifests itself in the appearance of the corresponding anisotropy in the description of the analogous physical processes, reproduced in another reference frame under, of course, the necessary condition that the same spacetime units of measurement be used in both reference frames.

The arbitrary choice of the initial coordinate system with isotropic description of the kinematics of processes governs only the specific form of the expression of the uncovered difference in the kinematics of processes in different inertial reference frames. The essence of this difference, however, remains unchanged. Thus, for example, it was established in the initial analysis that the velocity of light c in the direction of the x axis in the system K exceeds by an amount v the velocity of light $c - v$ in the same direction relative to the system K^*. On going over to the proper units of measurement of the system $K'(K^*)$, we found that the velocity of light in the first system turns out to be equal to $c + v$ in the same direction and, consequently, exceeds as before the velocity of light c in the same direction relative to the second system by an amount v. Thus, the fact that the velocity of light in the x direction in the first system is higher by an amount v in comparison with the velocity of light in the same direction in the second reference frame, does not, in fact, depend on the arbitrary choice of the initial coordinate system with the isotropic description of the kinematics of processes. However, this higher velocity of light in the first system does not at all make it a preferred system in comparison with the second coordinate system. The point is that in the opposite direction the velocity of light $c + v$ (or c) in the second reference frame turns out to be always higher by the amount v than the velocity of light c (or $c - v$) in the same direction relative to the first reference frame. An analogous situation for opposite directions in the reference frames under consideration obtains for the velocities of propagation of any other physical processes. All processes proceed in the direction of relative motion of coordinate systems slower in one system than in the other; but the inverse situation obtains for the opposite direction.

Thus, the difference in the kinematics of processes reproduced in inertial reference frames moving relative to each other is not the result of some conventions about the choice of the specific forms of description of physical processes. It constitutes the substance of the principal objective invariant of relativistic theory—the essence of the manifestation of the relative motion of the systems in the kinematic properties of the physical phenomena themselves. This difference, which actually exists in the kinematics of processes, satisfies that version of the similitude of the kinematic relations for which the equivalence of reference frames is not destroyed and for which it becomes impossible to distinguish by some absolute kinematic effects one of the systems in the comparison of the corresponding physical processes, reproduced in different reference frames. The substance of the relativity principle of relativistic theory consists precisely in making allowance for this difference in the kinematics of processes. In the same way as the concepts of similarity and identity are distinguished in the area of geometrical relations, we must for the kinematic relations also distinguish between these concepts, which respectively determine the substance of the Poincaré-Lorentz-Einstein relativity principle and the classical Galilean principle.

Attention was drawn in Lorentz's 1904 paper to this distinctive feature of the fulfilment of the relativity principle for electromagnetic processes. The use of the same space-time scales for the description of electromagnetic phenomena in both the initial system of the ether and the system K^*, moving relative to the former system, made it possible to uncover the difference between processes in these systems which was through only a misunderstanding ascribed by Lorentz to the influence of the absolute motion of the system relative to the ether. Lorentz further showed that in spite of the difference in the description of processes, no experiments conducted in the moving system will be able to detect its motion relative to the ether. But Lorentz did not analyze the kinematic aspect of this problem*. Unfortunately, no attention whatsoever was drawn in the subsequent development of the treatment of relativistic theory to the fact that the principle of relativity is fulfilled on the basis of similarity and not of identity of the kinematic relations. Only this circumstance can, in our opinion, explain why Poincaré's correct appraisal ([31], p. 52) of Lorentz's 1904 paper was never supported by other scientists. According to the generally accepted view, Lorentz is recognized as only the precursor of Einstein's, and not as one of the founders of the theory of relativity. The conclusion is even drawn in the paper by S. Goldberg that "the Lorentz theory can neither be considered as the predecessor nor the forerunner of the Einstein theory"[32]. We shall not pause to criticize such an extremely absurd viewpoint, since it is refuted by the same factual material cited in the paper by the author. On the whole, however, the underestimation of Lorentz's work arises because it has not been understood that Lorentz's quasiclassical approach is not only admissible, it also offers a mode of description of the theory which reveals in the best way the kinematic nonidentity of physical processes in different inertial reference frames*.

*) He drew attention only to the geometrical similarity of the transformation of spatial lengths in the moving system, not noticing the fundamental significance of the results he had actually obtained for the transformation of durations of material processes.

We dwelt at length on the discussion of this question, since the clarification of it is necessary for the subsequent development of the treatment of the theory on the basis of the solution of the problem of the separation of the essence of the content of relativistic theory from a number of theses pertaining only to the mode of representation of the theory. The establishment of the objective invariants with respect to the arbitrariness in the choice of the theoretical modes of description of physical phenomena which does exist, proves, moreover, the groundlessness of the positivistic attempts to interpret the natural-science conventions of the traditional presentation of relativistic theory in the spirit of philosophical conventionalism.

It may appear from the analysis presented in this chapter that we have inadmissibly excluded processes not connected with any translation in space. It must be noted in this connection that, strictly speaking, no physical processes exist in nature which are not connected with an translations—no matter how small—in space. Processes, which are conventionally described as processes taking place at a point (chemical reactions, radioactive decay, etc.), are, in fact, connected with translations of objects inside the physical systems under consideration. Therefore, the requirement of kinematic similitude for such processes implies that the relative change in their velocity should strictly agree with the general—for all processes—relative change in the total time of propagation over a certain distance and back in the given coordinate system.

In reality, however, the incompleteness of our formulation of the kinematic similitude of processes lies only in the fact that we have for simplicity restricted ourselves to the consideration of only processes with velocities constant in time. The fulfilment, however, of the principle of relativity implies, of course, the preservation of the kinematic similtude for any physical processes, including accelerated motion. Moreover, a dynamical process in one form or another precedes the appearance of motions of material objects with constant (in time) velocities which we have considered. Therefore, from the physical point of view, it

*) Incidentally, all authors, without exception, resort to the partial description of relativistic effects on the basis of the convention corresponding to the Galilean transformations. For example, the usual demonstration of the contraction of a moving reference rod consists in the expression of its length in the scale units of the other coordinate system. In §38 of L. D. Landau and E. M. Lifshitz's book, "The Classical Theory of Fields," to demonstrate the "squashing" of the field of a uniformly moving charged particle, the rest frame of the particle is directly introduced with the scale units of the initial system. Such a treatment requires, of course, a consistent execution of a convention on a single simultaneity. We cannot speak of a contraction of the arm of an interferometer during its rotation without assuming the velocity of light to be dependent on direction. Attention is also drawn in the present paper to the importance of a similar investigation of a kinematically arbitrary physical process.

would have been undoubtedly more logical to have begun the construction of the theory with the formulation of relativistic dynamics in the framework of the classical concepts about time and space and the establishment on the basis of it of the kinematic similitude in the description of physical processes in a moving system.

The first part of this problem was completely solved by Lorentz as long ago as in 1904. It remained only to consider to what kinematics in the moving coordinate system the dynamical law he assumed led, then to discover in this kinematics the complete similarity to the kinematics of the processes of the initial system and to uncover on this basis the true substance of the totally new nonclassical principle of relativity. And had Lorentz taken that step, he would have certainly discovered the inadmissibility of his thesis that the derived relativistic effects were explained by the absolute motion of the bodies relative to the ether.

The fundamental significance of the treatment of the theory given by A. Einstein lies in the negation of any role of the ether in the appearance of relativistic effects and in the establishment of the relative character of these effects. According to Lorentz, however, the rigorous fulfilment of the principle of relativity in a moving coordinate system is the result of the action of the ether on moving material objects. A detailed computation of this influence opened up a new horizon for the dynamical description of the causes of the appearance of relativistic effects. The artificiality of this explanation is, it would appear, unequivocally revealed by an analogous analysis in which the system K' is taken as the initial system. Nevertheless, for some scientists this argument was not sufficient enough for them to be convinced of the nonreality of the obvious explanation of relativistic effects on the basis of the properties of the ether. The attempts to further "develop" precisely these weak aspects of Lorentz's work have been repeated many times. And some saw in Lorentz's dynamical approach itself a possibility for developing the materialistic justification of the relativistic effects without the ether drag (see, for example,[33,34]). But the trouble is that the advocates of such an approach do not explain the basic property of the relativistic effects—their relativity.

L. Janoszy has analyzed in detail the dynamical description in some initial coordinate system of the changes in a material system accelerated to a velocity $v \sim c$. Of course, such an analysis is also quite possible in the framework of relativistic theory. But Janoszy bases his analysis of the field of an electric charge on principles which he relates only to the properties of the electromagnetic field, and not to the general properties of matter which determine the space-time metric. Therefore, the author comes to the conclusion that the Lorentz deformations arise as a result of the acceleration of the system and depend on the structure of the electron ([34], p. 157). In such a formulation of the problem the question about other fields, in particular, about the fields that are responsible for the strong interactions of particles, remains open. Such a treatment of the Lorentz deformations not only advances an erroneous explanation of the relativistic effects, it also deprives the theory of relativity of its principal advantage—the generality of its assertions and the possibility of its predictions to go beyond the concrete experimental material obtained before the theory was founded.

L. Janoszy thinks that the absence of an "experimentum crucis" that distinguishes his dynamical construction from the theory of relativity is sufficient enough for one to prefer for philosophical reasons precisely his construction, which repudiates the theory of relativity as the theory of space and time. However, there exist experiments in the field of nuclear and weak interactions, for which L. Janoszy's theory does not predict any concrete results, whereas the theory of relativity gives for them predictions which are in excellent agreement with experiment. Thus, the growth of the mass of protons with velocity, the separation of protons after undergoing nuclear scattering at an angle less than $\pi/2$, and the lifetime of fast particles disintegrating as a result of weak-interaction processes, all show the correctness of the generalization obtained in the theory of relativity from the total negation of absolute motion.

L. Janoszy takes a step backward even from Lorentz's work, which, the erroneousness of the interpretation notwithstanding, contains a generalization of the results obtained for electrodynamics. Only by accepting this generalization can one prove the complete identity of the predictions of the Lorentz theory with the predictions of the theory of relativity. Moreover, as will be shown later, proof of the legitimacy of the use in the moving reference frame K^* of the coordinates (x^*, y^*, z^*, and t^*) that are connected with the coordinates of the initial system by the Galilean transformations does not at all imply a return to the old concepts about space and time. The new properties of the relativistic metric are in this case clearly expressed in the kinematic relations of the velocities of propagation of different processes.

As regards the exposure in Janoszy's work of the role of acceleration in the development of the Lorentz deformations, a rigorous solution shows that the appearance of these deformations in a moving system makes it possible to choose the proper metric of K' (x', y', z', and t') relative to which lengths in the initial system K will be contracted. And, consequently, the contraction of lengths in a system not undergoing acceleration needs to be explained. The point is that, what we have to take into account in computing dynamical effects is only the velocity of the relative motion of the material objects.

The relation (3), which describes the angular dependence of the velocities of physical processes, can be obtained directly from Lorentz's general—for all objects—law of variation of mass with the velocity of motion of the object relative to the initial system and his postulate about the contraction of spatial lengths. In the present paper we restrict ourselves to only a qualitative analysis of the equation of motion $dm\mathbf{W}/dt = \mathbf{F}$, in which we adopt the general—for all objects—law of variation of the inertial mass $m = m_0[1 - (w^2/c^2)]^{-1/2}$ with the speed w relative to the initial coordinate system K.

Let us, for example, consider in the system K the process of acceleration of an electron in an accelerator tube which is at rest in the system K^*. When the electron is accelerated along the x axis, a further increase in the velocity and, consequently, in the mass of the electron, occurs relative to the system K. When it is accelerated in the opposite direction, however, the velocity of the electron relative to the system K decreases, its mass decreases accordingly, and its acceleration subsequently increases. The simplest computations of the acceleration process lead to a difference in the velocities of the electron relative to the system K* for the angles 0 and π, corresponding to the relation (4).

2. The Lorentz transformations. If we follow Poincaré's recomendation ([1], p. 13) that we should choose the definition of simultaneity that corresponds to the simplest formulation of physical laws, we can derive the convenient isotropic description of kinematics only in one of the inertial reference frames. In virtue of the properties of the physical phenomena themselves, we cannot on adoption of any convention obtain the convenient isotropic descriptions of the kinematics of processes in different inertial coordinate systems in the common space-time scales. The fact that there arises, in all other inertial coordinate systems moving relative to the initial system, an anisotropic description of the velocities of the corresponding physical processes, is a surprise of nature which constitutes the principal substance of the relativistic theory of space and time. To elucidate the important points of the treatment of the theory, we have resorted to the expression of this substance in the language of the space-time relations of classical mechanics, having proved beforehand the admissibility of the corresponding convention. We shall show in the present section that the simplest description of phenomena in each reference frame is the convenient one; in other words, it is possible to use simultaneously many appropriate conventions on the simultaneity of events, *owing to the transition to the new* space-time relations of relativistic theory.

Thus, the existence of a quantitative difference in the course of physical processes in these systems is an absolute fact which cannot be eliminated by choosing any space-time bases that use a single simultaneity for all reference frames. On the other hand, in each inertial reference frame there exists among the set of possible definitions of the simultaneity of events only one definition which is preferred in the sense that it guarantees a convenient isotropic description of physical processes only in the coordinate system in question*. A proper simultaneity can be established in each coordinate system by synchronizing the clocks with the aid of any physical process under the assumption that its velocity is independent of direction, as well as by means of an infinitesimally slow transport, to different points in space, of clocks which have been synchronized beforehand at one point**.

*)We shall henceforth call such a simultaneity the proper simultaneity of the reference frame in question.

**)At the same time, any other (different from the proper) simultaneity is established by means of the same clock-synchronization procedure with an arbitrary physical process under the assumption that the magnitude of its velocity depends on direction in accordance with the relation (3). An elementary calculation allows us to compute also the correction introduced by the desynchronization of the clocks during the arbitrarily slow transfer of them to different points in space, which corresponds to the chosen anisotropy in the velocities of physical processes.

Two world events which satisfy the proper-simultaneity condition in one coordinate system turn out, of course, to be nonsimultaneous according to the criteria for proper simultaneity in other inertial coordinate systems. It would appear that the concurrent use of the convenient—in each coordinate system—proper space-time bases violates the basic agreement about the use of a single simultaneity which guarantees the necessary uniqueness of the description of physical phenomena. However, the uniqueness of the description will be rigorously maintained in a concurrent use of different proper space-time bases of different reference frames, provided each time we go over from the *description of some process in one coordinate system* to the description of the same physical process relative to another coordinate system, we take into account the difference in the proper space-time bases being used. And this implies, following the convention on the use of the convenient proper space-time bases of the reference frames, the necessity to take instead of the Galilean transformations the space-time Lorentz transformations, in which the objectively existing difference in the course of corresponding processes in these coordinate systems, is taken into account. The use of the proper space-time bases constitutes the principal convention, adopted in the traditional representation of the special theory of relativity, which possesses, besides simplicity, the important advantage of completeness in the expression of the new properties of the space-time metric. At the cost of using different noncoincident space-time bases (of using different simultaneities and the corresponding space-time scales), we are able to obtain in each inertial coordinate system the simplest isotropic description of the kinematics of processes.

The main advantage of this traditional form of *presentation lies in the use of space-time scales*, which, although they do not coincide with one another, are physically equivalent*. If we disregard the fact that physical phenomena proceed differently in reference frames moving relative to each other, then we can establish in each such system equivalent units of measurement of space and time, which can be directly determined by means of physical standards. For example, as a unit of measurement of length in each coordinate system, we can take the lattice constant of a sodium chloride crystal that is at rest in the coordinate system in question, or the wavelength of a definite spectral line of cadmium atoms that are also at rest in the coordinate system in question. Similarly, we can choose in each coordinate system the appropriate natural standards of duration. The convenient units of measurement thus established, will be the expedient space-time scales used in the traditional presentation of the special theory of relativity. Such standards are usually called identical standards. In reality, however, we should in a more accurate definition speak of their physical equivalence, since their being different or identical is predetermined by the convention adopted. Such physically equivalent scales guarantee in each inertial coordinate system a description of processes in one and the same physical language, and this leads to the identity of the descriptions of analogous (corre-

*)As was noted by M. Born, this feature raises the theory of relativity "above the level of a simple conventionality" ([35], p. 305).

sponding) physical processes in different reference frames. And only when we want to convert quantities measured in one reference frame to another system, do we need to remember that the units of measurement used—the centimeters and seconds—do not at all coincide in magnitude with the units of the same names in the other reference frame. The distinctive feature of this difference in the proper space-time scales of the systems is that it does not, naturally, violate the basic thesis about the physical equivalence of inertial systems, moving relative to each other. The difference between, or the non-identity of the proper times of two systems, $t \neq t'$, cannot be expressed by a simple inequality of the type $t > t'$ or $t < t'$, which actually destroys the equivalence of the systems. In other words, we cannot assert that processes proceed more rapidly in some inertial system than the corresponding processes in another system. As we have seen, the difference in the course of processes in systems in relative motion is that in one of the systems processes in the direction of relative motion proceed more slowly than the corresponding processes in the other system, whereas for the opposite direction the inverse relation between the velocities of propagation of processes obtains. This difference, already by its very nature, cannot destroy the equivalence of the systems. Consequently, the relations between the proper space-time scales of the systems should express the same difference between the velocities of propagation of processes in corresponding directions relative to different reference frames. But it is impossible to express this property unless the concept of proper time at each point of the coordinate system, t_x and $t_{x'}$, is introduced. The necessity for the introduction of an intuitive image of synchronized clocks placed at different points of each reference frame arose from this. All the clocks of one reference frame are characterized by a definite rate at which they go, and by a definite relation between the initial readings of the clocks at the different points of the system. But it is impossible to compare directly the proper time t_x at a specific point of one system with the proper time $t'_{x'}$ at a definite point of the other system. It is clear that the very possibility of such a comparison would contradict the equivalence of the reference frames, since for $t_x \neq t'_{x'}$ we would have no choice but to accept one of the inequalities $t_x > t'_{x'}$, or $t_x < t'_{x'}$, which destroy the equivalence of the systems. But, in spite of this, it is quite rare to find a textbook on the theory of relativity in which the author refrained from the following simplified formulation of the relativistic slowing down of time, which contradicts the entire spirit of the theory of relativity: moving clocks are slower than stationary ones. The destruction of the equivalence of reference frames, allowed in this imprecise formulation, cannot be eliminated by citing the arbitrariness in the choice by the observer of the stationary and moving systems.

Laying aside the erroneous idealistic conclusions about the subjective concepts of time which arise on this basis, we would like to draw attention to the inadmissibility in such an exact science as physics of such simplified formulations, which distort the physical essence of established laws. Indeed, we deal in the special theory of relativity with the comparison of an interval of time which has passed at one point of some reference frame with the difference between the times at different points of another reference frame. In other words, at least three clocks, two of which are synchronized according to the proper simultaneity of some reference frame, always participate in the comparison. The result obtained in such a comparison is unique, does not depend upon the viewpoints of the observers, and is in complete accord with the equivalence of inertial reference frames. Taken alone, a clock at a definite point of some reference frame is always slower than the concurrent readings of a pair of synchronized clocks of another system. The result of such a comparison may then be uniquely fixed by observers in the most different inertial systems, Of course, the result obtained in the comparison of the clocks directly depends on the convention on the simultaneity of events, inasmuch as we choose, in accordance with this convention, simultaneous readings of the clocks, one of which is used to measure the beginning, and the other the end of the time interval under comparison. But if a specific convention has already been adopted, for example, if the proper simultaneity corresponding to the isotropic description of processes in each coordinate system has been chosen, then the comparison of the clocks being discussed yields a definite result which is an experimental fact, not depending on the observer*. It is only necessary that this result not be taken as an experimental confirmation of the adopted convention.

The clocks indicating the proper time in different reference frames, differ in their readings by the spacing of the initial readings adopted in each system and in the rate at which they go. The last difference does not have an absolute value that does not depend on the choice of one or another simultaneity for the description of the very comparison of the clocks of two reference frames. The comparison of the clocks of the system K with the clocks of another system K′ can be represented, together with its unique result cited above, in the most diverse manner. We can describe this comparison on the basis of the proper simultaneity of the system K, when the rate of its clocks will be taken as being faster. Then, at some initial moment according to the simultaneity of the system K, all the clocks of this system indicate one and the same time t_1 while the clocks of the system K′ show diverse readings, depending on where they are located, $t'_1(x) = t'_1(0) - (v/c^2)x'$. At a subsequent moment of the comparison the readings of the clocks of the system K increase by the same amount Δt and the readings of the clocks of the system K′, by the amount $\Delta t' = \Delta t[1 - (v^2/c^2)]^{1/2}$, with a simultaneous translation of them with respect to the clocks of the system K. Then not only are the individual clocks of the system K′ found to be slower with respect to a pair of the clocks of the system K, but each individual clock of the system K on comparison at the second instant with the other clocks of the system K′, which were set with a "lead," is found to be slow. We can depict the same comparison

*This assertion about the experimentally verifiable predictions, made in the framework of a definite convention, fully agrees with Poincaré's viewpoint, which is expounded in L. Rougier's book: "The Philosophy of the Poincaré Geometry"[36] (see also A. Grünbaum's book[18], p. 158).

together with its unique result on the basis of the proper simultaneity of the system K', when the clocks of this system will be taken as being the faster clocks.

Thus, only the relative difference between the proper simultaneities of the reference systems under consideration and the result of the comparison of the clocks remain unchanged, and this expresses in the framework of the concrete convention an actually existing difference between the velocities of propagation of the corresponding processes in inertial systems moving relative to each other.

A similar situation, satisfying the equivalence of reference frames, obtains for the relationship between the proper spatial scales of different systems. This relationship also cannot be formulated rigorously without making allowance for the relation between the spatial coordinates and the time coordinate. The concept of length of a moving-in some system-spatial section, expressed in the proper spatial scale of this system, is in its very essence connected with the proper simultaneity of the system. The standard of length for an intercept along the x' axis of the system K' when its end points are simultaneously fixed in the reference frame K (corresponding to a conventionally chosen paper simultaneity for this system) turns out to be shorter than the equivalent standard of length in the system K. As in the case of the comparison of the readings of clocks, this concrete result of measurement will be authenticated by any observer, irrespective of the inertial frame of reference to which he belongs. However, as is well known, we cannot draw the conclusion that the contraction of the standard length of the system K is absolute, since entirely the same contraction is observed when the positions of the end points of the reference length of the system K are simultaneously fixed in the system K', provided the arbitrarily chosen proper simultaneity of the system K' is used. This concrete result of measurements can also be recorded by any observer. This means that the question is not one of observers or their viewpoints, but one of relative motion of coordinate systems and the adoption of different conventions on the definition of the simultaneity of events in each coordinate system. It is evident in this case that the identity, in the lekguistic sense, of the adopted definitions of simultaneity in each reference frame only implies the establishment of physically equivalent simultaneities, and not of identically coincident simultaneities.

Let us now consider to what extent the result of the comparison of physically equivalent standards of length depends on a change in the adopted convention on the simultaneity of events and the corresponding scales. Nothing prevents us from choosing, for example, in the system K^* (K') a simultaneity which coincides with the proper simultaneity of the system K, and establishing a scale of length along the x^* axis, which coincides with the scale of the system K. In this case when the positions of the end points of an intercept of unit length, which is at rest in the system K^*, are simultaneously recorded in the system K, the value obtained will coincide with the unit of length. But has the previous contraction of the physically equivalent standard length then disappeared? For the chosen scale units in this case no contraction should by definition occur. However, if we consider in the system K^* the standard value of the length of a segment made by nature itself, for example, the value of the lattice constant of a specific crystal that is at rest in this system K^*, then we discover that in terms of the chosen scale units, it is smaller than the analogous physical quantity, expressed in terms of the same scale units, when the crystal is at rest in the system K.

Thus, with respect to the comparison of the lengths of physical standards in these reference frames, nothing essentially changes when we change to a new convention with respect to simultaneity. However, this decrease in the length of the physical standard along the x^* axis will now be observed when it is compared in the same system K^* with the same standard length in other directions. This is Lorentz's formulation of the problem of the contraction of the lengths of solid bodies, which in no way differs from the traditional formulation of the problem. This is only another, but just as legitimate, form of representation of the same relativistic effects*. Of course, we are immediately led by this form of representation to the erroneous explanation of the contraction of the standard lengths in terms of the absolute motion of the system K^*. But the untenability of such an explanation becomes clear after examining the other convention which stipulates the use of the proper simultaneity of the system K' in both reference frames. In this case we discover the analogous situation in which the standard length for the direction along the x axis of the other coordinate system undergoes contraction.

It is absurd to pose the question of a unique determination of some real relationship between the equivalent steps of the length of different reference frames; a comparison of their lengths is always based on the utilization of a conventional agreement on simultaneity.

It is just as important to convince oneself of the impossibility of a direct comparison of natural standards of duration for different inertial systems, irrespective of the adopted convention on simultaneity. As has already been noted, a direct comparison of time standards at definite points of two inertial reference frames is impossible. The above-considered comparison of the readings of the individual clocks of one system with the readings of a pair of the clocks of another system includes the synchronization of their initial readings in accordance with a conventionally chosen proper simultaneity of the given reference frame. However, in the framework of the special theory of relativity, there is one more method of comparison of durations, in which not less than three clocks also participate, although these clocks then pertain to different inertial systems. We have in mind the so-called "paradox" of the clocks, when after a direct comparison of the readings of two clocks at the same point, they fly apart with a constant relative velocity, and then after the lapse of some time,

*)We note in this connection a totally erroneous interpretation of the Kennedy-Thorndike experiment, which was performed in 1932 with a Michelson-type interferometer, but with arms of different length. Despite the opinion of A. Grünbaum ([18], p. 487) for complete identity of the Lorentz approach to the theory of relativity, no additional hypothesis about the slowing down of time is required, since this slowing down follows automatically from the present agreement to use a single simultaneity.

the state of one of them changes in such a way that the relative velocity of their motion changes sign and the second comparison of their readings is performed when they meet. The question of the legitimacy of the analysis of this problem in the framework of the special theory of relativity was at one time a thoroughly intricate question and it was only at the end of the fifties that this simple question was finally clarified[37]. To begin with it was explained that from the point of view of the special theory of relativity there was no basis to consider the result obtained in the problem in question as paradoxical, since the transition of one clock to another inertial state of motion implies the participation in the comparison being considered of three clocks, which are at rest in different inertial coordinate systems*.

No clock that is at rest in one system and whose initial readings are determined in accordance with some convention on the simultaneity of events participates in this comparison. The result obtained in such a comparison of physically equivalent standards of duration does not include additional agreements, besides the agreement to choose physically equivalent proper units of measurement in each coordinate system. Let us adopt as the unit of proper time in each reference frame the half-life of a specific radioactive substance. At the initial moment of the encounter of the chosen clocks K and K′ (event 1) the decay rate of each radioactive source is measured. At the next moment to be considered in this problem, the radioactive source K′, moving away from K with a velocity v, encounters a third source K″ (event 2), moving in the opposite direction with the same absolute velocity relative to the first source K. The decay rates of the sources K′ and K″ are measured at the time of the event 2. Let us assume for simplicity that this measurement showed the decay rate of the source K′ to have decreased to exactly one-half the initial decay rate. Consequently, the interval of time $\Delta t'_{12}$ between the events under consideration is equal to one unit of the measurement scale we have adopted for the proper time.

Let us now consider the final moment when the radioactive source K″ encounters K (event 3). The decay rate of K″ at this moment will be found to be exactly one-half the rate at the time of the event 2. Consequently, the time interval $\Delta t'_{12} + \Delta t''_{13}$ between the events 1 and 3, defined as the sum of the readings of the physically equivalent radioactive clocks K′ and K″, is equal to two units of the proper time.

The equivalent radioactive source K should, according to the theory of relativity, decrease its decay rate more than four times by the time the event 3 happens. If, for example, the velocity is $v = \sqrt{0.75c}$, then the source K will have by this time decreased its rate by a factor of 16, and, consequently, the interval of time Δt_{13} will, according to the clock K, be equal to four units of the proper time.

*)The apparent paradoxicalness of the result obtained emerges only when the problem is formulated in the framework of the general theory of relativity[37]. It is shown in Ch. Møller's book[38] that a consistent application to this problem of the formalism of the general theory of relativity allows us to obtain the same result, which follows trivially from the premises of the special theory of relativity.

What conclusion can be draw from this result of the comparison of the three physically equivalent standards of proper time? Diverse aspects of this problem have been repeatedly discussed in the scientific literature. G. Whitraw quite correctly notes that the vast literature which deals with this "paradox" is exceeded in volume only by the literature devoted to Zeno's paradoxes ([27]). However, attention was recently drawn in an article by N. S. Lebedeva and V. M. Morozov[39] to a previously undiscussed question, the elucidation of which has a direct bearing on the refinement of the formulation of the theory of relativity expounded in the present paper. These authors came to the conclusion that at least one of the standard clocks K′ or K″ is slower than the clock K. From this follows, in their opinion, that the basic thesis of the theory of relativity that identical clocks in different inertial states of motion are completely identical, does not agree with the result given by the same theory that the comparison of the clocks is absolute, and consequently "the logical structure of this theory is defective" ([39], p. 84). Finally, the authors arrive at the conclusion that there exists an absolute "hierarchy of inertial states with respect to velocity of translation in space" ([39], p. 87).

Actually, the foregoing comparison of the readings of the three clocks can be considered as absolute in the sense that it is independent of the convention on simultaneity of events in the corresponding inertial coordinate systems. On the other hand, the conclusion concerning the comparison of the clock K with only one clock, K′ or K″, utilizes a definite assumption about the simultaneity of events in the system K, in which the clock K is at rest. Thus, assuming that the interval Δt_{12} is equal to Δt_{23}, in other words, assuming that to the event 2 corresponds a four-fold decrease in the decay rate of the source K, we find that the clocks K′ and K″ are a factor of two slower than the clock K. Any other possible agreement with respect to the time of the event 2 will imply an assumption to the effect that one of the clocks, K′ or K″ is even slower.

The inequality $\Delta t_{13} > \Delta t'_{13} + \Delta t''_{23}$ is itself an experimentally verifiable assertion, which does not depend on the convention on the simultaneity of events.

Imagining that there exists for each pair of clocks quite a definite—albeit unknown to us—relationship between the rates at which the clocks go, the authors of[39] arrived at the conclusion that at least one of the clocks, K′ or K″, is, in fact, slower than the clock K. In reality, however, a conclusion about the rates of any two of the three clocks participating in this comparison is always conditional. Just as there does not exist even in one inertial coordinate system a true simultaneity for spatially separated events, so, for the same reason, there cannot be any objectively preferred true relationship between the rates of physically equivalent clocks in different inertial states. We can conditionally assume the rates of any two of the three standard clocks under consideration to be equal. This is a question of convention. The only absolute conclusion we can draw is that the rates of three clocks whose world lines form a triangle cannot be said to be equal. The differences in the inertial states of the clocks actually manifest themselves in this, but the states differ with respect to each other, and not with respect to some absolute space, as the authors of[39] erroneously supposed. The above-discussed circumstance that the velocities of propagation of physical processes for a definite direction in one reference frame absolutely exceeds the velocities of propagation in the same direction in another inertial reference frame leads perforce to the inequality $\Delta t_{13} > \Delta t'_{12} + \Delta t''_{23}$, which does not allow us to assume the rates of all the three clocks participating in the comparison to be the same. It follows, of course, from this that in measuring proper time in different inertial systems, we should speak not of absolutely identical, but of physically equivalent clocks. And only in the absence of clear explanations in this connection can we blame the generally accepted treatment of the theory of relativity. But one cannot attribute this deficiency to defects in the logical structure of the theory, since just the physical equivalence of clocks, and not their identity, is actually utilized in it.

Direct algebraic expressions connecting the proper space-time coordinates of one inertial system with the proper coordinates of another system can be found from the relation (3) in the analysis of any physical process. The transformations are found in this case from the condition that the velocity of some process in the moving system K^*, which when determined in terms of the time of the initial system is equal to $u^*(\theta^*)$, should, in terms of the proper space-time units of the system K', be equal to the same value as the velocity of the analogous physical process in the initial system, i.e., equal to u, irrespective of the direction of motion. The derivation of the Lorentz transformations usually follows these lines, except that the relation (4) is considered for only the propagation of light instead of an arbitrary physical process, i.e., for the case when $u = c$. It is from this that one gains the false impression that the arguments about the special role of light signaling and about the fundamental importance of the selection of the measurement procedure, which are adduced to justify the new properties of space and time, have something to do with the very physical content of the theory.

This delusion about the special importance of light signaling for the realization of an inseparable connection between space and time in nature is so great that some authors have even attempted to exclude from the signaling procedure the element connected with the subject by entrusting his function to the bodies themselves: "'radiation background,' 'exchange of signals,' between bodies determines their relative coordinates in space and time"[40]. But the fact is that a unique role of the light-propagation process in the determination of the Lorentz transformations is negated by the fact that any other physical process is suitable for this purpose*. Moreover, we should understand that the arbitrarily chosen process acts here not in the form of a direct signaling, but as a link in the theoretical construction, which establishes the relations between the proper space-time quantities in different moving systems.

In the Appendix B we present computations that show how we can accomplish the transition from the relation (3), describing the actual relative changes in the motion of matter, to the Lorentz transformations, which reflect the connection between the proper space-time bases of coordinate systems in relative motion. This is a derivation of the Lorentz transformations on the basis of the general properties of physical processes, formulated in the framework of the earlier ideas about time and space and corresponding to the basic postulates of the theory*. This way of deriving the Lorentz transformations enables us to avoid the illogicality of having to single out from the whole universe the processes involving proper scales and clocks, an illogicality which was noted by Einstein[41]. But the most important thing about this method of constructing the theory, besides the clear exposure of the adopted conventions, is the establishment of the fact that the formal sameness of the kinematic description in terms of the proper scales of corresponding physical processes in reference frames, moving with respect to each other, implies the generality—the universality—of that difference in the velocities of these processes which is expressible in relativistic relations connecting the proper space-time coordinates of inertial reference frames.

Indeed, the absolute values of the velocities in this case are determined by the ratios of the proper spatial intervals to the proper time intervals in the respective reference frames. And the coincidence of the values obtained does not, of course, prove the equality of the velocities of corresponding processes in different r reference frames, in virtue of the noncoincidence of the proper space-time scales used. Therefore, the constancy of the velocity of light relative to different inertial systems implies only the invariability in each reference frame of the ratio of the velocity of that process to the velocities of other corresponding physical processes and does not at all imply that a light ray advances with one and the same velocity relative to two moving coordinate systems. We cannot really take numberical coincidence of the values of two physical quantities for their equality, if this coincidence came about as a result of the choice of unequal units of measurement.

For velocities measured in terms of the proper scales of different inertial systems, the same addition law applies as for the addition of vectors in the Lobachevskiĭ geometry. Thus, the non-Euclidean geometry founded by N. I. Lobachevskiĭ as far back as in the first half of the last century is directly realized in the "velocity space" of relativistic mechanics[42,43]. It is interesting to note that Lobachevskiĭ himself, likewise considerably anticipating the development of physics, ingeniously foresaw the possibility of a connection between the "fictitious" geometry and new laws of mechanics.

The difference between the relativistic formula for the addition of velocities, measured in different coordinate systems and the classical formula of simple addition of the velocity quantities is just due to the allowance made for the difference between the space-time scales employed. The distinctive feature of the addi-

*)This circumstance was noted at one time by Einstein ([4], p. 148) and Pauli ([5], p. 22).

*)A distinctive feature of this conclusion, which was first cited in[28], is that it is based on the analysis of the velocity of propagation of an arbitrary physical process.

tion of the velocity quantities in the theory of relativity is of the same nature as that of the computation of a total distance, if one part of the distance is measured in nautical miles and the other part is measured in land miles.

If, however, we know the velocity $u^*(0)$ of some process along the x^* axis of the system K^*, measured in the scale units that coincide with the proper units of the system K, then the velocity of this process relative to the system K will be determined by the simple sum $v + u^*(0)$, and this leads, according to (4), to the relativistic formula for the addition of the quantities v and u:

$$w(0) = v + u^*(0) = v + u\{[1 - (v^2/c^2)]/[1 + (uv/c^2)]\} = (v + u)/[1 + (uv/c^2)].$$

It should be noted that problems are often encountered in physics in which all the initial data, as well as the sought-for quantity pertain to one and the same coordinate system. For example, a similar problem is encountered in pulse techniques in the determination of the coincidence time of two electrical pulses propagating along a high-frequency cable towards each other. The problem of the computation of the number of collisions in colliding particle beams in the laboratory coordinate system belongs to this type of problem. Despite the fact that the velocities figuring in these problems are commensurate with the velocity of light, the law of simple addition of velocities applies here. This result is often arrived at by using the Lorentz transformations, recourse to which is in this case, of course, unnecessary. The result obtained may cause surprise only because it is not understood that the relativistic formula for the addition of velocities should be applied not to all velocities commensurate with the velocity of light, but to velocities measured in different reference frames in the proper space-time scales.

III. CONCLUSION

We emphasize once again that the space-time transformations of the special theory of relativity express those general differences in the way physical processes proceed in inertial coordinate systems moving relative to one another, which, on account of the preservation of complete kinematic similitude, do not violate the relativity principle. This difference in the course of physical processes is, however, due to the finite velocity of propagation of interaction and the resulting dependence of the interaction on the velocity of the relative motion of the material objects.

We have expressed this difference in the course corresponding physical processes take in two inertial reference frames moving relative to each other, in the form of an anisotropic description of the velocities of the processes in one system. To this end we, like Lorentz in his 1904 paper, used in the moving system K^* space-time coordinates x^*, y^*, z^*, and t^*, connected with the coordinates of the initial system K by the Galilean transformations $x^* = x - vt$, $y^* = y$, $z^* = z$, and $t^* = t$. We have further shown that the transition to the proper coordinates x', y', z', and t', which are connected with the coordinates of the initial system through the Lorentz transformations, does imply that the universal difference in the course of processes has been allowed for in the space-time metric.

There is one more simple possibility by means of which we can convince ourselves of the validity of this assertion, and which, we believe, could be suitably used to construct a school course on the theory of relativity. For this purpose, we must convert with the aid of the Lorentz transformations the data in the proper coordinates, pertaining to processes in the moving system K', to the initial system K, i.e., describe in terms of the coordinates x, y, z, and t the results of observations performed in the system K on arbitrary physical processes, reproduced under standard conditions in the system K'. The very simple computations pertaining to this problem are presented in Appendix B. It can clearly be seen from these computations that the fulfilment of the relativity principle in the moving system K' does not at all contradict the predictions of classical physics about the process of light propagation, these predictions being rigorously fulfilled when the phenomenon is described in terms of the coordinates x and t of the initial system K.

This approach (the description in terms of the coordinates x, y, z, and t) enables us to accomplish the same things as does the method we applied earlier to uncover the difference in the course physical processes take in the systems K and K', owing to the description in terms of the coordinates x^*, y^*, z^*, and t^* which are connected through the Galilean transformations with the coordinates of the initial system. But the use of a co-moving inertial system of the Galilean transformations prevents the erroneous explanation of the observed kinematic effects not in terms of the general properties of the physical phenomena themselves, but in terms of the conditions of observation from another coordinate system.

The possibility that the relativistic kinematics of physical processes can be represented in a form based on the application of the Galilean transformations was demonstrated in our 1961 paper[28]. A formulation of the special theory of relativity with the aid of the Galilean transformations is also presented in[44], Of course, from the point of view of the principle of general covariance, a description of the relativistic effects with the aid of the Galilean group is, in principle, as trivial as the possibility of theoretical descriptions of physical phenomena which use different units of measurement of the physical quantities*. At this point we would, however, wish to most categorically stress that the proof of such a possibility of description does not at all imply a return to the prerelativistic ideas about space and time. We must disappoint the opponents of the relativistic theory that are still to be found, in that we used the Galilean transformations only as an auxiliary means for the eludication of those concrete general properties of the kinematics of physical processes, which predetermine the characteristics of the relativistic Lorentz transformations.

*)Yet, in contrast to this generally recognized principle, the possibility of unification of the basic postulates of the theory when the former Galilean transformations are used is negated in many textbooks on the special theory of relativity.

No experiment can, in principle, really distinguish one of these two groups of mathematical transformations as the true one. However, comparison with experiment allows us to establish unambigously that the Lorentz transformations more fully reflect the physical properties of the real space and time. We can, using the Galilean transformations, accurately describe the whole set of known experimental facts, but then for inertial systems moving relative to the initial system, we shall have to introduce general, universal changes into the kinematics of physical processes. And this means that the Galilean transformations do not sufficiently fully reflect the experimentally established properties of space-time, inasmuch as the general kinematic properties which they do not take into account are, by definition, properties of space and time. We directly take into account the generality of the changes in the kinematics of processes in one reference frame with respect to the physically equivalent processes in another system when we change to the proper spatial and time scales in each reference frame and establish for them the relation, described by the Lorentz transformations.

As was shown in our paper[2], the admissible arbitrariness in the selection of the metric means of description of the physical reality does not at all eliminate the question as to what the space-time metric of the real world is.

Poincaré was absolutely right when he asserted that "any experiment admits of an interpretation on the basis of Euclidean hypothesis, but it admits it also on the basis of a non-Euclidean hypothesis" ([9b], p. 89). He thought, in particular, that an experiment aimed at observing the parallax of a distant star can be interpreted in any of the geometries by introducing appropriate changes into the laws of optics. However, Poincaré did not analyze the most important—for science—case when, in order to obtain agreement with experiment, we must introduce changes into all physical equations of motion, which lead to the proper general changes in the description of the kinematics of physical properties. It is for this reason that he arrived at the idealistic conclusion that "it is not nature that provides (or imposes on) us the concepts of space and time; we give them to nature" ([45], p. 7).

After discussing the problem of the connection between geometry and physical experiment, A. Einstein[46], A. Eddington[47], A. A. Fridman[48], and other scientists rejected A. Poincaré's viewpoint on this matter, recognizing as their justification an organic connection between the general theory of relativity and Rieman's non-Euclidean geometry. But their absolutely correct belief in the existence of a definite geometry of the physical space, it turns out, in no way contradicts the recognition of Poincaré's basic thesis that the results of an experiment can be interpreted on the basis of any geometry. The validity of this thesis can be rigorously proved. In the present paper we have demonstrated it is possible to interpret the effects of the special theory of relativity in the framework of the Galilean transformations. W. Thirring[49] and V. I. Ogievetskiĭ and I. V. Polubarinov[50] have obtained in the framework of Euclidean geometry a formulation of the relativistic theory of gravitation, which is completely identical with respect to any observable effects with Einstein's general theory of relativity. The papers of M. Tonnelat[51] and of A. Z. Petrov[52] are also devoted to a discussion on the possibility of an isomorphic representation of the relativistic theory of gravitation.

In what way can we combine the ideas about the existence of a definite geometry of the physical space and a definite space-time metric of the physical world with the possibility of a conventional selection of a geometry and a metric for the description of physical phenomena? This problem has not been solved finally, although investigations by H. Reichenbach[16] have to a considerable extent prepared the answer to this question. He draw attention to the circumstance that in order to obtain agreement with physical experiments we should supplement the different conventions on geometry with the introduction of universal forces and that only one of the geometries is distinguished by the absence of such universal forces. Unfortunately, however, the fundamental importance of this refinement of Poincaré's conventional conception has not received due recognition, and these assertions by H. Reichenbach have even been unduly criticized by A. Grünbaum ([19], p. 101).

But, in our opinion, the solution of the formulated problem consists in understanding the fact that the inadequacy of the chosen geometry of space-time compels us to take into consideration certain properties of the physical metric in the form of the corresponding general kinematic effects, by introducing universal changes into the laws of motion. Therefore, a conventional agreement only determines which part of the properties of the physical metric will be allowed for in the kinematics, and which part will be directly taken into account in the space-time geometry used. Both these modes of taking the metric properties of the physical world into account are, in fact, identical in the factual content. In the general theory of relativity we encounter, for example, the assertion that the time at the point A is slower by a factor of two than at the point B, and this is completely identical with the assertion that all processes at the point A take place at a rate twice slower than processes at the point B.

Consequently, the geometry distinguished by the absence of the universal forces reflects most fully the known properties of the physical metric and does not require an additional consideration of these properties in the form of general changes in the kinematics of the processes. However, in the establishment and explanation of specific properties of the new metric of the physical space and time, a preliminary description of the physical phenomena in the framework of the former ideas about time and space is of paramount importance. This course excludes any possibility of treating the new metric separately from the properties of motion of the physical reality, and allows us to establish the specific general properties of physical phenomena, which predetermine the difference between the new and the previously known metric of the physical space and time. In this case the difficulty encountered in explaining new experimental facts in the framework of the old physical theory of space-time should be overcome through the discovery of new general properties of physical processes, which are then used to determine a new space-time metric. This way of constructing the special theory of relativity was begun by Lorentz. A brilliant guess about the possibility of eliminating the difficulties of the electrodynamics of moving bodies at the expense of a transformation of the metric relations allowed Einstein to immediately obtain the final solution to the problem, omitting the important—for the interpretation of the theory—stage in which the new general properties of motion of the physical reality should have been represented in the framework of the classical ideas about time and space. This circumstance was the cause of the appearance and dissemination of the limited interpretation of the theory, in which the primary substance of the Lorentz transformations was not revealed, to wit, the fact that the relationship between the spatial and time coordinates of the four-dimensional pseudo-Euclidean geometry reflects the existing difference in the velocities of propagation for the entire set of corresponding physical processes in the direction of relative motion of the inertial reference frames.

In 1955 Einstein made in his creative biography[41] a critical comment on the illogicality of his preference, in the construction of the theory, for scales and clocks over all other physical phenomena. We might add that it is also illogical to justify the properties of these scales and clocks on the basis of an analysis of solely the process of propagation of light with constant velocity, and then explain this constancy of the velocity of light in terms of the same properties of the scales and clocks. In the traditional exposition of the theory, we speak of the identity of the courses physical processes take in different inertial reference frames and at the same time establish the fact that the proper times and coordinates differ in these systems. It would appear that here we have a clear separation of proper lengths and durations from the metric characteristics of the physical processes in these coordinate systems. As we can see, this contradiction is eliminated by clarifying the inadmissibility of the assertion that the corresponding processes, which, in fact, take place with conservation of kinematic similitude, are identical. Of course, neither the concepts of space and time, nor the quantitative characteristics of length and duration are an independent reality which exists together with matter, or as a factor determining the properties of the motion of matter. These concepts only serve as an expression of the general properties of the motion of matter. Therefore, we do not simply single out scales and clocks from the entire manifold of physical reality, but ascribe to them those properties which are general for all physical processes without exception. But we can show that most clearly if we introduce the new characteristics of extension and duration after we have elucidated the corresponding general properties of physical phenomena in the framework of the ideas about time and space. The basic experimental material alone can never serve as the final proof of the generality of the observed properties of physical phenoma. It can only prompt one to advance a supposition about the generality of the observed properties and, consequently, a supposition about the discovery of new metric properties of the physical space and time. Therefore, the observation of relativistic effects in such unknown—at the time of the creation of the theory of relativity—phenomena as the disintegration of microparticles and nuclear interactions, is not simply a trivial result of the time and length transformations which does not bear any relation to these physical phenomena, but a new proof of the brilliant guess about the generality of the properties, discovered earlier in investigations of the electrodynamics of moving bodies.

The physical notions about time and space should necessarily change each time new general properties of the interaction and motion of matter are established. But any further development of the physical theory of time and space can proceed only along the line of ascent. A new physical theory of space and time should, no matter in which branch of physics it appears, reflect, besides the new and necessarily general properties of the motion of matter, the previously established properties of space and time. An obvious example of the development of physical theory of space and time is the relativistic theory of gravitation, which wholly includes the content of the special theory of relativity.

By investigating the interactions of elementary particles at high energies, modern physics obtains extremely important data on the fundamental properties of matter, including data on the properties of space and time in the region of ultrasmall dimensions. As the energy of electron and proton accelerators increases, it becomes experimentally feasible to penetrate matter into the region of still smaller spatial dimensions of elementary particles. Proceeding along these lines, physicists hope to obtain those valuable data, which will help overcome the fundamental difficulties encountered in the theoretical description of the various fundamental interactions of elementary particles. In particular, it is strongly hoped that information will be obtained which will make necessary a reconsideration of the space-time metric in connection with the existence of fundamental length and duration—unique quanta of space and time.

We should note in this connection that such changes in the metric in the region of small dimensions can arise only on the basis of a general interaction to which all elementary particles are exposed. In our opinion, in virtue of the fact that it will be possible to adjust the general, universal interactions to new properties of the space-time geometry, they ought not, unlike other interactions, be effected by an exchange of the quanta of the appropriate fields*.

Many physicists believe that in order to overcome the difficulties of modern theoretical physics, a fundamental step has to be taken which will radically change our present-day physical ideas. It should be understood, however, that by themselves new experimental facts may prove to be by far too inadequate to be able to concretely determine exactly which of the existing theoretical concepts should undergo a radical reconstruction. For this purpose a deep understanding of the very nature of the theoretical formalism of description of physical phenomena, which obtains in present-

*)The quanta of such interactions could be transformed by means of only metric transformations into, in our opinion, an absurd concept—a "portion" of space and time. An analogous viewpoint was also expressed by N. P. Konopleva and G. A. Sokolik in the paper "On Geometry and Quantization"[53].

day physics, is also required. Therefore, one of the most important problems facing physicists of the present generation is how to develop further our conception of the existing physical theories—a distinctive modernization of the historically arisen interpretations of contemporary physical concepts, consisting in bringing them into a unified orderly and systematic arrangement. Using as an example the special theory of relativity, which, incidentally, is the simplest of all the theories on which contemporary physical views are based, we see already the possibility of substantially deepening our understanding of it by elucidating a few formally accepted propositions.

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APPENDICES

A. THE GENERAL ANGULAR DEPENDENCE, WHICH IS EXPERIMENTALLY INDISTINGUISHABLE FROM THE CASE OF ISOTROPIC DESCRIPTION, IN THE DESCRIPTION OF THE VELOCITIES OF PHYSICAL PROCESSES.

Let a kinematic description be chosen in which a definite dependence on the angle θ^*, measured from some arbitrary direction, has been introduced for the velocity of propagation of each physical process:

$$u^*(\theta^*) = uf(\theta^*, u),$$

where u is the velocity of the same physical process for the case of isotropic description. Let us determine the admissible form of the dependence $f(\theta^*, u)$ from the conditions (i) and (ii) (see p. 00), guaranteeing the impossibility in principle of an experimental detection of the difference between the adopted and the isotropic descriptions.

According to the condition (i), the difference in the times of propagation of a physical process in the forward and backward directions for some length l^* inclined at an angle θ^*,

$$\Delta t^* = [l^*/uf(\theta^*, u)] - [l^*/uf(\theta^*+\pi, u)] = 2l^*\beta(\theta^*)$$

should be the same for all physical processes. Consequently, the function $\beta(\theta^*)$ should not depend on the magnitude of the velocity u of the process under consideration:

$$\beta(\theta^*) = [f(\theta^*+\pi, u) - f(\theta^*, u)]/[2uf(\theta^*, u)\, f(\theta^*+\pi, u)] = \mathrm{const}\,(u). \tag{A.1}$$

The total time of propagation of the same physical process "there" and "back" for the length l^* inclined at an angle θ^* will be equal to

$$t^* = [l^*/uf(\theta^*, u)] + [l^*/uf(\theta^*+\pi, u)] = (2l^*/u)\,\alpha(\theta^*).$$

For the condition (ii) to be fulfilled it is necessary to have

$$\alpha(\theta^*) = [f(\theta^*+\pi, u) + f(\theta^*, u)]/[2f(\theta^*, u)\, f(\theta^*+\pi, u)] = \mathrm{const}(u), \tag{A.2}$$

i.e., this quantity should also be independent of the velocity u of the arbitrarily chosen physical process.

A simultaneous fulfilment of the conditions (A.1) and (A.2) implies that the function, describing the angular dependence of the velocity of propagation of an arbitrarily chosen physical process, should depend on the quantity u in the following manner:

$$f(\theta^*, u) = [\alpha(\theta^*) + u\beta(\theta^*)]^{-1},$$

where the functions $\alpha(\theta^*)$ and $\beta(\theta^*)$ do not depend on u and satisfy the following conditions: $\alpha(\theta^* + \pi) = \alpha(\theta^*)$ and $\beta(\theta^* + \pi) = \beta(\theta^*)$.

B. DERIVATION OF THE LORENTZ TRANSFORMATIONS

Let the rectangular coordinate axes in the initial system K be parallel to the axes of the system K′ that moves in the direction of the x axis with velocity v. It is required to express the space-time coordinates of some event in the system K′ in terms of the coordinates of that event in the initial system K.

We shall assume that the required transformations are linear functions

$$x' = \gamma(v)(x - vt),\ y' = \mu_1(v)\,y,\ z' = \mu_2(v)\,z,$$
$$t' = \eta(v)\,t + \alpha(v)\,x + \beta_1(v)\,y + \beta_2(v)\,z. \tag{B.1}$$

The linearity of the coordinate-transformation functions is usually justified by an independent requirement of homogeneity of space, according to which no point in space is preferable over other points. The linearity of the coordinate-transformation functions can also be obtained if we require that a body, which moves uniformly and linearly relative to one coordinate system, should move in the same manner relative to other inertial coordinate systems, moving relative to one another.

To determine the space-time transformations, we should find the coefficients $\gamma(v)$, $\mu_1(v)$, $\mu_2(v)$, $\eta(v)$, $\alpha(v)$, $\beta_1(v)$, and $\beta_2(v)$. From the isotropy of space and the fact that only the x axis, which coincides with the direction of motion of the system K′, is a physically preferred direction, follow the relations: $\mu_1(v) = \mu_2(v) = \mu(v)$, and $\beta_1(v) = \beta_2(v) = 0$. To determine the coefficients γ, μ, η, and α, let us consider some arbitrarily chosen physical process, propagating in the system K′ in the direction of the x′ axis. The velocity of this process, defined with the aid of the space-time units of the initial system K, should, according to the relation (4) be equal to

$$u^* = \frac{dx^*}{dt^*} = \frac{dx}{dt} - v = \frac{dx'}{dt'}\,\frac{1-(v^2/c^2)}{1+(v/c^2)(dx'/dt')}.$$

It follows from this that the velocity of propagation of this process relative to the initial system will be equal to

$$\frac{dx}{dt} = \frac{(dx'/dt') + v}{1+(v/c^2)(dx'/dt')}. \tag{B.2}$$

Expressing the quantity dx'/dt' in the relation (B.2) with the aid of the transformation (B.1), we obtain

$$\frac{dx}{dt} = \frac{(\gamma + v\alpha)(dx/dt) + v(\eta - \gamma)}{\eta - (v^2/c^2)\gamma + [\alpha + \gamma(v/c^2)](dx/dt)}.$$

In order for this equality to be fulfilled for different arbitrary values of the velocity dx/dt, we should require the fulfilment of the following identities: $\eta(v) \equiv \gamma(v)$, and $\alpha(v)/\eta(v) = -v/c^2$. Thus, the sought-for transformations can now be represented in the following form:

$$x' = \gamma(v)(x - vt),\quad y' = \mu(v)\, y,\quad z' = \mu(v)\, z,\quad t' = \gamma(v)\,[t - (v/c^2)\, x]. \tag{B.3}$$

It is quite clear that if the system K′ were to move with velocity v in the direction of negative values of the coordinates of the x-axis, then the transformations should, in view of the available symmetry, not change. And this means that

$$\gamma(v) = \gamma(-v),\quad \mu(v) = \mu(-v). \tag{B.4}$$

In virtue of the physical equivalence of the inertial coordinate systems, the transformations relating the coordinates x, y, z, and t to the coordinates of the system K′ should have the following form

$$x = \gamma(-v)(x' + vt'),\quad y = \mu(-v)\, y',\quad z = \mu(-v)\, z',\quad t = \gamma(-v)\,[t' + (v/c^2)\, x']. \tag{B.5}$$

Solving on the other hand for x, y, z, and t in the relations (B.3), we obtain

$$x = \frac{x' + vt'}{\gamma(v)\,[1 - (v^2/c^2)]},\quad y = \frac{1}{\mu(v)}\, y',\quad z = \frac{1}{\mu(v)}\, z',\quad t = \frac{t' + (v/c^2)\, x'}{\gamma(v)\,[1 - (v^2/c^2)]}.$$

Comparing these relations with the transformations (B.5) and taking into consideration the equality (B.4), we find

$\gamma(v) = [1 - (v^2/c^2)]^{-1/2}$ and $\mu = 1$.

We obtain as a result the Lorentz space-time transformations

$$x' = \frac{x - vt}{[1 - (v^2/c^2)]^{1/2}},\quad y' = y,\quad z' = z \quad \text{и} \quad t' = \frac{t - (v/c^2)\, x}{[1 - (v^2/c^2)]^{1/2}},$$

relating the proper—for different reference frames—spatial and time coordinates of one and the same event among themselves.

C. PROOF OF THE UNIVERSALITY BASED ON THE USE OF THE LORENTZ TRANSFORMATION, OF THE ANISOTROPY IN THE DESCRIPTION OF PROCESSES

Suppose we have two inertial systems K and K′ whose coordinates are linked by the Lorentz transformations. Let us consider the motion of a ray of light along the x axis of the reference frame K in some segment AB, given in the system K′. Let us compute the time interval Δt_{AB} in the system K, corresponding to the moments the light pulse crosses the points A and B in the system K′:

$$\Delta t_{AB} = t_B - t_A = \frac{\Delta t'_{AB} + (v/c^2)(x'_B - x'_A)}{[1 - (v^2/c^2)]^{1/2}}.$$

Since the time interval $\Delta t'_{AB}$ in the system K′ is equal to $\Delta t'_{AB} = \Delta x'_{AB}/c$, where $\Delta x'_{AB} = x'_B - x'_A$ is the length of the segment AB in the system K′, the sought-for interval will be equal to

$$\Delta t_{AB} = \frac{\Delta x'_{AB}\, [1 - (v^2/c^2)]^{1/2}}{c - v} = \frac{\Delta x_{AB}}{c - v}.$$

Let us now compute the time interval Δt_{BA} corresponding to the measurement in the same initial system K of the moments the light pulse passes the points B and A of the system K′ in the opposite direction:

$$\Delta t_{BA} = t_A - t_B = \frac{\Delta t'_{BA} - (v/c^2)(x'_B - x'_A)}{[1 - (v^2/c^2)]^{1/2}} = \frac{\Delta x'_{AB}\, [1 - (v^2/c^2)]^{1/2}}{c + v} = \frac{\Delta x_{AB}}{c + v}.$$

Thus, according to computations, based on the Lorentz transformations, the measurements in the initial system K should for $u \sim c$ reveal a substantial difference in the time intervals Δt_{AB} and Δt_{BA}, proportional to the first order of magnitude of the ratio v/c. This difference in the measured intervals agree exactly with the predictions of classical physics, made in the framework of the stationary ether hypothesis about the motion of a light ray relative to the system K′ with velocity $c - v$ in the direction of motion of the system, and with velocity $c + v$ in the opposite direction.

It now remains to explain how this directly observable—in the initial reference frame—difference in the time intervals to the first order of the ratio v/c turns out to be compatible with the equality of the corresponding time intervals $\Delta t'_{AB} = \Delta t'_{BA}$ in the system K′ assumed in the theory of relativity. To do this let us consider the same problem of computation of the time intervals in the initial system for the case of propagation in the moving system K′ of an arbitrary physical process with some velocity $u = \Delta x'_{AB}/\Delta\tau'_{AB} = \Delta x'_{AB}/\Delta\tau'_{BA}$. In this case we obtain on the basis of the Lorentz transformations

$$\Delta\tau_{AB} = \frac{\Delta\tau'_{AB} + (v/c^2)\,\Delta x'_{AB}}{[1 - (v^2/c^2)]^{1/2}} = \Delta x'_{AB}\left[1 - \frac{v^2}{c^2}\right]^{1/2} \frac{1 + (vu/c^2)}{u\,[1 - (v^2/c^2)]} = \frac{\Delta x_{AB}}{u^*(0)}$$

and

$$\Delta\tau_{BA} = \frac{\Delta\tau'_{AB} - (v/c^2)\,\Delta x'_{AB}}{[1 - (v^2/c^2)]^{1/2}} = \Delta x'_{AB}\left[1 - \frac{v^2}{c^2}\right]^{1/2} \frac{1 - (vu/c^2)}{u\,[1 - (v^2/c^2)]} = \frac{\Delta x_{AB}}{u^*(\pi)}.$$

Let us now consider the difference and the sum of the time intervals obtained:

$$\Delta\tau_{AB} - \Delta\tau_{BA} = \Delta x_{AB}\,(v/c^2)\,[1 - (v^2/c^2)]^{-1},$$
$$\Delta\tau_{AB} + \Delta\tau_{BA} = \Delta x_{AB}\, u^{-1}\,[1 - (v^2/c^2)]^{-1}.$$

We see from these relations that the magnitude of the difference in the time intervals does not depend on the magnitude of the velocity u of the chosen process and, consequently, remains constant for any physical processes, while the sum of the time intervals changes, when different processes are chosen, in the same way as when the velocities of propagation of physical processes in the forward and backward directions are equal.

Consequently, we can, by measuring the time intervals $\Delta\tau_{AB}$ and $\Delta\tau_{BA}$ for different physical processes, verify the generality of the changes in the velocities of propagation of physical processes in the system K′ which preserve, in accordance with the relativity principle, any experimentally observable relations between different processes. Owing to the fact that kinematic similitude is taken into account in the Lorentz transformations, the fulfilment of the relativity principle in the system K′ is compatible with the predictions of classical physics (in the framework of the stationary ether hypothesis) of the results of the corresponding observations in the initial system.

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