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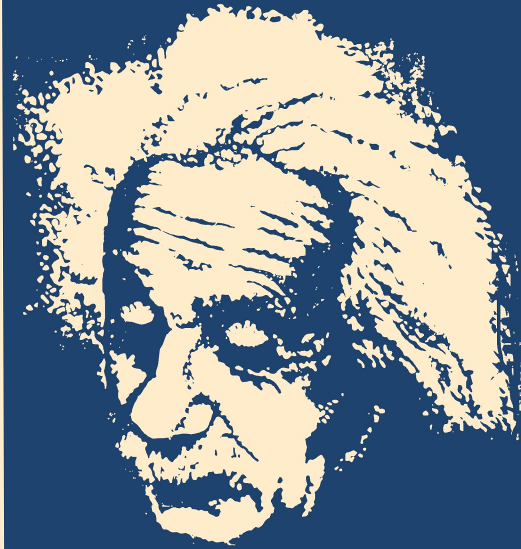

and the philosophical problems of 20th-century physics

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ЭЙНШТЕЙН И ФИЛОСОФСКИЕ ПРОБЛЕМЫ ФИЗИКИ XX ВЕКА

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PREFACE

March 14, 1979 was the centenary of Albert Einstein, the great physicist. The history of science knows but few scientists who were accorded the same popularity as Einstein. His fame far transcends the boundaries of physics: he is known not only to professional scientists but also to people whose interests are remote from science. This popularity is largely due to the fact that Einstein's work played a revolutionary role in the development of physical knowledge and, moreover, touched on the most profound problems of the scientific world outlook with which all thinking persons are concerned. Einstein's scientific creativity made a considerable impact on the development of 20th-century philosophical thought.

What were the factors that determined Einstein's part in the development of philosophical thought? The first of these was the role played by Einstein's special and general relativity theories in altering the scientific picture of the world. The picture of the world founded on these theories is radically different from that of classical physics, entrenched in the age-old tradition. The time-space structure of the universe was here explained in a new way. Thanks to Einstein, man in the 20th century sees the world in a different light from previous generations. The second factor was the impact of Einstein's scientific creativity on the style of scientific thinking. Einstein worked out new standards for scientific knowledge, which further developed the Copernican tradition rejecting anthropomorphic self-obviousness; these were standards for theories whose truth was substantively linked up with their paradoxical nature. The third factor here is Einstein's deliberations on the fundamental philosophical problems facing physics. Without these ideas, modern physics would be unthinkable. On the other hand, their solution goes beyond physics alone, assuming a general philosophical significance.

The present work deals with the philosophical meaning of Einstein's creativity within the philosophy of the natural sciences. Accordingly, it includes papers on the philosophical interpretation of the special and general theories of relativity, analysis of the concepts of space and time, philosophical evaluation of Einstein's search for a unified field theory, Einstein's views on the role of probabilistic laws in quantum mechanics, and the problem of determinism in physics.

Although Einstein's theories have in a sense become classic, they continue to be objects of the most divers, at times mutually exclusive, philosophical interpretations. This is true, in particular, of the general theory of relativity. Along with the traditional view that this theory emerged from a generalisation on the special relativity principle, it is also identified with the relativistic gravitation theory. Einstein's programme for creating a unified field theory is also variously evaluated in present-day Soviet literature. Such differences of opinion are an attribute of developing knowledge. For this reason the editors deemed it expedient not to restrict the book to representing only one of the existing viewpoints, providing the reader with an opportunity for studying various approaches to debatable problems.

However, current in foreign literature are also philosophical interpretations of Einstein's heritage of a different kind—those made from the positions of neopositivism, conventionalism, and other conceptions of modern bourgeois philosophy. Some of these were reflected in the articles collected in *Albert Einstein: Philosopher-Scientist*, which was published in the USA on the occasion of Einstein's 70th birthday and became widely known.[1] In his comments on the articles published there Einstein pointed out the inadequacy of these conceptions.[2] These com-

[1] *Albert Einstein: Philosopher-Scientist*, ed. by P. A. Schilpp, Evanston, Illinois, 1949. See in particular papers by Philipp Frank, Hans Reichenbach, Percy Bridgman, Kurt Gödel, and others.

[2] These comments were published in the collection in ref. 1 (A. Einstein, "Reply to Criticisms. Remarks Concerning the Essays Brought Together in This Cooperative Volume", *Op. cit.*, pp. 663-688).

ments elucidate some very important aspects of Einstein's philosophical position. Therefore the present book includes papers analysing Einstein's attitude to Machist philosophy, neopositivism, and operationalism.

Regrettably, it is still believed in the West that Soviet philosophers take a negative attitude to the theory of relativity which is allegedly incompatible with dialectical materialism. This view is completely unjustified. It should be pointed out, first of all, that the relativity theory had opponents amongst Western scientists adhering to the traditionally classical style of thinking and narrow empirical or idealist philosophical attitudes. We all know that the American scientist P. W. Bridgman gave an erroneous interpretation of the special theory of relativity and rejected the general theory of relativity. A more recent example is provided by the French physicist Léon Brillouin's book *Relativity Reexamined* containing a critique of the general theory of relativity which is, in the author's view, a purely speculative construction. Although there have been men, philosophers included, in the USSR, just as abroad, who rejected the relativity theory, their view does not reflect the position of dialectical materialism on this question. On the contrary, practically all Soviet philosophers believe Einstein's theory of relativity to be a most important natural-scientific premise of further development of materialist dialectics and in the first place of the doctrine of the dialectic connection between matter, motion, space, and time.

D. P. GRIBANOV

EINSTEIN'S PHILOSOPHICAL WORLDVIEW

The theory of relativity holds a prominent position amongst the outstanding attainments of modern scientific thought. It has enabled scientists to revise the traditional views and conceptions of the structure of the material world, revealing deep and close ties between philosophy and natural science. For this reason neither physicists nor philosophers were indifferent to Einstein's work. Both were attracted by its special novelty. Natural scientists saw the relativity theory as the resolution of the inner contradictions between classical mechanics and electrodynamics, while dialectical materialists regarded it as natural scientific confirmation of the ideas of matter and its attributes reflected in the doctrines of the founders of Marxism.

Einstein's worldview has been debated for several decades already. The most contradictory views are current in the abundant philosophical literature on this problem. Einstein has been made out to be a Berkeleyan, a Machist, a Kantian, a positivist, an adherent of conventionalism, an empiricist, a rationalist, and so on. Some philosophers included him among proponents of dialectical materialism.

One thing stands out, however. Einstein always had a great liking for philosophy: "The critical thinking of the physicist cannot possibly be restricted to the examination of the concepts of his own specific field " [1, p. 290]. On many occasions he emphasised that modern physics cannot cope with its problems without philosophical knowledge: "The present difficulties of his science force the physicist to come to grips with philosophical problems to a greater degree than was the case with earlier generations" [2, p. 279].

Einstein's articles analyse the most divers philosophical trends. He read the works of Aristotle, Plato, Democritus, La Mettrie, Spinoza, Berkeley, Hume, Mach, Kant, Russell, and others, but did not share any of the basic tenets of any single system of idealist philosophy he studied.

It would be a mistake to believe that Einstein's philosophical views were moulded by the idealist philosophy he was familiar with.

Einstein had a profound knowledge of the natural science, having absorbed the progressive science and culture of his times. It would be quite appropriate to apply to him Hegel's words that "in experience everything depends upon the mind we bring to bear upon actuality. A great mind is great in its experience; and in the motley play of phenomena at once perceives the point of real significance" [3, p. 206].

1. Attitude to Idealism and Positivism: the Relationship Between Experience and Theory

Apart from other problems, Einstein was interested in epistemological ones like the following: "What knowledge is pure thought able to supply independently of sense perception? Is there any such knowledge? If not, what precisely is the relation between our knowledge and the raw-material furnished by sense-impressions?" [2, p. 279].

He found extremely contradictory answers to these questions in the profuse philosophical literature. He sympathised with the "increasing scepticism" towards attempts to obtain knowledge of the external world through pure thought only. But Einstein did not share the views of those philosophers who took the stand of naive realism. He wrote: "This more aristocratic illusion concerning the unlimited penetrative power of thought has as its counterpart the more plebeian illusion of naive realism, according to which things 'are' as they are perceived by us through our senses" [2, p. 281].

To overcome these "two illusions" Einstein resorted to some propositions from Berkeley, Hume, and Kant. He rejected the basic philosophical ideas constituting the essence of their idealist systems, their conceptions of space and time, Hume's agnostic doctrine [2, pp. 283-289], referring to the fundamental Berkeleyan tenet "*esse est percipi*" as "untenable" [4, p. 669]. What attracted Einstein in the works of Berkeley, Hume, and Kant was their deviation from the generally accepted metaphysical epistemology dominating classical physics.

In Berkeley's teachings Einstein found, to take an instance, the proposition that our senses directly perceive only processes and not objects of the external world, as empiricists insisted. However, Berkeley viewed objects of the external world as complexes of ideas (sensations), whereas Einstein's materialist intuition prompted him to believe that the processes perceived by our sense organs are causally linked with the things which exist quite objectively and independently from the subject's perceptions.

Studies in Hume prompted Einstein that such general and most essential concepts as causality could not be directly and unambiguously obtained from sense data. Hume made that the basis of an agnostic conclusion: "Whatever in knowledge is of empirical origin is never certain", while Einstein, discarding Hume's agnosticism, used his idea to fight extreme empiricism: "All knowledge about things is exclusively a working-over of the raw-material furnished by the senses" [2, pp. 283, 285].

The gap in the chain of knowledge left by Hume had to be bridged. Einstein understood that. He found a kind of way out of the difficulty in Kant. Kant believed that if empirical data could not result in reliable knowledge (Hume's position), while without such concepts as causality, time, space, and so on, cognitive activity is impossible (they are, according to Kant, the premise of any thinking), it followed that reliable knowledge was based on pure thought, being apriori in nature. However, it was not this conclusion that attracted Einstein.

The positive elements he borrowed from Kant were formulated in this way: "I did not grow up in the Kantian tradition, but came to understand the truly valuable which is to be found in his doctrine, alongside of errors which today are quite obvious, only quite late. It is contained in the sentence: 'The real is not given to us, but put to us (*aufgegeben*) (by way of a riddle).' This obviously means: There is such a thing as a conceptual construction for the grasping of the inter-personal, the authority of which lies purely in its validation" [4, p. 680]. Einstein saw that Kant had taken a step forward in the solution of the Humean dilemma, but, as distinct from Kant, he came to the conclusion that our knowledge of the external world was obtained from actuality through mental working-over of the sense-data. Einstein did not share Kant's assertion of the existence of apriori concepts. He saw the cause of apriorism in that Kant "was misled by the erroneous opinion ... that the Euclidean geometry is necessary to thinking and offers *assured* (i.e., not dependent upon sensory experience) knowledge concerning the objects of 'external' perception. From this easily understandable error he concluded the existence of synthetic judgments *a priori*, which are produced by the reason alone, and which, consequently, can lay claim to absolute validity" [4, p. 679].

So we see that Einstein's familiarity with the works of Berkeley, Hume, and Kant did not bring him under the influence of the idealist direction in philosophy with which these names are linked. Einstein interpreted the works of these idealist philosophers as a spontaneous materialist and dialectician. He used certain ideas of these philosophers to fight against idealism, agnosticism, and metaphysics, in particular against the two illusions, referred to earlier, of the metaphysical and idealist approaches to the source of our knowledge.

Einstein often cites Mach's works. We must, of course, distinguish between Mach's natural scientific works and the philosophical ones. What attracted Einstein about Mach's philosophy was not its actual content but rather Mach's inclination for epistemological problems. Although Einstein did not at first study Mach's epistemology deeply, he found inspiring the very fact that the Austrian physicist was concerned with these aspects, to which he himself paid considerable attention in his works. That is why he began his obituary for Mach (1916) with questions that he was often asked about Mach's preoccupation with epistemology: "How come, in general, that such a gifted natural scientist should be concerned with epistemology? Isn't there enough worthwhile work to be done in his own field?" [5, S. 101]. His answer is: "I cannot share such convictions ... If I have turned to science not for some external reasons, such as making money or ambition, not (or at least not only) for the pleasure it affords as sport or mental gymnastics, then I as a servant of this science must be acutely interested in this question: what objective can and will that science achieve to which I have devoted myself? To what extent are its general results 'true'? What is essential and what is only dependent on the accidents of development?" [5, S. 101].

The content of Mach's philosophical ideas failed to become for Einstein the basis on which his worldview was founded. Neither did it become part of the fabric of his physical ideas. Mach's idealism affected rather the "styling of expression" in Einstein's creative work on various problems of epistemology and physics. Thus in his "Autobiographical Notes" Einstein wrote of Mach's epistemology that it appeared to him "essentially untenable" [6, p. 21]. His attitude to the ideas expressing the primary content of Mach's philosophy was more concretely outlined in a conversation with Rabindranath Tagore. Tagore insisted: "This world is a human world—the scientific view of it is also that of the scientific man. Therefore, the world apart from us does not exist; it is relative world, depending for its reality upon our consciousness" [7, p. 42]. Einstein's reply was quite categorical: "Even in our everyday life, we feel compelled to ascribe a reality independent of man to the objects we use.... For instance, if nobody is in this house, yet that table remains where it is" [7, p. 43].

The clarity of this rejoinder against the philosophy of subjective idealism and, by the same token, against Machism, leaves no room for comment. One may therefore assume that in his early years Einstein treated Mach's philosophy in a superficial manner, and its essence eluded him. The assumption is all the more justified that, as distinct from Mach, Einstein always discerned the objective world behind the sense perceptions, which for him were always images of this world.

At the same time Einstein was far from superficial in his attitude to Mach's historical-critical natural-scientific papers where Mach, as Lenin put it, reasoned in a straightforward manner, without idealist extravaganza. Mach the natural scientist, as is well known, put in a great deal of work studying the history of the development of classical physics. He was one of the first amongst physicists to overthrow the absolutes of classical mechanics, pointing to its relative character as a whole and to the relativity of some of its concepts and principles which had been believed to be final, and stressing the universal connectedness of natural phenomena. However, Mach's idea of the relative nature of scientific knowledge led him to negate its objective character, while Einstein's study of Mach's *History of Mechanics* only gave him a chance to see nature through the eyes of a spontaneous dialectician and materialist. "...All physicists of the last century [wrote Einstein] saw in classical mechanics a firm and final foundation for all physics, yes, indeed, for all natural science.... It was Ernst Mach who, in his *History of Mechanics*, shook this dogmatic faith; this book exercised a profound influence upon me in this regard while I was a student" [6, p. 21].

Einstein's world outlook was often linked with positivism. This view was taken by such positivists as Moritz Schlick, Philipp Frank, Lincoln Barnett, Herbert W. Carr, and others. We have made it clear already that Einstein did not share the main ideas of one of the basic varieties of positivism—Mach's philosophy. To show more conclusively the untenability of the assertion that Einstein's worldview was identical with positivism, let us see what Einstein himself wrote on the question.

Positivist philosophers are hostile to "metaphysics" (philosophy) and its problems. In their view, the basic concepts of "traditional" philosophy have no scientific meaning, and philosophy should be freed from them. This positivist attitude worried Einstein. He believed that Hume had "created a danger for philosophy in that ... a fateful 'fear of metaphysics' arose which has come to be a malady of contemporary empiricistic philosophizing" [2, p. 289]. In his comments on Bertrand Russell's book *Meaning and Truth* he pointed out the paradoxes that may arise out of the positivists' attempt to banish philosophy from science: "This fear seems to me, for example, to be the cause for conceiving of the 'thing' as a 'bundle of qualities', such that the 'qualities' are to be taken from the sensory raw-material. Now the fact that two things are said to be one and the same thing, if they coincide in all qualities, forces one to consider the geometrical relations between things as belonging to their qualities. (Otherwise one is forced to look upon the Eiffel Tower in Paris and that in New York as 'the same thing')" [2, p. 289].

Einstein understood that the positivists' intention to reduce philosophical tasks entirely to operations upon sense data and their neglect for studying the essence of the phenomena of the external world are profound errors fraught with fatal consequences.

He is even more critical of the positions of positivists in a letter to his friend Maurice Solovine: "In these days, the subjective and positivist viewpoint dominates in a most excessive manner. The need for conceiving nature as an objective reality is declared to be an obsolete prejudice, and thus a virtue is made of the necessity of quantum theory. Men are just as subject to suggestion as horses, and each epoch is dominated by a fashion, and the majority do not even see the tyrant who dominates them" [8, pp. 70, 71].

Einstein pointed out that the roots of positivism were in Berkeley's philosophy: "What I dislike in this kind of argumentation is the basic positivistic attitude, which from my point of view is untenable, and which seems to me to come to the same thing as Berkeley's principle, *esse est percipi*" [4, p. 669].

The indifference of some scientists to atomic theory Einstein imputed exclusively to positivism. "This is an interesting example [he wrote] of the fact that even scholars of audacious spirit and fine instinct can be obstructed in the interpretation of facts by philosophical prejudices. The prejudice—which has by no means died out in the meantime—consists in the faith that facts by themselves can and should yield scientific knowledge without free conceptual construction" [6, p. 49]. According to Einstein, "that which is" is the product of our conceptual, speculative construction, although knowledge is not the result of pure thought. It is extracted from the sense data which by themselves, without conceptual processing, give no idea of facts.

2. Attitude to Religion

On a few occasions, Einstein spoke of religion. Are there any grounds, however, to conclude that Einstein was religious—a conclusion that divers philosophising theologians have often endeavoured to substantiate? Let us consider Einstein's attitude to religion—what he said about it and how he understood it. In his autobiography he admits that in his young years, just as many of his contemporaries, he came "to a deep religiosity, which, however, found an abrupt ending at the age of 12. Through the reading of popular scientific books I soon reached the conviction that much in the stories of the Bible could not be true. The consequence was a positively fanatic [orgy of] freethinking" [6, p. 5].

In his article "Religion and Science" Einstein tried to identify the causes of religious ideas, belief in the supernatural forces, etc. He believed that religion was historical in nature, emerging as it did at a certain stage in the development of society. In different peoples at different stages of their development religious ideas were engendered by different causes. In Einstein's view, "eternal man ... is a realisation of human entity" [7, p. 42].

Einstein saw no reason to resort to religious dogmata in explaining mysterious phenomena. "The man who is thoroughly convinced of the universal operation of the law of causation cannot for a moment entertain the idea of a being who interferes in the course of events—provided, of course, that he takes the hypothesis of causality really seriously. He has no use for the religion of fear and equally little for social or moral religion. A God who rewards and punishes is inconceivable to him for the simple reason that a man's actions are determined by necessity, external and internal, so that in God's eyes he cannot be responsible, any more than an inanimate object is responsible for the motions it undergoes" [1, p. 39]. Despite Einstein's negative attitude to religion and the idea of God, he turns to the so-called "cosmic religion". What is it, this religious feeling, in actual fact? Disappointment in the dominant "official" religion demanding humbleness and pointing a way to eternal paradise, pushed Einstein in the opposite direction—towards the great world existing independently of man. "The contemplation of this world [he said] beckoned like a liberation, and I soon noticed that many a man whom I had learned to esteem and to admire had found inner freedom and security in devoted occupation with it.... The road to this paradise was not as comfortable and alluring as the road to the religious paradise; but it has proved itself as trustworthy, and I have never regretted having chosen it" [6, p. 5].

The mystery of the universe captivated Einstein. His most profound and fascinating experiences came from encounters with the unknown. "It is enough for me [he wrote] to make amazed surmises about these mysteries and to attempt humbly to form a limited impression in my mind of the perfect structure of all that exists" [9, S. 255].

Einstein believed in the power of the human mind, in its ability to solve the hidden mysteries of the universe. But he also believed that that goal could only be achieved through freeing oneself from the shackles of the "purely personal", from habits breeding the tyranny of primitive emotions. "To feel that behind that which is available to experience there is something inaccessible to our spirit, something of which the beauty and perfection reaches only indirectly and as a weak echo—*that* is religiosity. In *this* sense I am religious" [9, S. 255]. According to Einstein, "cosmic religious feeling ... can give rise to no definite notion of a God and no theology" [1, p. 38]. It merely inspires the scientist to perceive the loftiness and the marvellous order of the universe.

3. On the Independence of the World from Consciousness

We have seen that Einstein did not share the idealism as it was formulated by its classic representatives, although from time to time he turned to their works. He either ignored the basic philosophical propositions of the idealists or openly spoke of their negative impact on natural science. Of course, there are expressions in Einstein's works that were used by idealists. He did not always employ certain terms, borrowed from them, in a strict sense. As a result, the impression might be formed that Einstein shared certain idealist views of some of these philosophers.

There is another circumstance to be taken into account here. Einstein distinguished scientific propositions from literary digressions or, as he put it, "a literary fashion" [10, p. 213]: "You must distinguish between the physicist and the *littérateur* when both professions are combined into one.... What I mean is that there are scientific writers ... who are illogical and romantic in their popular books, but in their scientific work they are acute logical reasoners" [10, p. 211]. In these literary endeavours Einstein himself was guilty of certain "licence", so that if we, in reading these works, take into account only the form of expression and out-of-context formulations, ignoring the content behind the form and doctrine behind the isolated quotations, we may take Einstein for a Machist or Kantian or anything we please. It should be borne in mind, however, that this style of exposition of scientific ideas is characteristic not only of Einstein—many Western natural scientists are prone to this.

Taking for granted that Einstein was alien to idealism, we have a right to ask: and what was his attitude to the ideas of dialectical materialism? It is a fact that Einstein did not give a comprehensive exposé of his materialist world outlook in any of his works, and neither shall we find there any references to materialist dialectics as a science. So what we can discuss here is his attitude to separate propositions of materialism and dialectics.

Einstein clearly distinguished between two directions in philosophy and, consequently, between two views of the external world—the materialist and the idealist one. Unlike Mach and his followers, he rejected a third, intermediate, line in philosophy: "There are two different conceptions about the nature of the Universe:

"(1) The world is a unity dependent on humanity;

"(2) the world is a reality independent of the human factor" [7, p. 42].

To which of the two conceptions did Einstein adhere?

During a conversation with Einstein, the Irish writer James Murphy remarked: "You have already been widely quoted in the British Press as subscribing to the theory that the outer world is a derivative of consciousness", to which Einstein replied: "No physicist believes that. Otherwise he wouldn't be a physicist. ...You must distinguish between what is a literary fashion and what is a scientific pronouncement. ...Why should anybody go to the trouble of gazing at the stars if he did not believe that the stars were really there? ...We cannot logically prove the existence of the external world, any more than you can logically prove that I am talking with you now or that I am here. But you know that I am here and no subjective idealist can persuade you to the contrary" [10, pp. 212, 213].

Some idealists accused Einstein of solipsism. They alleged that only a separate individual and his consciousness could be deduced from his doctrine, the external world and other individuals in it existing merely in individual consciousness. Einstein's reply to this was: "Herr Gehrcke insists that the theory of relativity leads to solipsism; any specialist will regard this as a joke" [11].

However, along with these correct views of the status of the external world, Einstein sometimes made statements of the following kind: "The object of all science, whether natural science or psychology, is to co-ordinate our experiences and to bring them into a logical system" [12, p. 1], or: "The only justification for our concepts and system of concepts is that they serve to represent the complex of our experiences" [12, p. 2].

These and other statements in the same vein are often referred to by those who would have liked to see the great scientist as an idealist. Indeed, if one proceeds from the statements just cited, one may arrive at the conclusion that in terms of the cardinal question of philosophy Einstein adheres to a view that is far from materialism. However, if one considers his doctrine as a whole, one will see that his emphasis on sensations, sense-perceptions in his discussion of the goals of science and scientific concepts does not at all mean that he did not see the external world beyond the sense-perceptions, that they were for him, just as for Berkeley or Mach, the substance of the world. For Einstein, sense-perceptions were our images or rough copies of the objective world. The following statement confirms this view: "The belief in an external world independent of the perceiving subject is the basis of all natural science.... Sense-perception only gives information of this external world..." [1, p. 266].

As for the subject matter of science, and physics in particular, the very fact that Einstein recognised the objective character of nature and the subjective character of sense-perceptions rules out his reduction of the goals of science to the study of connections between sense-perceptions, assuming, on the contrary, a study of connections between the objects of the world, for Einstein assumed the existence of objective reality beyond the sense-perceptions. Einstein thus explained the goals of this science: "Physics is an attempt conceptually to grasp reality as it is thought independently of its being observed" [6, p. 81].

4. The Origin of the Concepts of Science: General Questions

Those who present Einstein as an idealist often use for arguments some of his statements on the origin of scientific concepts, asserting that Einstein viewed concepts as divorced from reality, as results of free cognitive activity.

We have indicated already that Einstein held a negative view of Kant's idea of the innate nature of scientific concepts or categories. Nonetheless, with regard to the origin of concepts, he sometimes wrote that the concepts arising in the process of thought are, from the purely logical viewpoint, free creations of reason. How is this thought of Einstein to be interpreted? Does it express the fact that scientific concepts are divorced from sense-perceptions, from the external world, and that man's reason, by itself, is their source?

Such a conclusion would be premature. In epistemological questions Einstein proceeded from the objective existence of the world reflected in human consciousness through sense-perceptions. For him, general concepts are an abstract quintessence of the most significant features of a certain area of phenomena or processes given to man through the senses. "The concepts [he wrote] originate from experience by way of 'abstraction', i.e., through omission of a part of its content" [2, p. 287]. Concepts have no meaning outside their links with sense-perceptions and the environment.

But these concepts "easily achieve so much authority over us that we forget their earthly origin and take them for something immutably given. They are then stamped as 'necessities of thought', 'a priori given', and so on. The path of scientific progress is often obstructed by these errors for long periods of time. It is therefore no idle amusement at all, when we are preoccupied with analysis of concepts that have been current for a long time and with showing upon what circumstances are dependent their justification and utility and how they emerge, individually, from experiential data. Thereby their excessively great authority is broken down. They are omitted, if they cannot be made properly legitimate; corrected, if their coordination with the given objects was too carelessly established; or replaced, if it is possible to construct a new system which we, for some reason, prefer" [5, S. 102].

Einstein also saw that sense-perceptions by themselves were not identical to the content of concepts, that they were only the building materials for the construction of the science's conceptual apparatus. He realised that empirical data had to be rationally processed. It is this complex dialectical transition from the sensuous forms of reflection to the origin of concepts that he interpreted as "free inventions of the human intellect" [1, p. 272]. Yet he had a rather curious idea of this "freedom": "The liberty of choice, however, is of a special kind; it is not in any way similar to the liberty of a writer of fiction. Rather, it is similar to that of a man engaged in solving a well-designed word puzzle. He may, it is true, propose any word as the solution; but, there is only *one* word which really solves the puzzle in all its parts. It is a matter of faith that nature—as she is perceptible to our five senses—takes the character of such a well-formulated puzzle. The successes reaped up to now by science do, it is true, give a certain encouragement for this faith" [1, pp. 294-295].

We thus see that "free" formation of concepts is by no means the same as divorcing them from objective reality, as Einstein sees it. As far as formation of concepts is concerned, Einstein uses the term "liberty" to show that concepts are qualitatively different from sense data as such, that they cannot be directly obtained from empirical material without some preliminary mental processing.

5. The Origin of Mathematical Concepts

Einstein is sometimes presented as an idealist on the strength of his interpretation of some general problems of mathematics. Certain passages in his work "Geometry and Experience" are cited to prove that. In that lecture he said that "the propositions of mathematics referred to objects of our mere imagination, and not to objects of reality", and that mathematics was "a product of human thought which is independent of experience" [1, p. 233].

However, if one reads the whole of that work as well as Einstein's numerous other expositions of the general problems of mathematics, it will become clear that there are no grounds for accusing him of an idealist interpretation of mathematics. Einstein proceeded from the fact that mathematics is rooted in the external world, arising out of men's practical needs: "It is certain that mathematics generally, and particularly geometry, owes its existence to the need which was felt of learning something about the behaviour of real objects. The very word geometry, which, of course, means earth-measuring, proves this. For earth-measuring has to do with the possibilities of the disposition of certain natural objects with respect to one another, namely, with parts of the earth, measuring-lines, measuring-wands, etc." [1, p. 234]. Of course, mathematics, having emerged to satisfy society's practical needs, later acquires a certain autonomy. Drawing upon new materials from the external world, it becomes an increasingly abstract discipline. It is this abstract character which may, at a certain stage, result in its propositions being divorced from the real world—something that idealists exploit towards their own ends. Einstein stressed the following point in this connection: "The fatal error that logical necessity, preceding all experience, was the basis of Euclidean geometry and the concept of space belonging to it, this fatal error arose from the fact that the empirical basis, on which the axiomatic construction of the Euclidean geometry rests, had fallen into oblivion" [1, p. 298].

Einstein realised that mathematics was connected with the external world not only in its origin, through its past, so to speak. Its propositions always reflect reality. The criterion of the truth and reliability of mathematics ultimately lies in practice: "Geometry may be true or false, according to its ability to establish correct and verifiable relations between our experiences" [13, pp. 159-160].

And here is what Engels wrote on the same questions in his polemics against E. Dühring: "Like all other sciences, mathematics arose out of the *needs* of men.... But, as in every department of thought, at a certain stage of development the laws, which were abstracted from the real world, become divorced from the real world, and are set up against it as something independent, as laws coming from outside, to which the world has to conform. That is how things happened in society and in the state, and in this way, and not otherwise, *pure* mathematics was subsequently *applied* to the world, although it is borrowed from the same world and represents only one part of its forms of interconnection—and it is only *just because of this* that it can be applied at all" [14, p. 52].

A comparison of the views of Einstein and Engels shows clearly that, on a general plane, Einstein gave a materialist interpretation of mathematics. He saw that its propositions were in the final analysis conditioned by the actual material relations between the objects of the world.

But can one bring into agreement Einstein's statements on mathematics cited at the beginning of this section and at the end of it? Isn't there a contradiction here? We believe that there is none, for in the second case Einstein speaks of the origin of mathematics and its links with reality, and in the first case, of the objects of mathematics. Mathematics, as we know, is the science of spatial forms and quantitative relationships. The objects of mathematics are abstractions and idealisations devoid of content yet reflecting the external world. It is this aspect of mathematics that Einstein focuses on when he says that its propositions are based on objects of our imagination rather than on real objects. By objects of imagination he means abstractions and idealisations deduced from the real world by our consciousness.

6. The World Is Cognisable

We have seen that, in terms of the cardinal question of philosophy, Einstein adhered, on the whole, to materialistic positions. He had no doubts that nature existed before man and that it could not be made dependent on perception and consciousness. Neither did he have any vacillations concerning the origin of scientific concepts, categories, scientific laws, mathematical propositions, and so on. He did not divorce them from material reality either. But what was Einstein's attitude to problems raised by the other aspect of the cardinal question of philosophy? As Engels put this question, "Is our thinking capable of the cognition of the real world? Are we able in our ideas and notions of the real world to produce a correct reflection of reality? " [15, p. 346].

Einstein attributed great significance to the cogniscibility of the external world. He believed in the ability of the human mind to cognize the world: "The basis of all scientific work is the conviction that the world is an ordered and comprehensive entity" [16, p. 98]. To cognize the essence of the world means to reflect it in concepts and compare these concepts with reality. "In speaking here of 'comprehensibility' [wrote Einstein], the expression is used in its most modest sense. It implies: the production of some sort of order among sense impressions, this order being produced by the creation of general concepts, relations between these concepts, and by definite relations of some kind between the concepts and sense experience. It is in this sense that the world of our sense experiences is comprehensible" [1, p. 292]. Einstein's optimism and his belief in the comprehensibility of the world stem from a profound belief in the existence of law-governed links and causal conditionality in nature. In his approach to the problem of cognition Einstein proceeds from the recognition of the external world as the object of cognition and not from sense-perceptions, as was often imputed to him.

We have already said that sense data, according to Einstein, are a reflection of the external world; Einstein referred to sense-perceptions as the object of knowledge in the spirit of the materialist tradition rather than in the sense of Berkeley or Mach. Beyond the sense-perceptions, he distinguished the external world. For Hume, knowledge based on empirical data is unreliable; in contrast to that Einstein insisted that sense data were the source of our knowledge. He wrote: "The sensory raw-material [is] the only source of our knowledge" [2, p. 285]. He stressed that unprocessed "raw" material of the external world "may lead us to belief and expectation but not to the knowledge and still less to the understanding of law-abiding relations" [2, p. 285]. Knowledge is therefore based on the formation of scientific concepts and discovery of the laws of nature that may be arrived at through rational processing of sense data.

Neither could Einstein accept agnosticism in the spirit of Kant, who regarded the essence of the objects of the external world as in principle incognisable. According to Kant, phenomena do not reflect the essence of things and are unconnected with it. As for Einstein, we have seen that he believed in the knowability of material objects' essence.

On numerous occasions Einstein turned to the question of the essence of scientific theory. We know that some of his distinguished contemporaries believed laws of nature to be arbitrary conventions. In their view, these laws were not necessarily reflections of actual processes of the objective world but rather convenient reference frames of scientific description. Einstein held, however, that scientific theories, just as scientific concepts, could not emerge unconnected with reality, and that they were results of the processing of information about the external world given us through sense-perceptions. "The theoretical idea [he emphasised] does not arise apart from and independent of experience; nor can it be derived from experience by a purely logical procedure. It is produced by a creative act. Once a theoretical idea has been acquired, one does well to hold fast to it until it leads to an untenable conclusion" [17, p. 14].

For Einstein, each theoretical proposition was, in its content, a reflection of the processes of the external world or, as he himself expressed that idea, "every magnitude and every assertion of a theory lays claim to 'objective meaning' (within the framework of the theory)" [4, p. 680]. On another occasion he wrote: "The most important demand to be made of every scientific theory will always remain that it must fit the facts" [18, p. 15].

A theory, as Einstein understood it, could not be brought into agreement with itself or with an "eternal idea", as some idealists assumed. For him, a theory was always verifiable by experience. In its very content, a scientific theory did not depend on man's consciousness. In a conversation with Rabindranath Tagore, for whom truth was perfect understanding of the universal reason, Einstein stressed this idea: "I cannot prove that scientific truth must be conceived as a truth that is valid independent of humanity; but I believe it firmly. I believe, for instance, that the Pythagorian theorem in geometry states something that is approximately true, independent of the existence of man. Anyway, if there is a *reality* independent of man, there is also a truth relative to this reality; and in the same way the negation of the first engenders a negation of the existence of the latter" [7, p. 43].

7. Spontaneous Dialectics

Although Einstein never touched on the theory of dialectics, a study of his works shows that he cannot be regarded as a metaphysically (antidialectically) thinking scientist. His world outlook is dialectical in its very essence. We shall not discuss here those elements of objective dialectics which follow from analysis of the special and general relativity theories, but shall merely consider some of Einstein's views of physical science as a whole, as well as some of his pronouncements on epistemological questions, which justify the conclusion that he had a profound dialectical intuition. They show that the following remark of Engels could well be applied to Einstein: "Men thought dialectically long before they knew what dialectics was, just as they spoke prose long before the term prose existed" [14, p. 170].

We know that in the 16th and 17th centuries the needs of social practice brought about a revolution in the study of nature. At the same time the metaphysical method of study was shaped which was gradually elevated to the rank of a universal philosophical methodology. For decades, the metaphysical worldview held sway; according to it, separate elements of nature and, consequently, concepts of these elements were considered without reference to their development or the universal connections between things. Despite all this, some dialectical ideas took hold. Scientists who had enough empirical data to justify general conclusions went beyond the limits of metaphysical views. Copernicus, Kepler, Newton and other natural scientists were guided in their discoveries by the dialectical idea of the universal coherence and unity of nature.

Natural scientists of the 18th and 19th centuries found themselves in a contradictory situation when, on the one hand, they were dominated by a metaphysical methodology, and on the other, the reality they studied pointed more and more clearly to the dialectical nature of the objective world. Einstein found himself in a similar situation, but a wealth of empirical data prompted him that the external world was an integral material entity, and Einstein saw "the sublimity and marvelous order which reveal themselves both in nature and in the world of thought" [1, p. 38].

Einstein was also profoundly influenced by the ideas of Lucretius and Spinoza. Einstein wrote that Spinoza "was utterly convinced of the causal dependence of all phenomena, at a time when the success accompanying the efforts to achieve a knowledge of the causal relationship of natural phenomena was still quite modest" [19, p. XI]. Einstein fully accepted the conception of the causal dependence of natural phenomena. He emphasised that causal links were objective in nature, being connections of the external world. Einstein therefore rejected Hume's and Mach's subjectivist view of causal dependence as the habit of perceiving one event after another. He wrote: "It is worthy of admiration, that firm belief in physical causality, which does not stop even at the will of the *homo sapiens*" [8, pp. 54, 55].

Some time ago the idea gained currency in the West that there was freedom of will in inorganic nature: it was insisted that mostly indeterminate processes went on in the microworld. The conclusion is sometimes drawn that there is no causality in the external world in general. Einstein was decidedly against the conception of indeterminism in any shape, manner, or form. He referred to that idealist proposition in the following terms: "That nonsense is not merely nonsense. It is objectionable nonsense.... Indeterminism is quite an illogical concept" [10, pp. 201-202].

However, Einstein did not have an entirely straightforward picture of the concept of causality as it originated in the study of quantum-mechanical processes. It is known that there may be different manifestations of causality depending on the properties of the object under study. For example, in the macroprocesses causality is expressed in the form of unambiguous or dynamic laws, and in the microworld, through statistical laws. Einstein held a skeptical view of the statistical conception of causal connection. He wrote that "modern quantum theory contains a weakening of the concept of causality" [20, p. 758]. However, as distinct from many bourgeois philosophers who interpreted the statistical nature of the laws of the microworld as signifying the end of the concept of causal connection in nature and society, as proof of the electron's "free will", etc., Einstein stressed that deviation from the former conception of causality did not "open a back-door to the advocates of free will", and that there was "no room for 'free will' within the framework of scientific thought, nor for an escape into what has been called 'vitalism'" [20, p. 758]. Einstein's dialectical frame of mind forced the conclusion that, before tackling the processes of the microworld, scientists operated with the principle of causality in its merely rudimentary form. Raising this proposition to an absolute, they extended it to embrace the processes of the microworld, too. In actual fact the current conception of causality is limited in character, forming part of a broader concept that has not yet been given an adequate interpretation. "Now I believe [wrote Einstein] that events in nature are controlled by a much stricter and more closely binding law than we suspect today, when we speak of one event being the *cause* of another" [10, p. 203].

Thus no processes in the world, according to Einstein, can be regarded as random or isolated. The universe is governed by a strict order or law, and everything in it is interconnected and mutually conditioned.

The dominant position of metaphysics also left its impact on the interpretation of the dynamics of scientific concepts, theories, and the foundation of science. Inasmuch as the objects of the external world and the world as a whole appeared to be immutable in time, their reflection in scientific concepts and theories was also accepted as given once and for all, as truth in the highest instance. We shall not touch here on the contribution of the founders of materialist dialectics to the overcoming of the metaphysical world outlook. Let us see how this problem was interpreted and solved by Einstein. On the whole he saw the defects of the metaphysical methodology, criticising those who accepted scientific concepts as something immutable and given once and for all. If we wish scientific concepts to facilitate the development of science, they must necessarily be revised from time to time and expanded to accommodate new developments in the cognition of the external world. "The situation changes, however [wrote Einstein], when one of the habitually employed concepts must be replaced by a more clear-cut one in accordance with the requirements of the development of the discipline in question. Then those who have used that concept in a rather loose sense, raise an energetic protest, complaining about a revolutionary threat to the most sacred things. Mixed with these cries are the voices of those philosophers who believe that they cannot do without that concept as they have included it in their treasury of the 'absolute', 'a priori', etc., in short, because by aligning them in a certain manner they have proclaimed them to be in principle immutable" [5, S. 102].

Inasmuch as the scientific concepts forming the logical basis of the laws of nature are neither static nor absolute, the laws cannot be regarded as absolutes either, according to Einstein: "A law cannot be definite for the one reason that the conceptions with which we formulate it develop and may prove insufficient in the future. There remains at the bottom of every thesis and of every proof some remainder of the dogma of infallibility" [16, p. 100].

The idea of presenting the whole of physics, together with its fundamental problems, as an immutable science was not accepted by Einstein either. Unlike some scientists, he saw physics as a dynamic and historical science. In this connection he wrote: "Our notions of physical reality can never be final. We must always be ready to change these notions—that is to say, the axiomatic basis of physics—in order to do justice to perceived facts in the most perfect way logically. Actually a glance at the development of physics shows that it has undergone far-reaching changes in the course of time" [1, p. 266].

The attitude of many physicists to Newton's mechanics is well known. Up to the 20th century it was presented as an immutable science that could give answers to all questions of the structure of inorganic matter; some saw it as the key to the cognition of organic matter, too. Einstein realised, however, that Newton's mechanics was essentially a relative science. In an article on the centenary of the birth of W. Thomson, the well-known physicist and one of the most brilliant defenders of the infallibility of Newton's mechanics, Einstein gave him his due for his contributions to the development of physics, yet at the same time spoke of "something tragic" about his scientific activity. This tragic element lay, in his view, in the fact that Thomson blindly believed, to his dying day, in the absolute character of Newton's mechanics. "Thomson, who viewed the foundations of physical knowledge as quite safe almost to the end of his days, would be shocked if he were able all of a sudden to see some of our present-day literature" [21, S. 601].

The conclusion that physical knowledge is relative did not compel Einstein to reject the external world and objective truth, as was the case with a number of physicists called "physical" idealists. Lenin believed that the reason why some physicists travelled the road to idealism via relativism was their ignorance of dialectics: "The other cause which gave rise to 'physical' idealism is the principle of *relativism*, the relativity of our knowledge, a principle which, in a period of abrupt break-down of the old theories, is taking a firm hold upon the physicists, and which, *if the latter are ignorant of dialectics*, inevitably leads to idealism" [22, p. 308].

Einstein did not discard Newton's mechanics. He put it in its proper place in the structure of physical knowledge, in accordance with his belief that the theoretical conclusions of mechanics were only applicable to a definite range of phenomena. He wrote: "First we try to get clearly in our minds how far the system of classical mechanics has shown itself adequate to serve as a basis for the whole of physics" [1, p. 301]. Unlike metaphysicians, Einstein insisted on the continuity of physical theories. Concerning the impact of Newton's mechanics on the shaping of a number of problems of theoretical physics, he wrote: "The whole evolution of our ideas about the processes of nature ... might be regarded as an organic development of Newton's ideas" [1, p. 261].

Einstein realised that all our knowledge was but relative truth, that all of it but formed stages in the attainment of complete knowledge. Although his works do not include a study of the correlation between absolute and relative truth, it may be observed that on several occasions he expresses a similar idea in terms of spontaneous dialectics. For example, he insisted that Newton's fundamental concepts and hypotheses were merely an approximation of the truth. Concerning the possibility of creating a complete physical picture of the world he asserted that theoretically one could conceive of a solution for such a task, but it could not be done practically [10, p. 12]. In "Physics and Reality", where he considers the dynamics of scientific thought, he draws the same conclusion, showing the way in which accumulated knowledge leads to more and more comprehensive knowledge [1, pp. 293-323].

The dialectical quality of Einstein's thinking was also manifested, as we have seen, in his interpretation of the correlation between the theoretical and the empirical. Unlike many metaphysically-minded scientists, he did not hold either of the two extremes. Giving logical reasoning in cognition its due, he did not divorce it from the objective world: "...thinking alone can never lead to any knowledge of external objects. Sense perception is the beginning of all research, and the truth of theoretical thought is arrived at exclusively by its relation to the sum total of those experiences" [20, pp. 757-758]. Or, on another occasion: "All knowledge of reality starts from experience and ends in it" [1, p. 271].[1]

In his polemics with those who attributed to Galileo a neglect for the deductive method, Einstein remarked: "It has often been maintained that Galileo became the father

[1] Lenin expressed this idea in the following form: "From living perception to abstract thought, *and from this to practice*—such is the dialectical path of the cognition of *truth*, of the cognition of objective reality" [23, p. 171].

of modern science by replacing the speculative, deductive method with the empirical, experimental method. I believe, however, that this interpretation would not stand close scrutiny. There is no empirical method without speculative concepts and systems; and there is no speculative thinking whose concepts do not reveal, on closer investigation, the empirical material from which they stem. To put into sharp contrast the empirical and the deductive attitude is misleading, and was entirely foreign to Galileo" [24, p. XVII].

It is a fact that differentiation of science facilitates a deeper penetration into the essence of the individual phenomena of the world. In the absence of adequate knowledge of dialectics, however, this process may bring about a mental separation of these phenomena. Einstein sensed this metaphysical danger quite acutely. Differentiation is fraught with the danger of losing the connecting thread in the mass of individual phenomena, a thread that is so necessary for a deeper cognition of the given thing. Einstein gives a fine illustration of that idea from the development of medical science: "In medicine, too, considerable specialisation has become unavoidable with increasing knowledge; but in this case specialisation has its natural limits. If some part of the human body has gotten out of gear, a person with sound knowledge of the whole complex organism is needed to put it right; in a complicated case, only such a person can obtain an adequate understanding of the disturbing causes. For this reason, a comprehensive knowledge of general causal relations is indispensable to the physician" [20, p. 755].

An analysis of Einstein's views on the epistemological problems of natural science thus shows the dialectical character of his thinking.

* * *

A study of Einstein's world outlook warrants the conclusion that it is not identical with any of the idealist philosophical systems. Attempts to link up his views with Berkeleyanism, Kantianism, neopositivism, solipsism, etc., are untenable. He did not share any of the basic notions underlying these idealist trends. In his attitude to the external world Einstein was a spontaneous materialist and dialectician. This conclusion also follows from the very nature of his physical discoveries. The theory of relativity may justly be regarded as one of the most significant natural-scientific discoveries confirming dialectical materialism. Einstein's physical discoveries led to a radical revision of the older metaphysical concepts of space and time. Thus, the special theory of relativity proved that changes in the velocity of an object's motion entail changes in its spatio-temporal characteristics. It revealed the dialectical unity of the attributes of matter. The general theory of relativity further developed the ideas of space and time. The discovery of the fact that the bodies' mass determines the geometrical structure of space and time, pointed to the existence of a deep organic bond between space, time, and matter. The dialectical materialist idea that space and time are forms of the existence of matter was thereby confirmed and further developed by natural science.

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M. E. OMELYANOVSKY

EINSTEIN, THE FOUNDATIONS OF MODERN PHYSICS AND MATERIALIST DIALECTICS

1

The theory of relativity and quantum mechanics that became the cornerstones of modern, or non-classical, physics, were arrived at by the royal road of the development of physical science in the 20th century. These are the fundamental theories of science; they are not reducible to the concepts and principles of the theory of previously existing classical physics, although they are linked with the latter. This idea, quite common in these days, at the time when it asserted itself meant a revolution in physical science whose basic principles and concepts had seemed immutable to Newton, Maxwell, Kelvin and other great representatives of classical physics; the question of the fundamental nature of physical theories now had to be formulated and solved in a way different from that customary in 18th- and 19th-century natural science.

This was first clearly expressed in the language of Einstein's theory of relativity (we mean the special and general relativity theories completed some time in the late 1910s) and, somewhat later, in the concepts and principles of quantum mechanics (completed in the late 1920s) largely founded by Niels Bohr.

Physics, just as natural science as a whole, believes its most important task, materialistically conceived, to be the reflection of nature such as it is by itself, without any arbitrary additions from the cognising intellect. This pervading spirit of natural science is the reason why eminent scientists, subjectively unconcerned with dialectics, unconsciously apply its principles and ideas in discovering new laws of nature and formulating new scientific theories, including fundamental ones. In connection with the discovery of the periodic law Engels said that "by means of the—unconscious—application of Hegel's law of the transformation of quantity into quality, Mendeleyev achieved a scientific feat" [1, p. 68]. The same thing may be said about the creators of the relativity theory and of quantum theory, and that is the subject, in one form or another, of the present article. As Lenin proved, the latest revolution in natural science organically combined, at the time when this revolution took its very first steps, the physics of our times with dialectical materialism.

The transitions from classical to modern physics and, much earlier, from the natural philosophy of antiquity and the Middle Ages to classical physics, were scientific revolutions closely linked with revolutions in philosophy. A revolution in physics (with reference to the science as a whole) is a transformation of its theoretical content which breaks up its established foundations, that is, an ensemble of its principles and fundamental concepts, along with the customary methods of cognition and style of thinking, and establishes new foundations, new methods of cognition and a new style of thought.

Unlike antique and medieval philosophy, philosophical cognition and natural science of the New Times rejected the idea of immutable philosophical and scientific values rooted in common sense. Physics becomes an experimental science; sense perception is combined in it with theoretical thinking; abstract methods and the closely related mathematisation of science become common. Experimental data are no longer characterised as common-sense notions but are rather interpreted by scientific theory featuring concepts that are remote from sensual givenness both in their content and mutual relations. The apparatus and experimental tools without which profound knowledge of nature in classical physics would be impossible enable scientists to see atoms in thought (with this regard, modern physics furnishes a wealth of data on elementary particles). The idea of development is introduced into the natural sciences from new philosophy, albeit in a one-sided and limited form: inherent in classical physics is the reduction of its theory to Newton's mechanics; there is a corresponding change in the spirit of scientific cognition and the style of thinking, if one compares the natural science of antiquity with that of the New Times.

In modern physics, the idea of the development of nature and knowledge of nature, the idea of development in its most profound and complete, that is, dialectical, sense, permeates all its branches and areas, including the foundations of the theoretical edifice of science. Modern physics is in principle a unified science consisting of fundamental theories connected in their origins and forming a hierarchical spiral the length of which grows with the development of human culture, technology, industry, and society as a whole. In modern physics, experimental data are described in terms of classical physics and are given an interpretation in terms of non-classical theories. In this epoch, the spirit of scientific cognition is the spirit of dialectical materialism. Physics, its history and theories, particularly the modern ones, are a field where the essence of dialectics is manifested in most divers forms, dialectics being, according to Lenin, the theory of "how *opposites* can be and how they happen to be (how they become) *identical*,—under what conditions they are identical, becoming transformed into one another,—why the human mind should grasp these opposites not as dead, rigid, but as living, conditional, mobile, becoming transformed into one another" [2, p. 109].

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The outstanding representatives of classical physics regarded the establishment of immutable laws of nature as the most important task of science, believing them to be the foundation of natural science. They thought that Newton's mechanics formed precisely such a foundation, and the development of physics after Newton appeared to them as a kind of reduction of what was known or seemed to be known to the propositions and models of classical mechanics. In actual fact, however, the development of physical science, of its fundamental theories in the first place, was in no way like the reduction of its theoretical content to the foundations of classical mechanics.

Sufficient proof of this is to be found in the development of classical physics—to wit, in Maxwell's theory of electromagnetism.

James Clerk Maxwell, studying Faraday's experimental data on electricity and magnetism in their entirety and expressing them in the language of mathematical abstractions, discerned a certain contradiction between the equations obtained. To eliminate the contradiction, Maxwell substituted one of the mathematical expressions for another without any experimental substantiation (that came later), and that was how the theory of electromagnetism was born. Max Born wrote of this development that Maxwell's decisive step was "first guided by mechanical models of the ether, later by reasons of mathematical perfection or beauty, or however you may describe the act of genius" [3, p. 10]. To this may be added that genius and dialectics always go hand in hand. The step that Maxwell took signified essentially that he combined within a single whole such opposites as electricity and magnetism.

The scientific revolution that yielded non-classical physics is radically different in its complexion and cognitive results from the revolution that produced classical, fundamentally mechanist, physics. For modern physics, it is essential not merely to find the laws of phenomena in a certain material system or area of interconnections: it is extremely important to find the laws of transition from laws governing a certain set of phenomena to the more profound and general laws of a new and more extensive set of phenomena (and that task arises in some form or other at a certain stage in the development of physics). That is the really dialectical fashion in which the special and general theories of relativity emerged and asserted themselves, as well as quantum mechanics and quantum electrodynamics, that is the way in which the modern theory of elementary particles and astrophysics are developing.

In creating the relativity theory, Einstein laid the basis for a new concept of the foundations of physics, quite different from the one current in physical science from the time of Newton and up to the end of the 19th century. It was the relativity theory that undermined the dogmatic idea of the immutability of the fundamental principles and concepts of the physical science that had seemed so self-obvious before Einstein. The very emergence of this theory at the borderline between classical mechanics and classical electrodynamics, which resulted from Einstein's solution of the contradictions between them, is a magnificent example of the efficacy of the law of the unity and struggle of opposites. The origin and content of the general theory of relativity cannot be interpreted without recourse to dialectics, either. All of this will form the subject matter of the rest of this work, but for the time being we shall restrict ourselves to a few introductory remarks.

In his "Autobiographical Notes" Einstein points out that in retrospect already Maxwell and Hertz appear as those who demolished the faith in mechanics as the final basis of all physical thinking, although in their conscious thinking they adhered throughout to mechanics as the secure basis of physics. He goes on to say: "It was Ernst Mach who, in his *History of Mechanics*, shook this dogmatic faith. ...I see Mach's greatness in his incorruptible skepticism and independence; in my younger years, however, Mach's epistemological position also influenced me very greatly, a position which today appears to me to be essentially untenable. For he did not place in the correct light the essentially constructive and speculative nature of thought and more especially of scientific thought" [4, p. 21].

Indeed, it was Einstein who, by creating the theory of relativity, undermined the tenets of immutability and unrestricted applicability of Newton's mechanics and thus effectually proved the relativity of its laws and propositions. But one could cope with the philosophical problem of the relative nature of scientific truth only from the positions of dialectical materialism. In formulating the relativity theory, Einstein applied the laws of dialectics to the cognition of the physical world unconsciously; subjectively, he was very far from Marxist philosophy. That explains, in the final analysis, his youthful enthusiasm for Mach's philosophical teaching which, as he saw it, opposed the physicists' dogmatic belief in Newton's mechanics.

Eventually, Einstein abandoned Mach's philosophy entirely, which became quite obvious by 1922. In 1910 Mach still accepted the relativity theory, but he soon came to reject in principle further generalisation of this theory by Einstein. During a discussion of the relativity theory organised by the French Philosophical Society in Paris in 1922, Einstein gave this answer to the question of his attitude to Mach:

"Mach's system studies relations obtaining between experimental data; the ensemble of these relations is, for Mach, the precise science of nature. That is a bad viewpoint; generally speaking, what Mach has done is a catalogue, not a system. Mach was just as poor a philosopher as he was a fine mechanist" [5, p. 11].[1]

This rather critical evaluation of Mach as a philosopher by Einstein speaks for itself. Unlike his contemporaries and followers, Mach acted quite consistently in the spirit of his epistemology and rejected the objective reality of atoms (Einstein made negative comments on that score on several occasions) and the relativity theory. As is well known, Einstein, besides formulating the theory of relativity, was also one of the founders of the modern theory of the atom. Thus Mach's attitude to Einstein's discoveries may be an indication of the positivists' hostility to modern physics, of the essential inability of positivism to be the philosophy of modern physics. It is appropriate to recall in this connection Lenin's words about the modern science of the atom: "The destructibility of the atom, its inexhaustibility, the mutability of all forms of matter and of its motion, have always been the stronghold of dialectical materialism" [7, p. 281]. In the same way, dialectical materialism has always been based on the conception of indissoluble unity of space and time, of organic links between space and time, on the one hand, and moving matter on the other. The philosophical line of the theory of relativity and of new physics as a whole is fully in keeping with the words of Lenin: "The mutability of human conceptions of space and time no more refutes the objective reality of space and time than the mutability of scientific knowledge of the structure and forms of matter in

[1] This answer (as well as other materials) is quoted in Friedrich Herneck's paper "Zu einem Brief Albert Einsteins an Ernst Mach". *Physikalische Blätter* (Mosbach-Baden), 1959, Heft 12. See also our comments on this article [6].

motion refutes the objective reality of the external world" [7, p. 175].

All of this is indicative of the reasons for Einstein's disappointment in Mach's positivism. Why was it that in 1922 Einstein referred to Mach's philosophy in terms so different from his statements of previous years? The obvious reason is that the relativity theory developed, contrary to what some modern bourgeois philosophers believe, in opposition to the positivist doctrine of space and time rather than on the basis of this doctrine, just as modern theories of the atom developed in opposition to positivism. The great physicist's spontaneous materialism and his unconscious application of dialectics to the foundations of science proved to be stronger than Mach's "poor philosophy". When Einstein developed his relativity theory, he disapproved of Max Planck's criticism of Mach's positivism, but later he took the same philosophical positions as the founder of quantum theory. Lenin referred to Einstein as a "great reformer of natural science", pointing out that his theory "has already been seized upon by a vast number of bourgeois intellectuals of all countries" and that "this applies not only to Einstein, but to a number, if not to the majority, of the great reformers of natural science since the end of the nineteenth century" [8, p. 233]. It would be quite justified to state definitely that the great reformers of natural science, Planck and Einstein, proceeding from the theories they created, rejected positivism as a philosophy for modern physics.

Now, in what way did the theory of relativity, which marked the beginning of non-classical physics, develop in terms of the logic of the problems involved? Let us restrict ourselves to a very brief exposition of the most essential points here.

According to Maxwell's electrodynamics, light travels in free space at a constant universal velocity; classical electrodynamics admitted the existence of luminiferous ether, and that accorded with the experimentally given fact of the independence of light velocity from the motion of its source. But how is this proposition concerning light velocity satisfied in an inertial system? A universal constant light velocity appeared to be an impossibility in inertial systems, since the existence of such a constant rules out Galileo's relativity principle. At the same time various experiments, including the famous Michelson experiment, ran counter to the ideas asserting in one form or another the existence of a preferred reference system.[2]

Thus when problems of applying electrodynamics to phenomena in moving bodies arose, a contradiction became apparent in classical physics between mechanics and electrodynamics, the contradiction between Galileo's relativity principle and the universal constant velocity of light propagation. Both of them were convincingly proved by experiments but appeared logically inconsistent. Einstein solved the contradiction in a genuinely dialectical fashion. He combined, and not by means of logical conjunction either, Galileo's relativity principle and the constancy of light velocity principle, mutually exclusive in classical theory, within a unified whole, and that meant the birth of a new physical theory—relativistic mechanics, in which both of these principles appeared in a new form and were necessarily linked with each other.[3] New fundamental physical concepts of space, time, and so on were formed, a new law of motion at near-light speeds for particles was formulated, and the law of mutual connection between mass and energy was discovered. The principal laws of classical mechanics were generalised, and all these conceptual transformations were essentially dominated by the dialectical idea of combining, in a kind of unity, time and space, which in classical physics were interpreted as the concept of space as such and the concept of time as such (cf. Hermann Minkowski's ideas).

A generalisation of the special relativity theory to include the phenomenon of gravitation led to a new theory which Einstein, its creator, called "the general theory of relativity". Not all scientists believe this to be an apt name; V. A. Fok was of the opinion, for instance, that "this term ill suits the actual physical content of Einstein's

[2] As is known, the theory of relativity was formulated independently of the Michelson experiment. At the same time Einstein insisted that without this experiment the theory of relativity would have remained a hypothesis.

[3] The propositions of relativistic mechanics concerning the principle of relativity apply not only to mechanical phenomena in inertial systems (as in classical mechanics) but also to some others.

theory and is thus quite unfortunate" [9, p. 289]. Much earlier, the prominent physicist Arnold Sommerfeld had also spoken against the term "the general relativity theory". In his view, "the positive achievement of the theory is not so much the complete relativization of space and time, but the proof that the laws of nature are independent of the choice of reference system, i.e., that events in nature are invariant under any change in the observer's viewpoint. The names 'theory of the invariance of natural events', or, as occasionally proposed, 'viewpoint theory', would be more appropriate than the customary name, 'general theory of relativity' " [10, p. 16]. Later we shall go back to the physical content of the general relativity theory bearing in mind these remarks by Fok and Sommerfeld.

Of greatest importance for the formulation of Einstein's gravitation theory, or the relativistic theory of gravitation, was the "equivalence principle" (Einstein's expression) assuming the identity of such opposites as inertia and gravitation. Essentially just as important was Newton's experiment with the pendulum proving that the mass of the body is proportional to its weight; it was in a sense a continuation of Galileo's experiments showing that all bodies fall with equal acceleration in vacuum. Newton did not include the facts of inertia and gravity being identical in the theoretical content of physics, accepting them only empirically.

It sometimes happens in the historical development of science that certain experimental facts are left uninterpreted by an established and well-formed theory. People grow accustomed to this, and not everyone can see that the theoretical interpretation of these facts lies far beyond the framework of the established theory. That is precisely the way in which the general relativity theory, or Einstein's gravitation theory, came into being, which at the time of its formulation was based on the same experimental data as Newton's theory of gravitation—with the addition, however, of a set of new ideas and the corresponding mathematical apparatus foreign to classical theories.

Classical mechanics and Newton's gravitation theory did not worry, so to speak, about the proportionality or equality (given the proper choice of units) of the body's gravitational and inertial masses; in Einstein's words, this equality was recorded but not interpreted. Finding a substantiation for the equality of the gravitational and inertial body masses or, to be more precise, finding a theoretical substantiation for the proposition that "the gravitational mass of a body is equal to its inertial mass" could signify nothing but a conceptul step beyond the limits of Newton's gravitation theory and construction of a theory that would be a metatheory, as it were, with regard to Newton's. That was exactly what Einstein did in evolving a relativistic theory of gravitation.

Pointing out that classical mechanics recorded but did not interpret the proposition "the gravitational mass of a body is equal to its inertial mass", Einstein developed this idea in the article "Relativity. The Special and the General Theory" in the following manner: "*The same* quality of a body manifests itself according to circumstances as 'inertia' or as 'weight' (lit. 'heaviness')" [11, p. 65]. In formulating this idea Einstein provided a theoretical substantiation to the equality, empirically stated in classical theory, of gravitational and inertial masses, thus laying a foundation for a new physical interpretation of gravitational phenomena. The dialectical nature of Einstein's approach becomes absolutely clear. The inertial and gravitational masses, regarded in classical theory as absolutely separate and independent, proved to be mutually correlative and dialectically inseparable in Einstein's theory; they became, in his words, aspects of "*the same* quality of a body", one that was unknown in Newton's mechanics [11, p. 65].

The following passage from Einstein's work "What Is the Theory of Relativity? " may contribute towards a more concrete realisation of his fundamental idea: "Imagine a coordinate system which is rotating uniformly with respect to an inertial system in the Newtonian manner. The centrifugal forces which manifest themselves in relation to this system must, according to Newton's teaching, be regarded as effects of inertia. But these centrifugal forces are, exactly like the forces of gravity, proportional to the masses of the bodies. Ought it not to be possible in this case to regard the coordinate system as stationary and the centrifugal forces as gravitational forces? This seems the obvious view, but classical mechanics forbid it" [12, p. 231].

The general relativity theory restricts the special theory of relativity which is only applicable as long as the effect of the gravitational field on physical phenomena can be neglected. For example, in a gravitational field light travels, generally speaking, along a curvilinear rather than rectilinear trajectory,[4] that is to say, the law of constant light speed (one of the basic premises of the special theory of relativity) cannot be claimed to be applicable without any limitations. Putting this more definitely, the special theory of relativity proves to be an extreme case of Einstein's gravitation theory; it shares the methodological and cognitive destiny of any *genuine* physical theory, and here it would be appropriate to quote Einstein: "No fairer destiny could be allotted to any physical theory, than that it should of itself point out the way to the introduction of a more comprehensive theory, in which it lives on as a limiting case" [11, p. 77]. This remark, clearly dialectical in nature, forms as it were the logical axis of the development not only of the relativity theory but also the whole of the theoretical content of modern physics. It follows from this, in particular, that one can hardly accept Sommerfeld's statement that his term "theory of the invariance of natural events" is better than the name "general theory of relativity": Sommerfeld's suggestion actually leaves out the development of relativistic theory itself out of classical physics.

It should be said about the general relativity theory that it furnished those gravitational laws which classical physics and the special theory of relativity had been unable to formulate. The road to this attainment was far from simple. It required a rejection of Euclid's geometry as applied to physical phenomena. Physical concepts of space and time were no longer interpreted as divorced from matter; the spatial characteristics of bodies, their physical behaviour and the flow of time proved to be dependent, first of all, on gravity fields, which do not

[4] The fact of the deflection of light required by theory was established experimentally during the eclipse of the sun on May 29, 1919.

exist outside of material bodies. The propositions of dialectical materialism concerning time and space as forms of the existence of matter were confirmed in a remarkable fashion by the general relativity theory, or the relativistic gravitation theory, not to mention the further impetus this theory gave to the development of dialectical materialist views on the subject.

We would like to emphasise some concrete details of the physical content of the relativistic gravitational theory. According to the Einstein equivalence principle, it is impossible to distinguish between free motion of bodies in an accelerated reference system and the motion of bodies in a gravitational field. In particular, all phenomena in a reference system rigidly connected to a body moving freely in a gravitational field, occur in such a way as if the gravitational field did not exist. In this way the gravitational field can be eliminated only in a certain restricted region of space. Through no choice of a reference system can one "eliminate" in all space the really existing gravitational field created, say, by the Earth.

Thus the equivalence of gravitation and acceleration is local and approximate.

At this point we come to the interpretation of relativity in physics, or physical relativity, as suggested by Fok. By physical relativity he means "the existence of identical physical processes in two mutually moving systems of reference" [9, p. 291]. In our view, this interpretation of physical relativity might be expanded something like this: physical phenomena in two mutually exclusive reference systems are governed by identical laws (the above discussion of the relevant questions was precisely in the spirit of this interpretation of relativity, which assumes dialectical contradiction).

In classical mechanics, Galileo's relativity principle obtained; keeping in mind the content of this principle, we have analysed the idea of the unity of a property of a body at rest and in uniform rectilinear motion. But Galileo's relativity principle did not cover electromagnetic phenomena, that is, its application was restricted to a certain area of physical phenomena, and it was therefore approximate. The limitations and approximativeness were overcome by relativistic mechanics with its more general principle of relativity, where the assertion of relativity covers not only mechanical but also electromagnetic phenomena.

In the special relativity theory, however, the relativity principle did not apply to gravitation, that is to say, it was still limited and approximate, in a way. These limitations and approximativeness were overcome by Einstein's gravitation theory based on the principle of equivalence of gravitation and inertia.

The latter principle also proved to be local and approximate, although it is more general in character than the relativity principle in classical and relativistic mechanics.

It follows that the relativity theory, which its founder called the general relativity theory, faces the task of further development and generalisation to become a new and more profound and meaningful theory; the latter will probably be concerned with phenomena unknown to modern physics.

Let us draw some conclusions. The principle of relativity of a certain physical theory, with which its formulation usually begins, and with which its development logically and historically began (as in the case of classical and relativistic mechanics as well as in Einstein's gravitation theory), shapes a new theory and permits its construction—a theory in which the opposites implemented in old theories as something immutable and existing independently of each other, become internally connected, unified, and at the same time differentiated in their essential content in the newly constructed theory, with its basic concepts and propositions unknown to old theories. In the progressive development of physical science, both as a whole and in the separate theories, the law of dialectical contradiction obtains according to which the unity of opposites is transitory, conditional, and relative, while the struggle of mutually exclusive opposites is absolute in the same way as the development of the material world and its cognition by man are absolute.[5] Interpretations of relativity in classical physics, relativistic mechanics, and Einstein's gravitation theory demonstrated this quite graphically.

If we were to sum up the conception of physical relativ-

[5] For details see [2, p. 359].

ity discussed above, we should arrive at the following results (expressing our conclusions through *Gedankenexperiments* of the type used by Einstein).

1. An observer on a Galilean ship does not conclude from the mechanical phenomena on board with absolute definiteness whether his ship moves or is at rest (with regard to the shore). From these phenomena he concludes that (a) the ship is at rest (relative to the shore) or (b) the ship moves at a uniform speed along a rectilinear trajectory (relative to the shore); in other words, the ship is in free motion.

The observer on the shore sees that the ship moves, let us say, uniformly and rectilinearly or, alternatively, that the ship is at rest. From observation of mechanical phenomena in the ship (say, collision of balls on a billiard table in a cabin) he insists that in both cases these phenomena occur in precisely identical fashion.

Thus the conclusion suggests itself that a body's free motion combines in a single quality its uniform and rectilinear motion with being in a state of rest. Both in uniform and rectilinear motion of bodies and in a situation when they are at rest (these conditions are recorded in corresponding reference systems called inertial) mechanical phenomena occur in an identical fashion. That is the way the motion relativity problem is solved in classical mechanics.

2. A light signal is emitted from a source in the centre of the cabin of a spaceship in uniform and rectilinear motion with regard to the Earth. The observer in the spaceship will find that the light signal reaches the walls of the cabin simultaneously: he is guided by the proposition that the speed of light in any direction is the same. A terrestrial observer will come to the conclusion, however, that two light rays do not reach two opposite walls at right angles to the ship's motion simultaneously. This proposition concerning changes in the rhythm of time in motion is inherently linked with the proposition that the speed of light in vacuum is identical in all the inertial reference systems, that is, in systems that are in uniform and rectilinear motion with regard to each other. That is exactly the situation in the relativity theory. The content of this theory is actually the idea that, inasmuch as the speed of light is

the same in all the inertial systems, moving clocks must change their rhythm (an excellent example in physics of the slowing down of time in motion was provided by the muons moving at near-light velocities) and moving standards, their length, that is, the constancy of the velocity of light is inseparable from the inner unity of time and space. Observation of electromagnetic phenomena led to the assertion of the relativity theory that moving a clock changes its rhythm, and moving a standard, its length; the knowledge of mechanical phenomena alone, with its idea of absolute time, cannot lead to the dialectics of cognition of space and time in their unity. This last step was only made by the relativity theory, which has asserted the principle that all physical laws, not only the mechanical ones, are identical in all inertial systems.

3. The observer in a spaceship notices that his pocket knife, handkerchief, cigars and the like, left to be, can be found after a while on the floor of the cabin. In interpreting these observations, he can say that his spaceship is at rest in the Earth's gravity field, and he may also say that his spaceship moves "upwards" with a constant acceleration. These two statements assert that gravity and inertia are in the final analysis one and the same quality.

The observer on the Earth sees, for instance, that the spaceship moves non-uniformly "upwards" or that the ship, let us say, is at rest in the gravity field. He insists, from observations of phenomena inside the ship, that in both cases these phenomena occur in the same manner.

Thus we come to the conclusion that in the two mutually exclusive systems, inertial and gravitational, the physical phenomena proceed in an identical manner, that is putting it more generally, that all physical laws are identical not only in inertial but also in all physical systems (the general principle of relativity).

The idealised experiment involving phenomena inside a spaceship may, however, prove inadequate for demonstrating the general relativity principle. Suppose the light ray enters the spaceship horizontally and leaves it after a short time. If we assume that the spaceship moves "upwards", the ray of light will seem to describe a trajectory within the spaceship that is not strictly rectilinear. If we assume that the spaceship is within the gravity field and that the ray of light is weightless, the latter will seem to move along a rectilinear trajectory.

It so appears at first sight that in the reference frames considered here the light ray behaves in different ways and, consequently, the general principle of relativity has no meaning. Actually things are quite different: the ray of light carries energy, energy is connected with mass, and any inertial mass is affected by a gravity field, since inertial and gravitational masses are equivalent. The ray of light therefore bends in the gravitational field, the general principle of relativity triumphs, and along with it triumphs the dialectical principle of unity of opposites in Einstein's gravitation theory.

3

The theory of relativity emerged and asserted itself in physics almost simultaneously with quantum mechanics. In turning to quantum mechanics, let us at once point out the dialectical nature of the content of this physical theory: just as the theory of relativity, it is a reflection of the nucleus of dialectics—the doctrine of the unity and struggle of opposites. Quantum mechanics emerged as the result of resolving the contradictions between thermodynamics and the theory of radiation.

Classical physics usually interprets matter as substance and field separate from each other. Quantum mechanics is based on the interpretation of matter in motion as interconnected substance and field simultaneously possessing both corpuscular (discrete) and wave (continuum) properties. As Planck formulated for the first time the quantum conception (1900), he tried to interpret the problems involved in terms of classical physics. Einstein propounded the idea of the photon and showed quite clearly that the quantum conception could not be comprehended on the basis of classical physics. Niels Bohr's atomic theory (1913), where the conditions of quantisation figured, retained some basic classical conceptions. Only as late as 1924 and later did the idea gain ground in the developing quantum theory (Bohr's school being its main exponent) that corpuscular and wave concepts, which were viewed as opposites in classical theories, were equally essential for the physics of atomic phenomena. A special role here was played by the discovery in 1927 of electron diffraction, theoretically predicted by Louis de Broglie: it became quite definitely clear that the electron has a dual (corpuscular and wave) nature.[6]

We shall limit our discussion to a few brief remarks on the pertinent aspects of the quantum theory.

In quantum mechanics, the corpuscular and wave concepts lose their "classical" independence. In accordance with the idea of the dual corpuscular-wave nature of the micro-objects, matter, that is, substance and field, is not an ensemble of particles or waves in the sense of classical physics, neither is it a combination of corpuscular and wave properties in some mechanical model. This conception accords with the fact that the motion of micro-objects can in some cases be interpreted as motion of "classical" particles or propagation of "classical" waves only as an approximation. There is not a single experiment where the properties of micro-objects would be manifested precisely as the properties of a particle or those of a wave studied by classical physics. Only in the limiting cases do micro-objects behave as particles under some physical conditions and as waves under others. Thus in describing phenomena on the atomic scale one must not ignore the physical conditions (experimentally recorded) under which these phenomena are observed. This kind of relativity with regard to the experimental devices or instruments of observation (the concept and term "relativity with regard to the instruments of observation" were first introduced by Fok) which is a distinctive feature of description in quantum mechanics, expresses the truth of the unity of the opposite corpuscular and wave properties of micro-objects.

From this it becomes clear why the quantum magnitudes in the uncertainty relation are qualitatively different from their classical analogues. Quantum magnitudes are inherently relative with regard to observation instruments, which makes them different from the classical magnitudes

[6] The idea of the corpuscular nature of electricity firmly asserted itself in physics with the discovery of electrons.

independent of observation instruments.

The above permits to outline a possible approach to the apparent paradox with which quantum mechanics begins its conceptual existence and which may be expressed in the following way: it is assumed that experiments with atomic scale phenomena must be described in terms of classical concepts, and at the same time it is asserted that the applicability of these concepts is restricted by the uncertainty relation.

The uncertainty principle (e.g., for momentum and coordinate) states in fact that in the quantum state proper values of momentum and coordinate operators do not exist simultaneously, that is, what is referred to is a law pertaining to quantum magnitudes (relative with regard to instruments of observation) rather than to classical ones. The uncertainty relation $\Delta_x \Delta_{p_x} \geqslant \hbar/2$ is obtained from the non-commutation relation $P_x X - X P_x = \hbar/i$, where the operators of the corresponding component of the momentum P_x and coordinate X mathematically express that the quantum magnitudes are something qualitatively different from the classical ones. The momentum and coordinate of a micro-object cannot take a definite value at one and the same point in time precisely because that micro-object, studied by quantum mechanics, has a dual corpuscular-wave nature and is not a particle in the classical sense. In other words, the very nature of the micro-object is the basis of the fact that its description is unthinkable without probabilistic concepts and potential possibility. The concept of probability in quantum mechanics is radically different from that of classical physics, for probability itself is part of the laws of quantum mechanics rather than something existing outside these laws.

Leaving aside other philosophical questions of the interpretation of quantum mechanics relevant for our topic, including Bohr's complementarity principle, let us note, however, that our analysis of the problems was in agreement with some aspects of this principle. In Bohr's words, "the wider frame of complementarity directly expresses our position as regards the account of fundamental properties of matter presupposed in classical physical description, but outside its scope" [13, p. 6].

We quoted these words from one of Bohr's last works, "Quantum Physics and Philosophy" (1958), which, from the materialist dialectical positions, is more free from the philosophical drawbacks of his earlier works, to which he referred in one form or another in specifying his conception of quantum mechanics and working out its deeper implications.[7]

If one considers Bohr's works in their chronological sequence, the antithetic quality of the corpuscular and wave concepts in the physics of the microworld is becoming clearer and clearer in the exposition. In his complementarity concept Bonr did not raise the question of the existence of dialectical contradiction in the field of science with which he was concerned but also made an original attempt at solving this contradiction, emphasising the synthetic aspect of the complementarity principle.

Complementarity is undoubtedly a form of reflection of the objective dialectical contradiction inherent in micro-objects; that was established by Soviet physicists and philosophers [14]. As was shown by Bohr and many of his adherents and followers, the logic of this dialectical contradiction is the logic of development of quantum physics.

[7] Thus in his 1949 article "Discussion with Einstein on Epistemological Problems in Atomic Physics" Bohr writes of the exposition of his ideas in the polemics with Einstein in the 1930s: "Re-reading these passages, I am deeply aware of the inefficiency of expression which must have made it very difficult to appreciate the trend of the argumentation aiming to bring out the essential ambiguity involved in a reference..." [4, p. 234].

Some authors alleged that Einstein rejected quantum mechanics just as the opponents of the theory of relativity rejected the latter. In actual fact, however, Einstein never rejected quantum mechanics as a scientific theory, although, as regards the philosophical aspects of the discussions of those times, he held a negative attitude to positivism and indeterminism closely intertwined with the conception of uncontrollability in principle propounded in the 1930s in the interpretations of quantum mechanics. Einstein endeavoured to formulate an interpretation of quantum mechanics free from positivism and indeterminism but failed to solve this problem. It was solved by Bohr and his followers, who proceeded from the complementarity principle—a point which is discussed in the main body of the present article. See in this connection also the works by Niels Bohr "Discussion with Einstein on Epistemological Problems in Atomic Physics" [4] and by Albert Einstein *Quanten-Mechanik und Wirklichkeit* (Quantum Mechanics and Reality).

4.

The concepts of elementariness and complexity as applied to the world of elementary particles have a content that is completely different from the content of these concepts in the old, classical atomic theory. What is shifted into the foreground is the idea of the "transformability of one thing into another", in the context of which the problem of elementarity is formulated and solved in a way quite different from the classical atomic theory (which interpreted transformation in microworld phenomena as combination and disjunction of some constant elements).

The question of the elementary and the complex in relation to electrons, protons, mesons, neutrons, and other elementary particles does not have the same meaning as it had in old atomism beginning with Democritus and persisting in classical physics and to some extent in the modern quark hypothesis. The modern conception of particle elementariness is markedly affected by the theory of relativity. Let us briefly discuss the problem.

According to the classical conception of change in bodies, the latter is based on combination and separation of fundamental discrete particles the number of which is immutable; these particles can only change their configuration, combination, and correlations with one another. This conception of change and development in bodies was not undermined, in its essential aspects, by quantum mechanics either. The particle of quantum mechanics is not the same as the particle of classical physics; its motion is of wave nature, and this conception of substance in quantum mechanics emphasised the affinity between substance and field. At the same time quantum mechanics was incapable of effecting the reverse transition from field to substance: fields remained "classical" in it and the number of kinds of fundamental particles of matter did not and could not vary.

Quantum field theory realised a deeper synthesis, than did quantum mechanics, of corpuscular and wave conceptions, unifying within an integral whole the concepts of field and substance. The synthesis was begun by P. A. Dirac's relativistic theory of the electron, which combined quantum mechanics and the special theory of relativity.

Of the essential and experimentally supported conclusions of this theory let us point out, first of all, the existence of the positron and the possibility of transformation of a photon into an electron-positron pair and back. In other words, Dirac's theory predicted the existence of anti-matter and showed, not merely assumed, that the number of elementary particles was not immutable.

The relativistic theory of the electron along with experimental evidence to support it opened the way to establishing universal transformability of elementary particles, the discovery of antiparticles and so on and so forth—we omit the details.

In the microworld, the elementary and the complex cease to be absolutely constant, identical and opposed to each other; they become fluctuating and interconnected, and their concrete content differs therefore from the conception of the elementary and the complex in the classical theories of physics. According to this conception of elementariness and complexity, these qualities are not inherent in, say, the proton as such, irrespective of the conditions under which its transformation takes place, but are firmly embedded in these conditions (which are recorded by experimental devices in the study of the transformations of elementary particles). There is not a single experiment where elementary particles would behave precisely as elementary objects or complex (composite) systems; in the individual cases, under some conditions of transformation, these particles resemble elementary objects, and under others, complex systems. Thus, in collisions with particles with energies less than 100 meV the proton behaves like an elementary particle, whereas in collisions with considerably greater energies it is transformed into hyperons and K-mesons, that is, it behaves as a complex system. In general, for the interacting particles to transform, certain definite laws of conservation must obtain, which in this case appear as conditions of the possibility of transformation.

The concepts of elementariness and complexity as applied to elementary particles thus lose their absolute meaning, becoming relative. This kind of relative elementariness and complexity of the material objects referred to in modern physics as elementary particles, distinguishes them from the elementariness and complexity of the atomic nucleus, the atom, etc. This relativity is in the final analysis a manifestation of the dual nature of the elementary and the complex inherent in the elementary particles of nature. The question of elementariness and complexity of subatomic objects is in some respects similar to the problem of identity of place for two events occurring at different times, and of simultaneity of events occurring in different places. According to classical mechanics, identity of place is relative while simultaneity is absolute, that is, independent of the reference frame. The theory of relativity rejected, in accordance with its principles, the concept of absolute simultaneity. Relativity of simultaneity and of spatial lengths and time durations in the theory of relativity essentially flows out of recognition of internal (immanent) unity of space and time.

If elementary particles can be complex, it is correct to assume that they may have structure. Robert Hofstadter showed in his experiments that the nucleon is not a point particle and indeed has a structure. But the structure of an elementary particle is different from what was meant by "structure" in pre-quantum physics. According to modern conceptions, an elementary particle comprises a system of "levels" of other virtual particles forming its structure, that is to say, the "composition" of an elementary particle includes other particles in a virtual rather than actual state. In other words, such concepts as "consist of", "structure" and others in the theory of elementary particles are not at all "classical" in their nature.

Let us try a more concrete exposition of what has been said here about "structure". Let a strong-interaction particle (hadron) A be transformed ("decay") into a combination (or become a system) of hadrons B and C. If the mass defect of the particle A is great, that is, particle A does not have sufficient energy for the transformation in question to be actually realised, it is stated that the particle A is composable of particles B and C. Particles B and C appear in this case as virtual particles, and particle A has a virtual structure; it thus appears that a particle of the given mass is built, as it were, out of particles of greater mass. In other words, particles B and C cannot in this case coexist and exist in the structure of particle A irreally, merely in potentiality, which becomes reality only under certain new conditions, when particle A is given sufficient additional energy.[8]

Heisenberg holds a different view of the concept "consist of", accepting the proposition that there is no difference in principle between elementary particles and composite systems.

"We ask: 'What does a proton consist of? Can an electron be divided or is it indivisible? Is a photon simple or compound? ' But all these questions are wrongly put, because words such as 'divide' or 'consist of' have to a large extent lost their meaning. It must be our task to adapt our thinking and speaking—indeed our scientific philosophy—to the new situation created by the experimental evidence.... Wrong questions and wrong pictures creep automatically into particle physics and lead to developments that do not fit the real situation in nature " [15, p. 38].

From what has been said in the above on the elementariness of particles, it is clear which part of Heisenberg's position is acceptable and where he is quite wrong. Heisenberg's treatment of elementariness is insufficiently dialectical; the concepts of "simple" and "composite", "divisibility", "consist of", "particle", and others change their old meanings, acquiring new ones in a new situation created by the experimental evidence. The scientific philosophy of dialectical materialism takes all these new factors into account and accordingly outlines the new paths of studying the emergent problems, paths that lead to new and more profound and all-embracing truths. In this connection, visualisation is seen in a new light, and this question is discussed in Marxist literature.[9]

Let us now consider the quark hypothesis. These "ge-

[8] It was in this way that the structure of the nucleon was discovered in the Hofstadter experiments in the scattering of fast electrons by protons. The structure of the nucleon is actualised through transmission of energy to the nucleon by moving electrons. It has been experimentally proved that the proton scatters electrons in such a way as if its charge were spatially distributed and not as if the proton were a charged point particle.

[9] See Chapter III, "Do Concepts and Theories of Modern Physics Have a Visual Content? ", of our work [16].

nuinely elementary particles", as some authors refer to them, were introduced because elementary particles, in the first place hadrons, are very numerous, and the adherents of this hypothesis hope that quarks will introduce simplicity into nature, so to speak, as the known elementary particles, so great in number, will prove to be built out of a small number of quarks.

Quite a great deal has been written about these hypothetical particles in the modern literature on elementary particle physics. In the words of Professor Sheldon Glashow of Harvard, "quarks are at once the most rewarding and the most mystifying creation of modern particle physics. They are remarkably successful in explaining the structure of subatomic particles, but we cannot yet understand why they should be so successful" [17, p. 38].

So far the existence of quarks has not been proved experimentally, that is, free quarks have not been found in experiments although a great number of studies have been undertaken. In the article cited above, Glashow propounds certain theoretical arguments and considers the explanation of the causes for the unobservability of quarks suggested by some physicists on the basis of these arguments. "If it should be proved correct [he writes in the article], it would show that the failure to observe colored particles (such as isolated quarks and gluons) is not the result of any experimental deficiency but a direct consequence of the nature of the strong force" [17, p. 45].

The main points of Glashow's analysis of the quark problem recur in many other physicists' works. Thus Yoichiro Nambu states that the invisibility of quarks is probably due to the fact that "they are held inside other particles by forces inherent in their nature" [18, p. 48]. Of some interest are the concluding lines of this article: "Now theories of quark confinement suggest that all quarks may be permanently inaccessible and invisible. The very successes of the quark model lead us back to the question of the reality of quarks. If a particle cannot be isolated or observed, even in theory, how will we ever be able to know that it exists? " [18, p. 60].

In our view, all statements in the articles by Glashow and Nambu concerning the causes of unobservability of isolated quarks are logically and epistemologically very much like the past of the theory of relativity and quantum mechanics, if one may put it so, when the latter were only becoming physical theories. We refer here to the Lorentz hypothesis which accepted the existence of one preferred reference frame (that is, of absolute velocity) and at the same time "explained" why it could not be discovered experimentally. We also refer to the Heisenberg uncontrollability principle in its original form (when it was not yet part and parcel of Bohr's complementarity principle), according to which we shall never obtain experimental evidence of the moving electron's trajectory, although we can assume its existence.

In this article we shall not consider the concrete content of the problems arising here. There is as yet no unified theory of elementary particles. We believe that the theory constructed at present is now passing, and will pass in the future, through certain stages reminiscent of those which the theory of relativity and quantum mechanics have gone through.

It should be noted in this connection that if, let us say, the quark hypothesis should be confirmed, "the fundamental problem of elementary particles would reappear at a higher level when it is asked: Why do quarks exist? " [19, p. 229], as was correctly pointed out by the eminent physicist Victor Weisskopf.

Thus the essential changes in the physical concepts of atom, elementary particle, complex system, do not eliminate the problem of elementariness, despite the views expressed in the literature, but rather formulate it in a new fashion. In Weisskopf's opinion, it is possible to escape the stereotype solution of the problem which envisages either absolute elementariness or the purely relative elementariness of infinite division. Victor Weisskopf writes: "Most probably, however, the actual solution of the problem will take a new and wholly unexpected form" [19, p. 229]. We believe that this view reflects the dominant tendency in modern elementary particle physics, combining as it does in a dialectical unity the opposite properties of the elementary and the complex.

Summing up his views on elementariness in physics, Heisenberg said on several occasions that contemporary development of physics turned away from Democritus's philosophy to that of Plato.[10] That is a completely erroneous idea: in our view, the development of modern physics has turned from the philosophy of Democritus to that of Epicurus rather than Plato. The philosophy of Democritus the atomist lacked the dialectics inherent in Epicurus's philosophy. Young Karl Marx made that quite clear in his doctoral dissertation *Difference Between the Democritean and Epicurean Philosophy of Nature,*[11] while Lenin in his *Philosophical Notebooks* countered Hegel's erroneous remark on the movement of atoms in Epicurus with one apt phrase: "And electrons?" [2, p. 292].

The dialectical idea of the unity of the opposing properties of elementariness and complexity in elementary particles thus serves as the philosophical key to the problematic of elementary particle physics in our days. The unambiguous conclusion to be drawn from what has been said in the above is this: the soul of dialectics—the principle of development in the form in which it is most free from one-sidedness, that is, the law of unity and struggle of opposites—inspires physics and natural science as a whole, particularly the physical science of today.

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B. G. KUZNETSOV

EINSTEIN AND CLASSICAL SCIENCE

1. Classical Science in a Non-classical Retrospect

Einstein's centenary makes one stop to dwell not only on the theory of relativity, photons, the years of search for a unified field theory, the sources, content, evolution and modern significance of the ideas of the great thinker. Apart from these problems and excurses into the history of science and physics proper, Einstein's anniversary inevitably poses more general questions, too. Wherein lies the historical significance of the emergence of this gigantic figure, wherein lies its greatness, what is the essence of the new style of scientific thinking that has been implemented in a new picture of the world and a new scientific and technological revolution? One of the special aspects of this fundamental question is the following problem: how is our evaluation of the scientific revolution which created classical science changed in a non-classical retrospect, in the light of Einstein's ideas? This evaluation goes far beyond the boundaries of history of science. It serves as the basis for the solution of extremely urgent problems of modern times. Here we can follow Einstein himself, who perceived Newton's creativity to be a historical triumph of reason. In his article "Isaac Newton" written for the tricentennial of the birth of that English thinker Einstein wrote that mind seems weak to us when we ponder the tasks facing it; and it seems especially weak when we oppose it to men's folly and passion which, it must be admitted, almost fully control human destinies both in trivial and great things. But, he added, intellectual creations go through the bustle of successive generations and illumine the world with the light and warmth for centuries.

For centuries.... One may be confident that that will be the destiny of Einstein's creativity, which by no means hides the light and heat radiated by Newton's ideas and will not itself be obscured by discoveries of later centuries. Why are the creations of reason immortal? What is the invariant basis of the light and heat they radiate? It is first of all the irreversibility of cognition, the fact that science cannot go back on or reject the creations of reason, however radically they may be modified and specified. That is not the immortality of a dead statue—it is genuine living immortality. The concept of invariant is inseparable from that of transformation. It is the search for the new, the transformation of the world picture, which is the general quality permeating man's intellectual activity and producing an emotional effect, bringing the feeling of light and warmth to later generations. The revolutionary, questing, and transforming force of Newton's creativity and of all classical science as a whole becomes clearer if one compares it with the modern transformation of the world picture in the light of the reappraisal (by no means devaluation) of Newton's scientific ideas consequent on Einstein's ideas. Before such a reappraisal, heliocentrism, the idea of inertia, the concept of force, the infinitesimal calculus, the differential conception of movement from point to point and from moment to moment—all of these components of classical science had not appeared to be revolutionary and still less stages in the indivisible, irreversible, and incomplete process of the world picture approximating the original. The idea of such a process was expressed many times, but it could not undermine the conviction, current almost as late as the 20th century, that classical foundations of science were unshakeable. At that time history of science spoke of insights into the laws of the universe and of the immutability of the laws thus discovered. If we apply the term "scientific revolution" to such an insight, its meaning will be different from that accepted today: whatever the definition of scientific revolution now, it is perceived not so much as the crowning of a quest as a more intense and radical continuation of the eternal and irreversible transformation of knowledge about the world. It is on the basis of a modern non-classical retrospect that we look for analogous features in the science of the 16th and 17th centuries that furnish evidence of a revolution at that time.

Apart from the illusion of immutable axioms of knowledge characteristic of the past, its other distinguishing feature was extreme limitedness of the properly scientific conceptions of the world. In the classical times the integral function of cognition of All was not attributed to science. Spinoza identified *natura naturans*, creative nature, with *natura naturata*, created nature, but creative nature did not figure in classical science as an object of experimental study and mathematical analysis; classical science did not dare to tackle by its methods the universe as a whole. In modern science, beginning with relativistic cosmology, with Einstein's cylindrical world, the *universe as a whole* became the object of mathematical analysis and experimental observation (we emphasise the "observation", for the problem of geometry of the universe is solved by the study of mean density of matter in space). When Walther Nernst said that the theory of relativity was not so much a physical as a philosophical theory, this remark rang true, for the philosophical treatment of the universe as a whole ("object created in one copy") and of cognition as a whole became after Einstein much closer to experimental and mathematical study of nature. Today, sixty years after the emergence of relativistic cosmology, when astrophysical problems are more and more intimately linked with the emergence of a unified theory of elementary particles, this tendency is becoming increasingly pronounced.

This tendency, as we have pointed out, proved to be the starting point of a new view of the past, of new historical-cultural, historical-scientific, and historical-philosophical evaluations of the classical picture of the world. Its classical quality has become more conventional, and its revolutionary nature, more and more noticeable. It now appears to be very general and integral, signifying not only the transformation of individual and particular physical, astronomical, biological and other branches of knowledge but also of the methods themselves, of the logical norms and canons of knowledge, of that which is referred to as the axioms of science. All of this requires a certain concretisation and modification of the very concept of scientific revolution, namely making it a more integral concept which now incorporates a reference to the transformation of the logic of cognition, of that which unifies the science of the given epoch. These unifying factors are the canons recurring in each field of scientific cognition, the methods and axioms of knowledge most fully preserved in the transition to a new field, the elements of the paradigm in the sense of Thomas Kuhn. Nowadays, however, the emphasis in defining scientific revolution is shifted to something else again—the transformation of the paradigm, which requires not only a historical analysis of each stage in the history of cognition but also a historiological analysis going beyond the boundaries of these stages and determining cognition as a whole, that is, determining the historiological general *invariants of cognition.*

The history of cognition offers instances of interdisciplinary transformations (that which changes in the transition from one branch of science into another) and interdisciplinary invariants (the subject of transformation, that which is preserved in the transformation). Then there are instances of historical-scientific invariants of shifts in time, the invariants of transition from one epoch into another. Analysis of these invariants forms the general theory of scientific knowledge. The study of the scientific revolution of the 16th and 17th centuries as an epistemological phenomenon from a modern viewpoint, that is, in terms of a comparison of classical science which emerged as a result of the above-mentioned revolution with the 20th-century scientific revolution, is based on a historiology of knowledge linking up the history of a scientific revolution with the history of knowledge in general.

These links make the concept of scientific revolution an integral one. In the literature on the history of science the term "revolution" is often applied to major discoveries and generalisations which do not apply, however, to the science of the given epoch as a whole. Mostly they deserve this designation. But when it is a question of scientific revolution as a stage in the general history of cognition, of the scientific revolution as an epistemological phenomenon, a transformation of the common interdisciplinary invariant is meant which determines the picture of the world as a whole created by the given epoch.

The conception of irreversible and infinite approximation of the picture of the world to its objectively real original is a fundamental conception of epistemology which becomes the starting point of defining scientific revolution. Now, how do revolutionary periods in the approximation to the objective truth differ from the overall movement of cognition which is on the whole irreversible? A great deal can apparently be explained here by the concept of *strong irreversibility of time* introduced by Reichenbach. Irreversibility of time is usually defined through the non-identity of the relations *earlier* and *later*. Reichenbach calls this definition *weak*, opposing to it a *strong* definition. In the last case irreversibility is revealed without juxtaposing the past and the future; time at a given moment is unidirectional; the time arrow is not defined by its target but at each moment of its flight, for each *now*. This is reminiscent of the definition of motion in Aristotle (always out of something and into something) and in the science of the New Times (velocity characterises the state of the body at a given moment and point, it is determined by differentiation). At certain periods, science is marked by strong irreversibility of development—that is precisely the distinctive feature of scientific revolutions. During revolutionary periods the style of scientific thinking, the impact of science on the general character of culture, the effect of science, explicitly depend on the movement of science itself; each answer science gives in response to some question modifies the question itself and causes new questions to be asked; the interrogative accompaniment of scientific development is never mute [3].

In the epistemological analysis of a scientific revolution the strong irreversibility criterion must be linked with the basic epistemological criterion—that of truth. It is appropriate to recall here Einstein's criteria for choosing a physical theory—the criteria of *external justification* and *inner perfection*, of which Einstein wrote in his "Autobiographical Notes" in 1949 [1, p. 23]. The first of these criteria is experimental confirmation, the second, naturalness of the theory, its deducibility out of maximally general principles without *ad hoc* assumptions. Characteristic of the revolutionary situation in science is the act of external justification—an experimental result which obviously requires new basic principles embracing the universe but finds them only through tentative intuition, searching for inner perfection, formulating at the start not so much unambiguous answers as questions addressed to the universe, and demonstrating within the framework of *now* the interrogative component of cognition, its irreversible movement towards truth. In the 16th century, the role of such experiment or observation was played by elliptical planet orbits, and early in the 20th century, by the independence of light velocity from the motion of the system in which it is measured. A similar situation, a revolutionary one, is created by a universal idea that finds no external justification for the time being and stimulates experimental research demonstrating irreversible advancement towards truth. These quests transform the logic of cognition and logical norms, conditioning paradoxes in the most general conceptions of the world. That is the kind of transformations (which can be called metalogical) which Laplace had in mind when he said that it was easier for reason to move ahead than to be immersed in itself. These immersions of reason in itself lead to the juxtaposition of *earlier* (long-established fundamental principles) and *later* (new principles that are yet to be justified externally), the juxtaposition contracting *earlier* and *later* into *now* and thereby demonstrating cognition's strong irreversibility.

The concept of scientific revolution as a period of strong irreversibility of cognition, linked with the treatment of scientific revolution as an epistemological phenomenon, as a stage in the development of cognition as a whole, apparently permits to extend the concepts of paradigm and invariant of cognition. Both of these concepts proceed from a certain identity of *positive assertions*. Invariant, a concept which was first used in mathematics, has now acquired a very general meaning, at any rate in physics, after Emmy Noether linked it with the concept of conservation of physical quantities. It may be assumed that this concept will acquire an even more general sense, including an epistemological one. The emphasis is shifted now onto a concept that is somehow connected with conservation but is in a sense opposite to it—the transformation of a positive *answer* to a *question* which remains unchanged. The invariant question, or the "interrogative invariant", is particularly important for a scientific revolution in which positive paradigms are changed radically—so radically that only the question remains unchanged, the question which was *earlier* answered in one way and *later*, in a different manner. During a scientific revolution answers change very quickly and explicitly, within the life span of a single generation, and in these days in the time it takes for a few consecutive issues of a physical journal to appear. This makes the constancy of the pervasive question more apparent. Its conservation is the concretisation, illustration, and conclusion from the principal feature of cognition as a whole, from the main premise of epistemology. The fact that the continuous content of science is represented by questions which each epoch inherits from the previous one and redirects to the subsequent one, is evidence of unlimitedness of cognition, of its historical approximation to the inexhaustible absolute truth.

Now we shall have to impose certain restrictions on the distinction between positive and "interrogative" invariants. We have discussed the inexhaustibility of the object of science, and the infinite approximation of cognition to the original object. But is this approximation irreversible? The concept of irreversibility points to the epistemological value of positive *answers*, their conservation in the most radical scientific upheavals. If we negate the truth of positive answers, if we reduce scientific revolutions to conserving the questions, presenting them as a sort of cataclysm wiping off the face of the Earth everything that is old, we shall arrive at absolute relativism, at a conception of the history of cognition as a history of errors. Although it may be admitted that the question "What is the structure of the world?" is conserved even in that kind of history, in actual fact its conservation and the inexhaustibility of cognition are inseparable from the progressive and irreversible movement of the latter. The question "What is the structure of the world?" is conserved in a modified form precisely because at each stage it is given an approximately correct if incomplete answer, one that does not close the door to the advancement of science. The interrogative component of science is in this sense inseparable from its positive component. Consider the question which was inherited by classical science from peripatetic science: "Why do bodies continue to move after the initial impulse? " This question could survive only because certain irreversible constants and generalisations were accumulated in antiquity and in the Middle Ages. Consider the interrogative sentence in the immediately preceding text. Each word in it is the product of irreversible positive results of experiment and logical reasoning that will forever remain as part of science. The word "why" is the outcome of a long and irreversible process of rejecting non-causal thinking, and whatever the possible changes in the causality concept, there can be no rejection of what underlies this word. The word "bodies" points to the conclusion, experientially substantiated, that the world is discrete. The word "continue" could only acquire meaning through accumulation of observations opposed to which was regular discontinuation of motion, through the emergence of an abstract image of a body left strictly alone, and of infinite motion without obstruction. The word "impulse", designating the universal cause of motion, could figure in the above question only after a certain irreversible positive statement was made rejecting in general any non-material sources of motion.

Classical science set the same question before the science of the future in a different form, which included the concepts of a body left alone, that is, a body outside of force fields, motion as state (Galileo), rectilinear inertia (Descartes), inertial forces (Newton). Without these concepts and images Einstein could not have answered this question by referring to some specific traits of space, its geometrical properties, its Euclidian or non-Euclidian quality.

There is any number of ready examples of this sort. They go to show that the questions of science cannot be asked in the absence of concomitant and determinant positive statements and cannot, if only for that reason alone, become links in the historically developing knowledge. The entire history of science shows the impossibility of formulating a question without definite answers—the kind of answers which form an irreversible series. The "interrogative" component of cognition and the "response" component are the basic characteristics of cognition. Cognition advances, because the question remains unexhausted at any given time. It forges ahead as a whole, and its time is irreversible, for scientific answers are not replaced by new ones after the fashion of the Cuvier catastrophes but rather in the order of growing precision of reflection of objective reality.

2. The Emergence of Classical Physics

There are certain conclusions concerning the chronological limits of the scientific revolution which created classical science, which follow from the nature of the scientific revolution outlined above, from the strong irreversibility of the succession of concrete forms assumed by the invariant question of the structure of the world, and from the struggle and connection between *earlier* and *later* that is a constant feature of a scientific revolution. *Earlier* signified in this case the dominance of the peripatetic ideas and deduction of the laws of being out of an immutable scheme including the centre of the universe, its boundaries and the "natural places". *Later* referred to the science of the 18th and 19th centuries that had considerable external justification and inner perfection. Between them lies a span of some two centuries, probably less, of searching for a new external justification and inner perfection, of a struggle between the old and still uneliminated and the new and as yet unattained, a period when the old and the new merged in their struggle and made each *now* a scene of conflict. When this general characteristic of 16th- and 17th-century science is historically concretised, it becomes possible to single out several successive stages in the scientific revolution.

Its first stage was the Renaissance. High Renaissance was the culture of the 16th century. At that time peripatetic science had not yet receded into the past, it was going through an internal transformation: the culture of the Cinquecento included the "Aristotelian Renaissance", and Averroës's philosophy kept developing and seeking for new arguments. Averroism, just as neo-Platonism, was going through a profound inversion of concepts, the accent was shifted to living matter in motion giving birth to changing forms; the old scheme of immutable harmony of being was pushed out of the limelight. The attitude towards the authorities of antiquity had changed; these were criticised, and the defenders of Aristotle no longer rejected new interpretations of peripatetic texts. The peripatetic picture of the world was no longer regarded as canonic. It was still alive, 16th-century natural philosophers, even when they declared themselves to be opponents of peripatetic science, often did not go beyond commentaries on Aristotle. Peripateticism was of the past, but that was the kind of past that is retained in the present. In a similar way, *later* the new conception of the world, the classical science, remained in the future, but that was the kind of future that was part of the present, struggling against *earlier*, against the past within the framework of *now*. Applied mechanics was already accumulating external justifications for the foundations of a new picture of the world, but the countertendency, the working-out of such foundations, was merely taking the first steps within the framework of 16th-century natural philosophy. The style of 16th-century scientific thinking was quite original. Cinquecento philosophers compressed time strata in their consciousness, as it were. Scientific thought followed in this respect the culture of the previous century and of the Proto-Renaissance. We find evidence of compressed time in Dante, not only in the structure of his *Divine Comedy*, where the author converses with men from previous centuries, but in the very content, in the ideas of the great poem, in the fusion of medieval reminiscences and Renaissance prognostications.

But was the science of the Renaissance in fact science? Is it justified to refer to a *scientific* revolution in the 16th century? It is obviously quite correct to say yes to these questions. During the Renaissance the system of causal conceptions of the world based on logical analysis and experiment had not as yet been separated from the moral and esthetic conceptions and was mostly expressed in natural-philosophical terms. However, these forms (esthetics, ethics, and natural philosophy) were closely linked with such scientific discoveries as Copernicus's system and

Columbus's feat. The singling-out itself of science as an autonomous component of culture was a result of the revolution in the views of the world and its cognition. The modern conception of science as a system free from external criteria arose out of the achievements of the 16th century. With reference to that epoch, a certain generalisation of the concept of science corresponds to its actual position in the culture of the Renaissance. The well-known fragment of *Dialectics of Nature*, where Engels depicts the emergence of modern natural science during the Cinquecento, begins with a general characterisation of the culture of the Renaissance and goes on to show the continuous development of science gradually assuming its modern form [2, pp. 159-176].

The end of the 16th and the beginning of the 17th century present a particularly visual picture of strong irreversibility of the process of cognition. Consider for instance the work of Giordano Bruno. There is a strong influence here of neo-Platonism, of Nicholas of Cusa, and 16th-century Italian natural philosophy. And at the same time a great deal belongs here to the 17th century—take for example a clear formulation of what is known as the Galileo-Newton principle of relativity. But there is an even more striking example of strong irreversibility—Galileo's two principal works, *Dialogo dei due massimi sistemi del mondo* and *Discorsi e dimostrazioni matematiche.* The first of these works still shows an inclination towards the style of thinking and exposition of the Renaissance, and the second is closer to Newton's *Philosophiae Naturalis Principia Mathematica.* There is an even more striking illustration: in the text of the *Dialogo* itself we observe a bringing together of *earlier* (the Renaissance natural philosophy) and *later* (mechanics of the New Times). They are brought together in the *now* which unites them. It is difficult to find in the entire culture contemporary with the *Dialogo* a more convincing argument for designating the beginning of the New Times as Post-Renaissance. The Post-Renaissance was the chronological boundary of the second stage in the scientific revolution.

The third stage in the scientific revolution (regarded as an epistemological phenomenon, as a stage in the cognition of the universe as a whole) is Cartesian physics, and the fourth, Newton's dynamism. These stages preserve the main feature of the first stage, of the Renaissance—the compression of the pre-revolutionary style of thinking and of the style characteristic of the post-revolutionary classical science of the 18th and 19th centuries, that is, compression in time and struggle between these *earlier* and *later*. But this compression characterises here not only the style of scientific thinking and presentation of scientific ideas but also the content of the basic physical conceptions, the difference between them creating, properly speaking, the basis for dividing the scientific revolution of the 16th and 17th centuries into stages. These conceptions were modifications of one physical idea common to the Renaissance, Post-Renaissance, Cartesian physics, and Newton's dynamism, of the focal idea of the scientific revolution in the 16th and 17th centuries. Yet that idea itself, the physical invariant of classical physics, was a modification of an even more general principle—the physical invariant of the entire historical evolution of cognition, including the antique picture of the world and the modern quantum-relativistic non-classical science.

We have thus come back to the content of the previous section, to a single historiological invariant embracing all successive stages in the development of science. However, we now have to find a link between the historical (epochal) invariants forming part of the paradigm of each epoch, and the pervasive historiological invariant of cognition—the pervasive physical problem beginning with Aristotle's *Physics* and ending with the further development of Einstein's ideas now being contemplated.

This pervasive physical problem is that of homogeneity or heterogeneity of the world, its isotropy or anisotropy. Aristotle's physics and cosmology were a theory of radially isotropic space (all radial directions from the Earth skywards have equal status), but that space was not uniform: it included an immovable centre, immovable boundaries, and immovable natural places over which was stretched absolute space with a privileged reference frame.

The scientific revolution of the 16th and 17th centuries was a triumph of the new conception of the world's homogeneity and isotropy. The transition was irreversible: such apparently fundamental concepts of classical science as absolute space and absolute time could not and did not survive the further evolution of cognition, they were not generally recognised even in the 17th century, but there was something in the new picture of the world which knowledge could not give up. That "something" was retained in the transition from the homogeneity of space to the homogeneity of space-time. The fiction of physical reality of space devoid of temporal extension, the idea of a purely spatial and "momentaneous" picture of the world, rejected by 20th-century science, had not yet disappeared in the 16th and 17th centuries—it only ceased to function as an interdisciplinary paradigm: what was taken over from mechanics into other areas of knowledge reflected the irreversible component of the classical conception of the world—the idea of the world as a system of *motions*. The entire history of classical science, starting with its first appearance on the stage during the revolution and ending with the non-classical epilogue, can be represented as a gradual growth in the complexity of the picture of relative motions, involving the addition to that picture of more and more new details. From this standpoint, Einstein's theory of relativity was a completion and continuation of classical science as far as its irreversible contribution to evolution was concerned. Such is in general the relation of new science to the *irreversible* content of old science. Classical science itself, with its ideas of inertia and homogeneity of space, with the Galileo-Newton relativity principle, was a continuation of the irreversible content of antique, peripatetic physics and cosmology—the concept of isotropy and, with certain reservations, homogeneity of space. According to Aristotle, it was homogeneous only on the spherical surfaces concentrically surrounding the centre of the universe: here the movements of celestial bodies were relative and their trajectories did not include privileged points. Copernicus generalised the concept of relative motion, depriving the universe of a privileged reference-system tied in antique cosmology to an immovable Earth. The absolute centre of the universe was relegated to the Sun. That is a typical situation of a scientific revolution: an old idea has been undermined, science moves on, but the old refuses to withdraw into the past, the revolution goes on, the old is retained in the new—

there is no time interval as yet between the old (*earlier*) and that which will dominate the future (*later*). That is a demonstration of strong irreversibility of cognition.

The second stage of the scientific revolution of the 16th and 17th centuries results in the concept of inertia. That is the principal contribution of Galileo's cosmology and mechanics to the irreversible evolution of the picture of the world. But the past has not become real past, it still exists in the *now*. Galileo's inertia does not yet break the ties with the circular relative motions on the spheres of Aristotelian cosmology. Celestial bodies, when left alone, move along circular orbits. Rectilinear inertial movement is the discovery of Descartes. That is the basic contribution of Cartesian physics to the irreversible development of cognition. But this new momentum which the scientific revolution received at its third, Cartesian stage, cannot form the basis for its completion and creation of a relatively stable and unambiguous picture of the world. Rectilinear inertial movement can explain movement along circular orbits and the entire sum of observed facts with the aid of some artificial *ad hoc* hypotheses. Cartesian physics obviously lacked inner perfection. The scientific revolution of the 16th and 17th centuries was concluded in its fourth stage that brought about Newton's dynamism, the concept of force, and *The Mathematical Principles of Natural Philosophy*.

This chronological division of the scientific revolution is of course very sketchy, and it is not too difficult to find historical facts contradicting this scheme. However, the sketchiness is in this case due to the objectively "aperiodic" nature of science in the 16th and 17th centuries. It resists division into periods by its basic definition. Division into periods always stems from a distinction between *earlier* and *later*, from a temporal interval between them. But that interval was only gained at the end of the 17th century, when the past was really relegated to history and the future became the content of prognostication, a genuine future. The positive content of science was-moreover separated from both past and future by science's claims on absolute verity, by its genuine and at times illusory unambiguousness.

To this we should add a few words about the interval of comparatively organic development of science opened by the publication of the *Principia*. One must not assume that the epithet "organic" rules out any struggle between different trends. Suffice it to remember the vigour with which 17th-century Cartesianism resisted being relegated from science to history of science. The organic quality of the evolution consisted in that the new areas discovered by experiment attained inner perfection on the basis of the already established axioms without any transformation of the latter. In the 19th century, a number of discoveries were made which revealed certain specific laws of complex forms of motion which could not be reduced to the laws of mechanics. It became clear that the laws of thermodynamics, electrodynamics, atomic chemistry, and evolutionary biology could not be squeezed into a general scheme. This signified the end of the conception of complete reducibility of the laws of being to the laws of classical mechanics. Yet these revolutionary events did not transform either the content of the laws of mechanics or the logical norms of science and did not lead to a general scientific revolution—for a while, at least. At the turn of the century, electrodynamics came into conflict with the laws of mechanics. The requirement of inner perfection of the new concepts of electromagnetic field resulted in a new view of the relationship between space and time, and that was the beginning of a new general scientific revolution. The revolutionary nature of 20th-century science has become particularly apparent in its second half: we do not have, as yet, a consistent theory of elementary particles that would explain the tremendous amount of accumulated experimental data within a unified conception encompassing the world from subnuclear units to the Metagalaxy; modern physics has not yet attained this ideal of inner perfection. The frequently recurring expression about formulating ideas in this area "on credit" signifies precisely the inclusion of *later* into *now*.

3. Two Problems in Newton's *Principia*

The starting point of the theory of relativity was the conflict between the conclusions of classical mechanics and those of classical electrodynamics. To find the historical antecedents of this conflict, the historical roots of Einstein's ideas in classical science, we should consider the sources of mechanics and those of field theory in Newton's *Principia*. These sources are in the two tasks which Newton set for the study of nature. The first of these is to determine the movement of bodies from the given forces, the second, to determine the forces acting on certain bodies from the latter's distribution. The first task was given a relatively definitive solution, while the second, that is, the field theory in its original form, contained a certain fundamental vagueness of the force concept in its solution, which included the law of gravitation. This concept could not be anything but vague, and here lie the roots of what has been called the physics of principles as distinct from the physics of models. In the third book of his *Principia* Newton included *The Rules for Philosophising (Regulae philosophandi)*, where he outlines his "inductive method". These rules, quite obviously anti-Cartesian in their colouring, were the subject of a great many panegyrics in England. In general, a great deal has been written about the "inductive method", but now we can take a fresh look at the relationship between empirical and relatively *apriori* roots of knowledge, in the light of contemporary science and of Einstein's concept of criteria for the choice of a physical theory. In the process, the properly historical evaluation of Baconian and Newtonian inductivism acquires greater precision.

Let us approach Newton's *Regulae philosophandi* from the standpoint of transition from one stage of the scientific revolution to another, namely, from Cartesian kinetic physics to the dynamic picture of the world. Both Descartes and Newton proceeded from observation to very general conclusions. Descartes placed special emphasis here on logical deduction, on that which three centuries later Einstein called inner perfection. Descartes was not overly concerned with unambiguousness of partial explanation. As for Newton, he laid emphasis on external justification, endeavouring not to include in mechanics ambiguous hypothetical models, although he often was not true to his motto, "Hypotheses non fingo", particularly in optics. Newton's "physics of principles" opened the way to phenomenological concepts, of which the concept of force proved to be the main one, without hypothetical kinematic models. Force became the object of rigorous mathematical analysis and at the same time of quantitative experiment. Mathematics and experiment converged here, and a certain accord was attained between external justification and inner perfection of physical theory. Unambiguous truth of such concept was thereby guaranteed, and relative truths coincided to a greater degree in their direction with the irreversible evolution towards absolute truth. The rejection of kinematic explication of force was raised to an absolute, which gave grounds for justified criticism of Newton's inductivist claims, but that is another matter.

At this point, however, other factors came into play—conservation of the interrogative invariant of cognition, conservation of the question of the source of force and further explication of force as the cause of motion, which Newton made the final point of analysis, defining it and measuring it phenomenologically. Here lay the beginnings of the shortcomings in inner perfection of classical physics which Einstein listed in his "Autobiographical Notes" (to describe them, Einstein introduced the above-mentioned concepts of external justification and inner perfection); these formed the basis for the transition to a non-classical picture of the world.

Where Newton abandoned the given force applied to a body to tackle the origin of this force, there appeared at once the ambiguous, contradictory, and patently unsatisfactory concepts of the first push, action at a distance, and concepts of absolute space and time. They appeared along with attempts to reject further analysis leading to hypothetical constructions, but now, when we know how these conflicts were subsequently resolved, we are interested in their epistemological characterisation, which is as follows. The unambiguousness of Newton's laws (which have retained their limited validity, as a classical approximation, in these days, too) is evidence of historical irreversibility of cognition, of the irreversibility and growing precision of its results. What is referred to as Newton's "Left hand"—ambiguity in optics, in the problem of action at a distance, the first push, and so on—all of this demonstrates continuity of knowledge, its inexhaustibility, conservation of questions as an invariant of cognition.

Here we have the main epistemological result of Newton's dynamism. When the question "Why does a body move? " was transformed into the question "What is force? ", the first question did not disappear but was conserved in a more complex form.

It would be wrong to say that only positive statements that have become part and parcel of science are the result of the scientific revolution of the 16th and 17th centuries. Earlier we have already dwelt on the inseparability of positive answers guaranteeing the irreversible direction of scientific progress, and of unsolved questions which guarantee further advances in this direction. This correlation is apparent in the history of the universal gravitation law, which was an answer to the question arising out of the discovery of elliptical trajectories of planets. After the discovery of the elliptical form of the orbits, after the formulation of the Kepler laws, a situation of conflict, so characteristic of scientific revolutions, arose: external justification, that is, Kepler's observations, could not be logically deduced from the picture of the world established by the second half of the 17th century. Kepler's laws could not be substantiated in a natural manner, without artificial *ad hoc* constructions, either by Galileo's system, which did not embrace gravitation and proceeded from circular movements of planets, or by Descartes's turbulences. They were explicated by Newton's conception. But then a more general restructuring of science became necessary. A positive and unambiguous conception of gravitation was only created in the 20th century. The general theory of relativity explained the equality of the gravitational and inertial masses and a number of other purely phenomenological premises of the theory of gravitation, satisfying at the same time the condition of high inner perfection. Action at a distance, quite obviously incompatible with Descartes's physics, held on, despite attempts to eliminate it by various artificial hypotheses like ether pressure, up till the time of Einstein, who introduced the concept of pressure of a heavy body on the geometry of surrounding space. Newton himself wavered between references to a material mechanism of transference of gravitational forces and to a non-material agent. This wavering, implying a question addressed to the future, was an essential result of the scientific revolution.

Already in the 18th century there was a great deal of debate on another question mentioned in the above—the question of the first push explaining the tangential component of the motion of a planet along an orbit. Newton ascribed this push to God and said that the movement of planets was a partition dividing Nature and the finger of God. Kant referred to this idea as a piteous, in the eyes of a philosopher, solution of the question, ascribing the first push, that is, the initial conditions of the system of moving bodies, to the rotation of the primordial nebula. This stepping beyond the limits of a given dynamic problem became an extremely powerful instrument of a unified cosmogonic and cosmological system.

All of this leads to a certain general conclusion: the "spots on the sun" of Newtonian mechanics are the result of insufficient elucidation of the source of forces, their dependence on the distribution of masses or, putting it differently, absence of a conception of the force field. Newton's second task outlined in the *Principia*, that is, determining forces from spatial distribution of the masses, a theory of gravitation without a physical explication of gravitation and actually assuming action at a distance—all of this is merely the *beginning* of a field theory, a beginning which bears the hallmarks of the old, with new concepts still merged with old ones, observations having no inner perfection, and generalisations having no external justification. Taken as a whole, that is a question addressed to the future and stimulating the future, stimulating the guidelines of preparation for a new scientific revolution, which took place three centuries after the first one.

This function—stimulating a field theory—was one of the darkest spots on the sun of Newtonian mechanics and classical science as a whole. What we have in mind here are the concepts of absolute space and absolute time. These concepts show once again that the result of a scientific revolution consists not only in its completion but also in a transition to a new stage, when inner tectonic displacements leading to a revolution take place under the hardening post-revolutionary surface of established axioms and methods. The external justification of the concept of absolute space in Newton are the inertial forces produced in accelerated motion of the given body relatively to world space; they are not produced by the movement of surrounding bodies relatively to the given one. Hence the inequality of the coordinate system connected with the given body in accelerated motion and the coordinate system of the surrounding space. But this conception had no inner perfection: in the picture drawn by Newton forces of inertia do not follow from a general principle, they are not connected with interaction of bodies, and the cause of physical phenomena is attributed to empty space and movement in it that is in principle non-representable. The "spots on the sun" pushed the picture of the world towards filling space with a physical medium, but these impulses resulted in the final analysis in a different interpretation of inertial forces—their equivalence to the gravitational field.

The concept of absolute time is based on the assumption of instantaneous transmission of signals, which lends physical meaning to a "snapshot" of the universe, a moment identical for all points of space. The concept of absolute time was externally justified by a great number of observations confirming unlimited increase of velocity under successive impulses, that is, constancy of mass. But these facts belong to the first of Newton's tasks—determining the behaviour of bodies from given forces. The second task—determining the forces—required a generalisation of constant mass mechanics, but such a generalisation was not available. Classical physics endeavoured to subordinate field theory to the concepts of Newton's first, mechanical, problem ascribing mechanical properties to the field known as ether. But field theory strove for emancipation and ultimately not only attained that goal but also dominated mechanics, making mass dependent on motion and equivalent to the body's inner energy.

Thus the classical science's *memento mori* was contained in its very origins, in the results of the scientific revolution of the 16th and 17th centuries.

These results embraced not only the positive invariants of cognition but also a guarantee of further transformation of the picture of the world—the invariant questions which, passing from epoch to epoch, are modified and, in the absence of a definitive solution, create the inner impulses of the development and transformation of conceptions of the world, never interrupted even during the "organic" periods.

4. Cosmos and Microcosm in Classical and Non-classical Science

Let us now try to determine the focal idea of the scientific revolution of the 16th and 17th centuries and its successive stages. We have observed the dialogue form of development characteristic of this revolution, the continual conflict of positive and interrogative deductions. What is the invariant subject matter of the dialogue? What is the pivotal point around which the positive answers are accumulated and preserved for the future, as well as the ever-present questions which constantly arise out of these answers like Phoenix out of the ashes? The subject matter of the dialogue, which united the relatively frequent conflicts in science in the 16th and 17th centuries, were the physical events in the *here and now*, at a given point and moment. Each answer to the question of the behaviour of a particle here and now was paradoxical enough: spatio-temporal events and processes cannot take place at a point without extension and at a given, precisely defined moment; there is literally no place and no time for them.

That is, of course, paradox of long standing, of which already Zeno of Elea was aware. But in the 16th and 17th centuries motion became an inalienable component of being, and the latter in its turn became at that time spatio-temporal moving being. How is the concept of local being to be combined with a spatio-temporal conception of the world? Without such a combination, the new conception of reality as *becoming* could not be created. This designation, included among the basic categories of being, was found by Hegel, but the idea of motion as criterion of reality was sufficiently clearly expressed in Galileo already. It was also present in 16th-century natural philosophy, which continued the tradition of the Trecento (the 14th century) and Quatrocento (the 15th century), which rehabilitated the instantaneous and local, the flowing and moving, that which is built out of elementary situations.

These were manifestations of the secularisation of the picture of the world, escape from the peripatetic apotheosis of the eternal, the immutable, and the immovable as definitions of the basic structure of being.

For mathematics, the concept of the infinitesimal was a way out of the conflict between the localised and the moving—the underlying conflict of Zeno's aporias. Euler's "calculus of zeroes" (zeroes which paradoxically had a direction) and Leibniz's negligibly small magnitudes proved to be various forms (their number, including divers shadings, was very great) of deducing real spatio-temporal relations for local situations. In the process, mathematics became ontological, it was transformed to suit the picture of actual processes. (In general, scientific revolutions result in elimination of apriori and conventionalist tendencies in the substantiation of mathematics.) Foundations of the infinitesimal calculus were laid not only in the properly mathematical works of the 17th century but also in mechanics. Galileo's *Discorsi* were particularly important in this respect. They are the starting point of the development of the notion of motion from point to point and from moment to moment, which replaced the Aristoteleian concept of motion from something into something. This replacement was a general, probably the most general, direction of scientific thought at the start of the New Times. "Thus [wrote Kepler] where Aristotle says there is a prime contrariness without intermediary between that and another, I find in philosophically considered geometry a prime contrariness but with an intermediary, so that where in Aristotle there is one term 'another', we have two terms, 'more' and 'less' " [3, p. 423].

These lines require some clarification. "A prime contrariness without intermediary" is an integral conception pointing to qualitatively different poles: absolute beginning and absolute end of movement from something into something. This integral conception attributes a certain substantional (the body emerges or disappears) or qualitative distinction to the beginning and end of a process. The poles of movement or logical juxtaposition are defined one with respect to the other by the word "another". What are the "intermediaries", then? That is a continuous series of spatial positions, velocities, accelerations, and an infinite set of points and moments to which definite states of moving bodies correspond. The objects, properties or states in juxtaposition, if they are to be defined through such "intermediaries", are characterised by a measure. They can occupy a certain position in the series of "intermediaries", they can be greater and smaller, and that determines their differences.

The origin of mathematical natural science, involving physicalisation of mathematics and mathematisation of physics on the basis of quantitative laws of being, is thus connected with the differential conception of motion. The main achievements of natural science in the 17th-19th centuries resulted from the emphasis on the infinitesimal. "On the precision [wrote Riemann] with which we follow events into the infinitesimal essentially depends our knowledge of their causal connections. The progress of the past few centuries in the cognition of mechanical nature are almost entirely conditioned by the precision of the construction which became possible through the discovery of the analysis of the infinite and the elementary basic concepts found by Archimedes,Galileo, and Newton which are used by contemporary physics" [4, S. 18-19].

The overwhelming interest for the infinitesimal has persisted till our times. At present, there is no *overwhelming* interest: in contemporary elementary particle theory, analysis of the behaviour of these particles in subnuclear space is linked with the analysis of cosmic processes. For classical science and its emergence during the scientific revolution of the 16th and 17th centuries, the differential conception was the all-pervading and dominant direction of physical thought. It is connected with the principal results of this revolution indicated in the previous section.

The differential conception is linked, in particular, with Newton's dynamism. A force applied to a body as the phenomenological cause of its movement makes it possible to do without an analysis of the integral cosmic situation, transferring the emphasis to the local points, to the *here—now*. Within the limits of Newton's first task—determining the position of bodies from the given forces—integral situations prove to be the result of differential laws. The opposite task—establishing the source of forces depending on the initial conditions, on the first push—becomes one of those "spots on the sun" where unsolved questions are concentrated acting as impulses for further evolution of classical science, an evolution resulting in the present finale.

This view of the ideas of classical science, of Newton's creativity, the correlation of the positive component of knowledge and its interrogative component necessitates a revision of the traditional conception of the "classicism" of science created in the 16th and 17th centuries. Newton ceases to loom as a thinker who defined immutable foundations of the conception of the world. Newton was a revolutionary not only because he completed the scientific revolution of the 16th and 17th centuries but also because 17th-century science, through the dialogue between the positive statements and the paradoxes, continually transformed its basic propositions.

This is also true of the problem considered here—the relation of the local *here and now* to the universal *beyond, here and now*, the relation of microcosm to cosmos. The fundamental conflict of classical science results from a difference in the level of non-ambiguity in the two basic directions: in the mechanics of bodies moving under the impact of forces applied to them, and in the beginnings of a field theory. These two tasks, Newton's right and left hands, so to speak, were themselves in a certain sense an antecedent of the non-classical conflict between motion and field. In speaking of it, Einstein no longer referred to the "right hand" and the "left hand" but to two parts of the building of the general theory of relativity: the "marble one"—the tensor of space-time curvature, and the inadequate "wooden part"—the tensor of energy-momentum.

The field theory of the 18th and 19th centuries inherited the characteristic Newtonian alienation from mechanics. The latter governed in the microworld the movements of atoms and molecules. In the 18th century it laid claims here to sovereignty, in the 19th, recognised a certain autonomy of the areas administered, but mechanics had difficulty entering the region where the nature of forces and of force fields was considered: here continual conceptions were in the foreground. (Planck was right to refer to ether as a child of classical physics conceived in grief.) The final samples of static being, atoms and their configurations, did not merge with the continual and infinitesimal conceptions of analytical mechanics and field theory. The wide gap between atomistics and continuum, bodies and fields, could not be completely filled up by statistical continualisation of atomistics. It was eliminated by atomisation of the field, by the establishment of its discreteness, and by continualisation of the particle, by the discovery of "waves of matter" within the framework of non-classical physics.

The non-classical finale of classical physics was prepared by consistent transition from local situations to extended and marginal ones, in connection with the search for initial and boundary conditions determining the behaviour of an isolated particle or an isolated system of particles. The starting point here as well was Newton's "left hand", unexplicatedness of the force concept, an inclination for including cosmic conditions in explanations of local phenomena that could not be realised at the time. The "left hand" also includes Newton's concept of the first push referred to in the above. The scheme suggested by Kant in his *General History of Nature and Theory of the Heavens* invokes the past, the processes that took place before the formation of the solar system, the primordial nebula that emerged at the time. In other words, the cause of tangential velocity lies in a system that is more extended in time and space: Kant's scheme embraces the entire cosmos in which primordial nebulae are formed. But the transition to broader systems is not restricted to an explanation of the first push. Here we encounter a very general trend in classical physics, which led to a new scientific revolution at the start of the 20th century. Let us quote a fragment from an article by Max Born about the preparation of non-classical science during the new epoch in physics.

"Its way was prepared [writes Max Born] by a long development which revealed the inadequacy of classical mechanics to deal with the behaviour of matter. The differential equations of mechanics do not determine a definite motion, but need the fixation of initial conditions. For instance, they explain the elliptic orbits of the planets, but not why just the actual orbits exist. But there are regularities concerning the latter: Bode's well-known rule. This is regarded as a question of the prehistory of the system, a problem of cosmogony, and still highly controversial. In the realm of atomistics the incompleteness of the differential equations is even more important. The kinetic theory of gases was the first example to show that new assumptions had to be made about the distribution of the atoms at a fixed instant, and these assumptions turned out to be more important than the equations of motions; the actual orbits of the particles do not matter at all, only the total energy which determines the observable averages. Mechanical motions are reversible, therefore the explanation of the irreversibility of physical and chemical processes needed new assumptions of a statistical character. Statistical mechanics paved the way for the new quantum era" [5, p. 502].

We have quoted this lengthy passage because it reveals very clearly the role of the search for initial conditions, that is, introduction of a broader spatio-temporal system for the transference of paradigms of classical physics to other regions and, consequently, for the origin of classical *science*. However, the transference concerns not only positive paradigms but also questions, paradoxes, and contradictions of classical physics. Philosophical generalisations of science play a considerable role in this search and in this introduction. They prove to be an essential aspect of discovering "spots on the sun", and not only in the starting point of classical science, in the results of the scientific revolution of the 16th and 17th centuries, but also in its subsequent, post-revolutionary development in the 19th century and in its transformation into non-classical science early in the 20th century.

In the science of the 17th, 18th, and even the 19th century philosophical generalisations were not a sufficiently explicit and direct motive force in the cognition of "spots on the sun" and in the endeavour to eliminate them. Kantian correctives to Newton's scheme of the universe were a very visual illustration of this function of philosophical generalisation, but such examples were not very frequent. In the 17th, 18th, and even 19th centuries philosophy was to a considerable extent a generalisation of what Engels, speaking of Hegel, referred to as the natural science of "the *old* Newton-Linnaeus school" [2, p. 249]. Joining the names of Newton and Linnaeus in this manner emphasises the positive paradigm—the assumption of the immutability and consistency of being. In this sense, philosophy and science followed their several ways and justified the words which Friedrich Schiller addressed to them:

"Let there be enmity between you! It is too early for a union:

Only if you separate for the search, will truth be known" [7, S. 173].

The particular emphasis on the positive paradigm and a certain neglect for the paradoxes of classical science are apparent even in Hegel, although on the whole his philosophy reflected a new stage, at which a number of natural-scientific discoveries demonstrated these paradoxes and produced quite a few new ones. However indirect and inexplicit the effect of philosophical generalisation on natural science might be, it was still quite far-reaching. That influence was exerted not only (and even not so much) through logical deductions as through social and scientific psychology, through an increasingly profound understanding of and feeling for the living paradoxes of being. But there were also direct and conscious transitions from philosophical deduction to the formulation and attempts at solution of the difficult questions of science—of the negative and interrogative components of the scientific revolution. These transitions were only explicit indications of the general links between the development of natural science and philosophical ideas. *General History of Nature and Theory of the Heavens* is by no means separated from the main line of the development of German classical philosophy—one of the fairways of the philosophical generalisation of the scientific revolution of the 16th and 17th centuries.

Now we are passing to the forms of that generalisation, considering it from the standpoint just outlined, as the motive force of the transformation of the picture of the world, the sources of which were contained already in the results of the scientific revolution of the 16th and 17th centuries. In Kant's pre-critical natural-philosophical works, from his *Thoughts of the True Evaluation of the Living Forces* (1746) to the work *On the Ground of*

Distinguishing Particular Divisions in Space (1768), we encounter the same tendency as in the *General History of Nature and Theory of the Heavens*, that is, attempts at a philosophical generalisation of the paradoxes of classical science. But in the critical period, too, in one way or another, directly or indirectly, Kant followed this path. The theory of antinomies is the philosophical equivalent of the contradictions of science that are not amenable to definitive solutions. In classical physics, the concept of infinity was the point of transition from external justification, from experimental substantiation of theories based on the observation of finite objects and processes, to inner perfection, to deduction of theory from more general principles under the assumption of unlimited, infinite applicability of the latter. Kant's "critical" conception of infinity was connected with antinomies (in the sense of positing a spiral of cognition as an absolute, as "ossified"). Hegel's solution of the problem of infinity is different, dialectical rather than critical. "True infinity", just as other concepts introduced by Hegel, infinity present in each finite element, was a reconciliation between the criteria of scientific theory later singled out by Einstein or, to be more precise, a programme of their realisation in the development of science. It should be noted that German classical philosophy exerted a very strong "feedback" impact on natural science. But this impact and its significance for the definition and solution of the paradoxes of classical science can only be evaluated *post factum*, when the paradoxes of classical science led it to its present-day non-classical epilogue.

5. Is Non-classical Physics the Completion of Classical Physics?

There can be no simple and unambiguous answer to this question. First of all, if we call the relativity theory the completion of classical physics, we shall find that the meaning of the concepts of "completion" and "classical physics" is changed. Generally speaking, whatever the aspect from which we consider the relativity theory, whatever epithet we apply to it, whatever class we include it in, we observe a certain deformation of the inclusive class. This situation is very characteristic of non-classical science. The latter links up, in an explicit way, special conceptions with general principles (cf. Einstein's criterion of inner perfection of a physical theory), changing to a considerable extent the content of these general principles. On the other hand, non-classical science changes, not so much in a relativistic spirit as in that of quantum physics, the object of definition in its interaction with the determining classical device. This very general indeterminacy embraces not only atomic physics and not only nature as a whole even, but cognition as a historical process. The Bohrian haze of indeterminacy in the modern quantum-relativistic retrospection spreads to classical physics. Reduced, implicit, hiding in the coulisses, we find in it the paradoxes of continuity and discreteness discussed in the previous section. This is also true of the specificity of scientific thinking, of the methods of science, of the relation between its initial premises, and in particular of the relation between the positive, assertive aspects of science and the interrogative ones implying the formulation of ever new modifications of the pervasive questions.

In classical science, paradoxes, questions, answers eliciting new questions, are by no means a reflection of a later style of cognition, they are not a result of retrospection. They are its basis. The epistemological value of non-classical retrospection consists in that it introduces clarity into the most general, historically invariant definitions of cognition. Cognition has always been and will always be a dialogue between man and nature and a dialogue of man with himself—a dialogue where not a single fundamental question is given a final answer, concluding the dialogue. That is the definition of fundamental questions: they modify, concretise, and generalise the pervasive and ever-present content of knowledge. The unending conflicts of the dialogue, the paradoxes of cognition, reflect the infinite character of the inexhaustible objective truth. This is genuine infinity, implemented, as Hegel was well aware of, in its finite elements.

How was the pervasive dialogue-like quality of cognition realised in the classical science of the 16th-19th centuries?

Let us go back to the characterisation of this quality outlined in the above. Classical science developed through a dialogue with peripatetic thought, a dialogue, one might say, between Newton and Aristotle—not the "tonsured" Aristotle, the militant official peripatetic science surrounded by a stockade of canonised texts and inquisitors' interrogations, but the peripatetic thought that could not be a party to those interrogations but rather a participant to the dialogue in Plato's sense, that is, of the process and method of cognition. The peripatetic conception of the universe was based on a scheme of immovable natural places, an immovable centre of world space and its immovable boundaries. This static world harmony was the first link in the historical chain of invariants that is the axis of the entire history of science: invariant positions of bodies (absolute space), conservation of momenta (inertia), conservation of energy, conservation of the direction of energy transitions (entropy), conservation of energy-momentum (the theory of relativity) and other, more complex invariants, each of which imposes limitations and lends relativity to the others. Static world harmony led from the outset to paradoxes, which essentially expressed its inseparability from the dynamic view of the world and an inevitable evolution of invariants. Aristotle's commentators laboured long to find a way out of the paradoxes of an immutable scheme of the universe. Constancy of the position of bodies becomes meaningless in the transition to the universe. This paradox, a solution for which was sought by such authors as Damascius, Simplicius, Philoponus and other commentators of Aristotle [8, 9], was logically cognate with the antique logical class-inclusion paradoxes such as those of Epimenides ("'All Cretans are liars,' says a Cretan"), Eubulides ("The utterance I pronounce now is a lie"), and others [10]. Commentators ran into difficulties in their attempts to introduce order and dogmatic spirit into Aristotle's cosmology and to include the universe among objects with a fixed place. Just as Zeno's aporias, these were paradoxes of stationary being. For Aristotle, these paradoxes were instances of his dialogue with himself, his lack of certainty in the existence of dynamic (in their tendencies) "growth points" within the static conception. At the same time Zeno's aporias were linked with the sensual-empirical tendency in the thinking of ancient Greeks. The aporias arose out of a demonstration of the reality of movement, out of concrete images of a flying arrow, running Achilles, out of the artistic-logical style of thinking that broke through the idea of static harmony. The logical substratum of the aporias—*the concepts of local being, point, localisations lead to a negation of movement*—went beyond the limits of Zeno's Eleatic tendency, and that step took antique thought beyond the framework of "monological" peripatetics, pointing to its dialogue quality. The aporias meant that local being, as it became the standard of cosmic harmony and was propagated without limitations, revealed its inadequacy and required dynamics, it required dynamic concepts. Aristotle embarked upon the path of such augmentation. In his attempts to find a way out of Zeno's aporias, he added to the infinite set of spatial positions of the arrow, Achilles, the turtle, an infinite set of moments of time. In other words, spatial manifold became spatio-temporal manifold. But that tendency remained a very quiet accompaniment within the framework of peripatetics with its defence of spatial positions as the basis of the harmony of being. And not only of its physical harmony either. The entire history of peripatetism was permeated by an identification of a purely spatial position with moral criteria: that which was higher in the topographical sense, was also higher in the hierarchy of religious and moral values. In the New Times, moral ideas were localised temporally, not spatially: Rousseau placed them in the past, Voltaire, in the future.

For classical science, the invariants on which the harmony of being is based, form a dynamic harmony: they are differential invariants. From now on, the basis of the harmony of being is cognised through representation of motion from one spatio-temporal localisation to another, from one point or moment to another point or moment. Infinity figures here as genuine infinity realised in its finite moments.

Classical science, just as peripatetic science, emerged and developed through a dialogue with itself interwoven with the dialogues in which the interlocutors were the 17th century and the 19th century, the past and the future.

The topic of the dialogues was a new one, but it was linked with the intellectual conflicts of antiquity. Zeno's aporias became the paradoxes of the differential calculus looming over the paradoxes of physics, and the class-inclusion aporias propounded by Epimenides, Eubulides and others, loomed over the physics of initial conditions leading towards the infinitely great, towards the universe, towards the Be-All. One of the class-inclusion paradoxes was the gravitation paradox (the inclusion of the infinite universe as an element in a set of gravitation centres, that is, in itself, leads to infinite gravitational forces affecting each body).

The same kind of class-inclusion paradoxes resulted from the problems of the first push, instantaneous action at a distance and explanation of the forces of inertia discussed above. Absence of an answer (or, which is the same, a theological answer) to the question of the initial conditions determining the form of planetary orbits, placed the tangential component outside the integral system of causal explanations embracing the entire nature. Instantaneous action at a distance is a gap in the spatio-temporal picture of the world. Newton's explanation of centrifugal forces and, in general, of inertial forces, places empty space outside the limits of the world as a particular kind of reality.

Yet none of these was merely a symptom of incompleteness of the classical picture of the world; those were rather the points where a rational answer required a transition to radically new conceptions.

Classical science subordinates each local situation to a differential law combining infinitely small distances with infinitely small moments of time and with modifications and combinations of these infinitely small magnitudes. Classical science is in this sense primarily based on the presumption of a differentially ordered universe, of order in the infinitesimal processes taking place in unlimitedly small intervals of time and space. It is precisely for this reason that the emphasis in the mainstream science of the 17th-19th centuries shifted to the analysis of infinitesimal magnitudes and processes on an infinitesimal spatio-temporal scale. We have seen, however, that the development of classical science was continually accompanied by other, mostly interrogative, remarks. The inner dialogue, evidence of incompleteness of classical science, went on, sometimes becoming an actual dialogue rather than a symbolic designation of conflict of ideas. Of this nature was, for instance, the argument between Leibniz and Clarke. The turning-point in the dialogue was marked by Faraday's *Experimental Researches* and, to an even greater extent, Maxwell's *Treatise on Electricity and Magnetism*.

Thus we see how virtually non-classical was classical science and how much of it was in what Ostwald called the style of the "romantics" as opposed to the style of the "classics". Here we have approached the question of completion, but so far only from the negative side, from the side of the concept of incompleteness. Let us try to approach this concept in terms of positive evaluation, that is, not as the absence of some knowledge as yet unattained but as a condition of this period of scientific progress contributing to the irreversible accretion to adequate knowledge. It is this approach that may be termed historical, for the development of science becomes genuine history of cognition through realisation of time asymmetry, the unidirectionality of time, its orientation from the past into the future, its irreversibility. In the history of science this irreversible process consists in comprehending the irreversibility of being itself, the actual irreversibility of the cosmic evolution, in comprehending the irreversible time and its inalienability from space, in other words, in comprehending the dynamics of being. Classical science added time to space as an irreversible component of reality. It moved away from peripatetic static harmony to dynamic harmony, to its spatio-temporal representation, to time derivatives as elements of such harmony. Herein is contained the immortality of classical science, one of its irreversible assets. The quality of incompleteness about these assets merely indicates the inexhaustibility of "four-dimensional" science moving through time. Its incompleteness pertains to any three-dimensional cross-section, even if this cross-section is not a momentaneous one but embraces several years or a whole historical period. The statement of endless incompleteness is a warning, as it were, that cognition is infinite.

It follows that a contribution to the irreversible evolution of cognition consists in comprehending the four-dimensional world and its dynamic nature, in gradually comprehending motion as a form of the existence of matter. The stages in this comprehension coincide, first and foremost, with the most noticeable landmarks in the history of science, the basic divisions in this history, the radical scientific revolutions. Those were the sources of peripatetic science, in which the paradoxes of static harmony indicated already the outlines of their dynamic revision. Those were the sources of classical science in the 17-19th centuries, which made the whole of the universe movable, with the exception of the static scheme of force interactions—the extratemporal *actio in distans*. But transitions from the statical aspect of nature to the dynamic one were moments not only in such radical transformations of the picture of the world. They also took place within larger periods and therefore characterised not only the critical stages in the history of science but also its "organic" phases. That is why we have to use the word "organic" in quotes: such phases were periods of preparation for and partial realisation and results of crises.

As has been pointed out, the most important inner conflict in the classical science of the 17th-19th centuries was the conflict between mechanics and field theory. We have referred to the conflict between dynamic mechanics and the extratemporal scheme of interaction in the *Principia* as a dialogue between Newton and Aristotle; the new conflict may be called a dialogue between Newton and Maxwell. It was indeed new: the former conflict faced the past, as it were, while the latter, the future; in the first case Newton's partner in the dialogue was a thinker of the 4th century B.C., while in the second, a thinker of the second half of the 19th century of the C.E. But the conflict was one and the same, the dialogue with Maxwell was a continuation of the dialogue with Aristotle. However, an inversion took place here: Newton became defender of static harmony which, being extratemporal, excluded motion. As for the dynamic trend, it was combined with the static trend in the first case, too: Aristotle already had a dynamic conception, only it was regarded as referring to forced motions violating static harmony; bodies moved in relation to an immovable configuration of natural places over which space was stretched. In Newton, space is no longer stretched over immovable points and surfaces like the centre of the world and the concentric spheres. He does not proceed from immovable absolute space to absolute motion; on the contrary, the criterion of absolute motion is the appearance of inertial forces in accelerated motion. Absolute motion is deduced from this effect, and absolute space, from absolute motion. Absolute time is also deduced from the local effect, from the unlimited increase of velocity, that is, the ratio of the differential of distance to the differential of time when a body moves under the impact of some force applied, and from the infinite velocity of the propagation of forces. Electrodynamics gave up the idea of infinite velocity of propagation of the electromagnetic field and was now a dynamic side in the argument with mechanics, which conserved infinite speeds and consequently absolute time. The conflict was resolved through subordinating the first programme of the *Principia*, that of determining the position of bodies, to the second programme or rather what grew out of it—the field theory.

We may now try a closer approach to the concept of *completeness* of the picture of the world. That is by no means accomplishment in the sense of returning to a heaven or Aristotelian return to a natural place. That is not elimination of a paradox but its transformation into a new one. It is all a little bit like Pushkin's description of the "white nights" in his *Bronze Horseman*: the twilight of one epoch merges with the dawn of another. A certain magnitude—an invariant determining the given picture of the world—gives way to another magnitude, remaining itself as an invariant of limited applicability. Accordingly, a certain paradox or conflict acquires clear-cut boundaries, while a different conflict becomes a general paradox. Thus one inner dialogue is replaced by another dialogue—that is what completion consists in. From this standpoint, completed theories receding into the shadows of limited approximations (the area of genuine "completion"), just as those that complete them, appear not so much as successive positive constructions but rather as successively modified questions. Paradoxes and questions are, however, inseparable from answers, and for this reason Thomas

Kuhn was quite right in linking up the concept of scientific revolution with the positive principles forming part of the paradigm [11]. History of science is a history of *science* precisely because its elements are the adequate answers to the questions of the truth. It is a *history* of science precisely because each answer is at the same time a question.

How is this structure of a scientific revolution realised in the theory of relativity?

The conflict between the theory of relativity and quantum mechanics seemed at one time to be external with regard to the theory of relativity. Now it appears to be an internal one. The dialogue between Einstein and Bohr progressed to Einstein's dialogue with himself. This dialogue is no symbol at all. It was carried on in his remarks in the "Autobiographical Notes" of 1949. Here Einstein made some critical remarks concerning the theory of relativity: the changes in measuring rods and clocks are not deducible from their atomic structure [1, p. 59]. The framework of world lines with its invariant—the four-dimensional space—is not linked up with the more general laws determining the existence of particles and their interaction. The conflict between the relativity theory and quantum mechanics—the basic paradox of elementary particle theory—proves to be the essence of non-classical science when we ask ourselves the question: what new paradox has replaced the classical one? Non-classical science thus becomes non-classical not only in its content but also in its style, structure, and the presence of the interrogative accompaniment of positive assertions. In this sense, non-classical science, which completes classical science, makes the latter more "classical", explaining those elements of the old theory which appeared contradictory. If one takes this view of "completion" regarding it as a scientific revolution, quantum mechanics turns out to be the same kind of completion of classical science as the relativity theory. Quantum mechanics eliminated, in a different way, the conflict of the first and second problems of *Principia*, the conflict between mechanics and field theory, by identifying, in a very paradoxical form, the field and discrete bodies. Non-classical science modified the principal paradox of classical science in both of its streams (the theory of relativity and quantum mechanics) in the same way as classical science modified the principal aporia of peripatetism.

Completions of the scientific pictures of the world—scientific revolutions—would not have been links in an irreversible advance of science had there remained a chance to return to the completed and thereby modified conceptions of the universe and to restore them.

Irreversibility of cognition is based, first of all, on philosophical results of scientific revolutions and their restructuring effect changing the basic conceptions of the world and the most general logical and epistemological norms. The reverberations of scientific revolutions modify not only the special results but also the potential of cognition. Mankind may go back to old ideas (as Copernicus went back to the heliocentrist ideas of antiquity) but the circle taking thought back to its antecedents of long-ago passes through higher cognitive potential zones, being a higher convolution of the spiral, so that there is no return to the starting point. The conception of history of science as an irreversible process is rooted in a very relativistic evaluation of the so-called "precursors" and "predecessors", in the idea of uniqueness of historical events. The main premise of the theory of irreversible time—the actual distinction between *earlier* and *later*, the existence of the arrow of time—is correct not only for the history of cosmos but also for the history of its cognition. The conception of completion as incorporation in cognition of a basically new problem, new paradox, or new ways for its solution, is one of the conditions of such a conception of the irreversibility of the history of science.

There is, however, another aspect to the matter. Cosmic evolution is irreversible owing to the unidirectional complexity of the universe, which increases with time. Cognition of the cosmos is irreversible due to the more and more adequate reflection of the complexity of being. The history of science as a process of cognition is irreversible. But is that true of historiography, of the very process of historical analysis, of history of science as a historical discipline? Travelling back in time is the professional occupation of the historian.

The whole point is that each new voyage of the historian into the past shows him a different picture. One must not think that the historian has the right to change the past, a right which religions refuse even gods. The historian does not reconstruct each time a *picture* of the past on the strength of certain subjective or group interests: that would have made historiography maximally reversible, depriving it of the pervasive irreversible ascent. The picture of the past is reconstructed because retrospection discovers in the past a deeper stratum, a deeper and more complex system of causal connections, a greater number of common features and delimitations, a greater number of dimensions—the historico-scientific equivalent of geometrical dimensionality. Excursions into the past affect the frame of reference. Historiography as a whole, having discovered the genuine motive forces of social transformations, cannot go back to providentialism.

This irreversibility of historiography is, however, relatively trivial. What is non-trivial is its connections with the irreversibility of the object of scientific historiography, the irreversibility of the process of cognition itself. These links make it possible not only to refer to a certain general irreversible direction of the historical analysis of science but also to establish the direction itself.

The very word "direction" signifies that a certain geometrical analogue is introduced into the problem. We consider cognition as a space of statements, definitions, explanations, evaluations oriented by some system of reference, some axes. These axes are definite basic directions of cognition, they are lines of continuous development of the principal conceptions of the universe. Having these axes, one can correlate with them definite tendencies, introducing order into the mass of historical facts and making them the subject of historical evaluations. The system of reference directly depends on modern retrospection. Non-classical retrospection now induces changes in such basic concepts as peripatetic science, classical science, mechanics, field theory, and so on. What occurs now reminds one somehow of the bending of coordinates or curvature of space. If we were to continue this analogy, changes in historical-scientific analysis and its reference frame remind one of the transition from Cartesian coordinates to a more general reference system. The impact of non-classical science on historical retrospection apparently directs historico-scientific analysis towards this kind of generalisation of the initial orientations, towards general, basic, fundamental principles and methods of cognition, the transformation of which makes the process of cognition of the world irreversible. This orientation corresponds to the epistemological function of the history of science and technology pointed out by Lenin in his *Philosophical Notebooks* [12, p. 294]. Since history of science and technology is so close to dialectical gnoseology, the evolution of basic directions—the epistemological reference frame of scientific theories—becomes the object of historico-scientific analysis.

That does not mean that the object of research includes only the basic, general principles and methods of cognition and their transformations—the scientific revolutions. Cognition follows a spiral path repeating the convolutions, and at each convolution the development of science includes particular branches and problems, applications and the effect of science. Yet each convolution prepares a transition to the following and higher convolution—a scientific revolution. Therefore history of science, including all the details of scientific progress, more and more becomes a theory of the preparation, content, and results of scientific revolutions.

I believe that the relation of the relativity theory to classical science, which is shared by quantum mechanics and frequently and correctly referred to as completion, throws light on a more general problem, namely on the role of the irreversible transformation of the basic conflicts of each period, the role of scientific revolutions, and on the relations within the irreversible spiral "world line" of cognition repeating its convolutions but including each time new levels. The concept of completion requires apparently a certain delimitation: the meaning of this concept is modified in the context of the relativity theory, quantum mechanics, and modern quantum-relativistic trends in elementary particle theory. In the case of the relativity theory classical physics remains valid at a certain level of approximation, when its postulates do not as yet undergo any internal modification although they are conceived as wholly unacceptable beyond the limits of such approximation. In non-relativistic quantum mechanics the relation between classical and non-classical concepts is quite different. Here classical concepts and the image of the classical body freed from the corpuscular-wave dualism are a necessary condition of the very formulation of non-classical theory [13, pp. 15-16]. As far as one can make judgements about relativistic quantum theory, it unites both types of completion: quantum criteria and corpuscular-wave dualism extend to the field interacting with the given one; classical postulates in their quantum function, that is, in the function of conditions of non-classical correlations, are applicable on a limited scale, retaining this significance in areas where relativistic effects may be ignored. Of course, we are dealing throughout with a completion of classical science as a complex fairway of cognition permeated with paradoxes and incomplete in its basic content.

The irreversibility of these completions, the irreversibility of the process of cognition as a whole, the "arrow of time" in the history of science—all of this follows from the fact that the instruments of cognition go through an irreversible evolution in the repeated convolutions of its spiral. Wolfgang Pauli objected to the evaluation of the relativity theory as completion of classical determinism as distinct from quantum mechanics—the start of a new scientific epoch. He spoke of group-theoretical properties of space which were analysed and generalised in the relativity theory, the analysis and generalisation making possible quantum physics in its contemporary form [14, p. VI]. This new conception of the connections between group-theoretical correlations and physical reality illustrates the immersion of reason in itself, in which reason encounters greater difficulties than in moving ahead, as Laplace wrote in his *Analytical Theory of Probabilities*. The contradictions and aporias of peripatetic physics were overcome through a radical renovation of the logico-mathematical apparatus and general conceptions of the world attained in classical science. That was a titanic feat of reason, an overcoming of gigantic difficulties of immersion in itself. The theory of relativity was no less a feat, as it freed science from the paradoxes of classical physics and in this sense proved to be its completion.

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ON THE PHILOSOPHICAL CONTENT OF THE RELATIVITY THEORY

1. Foundations of the Relativity Theory

Dialectical materialism provided a general definition of space and time in their philosophical acceptation as forms of the existence of matter. That was the view defended by Lenin against Kantianism and other systems of subjective idealism. The form of an object is not something external in relation to it, the form belongs to it and is determined by it, if the object was not cast in this form by some external forces. Therefore the forms of the existence of the world are its general structure determined by its basic properties rather than something into which the world is inserted, as it were. Accordingly, a rational theory of space and time necessarily deduces the properties of the latter as the properties of such a structure, it deduces them from the very properties of matter. That was the source of geometry: it reflected first of all the general property of relations between rigid bodies determined first and foremost by their potential for motion.

The conceptions of space and time in Newtonian physics were also intimately connected with the laws of motion of bodies established by classical mechanics. In particular, the concept of absolute simultaneity was rooted in the idea of the possibility of throwing a body with any speed whatever. However, as usually happens in science, these implications were not sufficiently realised, as the concrete tasks of physics did not induce scientists to do so. Space and time were thought of as given forms independent of matter. The discoveries of physics could be nicely accommodated by these forms.

But that could not go on indefinitely. The laws of electromagnetism formulated in the Maxwell equations came into contradiction with the laws of mechanics. In the latter, the basic property of space and time—their homogeneity—was expressed by Galileo's principle of relativity, including the geometrical principle of the relativity of Euclidean geometry. The latter may be defined as the equivalence of all orthogonal coordinates. Then Galileo's principle of relativity constitutes an extension of the geometrical principle, consisting in the fact that systems of orthogonal coordinates remain equivalent also in their arbitrary uniform and rectilinear motion relatively to one another. The somewhat indeterminate concept of equivalence may be precisely expressed in the language of transformation groups: the general laws of mechanics are invariant under transformations changing a system of orthogonal coordinates into any other system in rectilinear uniform motion relatively to the former. As for time, it is always invariable, except for changes in the starting point and units of measurement, that is, only transformations of the type $t' = at + b$ were permissible for time or, given invariable measurement units and starting point, $t' = t$. All such transformations of orthogonal coordinates and time form the Galileo group; what is important, of course, is not the fact that orthogonal coordinates are transformed (the coordinates may be arbitrary)—it is the group that is important, while the choice of a system of coordinates determines only its representation.

Inasmuch as physics was dominated by the view that any phenomenon is ultimately of mechanical nature, Galileo's principle appeared to be universal, that is, applicable to any laws, not just the laws of mechanics. It was established, however, that the laws of electromagnetism expressed in the Maxwell equations are not invariant relative to the Galileo group. That was established already in 1887 by Voigt, but his work remained unnoticed, and in 1904 Lorentz found the transformations under which the Maxwell equations are invariant. It transpired, as we know, that time cannot be viewed as invariable in the passage from one coordinate system to another moving relatively to the former.

It was either Newton's mechanics with the Galileo principle of relativity and absolute time or Maxwell's electrodynamics; if the latter, it was either the relativity principle or absolute time. That was the dilemma. A clear realisation of this dilemma was, of course, Einstein's starting point.

Before Einstein, the question was never formulated in just that way. There were various attempts to give a formulation of the laws of electrodynamics of moving bodies that would agree with the data of experiments and with classical mechanics. But none of these attempts yielded satisfactory results. In particular, no results came from the famous Michelson experiment intended to discover the Earth's motion relative to ether. It showed that the principle of relativity also obtained in the case of electromagnetic phenomena, and that a definition of absolutely uniform rectilinear motion here was just as impossible as in the framework of ordinary mechanics. The task thus actually consisted in searching for a proper formulation of the laws of electrodynamics. It was for this reason that Einstein gave the work that laid the foundation of the theory of relativity the title "On the Electrodynamics of Moving Bodies". In the dilemma we formulated above, "either mechanics or electrodynamics; if the latter, either the relativity principle or absolute time", he sacrificed mechanics and absolute time.

But, if we reject absolute simultaneity, we still have to give simultaneity some other definition. It is clear where such definition should come from: if we accept the electromagnetic picture of the world as the basis for theory, the definition must rest on electromagnetic processes. Besides, we can recall the role of practical operations in cognition and correspondingly accept the following epistemological principle: a definition has physical meaning if it is linked with a possible experiment. A mental experiment of this kind, that is, an experiment possible in principle, would involve exchange of signals. Einstein made it the basis of his famous definition of simultaneity. That was the cornerstone of his construction. In Einstein's definition simultaneity was not something conventional but a very general and real relationship of events objectively determined by their interaction through radiation. The "signals" originate from events irrespective of agreements and experiments, determining the objective material connection between phenomena. The abstract form of this connection is expressed in the concepts of simultaneity and succession in time. Einstein emphasised in his work the idea that his definition could be incorporated in the theory he developed without any contradiction. And that meant that it reflected the essential general features of reality.

The definition of simultaneity entails a specification of the concepts of the time t and, consequently, of the system of spatial and temporal coordinates x, y, z, t linked with some body—the basis of a system, which is taken to be at rest.

Further considerations, as Einstein pointed out, were based on the principle of relativity and the principle of the constancy of light velocity. The former is the old principle of Galileo extended to embrace all physical phenomena, not just the mechanical ones. What is actually new is the second principle, in accordance with which electromagnetic phenomena are taken as the basis. From these two principles, Lorentz's transformations are deduced and later consequences from them for kinematics, electrodynamics, and mechanics.

The theory of relativity discovered the connection between space and time. This connection is implied in the very constancy of light velocity. The velocity is the ratio of distance to time and its constancy or equality in all systems signifies accordingly a universal connection between spatial and temporal magnitudes. The absolute must be contained in the union of time and space rather than in space and time taken alone. This idea was realised by Minkowski, who expressed it in the opening words of his famous lecture on "Space and Time": "The views of space and time which I wish to lay before you have sprung from the soil of experimental physics, and therein lies their strength. They are radical. Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality" [1, p. 75].

Being a geometer, Minkowski considered the theory of relativity in terms of principles already developed in geometry, so that a certain geometry is defined as a theory of invariants of the corresponding group of transformations. In the theory of relativity, the transformations involved were the Lorentz transformations. We are therefore dealing here with a geometry defined by that group, which obtains in four-dimensional "space", as four coordinates x, y, z, t are involved here. The set of all places (x, y, z) in time forms a single manifold—space-time, which is the absolute form of the existence of matter.

With reference to the term "relativity-postulate" applied to the requirement of invariance under the Lorentz group, Minkowski said: "Since the postulate comes to mean that only the four-dimensional world in space and time is given by phenomena, but that the projection in space and in time may still be undertaken with a certain degree of freedom, I prefer to call it the *postulate of the absolute world* (or briefly, the world-postulate)" [1, p. 83].

Spatio-temporal relations and properties of bodies and processes do not depend on the reference frame but are only differently manifested in different systems. In general, physical magnitudes depending on a frame of reference and relative in that sense, are a kind of projections of more general magnitudes which no longer depend on the frame of reference. In accordance with this view, Minkowski gave a four-dimensional formulation of the laws of relativistic mechanics and electrodynamics.

Thus he not only developed a deeper understanding of the theory of relativity but also introduced greater clarity in its mathematical apparatus.

Nevertheless, Minkowski's view of the theory of relativity was not fully appreciated by physicists. The point of view of the theory of relativity, according to which every phenomenon is considered in relation to a certain frame of reference, was more customary: first, because such is the experimenter's or observer's position, and second, because the theoretician too views phenomena in terms of a certain coordinate system. But there was also a third element here—positivist philosophy which in principle ascribes reality only to what is given in direct observation; the rest of the content of physical theories is treated by that philosophy as constructions linking up observation data rather than as presentation of reality. From this standpoint, Minkowski's four-dimensional world was merely a scheme reflecting no reality over and above that which is already expressed in the initial exposition of the theory of relativity. Therefore the positivists regarded as unjustified Minkowski's objection to the term "relativity-postulate" and his proposal to substitute the term "the postulate of the absolute world" for it.

Thus two different approaches to the theory of relativity became apparent. The first is the Minkowski approach based on the conception of space-time as a real absolute form of the existence of the material world. The second is a purely relativistic approach; its focus is a certain system of reference. It is clear that the first approach is materialist in nature and is in agreement with the natural logic of the object: its form determines the relative manifestations of the logic. The second approach, when it is taken to the point where the four-dimensional world and four-dimensional magnitudes are refused any real status, proves to be positivist: it ignores the fact that the relative is merely a facet or manifestation of the absolute.

2. The General Theory of Relativity

Whatever the successes of the theory of relativity, gravitation resisted incorporation in the theory, despite the fact that Poincaré already in his first work, where he developed the theory of relativity simultaneously with Einstein, undertook such an attempt, soon to be repeated by Minkowski and others. It took Einstein ten years to solve the problem through generalisation of the theory of relativity, which came to be referred to as special as distinct from the new and more general one. The general theory of relativity is a theory of space-time explaining gravitation through the dependence of its structure on the distribution and motion of masses of matter.

In the special theory of relativity space-time is "flat", it is uniform and isotropic. All spatio-temporal relations and properties and, in accordance with the principle of relativity, all the laws of physics are invariant under the Lorentz transformations. But in the general theory of relativity this is true only approximately and for small domains; taken as a whole, space-time is non-uniform and anisotropic, while the relativity principle does not hold relative to it. The difference between the structure of space-time of the general theory of relativity and the flat space-time of the special theory is determined by the distribution and motion of masses of matter. In its turn, this structure determines the motion of masses under the impact of the gravitational forces, as it were. We see thus that masses of matter. determining the structure of space-time, thereby also determine their own movement. The gravitational field is not, properly speaking, a kind of force field but, in actual fact, the difference of the structure of space-time from the flat metric, that is, the field of the curvature tensor. Since the structure of space-time obviously depends on the distribution of masses of matter, it may be said that this structure itself is not absolute: space-time itself in this sense is not quite absolute. The division of space and time becomes even more relative and, on a large scale, may even prove to be impossible in a precise and unambiguous sense. It is the material world as a whole that is absolute, while all its forms, phenomena, etc. are to some extent or other relative. Lenin was quite right in stressing that dialectical materialism does not recognise any absolutes apart from the existence of the material world, and that we reflect the latter in our consciousness in ascending from one relative truth to another and cognising in this movement an increasingly greater share of the objective absolute truth.

In constructing a theory of gravitation, the essential difficulty that had to be overcome was the choice of frames of reference—frames of spatio-temporal coordinates. In the special theory of relativity there were preferred frames—the inertial ones. In these, the laws of nature were represented in the simplest form: their formulations did not include any quantities specifically characterising these systems. These systems are naturally connected with the very structure of flat space-time, in the same way as the ordinary orthogonal coordinates are naturally connected with the properties of Euclidean surface.

Discarding flat space-time has the unpleasant consequence that the very concept of inertial frames becomes meaningless. It is only conserved for small domains and as a first approximation. Moreover, the structure of space-time does not seem to be pre-fixed, so that it is impossible to indicate beforehand the grounds on which some coordinates should be preferred to others. Consequently, one had to proceed simply from an arbitrary set of coordinates without attributing beforehand any advantage to some of these over others. In other words, all systems of coordinates in general had to be recognised apriori equivalent, and spatio-temporal correlations and all laws of physics had to be expressed in arbitrary coordinates. Since the general form of equations in which they are suitable for any coordinates is called covariant, the requirement here formulated is called the covariance principle. The choice of a system of coordinates best suiting a given structure becomes meaningful only aposteriori, when the structure of space-time is determined to a sufficient degree.

This situation arose for the first time already in classical mechanics, when Lagrange formulated the laws of the mechanics of material points in "generalised coordinates" of the points rather than in orthogonal ones, the generalised coordinates being chosen in such a way as to take into account beforehand the connections imposed on the system. In geometry, arbitrary coordinates appeared in the works of Gauß; he developed the theory of geometry as applied to arbitrary curved surfaces, introducing arbitrary coordinates for such surfaces. All equations were given the form suitable for arbitrary coordinates, that is, they were written in covariant form. As for preferred coordinates, they may be determined depending on the properties of the surface and nature of the figure considered.

Thus the choice of arbitrary coordinates and the requirement of covariance are nothing new, as matters of principle, and neither do they have any physical meaning. Coordinates in an arbitrary space may in principle be chosen in an arbitrary manner. The advantages of one set of coordinates over another only become clear in connection with a concrete situation to the description of which they are applied.

However, in constructing a general theory of relativity the transition to arbitrary coordinates was deemed so revolutionary that it was elevated to the rank of a special principle termed the general principle of relativity. It was formulated as a principle of equivalence of all frames of reference regardless of the motion of bodies with which these frames are connected. In particular, the equivalence of the systems of Copernicus and Ptolemy was asserted. Moreover, it was even insisted sometimes that the principal task to be solved by the general theory of relativity did not lie at all in providing a theory of gravitation conforming to the theory of relativity, as was actually the fact, but in formulating the laws of physics in a manner suitable for an arbitrary system of coordinates, that is, in covariant form (see e.g. [2]).

But soon after the appearance of Einstein's main work on the general theory of relativity Erich Kretschmann drew attention to the fact that the "general principle of relativity" was not a physical principle or law but merely a requirement to write equations in covariant form—a requirement in which there was nothing new, as has been pointed out. After Minkowski gave a four-dimensional formulation of the laws of relativistic kinematics, mechanics, and electrodynamics, the task of writing equations expressing these laws in arbitrary coordinates was reduced to elementary formal transformations. Any coordinates are applicable to any theory, whether it be classical mechanics, the special theory of relativity or any other, and the question of writing equations in covariant form is a purely mathematical question.

Einstein saw the justice of Kretschmann's remarks, but the conviction of the special significance of the general principle of relativity persisted. One would have thought that there were no grounds for debate, and yet the debate continued. In particular, it was debated whether the systems of Ptolemy and Copernicus were equivalent, although experience would seem to have settled the argument a long time before. It is clear (and was clear to Ptolemy already) that the motion of luminaries can be described in different coordinate systems. We always describe this motion relative to ourselves, saying that the sun rises, that the moon rides high in the sky, etc. In a word, it is all quite trivial.

At the same time experience shows that the laws of physics vary in relation to the geocentrical and heliocentrical reference systems. In the inertial systems the laws of physics do not contain quantities distinguishing the systems themselves, while such a quantity (the Earth's angular velocity) does appear in the geocentric system, so that events take a different course. This is manifested on the Earth in the washing-out of the right banks of rivers in the northern hemisphere, in the rotation of the Foucault pendulum and other effects. On board a plane it is impossible to discover any effects of its uniform flight, while on the Earth itself, in a closed room, the effect of the Earth's rotation may be discovered. That means that although both systems are applicable, they are not equivalent in the sense in which inertial frames are equivalent (within the limits of precision of classical mechanics or the special theory of relativity).

Let us compare, in general form, the principles of covariance and relativity. The former consists in the requirement to express laws through equations in a form suitable for any coordinates. That is attained by inclusion in the equations of quantities characterising a certain system of coordinates. For example, if we use oblique coordinates on a surface, the formulas include the angle between the coordinate axes. When an equation is written in some given coordinates, it is easy to obtain its covariant form. It is sufficient to substitute arbitrary functions of some other coordinates for the given ones and transform accordingly the other quantities in the equation, if these quantities in general depend on a system of coordinates (as vector components, say). That is a purely mathematical operation, as we see. Clearly, the equations obtained are not concretely defined, containing as they do arbitrary functions. The choice of these functions determines the choice of a coordinate system and correspondingly the concrete form of the equation. As the concrete form of the equation is changed along with the transformation of coordinates, the general form of equation suitable for any coordinates is called covariant, that is, co-transformable.

If coordinate systems are realised physically, the dependence of a concrete equation on a coordinate system means that the law of realisation of the phenomenon relative to this system depends on the system. Thus equations related to a rotating system include its angular velocity, and the phenomena depend on that velocity. Physically, the principle of relativity consists in the fact that relative to certain systems, phenomena are realised according to identical laws. Mathematical expressions of these laws do not therefore contain any quantities distinguishing these systems. In the transition from one system to another the equations do not change at all, that is, they *are invariant, not merely covariant* under transformations of coordinates from one of the systems considered to another. Mathematically, the principle of relativity is expressed precisely in the requirement of invariance of equations under the Lorentz transformations. The principle of covariance and the principle of relativity are thus quite different things. The former is a purely mathematical requirement, the latter reflects the law of nature consisting in the property of uniformity owing to which phenomena take an identical course in different systems.

In the general theory of relativity, the principle of relativity, or Lorentz-invariance, is true only as an approximation and only locally. Owing to the heterogeneity of space-time there are, generally speaking, no transformations under which equations of physics would be invariant. They always include quantities characterising the structure of space-time and at the same time a system of coordinates (the components of the metric tensor g_{ik}). Incidentally, the difficulty lies precisely in the fact that these quantities simultaneously express two different things: the structure of space-time, that is, something "absolute" and independent of the system of coordinates, and the properties of the system of coordinates itself, that is, something relative. It is impossible to separate them within the framework of the mathematical apparatus commonly used in Einstein's theory.

Insofar as the structure itself of space-time proves to be variable, it may be viewed as a kind of physical field. In abstraction from it, space-time becomes merely four-dimensional space possessing no metric, no properties apart from continuity (and "differentiability": space-time proves to be a differentiable four-dimensional manifold). In this approach, all coordinate systems are equal for the simple reason that any possible grounds for distinguishing between them are ruled out beforehand. The general principle of relativity is satisfied, but only because of trivial disregard for any special properties of space-time. At the same time the concept of accelerated or unaccelerated motion becomes meaningless, for determining acceleration requires some measuring unit, and in a space without metric there are no measuring units. It is therefore meaningless to speak here of the equality of reference frames in different kinds of motion, for the very concept of their motion is not clear. In the absence of any structure, there is no concept of what time is. The motion of a point is described simply by a line in a four-dimensional manifold, and one line is no better and no worse than another, since there are no grounds for differentiating between their properties.

Thus any sort of physics disappears here, leaving behind just this proposition: "space-time is in general a four-dimensional manifold". But that is just as true in the special theory of relativity and in classical mechanics as it is true in the general theory of relativity. "The general principle of relativity" is true in all these theories. It does not express anything more than the same requirement of covariance, since the latter consists precisely in the requirement to write equations in a form suitable for any coordinates.

The specificity of the general theory of relativity is only revealed when the structure or metric of space-time is introduced into consideration. The non-uniformity of this structure is a specific feature of the theory. In short, its essence is not in the "general principle of relativity" or arbitrary choice of coordinate systems but in the specific propositions concerning the structure of space-time. In other words, it is not the relative but the absolute that is essential—namely, the properties of space-time independent of reference frames and coordinates.

Among the specialists on the theory of relativity, V. A. Fok was particularly insistent and consistent in his opposition to relativism. As evidence of acute differences in the interpretation of the general theory of relativity amongst physicists let us quote J. L. Synge's Preface to his fundamental treatise on the general theory of relativity written in 1960: "...the geometrical way of looking at space-time comes directly from Minkowski. He protested against the use of the word 'relativity' to describe a theory based on an 'absolute' (space-time), and, had he lived to see the general theory of relativity, I believe he would have repeated his protest in even stronger terms. However, we need not bother about the name, for the word 'relativity' now means primarily Einstein's theory and only secondarily the obscure philosophy which may have suggested it originally. It is to support Minkowski's way of looking at relativity that I find myself pursuing the hard path of the missionary. When, in a relativistic discussion, I try to make things clearer by a space-time diagram, the other participants look at it with polite detachment and, after a pause of embarrassment as if some childish indecency had been exhibited, resume the debate in their own terms. Perhaps they speak of the Principle of Equivalence. If so, it is my turn to have a blank mind, for I have never been able to understand this Principle... Does it mean that the effects of a gravitational field are indistinguishable from the effects of an observer's acceleration? If so, it is false. In Einstein's theory, either there is a gravitational field or there is none, according as the Riemann tensor does not or does vanish. This is an absolute property; it has nothing to do with any observer's world-line. Space-time is either flat or curved... The Principle of Equivalence performed the essential office of midwife at the birth of general relativity, but, as Einstein remarked, the infant would never have got beyond its long-clothes had it not been for Minkowski's concept. I suggest that the midwife be now buried with appropriate honours and the facts of absolute space-time faced" [3, pp. IX-X].

The following explanation is due in connection with the principle of equivalence. The disappearance of gravitation forces in a free-fall system was one of the starting points of Einstein's theory. But when it has been accepted that space-time is flat in the domain of the infinitesimal, the principle of equivalence as the possibility of excluding gravitational forces proves to be merely a physical expression of a familiar theorem of Riemann's geometry. Therefore in Einstein's theory itself, that is no more a "principle" than any other geometrical theorem. Relativism thus turns out to be merely the result of inadequate understanding of simple mathematical facts, and this kind of inadequacy occurs even in outstanding authors.

Let us further specify the concept of the principle of relativity. A physical law defines a connection between some characteristics of certain phenomena or one phenomenon. For simplicity sake let us agree that we are dealing with two characteristics or systems of characteristics which we shall designate x and y. Then the law will be represented by the dependence $F(x, y) = 0$. However, this representation is not quite exact, for we have also to take into account the conditions under which this dependence obtains. Designating the set of such conditions as A, we shall have to write the symbolic equation expressing the given law as follows:

$$F(x, y;\ A) = 0. \qquad (1)$$

We shall now analyse the conditions themselves. First, "the background" will have to be distinguished here—the invariant conditions that are usually merely implied. Let us designate them as B. That may be space-time in general or, for instance, the Earth's gravitational field at a given spot, and so on. Second, the conditions specify the system S relative to which phenomena are registered and the characteristics themselves x and y are specified. The phenomena may be perceived as taking place in the system S. Linked with it is a system of spatio-temporal coordinates, and it functions as a reference frame. Third, there are conditions in the system S itself which are defined with respect to it and may vary, determining the concrete course of a phenomenon. Thus the entire set of conditions is represented as $A = (B, S, C)$, and equation (1) is accordingly written

$$F(x, y;\ B, S, C) = 0. \qquad (2)$$

If for a certain class of systems S the dependence expressed here is the same in all such systems, S does not form part of (2), and the law has the form

$$F(x, y;\ B, C) = 0\ . \qquad (3)$$

In this case the law does not depend on the system S, and the equation is invariant under the transition from one system to another. If that is true of a certain class of phenomena P and systems S, the principle of relativity is said to obtain for these systems and phenomena. Thus Galileo's classical principle pertains to mechanical phenomena and inertial systems.

However, the very distinction between background B, system S and conditions C is relative and to some extent conventional. We can, generally speaking, always include the system into conditions C: the phenomenon occurs against the background B under conditions C, taking also into account the fact that it occurs in system S. If we adopt this view, general equation (2) assumes the form (1), for S is included in C, and the principle of relativity is satisfied here, but only for the simple reason that the systems themselves are included in the variable conditions C.

If we limit ourselves to the special theory of relativity, the space-time metric is fixed here. It is therefore not natural to include it in the variable conditions C; it is part of the constant background, and it is naturally included there. The same situation obtains in classical theory; the difference being that in the latter theory, the background is different—not the Minkowski space-time but Euclidean space combined with absolute time.

However, in the general theory of relativity the metric is no longer invariant but depends on physical conditions. It is therefore impossible to include it in the background in the general constructions of the theory. On the other hand, when the conditions are fixed, the metric is also fixed. It is natural in this case to include it in the given background. For example, in the Earth's neighbourhood the gravitational field and, correspondingly, the structure of space-time may be regarded as fixed, and coordinates naturally connected with the Earth may be introduced; in considering the solar system the natural coordinates will be those connected with the sun; in considering a model of the universe with even distribution of the masses quite different coordinates will be preferred. In a word, definite coordinates are preferred depending on the conditions, respectively on the concrete structure of space-time they define. The extent to which such special coordinates may be arbitrary and, consequently, the extent to which the principle of relativity is satisfied in them (if only as an approximation), again depends on the conditions and the factors that we take into account or ignore.

Relativity is relative—that is, to put it briefly, the crux of the matter. Everything in the world is relative, to some extent or other. But the relative is itself only an aspect or facet of the absolute and it contains the absolute as, say, the principle of relativity expresses a certain non-relative property of the world—homogeneity of its structure, be it for small domains and only approximately. The crux of the matter is in this dialectics of the relative and absolute. Unless it is thoroughly understood, it is impossible to gain a deep enough insight into either the theory of relativity or modern physics in general.

3. What Is Space-Time?

This question may seem an idle one, for an answer to it has already been formulated: space-time is the form of existence of matter. However, the question that we, properly speaking, have in mind here is that of a way to define exactly this form of the existence of matter. What we need is not an answer at a general philosophical level but one at a level which would form the basis for constructing a theory of space-time. Understandably, the answer must lie in the theory of relativity, inasmuch as it is exactly a theory of space-time. But this answer has yet to be extracted out of this theory.

The form of an object is, properly speaking, nothing more than the totality of the relations of its parts. Therefore what we must deal with here are the material links between the elements of the world, the ensemble of which (of the links, that is) defines space-time.

The simplest element of the world is what is referred to as an event. It is a "point" phenomenon like a momentaneous flare of a point lamp or, to use ostensive concepts of space and time, a phenomenon whose extension in space and time may be regarded as negligible. In short, an event is analogous to a point in geometry; imitating Euclid's definition of point, we may say that an event is phenomenon whose part is nothing: it is a "monatomic" phenomenon. Any phenomenon or process is conceived of as a certain coherent ensemble of events. From this standpoint the whole world is regarded as a set of events.

Disregarding all the properties of an event other than its existence, we present it as a point, a "world point". Space-time is the set of all world points. In this conception, however, space-time does not have any structure whatever as yet—it is merely a set of events retaining merely the fact of their existence as distinct events, without any regard for all the other properties or relations between them. We can introduce the concept of continuity of a number of events borrowing it from the ostensive conception or giving it some suitable definition. Space-time will then be simply a four-dimensional manifold in the topological sense. Space-time, that is, a set of events without any concrete properties whatever, without any structure except for the one that is defined by the relations of continuity, is exactly the background that figured in the consideration of the general theory of relativity. But we are not stopping here; we define space-time structure and continuity itself proceeding from the most general and basic relation of events that exists in the world. We refer to the motion of matter.

Each event acts in some way or other on other events and is itself acted upon by other events. In general, action is motion connecting one event with another through a number of intermediate events. The physical nature of action may be quite varied: it must be presented as propagation of light, emission of a particle, etc. Clearly, action need not always be direct: it may be implemented through a number of agents. The movement itself of a small body is a number of events in which preceding events affect subsequent ones. In physical concepts, action may be defined as transmission of momentum and energy. These concepts will then appear as basic, which is in accord with the essence of the matter, for momentum-energy is the principal physical characteristic of motion and action. But, just as we disregard the concrete properties of events, we disregard the concrete properties of action in the concept of action, too, except for the fact that it is a relation between events having the properties of the general relation of precedence (anti-symmetry and transitivity). In an axiomatically constructed theory of space-time, the concepts of event as a world point and of action as precedence would have to be taken as basic and undefinable. The events experiencing the action of the given event A form "the domain of the action of the event A". These domains define a certain structure in the set of all events. It is of course equipollent to the structure defined by the action relations themselves. That structure is precisely the spatio-temporal structure of the world. In other words, space-time itself may be defined as follows:

Space-time is the set of all events in the world having no properties except those defined by the relations of the action of some events on others.

The action of one event on another is an elementary form of causal connection, its "atom" or "quantum", as it were; in the same way the event itself is a "monatomic" phenomenon. What has just been said may therefore be expressed in less precise but more graphic terms as follows: *the spatio-temporal structure of the world is nothing but its cause-and-effect structure under a proper abstraction.* This abstraction consists in disregarding all the properties of phenomena and their causal links except for the fact that phenomena are made up of events, and their mutual influences, of the action of some events on others.

That this definition of space-time is actually possible in the framework of the theory of relativity is proved in purely mathematical terms (see [4, pp. 1119-1128]). The action relations without reference to any properties (not even continuity) indeed define the Minkowski four-dimensional space in the special theory of relativity. The definition of space-time in the general theory of relativity requires a certain addition. It may be formulated as a local fixation of certain scales of couples of infinitely close events to which a definite magnitude of the interval between them is ascribed.

This description of space-time is nothing but a concrete and precise expression, which is in accord with modern physics, of the fact that space-time is the form of the existence of matter. Matter itself in its motion and thereby in the interaction of its elements determines its spatio-temporal form. This definition is impossible in terms of classical physical concepts. Thus it was believed that action could be transmitted at an arbitrary speed. Under these conditions, the domain of possible action of the given event in principle extends to all events following it in time. As a result, the relation of action does not define anything but mere succession in time. The classical concepts of absolute succession in time and absolute simultaneity are in agreement with this. As for quantitative definition of the time t and of the geometry of space, they must be defined by some other factors. Moreover, no definition of time and space is known in general that would accord with the conceptions of classical physics and at the same time be as brief and precise as the definition of space-time given above. The very possibility of the existence of such a definition constitutes an enormous advantage of the theory of relativity, showing how deeply it has penetrated in the understanding of the fundamental structures of the world.

Defining space-time, the system of action relations defines thereby all possible relative times and spaces with their geometry. Naturally, the definition is originally given for space-time, that is, for the absolute form of the world, and not separately for space and for time which are merely relative aspects of this form. Without going into detail, one may briefly state that space is a set of parallel series of events linked by action. A point in space is not something elementary—it is defined, to put it simply, by a number of events occurring at a given place; to be more precise, the "given place" itself is fixed by this series of events. The relation between various points of space, that is, its geometry, is naturally defined by the structure of space-time, that is, relations of action. In its turn, time at a given place may be defined as a series of events fixing that place, under the condition that we disregard all the properties of these events except for those which are defined by the same action relations but, of course, not only within the given series of events but rather by the entire ensemble of action relations inflicted on and by these events. As for agreement of different local times and thereby some relative time extended to the whole world, it is further defined by the relations of action. (Incidentally, it may be noted that the general basis of Einstein's definition of simultaneity is elucidated here. It is proved that any definition of simultaneity subordinated to the natural requirements of symmetry and transitivity and based only on relations of action in their general structure, is necessarily equivalent to the Einsteinian. This is true, of course, only in the space-time of the special theory of relativity, for Einstein's definition is inapplicable to the general theory.)

The definition of space-time given here may be used as the basis for constructing a theory of relativity. Suitable requirements will have to be imposed, of course, on the structure of the relations of action or, equivalently, on the structure of the domains of action. But we shall not dwell on this here.

Going back to what was said at the beginning of the article, it may be noted that the definition of space-time given here and the later definition of space with its geometry contain an answer to Riemann's question concerning the causes which generate metric relations in space. They are contained in the very existence of causal links between phenomena. Action relations, defining the structure of space-time, define along with it a geometry—the metric of space.

Thus the relativity theory has answered the most profound questions posed by its predecessors concerning the nature of space and time, the basis of the metric properties of space, the links between the properties of space and time, on the one hand, and the properties of matter, on the other, the nature of universal gravitation, and so on.

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THE CONCEPT OF SIMULTANEITY AND THE CONCEPTION OF TIME IN THE SPECIAL THEORY OF RELATIVITY

That the special theory of relativity relies on a conception of time different from classical physics does not require either special substantiation or proof nowadays: it is generally recognised in the literature both on the special relativity theory and on the problem of time. However, it took considerable theoretical effort for this proposition to become established, and the process involved analysis of the physical content of the special relativity theory and of the philosophical implications of the spatial and temporal relations accepted in it. This view asserted itself amidst lively and at times fierce debate.

The debate centred on the interpretation of Einstein's definition of simultaneity. Incidentally, it still remains the object of close attention and highly sophisticated theoretical debate. That is not surprising. Interpretation of the simultaneity concept is closely linked with the conception of time in which it is formulated.

1. Various Interpretations of Simultaneity in Pre-relativistic Physics

As a very first approximation, the concept or relation of simultaneity expresses absence of temporal succession between the events considered, that is, absence of temporal relations between them. This circumstance largely explains the considerable attention paid to this concept in the discussion of the problem of time. Indeed, with a clear understanding of what temporal relations are not, it will be much easier for us to attain an adequate understanding and interpretation of temporal relations. However, this specific role of the simultaneity concept and its significance for comprehending temporal relations were almost never realised in the discussions of time, so that the need for a clear definition of this concept was almost completely ignored.

Probably the first thinker to analyse the concept of simultaneity was Aristotle; in his *Physics* we find profound and all-round treatment of the problem of time and an outline of its conceptual content. He emphasised such an important feature of the concept of simultaneity as reflection in it of the absence of temporal relations between events, distinguishing between the concepts of "simultaneity" and "now" [1, p. 298].

After Aristotle, the concept of simultaneity was largely ignored by researchers for more than two thousand years. This concept was not expressed or defined with sufficient precision even in Newton's theoretical scheme—in the first clearly and distinctly formulated conception of time as an objective essence independent of any other essences, that is, in the *substantial* conception of time.

True, Newton's theory of absolute time which "of itself, and from its own nature, flows equably" [2, p. 6], led to the interpretation of the simultaneity relation as pertinency of events to a single point on the absolute time scale, or to a unitary section across the "flow" of absolute time. This interpretation of absolute time and simultaneity, we must stress, was in no way linked with either the concept of momentaneous action at a distance or that of infinite velocity of light [7, pp. 57-58]. Inasmuch as Newton insisted that probably "there is no such thing as an equable motion, whereby time may be accurately measured", and that "all motions may be accelerated and retarded, but the flowing of absolute time is not liable to any change" [2, p. 8], and also defined space, that is, an ensemble of simultaneous events, as "God's sensorium" [4, pp. 542-543; 5, pp. 13, 16], it may be assumed that his conception of simultaneity is based on the notion of pertinency of events to a single point or cross-section of absolute time which is not established or fixed by any material interactions but may be grasped in the subjective act of mental momentaneous perception.

Newton's famous opponent, Leibniz, defending a *relational* conception of time opposed to the Newtonian one, tried to define simultaneity as the relation of physical events mutually compatible with each other. He took as his example the possibility of one and the same thing's being simultaneously white and warm and the impossibility of its being simultaneously young and old. Of course, this definition did not contribute much to an understanding of temporal relations, but in his polemics with Samuel Clarke Leibniz defined space as "an order of things which exist at the same time, considered as existing together" [5, p. 26], that is, he unambiguously linked up the relation of simultaneity, first, with spatial relations, and second, with absence of temporal relations.

An original approach to simultaneity is found in Immanuel Kant's *Critique of Pure Reason* [6, pp. 266, 268]. Although Kant does not offer a special definition of the relation of simultaneity, he links up this relation, quite unambiguously, with that of totality. In his view, simultaneity characterises all elements of a unitary and integral material system. However, the correctness of this interpretation depends quite essentially on the presence in nature of forces momentaneously acting at a distance. Inasmuch as the existence of such forces has not been proved, this interpretation should be regarded as highly approximate and conventional [7, pp. 75-76].

All these rather meagre theoretical fragments scattered mostly in philosophical works that are not too readily available, if not exactly little known, did not offer a consistent and logically clear definition of simultaneity—they did not even facilitate the realisation that a search for such a definition was necessary.

However, the concept of simultaneity and various methods for determining this relation were widely used in theoretical natural science and in practice, first of all in astronomic research and in navigation. In astronomy, it was believed to be self-obvious that simultaneity could be defined as pertinency of mutually remote events to a single moment of absolute or genuinely mathematical time earlier represented by mean astronomical time. Thus

Olauf Roemer could never have proved the finite magnitude of light velocity from the phenomenon of retardation of the eclipse of Jupiter's satellites, had he not postulated simultaneity of genuine previous positions of these satellites with regard to some past moments of absolute time marked by a terrestrial clock in his laboratory. That absolute time was established as something self-obvious, independent of any material interactions connecting events in different places.

In navigation, more or less precise position of ships was determined by means of clocks which supposedly guaranteed the establishment of simultaneity with events occurring at other places. It was generally understood, of course, that clocks could deviate from absolute time in some way or other, but genuine, mathematical, absolute time was everywhere the same, a guarantee that the position of the ship would be determined more or less precisely (depending on the quality of the clock).

In general, postulating unitary and unique world absolute time which, apart from other things, flows equably, and interpreting the relation of simultaneity of events in different places as their pertinency to one and the same point on the scale of absolute time yields the conclusion that *only one single event* at *any* point of space may be simultaneous with an event *at a given* point of space, and that this relation is *universal in nature,* that is, it holds in arbitrary reference frames. However, this conception of the relation of simultaneity was not theoretically formulated.

2. The Substantial and the Relational Conceptions of Time

The concept of simultaneity essentially depends on the conception of time in which it is formulated, regardless of whether this conception is a code of clearly formulated principles and propositions or is accepted unconsciously. Of the greatest importance in this respect are the substantial and the relational conceptions of time.

The *substantial* conception, which goes back to the philosophy of antique atomists, did not enjoy any popularity at all in philosophy from antiquity up to the times of Newton. Newton's doctrine of absolute space and absolute time presented, for the first time in the history of philosophy and physics, a clear formulation of the main propositions of the substantial conceptions of space and time. Beginning with his work *The Mathematical Principles of Natural Philosophy,* the substantial conception of time dominated physical theories until the early 20th century. According to this conception, *time* is a kind of *absolutely independent entity* subject to its own inner laws and existing independently from anything "external" with respect to it. That is exactly why the term "substantial" is applicable to it.

The *relational* conception of time is just as ancient as the substantial one. Its source is in Plato, but it was more distinctly expressed in the work of Aristotle. According to this conception, *time* is not something existing independently: it is something *derivative from a more fundamental essence.* Two principal varieties of the relational conception of time have been formulated in the past. Some thinkers regarded time as a property or attribute of some more fundamental essence, while others defined it as a relation (hence the term "relational").

The relational conception dominated philosophy throughout the history of human thought. (Let us recall that in physics, the substantial conception was dominant between the age of Newton and early 20th century.) However, materialist relational interpretation of time is an exception rather than the rule in the history of philosophy (Epicurus, Lucretius, Bošković, Toland). The absolute majority of thinkers (both idealists and materialists) regarded time as a property or relation or, to be more precise, as a product of a more fundamental *spiritual essence.* According to Plato time was created by God. Aristotle admitted the interpretation of time as resulting from the action of the soul, but he also accepted a materialist conception of time as a result (or quantity) of objective material motion. Neo-Platonists deduced time from the action of the world soul. For Catholic philosophy, time is generated by God, and so on. In the philosophy of the New Times, beginning with Descartes and ending with late 19th-century positivists, time is a property or relation expressing various aspects of the activity of *man's consciousness* (for details see [7]).

Thus up to the 20th century physics was dominated by Newton's materialist substantial conception of absolute time, and philosophy, by different variants of subjectivist relational conceptions.

The exception in the history of philosophy is the theory of dialectical materialism, which consistently defended (and that was a unique phenomenon in the history of philosophy) the *materialist* position on the objective nature of time. It was expressed in the well-known thesis of Engels that *space and time are the forms of the existence of matter* [8, p. 67].

3. Pre-relativistic Discussions

The development of physics and mathematics between the 1840s and 1900s resulted in the first cracks in the foundation, which was earlier believed to be unshakeable, of the classical conceptions of the essence of space and time. The formulation of non-Euclidean geometries by Lobachevsky, Bolyai, Gauß, and later by Riemann showed the need for substantiating geometry by an analysis of the properties of *actual physical interactions* and processes. In this way the idea was undermined of the self-sufficient and entirely independent nature of space and thereby also of time.

The development of classical thermodynamics, the formulation of its second principle (the law of entropy growth) were a stimulus for linking up with this principle the irreversible and unidirectional character of the real processes of the world and by that token of time. The idea gained wide currency that one of the principal properties of time—its irreversibility and unidirectionality—is ultimately determined by the nature of *real physical processes*.

Finally, the works of some positivistically minded physicists and philosophers, particularly of Ernst Mach and J. B. Stallo, became increasingly concerned with *empirical verification* and substantiation of the basic propositions of the substantial conceptions of space and time formulated in the Newton doctrine. The obvious impossibility of discovery of these empirical foundations, on the one hand, compelled positivists to give up the idea of the objective character of space and time, and on the other, directed the attention of researchers to the quest for these foundations and to working out new physical conceptions of the essence of space and time that would in a sense be an alternative to those of Newton.

Late in the 19th century, scientists became interested in the problem of defining simultaneity. The essence of the discussion of that time can be gauged by Henri Poincaré's article "The Measurement of Time" published in 1898 [9, pp. 1-12], which summed up the discussion.

Poincaré analyses various attempts to find an adequate definition of simultaneity. First of all he considers the definition which is unconsciously accepted in everyday experience and is given theoretical expression by Henri Bergson. According to that definition, those events are simultaneous that can be grasped "by a simple act of thought" [10, p. 175]. Poincaré shows up the naive nature of this definition and its complete untenability. He also analyses the definition of simultaneity through moving clocks and through different variants of the signal method, from sending letters and telegrams to light signals. In actual fact Poincare considers *experimental* procedures intended to fix the relations of simultaneity rather than *conceptual* or *logical definitions* of these relations. As for definitions of the latter type, he says merely that "two facts must be regarded as simultaneous when the order of their succession may be inverted at will" [9, p. 8].

In the final analysis Poincaré comes to the conclusion that most divers rules can be used to fix or define simultaneity: "No general rule, no rigorous rule here; a multitude of little rules applicable to each particular case. These rules are not binding on us... All these rules, all these definitions are nothing but the product of unconscious convention" [9, p. 13]. Thus, although Poincaré understood the whole complexity of defining simultaneity, he assumed that such a definition could be introduced in an *arbitrary* manner having no objective basis but being rather the *result of "unconscious convention"*.

The problem was thus formulated, but no attempts at its solution were undertaken.

4. The Procedure for Establishing Simultaneity Suggested by Albert Einstein

In his famous article "On the Electrodynamics of Moving Bodies" Einstein suggested a procedure for establishing simultaneity that is now called "signalling procedure" [11, pp. 35-65]. The principle of the procedure was not novel (as we have seen, it was considered by Henri Poincaré). However, in using it Einstein obtained unusual conclusions about the properties of space and time; this can be seen as the secret of rapid recognition of the special relativity theory, whose mathematical formalism was not original, either (the mathematical formalism was identical to the fairly well-known Lorentz transformations). Before proceeding to the analysis and interpretation of Einstein's procedure as well as the conclusions which follow from it, let us recall its scheme.

To obtain a description, ordered in time, of the events occurring at different points of space, *A* and *B*, it is necessary, says Einstein, to establish a common time for these points. Time flowing at points *A* and *B* is measured by clocks placed there. To establish "a common time for *A* and *B*", a *synchronisation* of the clocks at these points is needed, that is, they should *simultaneously produce the same readings.* That is possible on condition that the observer at, say, point *A* will be able to establish which of the indications of clock *A* will be simultaneous with some definite event at point *B.* The signalling procedure consists in a light signal being sent from point *A* to point *B* at a definite moment of time recorded by the clock *A;* at point *B* this signal is instantly reflected and after some time (due to the finite magnitude of light velocity) comes back to point *A* at a moment of time recorded by clock *A*.

Poincaré had been content merely with describing this procedure, insisting only that the relation of simultaneity was established by a "complex rule" which "is nothing but the product of unconscious convention" [9, pp. 12, 13]. Einstein took a step further and formulated that rule, which incidentally proved to be not very complex at all: "the latter (a common 'time' for *A* and *B*) cannot be defined at all unless we establish *by definition* that the 'time' required by light to travel from

A to *B* equals the 'time' it requires to travel from *B* to *A*" [11, p. 40]. Thus simultaneous with the event of signal reflection at point *B* will be an event at *A* which will occur *precisely in the middle* of the time interval separating the events of emission of the signal and its return to point *A*.

Let us also emphasise that the place of Poincaré's "unconscious convention" is here taken by a quite conscious definition postulating equality of light speeds in opposite directions. Although this definition is undoubtedly a step forward as a concretisation of the "unconscious convention", it is not in principle original, for it merely specifies the fundamental principle of Poincaré, who added, besides, that in such procedures for establishing temporal relations the speed of light is taken to be "constant and, in particular, identical in all directions" [9, p. 11].

But further, after an analysis of application of this procedure for the establishment of simultaneity in considering correlations of events occurring in different inertial frames, there followed a truly sensational conclusion that *had not been drawn by anyone at any time* in the history of the theories of time: "so we see that we cannot attach any *absolute* signification to the concept of simultaneity, but that two events, which, viewed from a system of co-ordinates, are simultaneous, can no longer be looked upon as simultaneous events when envisaged from a system which is in motion relatively to that system" [11, pp. 42-43]. This conclusion served as the main (but not of course the only) cause for the universal and immediate attention to the special theory of relativity.

Thus the new theory, at its very inception, established an essential difference of the conception of simultaneity from all the previous interpretations.

The classical approach to simultaneity was characterised by two principal assumptions (explicit or implicit, conscious or unconscious).

1. *One and only one event at any point in space is simultaneous* with an event occurring at a given point in space.

2. This relation of simultaneity between two given events holds *everywhere, in all possible reference frames.*

It is easy to see that the seeming correctness of these propositions does not depend on our interpretation of the mechanism of establishing temporal relations and the relations of simultaneity; it does not depend on whether they are established by themselves irrespective of anything that is external, through hypothetical momentaneous action at a distance, or through grasping them "in one momentaneous perception" [10, p. 56].

The procedure for establishing simultaneity suggested by Einstein resulted, first of all, in the explicit and unambiguous rejection of the *second* of the assumptions of the classical interpretation of simultaneity, namely, the assumption of the *universal* nature of any given simultaneity relation, leaving the *first* assumption apparently unshaken, for "by definition" *one and only one event, simultaneous* with the given one, was established at any other point of space. This procedure, however, contained a number of veiled questions of principle, analysis of which inevitably resulted in a completely new conception of temporal relations.

5. Consequences from the Procedure of Establishing Simultaneity

We must stress first of all that the procedure for establishing simultaneity described in the above, or, to be more precise, the procedure for synchronising clocks, usually referred to in the literature as "Einsteinian definition of simultaneity", is neither a conceptual nor a logical definition. The procedure is intended to synchronise clocks, not to define simultaneity, although this word is mentioned by Einstein along with the word "time" in describing the results of the procedure. The basic theoretical considerations on which it was constructed remained outside its description and were later specified and clearly formulated by Einstein and other researchers.

But what are synchronised clocks? They are clocks simultaneously producing identical readings. Therefore, to synchronise them, one must proceed from some concept or conception of simultaneity. That is the kind of conception from which Einstein proceeds in saying or rather assuming (since it is a question of light speed being equal in opposite directions) that simultaneous with the event of signal reflection at point *B* will be an event at point *A* which has occurred (a past event is referred to here) precisely in the middle of the time interval (=light speed being equal in opposite directions) dividing the events of sending the signal from point *A* to point *B* and the event of the signal's return from point *B* to point *A*.

But why must we ascribe simultaneity to an event exactly from the interval between the sending of the signal and its return? Why cannot we regard as simultaneous events from time intervals before the sending of the signal and after its return? The answers to these questions lead to the formulation of the basic propositions of the *materialist relational conception of time.*

Let us recall two important facts mentioned above. First, all or almost all relational conceptions of time dominating philosophy before the 20th century were idealist (the views of Lucretius, Toland, and Bošković that are the exception can hardly be called conceptions: they were vague formulations with intuitive implications). They regarded time as a derivative of a certain spiritual substance —human or divine consciousness. Second, positivists (in particular Stallo and Mach) insisted on finding an empirical basis for time and space.

Simultaneity is ascribed to one of the events occurring between the sending and the return of the signal, because none of these events, owing to the finite (and limited) magnitude of light velocity, *can in principle physically interact* with the event of signal reflection at point *B*. There can be no *temporal* relations between these events, they are *simultaneous.* Those events which occur at point *A* before the sending and after the return of the signal, are not simultaneous. There exist temporal relations between them and the event of signal reflection at point *B*. Why is that so? Because they can either produce a material action on the event of signal reflection at point *B* (events preceding the sending of the signal) or be subjected to material action on the part of the event of signal reflection at point *B* (events taking place after the return of the signal). The former takes place *absolutely earlier* than the event of signal reflection at *B*, the latter, *absolutely later.*

Thus temporal relations are conditioned by the existence of material interactions between events. Absence of temporal relations, or existence of the relation of *simultaneity,* is conditioned by the impossibility of material interactions between events. Later, in the work "The Meaning of Relativity", Einstein wrote: "In order to give physical significance to the concept of time, processes of some kind are required which enable relations to be established between different places... Space and time data have a physically real, and not a mere fictitious, significance" [12, pp 28, 29].

Thus on the one hand temporal relations prove to be derived from physical interactions, and time acquires a material basis, and on the other, it acquires simultaneously an *empirical basis.* That is the fundamental proposition of the materialist relational conception of time.

Now we can approach the theoretical conception of simultaneity which, although it was not explicitly formulated by Einstein, underlies the signalling procedure. A conceptual definition may also be formulated in accordance with this notion: by *simultaneous* are meant events *which cannot in principle interact with one another.* This impossibility is conditioned by the absence of momentaneous action at a distance in nature, that is, by the fact that all material interactions are implemented at a certain finite speed.

In the modern view, the upper limit of this speed is light velocity. Although the latter proposition is contested by some scientists, superlight speeds of interaction are also finite.

In the procedure of establishing simultaneity described here, there are at point *A* not one but a certain set of events situated or rather occurring in the interval between the sending of the signal from *A* and its return from *B*. *None of these events,* owing to finite light speed, *can* in principle *interact* with the event of signal reflection at point *B*. So all of them, according to the definition formulated above, are simultaneous. Out of this set of events, which it would be appropriate to regard as *objectively simultaneous,* Einstein chooses *one and only one event* occurring precisely in the middle of the time interval between the sending and the return of the signal, and regards it as *simultaneous.* It follows that all the other events in this interval are not simultaneous.

This seeming contradiction between Einstein's definition of only one event as simultaneous and the tacitly assumed idea of a number of objectively simultaneous events occurring in the interval between the sending and the return of the signal, is due to an insufficiently clear realisation of the fact that the classical relation of absolute simultaneity is characterised by two aspects—*uniqueness* and *universality* [7, pp. 135-144]. Einstein rejected the universality aspect in a clear and unambiguous manner, stressing that events simultaneous in one inertial frame will not be simultaneous in another; and the aspect of uniqueness he rejected implicitly. At any other point in space, simultaneous (or rather absolutely simultaneous) with the event taking place at the given point in space will be, just as in the classical view, one and only one event. However, for the classical interpretation of simultaneity, the existence at some other point in space of one and only one event simultaneous with the given one is an *objective inner property* of the relation of simultaneity established by itself, regardless of anything external, while according to Einstein, this one and only one simultaneous event is established "*by definition*", that is, it results from the convention that the speeds of light in opposite directions are equal.

This terminological and conceptual vagueness in the interpretation of the content of the simultaneity relation both in classical and relativistic physics proved to be, along with other causes, the source of the debate, still going on, about the physical meaning of the concept of simultaneity and the role and significance of convention in its theoretical definition and experimental operations of establishing simultaneity.

6. Debate on the Meaning and Significance of the Concept of Simultaneity

The debate about the physical content and philosophical significance of the special theory of relativity began at its very inception and has continued to the present. However, the focal aspects of the discussions varied all the time. We shall not consider the interpretations of the Lorentz transformations and conclusions that follow from them since these, on the one hand, go beyond the framework of the present paper, and on the other, were not as central for that debate as the problem of simultaneity. In the 1930s L. I. Mandelshtam said that in the problem of simultaneity "lies the essence of the theory of relativity. If understanding is reached on this point, the rest becomes clear of itself..." [13, p. 57].

In the first period, from the inception of the special theory of relativity up to the end of the 1940s, the debate centred on the proposition of the relativity of the universal nature of the simultaneity relation, that is, of the non-invariance of this relation in different inertial frames. Einstein's opponents did their best to refute this proposition, while his adherents always stressed the novel and original nature of the conclusion, mostly expressing their amazement and admiration without any attempts at a deeper analysis and interpretation of the problem.

The second period, if one may put it that way, begins with the works of Hans Reichenbach in the late 1920s [14, 15] and is continued into the present. The debate now centres on the unique nature of the relation of simultaneity and its basis. Scientists are concerned here not so much with the question whether an event occurring at some definite point in space has not one and only one simultaneous event corresponding to it in any other point in space but a whole set of such events (and why that is so); they are more concerned with the grounds for choosing out of this set one and only one event which is referred to in Einstein's definition as simultaneous with it.

There is practically a consensus as to the first aspect of the question—the fact that for various points in space the relations of simultaneity characterise sets of events rather than pairs of unique events. Opinions vary only on terminological matters. Thus Hans Reichenbach calls these sets "areas... indeterminate as to order of time" [16, p. 41]; G. J. Whitrow speaks of them as "the relativistic analogue of the world-wide simultaneity of Newtonian physics" [17, p. 299]; V. A. Fok defines them as domains of "quasi-simultaneous" events [18, p. 52]; Adolf Grünbaum refers to these events as "topologically simultaneous"

[19, pp. 28-32; 341-417]. The present author has suggested that they should be regarded, on the one hand, as "objectively simultaneous", and on the other, as "relatively simultaneous in the sense of uniqueness" [7, pp. 138-144]. In the physical literature these areas are characterised as divided by "space-like intervals".

Despite the difference in the terminology, which characterises, more or less aptly, the various aspects of the relation considered here, the physical meaning is identical. Inasmuch as, firstly, temporal relations are conditioned by physical interactions, and, secondly, there is no "momentaneous action at a distance" in nature, or physical interactions transmitted at infinitely great speeds, there will always be certain sets of events at different points in space, rather than isolated events, which cannot in general interact with one another. To put it briefly, Einstein chooses "by definition" one and only one couple out of the two sets of events which take place at various points of space and cannot in principle interact with each other. This thesis is now shared, explicitly or implicitly, practically by everybody, and the debate centres mostly on the foundations of this "definition".

Before we consider the substance of the debate, let us recall that the time of an event at point *A* simultaneous with the event of signal reflection at point *B* is determined by the formula

$$t_{A_t} = t_B = t_{A_0} + \epsilon (t_{A_n} - t_{A_0}),$$

where t_B is the time of the event of signal reflection at point *B*; t_{A_t} is the time of the event at point *A* simultaneous with the event of signal reflection at point *B*; t_{A_0} is the time of sending of the signal from point *A* to point *B*; t_{A_n} is the time of the return of the signal from point *B* to point *A*; and ϵ is a certain coefficient which we shall refer to below as "simultaneity coefficient"; its magnitude varies between 0 and 1. If $\epsilon = 0$, that means that the speed of the signal equals infinity: the signal is transmitted instantaneously. If the speed of the signal is finite, ϵ cannot be greater than 1, otherwise the definition becomes meaningless, for simultaneous with the event of signal reflection at point *B* will be an event which took place after the return of the signal from point B to point A. The magnitude of the second extreme limit of ϵ being equal to 1 means that the speed of the signal as it travels from point A to point B is finite and equals the distance divided by the entire interval of time between the sending and the return of the signal, and on the way back, from point B to point A, it was infinite, or vice versa. No other restrictions are imposed on the magnitude of ϵ by the conditions of the given procedure. Thus, $0 \leqslant \epsilon \leqslant 1$, and if the possibility of infinite speeds is rejected, then $0 < \epsilon < 1$.

The choice of the magnitude of $\epsilon = 1/2$ corresponds to Einstein's "definition" concerning the equality of speeds of light (of the signal) on the way "there" and "back"; it is called in the literature "the condition of standard synchronisation", or simply "standard synchronisation". The choice of any other values of ϵ in the interval between 0 and 1 results in "non-standard synchronisations", implying that the speed of the signal on the way "there" is not equal to the speed of the signal on the way "back".

Two viewpoints, opposed to each other in a certain sense, are clearly distinguishable in the debate on this question.

Some authors believe it possible to advance convincing arguments in favour of the "standard synchronisation" condition—either through mental experiments (transporting clocks at an infinitely slow speed) or else proceeding from certain theoretical considerations (conditions of symmetry, transitivity, and so on); the definition of simultaneity will thus be given objective substantiation, and the conventional nature of the choice $\epsilon = 1/2$ will be eliminated [20-22].

The arguments of the opponents of this view are mostly directed at demonstrating the inadequacy of these procedures or of the theoretical conditions assumed [23-25]. We have discussed this argument in considerable detail [3, 7], so there is hardly any need to recur to it. Besides, we believe that, to solve the question whether the choice of simultaneity coefficients is a necessary result of *agreement* or may be made on some *objective* grounds, it is better to resort not to a meticulous analysis of mental experiments and theoretical conditions but to determining, at an obvious and accessible level, the actual physical meaning in theory of the concepts of temporal relations and simultaneity.

If we accept, following Einstein, that *temporal relations acquire physical significance* only when ensembles of events under discussion *are connected by physical interactions,* we shall have to regard as simultaneous (that is, having no temporal relations) such ensembles of events which are not connected or, to be more precise, *cannot in principle be connected by material, physical interactions.* In the above, we showed that these considerations are, so to speak, in the wings of Einstein's procedure for establishing simultaneity, being its necessary but tacitly assumed premise.

Furthermore, if we *negate* the existence in nature of material interactions transmitted at *infinitely great velocities,* that is, if we negate the existence of instantaneous action at a distance, we have to accept that at points in space remote from one another there will always occur some *sets of events* which cannot in principle interact with one another and which, because of these *objective* conditions and the *relational definition of temporal relations* that we adopt, should be regarded as objectively simultaneous. *No choice* of some unique couple of events from this set, which will be regarded as simultaneous or, to be more precise, as *absolutely simultaneous* in the sense of uniqueness, *will deprive* the other elements of these sets of events of their fundamental *objective property—impossibility to interact with one another,* that is, to be in the relation of objective simultaneity. Therefore, even if we should be able to prove experimentally, rather than to postulate "by definition", equality of light speeds (or some other signal) in opposite directions, in that case, too, the choice of a given couple of events as absolutely simultaneous would have been necessarily *conventional* within the framework of the materialist relational conception of time adopted here.

There is another interesting aspect of interpretation of the relation of simultaneity bearing on problems of epistemology. However, before we pass on to it, we must consider one of the attempts of a different interpretation of the definition of simultaneity.

Some scientists believe that Einstein's procedure for establishing simultaneity raises no problems; everything is well defined here and put in its proper place. P. G. Kard, defending this view, suggests his own reading of the "definition of simultaneity". "According to Einstein [he writes], simultaneity *is defined* as a relation between two events occurring within distance l from each other when a light signal emitted by one event in the direction of the second arrives there after a delay l/c relative to the occurrence of the second event" [27, p. 82].

It is easy to see, however, that this "definition" has no greater physical sense than defining the simultaneity of events occurring at different places through the possibility of "grasping them in one momentaneous perception or act of consciousness". The definition assumes that we know apriori that the events did take place and, besides, we know what distance separates them. It is well known, however, that to determine distance we need a definition of simultaneity, so that the author falls into circularity already at this point. But that is not all.

The definition suggested by P. G. Kard is fundamentally different from the procedure suggested by Einstein. Einstein deals with real, empirically recorded events and relations. A signal is emitted from point A which then returns, bringing proof that there exists point B, that the signal reached it, was reflected at that point, and travelled back. The existence of point B and of the event of signal reflection in it is *an empirically attested fact,* and this substantiation is the consequence of the condition of the signal's return. In Kard's definition, however, the signal travels one way only, and, if we reason from the point of view of the place from which the signal was emitted, we can know nothing about either the point at which it was directed or whether the signal was received there at all. We can *only postulate that apriori.* If we reason in the context of the place where the signal was received, again we need apriori knowledge of the moment of time when the signal was emitted as well as of the distance between these points in space.

Thus in Einstein's procedure absolutely simultaneous events are chosen "by definition" from a certain set of objectively simultaneous events (with good empirical substantiation), whereas Kard establishes simultaneity on a number of apriori assumptions.

The arguments above warrant some conclusions concerning the epistemological status of the simultaneity concept. This concept is of great significance, for, as Einstein remarked, "all our judgments in which time plays a part are always judgments of *simultaneous* events" [11, p. 39]. Here belong all judgments of the future and past events, that is, all judgments connected with man's temporal orientation in the world. But how can we establish simultaneity of given events?

We can say nothing about events actually simultaneous with the given one and occurring at other points in space, for they in no way affect us and therefore simply do not exist. As for the simultaneity of future events, it is defined theoretically on the basis of past experiences. We can have empirically substantiated and reliable knowledge only about events in the past (more or less remote) derived from the signals that we received from them. However, inasmuch as all of these are events from the *past,* which no longer *actually exist,* there will be again a substantial *theoretical, or conceptual, ingredient* along with the *empirical* one in defining the simultaneity of these events. Therefore conventional choice and conventional evaluations are quite natural in the procedure for establishing simultaneity.

Conclusion

Einstein's procedure for establishing simultaneity is central to the discussion of the philosophical and methodological problems of the special relativity theory, for two reasons.

First, it carried out the task that was shifted in the foreground of the methodological issues of physics as a result of the critique by positivists of the concepts of Newton's absolute space and absolute time. Namely, it resulted in the establishment of the *empirical* status of the concepts of "*temporal relations*" and "*simultaneity*" or, to be more precise, it resulted in the empirical substantiation of these concepts, linking them up with the properties of *actual physical interactions.*

Second, this empirical substantiation resulted in the establishment of a *materialist relational conception* of time which considers *temporal relations to be derivative from the properties of actual physical interactions.*

This conception was not explicitly formulated in Einstein's first work, although it was a fundamental premise which he tacitly assumed in considering the signal procedure of establishing simultaneity. Later he expressed this conception in a more explicit form. Thus in his article "On the Principle of Relativity and the Conclusions Drawn from It" published in 1907, Einstein wrote: "Imagine a number of clocks at many points at rest in relation to a coordinate system. Let them all be equal, that is, the difference in the readings of two such clocks should remain unchanged if they are located side by side. Assuming that these clocks are somehow adjusted, the ensemble of these clocks, if they are arranged at sufficiently small distances from one another, permits a time evaluation of an arbitrary point event—say, by means of the nearest clock. However, the sum total of these clock readings does not yet provide us with 'time' such as we need it for physical purposes. Moreover, we shall also require, in addition to this, instructions according to which these clocks may be adjusted with regard to one another" [28, S. 415].

In the first article Einstein needed the *signal method* for *synchronising* clocks located at different points in space, that is, the method served as an *auxiliary* instrument for attaining the prime objective—the synchronisation of these clocks, while the fundamental role of the physical interactions remained in the background; in the second one, however, physical interactions come to the fore. It becomes clear that a set of identical and synchronised clocks (a material model of Newtonian absolute time) is not a sufficient condition for physical purposes. They have to be adjusted to each other, that is, connected by actual physical interactions. "In order to give physical significance to the concept of time [writes Einstein], processes of some kind are required which enable relations to be established between different places" [12, p. 28].

Thus a significant achievement of Einstein, one of "the great reformers of natural science", in the words of Lenin [29, p. 233], was the formulation of a *modern materialist* *relational conception of time,* as well as making it part and parcel of physical science both in theory and in experiment.

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EINSTEIN AND THE DEVELOPMENT OF THE CONCEPT OF SPACE

The greatness of Einstein's revolution in the conception of space and time can only be properly assessed in comparison with the conceptions that he revised. Therefore the way that led to Einstein's revolution deserves at least brief mention, for it contains some tendencies of later, post-Einsteinian development of the concept of space. This digression is all the more necessary since Einstein himself paid great attention to the study of the origin of our conceptions of space and time, to the analysis of their status in classical mechanics, electrodynamics, etc. These studies contain a wealth of material of great interest for the analysis of the development of the space concept within the framework of relativistic ideas.

1. Space (and Time) in Newton

We shall not go too far back, starting our analysis of the development of the concept of space (and, necessarily, of time) directly with the mechanics of Newton, whose conceptual system was decisively revised in Einstein's relativity theory.

The concepts of space and time are introduced by Newton as the primary terms of the system (that is, of the Mathematical Principles of Natural Philosophy) and are defined and physically interpreted through axioms and laws of motion. However, they precede the axioms not only because they are defined by the latter but also because they form the background of the realisation of the axioms themselves. These laws of motion of classical mechanics obtain in inertial reference frames, which are defined precisely as systems in inertial motion relative to absolute space.

At this stage the original theoretical status of absolute space and time comes to light—the "box without the walls" and pure duration. That is reflected in the well-known propositions of Newton's *Principles* [1, p. 6].

Absolute, genuine mathematical time, by itself and by its very essence, regardless of anything external, flows uniformly and is otherwise referred to as duration.

Absolute space in its very essence, regardless of anything external, always remains identical and immovable.

Newton's absolute space appears as an analogue of Democritus's vacuum and is the scene for the dynamics of physical objects. As distinct from Democritus's vacuum, Newton's absolute space is linked with a definite mathematically formed dynamics and filled with physical meaning through laws of motion, while the symmetry of this space is responsible for the fundamental conservation laws of mechanics. This space, as Einstein indicates, "is assigned an absolute role in the whole causal structure of the theory" [2, pp. XIV-XV].

However, the mode of specifying absolute space appeared to be contradictory, as pointed out by the numerous critics of Newton's conception (Leibniz, Berkeley, Mach, and others). One often encounters the view that inasmuch as absolute space has no operational significance, it is a fiction. To get rid of this fiction, the following two premises are introduced (going back to Mach): (1) the law of inertia obtains relative to absolute space, and (2) immovable stars are at rest relative to absolute space. The conclusion is drawn from these premises that the law of inertia holds for immovable stars. Moreover, from this the possibility is inferred for eliminating absolute space from classical mechanics and its laws. It may be argued that immovable stars indeed provide support for our empirical research, but they cannot play the role of a theoretical structure (the structure of the theoretical world of classical mechanics), for it is the symmetries of absolute space and time that specify the fundamental laws of conservation, etc., rather than those of immovable stars.

Although some aspects of Mach's criticism impressed Einstein, he stressed that Newton was particularly consistent when he specified absolute space in his system. "He had recognised [wrote Einstein] that the observable geometrical magnitudes (distances of material points from one another) and their change in process of time do not completely determine movements in a physical sense. He shows this in the famous bucket experiment. There is, therefore, in addition to masses and their distances, varying with time, something else, which determines what happens; this 'something' he conceives as the relation to 'absolute space' " [3, p. 150]. Absolute space and time appear as the necessary theoretical basis of classical mechanics.

In accordance with absolute time, classical mechanics postulated absolute and universal simultaneity. Absolute synchronism could only be based on long-range instantaneous forces, the role of such forces being played by gravitation (the universal law of gravitation). In fact, these features were characteristic already of classical kinematics in which the time concept was based on the following hypothesis: "Two events simultaneous for the observer linked with some mark [reference frame—*Authors*] will appear equally simultaneous to any observer linked with an arbitrary mark moving relatively to the former" [4, p. 24]. Physically, this coordination is implemented in the presence of signals travelling at infinite speed. That means that action at a distance was not a child of Newton's dynamics but was implicitly contained already in kinematics. Even if Newton had managed to construct a short-range gravitation theory within the framework of the ether model (Newton did not approve of action at a distance and indeed tried to develop ether models), he would have had to look for a long-range replacement or start rebuilding mechanics along relativistic lines without waiting for Lorentz, Poincaré, and Einstein. The status of action at a distance is determined by the substantive concept of space and time within the framework of the mechanistic world scheme rather than by the nature of gravitation.

Apart from the theoretical absolute space and time that are given by the laws of mechanics and are mathematical (in the terminology of Newton himself), Newton introduced empirical space and time which are perceived by the senses, serve as a measure of theoretical structures, are used in everyday life, and specified in the language of observations. These are relative space and time. Because of this duality, Euclidean geometry itself is given different interpretations at the theoretical and empirical levels of classical mechanics. For example, the geometrical straight line is interpreted correspondingly through inertial motion and a solid ruler.

Riemann raised the question of the possible macroscopic quality of Euclidean space with which classical physics operates. He wrote: "The empirical concepts on which the establishment of spatial metrical relations is based—the concepts of solid body and ray of light—apparently lose all definiteness in the infinitesimal. It is therefore quite conceivable that metrical relations of space in the infinitesimal do not conform to the geometrical assumptions; indeed, we would have had to accept this proposition if it explained the observable phenomena in a more simple fashion" [5, S. 19, 20].

This interesting argument of Riemann contains not only the idea of the possible macroscopic quality of the space and time of classical physics, which assumes a change in its operational procedures in the transition to the microworld, but also incorporates a proposition the revision of which defines a different way of changing them. We refer here to the one-level, isotheoretical use of a *solid body* and a *light ray* for the physicalisation and metrisation of the space of classical physics. Behind this lies an important feature of physics.

In classical physics, mechanical and optical processes formed a unity, for optics belonged to mechanics. Classical mechanics had a mechanical operational basis. At first, mechanics made do with rulers, compasses, pendulums, etc., that is, it used the geometrical-mechanical operational basis, and later astronomical research showed the advantages of the optical processes, and mechanics came to be based on optical-mechanical operations. (For instance, it was precisely the fact that Sir William Hamilton used the astronomical approach that led him to the development of the theory of optical instruments and the optics-mechanics analogy.) Accordingly, the methods and ideas of optics such as the principle of least action began penetrating into the field of mechanics. The specific traits of the operational level had a corrective impact on the fundamental theory (a theory of the operational level, that is, optics, corrected the fundamental theory, that is, mechanics). Although it was regarded in mechanist terms,[1] optics nevertheless contained distinctive features which affected the development of mechanics itself—e.g., in the framework of the ideas of the least action principle.

With the development of physics, however, these optical specific features became less and less amenable to harmonious incorporation in the conceptual apparatus of mechanics. For instance, the development of the wave optics of Huygens, Joung, and Fresnel permitted an explanation of the phenomena of light interference and diffraction. But the overcoming of partial difficulties in optics entailed general difficulties in the very mechanist world scheme. "This [wave—*Authors*] theory upset the view [stressed Einstein] that everything real can be conceived as the motion of particles in space. Light waves were, after all, nothing more than undulatory states of empty space, and space thus gave up its passive *rôle* as a mere stage for physical events" [6, p. 13]. All kinds of ether palliatives were resorted to in order to save the mechanist worldview, but the development of the Maxwell-Lorentz electrodynamics showed the impossibility of reducing electrodynamics to mechanics. In the field doctrine, space came to life, here "the physical states of space itself were the final physical reality" [6, p. 13]. And one fact should be stressed here in particular: light belongs to the realm of electrodynamics.

Under these conditions, if physicists wanted to be consistent, they would somehow have to take into account the fact that utilisation of optical processes in the operational

[1] At a time when even non-physical objects and processes, such as society or man, were considered in mechanist terms, it would have been quite strange to treat physical phenomena, including optical ones, in non-mechanist terms.

devices of classical mechanics characterises the latter as mechanics at an electromagnetic operational level; ignoring this fact could lead to paradoxes in the near-light velocity area. Accordingly, the question arose of consistent development of the electrodynamics of moving bodies. The cornerstone of physics at the turn of the century became the problem of interconnection and unity of mechanics and electrodynamics. Such outstanding thinkers (not just physicists) as Lorentz, Poincaré, and Einstein tackled precisely these problems.

2. Einstein's Conception of Space

In his work *On the Electrodynamics of Moving Bodies,* which marked the beginning of the special theory of relativity, Einstein clearly formulated the basic premises of the new theory. First, the failure of attempts to discover the motion of the Earth relative to ether resulted in the supposition that "the phenomena of electrodynamics as well as of mechanics possess no properties corresponding to the idea of absolute rest. They suggest rather that, as has already been shown to the first order of small quantities, the same laws of electrodynamics and optics will be valid for all frames of reference for which the equations of mechanics hold good" [7, pp. 37-38]. This assumption formed the new principle of relativity. Second, Einstein made another assumption, which only *seems* to contradict the first one: "Light is always propagated in empty space with a definite velocity c which is independent of the state of motion of the emitting body" [7, p. 38]. It is interesting to note one point here: although Newton's empty space is banished from the formal language of theory and only relative space is referred to in it, empty space continues to figure in nonformal language, in which light is propagated at a finite and limited speed.

These two premises (the principle of relativity and the principle of constancy of light velocity) enabled Einstein to proceed from Maxwell's theory of bodies at rest to a consistent electrodynamic theory of moving bodies.

The operational procedures used in classical physics to physicalise Euclidean space proved to be inapplicable to processes whose speeds approached the speed of light. Einstein therefore begins the construction of the special theory of relativity by considering the definition of simultaneity which resorts to the operation of light signaling. L. I. Mandelshtam emphasised that "the fact that light is propagated at a definite finite speed assumed an exceptionally great significance in the theory of relativity. ... It is just as important for the theory of time as the fact of the existence of rigid bodies is for the theory of space" [8, p. 88].

Einstein then considers the relative character of lengths and of time intervals, and that compels him to draw the conclusion that the concept of simultaneity has no absolute significance: "Two events which, viewed from a system of co-ordinates, are simultaneous, can no longer be looked upon as simultaneous events when envisaged from a system which is in motion relatively to that system" [7, pp. 42-43]. Accordingly, the need arises for developing the theory of transformation of coordinates and time from a system at rest towards a system in uniform and rectilinear motion relative to the former (the special theory of relativity considers inertial systems). In developing this theory Einstein arrives at the Lorentz transformations. However, Einstein arrived at these transformations in an original way, proceeding from his postulates, whereas Lorentz introduced them apriori to obtain the invariance of the Maxwell equations for empty space.

In Einstein's approach the Lorentz transformations are organically linked with the new properties of space and time: with the relativity of length and time intervals, with equality of space and time (they have identical status in the transformations), with invariance of the spatio-temporal interval, and so on. With the introduction of the Minkowski formalism into the theory of relativity, the organic links between space and time became particularly obvious: they proved to be components of a single four-dimensional continuum. Space and time emerge in Einstein's theory as elements of a relational conception: they are not separate substances, but structures of relations, ordered coexistence and coordination of the objects, phenomena and processes of objective reality. In his preface to Max Jammer's book *Concepts of Space* Einstein thus characterised this conception: "Space as positional quality of the world of material objects" [2, p. XIV].

It would be wrong, however, to present the theory of relativity and its spatio-temporal basis as a completely relative universe. Thus the introduction of the four-dimensional formalism by Minkowski helped to reveal some aspects of an "absolute world" given in the absolute spatio-temporal continuum [7, pp. 82-83]. Just as in classical physics, there is in the theory of relativity a complex interrelation of absolute and relative aspects in the spatio-temporal problems. We do not therefore believe the view to be correct, though it has some currency, that the transition from classical physics to the theory of relativity is accompanied by a replacement of the substantional conception of space and time with a relational one. This view simplifies the process of revision and generalisation of the concept of space involved in the construction of the theory of relativity, and neither does it take into account the separation of the empirical and theoretical levels in the structure of a physical theory.

In the theory of relativity, just as in classical mechanics, two types of space and time function, implementing respectively the substantial and attributive (in this case relational) conceptions.

In classical mechanics absolute space and time functioned as a structure of the theoretical level, representing the substantial conception. In the theory of relativity, the same status is ascribed to the unified four-dimensional space-time. Einstein described this situation in sufficiently clear terms: "Just as it was consistent from the Newtonian standpoint to make both the statements, *tempus est absolutum, spatium est absolutum,* so from the standpoint of the special theory of relativity we must say, *continuum spatii et temporis est absolutum.* In this latter statement *absolutum* means not only 'physically real', but also 'independent in its physical properties, having a physical effect, but not itself influenced by physical conditions' " [9, p. 55].

On the other hand, the special theory of relativity obviously makes use of a relational conception of space and time. It is this conception of space and time that was originally formulated in Einstein's first works, where operations of measuring simultaneity, etc., figured prominently. As for unified four-dimensional space-time, it is the product of a later logico-mathematical reconstruction of the theory by Minkowski. In this reconstruction relational space and time become structures of the empirical level of the theory.

This interpretation of the separation of the theoretical and empirical aspects in the theory of relativity has sufficiently great currency. For example, A. M. Mostepanenko writes: "The four-dimensional manifold is the principal theoretical object described in the theory of relativity. As for space and time taken separately, they become empirical objects within the framework of this theory, being in actual fact 'projections' of unified space-time onto a corresponding reference system" [10, p. 27].

In accordance with this view, the transition from classical mechanics to the special theory of relativity may be presented in the following way: (1) at the theoretical level, a transition took place from absolute and substantial space and time to absolute and substantial unified space-time; (2) at the empirical level, a transition took place from relative and extensional space and time to relational space and time [11, p. 383].

The special theory of relativity revealed the close links between space and time, but Einstein did not stop there: in his general theory of relativity he tackled the question of the relationship between space-time and matter.

3. Geometrisation of Physics

The subsequent development of the relativity conception drew Einstein's attention to non-inertial reference systems. Could the theory of relativity be generalised to include this type of systems? To solve this problem, Einstein introduced a series of original hypotheses in physics, such as the concept of the geometrical nature of gravitation and of the interconnection between the geometry of space-time and matter. All of this requires further generalisation of the conception of space-time: the general theory of relativity functions within the framework of the Riemann space.

According to Newton, non-inertial systems are in accelerated motion relative to absolute space. Some critics of the absolute space concept (e.g., E. Mach) suggested that this accelerated motion should be considered in relation to the horizon of remote stars, so that observable masses of stars might be the sources of inertia. Einstein offered a different development of this concept on the basis of the equivalence principle which states that non-inertial systems are locally indistinguishable from the gravity field. If inertia is conditioned by the masses of the universe and the field of inertia forces is equivalent to the gravitational field manifested in space-time geometry, the masses then fully define the geometry itself. This proposition represents an essential shift in the problem under analysis from Mach to Einstein, as correctly pointed out by E. M. Chudinov: "Einstein transformed the Machian principle of the relativity of inertia into the principle of relativity of space-time geometry" [12, p. 112].

The general theory of relativity generalises the Minkowski space-time and the analysis is conducted on the basis of the Riemann metrics: $ds^2 = \sum_{ik} g_{ik} dx_i dx_k$. The development of the general theory of relativity was considerably accelerated by the fact that Einstein used ready-made mathematical apparatus—the theory of covariants of similar four-dimensional manifolds, developed by Cristoffel, Ricci, and Levi-Cività. But the availability of the necessary mathematical apparatus was half the battle won. New physical ideas were also needed—and generating these inexhaustibly was a most characteristic feature of Einstein's creativity. The novelty of Einstein's approach to space-time was in that the functions g_{ik} are at the same time components of the fundamental metric tensor responsible for the geometry of space, and the potentials of the gravitational field in the basic equation of the general theory of relativity

$$R_{ik} - \frac{1}{2} g_{ik} R = -\chi T_{ik}.$$

The left-hand side of this equation describes the geometry of space-time, whereas the right-hand side, using the tensor of matter-energy-momentum T_{ik}, describes "matter".

In his work "Relativity and the Problem of Space" Einstein at length deals with the question of the specificity of the concept of space in the general theory of relativity: "We are now in position to see how far the transition to the general theory of relativity modifies the concept of space. In accordance with classical mechanics and according to the special theory of relativity, space (space-time) has an existence independent of matter or field. In order to be able to describe at all that which fills up space and is dependent on the coordinates, space-time or the inertial system with its metrical properties must be thought of at once as existing, for otherwise the description of 'that which fills up space' would have no meaning. On the basis of the general theory of relativity, on the other hand, space as opposed to 'what fills space', which is dependent on the coordinates, has no separate existence. Thus a pure gravitational field might have been described in terms of the g_{ik} (as functions of the coordinates), by solution of the gravitational equations. If we imagine the gravitational field, i.e., the functions g_{ik}, to be removed, there does not remain a space of the type (1) [that is, the Minkowski space-time—*Authors*], but absolutely *nothing*, and also no 'topological space'." That is due to the fact that, from the standpoint of the general theory of relativity, the Minkowski space-time is not space without the field but only a special case of the field g_{ik} (the g_{ik} functions have values independent of the coordinates). Einstein concludes: "Space-time does not claim existence of its own, but only as a structural quality of the field" [13, pp. 154-155].

The general theory of relativity served as the basis for two fundamental directions in modern physics: geometrised unified field theories and relativistic cosmology. In the present work we shall focus on the former.

Successful geometrisation of gravitation compelled many physicists to dwell on the essence of physics. There are two opposing views of this problem, which were clearly formulated by Ch. W. Misner and J. A. Wheeler:

"(1) The space-time continuum serves only as *arena* for the struggles of fields and particles. These entities are foreign to geometry. They must be added to geometry to permit any physics.

"(2) There is nothing in the world except empty curved space. Matter, charge, electromagnetism, and other fields are only manifestations of the bending of space. *Physics is geometry*" [14, p. 526].

Einstein's general theory of relativity is a limiting or transitional theory. It can still be classed among the physical theories of the first type, permitting a split into the geometrical background (*G*) and the physical "filling" (*P*), but at the same time it shows features of the second type of theories, for gravitation is geometrised in it. In the general theory of relativity a mixed type of reality description dominates: particles and fields distinct from gravitation are added to geometry. However, the success of geometrisation of gravitation compelled many scientists (Einstein himself first and foremost) to attempt a unification of the electromagnetic and gravitational fields within the framework of a sufficiently general geometrical formalism on the basis of the general theory of relativity. With the discovery of various elementary particles and their respective fields the problem naturally arose of including them within the framework of such a unified theory as well. That was the start of the long search for a geometrised unified theory of the field in which the second type of physical theory is realised, where physics is reduced to geometry and geometrodynamics is created.

It should be noted that attempts at creating the so-called spatial theory of matter had been made even before the general theory of relativity. Their logical foundations were integrally linked with the elaboration of a non-Euclidean geometry, in particular with Riemann's development of a generalised (differential-metrical) method of studying geometrical objects, within the framework of which the general geometry of *n*-dimensional Riemann spaces was developed. The point is that, as Einstein indicates, "in accordance with this more general geometry, the metrical properties of space or the possibilities of arrangement of an infinite set of infinitely small rigid bodies over finite areas are not defined by the axioms of geometry. Instead of letting this realisation confuse him, or make him draw the conclusion of the physical meaninglessness of his system, Riemann had the bold idea that the geometric behaviour of bodies could be conditioned by physical realities or forces" [15, S. 20]. In the light of this, space appears as a metrically amorphous manifold in which a certain organisation is introduced by the material objects and processes filling it, so that various structural levels of matter determine, generally speaking, different organisations of the spatio-temporal manifold.

In characterising this fruitful doctrine, H. Weyl stressed that Riemann "opposes here the opinion, previously shared by all mathematicians and philosophers, that the metric of space could be posited independently of the physical processes going on in it, and that the real moved into this metrical space as if the latter were a furnished apartment" [16, S. 47]. The development of these ideas led Clifford (1870) to an attempt to identify material particles with areas of strongly curved space. But this programme of identification of space with matter [17, p. 202] remained unrealised: Clifford failed to provide a purely geometrical interpretation of mass.

The real development of a spatial theory of matter began only with the formulation of the general theory of relativity. In a speech at the University of Nottingham on June 7, 1930, Einstein presented a rather symptomatic conception of the unified theory of field: "The strange conclusion to which we have come is this—that now it appears that space will have to be regarded as a primary thing and that matter is derived from it, so to speak, as a secondary result. Space is now turning around and eating up matter" [18, p. 610]. We see thus a balance again established between the absolute and the relative aspects of space-time: substantial absolute space functions on the theoretical level, being the genetic beginning of matter, while relational space and time function on the empirical level.

Thus geometrisation of gravitation was only the first step on the path of constructing the field theory as such. The construction of a geometrised unified theory of field was conceived precisely as a generalisation of the mathematical foundations of the general theory of relativity. As Einstein writes, the fact is that "the Riemannian geometry leads to a physical description of the gravitational field in the general theory of relativity, but it provides no concepts which could be applied to the electromagnetic field.

Therefore the efforts of theoreticians are directed at finding natural generalisations of or additions to the Riemannian geometry that would be more conceptually fruitful than the latter, in the hope to arrive at a logical construction that would unify all physical field concepts from a single standpoint" [19, S. 217].

Indeed, if the Riemann geometry describes the gravitational field as a curvature of space-time, cannot this geometry be generalised in such a way that such spatial entities as twist, dimensionality, affine connectivity, fluctuation of metric, multiple connections, etc., might be used to describe electromagnetic, meson and other fields within a single geometrical formalism?

The realisation of such attempts was begun in the work of Weyl [20, S. 465-480] which proposed a geometrical interpretation of the electromagnetic field passing beyond the framework of the Riemann geometry (Weyl's gradient-invariant theory). The fact is that the law of parallel transportation of vectors (affine connectivity) is reduced to the Riemann metrics only when the vector length does not vary during the transportation. This assumption, however, is not logically necessary; giving it up, Weyl built a generalisation of the Riemann geometry which in his view contains the theory of the electromagnetic field. He introduced the conception of a change in the vector length in parallel transportation depending on the potential of the electromagnetic field φ_i. Another variant of this direction in the unified field theory (the affine field theory) was developed by Eddington, and at one time physicists put great hopes on this direction. Einstein greeted it with enthusiasm and spent a great deal of effort to attain a logical conclusion of a variant of this theory. But this direction ended in a failure. The formalism obtained was cumbersome and very unnatural, the field equations did not yield a satisfactory theory of the electron, etc.

However, attempts to construct a geometrised unified field theory continued, for there is a great number of ways of formal generalisation of the Riemann geometry. One may, for instance, use higher-dimensional spaces than the spatio-temporal manifold of the general theory of relativity. Of this nature is the theory of Th. Kaluza

[21, S. 966-972], in which the unified field is described in a five-dimensional continuum. Einstein also did some work on five-dimensional space [22, S. 130-137].

The concept of a five-dimensional continuum did not result in the construction of a geometrised unified field theory. But the use of five-dimensional space signified the construction in physics of a very powerful formalism which helped, for instance, to deduce the quantum relativistic equation describing scalar and pseudo-scalar particles (π, K—mesons). As for a geometrised unified field theory, it could not be constructed either in Einstein's generalised formalism or in Veblen's projective variant or in Klein's six-dimensional space or even in Kalitsin's ∞-dimensional version.

Researchers were attracted by yet another generalisation of the foundations of the general theory of relativity—Einstein's attempt to develop a unified field theory on the basis of Riemann's geometry retaining the concept of absolute (remote) parallelism. Space is here given not by a metric but by n-podes (n-dimensional orthogonal datum marks). Naturally, if n-podes are given for all points of space, the metric of the space is thereby also defined, but the reverse is not true. Description of space by means of n-podes is more meaningful than by means of a fundamental quadratic form. "One conceives the idea [wrote Einstein] that one may find in the arbitrariness that introduces this description the means to link up the structure of space and the cause of electromagnetic phenomena, for which no place has so far been found in theory" [23, pp. 3, 4]. In this approach the structure of space is given by n-podes which prove to be parallel for any two points. That means that we can establish for any two points of space not only metric correlations but also directional ones (by orienting the n-podes). Thus the approach to a geometry more general than the Riemann geometry is based on singling out "directions" and correlations between them in the structure of space.

As Einstein emphasised, "this notion of direction is not contained either in the notion of continuum or in that of space" [23, p. 4].

In this approach we obtain two groups of equations: a group of symmetric equations expressing the laws of the gravitational field, compatible with the Newton-Poisson law, and a group of antisymmetric equations expressing the Maxwell equations in a generalised form. The ideas of the relativistic theory of asymmetric field seemed to Einstein to be the most promising, and he worked on various modifications of this theory up to 1955. The result was that certain general equations of the field were obtained from the generalised structure of space, which at a first approximation lead to the well-known equations of the gravitation theory and Maxwell's electromagnetism. However, advancing beyond that point proved impossible. The reduction of the unified field theory equations to the familiar equations of traditional special field theories is not sufficient, although it is a necessary condition of constructing a unified field theory. The results obtained did not provide a basis for experimental verification of the theory's predictions; the law of the motion of particles could not be deduced from the equations of the field. Then again, the theory of the field is not fully defined by the system of field equations. The researcher faces also the problems of singularities, of boundary conditions, etc., and the framework of unified field theories offers no systematic method of arriving at solutions that would be free from singularities.

We have cited here only the most characteristic variants of geometrised unified field theories closely interlinked with the development of Einstein's spatio-temporal concepts. They remained unrealised. Einstein undertook numerous attempts to carry out this programme, but all of them proved unavailing.

But was this search useless? And is the failure of several attempts indicative of the defectiveness of the research programme itself, as well as of the new spatial conception? That is not so. Firstly, isolated failures do not eliminate apriori the possibility of any other generalisation of the Riemann geometry. Secondly, even the unsuccessful attempts have introduced into modern physics a great number of valuable ideas, which are fruitfully applied in the present and underlie the studies of tomorrow. For example, the description of space by means of *n*-podes which was used by Einstein in the construction of the unified field theory is directly linked with the modern generalisation of the general theory of relativity on the basis of a tetradic formalism. That is all the more important as the usual metric potentials g_{ik} are only suitable for the description of interactions with the gravity of macroscopic bodies and of atomic systems of the boson type, inasmuch as fermions described by spinors interact with tetradic magnitudes $h_k(a)$ that are roots of g_{ik}. Extremely topical in this connection is the problem of revising the whole of the theory of relativity in terms of tetrads. "From the standpoint of a unified theory [says D. D. Ivanenko], the tetradic formalism of gravitation not only unifies it with other fields through a compensatory interpretation but also predicts the use of $h_\nu(a)$ components as the most basic quantities, along with some best-chosen spinor of a unified theory of 'common' matter. The spinor notation of Einstein's equations becomes particularly significant in this connection" [24, p. 51].

On the other hand, it should be noted that all attempts to create a geometrised unified field theory in the 1920s and 1930s did not go beyond a generalisation of the metric characteristics of the Riemann geometry. However, there are also topological characteristics of space. The modern unified theory, Wheeler's geometrodynamics, is built precisely on the basis of a revision of the trivial Euclidean topology of space-time.

Towards the end of his life, in the well-known collection of papers *Albert Einstein: Philosopher-Scientist* published on the occasion of the seventieth anniversary of the creator of the relativity theory, Einstein approved Karl Menger's proposal (in an article in the same volume) to use not only metrical but also topological structures of mathematics for the modelling of most diverse physical phenomena (see [25, pp. 459-474]). But it took several decades and a great deal of painstaking work by the new (and, of course, the old) generations of physicists to arrive at the assertion that further geometrisation of the most important physical concepts is apparently connected precisely with this class of fundamental mathematical concepts revealing new and extremely profound traits of the inner generalised geometrical unity of the different branches of physical science. It may now be said that the original Einsteinian programme of the 1920s and 1930s for discovering a geometrical unification of the whole of physics has undergone, in the course of the development of the latter in the 20th century, a profound and all-round topological modification.

4. Topological Fiber Spaces and the Dynamical Structures of the Basic Conceptual Systems of Physics

The foregoing must not create the impression that the topological structures of physics are just another new class of its purely empirical structures similar, for example, to the new groups of internal symmetry of the "strange" or "charmed" elementary particles. The most striking feature of the "leader of natural science" discovered in recent years consists in the fact that all its most fundamental theoretical constructions of even the past years and centuries proved to be founded on the so-called topological fiber spaces—generalisations of the usual spaces in which a specific axiom of covering homotopy holds which characterises topological invariance (or permanence) of connections between the points of a basis (independent variables) and a fiber (dependent variables) of such spaces. Probably the first strikingly impressive example of fiber structures was given by Plato through his reference to shadows on a cave wall.

Simplest in structure are the fiberings of the Galileo-Newton classical mechanics: here the basis, or the independent variable determining the changes of all the other dynamic characteristics of objects moving in an arbitrary way is time. The basis in mechanics is unidimensional, whereas fibers are three-dimensional: they are "fluent" spatial coordinates of each moving point. Fibers are ensembles of dependent variables whose variations characterise mechanical processes of any degree of complexity interpreted as definite spatial translations of some objects relatively to others. This initial and purely descriptive or, to be more precise, kinematic division of dependent and independent variables of mechanics serves as the basis for singling out more profound and important theoretical structures of this science—forces that are the only causes in it of changes in the dynamic states of moving objects.

The laws of classical dynamics—the Newton equations—applied to the second derivatives of the coordinates of each moving point, permit the discovery of the forces acting on this point—the new elements of physical reality that are much more important for the theoretical understanding of any mechanical movements. Using the law of the action of forces (given by experience or some theory) and the data on initial state of mechanical motion of bodies, we can unambiguously compute (or predict) the smallest details and results of any interconnected movements of points of any degree of complexity (at any rate in principle, using large computers for the solution of concrete equations of dynamics).

From the standpoint of topology, of the simplest type are the fiber spaces of mechanics involved in the uniform (that is, proceeding with a constant velocity) and uniformly accelerated motion. In this case, the fiberings are reducible to the trivial (Cartesian) products of the spaces of corresponding parameters: the distance travelled by a body in uniform motion always equals a "trivial" product of velocity multiplied by time, and if the body is in uniformly accelerated motion, its velocity equals acceleration multiplied by time. In the latter case, however, the fiber space of the distance travelled by a body in uniformly accelerated motion is structurally more complex: it ceases to be a globally trivial fibering, becoming such only locally. With the very first increase in the complexity of the "quality" of mechanic movements, with the transition from motion at constant speed to motion at constant acceleration, an abrupt qualitative leap thus takes place in the complexity of the fiber spaces describing them: only locally, in the infinitely small neighbourhood of each point, does the element (or differential) of the distance travelled by a uniformly accelerated object equal the product of a variable (growing or decreasing) velocity multiplied by the element (differential) of time. To obtain the whole of the path travelled by a uniformly accelerating body, one must be able to sum up such local infinitesimally small products, i.e., compute integrals of these differentials within certain limits.

Thus the entire classical analysis appears, from the angle of modern topology, as a systematic method to "compute" any variable (extensional) quantities in local trivial fiber spaces that have been studied for the first time in dealing with diverse theoretical problems of analytical mechanics.

Furthermore, the structure of modern algebraic topology makes it possible to understand the singular role played in a systematic theoretical construction of dynamics by the so-called inertial reference frames that can alone help, as we know, correctly formulate its basic laws—Newton's first, second and third laws of motion. A distinguishing feature of inertial frames is that for their relative motions second derivatives from coordinates in time equal zero; these frames are free from the action of external accelerations and differ from one another only in their constant velocities of mutual relative translations.

Modern algebraic topology treats second derivatives from coordinates in time being equal to zero as a kind of topological simplicity, triviality, i.e., as the so-called dynamic acyclicity of the initial (dynamic) complex of mechanics. Mathematically, it is characterised precisely as the result of iterative application, to coordinates in the relevant dynamic system of objects, of some abstractly defined operator of dynamic boundary (dynamic differential) being equal to zero. In this respect any forces causing a change in the mechanical state of moving objects acquire a completely new mathematical interpretation—as topological (or cohomological) measures of deviation of the dynamic systems under study from the inertial motion state (as the highest degree of topological-dynamic triviality). In terms of algebraic topology even the quantitative magnitudes of forces are not always essential for the prediction of results of motion, particularly of global nature, as compared to their generalised geometrical (topological) characteristics determining the places and the degree of deviation of the mechanical system from the inertial state as the state of motion of the highest cohomological simplicity—dynamic acyclicity.

A great number of studies in the topological structures of mechanics conducted in recent years and only partially summed up, for instance, in C. Godbillon's book [26] showed that these structures play a decisive role even in the solution of concrete dynamic problems. All of them

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proved to be closely related to the so-called simplectic manifolds, that is, manifolds with such simplest dynamic geometrical structures (simplexes) that repeated application to them of the operators of dynamic boundary (dynamic differentiation) yields zero.

Newton's first law of mechanics asserts in these terms the necessary presence, in any dynamic system, of "kinematic" simplexes that are physically interpreted as the states of the most "natural"–inertial, topologically most elementary and unperturbed by any forces–mechanical motion. The second law interprets forces as cohomological measures of deviation in the behaviour of moving systems from "inertial states" as the maximum of topological-dynamic simplicity. Newton's third law appears as the requirement of obligatory antisymmetry of the action of forces: deviations from the inertial motion state never come singly, so to speak, being always accompanied by similar deviations in the inertial motion of other objects—those with the opposite sign. A similar topological interpretation may also be given to the Lagrange or Hamilton equations of dynamics, although this requires more complex mathematical and topological concepts (those who are interested in the subject should consult Godbillon's book mentioned above [26]).

Let us now give a brief methodological analysis of the recent topological revision of the basic concepts and laws of another fundamental physical theory—the classical theory of the electromagnetic field. The proof that this theory is also based on simplectic structures was probably the most interesting result of the theoretical physics of our times.

The principal object of classical electrodynamics is the behaviour in space and time of the force fields as the most essential elements of physical reality revealed by mechanics. The principal laws of such behaviour, the Maxwell equations, are essentially connected, just as in mechanics, with fiber space structures, but the basis (the ensemble of independently varying parameters) is extended in field theory: the basis is here represented by the entire four-dimensional set of the points of the space-plus-time continuum (and not just time as was the case in mechanics). As for the fiber (the set of fundamental physical variables dependent on this basis), it is represented by vectors of forces acting on a single charge (or current) at each given point at a given moment of time (that is, strengths of electric and magnetic fields).

Field equations for certain combinations of derivatives of field strengths with respect to the coordinates and time permit the discovery in this fiber space of new and even deeper and more fundamental elements of physical reality—charges and currents generating the force fields under study. The fiber spaces of field theory thus possess, as in the case of mechanics, the property of universality which is applicable to the solution of all tasks, a property that is of greatest importance for methodology: when the law of motions of charges and currents in space and time is known, if only on a purely empirical basis, the local structures of field equations permit the computation (in principle, with any degree of precision that might be needed) of the spatial distribution of any combinations of physical fields as well as their dependence on time.

The electromagnetic field in a fiber space has a wealth of properties of spatio-temporal symmetry (like the invariance of field quantities relative to translations and rotations in a four-dimensional space-plus-time continuum) which yield, according to the well-known Hamel-Noether theorem, a rather great number of conservation laws—for energy, momentum, angular momentum, etc. Of the greatest interest for a definite topological isomorphism of the dynamic structures of mechanics and electrodynamics are, however, the recently discovered simplectic structures of the fiber spaces of field theory.

Methodological studies in the foundations of physics have so far failed to analyse the rather mysterious fact that the equations of electrodynamics can be equivalently formulated (and in many cases more quickly solved) in terms of special auxiliary quantities—four-dimensional electromagnetic potentials. The mode of introduction of the latter is, from the standpoint of algebraic topology, quite analogous to the mode of introduction of inertial reference frames in mechanics: it appears that a definite class of four-dimensional potentials also has the property of being simplectic. The requirement of the so-called gauge invariance of potentials results in the latter always being selected, just like inertial reference frames, in a rather arbitrary fashion, although from a definite additive class.

Any concrete four-dimensional potential differs from another concrete four-dimensional potential from the same class by a certain four-dimensional vector, whose components satisfy a wave equation without sources (that is, one in which the right-hand side equals zero). The topological significance of this condition is fully analogous to the topological significance of inertial motion state in mechanics: it singles out simplectic structures in the fiber electrodynamic spaces. The fact is that the left-hand side of the wave equation (the so-called d'Alembert operator) may be represented as a result of repeated application to the field potentials of a certain abstract four-dimensional operator of dynamic (four-dimensional) boundary. The fact that it equals zero for arbitrary (four-dimensional) additional quantities changing the gauge of field potentials, signifies merely their simplectic character.

Just as in the case of fiber spaces of mechanics, the fiber spaces of electrodynamics thus reveal universal dynamic states of extreme dynamic simplicity—topologically acyclic simplectic structures characterising the propagation of the field in the simplest dynamic case—in the absence of charges and currents. These states appear in electrodynamics as a kind of "standards" of particularly simple dynamic field configurations: the Maxwell equations are interpreted in the simplectic field theory as topological (cohomological) measures of deviations in the behaviour of the analysed electrodynamic system from "standard" simplicity. The basis of this new, purely topological, interpretation of electrodynamics was laid in the paper by Ch. W. Misner and J. A. Wheeler (see [14, p. 556 ff.]) and has since undergone interesting developments.

In a certain sense, the new interpretation is simpler and even more "graphic" than the usual (differential or integral) form of notation of the Maxwell equations, for it shifts into the foreground the purely qualitative (topological) features of the behaviour of electromagnetic dynamic systems. Thus in any such systems, magnetic force lines never have either a beginning or an end—they always appear as concentric circles on a plane perpendicular to the currents or electric fields changing with time, wound on the latter according to the familiar right-hand screw rule. As for the force lines of an electric field, they may either have their beginnings (or ends) in the electric charges that cause them, or they may also appear as concentric circles in a plane perpendicular to any magnetic field changing with time.

The normal form of the Maxwell equations may be obtained from these purely qualitative (topological) formulations with the aid of the extremely profound de Rham theorems establishing isomorphism (under definite conditions) between the algebraic groups of homology (and cohomology) and the differential groups given by derivatives (and integrals). Coulomb's law,for instance, will then be the consequence of a very simple and well-known qualitative fact that in static fields electric force lines begin and end only on charges. The electrodynamic analogue of the state of relative mechanical rest may be seen in the state of the field with invariable and everywhere identical four-dimensional potentials, which satisfies in a trivial manner the wave equation with the right-hand side equal to zero.

One of the most important and vital problems of modern theoretical physics is a study of the basic dynamic structures of the fiber spaces of quantum theory that would be as thorough as in the case of mechanics and electrodynamics. Indeed, this fundamental physical theory of a level of organisation of the material world different from the macroscopic one takes the next step forward in establishing new and deeper elements of physical reality. Classical mechanics studies the forces underlying all the mechanical phenomena, and classical electrodynamics investigates the charges and currents generating these forces (and their fields); whereas quantum theory is an inquiry (according to the law of negation of the negation, as it were, at a higher level of theoretical generalisation) into the various states of stable (and quasi-stable) motion of the charges and currents themselves. However, it no longer studies elementary mechanical motions of bodies, that is, motions which always follow one and only one trajectory, but rather motions which, with a certain degree of probability, occur simultaneously along all the paths (of arbitrary degree of complexity and strangeness) that may connect its initial and final points. That is precisely the way in which quantum-mechanical motion of any charges and currents is interpreted in the modern Feynmanian formulation of quantum theory, in which the basis of the fiber space is the topological space of all possible paths in a four-dimensional space-plus-time manifold, and the fiber is the possibility of the presence of a quantum object at each concrete point of such a path, characterised by probabilistic wave function.

The basic dynamic equations of quantum theory (the equations of Schrödinger, Dirac, etc., or the methods developed by Feynman and mathematically equivalent to the former—the so-called functional integration, making it possible to take into account the contribution of each virtual trajectory of motion to the overall result) reveal entirely new and universal elements of physical reality formerly unknown in science. These are the most frequently recurring and theoretically most probable forms of stable or quasi-stable motions of microparticles in atoms and their excited states, in solids, molecules, semiconductors, etc.

In the fiber spaces of quantum theory, topologically most elementary dynamic states have also been discovered connected with simplectic geometrical structures. However, their physical interpretation is so far uncertain: the international conferences on "simplectic physics" (Rome, 1973; Aix-en-Provence, 1974; Bonn, 1975 and 1977) failed to discover the simple physical meaning of quantum "simplexes" and to give them visual interpretation in terms of the better studied states of quantum motion (oscillator, rotator, quasi-periodic field, Keplerian systems, etc.). The physical meaning is not yet quite clear even of the "conditions of simplectic quantisation" of an (arbitrary classical) dynamic system that take the form of certain topological conditions—say the condition that certain integrals (of action, etc.) must be whole numbers.

Progress will probably be achieved here if the problem of quantisation of conditions is formulated in the most general form as the establishment of a functor correspondence between classical and quantum concepts on the basis of a transition from the latter to some new and essentially non-trivial topology. The studies in simplectic quantisation by the Soviet scientists F. I. Berezin [27], A. S. Mishchenko [28] and others appear to be quite promising in this light.

5. Toposes, or Spaces with Variable Topology

A methodological analysis of the basic topological structures of modern physics confirms the assumption that an important role in its further development may be played by the analogues of spaces with variable metrics (the Riemann manifolds) introduced in the middle of this century—"etendues" with variable topology, or toposes [29]. Constructed to satisfy the concrete theoretical needs of abstract algebraic geometry, they have proved to be an exceptionally effective means of unification, of establishing inner theoretical unity, first and foremost in mathematical science itself. Toposes turned out to be abstract mathematical structures endowed with fundamentally new and very high types of abstract symmetry—the symmetries of logic and topology.

Along with the initial definition (by Grothendieck and Verdier) of toposes as generalised "etendues" with variable topology, they also allow quite a different, and purely logical, representation—as generalised spatial models of certain (mostly essentially non-classical) logical constructions, e.g. systems of intuitionist mathematics or modal logic [30]. This representation of toposes was discovered by the American mathematician F. W. Lawvere and his pupil M. Tierney and is therefore called the Lawvere-Tierney representation. It permits the discovery of fundamentally new connections between such apparently entirely unconnected branches of mathematics as topology and modal logic, algebraic geometry and set theory, and even intuitionism. It appears that the Lawvere-Tierney axiomatic definition of toposes may be given an elementary (first-order) logical form (that is, one in which only first-order logical calculi are used and the existential and universal quantifiers are applied in the corresponding axioms only to individual logical variables). Because of this, the topos theory assumes the status of a mathematical construction that is entirely independent in its logical structure even from the set theory. Moreover, sets prove to be a very special case of toposes. To put it informally and "visually", the set concept described on the whole only collections of objects that are temporarily "frozen", interrupting their inner development. For instance, the set of points on this page possesses, within certain limits, the property of being temporarily excluded from the universal dialectical process of becoming. But nothing of the kind may be said, for instance, of the sets of points situated, let us say, in the centres of new elementary particles—gluons, quarks, hyperons, resonons, least of all of the "charmed" or "strange" corpuscles. These points are not given to us with the same degree of identification at all moments in time (or definiteness outside time) as the points of this or the following page. It appears that application to the points at the very centre of the resonon of the set concept reflecting the most essential properties of collections of only invariable, undeveloping objects ultimately results in the logical contradictions of the modern quantum field theory—the infinitely great self-energy of particles, their infinitely great "naked" electric charge, etc.

The basic concepts of the topos theory are not the point or its property of membership in a certain class of sets but definite mappings whose properties are characterised in another and simpler system of axioms and which appear in modern science at the operational level much earlier than many classes of points. The latter are fixed, for instance, in high-energy physics, not directly, as say points on a page, but only as a result of a definite limiting process for some physical parameter—strength of the electric or magnetic field, time of flight, etc. Indeed, what is the practical, i.e., operational, way to single out some point of space in elementary particle physics? We identify it by the fact that the strength of the physical field in it equals a definite value or that it is this particular point through which some corpuscle passes at a definite moment of time. The topos theory endeavours to take into account in its logical constructions this history, the origin of the operational formation of the points of real physical space in modern science. In its epistemological status it seems to be a precise mathematical explication of an old and very important tendency of natural science, going back to Gauß—to reflect in theory the process of gradual formation and operational specification, due to the perfection of technical instruments, of the position of "separate" points in actual physical space.

It will be appropriate to remark here that Hans Reichenbach in his philosophical studies of the foundations of quantum theory of 1944 [31] came very close to discovering the higher-type symmetry, the symmetry of logic and topology revealed by means of toposes, and stopped short of formulating their extremely original complementarity (duality) because of unfamiliarity with the Geroch theorem (see Section 5), absence at the time of a general concept of space with variable topology and, of course, the theoretical feebleness of positivist methodology. He nevertheless gave a very thorough analysis of the arguments of Bohr and Heisenberg substantiating the indeterminacy principle and the ideas of complementarity, coming to the conclusion that quantum mechanics faced this dilemma: to introduce three-valued logic to describe certain physical states in the microworld, as distinct from the usual two-valued logic; or else to accept the idea that for some classes of microphenomena (which he called interphenomena) the law of causation is violated, and the so-called causal anomalies take place.

If we now apply to this fundamentally significant result obtained by Reichenbach Geroch's theorem concerning the equivalence between changes in the topology of physical objects and the apparent violation of the law of causation for these objects (from the standpoint of the old topology), a new fundamental property of complementarity for any physical theories will come to light: in physical theories one can always use only classical (two-valued) logic at the cost of dynamic changes of topology in quantum (and certain gravitational) processes, which is perceived as obvious violation (in terms of the old topology) of the principle of causality (the principle of propagation of any physical actions only from one neighbourhood of a given point to the nearest neighbourhood).

The general topos theory of Lawvere-Tierney shows that this change in the topology of physical objects must lead (sooner or later) to a complete reconstruction of the physical theory of these objects as a definite mode of perceiving them (in the sense of their being composed, for instance, of certain structures that are the most elementary ones in the given theory, of the global space of the possible variations of the latter, etc.). Or else we can leave the topology of the objects under study invariable (conserving, for instance, the classical trivial topology of Eudoxus and Archimedes), but then we shall have to admit that certain of their states are not subject to the classical (two-valued) logic, which, as Reichenbach showed, is precisely what the Copenhagen interpretation of quantum mechanics asserts.

We believe that this new fundamental principle of complementarity (duality) of topology and logic in physics is interesting, first of all, for the application of non-classical logics in physical and, generally speaking, in natural-scientific theories. Rather serious objections have been raised against this kind of application, the gist of which is that in all these applications an elementary analogy with non-Euclidean geometry simply does not work: the latter is not used, for instance, in the logical construction of the general theory of relativity, whereas classical logic is essentially necessary for the new construction of quantum mechanics which in some respects uses also non-classical logic. In the light of the above, however, we have a kind of freedom of manoeuvre: at the initial stages of constructing a theory the logic is rigorously fixed and only changes in the topology are admitted, while after the theory is largely built, changes in logic are also permitted at some points.

Application of the new complementarity principle is certainly most promising in theoretical physics itself—cf. the recent generalisation of the uncertainty principle by S. Hawking. The possibility of virtual (quantum) formation of black holes in any region of space poses the very acute problem of determining the physical processes in it not only by initial and boundary conditions on the hypersurfaces defining that region but also by states of matter, unknown to us, in remote galaxies, with which it becomes connected through a "wormhole" (what is meant here is the generalisation of uncertainty principle introduced by S. Hawking, according to which "God not only plays dice. He sometimes throws the dice where they cannot be seen") [32, p. 2464].

6. The General Topological Structures of Physics

The painstaking methodological analysis, undertaken in recent years in different countries, of the basic conceptual systems of modern physics (of classical mechanics, classical electrodynamics, the special and general theory of relativity, thermodynamics and statistical physics, and finally of quantum mechanics and quantum field theory) has shown that, along with algebraic structures, which on the whole characterise individual results of certain physical actions of the objects under study upon each other, underlying any physical theory are also structures of limiting processes over the whole ensemble of such objects—topological structures. Algebraic tables of the results of various actions of physical objects upon each other, taken separately, do not yet form a theory. They are rather only its empirical basis, in a certain sense. They only become a theory, according to Aristotle and Kant, when we begin to regard them as something complete and whole, as "all". This short but very pithy word "all", the universal quantifier necessarily present in any scientific theory, contains the rudiments of the topological structures of any such theory, for this word assumes that we are able to form, in one sense or another, and consider as wholes maximally broad collections of the objects we are interested in—in all the fullness of connections and relationships of systemic, generalised-spatial, *Gestalt* nature, rather than of individual (algebraic) correlations with one another.

Any scientific theory thus assumes that we can grasp at one glance the entire totality of the connections of the objects studied by the theory with one another. An absolutely necessary condition of this, as shown by modern psychology and geometry, are some conceptions, intuitive but always very clearly fixed, of the objects' definite "nearness" to or "remoteness" from one another (in some respect or other) over their total and complete collection.

Topological structures in modern theoretical knowledge are thus pushed into the foreground only when the question arises of the theoretic quality of this knowledge—its ability to explain, in a sufficiently general and necessary manner, all phenomena of the domain of material reality in question. On the one hand, as has been stated above, topological structures explicate and specify the very concept of universality with regard to a concrete range of phenomena. On the other hand, they explicate the concept of explanation itself with regard to a concrete range of phenomena (as the studies of specialists in the methodology of science have shown, to explain means to deduce in some logical sense or other the properties of the objects under consideration from those of some other objects, the most elementary ones in the given concrete scientific theory).

Now, the most elementary objects of any concrete scientific theory are defined by the topology given for it; it is the topology which specifies the manner in which, in the limiting case, any set that is necessary for the theory, is constructed out of its subsets, and the way these subsets adjoin, in the limiting case, each other. Therein lies, in our view, the methodological significance of the singling out of topological structures in any theory, for the content of the basic axioms defining any topology is at first glance very meagre.

One would have thought that the philosophical analysis of large conceptual systems of modern science with their quasars, black holes, partons, quarks, charmons, conformons, promotors, terminators, plasmaides, restrictases, etc., etc., would not be much advanced by the singling out over the sets which they form and of which they are formed of such systems of subsets as (1) any finite sums, (2) any intersections (common parts) of such subsets, as well as (3) the empty set and (4) the set in question itself. Recent developments in topology have shown, however, that precisely these abstract topological structures fix the limiting properties of any objects of scientific theories—the way they adjoin each other in the limiting case, and the objects to which they prove to be equivalent as a result of the completion of these limiting processes. Both the universal quantifier and the concept of explanation in any modern scientific theory are inseparably connected with the limiting properties of the sets of objects under study.

Further, a theoretical rather than accidental solution of any problem assumes that the search for a certain element is guided by properties of its generality or "nearness" to some "neighbours" also having these (or similar) properties, rather than by intuition or shaman-like trial-and-error search procedures. In this way another most important topological concept, the concept of neighbourhood, appears in the methodological constructions of any scientific theory—at first rather implicitly and intuitively yet quite definitely. Just as necessary for any theoretical construction is another important topological concept—the boundary concept: it is the latter that divides objects with certain properties from objects with quite different properties or, to put it bluntly, what we need from what we do not need at all.

When modern systems of hodoscopic and stereoscopic scintillation counters weighing many tons identify in extremely complex magnetic fields the masses and lifetimes of elementary particles of a fundamentally new, "charmed" nature, we no longer stop to muse that from the standpoint of the methodology of physics they mark the very first boundaries in the new physical world, that is not "strange" even but "charmed". The situation is here largely analogous to the conceptual situation in the electrodynamics of moving mediums in the epoch immediately preceding the appearance of the works of Einstein: almost all of the modern topological concepts (just as the concepts of absolute space and absolute time in that period) seem to us too intuitively clear and too self-obvious. But that is apparently due merely to the fact that we almost literally absorbed our first intuitive notions of the most elementary and trivial Eudoxus-Archimedes topology at our mother's breast: the operational interpretation of any topological structures through the empirical procedure of "cutting out" certainly came to us (and was remarkably firmly planted in our subconscious) along with our first childish attempts to take possession of the objects of the external world by the method of "biting off". The subsequent steps in this direction (the use of hands, feet, mechanical instruments, observation and measuring instruments) did not change essentially this operational archetype of empirical interpretation of topology, although the use of rays or particle beams for the fixing of subsets signified a gradual, implicit, and so far theoretically unrealised transition from the common topology of "cutting out" to a fundamentally new topology—that of mappings, generalised topology of Grothendieck.

For a strictly defined area (in the absence of singularities), both topologies are isomorphic to each other (with certain specifications and reservations concerning the cyclicity of the groups involved). This ensures a smooth and gradual transition from the common topology of "cutting out" an apple or a roll to the topology, just as distinctly different from the former, of mappings of some quasar or "charmed" elementary particle. Clearly, no one can perform the operation of "cutting out" on these objects for singling out certain subsets in them. We can form judgments about their "parts" in a very roundabout way—through some types of radiation and their theoretical interpretation.

Thus the principal conceptual difficulties of modern physics are concentrated around the fundamentally important problem of empirical interpretation of topology for very great and very small distances. The mysterious ambiguity of distances to quasars, measured by their emission and absorption spectra (or to their separate components, which also move relatively to one another at speeds several times greater than the speed of light—according to the latest measurements of I. Shapiro, these speeds are greater than light velocity by a factor of 25), is probably the first serious indication of the fact that the concept of distance loses its unambiguous meaning in the presence of topological singularities. It would be very interesting to analyse, on a methodological plane, the general metrisation theorems of topology (the theorems of Uryson—Bing—Nagata—Smirnov) and to indicate the concrete physical (and topological) causes on account of which any lengths and distances in the neighbourhood of certain types of singularities in quasars become ambiguous.

At present, physical science has only one sufficiently reliable indicator of changes in topology connected with the seeming violations of causality in all such situations—Robert Geroch's "Theorem 2". It asserts that if in some physical processes the topology is changed, it is initially perceived by the external observer (from the standpoint of the old topology) as an abrupt violation of causality, that is, of the gradual propagation (from one neighbourhood of the given point to another) of all the physical actions.

For a rigorous proof of Geroch's theorem we refer the reader to the original work [33, p. 782]; we shall describe here only his basic intuitive idea. The idea is this: systems of neighbourhoods explicating the gradual transmission of causal physical actions are defined precisely by topology, and any changes in the latter lead to changes in the corresponding system of neighbourhoods. Thus from the standpoint of the old topology (and the system of neighbourhoods it defines), the new, modified topology and the physical interactions in it will be perceived by the observer, who has no idea of the change in topology, as the appearance of velocities greater than light or mysterious coordination of processes going on at points in the spatio-temporal continuum extremely remote (from the standpoint of the old topology) from each other.

How can this litmus-paper of modern theoretical physics react to changes in the topology of some physical processes? For example, enormous and apparently "causeless" (that is to say, difficult to explain by the known causal physical laws) release of energy is observed in quasars. There are grounds to assume, therefore, that physical processes in quasars are connected with some change of the topology of real physical space "near" and "inside" them. Then again, baryons disappear without proper cause as they fall into black holes, and that is an obvious and just as "causeless" violation of the law of conservation of the baryon charge—one of the most rigidly observed laws of nature. It follows that in the neighbourhood of black holes the topology of the spatio-temporal continuum is changed very strongly.

We must not think, however, that variations in the topological structures of physics can only occur very far from us, on the borderline of what has been learnt by man, in quasars or black holes. All quantum processes are probably conditioned, in the final analysis, by changes in the topology of the objects under study. For instance, in the experiments in observation of the Einstein-Podolsky-Rosen effects, so characteristic of the quantum world, where two quantum subsystems, which initially form a single quantum system, later fly apart very far from each other (without interaction with anything else), the fixation of the state of one quantum subsystem directly determines the state of the other—without any causal propagation of some physical action across the space between them. It follows that quantum processes are also connected with some variations of the "ontological" topological structures of physics.

Of course, in the philosophical sense the Geroch theorem cannot be interpreted as a rejection of the principle of causality, for in the new topology causality holds quite strictly—it is only seemingly violated from the standpoint of the old topology unsuitable to the new phenomena. So the Geroch theorem enriches and extends our conception of the principle of causality, making it applicable to a much wider class of objects characterised by fundamentally new connections and types of their determination by one another.

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COMPLEMENTARITY OF PHYSICS AND GEOMETRY (EINSTEIN AND POINCARÉ)

Introduction

The problem of complementarity of geometry and physics is part of the very important methodological problem of the correlation of physical geometry and reality, so profoundly formulated and analysed by Einstein. Abstract geometrical spaces, as Einstein emphasised, acquire actual physical significance only after the conceptual schemata of axiomatic geometry are coordinated with real objects of experience. Geometry thus completed becomes a natural science, that is, a science verifiable by experience [1, p. 235]. Exactly this conception of geometry enabled Einstein to create the theory of relativity. On the other hand, according to Poincaré, no geometry (Euclidean geometry included) can contradict reality if it is complemented by appropriate physical propositions [2, pp. 92-109]. It would appear that Einstein and Poincaré took opposite approaches to the question of connections between geometry and physics. Inasmuch as Einstein's approach proved to be methodologically more promising, it is often viewed as fully confirmed by the development of physics. One would do well to remember, however, that Einstein himself was much less categorical in his evaluation of Poincaré's approach. Thus, in his article "Geometry and Experience" he wrote: "*Sub specie aeterni* Poincaré, in my opinion, is right" [1, p. 236]. It is also noteworthy that in Einstein's article Poincaré's position was given a generalised and logically transparent expression that is in some respects even clearer than in the works of Poincaré himself. While rejecting Poincaré's solution, Einstein apparently understood better than anybody else the fundamental quality of the problem he had formulated. This circumstance prompts a more careful attitude to the idea of complementarity of geometry and physics and to the evaluation of its probable methodological significance for the development of physical knowledge.

1. Geometry and Experience

The history of scientific cognition knows two opposing views of the nature of geometry. According to one of them, geometry is an empirical science, and the truths of Euclidean geometry have experiential origin. According to the other view, expressed by Kant, the truths of geometry are apriori truths serving as premises for any experience. The discovery of non-Euclidean geometries in the 19th century undermined the foundations of Kantian apriorism in the doctrine of space. At the same time simplistic views of empirical nature of geometrical truths were also beneath criticism as they did not take into account the specificity of the subject matter of mathematics as compared to the subject matter of empirical natural science. Against this historical background there emerged Poincaré's thesis that geometrical truths were nothing but conventions. "*Geometrical axioms are neither synthetic apriori judgements nor experimental facts.* They are *conventions* [wrote Poincaré]... Now, let us think of the question: Is Euclidean geometry true? It has no sense at all. We might as well ask if the metric system is true and the ancient measures false.... One geometry cannot be more true than another; it can only be *more convenient.* Thus, Euclidean geometry is and will remain the most convenient (1) for it is the most simple... (2) for it accords well enough with the properties of the natural solid bodies" [2, pp. 66-67].

What arguments does Poincaré adduce in defence of his view? First of all he stresses the fundamental difference between physical and geometrical objects. Geometry does not study real physical bodies but rather ideal and absolutely invariable objects that are never realised in pure form. There are no ideal points, straight lines, planes, etc., in nature. "The notion of these ideal bodies [writes Poincaré] is extracted from all the parts of our spirit, and experience is nothing but an occasion which compels us to make it stand out" [2, p. 90]. The comparison of ideal geometrical objects and physical objects is not unambiguous, it may, generally speaking, be performed in various ways, so that identical facts will be described in terms of different geometrical spaces. Moreover, according to Poincaré, the laws of physics can always be corrected in such a way that descriptions of phenomena will not go beyond any arbitrarily chosen geometry. The physical and geometrical parts of description are in this sense complementary.

To illustrate these propositions, Poincaré cites a number of interesting examples, one of which comes very close to the problematic of the general theory of relativity. Suppose, says Poincaré, observation of a stellar parallax showed that a light ray of some star does not satisfy an Euclidean postulate. Two interpretations of this phenomenon are possible: we either accept that the properties of space on a great scale deviate from the Euclidean properties, or else we assume that space possesses Euclidean properties but some force bends the light rays. The choice between these two variants is arbitrary, but it is connected with changes in physical laws [3, pp. 189-190].

Another well-known example which Poincaré constructs to confirm his view is a hypothetical world contained within an enormous sphere in which all distances decrease from the centre to the periphery [2, pp. 83-87]. An observer in this world would not be able to notice changes in distances—he would believe, as we usually do, that rigid bodies do not change their properties under transposition to other spheres of space. In this case he would arrive at the conclusion that his space is non-Euclidean. This conclusion about the nature of geometry rests on the convention of congruence, according to which rigid bodies retain their size under transposition, and which cannot be verified by direct experiments. It is obvious at the same time that acceptance of a non-Euclidean mode of description affects the character of the physical laws adopted. For example, if we accept a non-Euclidean geometry, no physical explanation of changes in the size of bodies in transposition will be required (these changes are believed to be non-existent).

In his article "Geometry and Experience" Einstein characterised Poincaré's position in the following manner: "Geometry (G) predicates nothing about the behaviour of real things, but only geometry together with the totality (P) of physical laws can do so. Using symbols, we may say that only the sum of (G) + (P) is subject to experimental verification. Thus (G) may be chosen arbitrarily, and also parts of (P); all these laws are conventions. All that is necessary to avoid contradictions is to choose the remainder of (P) so that (G) and the whole of (P) are together in accord with experience" [1, p. 235]. Accepting Poincaré's view "*sub specie aeterni*", Einstein rejects it as a basis for constructing a physical theory, bearing in mind the essential difference between the methodology of experimental natural science and that of mathematics.

Physical concepts, inasmuch as they are applicable to the real world, cannot be just as rigorous as the mathematical ones which, according to Einstein, are certain only as long as they do not refer to reality [1, p. 233]. It is therefore necessary to distinguish between pure geometry as a mathematical discipline and physical (or practical) geometry as an experimental science and essentially the most ancient branch of natural science. In practical geometry, the practically rigid bodies of physics correspond to the ideal objects of mathematics. This correspondence is of course approximate, but such a level of precision is quite sufficient for physics. "...As to the objection that there are no really rigid bodies in nature, and that therefore the properties predicated of rigid bodies do not apply to physical reality [writes Einstein]—this objection is by no means so radical as might appear from a hasty examination. For it is not a difficult task to determine the physical state of a measuring-body so accurately that its behaviour relative to other measuring-bodies shall be sufficiently free from ambiguity to allow it to be substituted for the 'rigid' body" [1, p. 237]. Einstein further formulates the following two propositions. If the lengths of two practically rigid bodies are found to be equal once and anywhere, they are equal always and everywhere.

In a similar way, if two clocks are going at the same rate at any time and at any place, they will always go at the same rate everywhere. The latter proposition is proved, in particular, by the existence of sharp spectral lines of atoms. Einstein sums up: "According to the view advocated here, the question whether this continuum has an Euclidean, Riamannian, or any other structure is a question of physics proper which must be answered by experience, and not a question of a convention to be chosen on grounds of mere expediency" [1, p. 238].

2. Two Paths in the Development of Physical Theories: The Path of Einstein and the Path of Poincaré

The absence of a rigid one-to-one relation between geometry and reality emphasised by Poincaré leads to the possibility of two paths in the development of physical knowledge. The first path involves selecting the simplest and the most convenient geometry and adapting the laws of physics to it (the path of Poincaré). The second consists in changing the adopted geometrical model with the object of possible simplification of the apparatus of physical concepts (the path of Einstein). If in describing a complex ensemble of physical phenomena we use an elementary geometrical model, it may be required, to ensure adequacy of description, to introduce a number of additional physical assumptions. On the other hand, one may try to change the spatio-temporal description employed in such a way as to reduce the number of assumptions to a minimum.

These two paths may be explained with the help of the universal force concept introduced by Reichenbach [4, pp. 13, 35, 66]. By a universal force he means a force which acts on all bodies in the same way and which cannot in principle be isolated. This force can change the absolute size of any body as it is translated to another area of space, the changes in question being inaccessible to direct experimental verification, since the size of measuring standards changes in the same proportion. According to the principle of relativity of geometry formulated by Reichenbach, we obtain a statement about physical reality only if a field of universal force is fixed in addition to space geometry. Reichenbach suggests that a convention be accepted that there are no universal forces. In this case the choice of space geometry becomes a matter of experience. If we conserve the simplest space geometry once and for all, we shall have to introduce universal forces, sooner or later, for the description of complex physical phenomena (the path of Poincaré). On the contrary, if we reject their existence, we adapt geometry to the modified physical situation (the path of Einstein). Einstein used this path of development already in constructing the special theory of relativity.

As we know, Lorentz and Fitzgerald assumed that a moving body undergoes an absolute reduction in size in the direction of motion, for during motion in ether a universal force emerges which is independent from the body's material and determined only by the velocity of motion. Later Lorentz assumed that all processes slow down in moving systems. Thus Lorentz's theory of moving bodies chose the path of Poincaré: it left intact the traditional concepts of classical physics concerning space and time at the expense of introducing a universal force reducing all moving objects and slowing down all processes in moving systems. Although Lorentz's theory of moving bodies can be brought in agreement with facts, it was rejected on the grounds of its artificiality and the assumption of the in principle unobservable ether. As distinct from Lorentz, Poincaré accepted the idea that ether does not exist and made the principle of relativity the basis of his studies.He came very close to formulating the special theory of relativity and developed its mathematical apparatus in a profound manner, proving covariance of the Maxwell equations under transformations from the Lorentz group and finding the invariants of this group [5, pp. 489-550]. However, Poincaré, too, laid no claims to a revision of the spatio-temporal concepts of classical physics, paying great attention to the forces capable of producing the Lorentz contraction. On the contrary, when Einstein built the special theory of relativity, he explicitly introduced new concepts of time and space, giving up the concept of ether and in general any artificial assertions about the behaviour of physical objects. The relativistic effects of shortening of moving bodies and slowing down (dilatation) of time in moving systems were thus given kinematic rather than dynamic interpretation.

Einstein chose a similar path in constructing the general theory of relativity. The difference is that the universal force here was invented already in antiquity, and the idea of it deeply rooted in men's consciousness. The universality of the gravitational force follows from the empirical fact, known already to Newton, of the equality of gravitational and inertial masses. Gravitation as distinct, say, from electromagnetism affects all bodies in the same way, and it cannot be screened. Einstein rejected the traditional concept of gravitational force, connecting the phenomenon of gravitation with curvature of the spatio-temporal continuum under the action of massive bodies. According to the general theory of relativity, inertial motion of bodies occurs along geodesic lines in curved space-time.

Let us now recall Poincaré's example with two different interpretations of the bending of a light ray from a remote celestial body. Poincaré favoured the interpretation where the notion of Euclidean space is retained and the bending of the light ray is attributed to some disturbing force. On the contrary, the general theory of relativity accepts the interpretation (rejected by Poincaré) in which the ray moves along the geodesic line in curved space-time without any influence of any forces. For example, the bending of a ray of light in passing in the neighbourhood of the sun is here considered as one of the principal experimental effects of the theory.

According to Reichenbach, the rejection of the concept of universal force is a convention. In this approach the assumption is that Einstein's theory itself is based on convention. One can hardly accept this view. It is obvious, first of all, that Einstein's approach is in this connection more adequate than Poincaré's. Thus, if an observer in a gravitational field adheres to an Euclidean rather than Riemannian geometry, a free-moving particle deviates, although apparently undisturbed, from the geodesic line (that is, from uniform rectilinear motion). In order to remove this contradiction, the observer will have to introduce a force field and ascribe to it concrete physical properties. But if the force thus introduced does not have these properties due to its universal quality, it is natural to describe it as a fiction invoked by the discrepancy between the appropriate natural geometry induced by the field equations and the observer's inadequate Euclidean geometry [6, p. 164].

Moreover, universal force is a metaphysical concept which has no place in the modern physical picture of the world. If this concept were to be accepted without reservation, one would have to conserve the classical notions of space and time once and for all, interpreting any new facts of physics in terms of new forces, which in the final analysis must become very complicated and artificial. This is fraught with the danger of transforming science into a kind of demonology. On the other hand, the rejection of the concept of universal forces permits unlimited development of our spatio-temporal conceptions. Properties of space and time are now closely linked with those of matter and can only be established in a physical experiment. A natural boundary is drawn between geometry and physics or, to be more precise, between those parts of physical reality which can be geometrised in a natural way and those that have dynamic nature. In other words, the rejection of the concept of universal force is not just a convention but an important methodological principle closely connected with the modern physical picture of the world.

It is also important to note that on the path of Poincaré, that is, remaining within Euclidean geometry, the construction of a perfect and heuristic theory of gravitation proved to be impossible. Many attempts were undertaken to construct a theory of gravitation in pseudo-Euclidean space-time (linear Lorentz-covariant theories of gravitation). Certain steps in this direction were made already by Poincaré himself in the above-mentioned article "On the Dynamics of the Electron". Some of the linear gravitation theories yielded correct first-approximation values for the three famous experimental effects of the general relativity theory (Mercury's perihelion precession, the shifting of a ray of light near a massive body, the gravitational red shift). Among these theories are the tensor theories of Birkhoff [7, pp. 231-239] and Whitehead [8, pp. 202-209] and the vector theory of Kustaanheimo [9]. The main drawback of these theories is the complexity and artificiality of the non-geometrical part of the description, including the introduction of a great number of *ad hoc* concepts and notions (first and foremost, of the universal gravitational force). They postulate very artificial equations describing the gravitational field, and equations of motion which, as distinct from Einstein's theory, do not follow the field equations. The main thing is, however, that all these theories merely confirm, after the fact, the conclusions of the general theory of relativity without predicting any qualitatively new effects. They artificially combine the ideas and principles of mechanist physics and the spatio-temporal conceptions of the special relativity theory.

Of the more recent attempts to realise the path of Poincaré in the theory of gravitation, in one form or other, we should mention the Brans-Dicke theory. According to R. Dicke, it is possible to remove a geometrical interpretation of gravitation if one interprets it instead as the effect of a force field in a geometry without a metric regarded as an unconnected differentiable manifold [10, p. 58]. In this case, the $g_{\mu\nu}$ tensor is treated as a force field similar to the electromagnetic and other fields. However, as R. Dicke admits himself, giving up Einstein's geometric interpretation (and, in actual fact, the relativistic picture of the world) deprives the theory of gravitation of consistency and unambiguousness. In this framework, a great number of variants of the theory may be constructed in which gravitation will be treated as various combinations of scalar, vector, and tensor fields. One of these variants is implemented in the Brans-Dicke tensor-scalar theory introducing two gravitational fields, a tensor and a scalar one. According to Mach's principle, it is assumed that the gravitational field is the source of inertia of bodies in the whole of the universe. However, although Mach's principle played a definite heuristic role in constructing the relativity theory, there are grounds to assume that it is unacceptable in this formulation [11, p. 586]. Apparently bodies do not cease to possess inertial properties even in empty space free of masses. It is quite probable that the property of inertia in macrobodies is conditioned by the microlevel (quantum fields and the physical vacuum), and the search for its source at the macrophenomenal level is hopeless. The scalar field in the Brans-Dicke theory is essentially a new universal force introduced *ad hoc.*

These two paths in the construction of physical theory were also reflected in cosmology. It is interesting to compare in this respect two approaches to the solution of the cosmological problem—the relativistic cosmology of Einstein and Friedmann and the theory of a stationary universe. As is known, if the cosmological constant is taken to be zero, the theory of a uniform and isotropic universe yields only a non-stationary solution. Any Friedmannian model is characterised by singularity and changes in space geometry with time. On the other hand, according to the theory of a stationary universe suggested by Bondi and Gold [12, pp. 252-270], as well as by Hoyle [13, pp. 372-382; 14], the decrease of the density of matter due to the expansion of the universe is made up for by continuous spontaneous generation of matter. However, the theory of a stationary universe, as distinct from the Friedmann cosmology, runs into some difficulties and anomalies. Thus spontaneous generation of matter may be interpreted as a kind of causal anomaly. To eliminate it, Hoyle postulated a specific physical agent, the *S*-field, responsible for the mechanism of generation. But the *S*-field concept is a typical *ad hoc* notion which has no convincing physical substantiation. From the physical viewpoint it appears paradoxical that the *S*-field can create a negative density of energy. The Hoyle theory is also undermined by some modern astrophysical data concerning the number of remote radio sources. It may be assumed that the principal cause of the difficulties of the stationary universe theory is rooted in the rejection of consistent use of spatio-temporal conceptions of the relativistic picture of the world, that is, actually, in the acceptance of the path of Poincaré.

The question of the relationship between the path of Einstein and that of Poincaré in quantum physics is more complicated. Einstein was one of the first to express the assumption that inherent in the microworld is a specific system of spatio-temporal relations qualitatively different from the macroscopic one. He admitted the possibility that quantum theory will show inapplicability of the concept of invariable measuring-rod for small distances [15, S. 19], and even expressed doubt about the applicability of the continuum theory for the description of reality [16, pp. 165, 166]. However, neither he himself nor anyone else has proposed an adequate variant of microgeometry. So far quantum physics has developed along the Poincaré path rather than that of Einstein. In describing quantum objects it uses classical spatio-temporal conceptions (non-relativistic and relativistic), which in some cases causes serious methodological difficulties.

Although the three-dimensional Euclidean space of classical physics remains the main geometrical model of non-relativistic quantum mechanics, it determines the structure of the theory but on a limited scope. In classical models there existed a single model of the object localised in Euclidean space. On the contrary, a quantum-mechanical object manifests itself as a "spatial" one only in limiting situations which follow from the uncertainty relation. The wave function of a quantum system can be compared to physical experiments in three-dimensional space only through the concept of probability. This creates a gap between the geometrical and non-geometrical components of the theory, resulting in the paradoxical behaviour of quantum objects.

Infinite-dimensional Hilbert space to which ψ-functions belong does not have the status of a physical geometry, for it has no direct experimental interpretation. Yet it largely determines the structure of the theory. The logical structure of quantum mechanics may be said to be doubled. Apart from the geometrical and non-geometrical components in the traditional acceptation (three-dimensional Euclidean space and its transformations; quantum objects subject to the uncertainty principle), it contains the "quasi-geometrical" and "quasi-nongeometrical" components (Hilbert space and operators in Hilbert space; the ψ-function and the physical magnitudes as the eigenvalues of the operators).

There is a certain analogy between Bohr's principle of complementarity and the complementarity of geometry and physics in the sense of Poincaré. In accordance with the complementarity principle, the spatio-temporal and momentum-energy descriptions of quantum objects exclude each other. Viewing a quantum particle as a material point localised in Euclidean space results in causal anomalies, and attempts to retain classical causality, in the assumption that a quantum particle is not localised in three-dimensional Euclidean space. These two modes of description remind one of the two systems (G) + (P) in the sense of Poincaré. But causal anomalies may also arise, in particular, in the description of phenomena through a geometrical model with an inadequate topology [4, pp. 65, 66]. Indeed, comparison of two structures with different topologies leads to disturbances either in the one-to-one relations or in the continuity of mapping, which at the level of physical consideration results in causal anomalies. From this standpoint one can imagine the realisation of the path of Einstein in quantum theory. For this, it is necessary to restructure the quantum-mechanical description on the basis of a geometry with a specific topology, in order to remove the duality of description and the causal anomalies. But this solution of the problem does not appear quite feasible, for it assumes a return to the classical form of causality. What is really beyond doubt is the fact that the search for an adequate microgeometry and the corresponding rebuilding of the theory are in themselves justified and necessary.

Following the path of Poincaré, quantum field theory and elementary particle physics have attained impressive results. That is apparently due to the fact that classical spatio-temporal relations are universal at the empirical level of scientific research, that is, in the sphere of macroscopic experience. At the same time extrapolation of the classical spatio-temporal conceptions to the microworld has caused a number of considerable difficulties [17, Ch. 7, 8]. Thus, unobservable objects appear in quantum electrodynamics (virtual particles and states; "longitudinal" and "time-like" photons), indefinite metric is used, which admits "ghost" states with negative probability, etc. As the axiomatic quantum field theory has shown, if the standard requirements of relativistic theory are correct, the field given at a definite point of space-time cannot have the meaning of an operator in Hilbert space that would be distinct from the numerical constant (the Wightman theorem). According to the Haag theorem, a theory of interacting fields is impossible within the framework of the usual principles of the relativistic invariant quantum field theory under the condition that free and interacting fields are connected by a unitary transformation, since such a theory proves to be equivalent to the theory of a free field. These and other results prove the need for an essential reconstruction of the modern theory on the basis of new spatio-temporal conceptions.

3. The Principle of Complementarity of Geometry and Physics

As the previous exposition has shown, Poincaré's view of the conventional nature of physical geometry was not borne out in practice. But the methodological problems raised by Poincaré are still valid. In constructing a physical theory, the researcher may come up against several descriptions of type $(G) + (P)$ which correspond, at the given level of cognition, to all the experimental data available. According to Poincaré, all these descriptions are equal in their relation to reality, and we choose the one in which the most convenient and simple geometry is used. Since we reject this solution, we have to offer a different and more adequate one, and to explain why some of these descriptions prove to be fruitful in the subsequent development of knowledge, and others turn out to be *cul-de-sacs*. With this aim in view we must first turn to an analysis of equivalent descriptions.

According to the Reichenbach-Carnap conception, theories are considered to be equivalent descriptions if they describe the same facts and yield the same predictions about observed events [18, p. 218]. One of these descriptions is chosen out of considerations of convenience, expediency, and other subjective criteria. It should be remembered, however, that empirical equivalence of theories does not necessarily entail their physical (semantic) equivalence. That is all the more true of cases where theories are empirically equivalent only as a first approximation or only at the given level of knowledge, later ceasing to be equivalent.

A fundamental physical theory is not reducible to the mathematical formalism provided with an appropriate empirical interpretation. It also possesses a semantic aspect linked with those ideal models which are directly described by the equations of the theory and embody the physical reality for the theoretician. It follows that two theories may be empirically equivalent but physically of different value. True, in order to establish this, one must consider the data of the theory not as isolated fragments of an already formed scientific knowledge but in dynamics, in the process of formation of new knowledge, taking into account philosophical-epistemological as well as empirical considerations and criteria.

In constructing a theory, the researcher proceeds from a limited number of facts at his disposal. The fundamental irreducibility of theory to experience entails that one and the same empirical domain may be described by a number of different theoretical models. With this in mind, Einstein often stressed that "there is no inductive method which could lead to the fundamental concepts of physics" [1, p. 307], and that the fundamental concepts and laws of a theory "are free inventions of the human intellect" [1, p. 272]. It is therefore clear that the choice of a single variant of description as methodologically more preferable is a most important theoretical task. The point here is not only the psychological reasons for the non-equivalence of different modes of description of which Feynman writes [19, pp. 167, 168]. That one theory leads to further development of theoretical knowledge while another, empirically equivalent to the former but based on different physical principles, does not, is not merely a fact of the psychology of scientific creativity but an important epistemological fact. The development of physical theories does not proceed in isolation but within the framework of an integral process of theoretical cognition, being closely linked with the physical picture of the world and a system of metatheoretical principles. Of great cognitive significance in this process are not only those elements of cognition which have an unambiguous empirical substantiation but also those which are linked with general philosophico-epistemological considerations. As a rule, preference is given to that theoretical approach which is in better agreement with an advanced physical picture of the world, or paradigm, or the tendencies of the development of theory connected with them. Thus, Lorentz's theory of moving bodies was based, as distinct from the special theory of relativity, on obsolete notions of the mechanist picture of the world—those of matter, space and time, and it also violated the principle of observability. Therefore, though both theories were empirically equivalent, Einstein's theory has won out. In the final analysis, relativistic notions won because the relativistic picture of the world constituted the mainline of the development of physical theory after the emergence of Maxwell's electrodynamics, serving as a "springboard" for the construction of the general theory of relativity and subsequently of the relativistic quantum theory. As for the theory of Lorentz, it may be made empirically equivalent to the special theory of relativity only by the addition of some artificial assumptions which violate the consistency of the theory. From this standpoint it becomes clear that the non-uniqueness of spatio-temporal description of which Poincaré spoke is eliminable only outside the narrow empirical approach, in the context of a wider philosophico-epistemological analysis.

On the basis of the above we can try to single out the rational content of the idea of complementarity of geometry and physics. It consists, in our view, in the following:

(1) The geometrical (G) and the physical (P) components of a physical theory complement each other, constituting an integral theoretical system. Alteration of one of them entails corresponding alteration of the other. For instance, simplicity of (G) assumes complexity of (P), and vice versa.

(2) At any stage in the development of physics several descriptions of the type $(G) + (P)$, $(G)_1 + (P)_1$, $(G)_2 + (P)_2$, . . . , may exist, each of which accords with all the empirical data available.

(3) There are methodological criteria of adequacy of spatio-temporal description.

These propositions we shall refer to as the "principle of complementarity of geometry and physics".

In starting out on an investigation of a qualitatively new field of physical phenomena, one should always reckon with two possibilities; either the properties of space and time have not changed and the new phenomena exist against the same spatio-temporal background, or else a new system of spatio-temporal relations is inherent in them. It is at first not clear which of the two possibilities is realised. Even if there are signs that the properties of space and time have changed, it is not so simple to establish the nature of the change. Attempts are therefore quite justified and natural to give a description of the phenomena under study in terms of customary geometrical models. Difficulties and anomalies may arise in the process of such description and these stimulate the quest for new spatio-temporal conceptions. If the spatio-temporal relations are indeed specific, the new concepts will sooner or later assert themselves and the optimal variant of the correlation between physics and geometry will thereby be recognised. But this process may prove to be very long and agonising, including departures from reality and inadequate interpretations of facts. As we see, the complementarity of physics and geometry is closely linked with the dialectics of absolute and relative truth. This complementarity may be regarded as one of the manifestations of the dialectical nature of scientific cognition and its tendency towards an ever more complete and adequate reflection of reality.

Although different descriptions of the $(G) + (P)$ type are not, strictly speaking, equivalent, they may seem such for quite a long time from the positions of narrow empiricism, and only further development of physics may eliminate their "equivalence". The difficulty of the problem lies in that practice confirms a $(G) + (P)$ description only in the final analysis, in the course of subsequent development of theory, and at each stage of scientific cognition one has to use propositions that are not directly empirically verifiable.

One such proposition, of great importance for the establishment of an adequate physical geometry, concerns spatial and temporal congruence. Although the problem of congruence has been widely discussed in the literature (in the works of Carnap, Reichenbach, Grünbaum, and others), only one aspect has usually been emphasised—the role of conventions in defining congruence. Less attention was given to the objective foundations of this definition and its links with the general conception of space and time. It was usually disregarded that science employs various kinds of conventionality. The first (formal) type of conventionality includes conditional conventions alteration of which entails changes in the form of scientific knowledge but not in its content. Such examples may be cited here as choice of units for measuring physical magnitudes, choice of measuring scales, etc. The second (meaningful) type of conventionality comprises conventions which, although lacking direct empirical substantiation, ultimately affect the content of scientific knowledge. These conventions are usually introduced not only because of their convenience or expediency but on philosophico-epistemological grounds. A typical example of this kind of convention is Einstein's definition of simultaneity. The definition of congruence belongs precisely to this kind of conventions.

To get a deeper insight into the objective foundations of different definitions of congruence, it is necessary to proceed from a general philosophico-methodological conception of spatio-temporal relations. Significant in our view are the following propositions bearing on this:

(1) The proposition concerning the possible diversity in the universe of qualitatively different spatio-temporal structures having specific metrical and topological properties.

(2) The thesis that any spatio-temporal structure partially determines the specificity of the class of physical objects localised in it, being in this sense a premise of its existence.

(3) The proposition that all properties of the spatio-temporal structure (metrical and topological ones) are ultimately determined by fundamental physical phenomena and connections [17, 20].

The first and the third of these propositions conform well with the relativistic picture of the universe, according to which spatio-temporal relations are defined by physical conditions and vary with the latter. The second proposition establishes certain independence of the properties of space and time from physical objects and processes, which is not refuted by the relativity theory.

From the standpoint of nominalism, the status of objective existence can only be ascribed to empirical objects directly fixed in experience. But this position is too narrow. In physical methodology objective existence is usually ascribed to anything that satisfies the methodological criteria of existence, such as observability in principle, invariance, system quality, etc. It is thus clear that not only physical objects exist but also fundamental structures, connections, and relations, including spatio-temporal ones.

The spatio-temporal structure is not perceived directly but through the mediacy of a class of corresponding physical objects and processes. For example, in the case of macroscopic space-time such objects are, first of all, rigid bodies and light rays. But in actual fact the class of such objects is broader. These objects and processes reflect to some extent the specific features of the spatio-temporal structure of the given type and precisely for this reason may be used for its partial empirical interpretation. From this viewpoint the convention concerning congruence is not arbitrary—it has a scientific basis stemming from the objective agreement of the given spatio-temporal structure with the class of physical objects localised in it.

One of the causes of ambiguity in choosing the definition of congruence is that, taking measurements within the spatio-temporal structure of the macroworld, we have no independent spatio-temporal standards that would go beyond the macroscopic system of spatio-temporal relations and therefore be absolute with regard to it. It is possible, however, that such standards will be found in microphysics, which will permit a new approach to the solution of the entire problem of congruence. The solution of many problems of space and time, including that of congruence, has been essentially impeded by the researchers' confidence in the universal quality of macroscopic space and time. The thesis of diversity of spatio-temporal structures offers a solution to these difficulties.

In view of the above, special importance attaches to the quest for such objects and processes which adequately reflect the properties of the spatio-temporal structure under study. In macrophysics, despite the above ambiguity, this problem is solved in a relatively simple way, but in elementary particle physics and cosmology the situation is quite different. Inasmuch as the usual standards of extension and duration do not apply in the microworld, it is necessary to look for specific microprocesses which reflect in a natural way the metric relations at the microlevel. A. L. Zelmanov believes [21, p. 279] that future physical theory will be ametrical or polymetrical, admitting of a great number of various types of metrics. In our view, however, the investigators who insist that the concepts of extension and duration are inapplicable to the microprocesses are wrong. Their arguments do not as a rule distinguish between macroscopic extension and duration implemented in normal spatio-temporal standards, and extension and duration in a broader sense—in the sense of the presence in a spatio-temporal structure of a certain set of metrical properties. The metrical relations at the microlevel may be qualitatively different from the macroscopic ones, and they may be realised in specific types of physical reality. In our opinion, the idea of polymetric geometry in the microworld has some interest, although it is not so far clear how it will come into the structure of physical theory. If this idea is confirmed, we shall have to deal with a new aspect of complementarity of physics and geometry.

There is also a great deal of vagueness about the choice of spatio-temporal standards for the initial stages of the evolution of the universe when matter was in a superdense state. Research has shown [22, p. 463] that there exists a complex fluctuation in approaching the singular point during the evolution of the universe. As singularity is approached, the period of oscillations of space scales decreases, so that an infinite number of oscillations fills the interval between any moment of evolution and the singularity. If we re-define temporal congruence, regarding this oscillating condition as uniform, the time of the existence of the universe proves to be infinite. Thus the choice of standards for measuring time duration determines finite or infinite time of the cosmological model. This situation is similar to Poincaré's example discussed in the first section, in which the definition of space congruence determines the conclusion as to the model's finiteness or infiniteness. We cannot go into a more detailed analysis of this problem here; we shall merely indicate that there are no sufficient grounds so far for re-defining cosmological time. As there are no natural laws prohibiting the measurement of cosmological time as near the singularity as one desires, these measurements can be performed at the present stage of expansion with the help of the usual time standards.

Just as the problems of congruence, the principle of complementarity of geometry and physics has a definite objective basis. To establish the latter, we must consider complementarity of physics and geometry as part of a broader epistemological problem—that of conceptual expression of integral physical reality. The tendency has become explicit in the development of physical knowledge to divide physical reality into two independent components—the geometrical and the non-geometrical. Accordingly, all the properties of matter are divided into two groups, as it were: space-time on the one hand and all the other properties on the other (motion, causality, interaction, etc.). A serious problem arises here: in what way are these two aspects of integral reality to be delimited in a rigorous and unambiguous manner? If changes occur in the world of phenomena which affect the basic characteristics of reality, what are these changes to be ascribed to—the geometrical or the non-geometrical properties of being? In our experience these characteristics are not given in isolation from each other and it is by no means always easy to establish a clearcut boundary between them. As Sommerville writes, "all measurement involves both physical and geometrical assumptions, and the two things, space and matter, are not given separately, but analysed out of a common experience. Subject to the general condition that space is to be changeless and matter to move about in space, we can explain the same observed results in many different ways by making compensatory changes in the qualities that we assign to space and the qualities we assign to matter. Hence it seems theoretically impossible to decide by any experiment what are the qualities of one of them in distinction from the other" [23, pp. 209-210]. To this should be added that the thesis of "changelessness" of space on which Sommerville relies is in itself debatable: it is violated in particular in relativistic cosmology and geometrodynamics. This complicates even more the solution of the problem.

It may be assumed that the indissoluble unity of all the properties and aspects of physical reality is expressed in the absence of a sharp boundary between its geometrical and physical components, which explains their possible variability in theoretical description. One of the methods to restrict this possibility is to pay attention to a circumstance that has already been pointed out, namely the natural correspondence between these components of description where the correlation between them is correct. Moreover, there is a definite correspondence between some classes of the properties of space-time and separate non-geometrical properties of matter:

metrical properties	⟷	*motion*
symmetry properties	⟷	*conservation*
topological and other properties	⟷	*causality*

Thus the normal causal order corresponds to the linear temporal order; the local propagation interaction principle, to continuity of space and time; the dynamic laws of conservation (of energy, impulse and momentum), to the properties of symmetry in time and space; the physical laws of motion are usually formulated in terms of a spatio-temporal metric, and so on. In an adequate theoretical description the correspondence between these pairs of concepts is not violated. The idea of complementarity of geometry and physics must thus be considered together with the idea of their correspondence.

Some new effects related to the geometry-physics complementarity come to light in new physical theories. One of them emerges in the study of particle generation out of vacuum by a non-steady-state gravitational field. In this situation, the concept of particle and the number of particles generated may change in the transition from one coordinate system to another [24, 25, p. 2850, 26]. As a result, it appears that space-time geometry depends on the choice of a reference frame. Here too we deal with the general thesis that a change in the non-geometrical part of the description is accompanied by a corresponding change in its geometrical part. However, we are not speaking here of a conventional choice of a spatio-temporal model but rather of its objective dependence on the conditions of cognition connected with a certain new type of physical relativity. This shows that the principle of complementarity of geometry and physics goes beyond the purely epistemological framework and may be used in expanding the modern physical conception of the world.

4. From Complementarity to Harmony

What are the methodological criteria of adequacy of spatio-temporal description assumed by the principle of complementarity of geometry and physics? According to Poincaré, physical inquiry should always employ the most elementary geometrical model. In Carnap's words, Poincaré did not think that the price to be paid for this would ever be too high [26, p. 149]. As the general theory of relativity showed, the simplicity of the geometrical part of the description cannot be viewed as a criterion of its adequacy. Moreover, analytically more complicated geometry proves to be preferable here. But, according to the principle of geometry-physics complementarity, growing complexity of the geometrical part of the description entails a simplification of its non-geometrical part. Thus introduction of a non-Euclidean geometry in the general theory of relativity permitted not only elimination of the universal force (the force of gravitation) from the description but also elucidation of the unity of inertia and gravitation, deduction of the equations of motion from field equations, etc. One has the impression that it is not simplicity of the geometrical part that is to be preferred but, on the contrary, simplicity of the non-geometrical part of the description.

The simplicity criterion cannot be applied simultaneously to both (G) and (P) in a description of the $(G) + (P)$ type. It is therefore more correct to apply this criterion to the theoretical system as a whole [26, p. 150] and only later to find out which of the components should be simpler to make the whole system more adequate. That was actually done by Einstein in the construction of the theory of relativity.

Simplicity of a physical theory is not identical to the simplicity of its mathematical apparatus. The fewer the meaningful physical ideas and principles underlying a theory and the greater the objective sphere it covers, the simpler it is. But mutual coordination of the last two requirements is only possible where a well-developed mathematical apparatus is available. Einstein wrote in this connection: "our final aim is always a better understanding of reality. Links are added to the chain of logic connecting theory and observation. To clear the way leading from theory to experiment of unnecessary and artificial assumptions, to embrace an ever-wider region of facts, we must make the chain longer and longer. The simpler and more fundamental our assumptions become, the more intricate is our mathematical tool of reasoning; the way from theory to observation becomes longer, more subtle, and more complicated. Although it sounds paradoxical, we could say: Modern physics is simpler than the old physics and seems, therefore, more difficult and intricate. The simpler our picture of the external world and the more facts it embraces, the stronger it reflects in our minds the harmony of the universe" [27, p. 213].

According to the classical ideal of constructing a physical theory, its mathematical apparatus is based on a chronogeometrical model and a fundamental group of transformations corresponding to the latter. It follows that the complication of the mathematical apparatus of which Einstein speaks concerns first of all the geometrical part of the description. Thus, the mathematical apparatus of the general theory of relativity is based on the formalism of Riemannian geometry and tensor analysis, and the principal transformation group is the group of arbitrary homeomorphisms. This apparatus is rather complicated from the analytical viewpoint. On the other hand, the physical part of the description contains the main physical principles and will, according to Einstein, be simplified with the development of physics. It follows that the all-round simplicity of a physical theory is in agreement with the complexity of the chronogeometrical model but requires comparative simplicity of the non-geometrical part of the description. This simplicity is the criterion of the adequacy of the description as a whole and of its geometrical component.

One of the reasons to prefer a simpler description to a more complex one is that the former is potentially more general. The fewer the basic propositions explaining a certain factual area, the greater the number of new facts one can hope to describe with their help in the future. Adequacy of description is largely determined by its ability to extend the investigation to encompass ever new fields of phenomena [28, pp. 315-332]. Thus, the general theory of relativity and Riemannian geometry were at first considered by many physicists as curious but excessively abstract and practically nearly useless constructions. The situation was altered essentially with the construction of relativistic cosmology and astrophysics, that is, with the extension of the relativity theory to encompass the whole of the observed universe. Consequently, methodologically important is not only the degree of descriptive generality attained but also a kind of "potential" degree of its generality.

Einstein believed that physical reality has such properties as harmony and perfection that are esthetic rather than physical. In his opinion, an adequate physical theory must therefore satisfy not only the criterion of "external confirmation" but also that of "inner perfection", which is sometimes even more important. The former criterion is identical with the generally accepted proposition that a theory must not contradict experimental data, whereas the second criterion has to do with "naturalness" and "logical simplicity" of the premises of the theory rather than the relation of theory to experience [28, p. 23]. Both in his treatment of physical theory and in his attitude to experimental verification of physical geometry, Einstein gradually departed from the empiricism which was characteristic of the first period of his creativity [29, p. 176]. According to Einstein, confirmation of a theory by experiment is by no means sufficient for accepting a theory. He stressed that "it is often, perhaps even always, possible to adhere to a general theoretical foundation by securing the adaptation of the theory to the facts by means of artificial additional assumptions" [28, p. 21]. That is exactly the case in the attempts to extrapolate the traditional geometrical models to areas where they are no longer valid. Here theory ceases to satisfy the criterion of inner perfection referred to by Einstein.

Where the chronogeometrical model is inadequate, a whole series of anomalies arise in theoretical description, violating its consistency. We have already mentioned causal anomalies in spatio-temporal models with an inadequate topology. To this should be added that where an inadequate physical geometry is employed, "object anomalies" can also appear, that is, anomalies in the conceptions of physical objects and their basic properties. Physical objects are usually thought of against an appropriate spatio-temporal background, and their properties are formulated in explicit or implicit geometrical terms. It is therefore clear that inadequacy of geometry may entail paradoxes in the notions of physical objects themselves. Objects that cannot in principle be observed and other types of pseudo-objects may appear in descriptions, such as infinities, imaginary masses, negative probabilities, etc. We have already touched on this in considering the problem of spatio-temporal description in microphysics. Finally, in a theory using an inadequate geometrical model there may appear a kind of "descriptive anomalies" involving an artificial non-geometrical part of the description, a great number of *ad hoc* concepts and notions, or incomplete and inconsistent description [17, pp. 86-94]. The presence of such anomalies indicates a violation of harmonious correspondence between the geometrical and the non-geometrical components of physical theory, without which there can be no perfect theory.

Correspondence between physics and geometry cannot be established in a purely empirical way, without resorting to methodological criteria. The reason is that geometry in a description of the $(G) + (P)$ type is not separately falsifiable in a purely empirical fashion. As a way out of this difficulty, Grünbaum indicates [30, pp. 131-138] that absence of an unambiguous falsification of geometry (G) does not at all mean that it can be adapted to any kind of possible experiment by correcting (P). Inasmuch as (P) is empirically verifiable, this solves in the final analysis the problem of falsification of (G). Grünbaum's first argument is indisputable, whereas his second proposition is in our view unfounded. The truth of (P) "by itself" is not always directly verifiable. The physical (dynamic) part of a description is often just as closely linked with the creative constructive elements of cognition (the formation of a system of abstract objects, etc.) as is the geometrical part, and it is only obliquely and in a mediated manner confirmed by experiment. Correct interpretation of such "non-geometrical" concepts of physics as mass, force, causality and others gives rise to just as serious debate as the problem of physical geometry. The way out of this difficulty lies in applying a system of methodological criteria to descriptions of the $(G) + (P)$ type.

Rejecting empiricist solutions of the above problems, we can formulate two aspects of correspondence between geometry and physics. The first (empirical) one is connected with the existence of a natural empirical interpretation of chronogeometrical concepts in terms of a corresponding class of empirical objects and processes (rigid bodies, light rays, etc.). The second (semantic) aspect assumes a semantic interpretation of the chronogeometrical model within a physical picture of the universe. This interpretation requires the establishment of a natural connection between the chronogeometrical model and the principal abstract objects of the theory expressing physical reality. Both of these aspects of correspondence between geometry and physics are present in the theory of relativity. On the one hand, it proved to be necessary in the construction of the relativity theory to emphasise the connection between the concept of simultaneity and the empirical process of propagation of light in empty space, the role of the rigid body in the empirical interpretation of geometry, etc. On the other hand, close links between the space-time concept and the concepts of physical field, gravitation, mass, inertia, etc., became apparent. One important circumstance was discovered connected with the role of geometrisation of physics in the establishment of a semantic correspondence between (G) and (P). As the relativity theory showed, the interconnection between space-time and other abstract objects of the theory expressing physical reality becomes particularly obvious in geometrisation of some important concepts, as for example the concept of gravitation, in the general theory of relativity.

It would appear that geometrisation of physics ensures an explicit and harmonious correspondence between physics and geometry, the most natural path towards creating a single theory. In a fully geometrised theory, physical reality is expressed exclusively in geometrical characteristics. Not only is physics geometrised, but geometry is filled with real physical content. Any motion is explained in a purely geometrical manner as occurring along certain limiting curves of an adopted physical geometry; particles are regarded as aspects of a field "merging" with space-time. Space-time itself has the property of universality, and if a single physical field were to be constructed which would "merge", just as the gravitational field, with the spatio-temporal continuum, one would have the impression that the task of constructing a unified universal theory can be solved. In this theory, there would be no phenomenological elements that have no geometrical substantiation in it (as, e.g., massive objects in the general theory of relativity) and thus hint at possible extension of the theory in the future. Such a theory would be absolutely closed and accomplished. Hence Einstein's hopes that his unified field theory, wholly based on the continuum concept, will ultimately yield the laws of elementary particles. However, a fully geometrised theory is usually very far from experiment and escapes experimental verification. The unity of its geometrical and non-geometrical components is ensured in its semantic rather than empirical aspect, for absence of phenomenological elements in its structure impedes the solution of the problem of empirical interpretation of the chronogeometrical model. To some extent this is true not only of Einstein's unified field theory but also of Wheeler's geometrodynamics, in which the interconnection between theory and experience is substantially hampered.

The above must not be understood as underestimation of the method of geometrisation of physics. Without this method it is obviously impossible to attain a harmonious correspondence between physics and geometry. One must remember, however, that geometrisation of theory can never be complete and is only justified if appropriate methodological criteria are observed. The principal of these is the universal nature of the geometrised reality, which thus uniformly affects all the physical objects localised in the given type of space. For example, according to the equivalence principle, all bodies move in a gravitational field strictly conforming to an identical law. Their trajectories in space-time are universal curves that can be compared to the geodesic lines of Riemannian geometry. It is therefore possible to introduce space-time, the same for all bodies, in which these bodies move. As has been pointed above, elimination of universal forces from physical theory is the typical mode of geometrisation of physics. It is this approach to geometrisation of physics that enabled Einstein to attain such splendid results in constructing the general relativity theory.

Conclusion

The above has shown that Einstein's approach to the interconnection of physics and geometry has proved more fruitful for the development of physics than Poincaré's. The choice of an adequate spatio-temporal description is not a matter of convention but of experience and of philosophico-methodological criteria explicitly or implicitly used by the theoretician. Neither was Poincaré's opinion confirmed that a physical theory should always be based on the simplest geometrical model. Nevertheless the problems raised by Poincaré have not ceased to be vital and topical. The Einstein vs. Poincaré controversy on the correlation between physics and geometry will apparently be of interest to specialists in methodology of science for a long time to come. Poincaré was right in asserting a kind of complementarity between the geometrical and the non-geometrical components of physical theory, which must be taken into account in constructing and developing the theory. The task consists in choosing, out of a number of descriptions of the $(G) + (P)$ type, the most adequate one, ensuring a harmonious correspondence between geometry and physics in physical theory.

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V. A. FOK

THE PHYSICAL PRINCIPLES OF EINSTEIN'S GRAVITATIONAL THEORY

The subject of this paper is critical analysis of the physical principles of Einstein's theory of gravitation. Our critique is not levelled at the theory of gravitation itself, which is indubitably correct, but against its interpretation, stemming from Einstein, which has become traditional and is characterised by the words "the general theory of relativity".

Einstein's theory is an integral fusion of a theory of gravitation and a theory of space and time, and this unity is its most characteristic feature. It would therefore be more correct to call it a chronogeometric theory of gravitation.

The term "chronogeometry" was suggested by the Dutch physicist Fokker for Einstein's theory of 1905, the so-called special theory of relativity. It characterises the essence of this theory much more precisely than the traditional designation, "the theory of relativity". True, Galileo's principle of relativity in its Einsteinian formulation which takes into account the existence of a limit to velocity, plays a sufficiently great role in the relativity theory to justify this name (but without the addition of the word "special", for a more general relativity in space and time does not exist). But the essence of the theory of relativity, whatever its name, is contained in the postulates concerning the properties of space and time that are absolute in their nature. These chronogeometric postulates are: the existence of a limit to the velocity of propagation of any kind of action and uniformity of space and time.

However, we are not speaking here of Einstein's theory of 1905 but of his theory of gravitation created in 1915. The name "the general theory of relativity" suits the latter even less than the name "the theory of relativity" suits the 1905 theory. Indeed, it is not the relativity concept that is generalised in the theory of gravitation (on the contrary, it is narrowed) but other concepts, and in the first place the character of geometry.

I must explain why I dwell in such detail on the name of Einstein's theory. The objection may be raised here that it is all the same what name to give to a theory. The name does not change anything in it. But we cannot concede this point. The name of a theory and in general of some discovery often contains in itself an interpretation of this theory or discovery, and an inappropriate name reflects an erroneous interpretation. Consider for example the name "West Indies" given by Columbus to a chain of islands adjoining America. No one will doubt the greatness of Columbus's discovery. Columbus discovered something even greater than he assumed—a whole new continent rather than a way to a well-known country. Yet it is not to be gainsaid that the name "West Indies" was extremely inappropriate. True, hardly anyone will now say that the West Indies are part of India. This misnomer is simply a reminder of a mistake once made by Columbus.

The name "the general theory of relativity" is similar to the name "the West Indies" in the sense that both of them are due to a mistake made by the discoverer. But the term "the general theory of relativity" is more dangerous than the term "the West Indies": no one is likely to think now that the West Indies are situated in India, but many still believe that the essence of the general theory of relativity lies in the generalisation of the concept of relativity. To avoid this kind of misunderstanding, it is better to use a term that does not give rise to arbitrary (and erroneous) interpretations.

We shall therefore call Einstein's theory of 1915 "the chronogeometric theory of gravitation", or simply "the theory of gravitation".

In may seem risky to use the words "the discoverer's error" with respect to Einstein: they mean actually that Einstein's great discovery, his theory of gravitation, was erroneously interpreted by him. One may well ask: can we mere mortals criticise Einstein? I cannot subscribe to this kind of deification of Einstein; we must not build up an aura of infallibility around his name. Einstein's scientific attainments are indeed great, but I am sure that a business-like criticism of his errors, free from any prejudice, is not only permissible but is the highest tribute we can pay to the freedom-loving spirit of Einstein who often expressed his intolerance to any prejudice, however deeply rooted it might be.

Free criticism and consistent logical analysis are necessary for the correct understanding of any physical theory. They are particularly needed for understanding a theory of such fundamental significance as Einstein's theory. A fundamental physical theory often contains more than its originator assumed; the theory may thus prove to be wiser than the author, so to speak.

History of science knows many cases where the author of a physical theory of great fundamental significance himself erroneously understood its foundations. Recall Maxwell, who thought in terms of mechanical concepts and viewed his famous equations as expressions of the laws of mechanical vibrations of an elastic medium, the ether. Recall de Broglie and Schrödinger, who thought in terms of the classical field theory. These misunderstandings are not so surprising, after all. The author of a fully justified physical theory sees it not only as the culmination of a definite chain of reasoning but also as substantiation of the whole of that chain—a substantiation for both the basic premises and all the links in the chain of reasoning. However, the creative chain of thought is something quite different from the strictly logical process. It is best of all expressed in the words of Einstein himself: "*Das Erfinden ist kein Werk des logischen Denkens*", "Invention is not the work of logical thinking". It is therefore quite probable that there are logical gaps in the chain of thought culminating in a certain theory, gaps that obscure its genuine content.

When Einstein formulated the theory of gravitation, his guiding idea was the idea of "general relativity". It is difficult to say what exactly Einstein meant by this, but he spoke of "the general principle of relativity" as a kind of generalisation of Galileo's "special" principle of relativity applicable to uniform rectilinear motion. Einstein apparently connected other physical possibilities as well with the idea of "general relativity", not just the solution of the problem of relative motion. Indeed, in his autobiography he wrote of the disappointment he felt when he saw that the idea of "general relativity" led him "merely" (Einstein's word) to a theory of gravitation. This shows just how precious the idea of "general relativity" was to him.

Apart from the "general principle of relativity", a great heuristic role was played in Einstein's creativity by his "equivalence principle" (in the sense of indistinguishability of gravitation and acceleration).

We shall analyse both of these principles here and see whether they are indeed the basis of Einstein's theory of gravitation. Let us first of all specify the principle of relativity.

The physical principle of relativity asserts the existence of corresponding processes in two laboratories (reference frames) in motion relative to each other. Under the principle of relativity, any possible physical process in one laboratory is associated with an identical process in another laboratory. In other words, the physical principle of relativity asserts identity of physical conditions for two laboratories in motion relative to each other (for two reference frames). This definition precisely corresponds to Galileo's principle of relativity valid for uniform and rectilinear motion of two inertial frames. (This is very visually explained by Galileo himself in his discussion of phenomena occurring in the cabins of two ships.) The principle of relativity underlying Einstein's theory of 1905 also accords with this definition. Einstein's principle of relativity, just as the principle of Galileo, pertains to rectilinear uniform motion of two inertial frames, but it takes into account the existence of a limit to velocity (equalling the velocity of light). It is expressed by the Lorentz transformation generalising Galileo's.

The Galileo-Lorentz principle of relativity is thus applicable only to inertial frames. The physical principle of relativity does not hold at all for reference frames in accelerated motion: the physical conditions there are different. Consider an example of two reference frames in accelerated motion relative to each other: the Earth and a satellite. A wall clock with weights and a pendulum goes fine on the Earth and not at all on a satellite. Indeed, there is no physical process on the satellite that would correspond to the motion of a wall clock on the Earth. This example should suffice as illustration of the impossibility of a "general principle of relativity" interpreted as a physical principle.

The concept of a physical reference frame or laboratory does not coincide with the concept of a coordinate system (even where the structure of the laboratory is not considered and only its motion as a whole is taken into account). Correspondence between a reference frame and a coordinate system is not, generally speaking, unambiguous, even if the term "frame of reference" is to be understood in a mathematical sense. Different coordinate systems may correspond to one and the same frame of reference.

Let us now consider the concept of covarience. Covariance of differential equations under transformations of coordinates is used in the formulation of the physical principle of relativity, but it is not identical with this principle. It is not any group of transformations that is connected with the physical concept of relativity but only transformations admitting of "physical adaptation". This is interpreted as such a change of the initial conditions or, in general, the conditions of an experiment, as a result of which all the altered fields will be expressed in the transformed variables in the same way as the original fields were expressed in the original variables. Thus physical relativity requires *invariance* (under transformation of coordinates coupled with physical adaptation) and not only covariance (under a simple transformation of coordinates). Covariance is a necessary but not a sufficient condition for physical relativity. For example, in considering an electromagnetic wave passing along the X axis and polarised along the axes Y and Z, invariance is attained if the transformation of the coordinates $(x, y, z) \to (x', y', z')$ expressing a turning of the axes is accompanied by the replacement of this wave by the same kind of wave but passing along a new axis X' and polarised along the new axes Y' and Z'.

In the case of the Lorentz transformations, in the "special" theory of relativity the possibility of adaptation for all explicitly introduced fields is assumed, and adaptation is not needed for the field of the metric tensor, since components of this tensor are invariant (there is a group of motions). In the Lorentz transformations for the harmonic coordinates of the theory of gravitation, the adaptation of the metric tensor is attained through changes in the distribution and motion of masses. Under arbitrary transformations of coordinates physical adaptation is impossible, and that makes these transformations completely unconnected with the concept of physical relativity. Thereby formal and not a physical character of "the general relativity principle", interpreted as the requirement of general covariance, is established, contrary to what Einstein believed.

Passing on to the equivalence principle, let us stress first of all that the concept of "force" is unambiguous only in an inertial reference frame; it can there be defined according to Newton. If we write the equations of motion in some non-inertial frame, the concept of force cannot be applied to separate terms of these equations, for it loses definite meaning if we do so. Thus the term "centrifugal force" is purely conventional: centrifugal force is no force at all. Einstein uses this kind of ambiguity of the force concept (in considering uniformly accelerated reference frames) for substantiating the "equivalence principle" which he formulated and which is reducible to a kinematic interpretation of gravity force.

The principle of equivalence of acceleration and gravitation is purely local and merely approximate. It may prove useful only for certain kinematic analogues and some heuristic arguments, but it can in no way form the logical basis of the theory of gravitation. Besides, Einstein's gravitational theory is neither local nor kinematic.

Thus the "general principle of relativity", interpreted as a physical principle, does not exist; and if it is to be understood as a formal mathematical requirement of general covariance, it is devoid of any physical content. It follows from this, in particular, that the "equivalence principle" is local and kinematic. How did it come about then that Einstein regarded both of these principles as the basis of the theory of gravitation which he created?

A general answer to this question may be found in the words of Einstein quoted above: "Invention is not the work of logical thinking." The creativity of a genius may span logical gaps. But when a theory has been created, it is necessary to analyse these gaps and eliminate them, if it is to be correctly understood.

In his desire to extend the concept of relativity to non-uniform motions, Einstein silently introduced two very essential changes into the meaning of the words "reference frame" and "relativity principle" (see table).

First of all, Einstein came to understand a reference frame as something different from what was meant by it earlier (both in the pre-relativistic physics and in Einstein's theory of 1905): a mathematical concept, a spatio-temporal system of coordinates rather than a material physical system, a laboratory. If one adheres to this standpoint consistently, any connection with the physical principle of relativity will be severed. If one tries to retain this connection, considering arbitrarily moving laboratories (which is, however, hardly possible as the general case), one will have to admit that physical conditions will be different in different laboratories: for instance, objects become weightless, as it were, inside a satellite. But that means that the physical principle of relativity does not hold.

Table

Various Interpretations of the Relativity Concept

Physical relativity—existence of corresponding processes—identity of physical conditions	in two laboratories
Identical form of the laws of nature	in two reference frames
Identical form of differential equations (field equations and motion equations)	in two coordinate systems
Covariance of differential equations (irrespective of the possibility of physical adaptation)	

In order to save, despite all this, the concept of the relativity principle, Einstein switched from the physical to the mathematical interpretation of this term. At first he ascribed to it a somewhat vague interpretation: identical form of the laws of nature in different reference frames. Later he substituted differential equations (equations of motion and equations of field, although the latter do not determine the course of physical processes without initial [boundary] conditions) for the laws of nature, and coordinate systems, for reference frames. The idea of "general relativity" was thus formally retained by means of this double substitution. But the term "general relativity" came to signify nothing more than covariance of differential equations under any transformations of coordinates (regardless of the possibility of adaptation, which Einstein did not consider at all). The requirement of covariance is almost trivial, expressing merely the fact that equations written in different coordinate systems must not contradict each other but must be mathematically equivalent. This requirement is of a purely logical order, and it cannot contain any physical law (this was first pointed out by Kretschmann as early as 1917).

The Galileo-Lorentz principle with its wealth of physical content, constituting one of the foundations of Einstein's theory of 1905, is transformed by this "generalisation" into a formal logical requirement devoid of direct physical content.

If the terms "physical relativity" and "general relativity" are to be understood in the sense explained above, it may be said that physical relativity cannot be general and general relativity cannot be physical. Einstein's theory is not founded on the idea of general relativity but on other ideas.

Einstein failed to realise this. This circumstance has undoubtedly some bearing on the fact that all his attempts to formulate a unified theory of electromagnetic and gravitational field through extending the group of transformations ended in decided failure. The same circumstance interfered even with correct evaluation of his own remarkable equations of gravitation: that the right-hand side of these equations contained mass tensor including other magnitudes apart from the metrical tensor, was regarded by Einstein himself as their defect. In his autobiography he emphasised that he regarded the equations of gravitation containing mass tensor as only a makeshift solution.[1] In his works on deduction of motion equations from gravitational equations Einstein tried to do without mass tensor. This actually compelled Einstein and his colleagues to give up the consideration of the motion of extended bodies having inner structure and capable of rotating, and to restrict themselves to consideration of the motion of point masses (material points).

This attitude of Einstein also probably determined his desire to consider particles as special points of a certain classical field rather than to follow the path of quantum mechanics. It is really amazing that Einstein, who was the first to introduce the photon concept, did not accept quantum mechanics. Niels Bohr quotes the remark of Ehrenfest at the 1927 Solvay Meeting. Ehrenfest there pointed to an obvious analogy between Einstein's attitude to quantum mechanics and the positions of the opponents of the relativity theory. This fact appears even more paradoxical when one attempts to grasp the reasons for Einstein's rejection of quantum mechanics. I believe that the conclusion may be drawn from the publication of the discussion between Bohr and Einstein that the primary cause of Einstein's negative position was his rejection of the idea of "relativity with respect to the means of observation". And yet this idea, constituting the epistemological essence of quantum mechanics, may be regarded as a direct development of the concept of relativity underlying Einstein's theory of 1905. A great deal more can be said about the contradictions of Einstein's scientific position. In evaluating it as a whole, one cannot get rid of the impression that during the last two or even three decades of his life Einstein followed a false trail.

Let us now go back to those ideas which Einstein regarded as the foundation of his theory of gravitation. How-

[1] Einstein wrote: "Not for a moment, of course, did I doubt that this formulation was merely a makeshift in order to give the general principle of relativity a preliminary closed expression ["Autobiographical Notes". In: P. A. Schilpp (ed.) *Albert Einstein: Philosopher-Scientist*, Evanston, Illinois, 1949, p. 75].

ever we might evaluate them, the idea of general covariance and the idea of kinematic interpretation of the force of gravity ("the general principle of relativity" and "the equivalence principle") undoubtedly played a great heuristic role in the formulation of the theory by Einstein.

The requirement of general covariance of equations must probably be regarded (psychologically rather than formally) as a hint or indication of the fact that it is not always possible to single out a definite coordinate system and view it as a favoured one (we have in mind here the cosmological problem). As for the "equivalence principle", it may be regarded as an indication that the solution for the problem of gravitation should be sought for in chronogeometry. Of enormous significance for Einstein was his conviction that a correct (that is, corresponding to nature) theory must at the same time be consistent and elegant from the esthetic point of view, so to speak. Einstein lent great convincingness to this requirement by creating his theory of gravitation which fully satisfies it.

We now come to the discussion of the actual ideas and principles underlying Einstein's theory of gravitation.

The first basic idea is that of chronogeometry, that is, unification of space and time in an integral four-dimensional manifold with an indefinite metric (this idea was implemented already in the 1905 theory). The second basic idea is that of unity of the metric and gravitation. This idea is formally expressed in both the metric and gravitation being described by identical quantities—a metrical tensor whose components are at the same time gravitational potentials. The unity of the metric and gravitation compels one to take into account the dependence of the metric on the processes of nature. The first indication of the possibility of variable metrics is found in Riemann, but it was Einstein who established on this basis the unity of the metric and gravitation and connected both with the distribution and motion of matter in the universe. This connection is expressed in Einstein's gravitation equations that should be recognised as one of the greatest achievements of human genius.

There are the two ideas forming the actual basis of Einstein's theory of gravitation. As for the "equivalence principle", historically it may be regarded as an indication of a possible (namely, chronogeometric) mode of constructing the theory, and physically, as its approximate consequence assuming practical significance in the study of the local properties of the gravitational field. Finally, the "general principle of relativity" interpreted as the requirement of general covariance of equations has, as we have seen, a purely formal character, and no physical consequences can be obtained from it.

Let us go back to the question of physical relativity. We have already stressed that physical relativity cannot be general. In the normal (the so-called special) theory of relativity, physical relativity is made possible by uniformity of space. It is expressed there by means of the Lorentz transformations. But in the framework of Einstein's theory of gravitation, too, if space is regarded as non-uniform, physical relativity connected with the Lorentz group can sometimes be realised. The essential point here is rejection of a rigid metric. If the metric is rigid, physical relativity is only possible in flat space (as in the normal theory of relativity) or in constant curvature space. Where metric depends on the distribution and motion of masses, the situation will be different. Transformations of coordinates which permit physical adaptation and thereby correspond to the concept of physical relativity, become then possible in anisotropic space, too. Adaptation is attained through changes in the distribution and motion of masses. The changes of the mathematical form of the metric tensor are compensated for as a result of such adaptation, and the tensor remains invariant. If there are other fields apart from the gravitational field, they too can be adapted in such a way that the physical conditions in the new reference frame will be the same as they were in the old one, and that means that the physical principle of relativity holds.

Let us consider a simple example of adaptation of the gravitational field. Space over the Earth's surface is anisotropic; we have to distinguish between the directions "up" and "down". If we take two identical laboratories and turn one of them upside down, the physical conditions in it will be quite different from those in the other laboratory which retains its initial position. But, instead of this turning the laboratory upside down, we can carefully take it down to the antipodes; then the physical conditions in it will remain the same (just as in the other which has retained its initial position), although the second laboratory will be antiparallel relative to the first.

Physical relativity will always obtain where masses are distributed in an insular mode. In this case harmonic coordinates exist which satisfy the wave equation and definite boundary conditions expressing Euclidean quality at spatial infinity and absence of waves coming from the outside. In these coordinates, the connection between two equal reference frames (for which physical adaptation is possible and the physical principle of relativity obtains) is expressed by linear transformations, namely by the Lorentz transformations. The fundamental significance of harmonic coordinates consists precisely in the fact that transformations expressing physical relativity are linear in these coordinates and only in them. The practical significance of harmonic coordinates, which greatly simplify computations, is also connected with this fact. These coordinates are the nearest analogue of the Galileo coordinates of the so-called special theory of relativity.

Harmonic coordinates do not exist for any distributions of masses. Thus the tasks of cosmological type do not permit their introduction, although coordinate systems that are marked (or favoured) in one way or another may exist in these tasks, too, in idealised cases (e.g., in the Friedmann space). The existence of harmonic coordinates is an integral (rather than local) property of space-time. To obtain them, it is necessary to integrate differential equations under definite boundary conditions. These integral properties are not less important than the local properties true in the infinitesimal or having the form of differential equations. It cannot in general be asserted that the laws of nature are exhausted by tensor correlations.

We have said that physical relativity is sometimes possible in heterogeneous space, too. It should be remembered, however, that this case is an exception rather than the general rule. The exception is made possible by the assumption that space at infinity is uniform. As a general case in Einsteinian space, physical relativity (interpreted non-locally) is apparently impossible.

In conclusion I would like to emphasise that Einstein's brilliant chronogeometric theory of gravitation gains in added clarity as a result of criticism free from prejudice, and comes to no harm at all. In my view, scientific critique of Einstein is unquestionably compatible with the greatest respect for his genius.

M. A. MARKOV

MODERN PROBLEMS OF THE GENERAL THEORY OF RELATIVITY

The gravitational field, as compared to other physical fields, has the greatest or, to be more precise, absolute universality: it is generated by all forms of matter. This universality of gravitational field is a fundamental factor responsible for the richness of the content of the general relativity theory, the diversity and significance of which has been so rapidly and generously revealed in the last decade both in macrophenomena and in the microworld. The appearance in the general relativity theory of new conceivable, and probably real, objects, new concepts, images, and earlier unsuspected situations compels one to think that a great many facts that are so far unknown may be discovered in later studies of the consequences of absolute universality of gravitational interactions.[1]

In recent years the essential role of gravitation was realised in the formation of such celestial bodies whose very possibility of existence was not earlier discussed (black holes, neutron stars, etc.). It has become clear that other fields and their quantum effects in strong gravitational fields play a fundamental role both in the formation and characteristics of new ultramacroscopic objects.

On the other hand, even the empty space of non-static universes, where invariance of theory under transformations of times is violated, must be the birth-place of pairs

[1] Not only of the universality but also of the specificity of gravitational field as a field of the non-Abelian type.

of various elementary particles. The concept of vacuum in the general relativity theory therefore ceased to be as definite and clear as it has earlier appeared. The birth of particles in a non-stationary universe, as evaluations show, cannot explain the emergence of all matter observed in the universe: the Big Bang epoch has so far found no physical interpretation. It is not excluded, however, that matter in the universe was accumulated as a result of its birth in multiple oscillations (successive expansions and compressions), and the original explosion did not at all require an enormous amount of matter localised in an infinitesimal volume. It may be linked to fluctuational emergence of an initial microuniverse with negligible amount of matter, which grew with these oscillations. Let us note that we are not suggesting here a concrete scenario of the origin of the universe: that would require special investigation, in particular the elaboration of the thermodynamics of an oscillating universe; we do not as yet know a way to describe the state of matter at a time of maximal compression. Here we merely give an example to illustrate the new situation in the general relativity theory arising from consideration of the quantum properties of matter.

In the modern context of studies in the interaction between the gravitational and other physical fields, there is a long list of problems of conceptual nature. Thus, the destiny of the final state of the black holes raises the question of conservation of the baryon and weak charges. The problem also arises of the stability or non-stability of elementary black holes, that is, objects which are a natural (stable or unstable) limit of a disintegrating black hole, provided, of course, that we have doubts, arising out of quantum considerations, about the existence of black holes with a mass less than $m^0 \sim \sqrt{\hbar c/\kappa}$. This problem is also important because the existence of stable or unstable elementary black holes may have a bearing on the upper limit of the spectrum of the mass of elementary particles and on a number of cosmological problems.

Solutions of the equations of the general theory of relativity recently found by O. Klein permit the possibility of the emergence of elementary black holes as worlds with an almost closed metric (friedmons) (that is, cases where the Friedmann variable χ_{max} is inclosed between the limits $0 < \chi_{max} < \pi - \delta$, where δ is small). The disappearance of such objects would signify the closing of a Friedmann world, and their quantum stability, the impossibility of the emergence of a closed metric.

Disappearance of many external fields in the formation of black holes and thermodynamisation of the characteristics of the latter pose fundamental problems of the role of the observer in the description of the physical world of phenomena, compelling a further discussion of the Copenhagen interpretation of quantum mechanics. Thus the familiar problems of description by the ψ-function of wave mechanics also arise in the cosmology of closed universes and in the formulation of the *S*-matrix method.

The ideas of asymptotic freedom of interactions, including the gravitational one, will apparently affect in an unusual manner the concepts of the states of matter at times adjoining the Big Bang, as well as those of the final state of collapsing celestial bodies. It is not ruled out that the emergence of singularities in the latter process may be impeded by intense radiation (in particular, the birth of pairs) from the surface of the collapsing volume of matter lying deep under the Schwarzschild sphere. It is also true, however, that the character and role of processes under the Schwarzschild sphere are not as yet clear.

The emergence of conceptions of supersymmetry, a promising direction in formulating a general theory of matter, has given rise to certain ideas and later to concrete variants of the theory of supergravitation. But the study of the physical content of the latter and of their relation to the traditional theory of gravitation is as yet in the initial stage. We cannot say yet if the supersymmetric field theory is the final form of the unified field theory of which we dream or if it is only a stage to an even more general spinor theory of matter.[2] The situation will be essentially more acute, or it may be clarified, if there is no intermediate meson beyond the unitary limit of weak interactions.

On the other hand, it is becoming more and more

[2] Since spinors appeared, the realisation has grown in the theory of matter that magnitudes with any transformation properties (scalars, vectors, tensors) can be built out of spinors.

probable that gravitation will play a fundamental role in elementary particle theory where remaining divergences are logarithmic in nature. That is essential, for the practice of computing self-energies in elementary particle theory so that the enormous (infinitely great) values of energy in intermediate states, localised in small areas, are taken into account, and at the same time gravitational self-action is completely ignored, has so far remained an accepted absurdity. If in a unified theory of all fields unremovable divergences of an order higher than the logarithmic are discovered, the significance will grow of the idea of "heavy" gravitation of a tensor and probably scalar type with a great gravitational constant, that is, of the case (possible in principle) where the quantum of the field is a "heavy" graviton.

Thus problems of re-valuation acquire a specific meaning in models of unified field theories. Theories are possible that cannot be re-valued but are finite and devoid of the customary divergences.

Of some interest are also various directions in unconventional gravitation theories. The point is that experimental verification of the general relativity theory involved, as we know, the weak gravitational field. Different unconventional variants of this theory may apparently satisfy experiment in this field. The theory of gravitation for strong non-linearity still awaits its experimental data. In the traditional theory of gravitation, too, many problems still cause divergence of opinion amongst physicists. In particular, that concerns Mach's principle in its various formulations.

Conceptual problems arise already in the classical theory of elementary particles. If we believe (on good grounds) that a particle with a non-zero mass cannot be a point particle, i.e., that there are no ultraviolet divergences in the classical theory, the problem arises of the non-local character of the theory. This problem becomes real already in the classical dynamics of black holes. It does not seem to be a simple matter to describe the interaction of a black hole as an object as a whole and its motion under the impact of external fields. Special difficulties emerge when we are compelled to use in the description of the interaction the Schwarzschild coordinates, in which interaction reaches the Schwarzschild sphere only in what appears as an infinitely long period of time to the external observer.

In the classical (non-quantum) theories of gravitation no divergences are conserved in quantisation, as distinct from the familiar classical field theories. This question alone is therefore relevant to the quantum theory of gravitation: do divergences that are absent from the classical, non-quantised variant of the gravitational field, emerge in quantisation?

It follows from the above that problems of the ultramacroscopic world now become more and more closely linked with problems of the microworld.[3] It is difficult to say whether the state of matter in the Big Bang epoch is the subject matter of the physics of the microworld, or whether this field belongs to the ultramacroworld, where the specific physics of matter at ultramacrodistances is manifested. The general theory of relativity, which has always been regarded as an example of purely abstract speculative constructions based on very remote extrapolations and rich in ambiguous variants, is gradually turning into a science where experiment begins to play an essential role in limiting the variants. Thus, experimental discovery of the red shift effect and of the relict photon radiation greatly restrict the number of possible scenarios of the origin and evolution of the universe.

The discovery of relict photon radiation and the study of the limits of its isotropy can yield important data on a certain stage in the development of the universe. The very fact of the discovery of relict photon radiation suggests the idea of the possibility of a relict neutron or even gravitational radiation. Experimental possibilities here so far appear fantastically unreal, but reality is more fantastic than any human fantasy.

The general theory of relativity more and more becomes an experimental branch of science. Neutrino astronomy will apparently make a great experimental contribution to it. Owing to its high penetration capacity and low absorptivity in matter, neutrino may in principle bring us informa-

[3] Another elementary example: a neutron star is a macroscopic nuclear-matter medium with many specific properties which had earlier been encountered in the study of atomic nuclei.

tion about the most remote objects of our universe—information about objects belonging to its states remote in time.

Experiment is now coming very close to detecting gravitation waves. There is of course no question of detecting a relict gravitational radiation, which is in principle identical to detecting short sound waves or rather single phonons in matter. But, to be on the safe side, we shall not assert that this will never be possible, for we cannot now foresee the new elements which the emergence of the gravitational astronomy of the future promises for science.

It should be noted that in a certain sense we have not gone far beyond the understanding of the basis of the universe that the ancient Greeks had. Just as ancient Greeks, who regarded nature as a combination of four elements (earth, water, air, fire), we view the universe in terms of four fields—strong, electromagnetic, weak, and gravitational. Just as the ancients, we have not as yet penetrated into the essence of things, which is only attainable through an understanding of the inner unity of these elements. True, the ideas of Weinberg and Salam have recently stimulated real hopes of understanding the unity of weak, electromagnetic, and possibly strong interactions. The conviction is gradually taking shape that it is impossible to describe exhaustively one of these four fields without taking into account the existence of the others, that nature is built without excessive luxury, so to say. An understanding of organic unity of all the fields, including gravitational, is exactly the task which physical science is and will be striving to solve.

E. M. CHUDINOV

EINSTEIN AND THE PROBLEM OF THE INFINITY OF THE UNIVERSE

The interest taken in the general relativity theory by the broad public is largely explained by its relevance for the fundamental philosophical problems that go far beyond the framework of physics. These include the problem of the infinity of the universe. Einstein showed that the traditional solution of this problem—representation of the universe as an infinite system of material objects filling Euclidean space—does not accord with reality. The structure of the universe is much more complicated, and the question of its infinity is not as simple as might appear to someone brought up in the spirit of classical physics and cosmology.

1. Paradoxes of Infinity

The idea that the universe is infinite in space seems to be intuitively clear and admitting of no rational alternative at the speculative level. However, serious difficulties arise in any attempt at its rigorous scientific substantiation. Scientists encountered these difficulties already in the framework of classical cosmology.

In classical cosmology (in the form in which it was formulated by Newton himself) the question of the infinity of the universe was solved in the following way. The universe was believed to be infinite, but the thesis of infinity contained two unequal parts. First, it included the supposition that the universe was spatially infinite. Substantiation of this assertion did not occasion any objections in prin ciple. The laws of Newton's physics, applied on a cosmc logical plane, assumed Euclidean space and, consequently its infinity. To put it pedantically, these laws are invarian under the Galileo transformations, which correspond tc the metric of infinite Euclidean space. Thus spatial infinity of the universe was determined in classical cosmology by the laws of Newton's physics employed for its description.

The structure of the universe in Newtonian cosmology looked as follows. Absolute space was assumed, independent of matter. It was believed that space could exist even in the absence of matter and, moreover, that matter did not condition its metric. Corresponding to absolute space was absolute time which flowed through the whole of the universe at the same rate.

Although it was always assumed in classical cosmology that an infinite quantity of matter in the form of planets, stars and other objects corresponded to infinite space, the assertions of infinity of space and of infinity of matter were different because space was not here regarded as a form of existence of matter. Moreover, whereas the laws of Newton's physics required infinity of space, through its Euclidean nature, it was not always possible to deduce from this the infinity of the quantity of matter. Attempts to solve this problem revealed the contradictions and limitedness of Newton's conception of the infinity of the universe.

Newton attempted to substantiate the idea of infinity of matter in infinite space by the law of gravitation. He assumed that if a finite quantity of cosmic matter collected in one place existed in an infinite universe, it would merge into one lump under the impact of gravitational forces, which contradicts the actual state of things. As an alternative, Newton suggested a picture of the universe in which there are infinite numbers of material objects uniformly distributed in infinite space. But the assumption of infinity of matter uniformly distributed in space led to contradictions—the photometric and gravitational paradoxes.

The photometric paradox discovered by the astronomer Olbers early in the 19th century was this: given an infinite number of radiating stars uniformly distributed in space, the luminous emittance of the sky must be substantially different from the one observed. Two formulations of the photometric paradox are possible. According to the one which does not take into account the finite extension of the sources of light, the observable surface brightness of the sky must be infinite. According to the other formulation, the one which takes into account the finite extension of the stars and their mutual screening effect, the observable surface brightness of the sky must equal a certain mean surface brightness of the stars [1, pp. 325-326]. However, neither of these effects is observed. The night sky is visible as a dark background with separate stars. A contradiction thus arises: the assumption of an infinite number of stars leads to conclusions that contradict observation.

The gravitational paradox caused even greater complications in the Newtonian picture of the universe. In its original formulation it appeared as follows. An infinite mass of matter in the universe would have to create a gravitational field possessing infinite potential and intensity. But these values are physically meaningless.

Some scientists believe this formulation of the gravitational paradox to be incorrect. They maintain that, since the potential and vector of the field are unobservable magnitudes, their tendency to infinity causes no difficulties. This circumstance cannot therefore be called a paradox. The gravitational paradox consists in the fact that Newton's gravitational law does not define completely the relative acceleration of neighbouring particles and is therefore insufficient for the solution of the cosmological problem [2, ch. 21, § 3]. But in any case the gravitational paradox signified a defect in the Newtonian picture of the world.

Cosmological paradoxes stemmed from two basic assumptions: the possibility of applying the laws of Newton's physics to the whole of the universe, and uniform distribution of matter in space, The two principal directions in the search for overcoming these paradoxes were linked with these two assumptions.

One of the ways out of the difficulties lay through rejection of the postulate of uniform distribution of matter. The hierarchical model of the universe was obtained on this path.

The hierarchical model of the universe was suggested already in the 18th century by the German scientist Lambert. He believed that the universe is an infinite hierarchically constructed system consisting of subsystems of increasing complexity. Systems of the first order are stars. Clusters of stars are second-order systems. Systems of the second order, in their turn, are elements of third-order systems, and so on.

The Lambert model was mathematically improved in the 20th century by Charlier, who believed that with the increase in the order of systems the squares of their radii (the systems were assumed to be spherical) grew faster than their mass. If this condition is satisfied, the density of matter decreases with the increase of system order and in the limit equals zero. Despite the infinity of masses, the strength of the gravitational field proves to be finite in any observable region of the universe. Mathematically this is expressed in the gravitational forces being represented by a convergent series consisting of M/R_i^2 $(i \to \infty)$. The photometric paradox was also eliminated in the Lambert-Charlier model.

Charlier overcame the cosmological paradoxes on the basis of classical physics by revising the postulate of uniform distribution of matter in the universe. But this solution has an essential defect pointed out by Einstein. He noticed that this theory "rather requires that the universe should have a kind of centre in which the density of the stars is a maximum, and that as we proceed outwards from this centre the group-density of the stars should diminish, until finally, at great distances, it is succeeded by an infinite region of emptiness" [3, pp. 105-106]. Einstein believed this conception of the structure of the world unjustified from the philosophical standpoint.

The way of overcoming cosmological paradoxes and formulating a consistent picture of the world suggested by Einstein was in a sense opposite to the one taken by Charlier. It did not involve a revision of the postulate of uniform distribution of matter in the universe but rather a revision of the laws of classical physics and of the Newtonian theory of gravitation, and a reconstruction of cosmology on the basis of the general theory of relativity.

It would be erroneous to assume that the discovery of cosmological paradoxes was the immediate cause of the emergence of the general theory of relativity. This theory was formulated by Einstein independently of any facts relating to astronomy. The only empirical fact that played a fundamental role in its construction was the equivalence of the inertial and gravitational masses. The general relativity theory was regarded by Einstein as a further development and generalisation of the principle of relativity for non-inertial frames. But, once it was created, the theory proved to be an important instrument of the description of the cosmological structure of the world. This theory marked the start of a new direction in cosmology—relativistic cosmology.

2. Einstein's "Finite World"

Relativistic cosmology opened a new way to the solution of the problem of infinity of the universe. Einstein obtained the first relativistic cosmological model in 1917 from the gravitational equations complemented by the Λ-term. In solving these equations he was guided by two considerations. First, a cosmological model must satisfy Mach's principle according to which inertia and, consequently, space curvature in the model are fully determined by the mass of matter and field. Second, a model must not contain the cosmological paradoxes, the photometric and the gravitational ones.

In Einstein's view, these requirements can be satisfied if we assume that the spatial extension and mass of material objects of the universe are finite. In a finite model of the universe Mach's principle is fulfilled, since the curvature radius is here expressed through the total amount of matter $r_i = M_K/4\pi^2$. Besides, paradoxes are also removed here, for they stemmed from the postulate of infinitude of the masses of material objects (stars, planets, etc.).

Generally speaking, a model of the spatially infinite universe is also logically admissible from the standpoint of the general theory of relativity. Its description then is as follows. The mass of matter is a kind of insular formation. The space occupied by matter has a non-Euclidean metric.

But in an infinite universe mean density equals zero, and space is Euclidean at infinity.

In this variant, cosmological paradoxes are eliminated by a method analogous to the one applied in the Lambert-Charlier model. But Mach's principle is not satisfied here, for space curvature is only partially determined by matter. It is for this reason that Einstein considered this variant of the infinite model to be unsatisfactory. He wrote the following in this connection: " this idea of Mach's [that inertia depends upon the mutual action of bodies—*Tr.*] corresponds only to a finite universe, bounded in space, and not to a quasi-Euclidean, infinite universe. From the standpoint of epistemology it is more satisfying to have the mechanical properties of space completely determined by matter, and this is the case only in a closed universe" [4, p. 108]. And further he wrote: "An infinite universe is possible only if the mean density of matter in the universe vanishes. Although such an assumption is logically possible, it is less probable than the assumption that there is a finite mean density of matter in the universe" [4, p. 108].

A characteristic feature of Einstein's model is its static character, which is taken to mean immutability of its geometrical structure—constancy of its curvature radius. To avoid compression of matter by the forces of attraction created by the model's matter, Einstein introduced in it hypothetical forces of repulsion counterbalancing the forces of attraction.

Einstein's model has often been criticised philosophically. The critics saw its drawback in its finiteness which allegedly contradicts materialism. These conclusions are based on the assumption that the model posits the existence of something different from matter beyond the limits of the universe. Actually, this criticism of Einstein's model of the universe, as well as of all the other finitary relativistic models, is rooted in a misunderstanding. These models are not finite in the same sense as the models of the universe in medieval theology. In relativistic models space is finite in size but has no limit. That is the specific feature of the Riemann space of constant positive curvature, which combines the properties of finiteness and unlimitedness. From any point in any direction the shortest lines ("straight lines") may be drawn without limit; in this case the lines will be the geodesics, which are all closed, and their lengths will have finite values.

Positive curvature space, despite its finiteness, may be regarded as all-embracing space. This conclusion is based on the following circumstances.

First, this space is an unbounded manifold. There is a direct connection between the categories of unboundedness and universality of space. Indeed, if the given space is bounded, it cannot be all-embracing, as it assumes the existence of a certain boundary which is the locus of points common to the bounded space and the limiting spatial background. Contrariwise, the all-embracing nature of the given space assumes its unboundedness as the necessary condition.

Second, the assertion that the Riemann space is an all-embracing space of positive curvature, is founded on certain traits of the Riemann curvature. The Riemann curvature at a given point and in the given direction coincides with the Gaußian curvature which is a measure of the non-Euclidean quality of space, that is, a property of its inner geometry. Positive curvature space does not therefore assume a "hyperspace" embracing it.

Inasmuch as the evidence of our senses is Euclidean in nature, it is, strictly speaking, impossible to visualise a positive curvature space. However, a certain degree of visual representation can be attained through the following reasoning. Consider a normal sphere. It can be regarded as two-dimensional space of constant positive curvature. A hypothetical two-dimensional being, moving along the sphere's surface, will find that its area is finite although unbounded.

Our space is three-dimensional, not two-dimensional. If it is positively curved, it could be represented, on the analogy of the previous example, as a three-dimensional hypersphere in a four-dimensional Euclidean space. A three-dimensional being on this hypersphere could perform the same experiments as the two-dimensional being on the sphere. It would also discover that the three-dimensional hypersphere was finite but unbounded.

A closed three-dimensional space can also be imagined without resorting to a fictitious four-dimensional Euclidean space. To do this, it is necessary to adopt another criterion of evidence, like the one suggested by Einstein. "To imagine a space [wrote Einstein] means nothing else than that we imagine an epitome of our 'space' experience, *i.e.* of experience that we can have in the movement of 'rigid' bodies" [3, p. 111].

In accordance with this criterion, we might carry out the following spatial experiments. Rigid rods or tense cords of the length r are stretched from a certain point in all directions. All the opposite ends of rods or cords are lying on the sphere. If we measure the surface of this sphere and discover that it equals $4\pi r^2$, our world is a Euclidean one. If it is less than this magnitude, our space has positive curvature. Continuing these experiments, we shall find that at first the surface of the sphere grows with the growth of r, attaining a certain maximum. As r grows further, it gradually vanishes.

But is "Einstein's universe" absolutely finite? Some scientists believed that that was exactly the case. The famous mathematician D. Hilbert even tried to use Einstein's model as a natural historical argument in favour of his finitist programme in mathematics. He wrote in this connection, among other things, the following: "The view that the world is endless dominated for a long time: before Kant and even later one did not doubt the endlessness of space at all. Here again it is modern science, in particular astronomy, that raises this question again, trying to solve it by arguments that are based on experience and on the application of natural laws rather than by the insufficient instruments of metaphysical speculation. In the process, weighty arguments against endlessness were posited. *Euclidean* geometry necessarily leads to the assumption that space is endless... And the rejection of Euclidean geometry is today not only a purely mathematical or philosophical speculation: we have also come to this from another side, which originally had nothing to do with the question of the endlessness of the world. Einstein showed the need for a departure from Euclidean geometry. On the basis of his theory of gravitation he also attacks cosmological questions, showing the possibility of a finite world, and all the results obtained by astronomers are also fully compatible with the assumption of an elliptical world". [5, S. 164-165]. And further Hilbert concludes: "The general conclusion is as follows: the infinite is nowhere realised; it is neither present in nature nor admissible as the basis of our rational thinking: a noteworthy harmony between being and thinking" [5, S. 190].

Although the appellation of "finite" has been traditionally applied to the Einstein model, it is only finite in a certain respect and under additional hypotheses. There are two essential points here. First, from the standpoint of the theory of relativity, three-dimensional space is a cross-section of the four-dimensional spatio-temporal manifold. The Einstein model is finite only with regard to its spatial cross-section, but its spatio-temporal world is infinite. Applying Euclidean analogies, it can be represented as a four-dimensional hypercylinder in a five-dimensional Euclidean space. The four-dimensional space of this hypercylinder is infinite. It consists of an infinite number of objects, or events.

Second, although the three-dimensional space of the Einstein model is believed to be finite, its finitude is not unconditional. The following statement of A. A. Friedmann on this question appears to be of interest for the discussion of this question: "It is insisted that, finding a constant positive curvature of the universe, one can draw the conclusion of its finitude and, first of all, of the fact that a straight line in the universe has 'finite length', that the volume of the universe is also finite, etc. This assertion can only be founded on a misunderstanding or on additional hypotheses. *It does not follow at all from the metric of the world* ... The question of the finitude of space depends not only on its metric but also on the condition under which two coordinate systems define one and the same point" [6, p. 102].

The crux of the matter is that Riemannian space of constant positive curvature may be regarded either as single-layered or as multilayered. In the latter case it must be specified as endless. To eliminate this supposition, additional agreements must be adopted—the view, for instance, that one and only one geodesic can pass through two points.

3. The Relativistic Theory of an Evolving Universe and the Problem of Infinity

The basic defect of Einstein's model was its static character, not its finiteness in some aspects. The British physicist A. Eddington in his studies in the Einstein model conducted in the late 1920s found that it was unstable. It was enough to disturb the equilibrium between gravitation and the Λ-field even slightly for the universe to collapse or to extend without limit. Even before Eddington, the Soviet mathematician A. A. Friedmann obtained in 1922 fundamental results pertaining not only to Einstein's model but also to the equations of the general relativity theory. In essence, they proved the compatibility of these equations with the idea of non-static character of space. A. A. Friedmann showed that the equations are satisfied by non-static spatial structures, and that in a more natural manner even, for no change was required in the equations of the general relativity theory, no introduction of the Λ-term.

At first, Einstein did not appreciate Friedmann's results. He wrote that they appeared suspicious to him. But very soon the great scientist found courage to admit his mistake: "My objection was based, as I found out..., on an error in computation. I consider the results of Mr Friedmann to be correct and illuminating. It appears that field equations yield, apart from static, also dynamic (that is, varying with time coordinates) central-symmetry solutions for space structure" [7, S. 228].

At first there were few people who believed that Friedmann's solutions had any relation to the structure of the real world. Further development of cosmology showed, however, that these solutions were not just mathematical possibilities. The decisive role was played here by the discovery of the "red shift" effect.

The "red shift" effect, discovered by the American astronomer Slipher, essentially consists in the spectral lines of extragalactic nebulae (of other galaxies) being shifted towards the red end of the spectrum. That means that the frequency of the electromagnetic radiation of the galaxies recorded on the Earth decreases. There is only one satisfactory explanation of this phenomenon: the change in the frequency of radiation is a consequence of the radiation source moving away (the Doppler principle). The "red shift" was thus proof of the runaway of galaxies.

In 1929, another American scientist, Hubble, discovered yet another curious law: the velocity of the galaxies' motion was directly proportional to the distance between them. The proportionality coefficient is a magnitude that came to be known as the Hubble constant.

Two remarks must be made in connection with the "red shift". First, all galaxies are not moving away from some centre of the universe—the point where the Earth is. In the course of time, the distance grows between all galaxies. That means that the "red shift" is not geocentric in character. It can be observed from any point in the Metagalaxy. Second, the "red shift" should not be interpreted as actual "runaway" of galaxies, that is, as their motion relative to some independent space. The existence of such a space is negated in the general theory of relativity. From the relativistic standpoint, the "red shift" does not signify movement of galaxies through space but expansion of space itself.

The discovery of the "red shift" thus proved the non-static nature of our Metagalaxy, as predicted by Friedmann. The non-static solutions of gravitational equations proved to have greater possibilities than the static variant. Both finite and infinite models were obtained as solutions of gravitational equations. Given the diversity of cosmological models, the problem arose of choosing the one which is the most adequate reflection of the real world. This task constitutes the problem of infinity in relativistic cosmology or, to be more precise, in the relativistic theory of a uniform and isotropic universe.

In relativistic cosmology, both types of models of the universe (finite and infinite) are logically equal. Therefore one cannot prefer one of them at the level of theoretical cosmology. The question of which model is realised in reality substantially depends on empirical data. The connection between finiteness and infiniteness of space and the empirical magnitudes is expressed by the formula

$$\frac{K}{R^2} = \frac{1}{3}\rho_0 \kappa - H^2,$$

where K/R^2 is the Gaußian curvature of the spatial cross-section of the model, ρ_0 is mean density of matter, κ, the gravitational constant, and H, the Hubble constant. If we take that H is sufficiently well-defined and equals 25 km/sec per one million of light years, the curvature of spatial cross-section is entirely determined by the magnitude ρ_0. If $\rho_0 \approx 10^{-29}$ g/cm^3, the curvature of spatial cross-section has zero value and space is infinite. If ρ_0 is greater than the magnitude indicated here, space has positive curvature and is finite. If ρ_0 is smaller than this magnitude, space is characterised by negative curvature and has infinite three-dimensional volume.

At present, the magnitude of mean density of matter has not yet been determined with precision sufficient for us to answer the question whether our universe (or, more correctly, Metagalaxy) is spatially finite or infinite. The problem of infiniteness of the universe is in this sense still unsolved in relativistic cosmology.

Many scientists believe that this situation is temporary and that the problem will ultimately be solved on the basis of a more precise definition of empirical values connected in theory with the curvature of metagalactic space through theoretical dependencies. The solution of the infinity problem is conceived in terms of choosing one of the alternatives: "the universe is infinite" and "the universe is finite". However, a third solution is not excluded either: the problem of infinity cannot in general be solved in the form of an alternative.

The idea of non-alternative solutions of the problem of infinity was suggested already by Kant. As it was not in agreement with classical cosmology, it receded into the background, at least in the natural-historical aspect. But it gained a new lease of life in relativistic cosmology, although its concrete scientific content is naturally different from what Kant meant.

Two non-alternative forms of the solution of the problem of spatial infinity of the universe may be considered in connection with relativistic cosmology. One of them is based on the establishment of the relative character of differences between the finite and the infinite. An interesting solution of this kind was suggested by A. L. Zelmanov. The heuristic idea which he used was as follows. In the relativity theory, it is not space and time separately from each other but the spatio-temporal continuum that is invariant. Zelmanov shows that the non-invariance of space and time goes so far that such of their quantitative characteristics as finiteness and infiniteness prove to be non-invariant.

In considering various models, Zelmanov finds relations between them that are at first sight paradoxical. For example, there exist models each of which possesses an infinite space in its frame of reference, yet at the same time the space of one of the models occupies a finite part of the space of another model.

Even more interesting is the following relation between models: a model possesses infinite space but takes up a limited region in the space of another model, which is finite.

One of the consequences that follow from these examples is that infinity does not necessarily encompass all. Although this conclusion is in the nature of a theoretical possibility, it is interesting and important from the philosophical standpoint. Traditional in philosophical literature is the consideration of infinite space as all-embracing. The result obtained on the basis of relativisation of the differences between the finite and the infinite, shows that infinity of a given system does not yet mean that it embraces entire space. This system, though its dimensions may be infinite, may be local and bounded.

Another non-alternative form of solving the infinity problem is founded on the following considerations. The relativistic theory of an evolving universe is a theory of a uniform and isotropic universe. It is based not only on the equations of the general relativity theory, but also on the so-called cosmological postulate asserting equality of all points in space and all its directions. In this theory, infinity and finiteness of space are linked with the sense of the Riemann curvature. Zero and negative curvature are equivalents of infinity, while positive curvature is equivalent to finite space. Besides, it is assumed here that, having defined curvature for a local region accessible to observation, we thereby define it for the whole of the universe and thus solve the problem of infinity.

Although the modern astronomical data apparently provide evidence for uniformity and isotropy of metagalactic space, it is still possible that real large-scale space is non-uniform and anisotropic. It means that it is not the special instance of relativistic space that is realised in nature but rather the general case envisaged in the general theory of relativity. In non-uniform space, the direct connection between space curvature and its finiteness or infinity disappears. As a result, any observer with access only to local, bounded regions of space, is unable to solve the problem of finiteness or infinity of space knowing curvature in a local region. Both alternatives of the solution of this problem in the relativistic theory prove to be non-contradictory, while experimental data provide no basis for choosing one of them, because curvature sense ceases to be a quantitative characteristic of space as a whole.

One should not of course draw agnostic conclusions from the above about the problem of infinity of the universe. The situation discussed here merely indicates changes in the very logic in terms of which the problem is formulated and solved. This situation is probably analogous to the state of the art in mathematics which requires the use of logic without the law of the excluded middle. A trivial limitation of this law is the discussion of the existence of, say, eleven zeroes in succession in the expansion of the number π represented by a non-repeating fraction with an infinite number of decimal digits. We know that the existing expansions of the number π do not contain eleven zeroes in succession, and we cannot indicate the place where they must be. The mathematician will therefore assume that the statement of the existence of these zeroes as an existentional proposition is meaningless and cannot be assigned a truth value. The same may be said about the other alternative, for the impossibility of zeroes does not follow from the number π itself. A third possibility is open here, namely, to leave the question of the existence of zeroes open.

In the case of non-uniform space, the solution of the problem of infinity will be to some extent analogous to the one discussed here. Its solution will not consist in recognising the thesis of the existence of infinity to be true and the thesis of finiteness of the universe to be false, or vice versa. This solution must consist in leaving the question of infinity open. This assertion of the openness of the question of infinity is a matter of principle here. It expresses the very essence of the problem, its actual content.

4. The Problem of the "Beginning" of Time

A new formulation of the problem of spatial infinity of the universe is not the only and probably not the most striking of the surprises of relativistic cosmology. The problem of time is even more paradoxical, the paradoxicality being conceptual rather than psychological. It may be called one of the most acute and fundamental problems of modern cosmology.

Einstein's first cosmological model, and all stationary models in general, faced no fundamental difficulties of describing their evolution in time. The time of these models was infinite both in the direction towards the past and towards the future. A different picture is encountered in the Friedmann models with expanding space where $\Lambda = 0$. Their evolution begins with a certain specific (singular) state represented mathematically as a point. Corresponding to the initial moment of time $t = 0$ are a zero volume of space and an infinite value for matter density. If this cosmological model reflects the evolution of our universe, we shall have to admit that our universe emerged from a point.

This conclusion was acclaimed by theology and physical idealism. Cashing in on the difficulties of modern cosmology and its unsolved problems, theologians tried to use the idea of the origin of the universe from the mathematical singularity as evidence for the creation of the world and to bring it in agreement with the Biblical legends. These theological speculations were supported by a number of Western scientists adhering to physical idealism in the philosophical interpretation of the attainments of astrophysics and cosmology.

Creationism—the theory of origin of the universe out of "nothing" by a supernatural act of creation—has nothing in common with science and is rejected by most cosmologists. Scientists are least of all inclined to mystical interpretations of mathematical singularity. On the contrary, their efforts are directed towards finding a natural-scientific explanation of this phenomenon. That is not a simple problem, and scientists do not have a common approach to its solution. Still, many of them believe that the mathematical singularity paradox arises from unlimited extrapolation of the general theory of relativity. The general theory of relativity studying the gravitational field is a classical, i.e. non-quantum, theory. However, as distances decrease and matter density increases, the quantum effects of the gravitational field, ignored in the general relativity theory, must manifest themselves. For example, they must necessarily manifest themselves in a region whose spatial dimensions are of the order of 10^{-33} cm, temporal dimensions, of the order of 10^{-43} sec, and where matter density is of the order of 10^{93} g/cm^3. In this region, which has finite characteristics rather than singular ones, in the mathematical sense, the general theory of relativity is no longer applicable. It cannot therefore be extrapolated to this region, still less to $t = 0$ and $R = 0$.

That was exactly the view of singularity which Einstein held. He wrote this, in particular: "For large densities of field and of matter, the field equations and even the field variables which enter into them will have no real significance. One may not therefore assume the validity of the equations for very high density of field and of matter, and one may not conclude that the 'beginning of the expansion' must mean a singularity in the mathematical sense. All we have to realize is that the equations may not be continued over such regions" [4, p. 129].

Rejecting singularity as a mathematical point from which the universe emerges in some mystical manner, Einstein nevertheless uses the physical singularity concept pertaining to a specific superdense state of matter. This is a key concept in the relativistic theory of an evolving universe. The evolution of the universe is presented in this theory in the following manner. In the remote past all matter was in a physically singular state. Some 20,000 million years ago the superdense matter exploded. Some time later the whole of matter was extremely dense high-temperature plasma consisting of particles and antiparticles (the former predominating), as well as of radiation. As plasma expanded and its temperature fell, the processes of annihilation of particles and antiparticles prevailed over their generation. As a result, pairs of particles and antiparticles disappeared, but a number of excessive nucleons and electrons were preserved. Later, formation of nuclei of light elements, hydrogen and helium, took place. Later still, nuclei and electrons were combined, and heavier chemical elements emerged. During further expansion of matter and decrease of its temperature the medium was formed out of which galaxies and stars emerged.

This picture of the evolution may appear fantastic—so unusual it is. But, to make judgments about its correctness or incorrectness, it has to be compared to facts, to observation results, rather than to common sense. So far the criterion of practice provided evidence in favour of the so-called evolving model of the universe. This model is in fine agreement with the "red shift". An important confirmation of this model was the discovery in 1965 of 2.7°K relict radiation, the existence of which had been predicted by the hot universe model. A number of other empirically verifiable consequences follow from it: relict neutrino radiation, gravitational waves from the "Big Bang", etc.

The relativistic theory of an evolving universe cannot of course be regarded as absolute truth in the last instance providing definitive answers to all problems of the spatio-temporal structure of the universe. We may take the problem of time as our example. Let us consider four approaches to its solution.

(1) Some relativistic cosmologists hold the view that the beginning of the expansion also marked the beginning of the time of the universe's existence. This solution is founded on the following philosophical consideration: time is a form of the existence of matter inseparable from the latter. On a cosmic plane it appears as an aspect characterising the expansion of the universe. Inasmuch as time is inseparable from the material substratum realising it, assuming the existence of "pure" time "before" the universe is absurd. "Before" the universe, there is neither matter nor time. Academician V. L. Ginzburg writes of this circumstance: "The universe in the past was in a 'spe-

tial' state, which corresponds to the 'beginning' of time, the concept of time 'before' that 'beginning' is devoid of physical or any other meaning... Indeed, if it were possible to speak of time 'before' the beginning of the evolution of the universe, with the universe itself not yet in existence, we would have to assume 'creation'" [8, p. 100].

The idea of the "beginning" of time appears unsatisfactory to many philosophers. To reveal its rational kernel, let us explain the following points. When we say that an expanding universe has a "beginning" in time, we refer to the so-called coordinate time. Coordinate time t is a member of the expression $R(t)$ which is a function characterising the expansion of space. R, that is, distances between any points of space, grows with the increase of t. If t tends to 0, we obtain a zero value for R, which corresponds to the singularity. In this line of reasoning, the question of what existed "before" the singularity cannot be rationally formulated.

(2) The conclusion that an expanding universe is finite only in the sense of the special, so-called coordinate, time, may be regarded as the starting point of another solution of the problem. If we replace this type of time by other types, we can expect another solution. As shown by the Soviet physicists V. A. Belinsky, Ye. M. Lifshits, I. M. Khalatnikov, and the American scientist Ch. Misner, in the contraction of space near the singular point (the t's being small) the basic parameters, including the radius R, oscillate, so that an infinite number of oscillations takes place within a finite time. If time is to be measured by the number of such cycles, it is infinite. Thus the distinction between the finite and the infinite, as applied to time, is relativised.

(3) There is one defect inherent in both of these approaches: they are based on the extrapolation of spatiotemporal relations, worked out for the macroworld, to very small regions, even to the singularity, which is identified with the mathematical point. But this extrapolation is hardly justifiable. The point is that under physical conditions characterised by a very high density of matter of the order of 10^{93} g/cm^3, the concept of metric spacetime and probably of the temporal topological relation "before/after" loses its meaning. There is nothing mystic

about this fact. In this case physics probably leads us to new and more fundamental forms of the existence of matter than time and space, the latter two being only limiting manifestations of these forms under the definite physical conditions of rarefied matter.

(4) Finally, an attempt may be made to generalise the concept of time itself for the solution of the problem of time encountered by the relativistic theory of an evolving universe. As we know, time is a sequence of events ordered by the relations "before" and "after" (as distinct from space, which is an ensemble of events ordered by the relation of simultaneity). A materialist philosopher considering the development of the material world in a more general sense than in, say, modern physics, namely, as succession or transformation of qualitatively distinct forms of matter, could regard these forms as a kind of "events", introducing a more general concept of time than the one used by physics, for characterising series of such "events".

In the framework of this more general conception of time we might discuss the question of what existed "before" the singularity, for instance, a possible contraction which resulted in its formation. In this conception the question of any beginning of time in the universe has no meaning at all. The very concept of the beginning of time may in this case be regarded as an attempt to grasp the development of the universe in terms of some special type of time, e. g., coordinate time.

5. Does Closed Time Exist?

We shall consider yet another aspect of the problem of infinity of time, the so-called closed time constructions.

As we have indicated, relativistic cosmology permits cosmological models with closed space. But time in the models considered above is open. Thus in Einstein's model it is represented by time lines (orthogonal to the three-dimensional space) directed into infinity. This imposes an imprint on the Einstein spatio-temporal world, which also proves to be infinite. Of the same type is time in a finite evolving model periodically contracting and expanding.

That does not mean, however, that relativistic cosmology in principle excludes models with closed time. One such model was obtained by K. Gödel in 1949. Space-time in this model is homogeneous but anisotropic: the model is characterised by absolute rotation.

Time lines cannot be selected unambiguously in the Gödel model. It has no single world time inherent in isotropic models. An interesting feature of this model is the presence of closed time lines. For example, if we single out two points *A* and *B* on the world line of some fundamental particle (which is not closed in itself) in such a way that *A* precedes *B*, there exists a time-like line connecting *B* and *A* on which *B* precedes *A*.

Gödel's model is not the only model with closed lines of time. Time in the de Sitter model for $\lambda < 0$ has a similar property. Space-time in this model has negative curvature and is therefore infinite, but its temporal cross-section is characterised by a finite magnitude.

The following point is essential for understanding the nature of closed time: it is by no means any cyclical process that is characterised by closed time. The general theory of relativity distinguishes between two kinds of cyclicity: state cyclicity and event cyclicity. Cyclicity of the first type is observed in the so-called oscillating models, that is, models which periodically expand and contract. If we ignore the growth of entropy in the evolution of the model, we shall obtain a certain repetition of states in this abstract case, but no repetition of events. The time of this model is infinite. One and the same thing, even if it should occupy an identical position in space in different cycles, is associated with different values of the time coordinate. One and the same thing is therefore two different events in two different cycles.

Cyclicity of the second kind permitted by the general theory of relativity (cyclicity of events) is expressed by a closed time construction. Repetition is here absolute in nature, including repetition of the values of the time coordinate. State cyclicity is logically consistent, but the same is not true of event cyclicity and the closed time construction. The closed time model obviously contradicts the principle of causality. Besides, considered in the framework of the theory of relativity, it is also internally contradictory.

In should first of all be noted that the closed time conception leads to the notion of closed causal chains. Here we encounter the following logical difficulty. From the standpoint of the special relativity theory, causal connection between two events is impossible if they are simultaneous. These events belong to the spatial cross-section of the spatio-temporal continuum. Non-simultaneity of events is a necessary condition of establishing a causal connection between them. Assume that the time-like line, along which the causal chain is situated, is closed. A closed line describing the course of time contains the following contradiction. If, moving along a closed time-like line we return to the starting point with the same time value, it follows that a zero duration of time corresponds to this line, although metrically it is distinct from zero. Causal connections along such lines are impossible from the standpoint of the relativity theory. It is required, however, that we build a causal chain along such a line.

A different view of the closed causal chain construction is held by the adherents of the causal theory of time—H. Reichenbach, one of the founders of neopositivism, and A. Grünbaum, an American philosopher. They believe it to be logically faultless, seeing no defect in the relativistic cosmological models in which it is obtained. For example, Reichenbach insists that "it should be kept in mind that the openness of the causal chains represents an empirical fact and cannot be regarded as a logical necessity. There is nothing contradictory in imagining causal chains that are closed" [9, p. 37]. Grünbaum, who holds similar views of time as Reichenbach, believes it possible to construct a functioning model of closed causal order with corresponding closed time. Let there be a "universe", he writes, consisting of a plane and one point particle moving along a circular trajectory on it. Instead of periodically reappearing at one and the same point *A* at different moments of open time, the particle undergoes a return to the same event at the very same moment of closed time. "This conclusion [writes Grünbaum] rests on Leibniz's thesis that if two states of the world have precisely the same attributes, then we are not confronted by distinct states at different times but merely by two different names for the same state at one time" [10, p. 197].

We believe that the attempts to save closed time correlated with a closed causal chain by the Leibniz principle are incompatible with the relativity theory. The theory of relativity does not accept this principle. Indeed, the Leibniz principle in the form given it by Grünbaum requires the reduction of temporal properties of things to other properties. But the relativity theory singles out time as a specific property irreducible to other properties. It obviously forms part of the event concept which is characterised by two parameters, spatial and temporal, irreducible to each other. Consistent application of the Leibniz principle excludes the concept of even a central concept of the theory of relativity. On the other hand, assertion of the event concept is tantamount to recognition of the unjustifiability of the Leibniz principle.

If we give up Leibniz's principle, Grünbaum's example will no longer serve as a model of closed causal and temporal orders. As has been mentioned, the relativity theory distinguishes cycles of states and cycles of events. According to this theory, a repetition of a past state need not necessarily mean its repetition with regard to time. For example, it may be theoretically assumed in a closed oscillating model that properties of things are identically repeated in the repetition of the cycle of the expansion (or contraction) of their structure. However, two different values of the time coordinate would correspond to these two phases in the evolution. If the Grünbaum universe is a point moving along a circular trajectory, the circle will in this case represent only the "space" of this "universe". According to the relativity theory, this space is associated with time represented by lines orthogonal to space. In themselves, these lines need not at all be closed. We can therefore arrive at the following conclusion: Grünbaum's spatio-temporal world is not a circle on a plane but the surface of a cylinder in which the history of the particle is represented by a line directed into infinity. There is no repetition of events here, for in different cycles different values of the time coordinate correspond to one and the same place of the moving point.

What was Einstein's attitude to the concept of closed time? After reading Gödel's article expounding the essence of one of the possible constructions of closed time, Einstein formulated a number of arguments concerning the possibility of closed temporal and causal orders in cosmological solutions of the equations of the general relativity theory. He noted in particular that the expression "*B* is before *A*" has unambiguous physical meaning only where *B* and *A* are sufficiently neighbouring world-points connectable by a time-like line. "But does this assertion still make sense [asks Einstein], if the points, which are connectable by time-like line, are arbitrarily far separated from each other? " His answer is: "Certainly not, if there exist point-series connectable by time-like lines in such a way that each point precedes temporally the preceding one, *and if the series is closed in itself.* In that case the distinction 'earlier-later' is abandoned for world-points which lie far apart in a cosmological sense" [11, p. 688].

On the whole, Einstein welcomed the result obtained by Gödel, referring to it as an important contribution to the general relativity theory. But he rather assessed Gödel's model as a possible theoretical construction devoid of physical meaning. He wrote, in particular, that it would be "interesting to weigh whether these [solutions] are not to be excluded on physical grounds" [11, p. 688].

In order to exclude closed time constructions, it is necessary to have a clear idea of the causes which give rise to them. The main cause is, in our view, the geometrical description of time accepted in the relativity theory.

Modelling time geometrically, we thereby operate with it according to the laws of space. There is no logical contradiction in the fact itself of a closed line if it is regarded as a spatial object. But a contradiction does arise if to this line is ascribed the topology of time which is a linearly ordered series of events. A closed line is incompatible with temporal relations defined over it, the "later-earlier" relations.

The appearance of closed time constructions in the general relativity theory can be explained by the fact that the geometrical description of time with which this theory operates does not take into account explicitly the topology of time as an order relation. As is known, time is distinguished from space in the relativity theory only by the sense of the signature of the spatio-temporal element.

But that is obviously not enough. Only formulation of topological axioms of time, that is, axioms determining temporal order, might permit exclusion of closed constructions from consideration. Explicitly given topological time axioms could serve as an instrument of selecting solutions for the equations of the general relativity theory and of discovering among them "superfluous" solutions. Thus, the problem of analysing constructions of closed temporal and causal series may be correctly understood and solved through a realisation of the incompleteness of a geometrical description of physical time.

To sum up. Relativistic cosmology rejected the image of Euclidean infinity of the universe as inadequate. Some of its results could be, and actually were, interpreted in the spirit of finitism. However, if we consider relativistic cosmology in the entire totality of its results, we shall have to draw the conclusion that in its spirit it is alien to the finitist view of the material world, offering a more profound and complete conception of its infinity than classical cosmology.

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V. L. GINZBURG

THE HELIOCENTRIC SYSTEM AND THE GENERAL THEORY OF RELATIVITY (FROM COPERNICUS TO EINSTEIN)

We are honouring today, with joy and gratitude, the memory of a man who, more than almost anyone else, contributed to the liberation of the mind from the chains of clerical and scientific dominance in the Occident. ...A rare independence of thought and intuition as well as a mastery of the astronomical facts, not easily accessible in those days, were necessary to expound the superiority of the heliocentric conception convincingly. This great accomplishment of Copernicus not only paved the way to modern astronomy; it also helped to bring about a decisive change in man's attitude towards the cosmos.

A. Einstein. "Message on the 410th Anniversary of the Death of Copernicus" [1, p. 359]

Mechanics and the theory of universal gravitation have traveled along a path almost five centuries long, from Copernicus on to Galileo, Kepler, Newton and Einstein. The history of this development, the drama of ideas that carved their way with great difficulties, is fascinating. Regrettably, the topic "Copernicus and Einstein" (or "The Heliocentric System and the General Relativity Theory"), on the whole, did not have much luck in the literature of the last few decades. Various authors were mostly content with quoting from popular literature (including "Einstein himself"), in which the struggle between the views of Ptolemy and Copernicus was declared to be aimless and absurd, in the light of the general theory of relativity. These assertions were then refuted by arguments whose tone and content were largely determined by the style of polemics prevalent at the time rather than by the essence of the problem. An impression was thus created of the general relativity theory (or rather of some of its adherents and propagandists) having something to do with rejection of the progressive role of Copernicus's teaching. But this conclusion is entirely unfounded. In particular, Einstein's words cited above as epigraph speak for themselves. There is no doubt that trying in these days to prove Copernicus's great role and achievements would be much like forcing a wide open door. One hardly needs to pay much attention to various imprecise or unfortunate remarks and pronouncements occurring in the literature, particularly in popular literature, where authors take the greatest pains about the beauties of style and accessibility of content. However, I was on many occasions struck by the wide currency of misconceptions about Ptolemy's system, the content of Copernicus's work, and finally about the real or imaginary connections between heliocentric conceptions and the general theory of relativity. Therefore the appearance of the present paper probably needs no special justification.

We must emphasise at the same time that the article lays no claims at all to exhaustiveness. Its objective is limited to removing some misunderstandings and to facilitating a deeper discussion of the subject. It is a different matter that some of the author's remarks and conclusions may appear to be debatable and give rise to objections. There is no harm in that, however: one need hardly write articles on questions that are so clear to everyone that they cause no divergence of opinion.

1. Ptolemy

The first theory of the motion of celestial bodies (the Sun, the moon, and the planets), which permitted calculation of their position in the sky, was formulated in ancient Greece. Hipparchus (2nd century B. C.) was regarded as a particularly great astronomer of that epoch. The astronomical system of the Greeks was to some extent given an accomplished form in the work of Claudius Ptolemy (2nd century A. D.). For many centuries Ptolemy's book *Syntax* (which was given the name *Almagest*, which means "the greatest") was believed to be the crowning glory of ancient astronomy. It was only very recently discovered [2,3] that Ptolemy was unscrupulous concerning the results of astronomical observations of which he wrote (to put it crudely, Ptolemy counterfeited the data of position of celestial bodies, passing them for his observations). Because of this, one may also doubt the main part of Ptolemy's activity—the computation of the positions of planets, and generally doubt his reputation as a great astronomer. However, the whole question is not yet sufficiently clear, and the term "the Ptolemaic system" is rooted so firmly that it can hardly be changed. In any case, we are not going to do so in this article, following the convention of ascribing to Ptolemy the achievements of ancient astronomy, which were indeed considerable.[1] It is necessary to stress this circumstance because of the fact that the Ptolemaic system is associated in the minds of the modern wide public with something obsolete, interfering with the progress of science, etc. In actual fact this situation is due to the raising of the Ptolemaic system to an absolute by the church, rather than to the system itself; it is due to the fact that many centuries after the formulation of the Ptolemaic system it was used by the opponents of Copernicus.

As is generally well known, the Ptolemaic system is geocentric: at the centre of the world is the motionless Earth, with the moon, Mercury, Venus, Sun, Mars, Jupiter and Saturn rotating round it. In the simplest case, the planets move in the following manner: a planet is in uniform motion along a smaller circle (the epicycle), whose centre is also in uniform motion round the Earth along the great circle (different). It is interesting to note that in a

[1] See books by A. Pannekoek [4], Th. Kuhn [5], articles by N. I. Idelson [6, 7] and other books and articles on the history of astronomy. We shall not go into the details of the question, but we do quote copiously below from various sources, for the quotations are quite striking in themselves, recreating the spirit of the epoch.

better developed scheme of planetary motions Ptolemy gave up the idea of uniform circular motion, which was a philosophical dogma in ancient times [6]. In general, he was concerned in the first place with explanation of facts and observations, with learning to compute beforehand the positions of celestial bodies, without bothering much about the requirements of contemporary philosophy. This may be confirmed by the following quotation from Ptolemy:

"Let it not be objected against these hypotheses that they are difficult to assimilate because of the great number of methods that we use. For what comparison may be made between the terrestrial and the celestial and what examples could reflect things that are so different? The simplest hypotheses must be applied to celestial bodies, wherever possible; but, if they do not suffice, other and more suitable ones should be found" [7, p. 19].

This approach can only be properly appreciated if one remembers the demands of philosophers prevalent in those times. For example, the following proposition is ascribed to Plato:

"He accepts, as the main rule, that celestial bodies move in circular, uniform, and quite regular (that is, always headed in the same direction) motions, and he then poses the following task for mathematicians: to find the uniform and regular circular motions, that are to be given to rescue the phenomena represented by the planets."

Aristotle held, besides, that the rotation of celestial bodies must pass along circles in the centre of which was the Earth. But the visible motions of planets could not be "rescued" unless this requirement was violated. It had to be assumed, on the contrary, that the distance from the planets and the moon to the Earth varies with time. Thus the system with the epicycles, mentioned above, first appeared in Hipparchus and was later developed by Ptolemy. Ptolemy's system with its circular (but non-uniform) motions round empty points (centres of the epicycles) thus decidedly departs from the prescriptions of Plato, Aristotle, and their followers. In the Middle Ages, this even resulted in the well-known opposition to the Ptolemaic system from Aristotelian positions. Curiously, Copernicus was in this respect closer to Aristotle than Ptolemy.

Indeed, Copernicus wrote:

"The Movement of the Celestial Bodies is regular, circular and everlasting—or else compounded of circular movements... For it is only the circle which can bring back what is past and over with; ... since it is impossible that a simple heavenly body should be moved irregularly by a single sphere. For that would have to take place either on account of the inconstancy of the motor virtue ... or on account of the inequality between it and the moved body. But since the mind shudders at either of these suppositions, and since it is quite unfitting to suppose that such a state of affairs exists among things which are established in the best system, it is agreed that their regular movements appear to us as irregular..." [8, pp. 513, 514].

The attacks [7] on Ptolemy's system (critique from the right, so to speak) were unsuccessful, apparently, only due to the genuine attainments of the constructions and computations of Ptolemy and his followers; these computations are correctly referred to as "genuine theoretical astronomy" [6, pp. 85-86]. The Ptolemaic system is, generally speaking, the solar system as seen from the Earth. In this form it is of course widely used by modern astronomy as well: an astronomer usually defines the position of a luminary on the celestial sphere in earthbound coordinates and only later passes on to other coordinate systems.

Given the precision of observation (about 10 minutes of arc) and the calculation methods which existed already at the time of Copernicus, computations on the basis of Ptolemy's system satisfied the requirements (although with some difficulty) imposed by such tasks as compiling calendars (an urgent problem in those times) and predicting celestial phenomena (eclipses, etc.). This circumstance explains a great deal.

It becomes clearer why the rudiments of heliocentric views of antiquity did not develop and were almost entirely forgotten (that is not true of Copernicus, who knew those views well and specifically mentioned the fact). Thus Aristarchus of Samos placed the Sun in the centre, round which the Earth revolves, which also rotates round its axis [4]. But neither the author of that heliocentric system nor other astronomers who expressed the same ideas developed them to a degree when they could compete with the incomparably better developed system of Ptolemy. Only Copernicus was able to revive the heliocentric system not just through physical arguments, of which we shall speak below, but also through working out his scheme of computations and formulating a new manual of astronomy capable of supplanting Ptolemy's. Yet even on the purely practical plane (compilation of tables, etc.), the advantages of the Copernican system were not sufficiently impressive and effective as far as observed astronomical predictions were concerned—until the works of Tycho Brahe and Kepler appeared. This makes clearer one of the causes of the comparatively slow and hard-won victory of Copernicus's views. Other and more essential causes are objections of physical nature and, finally, the role of the church[2]. The Ptolemaic system was in fact canonised by the church, permeating the entire world outlook of the epoch; as an example, we might mention that Dante's *Divine Comedy* and in particular the third part, "Paradise", were built on the model of Ptolemy's system.

2. Copernicus

The high precision of computations (high for those times) attained in the Ptolemaic system naturally imposed great demands on a heliocentric system capable of competing with an already well-developed geocentric system—thus can we summarise the last part of the previous section. We do not yet touch upon the reason that made the ancient astronomers accept, develop and perfect precisely the geocentric system. The explanation cannot be attributed to the church, either, for canonisation of the geocentric system took place later—it did not precede its spreading.

There can hardly be any doubt that the whole point is simply the affinity of the geocentric system with the direct observation of celestial phenomena from the Earth.

[2] All of these reasons were interwoven and hard to distinguish. The author therefore finds it difficult to determine the share of the various factors, although that is quite an interesting task.

The transition to heliocentric conceptions, so easy under the present-day development of science and culture, was in antiquity, and of course in Copernicus's times, a very difficult act demanding courage of thought, capacity for abstraction, etc. This difficulty is similar in type to the difficulties arising in the way of comprehending the global form of the Earth, creation of the theory of the electromagnetic field, the theory of relativity and quantum mechanics. In all these cases one and the same phenomenon was observed: essentially new conceptions arose and, still more so, emerged victorious only under the impact of facts which proved more and more difficult to comprehend, describe and "rescue" on the basis of the old, less accomplished schemes and theories. Obviously, the less facts are known and the cruder the measurements and observations, the easier it is to stick to the old positions and the more difficult to prove the need or at any rate the advantage of the new views. The history of the development of astronomy may serve as an excellent illustration for these assertions, which are sufficiently trivial in our days.

Let us therefore go back to the topic of this article, noting that Ptolemy knew of the opinion that the Earth revolves while the heavens are motionless, and he even remarked that "owing to the great simplicity of this construction, there is nothing to obstruct it, as far as phenomena of the stellar skies are concerned". But he immediately declared this opinion to be ridiculous and rejected it invoking the physical arguments and views current in those times. These arguments are essentially founded on a failure to grasp relativity of motion, on the opinion that rotation of the Earth rather than of the sky would affect terrestrial phenomena: a storm would rage on the Earth, no bodies would fall vertically, and so on. This view was clearly set out by Galileo in his *Message to Ingoli* written in 1624, that is, about a hundred years after the Copernican system began to spread:

"Together with Aristotle and others you say: if the Earth rotated round its axis in 24 hours, then stones and other heavy bodies falling from above, for instance from a high tower, could not strike the earth at the foot of the tower; pointing that in the time while the stone is in the air descending to the centre of the Earth, the Earth itself, moving at a great speed to the east and carrying on it the foot of the tower, would necessarily have to leave the stone at the same distance behind itself; and that would be many hundreds of feet" [9, p. 543].

The whole of the *Message to Ingoli*, about fifty printed pages, is devoted to refutation of these objections against the heliocentric system. The objections included, of course, not only physical but also astronomical ones (the remark of Ptolemy quoted above should not mislead the reader). Thus, in Galileo's words, "all these adversaries of Copernicus assert by calculations that the revolution of the Earth along its annual orbit, producing such considerable and amazing changes in the positions of planets, would not cause similar phenomena in the positions of stars only if the stellar sphere were so remote that any star could possess the visible magnitude that we observe. But that were [possible] if it were many times greater than the whole of the Earth's orbit and, consequently, many times greater than the size of the Sun itself; and all this they believe to be the greatest absurdity. But my calculations show that the situation is quite different" [9, p. 524].

Thus, physical and astronomical arguments against the heliocentric system (we are not concerned here with church dogmas) were seriously discussed a hundred years after the death of Copernicus and publication of his main work in the same year 1543. Small wonder that in the pre-Copernican period the debate was even more acute. It is quite clear therefore that one of the principal tasks (and deserts) of Copernicus was refutation of the objections against heliocentric conceptions. Indeed, Copernicus clearly understood and formulated the basics of the principle of relativity, let it be in an elementary and incomplete fashion. He wrote:

"For every apparent change in place occurs on account of the movement either of the thing seen or of the spectator, or on account of the necessarily unequal movement of both. For no movement is perceptible relatively to things moved equally in the same directions—I mean relatively to the thing seen and the spectator. Now it is from the Earth that the celestial circuit is beheld and presented to our sight. Therefore, if some movement should belong to the Earth it will appear, in the parts of the universe which are outside, as the same movement but in the opposite direction, as though the things outside were passing over." [8, p. 514-515].

Here Copernicus discusses the relativity of mechanic movement from the point of view of the observer or, if the reader prefers, of kinematic relativity (only the changes in mutual alignment may be fixed); further he proceeds to dynamic relativity (equality of reference systems in uniform and rectilinear motion relatively to each other)[3]. Indeed, Copernicus remarks: "And why not admit that the appearance of daily revolution belongs to the heavens but the reality belongs to the Earth? ... As a matter of fact, when a ship floats on over a tranquil sea, all the things outside seem to the voyagers to be moving in a movement which is the image of their own, and they think on the contrary that they themselves and all the things with them are at rest. So it can easily happen in the case of the movement of the Earth that the whole world should be believed to be moving in a circle. Then what would we say about the clouds and the other things floating in the air or falling or rising up except that not only the Earth and the watery element with which it is conjoined are moved in this way but also no small part of the air and whatever other things have a similar kinship with the Earth? ... Hence the air which is nearest to the Earth and the things floating in it will appear tranquil, unless they are driven to and fro by the wind or some other force, as happens" [8, p. 519].

These lengthy quotations are necessary here to show that it was precisely Copernicus who stood at the fountainhead of modern mechanics, and that it was precisely Copernicus who was Galileo's direct predecessor in this re-

[3] From the viewpoint of Copernicus, and of Galileo as well, the Earth was regarded, to put it in modern terms, as an inertial frame of reference, and could only be so regarded at a level of precision available to them. Therefore the proposition that phenomena on a ship in uniform and rectilinear motion relative to the Earth take place in the same way as on the Earth itself, fully corresponds to the principle of relativity—to the proposition of equality of all frames of reference in uniform and rectilinear motion relative to some inertial reference frame.

spect (who, by the way, called Copernicus his teacher).

Thus Copernicus's first principal attainment was the refutation of the objections against the possibility of the motion of the Earth and the proof that this motion was admissible in terms of physics and astronomy.

The second basic proposition, which is of course connected with the first, consists in the development of the heliocentric system itself. The line of Copernicus's reasoning is as follows:

"Therefore, since nothing hinders the mobility of the Earth, I think we should now see whether more than one movement belongs to it, so that it can be regarded as one of the wandering stars. For the apparent irregular movement of the planets and their variable distances from the Earth—which cannot be understood as occurring in circles homocentric with the Earth—make it clear that the Earth is not the centre of their circular movements. Therefore, since there are many centres, it is not foolhardy to doubt whether the centre of gravity of the Earth rather than some other is the centre of the world. I myself think that gravity of heaviness is nothing except a certain natural appetency implanted in the parts by the divine providence of the universal Artisan, in order that they should unite with one another in their oneness and wholeness and come together in the form of a globe" [8, pp. 520-521].

Assuming then that the Earth performs an annual revolution round the Sun, Copernicus indicates that "it will be seen that the stoppings, retrogressions, and progressions of the wandering stars are not their own, but are a movement of the Earth and that they borrow the appearances of this movement. Lastly, the Sun will be regarded as occupying the centre of the world. And the ratio of order in which these bodies succeed one another and the harmony of the whole world teaches us their truth, if only—as they say—we would look at the thing with both eyes" [8, p. 521].

All of these quotations come from the first few chapters of the first book of Copernicus's work *On the Revolutions of the Heavenly Spheres* consisting of six books. Most of the rest of the text, much greater than the part quoted here, is devoted to calculations of the movements of heavenly bodies, and re-calculations on the basis of the new system of the results of observations and computations conducted on the basis of Ptolemy's system. What Copernicus did there is, in modern terms, the solution of a rather simple kinematic task: correlation of the motion of a system of points with a new centre. But in Copernicus's times the appropriate calculations were complicated and awkward, to say nothing of the fundamental theoretical aspects of the problem. The complexity of the task will be clear if one takes into account that the planets are actually in non-uniform motion along ellipses (ignoring perturbations) with the Sun situated in one of the foci. Copernicus, however, reduced everything to uniform movements along circles (roughly speaking, this corresponds to approximation of non-uniform motion along ellipses by several members of a Fourier series, as many as there are circumferences introduced). Therefore epicycles were not banished from his system, their number merely decreased by a factor of two or so[4].

Thus the new system, however harmonious and simple it might be on the whole, proved to be extremely complicated in detail. This fact, as we have already stressed, slowed down the transition of astronomy to the new approach. Nevertheless Copernicus's system even in its first variant was simpler than Ptolemy's for calculations, and its potential for practical astronomy was even greater. It is therefore indubitable that the main obstacle in the way of the triumph of the Copernican system was the departure from old notions that were deeply rooted in the consciousness of men, literally permeating contemporary science, and, besides, canonised by the church.

We shall later come back to this question. It is now ne-

[4] One of the latest variants of the Ptolemaic system introduced 73 circles for the description of the Sun, the moon, and the planets. Copernicus used 34 (4 for the moon, 3 for the Earth, 7 for Mercury and 5 for Venus, Mars, Jupiter and Saturn each). True, the role (radius) of epicycles is smaller in Copernicus's system than in Ptolemy's owing to the smallness of the eccentricity of the elliptical orbits of planets (for example, for Mars the eccentricity equals 0.093, and for the Earth, 0.017). In the heliocentric system a single circumference is not so bad an approximation to the planet's real orbit. In the geocentric system the planets move in a more complicated manner; for instance, they sometimes describe a loop in the sky (relative to the stars).

cessary to note that both of Copernicus's remarkable attainments—first, realisation of the relativity of motion and elimination of objections to the Earth's motion and, second, formulation and development of the heliocentric system—are, one may say, an absolute achievement of science. We are not aware of any objections to this statement in the scientific circles of the 20th, 19th, and even 18th centuries. One should merely stipulate precisely what should be understood by heliocentric system. In modern terms the Copernican system may be described approximately like this: in a Cartesian system of coordinates whose centre coincides with the centre of the Sun (or the centre of gravity of the solar system) and the axes are directed at the stars[5], all planets (including the Earth which also rotates round its axis) move in an extremely law-governed manner; all of them revolve in the same direction along orbits that are close to circular ones, and, besides, the planes of these are near one another.

Copernicus himself and his followers associated something greater than that with the concept of heliocentric system: they regarded the Sun as the "centre of the world"; the Sun thus took the place formerly accorded to the Earth in the geocentric system: "and so the Sun, as if resting on a kingly throne governs the family of stars which wheel around" [8, p. 528].

The place of one absolute was taken by another.

But, as we know quite well, the Sun can in actual fact claim the status of the "centre of the world" with as little title as the Earth. There is no such centre in general. The Sun moves relatively to the nearest star at a speed of some 20 km/sec; it revolves relative to the centre of our Galaxy at a speed of about 300 km/sec; the whole of the Galaxy moves relative to other galaxies making up the Local Group (a comparatively small cluster of galaxies including, apart from our Galaxy and the somewhat larger M31 spiral galaxy—the Great Nebula in the Andromeda constellation,—also some two dozen small galaxies); the Local Group moves relatively to other clusters; and the clusters take part in the expansion of the universe.

[5] The Sun itself rotates in this system with a period of approximately 28 days.

But the main task of Copernicus and the Copernicans was, of course, "to shift" the Earth, to deprive it of absolute immobility and central position. After that it was not difficult to give up similar assumptions about the Sun, and we are not aware of any debates on this score. This is an extra proof that Copernicus's principal attainments were in the two fields referred to above, but not in the raising to an absolute of the heliocentric system. It will probably be better to say that this absolutisation, natural in those times, did not subsequently play any special negative role and was painlessly discarded.

All of this appears to be quite clear. Nevertheless, one hears from time to time echoes of the debates about "what revolves round what", what reference systems are equal or unequal, which of them are true and which are not, and were the battles between the adherents of the Ptolemaic and Copernican systems in vain or not.

3. What Is Truth?

According to the New Testament legend, when Pontius Pilate asked, "what is truth? ", Christ did not answer. Fifteen hundred years later, at the time of Copernicus and Galileo, the Christian church knew firmly what was "true" and what was "false" or "erroneous". From the historical viewpoint it was quite natural that the reaction of the new zealots of faith—the Protestants—was particularly quick and sharp. Their head Luther thus reacted to Copernicus's teaching: "This fool wishes to reverse the entire science of astronomy; but sacred Scripture tells us that Joshua commanded the sun to stand still, and not the earth." Melanchton also defended the Earth's immovability; he insisted that "it is a want of honesty and decency to assert such notions publicly, and the example is pernicious". For several reasons (which will be partially made clearer below) the Catholic church at first did not oppose the publication and using of Copernicus's work which the author himself dedicated to Pope Paul III (this dedication was accepted or, as we would now say, duly approved by the Pope). In general, Copernicus, a canon of a Catholic monastery, who was personally or through correspondence acquainted with many dignitaries of the Catholic church, acted quite carefully. The anonymous preface in the first edition of his book was also intended to camouflage Copernicus's breakaway from theclerical "truths". The author of the preface (the theologian and mathematician Osiander) wrote:

"If, however, they [philosophers—*Ed.*] are willing to weigh the matter scrupulously, they will find that the author of this work has done nothing which merits blame. For it is the job of the astronomer to use painstaking and skilled observation in gathering together the history of the celestial movements, and then—since he cannot by any line of reasoning reach the true causes of these movements—to think up or construct whatever causes or hypotheses he pleases such that, by the assumption of these causes, those same movements can be calculated from the principles of geometry for the past and for the future too. This artist is markedly outstanding in both of these respects: for it is not necessary that these hypotheses should be true, or even probable; but it is enough if they provide a calculus which fits the observations" [8, p. 505].

Thus the Copernican system, as long as it was known only in the narrow circle of astronomers, did not cause great anxiety and was used for the compilation of astronomical tables (The Prussian Tables of 1551) and in reforming the calendar (the "New Style" was introduced in 1582). The situation changed when the heliocentric views became widely known and began to threaten seriously church authority. In 1660, Giordano Bruno was burnt at the stake, and in 1616 Copernicus's work was included in the *Index Librarum Prohibitorum* on the strength of the following conclusion by eleven "theologian classifiers" (that is, censors)[6]:

"The first proposition, that the sun is the centre and

[6] The inertia of the bureaucratic machine of the church, apart from other factors, is clear from the fact that the ban on Copernicus's work was lifted only in 1822, and the works of Copernicus, Galileo, and Kepler ceased to be included in the *Index Librarum Prohibitorum* in 1835. In Russia, the heliocentric system was defended by Lomonosov—in particular, in 1752 and 1761 (for details see [11]).

does not revolve about the earth, is foolish, absurd, false in theology, and heretical, because expressly contrary to Holy Scripture; the second proposition, that the earth is not the centre but revolves about the sun, is absurd, false in philosophy, and, from a theological point of view at least, opposed to the true faith" [10, p. 137].

The attitude of religion to science is sufficiently clearly characterised by Tertullian's dictum *Certum est quia impossibile est* ("It is certain because it is impossible"), or reflected in Cardinal Baronius's remark: "Bible is given to teach us, not how the heavens go, but how men go to heaven." But in the 16th and 17th centuries one could no longer adhere to these positions, for science increasingly came into contradiction with the clerical dogmas. Therefore, the transition took place to the positions reflected in Osiander's preface and also strikingly expressed in the letter of Galileo's chief "exhorter" Cardinal Bellarmino written in 1615 to Pater Foscarini, a Copernican:

"I believe that you and Sig. Galileo would have acted prudently had you been content with pronouncements *ex suppositione* and not absolute ones: thus spoke Copernicus as I have always believed. Indeed, when it is asserted that the supposition that the Earth moves and the Sun is motionless rescues all the observable phenomena better than giving eccentricities any epicycles, that is all very well said and contains nothing dangerous; and that is quite enough for mathematics; but when men begin to say that the Sun indeed stands in the centre of the world and that it merely rotates round its axis but does not move from the east to the west and that the Earth is in the third heaven (the third in the order of distance from the Sun) and revolves round the Sun at a great speed, that is a very dangerous thing, and not only because it annoys all philosophers and learned theologians ... but also because it does harm to the holy faith, for it follows from it that the Holy Scripture is false" [12, p. 171].

The gracious permission to "rescue" phenomena and pursue mathematical topics without, however, encroaching upon reality and the essence of things, made Galileo furious, and that is quite understandable[7]. In a letter to the Grand Duchess of Tuscany he wrote: "Prescribing the professors of astronomy themselves that they should employ their own abilities for finding a defence against their own observations and conclusions, as if all of these were mere deceipt and sophistry, would mean imposing upon them injunctions that are more than unrealisable; that would be the same as to order them not to see what they see, not to understand what is clear to them, and to deduce from their studies precisely the opposite of what is obvious to them" [14, pp. 325-26].

Remarkable words, which are quite topical hundreds of years after Galileo's death!

We shall end our excursus into history with the words of Einstein from the foreword, which he wrote at the end of his days, to the English edition of Galileo's *Dialogue Concerning the Two Chief World Systems*:

"Once the conception of the centre of the universe had, with good reason, been rejected, the idea of the immovable earth, and, generally, of an exceptional role of the earth, was deprived of its justification. The question of what, in describing the motion of heavenly bodies, should be considered 'at rest' became thus a question of convenience. Following Aristarchus and Copernicus, the advantages of assuming the sun to be at rest are set forth (according to Galileo not a pure convention but a hypothesis which is either 'true' or 'false'). Naturally, it is argued that it is simpler to assume a rotation of the earth around its axis than a common revolution of all fixed stars around the earth. Furthermore, the assumption of a revolution of the earth around the sun makes the motions of the inner and outer planets appear similar and does away with the troublesome retrograde motions of the outer planets, or rather

[7] It should be borne in mind, however, that quite correct physical theories can be criticised from the standpoint of the search for the real world picture. Thus in 1622 F. Bacon called Copernicus a man "who thinks nothing of introducing fiction of any kind into nature provided his calculations turn out well" [13, p. 33]. Bacon's very weak argument against the Copernican system is based on the requirements of "common sense" rather than on scholastic principles. These requirements are usually all the louder the less the critic knows the subject with all the details, quantitative considerations, etc.

explains them by the motion of the earth around the sun.

"Convincing as these arguments may be—in particular coupled with the circumstance, detected by Galileo, that Jupiter with its moons represents so to speak a Copernican System in miniature—they still are only of a qualitative nature. For since we human beings are tied to the earth, our observations will never directly reveal to us the 'true' planetary motions, but only the intersections of the lines of sight (earth-planet) with the 'fixed-star sphere'. A support of the Copernican system over and above qualitative arguments was possible only by determining the 'true orbits' of the planets—a problem of almost insurmountable difficulty, which, however, was solved by Kepler (during Galileo's lifetime) in a truly ingenious fashion. But this decisive progress did not leave any traces in Galileo's life work—a grotesque illustration of the fact that creative individuals are often not receptive" [15, p. XV].

Although there are too many quotations in this article as it is, the author cannot resist the temptation of quoting a few more lines from the same foreword by Einstein:

"The *leitmotif* which I recognize in Galileo's work is the passionate fight against any kind of dogma based on authority. Only experience and careful reflection are accepted by him as criteria of truth. Nowadays it is hard for us to grasp how sinister and revolutionary such an attitude appeared in Galileo's time, when merely to doubt the truth of opinions which had no basis but authority was considered a capital crime and punished accordingly. Actually we are by no means so far removed from such a situation even today as many of us would like to flatter ourselves: but in theory, at least, the principle of unbiased thought has won out, and most people are willing to pay lip service to this principle" [15, p. XVII].

Let us go back, however, to the topic "Ptolemy and Copernicus".

As we have seen, the discussion of the structure of the solar system was shifted to the realm of philosophical debate of what is truth. Taking into account this fact as well as the level of then prevailing conceptions of the motion and structure of the universe, one can understand the opposition that took shape in those times: the Earth is at rest in the centre of the universe while the Sun revolves round it—that is one of the possible truths (tentatively, the Ptolemaic truth); or else the Sun is at rest (is situated) in the centre of the universe while the Earth revolves round it—that is the other of the two possible truths (the Copernican one). One of these candidates for the title of truth must be genuine truth, while the other, falsehood.

However, further development of physics, begun by Copernicus and Galileo, proceeded in the direction of an ever deeper penetration into the meaning of the concepts of rest and motion, in the direction of realisation of their relativity.

The following definition of a "deep" statement or remark is ascribed to Bohr: "In order to define a deep statement it is first necessary to define a clear statement. A clear statement is one to which the contrary statement is either true or false. A deep statement is a statement to which the contrary is another deep statement" [16, p. 597]. Both in this sense and from other viewpoints, the concepts of motion and rest are deep concepts, and statements about them, deep statements.

A frame of reference or of coordinates[8] may be associated with the Earth, and in this frame the Sun revolves round the Earth. This system is no more "false" and no more "true" than the system associated with the Sun (and, say, with the stars) in which the Earth, of course, revolves round the Sun. This equality and permittedness of different reference frames has long ceased to cause a shadow of doubt in kinematics. The same is true of the fact that the Sun is not immovable in reference frames connected with the nearest stars or other galaxies. It is thus clear that the terms "true reference frame" and "false reference frame" are inapplicable to characterising the systems of Ptolemy and Copernicus, and in general to reference frames, just as many other concepts of some complexity and profundity. The truth in this case lies elsewhere—in the specificity and

[8] The difference is often stressed in the literature, particularly in recent literature, between a frame of reference and a coordinate system. Indeed, not any coordinate system can describe real space-time or be realised in real bodies (see e. g. [17]). But there is no need here to go deeply into this problem, and all coordinate systems mentioned here may be identified with reference frames.

entire totality of parameters determining the structure of the solar system and capable of being reflected and described both in the geocentric and heliocentric coordinates. None of this contradicts, of course, the possibility of recognising the advantages, specific properties, etc., inherent in some reference frame or other. Rather characteristic in this respect (and quite true in its meaning) is the quotation from the book by A. Rey which Lenin cited in his *Philosophical Notebooks*: "Ptolemy's system ... shows us experience encumbered with individual ideas which depend on the terrestrial conditions of astronomical observation: it is the stellar system as seen from the earth. *The system of Copernicus and Galileo is much more objective*, since it does away with the conditions which depend on the fact that the observer is situated on the earth" [18, pp. 461-462].

4. Revival of the "Struggle of Ideas about the Structure of the Universe" or a Misunderstanding?

The ideas discussed at the end of the preceding section were sufficiently well realised even before the formulation of the general theory of relativity. One might therefore declare: "Ptolemy and Copernicus are equally right. What point of view is chosen is a matter of expediency." Or: "The struggle, so violent in the early days of science, between the views of Ptolemy and Copernicus was quite meaningless. Either coordinate system could be used with equal justification. The two sentences, 'the sun is at rest and the earth moves' or 'the sun moves and the earth is at rest', simply mean two different conventions concerning two different coordinate systems."

What can one say about statements like these? One may, of course, declare their authors to be idealists, reactionaries, and even supporters of the Inquisition. That would be either ignorance or demagogy (though both of these unedifying qualities get on very well with each other). The correct reaction must be something like this. The real struggle between the ideas of Ptolemy and Copernicus raged around the fact that the adherents of the Ptolemaic system regarded the Earth as immovable in some absolute sense of this notion and rejected the possibility of the Earth moving. They also rejected conclusions of Copernicus and his followers about the structure of the solar system and, to put it concretely, did not recognise the reality of laws in the motion of planets that were discovered in the heliocentric system. On both these points the Copernicans were absolutely in the right and their struggle against the old views was of course quite meaningful. The authors of the quotations above, in the teeth of historical realities, reduced the opposing views of Ptolemy and Copernicus to quite a different question, one of the possibility of using different reference frames and of their equality. One would naturally think that the main cause of this was the desire to focus attention on a certain point, or merely a *façon de parler* which was rather unfortunate, for it gave rise to misunderstandings, but that is a different question.

The reader must be surprised and even probably indignant at the author who invented certain "quotations" and then comments on them in an arbitrary manner: does this prove anything?

The point is, however, that the quotations were not invented. The first one is taken from Max Born's popular-science book widely known in this country [19, p. 345], the second, though in a slightly changed form, comes from an even better known popular book by Einstein and Infeld *The Evolution of Physics* [20, p. 212]. As for our comments, they are fully borne out by the entire context of these quotations as well as other "quite clear" pronouncements by their authors. True, the question is now not of kinematics but of the role and consequences of the general theory of relativity for the dynamic equality of reference systems. This circumstance, however, merely sets the questions debated even further apart from historical reality.

Thus what came to be connected with the general theory of relativity was not the real historical theme "Ptolemy and Copernicus" but, at best, its echoes and the more general (but more topical and much less acute) question of the existence of favoured, in regard of dynamics, frames of reference.

One of the variants of formulating this question, particularly interesting for our exposition, is clear from the article of V. A. Fok about the Ptolemaic and Copernican systems, where the author says:

"Within a narrow mechanist approach what is under discussion is the kinematics of the solar system. In the second century Ptolemy suggested one kinematic system of the solar system. In the 16th century, Copernicus suggested another. Copernicus's system proved to be the correct one. The truth of the Copernican system can only be solved by dynamics, by a science which studies masses and forces as causes of motion. Only dynamics can provide an answer to the question about the nature of acceleration: whether acceleration is absolute or relative. But this question is closely linked with the existence of favoured reference frames. Two points of view are possible here. According to one of them, favoured reference frames can be singled out having the property that, if acceleration equals zero relatively to one of them, it also equals zero relatively to any other. That means that the existence of acceleration different from zero is an objective fact independent from the choice of a favoured reference frame. (That is exactly what we understand by 'absolute nature of acceleration'). If acceleration is absolute in this sense, then Copernicus is right: for the solar system, the reference frame with the starting point in the centre of inertia of the Sun and the planets and with axes directed at three immovable stars is the favoured one (and also other reference frames in rectilinear and uniform motion relative to the first one). But another view is also possible, according to which there are no favoured frames, so that acceleration, just as velocity, is relative in nature. From this viewpoint both systems, the Copernican and the Ptolemaic, are equal. The former is connected with the Sun, the latter with the Earth, but neither of them has any advantages over the other. In this case the controversy between the adherents of the Copernican system and of the Ptolemaic system becomes aimless. Thus the question of whether one should decidedly prefer the heliocentric system to the geocentric is closely linked with the existence of favoured reference frames" [21, pp. 57-58].

Further Fok quotes the books by Born and by Einstein and Infeld mentioned above. We shall have to quote again from the latter source a passage which is always cited in our literature whenever Einstein's "errors" are referred to, and also the connections between the heliocentric system and the general theory of relativity: "Can we formulate physical laws so that they are valid for all CS, not only those moving uniformly, but also those moving quite arbitrarily, relative to each other? If this can be done, our difficulties will be over. We shall then be able to apply the laws of nature to any CS. The struggle, so violent in the early days of science, between the views of Ptolemy and Copernicus would then be quite meaningless. Either CS could be used with equal justification. The two sentences, 'the sun is at rest and the earth moves', or 'the sun moves and the earth is at rest', would simply mean two different conventions concerning two different CS. Could we build a real relativistic physics valid in all CS; a physics in which there would be no place for absolute, but only for relative motion? This is indeed possible! " [20, p. 212].

We shall discuss this passage later. It follows from this quotation (and, chiefly, from other materials) that Einstein and Infeld (and many others) believe that, in the light of the general relativity theory, no favoured reference frames, analogous in this respect to the inertial frames of classical mechanics, can be introduced; they do not exist. On the contrary, Fok [21, 22] insists on the existence of favoured reference frames in the general relativity theory as well, hence "the absolute (in the sense indicated above) character of acceleration in Einstein's theory of gravitation" [21, p. 68]. Here we deal with differences of opinion on physical questions, although with a certain admixture of terminological (and therefore not exactly substantive) character. We shall dwell on this in later sections of the article. But, whatever conclusion we might arrive at, the historical controversy between Ptolemy and Copernicus has essentially no bearing on this, it becomes neither aimless nor meaningless, unless one prefers to call the favoured reference frame, if it exists, "true", and the non-favoured, "false", which will neither add to or detract from the advantages of the one and the defects of the other.

In the light of the above the present author obviously cannot agree with A. D. Alexandrov, who, in a paper with the meaningful title "Truth and Error", writes the following about the discussion of the general relativity theory:

"The old dramatic struggle of ideas about the structure of the universe, which at one time led to Galileo's trial, was revived", and further:

"The situation was dramatic in that a question so acute at one time and seemingly long solved was raised..." [23, p. 100].

We have taken pains to remind the reader of the fact (and to confirm it) that the "seemingly long-solved" question was in fact long solved (the Earth is not an absolutely immovable centre of the world), and that we are not dealing here with a revival of the "struggle of ideas about the structure of the universe" but first of all with the misunderstandings arising out of imprecise and careless exposition of views sometimes occurring in the literature (first of all in popular science). Apart from that, in the light of the general relativity theory the discussion continues, though it had never stopped, about the possibility of introducing inertial or some other favoured reference frames; this question is at best only remotely related to the structure of the universe.

In concluding this section, we would like to remark on one particular point pertaining to the study of Einstein's creativity. The fascinating thing about Einstein the man was his modesty, a self-critical attitude, complete absence of majestic hauteur or megalomania traits that are not infrequent among learned men of extremely diverse calibre. There are no grounds for canonising Einstein, of course. On the contrary, analysis of his mistakes and errors is quite appropriate and interesting. Historically speaking, the errors and mistakes of great men are no less instructive than their strong points. There is one thing, however, that we owe in our respect for great men, for Einstein in this case, and that is careful attitude to their literary heritage. In the light of this requirement one must admit, we believe, that *The Evolution of Physics* [20] cannot be a source for an analysis of Einstein's views, particularly where concrete formulations and the text itself in general are concerned.

This will be quite obvious to anyone who will read

Infeld's biographical book [24] and his memoirs [25, 26]. The stipend which allowed Infeld to live and work at Princeton came to an end, and he had an idea to write a popular-science book as a way out of financial difficulties. But, to ensure the book's commercial success, it had to appear under Einstein's name. Einstein agreed to this, possibly out of kindness and also to be able to continue working together with Infeld on the deduction of the equations of motion of material points from the equations of the gravitational field theory (i.e., the equations of the general theory of relativity for the metric tensor g_{ik}). Later Einstein must have been carried away by the idea to write a popular book–something he had never been able to do. But the book was written by Infeld only, and Infeld, because of his poor command of English, often had to resort to his friends' help. He then read the text out loud to Einstein, who often said:

"It is all the same to me in what way you will write it. You know better. But this idea must be in the book by all means" [25, p. 165].

Further Infeld narrates:

"When the copies of the book came, I brought them to Einstein. He was not interested in the book at all, he did not even bother to see how it looked, just as he had not looked at the proofs" [25, p. 169].

With reference to the subsequent discussion of the book in the press, Infeld writes:

"One of the objections, so stupid that it was difficult to reply to it, was that we were allegedly against the Copernican theory, that we wrote that the theory of Copernicus and that of Ptolemy were the same, for everything depends here on the frame of reference, and in the relativity theory the reference frame is arbitrary. For this reason we were obscurantists (guilty of "popery"), as some reviewers insisted, and apparently also (this I shall add myself) supporters of the Inquisition. Indeed, the point in question was not formulated clearly enough, but to draw the conclusion that the theory of relativity in any degree underestimated the cause of Copernicus was tantamount to an accusation that is not worth refuting even" [25, pp. 165-166].

We have discussed this point substantively in the above;

the position of Infeld is also quite clear. Here we merely wanted to explain why *The Evolution of Physics* cannot be used as a source for the study of Einstein's views. Furthermore, there is no need to use it, for even the very incomplete (as regards publicistic works, letters, etc.) edition of Einstein's works published in the Soviet Union in 1965-67, consists of four bulky volumes. We would like to express the hope that the unfortunate quotation from *The Evolution of Physics,* which we had to cite above, too, will no longer figure in the literature.

Newton

The system of concepts and laws constituting the basis of classical mechanics assumed an accomplished form, in a certain respect, only in the works of Isaac Newton who published his *Mathematical Principles of Natural Philosophy* in 1687. Thus it took about a century and a half to overcome the concepts worked out in antiquity, based on everyday observations and "common sense", and to replace them with new ones through the efforts of Copernicus, Galileo, Kepler and, of course, many others (whose names one can at best find in books on the history of science).[9]

The laws of mechanics were formulated by Newton in the following manner:

"Law I. Every body continues in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed upon it.

"Law II. The change of motion is proportional to the motive force impressed; and is made in the direction of the right line in which that force is impressed.

"Law III. To every action there is always opposed an equal reaction; or, the mutual actions of two bodies upon

[9] Antique mechanics was founded on the law of motion according to which a body moves uniformly or in general is not at rest only as long as a force is applied to it, which precisely corresponds to everyday reality with its considerable friction forces. Only Galileo gave up this principle clearly and decisively, adopting the opposite one—the law of inertia: in the absence of forces a body moves uniformly along a rectilinear trajectory.

each other are always equal, and directed to contrary parts"[27, p. 13].

All these three laws, as applied to the fundamentally important case of a system of material points, where the forces depend only on distances between points, are now usually written in the following form:

$$m_i \frac{d^2 \vec{r}_i}{dt^2} = \Sigma \vec{F}_{ik} (r_{ik}), \tag{1}$$

$$\vec{F}_{ik} (r_{ik}) = - \vec{F}_{ik} (r_{ik}), \tag{2}$$

where m_i is the mass of the point (body) i; $\vec{r}_i\ (t)$ is the radius vector corresponding to this point, and $\vec{F}_{ik}$ is the force acting on point i from the side of point k which is at the distance $r_{ik} |\vec{r}_i - \vec{r}_k|$ from it.

We do not intend to go into detailed analysis of the physical content of various concepts[10] and laws of classical mechanics but shall merely touch upon the question of reference frames directly bearing on the subject of this article. The importance of this question is obvious, for Newton's Laws I, II and III are simply meaningless until a reference frame is indicated (including the method for measuring or computation of time) with regard to which the vectors $\vec{r}_i\ (t)$ are defined. Suffice it to point out that uniform and rectilinear motion of a material point in some reference frame K may be non-uniform and curvilinear in other reference frames K' (this occurs, e.g., if the frame K' revolves round K or if a clock in the frame K' goes non-uniformly relative to the clock in K, etc.). Thus Newton's laws (in their entirety and in the form indicated above) are only correct for a definite class of reference frames. These are now called inertial, though this concept became current rather late (only in the 19th century; see below). But Newton treated his laws as something absolutely precise, believing them to be valid in some absolute space and absolute time defined in the following manner:

[10] The concept of mass, for instance, is dicussed in detail in [28].

"Absolute, true, and mathematical time, of itself, and from its own nature, flows equably without relation to anything external, and by another name is called duration: relative, apparent, and common time, is some sensible and external (whether accurate or unequable) measure of duration by the means of motion, which is commonly used instead of true time; such as an hour, a day, a month, a year.

"Absolute space, in its own nature, without relation to anything external, remains always similar and immovable. Relative space is some movable dimension or measure of the absolute spaces; which our senses determine by its position to bodies; and which is commonly taken for immovable space..."[27, p. 6].

The metaphysical nature of absolute space and absolute time is quite obvious to the modern reader. But absolute space and absolute time, comprehended as something immutable and external, were finally ousted from physics only two centuries later, after the formulation of the theory of relativity. At the same time many works published much earlier contain a critique of Newtonian conceptions of absolute space and time, as well as a physical definition of reference frames in which Newton's laws are true (see, e.g., [29, 30], as well as a number of references in [31]). The crux of the matter is that there actually exist reference frames (they were called inertial) in which Newton's laws obtain at a level of precision which corresponds to the sphere of application of classical mechanics. It is this statement that expresses the meaning of Newton's first law (the law of inertia), whereas in Newton's formulation it is just a particular case of the second law.[11] In practice, both in physics and astronomy, an inertial frame is introduced, defined and used by quite

[11] That is so if it is known that the body is unaffected by any forces $\vec{F}_{ik}$. On the other hand, it would appear that one could only learn that a body is unaffected by any forces if it moves by inertia, that is, uniformly and in a straight line in an inertial reference frame. For this reason if one wants to avoid a vicious circle, one cannot define inertial frames as those for which the law of inertia obtains. Experience shows, however, that in some reference frames (best of all in the reference frame used in astronomy and associated with the centre of gravity of the solar system and "immovable" stars, see below) Newton's second and third laws obtain with high precision and in the absence of any forces but those caused by the bodies in

concrete physical operations, for example, by application of the Foucault pendulum and such points of control as "immovable stars" or the real stars and galaxies. In this approach it is quite obvious that no inertial frame may be regarded as such with some absolute precision.[12]

The number of inertial frames is infinitely great, for any reference frame moving at a constant speed $\vec{v}$ = const relatively to any inertial frame is also an inertial frame. This circumstance, based on experimental data, constitutes the content of the principle of relativity of classical mechanics. Formally, this principle consists in the fact that the equations of motion (1) are not altered, that is, they obtain, under the Galileo transformations

$$\vec{r}'_i = \vec{r}_i - \vec{v}t, \quad t' = t, \tag{3}$$

where $\vec{r}'_i$ and $\vec{r}_i$ are the radii vectors of the point i in the new and the old systems of coordinates respectively, moving relatively to one another at a constant speed of $\vec{v}$ = const.

Thus in all inertial reference frames mechanical phenomena occur in an identical manner (provided, of course, that the initial conditions are identical). Equality of all inertial frames (the principle of relativity) does not permit, at any rate within the framework of mechanics, to regard one of them as "absolute". However, acceleration is identical relatively to all inertial frames, and it may be called "absolute" in this sense. In particular, if a body rotates relatively to one inertial frame of reference, it rotates in other frames as well. In a rotating reference frame (in a frame connected with a body rotating relatively

the solar system. In this reference frame a body sufficiently remote from all others will move by inertia.

If we take that the absence of forces (external influences) acting on the body may be guaranteed and controlled (this is to some extent ensured by sufficient remoteness of all the other bodies), the existence of an inertial reference frame may be identified with the possibility of finding a reference frame relative to which space is uniform and isotropic and time, uniform [32].

[12] It is a different matter that the question of "the degree of inertiality" or, in other words, of the precision with which the given reference frame may be regarded as inertial, remains in most cases in the background (see in this connection [33, 34]).

to the inertial frame) the law of motion (1) no longer obtains in the sense that, apart from the forces $\vec{F}_{ik}\ (r_{ik})$ the so-called inertial forces appear—the centrifugal force and the Coriolis force.[13] By their action, the plane of oscillations of a pendulum whose point of suspension is fixed relatively to the rotating body (of this type is the Foucault pendulum) keeps rotating relatively to the body. In particular, the Foucault pendulum may be used to prove the Earth's rotation, that is, the fact that it is not an inertial frame. True, the Foucault experiment was first performed in the middle of the 19th century, when rotation of the Earth relatively to inertial frames was no longer doubted.

In Newtonian mechanics, inertial frames are obviously marked out compared to non-inertial ones and may with sufficient justification be called favoured reference frames. Yet this favoured status is rather relative. Only Newtonian absolute space would be genuinely favoured here, as well as the "most favoured" reference frame connected with it. All the real, practically applied inertial frames of classical mechanics and frames equivalent to them by the principle of relativity, first, form a whole infinite family and, second, are defined only approximately. The latter point, just as the use of approximate concepts in general, is from the modern viewpoint quite natural and causes neither astonishment nor objections. But this conclusion was the result of a long development. Until the formulation of the general relativity theory, inertial frames were raised to an absolute, in one degree or another; it was believed that there existed some "absolutely exact", absolutely favoured inertial frames, and that the limited "degree of inertiality" of all the reference frames practically used was not a matter of principle. It turned out, however, that this was not so, and that is one of the essen-

[13] Thus, if in the law of motion (1) we do not specify the type of the forces $\vec{F}$, regarding them as dependent only on r_{ik}, and if condition (2) is satisfied, law (1) obtains in all reference frames; in the vector form of notation the reference frame is not explicitly expressed. For the notation of the equations of mechanics in covariant form (in an identical form for all reference frames) there is no special need even to introduce generalised coordinates and to write equations in the Lagrangian form.

tial results of the general theory of relativity.

Before we pass on to this stage in the development of physics, let us return to the question of geo- and heliocentric reference frames. The degree of inertiality of a reference frame connected with the Earth, in the observation of phenomena on the Earth's surface, is determined by the ratio of centrifugal or Coriolis's acceleration a to free fall acceleration $g \sim 980$ cm/sec^2. For example, on the equator the ratio of centrifugal acceleration to free fall acceleration[14] is $a/g \sim 10^{-3}$. Of the same order is the ratio of acceleration connected with the motion of the Earth round the Sun to free fall acceleration g. Therefore, not only in the times of Galileo (not to mention Copernicus), but also much later the Earth could be, and was actually regarded, with a sufficient degree of precision, as an inertial frame. (This is true, however, only of motion on the Earth's surface or comparatively near it).

It is thus obvious that dynamic considerations (as regards the role of inertial forces or the non-inertial quality of the reference frames chosen) did not play any role in the development of the Copernican system. We take it as indubitable that, if some effects resulting from the difference of the heliocentric reference frame from the inertial one were several orders of magnitude greater than the actual non-inertiality of the heliocentric system (including relativistic corrections), that would not have been noticed by Copernicus and would not have affected his studies. This remark may, we hope, appear less scholastic (which it undoubtedly to some extent is) if instead of the solar system we consider a planetary system associated with one of the components of a double star. Under these conditions, for a wide region of values of masses of stars and planets the reference frame associated with one of the stars (and analogous in this respect to the heliocentric system) may prove to be much more con-

[14] Centrifugal acceleration $a = v_{\oplus}^2/r_{\oplus} = \omega_{\oplus}^2 r_{\oplus} \sim 1$ cm/sec^2, where $v_{\oplus} = \omega_{\oplus} r_{\oplus}$ is the velocity of the Earth's surface; $\omega_{\oplus} = 2\pi/T_{\oplus} \sim 6 \cdot 10^{-5}$ sec^{-1} is the Earth's angular velocity; $r_{\oplus} \sim 6 \cdot 10^8$ cm is its radius. The Earth's acceleration as a result of its revolutions round the Sun is $a = v_0^2/R = 0.6$ cm/sec^2 as the speed of the Earth in orbit is $v^0 = 3 \cdot 10^6$ cm/sec and the orbit radius $R = 1.5.10^{13}$ cm.

venient compared to an inertial frame associated with the mass centre of the double star. Further, for the analysis of the motions of Jupiter's numerous satellites, the most convenient is the reference frame associated with Jupiter and analogous in this respect to the geocentric system. These examples (and their number is easy to increase) illustrate the thesis that the dynamically favoured position of the heliocentric system is of no consequence in an evaluation of Copernicus's historical achievements and the actual content of the arguments between Copernicans and the opponents. In other words, the controversy between the adherents of the Copernican and the Ptolemaic system would in no degree become aimless, if the heliocentric system was much less near to an inertial reference frame than it actually is. This should not be taken, of course, as a negation of the indubitable fact that is was the use of the heliocentric system in the analysis of the kinematics and dynamics of the solar system which essentially simplified the establishment of Keplerian laws and of Newton's laws of motion.

These remarks apply, in our view, to the general problem of favoured reference frames. Whether such frames exist or not is to a considerable extent a matter of definition, and discussion of this question is strongly reminiscent of similar discussions in the past. Yet we shall still have occasion to dwell on favoured reference frames in our analysis of the evolution of concepts of reference frames and of the physical content of the general theory of relativity.

Einstein

In pre-relativistic, pre-Einsteinian physics, despite the impossibility of singling out some inertial reference frame in mechanics among other such frames, the belief was still alive in the existence of some "absolute" or "super-inertial" reference frame which materialised Newtonian absolute space. This belief was based on an interpretation of electrodynamic (in particular, optical) phenomena in terms of concepts of ether and especially of immovable ether. This ether ideally suited the role of an absolute (and absolutely favoured) reference frame. But immovable ether proved to be essentially the same kind of metaphysical category as absolute space, and the ether concept was discarded after the creation in 1905 of the special theory of relativity. In the article "Relativity and the Ether" (1920) Einstein remarked of it: "As regards the mechanical nature of Lorentz's ether, one might say of it, with a touch of humour, that immobility was the only mechanical property which Lorentz left it. It may be added that the whole difference which the special theory of relativity made in our conception of the ether lay in this, that it divested the ether of its last mechanical quality, namely immobility" [35, p. 127.][15]

The special theory of relativity thus destroyed the hope that one of the inertial reference frames will somehow be raised to the rank of "an absolute reference frame", which is a synonym of absolute space; nevertheless inertial frames and their favoured position were fully retained. Dissatisfaction about this circumstance was one of the sources and motive forces which led Einstein to the formulation of the general relativity theory.

It is rather symbolic that the question of inertial frames in connection with the general theory of relativity was fairly thoroughly considered in Einstein's last publication "Relativistic Theory of the Non-Symmetric Field" which appeared in 1955, the year of his death, and contained an attempt at a generalisation of the general theory of relativity. Einstein wrote there: "It is an essential achievement of the general theory of relativity that it has freed physics from the necessity of introducing the 'inertial system' (or inertial systems). This concept is unsatisfactory for the following reason: without any deeper foundation it singles out certain coordinate systems among all conceivable ones. It is then assumed that the laws of physics hold *only* for such inertial systems (e.g. the law of inertia and the law of the constancy of the velocity of light).

[15] This idea is contained already in Einstein's main work "On the Electrodynamics of Moving Bodies" devoted to the special theory of relativity: "... the view here to be developed will not require an 'absolutely stationary space' provided with special properties, nor assign a velocity-vector to a point of the empty space in which electromagnetic processes take place" [36, p. 38].

Thereby, space as such is assigned a role in the system of physics that distinguishes it from all other elements of physical description. It plays a determining role in all processes, without in its turn being influenced by them. Though such a theory is logically possible, it is on the other hand rather unsatisfactory. Newton had been fully aware of this deficiency, but he had also clearly understood that no other path was open to physics in his time. Among the latter physicists it was above all Ernst Mach who focused attention on this point.

"What innovations in the post-Newtonian development of the foundations of physics have made it possible to overcome the inertial system?

"First of all, it was the introduction of the field concept by, and subsequent to, the theory of electromagnetism of Faraday and Maxwell, or to be more precise, the introduction of the field as an independent, not further reducible fundamental concept. As far as we are able to judge at present, the general theory of relativity can be conceived only as a field theory. It could not have developed if one held on to the view that the real world consists of material points which move under the influence of forces acting between them. Had one tried to explain to Newton the equality of inertial and gravitational mass, he would necessarily have had to reply with the following objection: it is indeed true that relative to an accelerated coordinate system bodies experience the same accelerations as they do relative to a gravitating celestial body close to its surface. But where are, in the former case, the masses that produce accelerations? It is clear that the theory of relativity presupposes the independence of the field concept" [37, p. 139-140].

And now let us go almost fifty years back and turn to Einstein's work "On the Principle of Relativity and the Consequences Deducted from It" [38, S. 441-462] in which he began, in 1907, the construction of the general relativity theory.[16] Section 17 of this work, which has the

[16] The works "On the Electrodynamics of Moving Bodies" and "On the Principle of Relativity and the Consequences Deduced from It" are separated by an interval of some two years, but Einstein must have begun thinking about the problem of gravitation within the

title "The Accelerated Reference System and the Gravitational Field", is rather brief, so we can quote it in full.

"So far [writes Einstein] we have applied the principle of relativity, that is, the condition of independence of the laws of nature from the states of motion of the reference system, only to *non-accelerated* reference systems. Is it conceivable that the principle of relativity is also valid for systems that are accelerated relative to each other?

"True, this is not the place for a thorough handling of this question. But, since the latter necessarily arises before anyone who has so far followed the applications of the principle of relativity, I will not avoid expressing my position on the problem.

"Consider two moving systems Σ_1 and Σ_2. Let Σ_1 be accelerated in the direction of its X axis, and let γ be the magnitude of this acceleration (constant with regard to time). Let Σ_2 be at rest; but let it be in a homogeneous gravitational field that imparts all bodies a γ-acceleration in the direction of the X axis.

"So far as we know, physical laws in regard of Σ_1 do not differ from those of Σ_2; that depends on the fact that all bodies are identically accelerated in the gravitational field. Therefore we have no reason to assume, at the present stage of our knowledge, that the systems Σ_1 and Σ_2 differ from each other in any respect, and we shall therefore assume below complete physical equiva-

framework of the relativity theory much earlier than that. This conclusion follows first of all from the remark, occurring in the article "Notes on the Origin of the General Theory of Relativity" [1, pp. 285-290] and in the "Autobiographical Notes" [39, pp.65-69], that he tried at first to construct a scalar relativistic theory of the gravitational field. But the article "On the Principle of Relativity and the Consequences Deduced from It", which is based on the equivalence principle, does not even mention this attempt. It is curious that in 1912 G. Nordström began to develop a scalar theory of the gravitational field, and it was abandoned only after it was proved in 1919 that light rays passing in the neighbourhood of the Sun deviate (this effect is entirely absent in the scalar theory). But a mixed tensor-scalar theory of gravitation is discussed even now (see, for example [45, 46], and it may be regarded as one of the alternatives to the general relativity theory in the construction of a theory of the gravitational field, under certain assumptions (like the choice of parameters, etc.) which do not contradict experiment and observation (see below).

lence of the gravitational field and corresponding acceleration of reference systems.

"This assumption extends the principle of relativity to the case of uniformly accelerated rectilinear motion of the reference system.

"The heuristic value of this assumption lies in that it allows to replace a homogeneous gravitational field by a uniformly accelerated reference system, which latter case is to a certain extent amenable to theoretical treatment" [38, S. 454].

That was the beginning of the construction of a theory which many (including the present author) regard as an unsurpassed attainment of theoretical physics.

The passage quoted here treats of a homogeneous gravitational field and a uniformly accelerated reference frame, but there is no hint here at "excluding" any gravitational field through a choice of a reference frame. And in the next paper, "On the Influence of Gravitation on the Propagation of Light" (1911) he specially emphasises the following point: "Of course, we cannot replace any arbitrary gravitational field by a state of motion of the system without a gravitational field, any more than, by a transformation of relativity, we can transform all points of a medium in any kind of motion to rest" [36, p. 100].

Let us quote another of Einstein's remarks on this score:

"*But* one *cannot go* further and say: If K' is a reference system provided with an *arbitrary* gravitational field, then one can always find a reference system K in relation to which isolated masses move rectilinearly and uniformly, that is, in relation to which no gravitational field exists. The absurdity of such a premise is quite apparent. If, for example, the gravitational field assigned to K' is that of a point mass at rest, this field in the whole neighbourhood of the point mass cannot be of course transformed away by transformational sleight-of-hand. One cannot therefore assert that the gravitational field can be to some extent explained kinematically; a 'kinematic, not dynamic conception of gravitation' is impossible. We cannot cognise any *arbitrary* gravitational fields by a mere transformation from one Galilean system to another through acceleration transformations, but only those of a quite special kind which, however, must satisfy the same laws as all other gravitational fields. That is merely another formulation of the equivalence principle (as specifically applied to gravitation)" [40, S. 640-641].

These quotations, to which may be added many more, do not leave any doubt, in our view (see also [41]), that Einstein never adhered to the "kinematic" conception of gravitation and thus considered the principle of equivalence to have, generally speaking, only local character.

The principle of equivalence is an assertion of complete identity of all physical processes and phenomena in a uniform gravitational field and in a corresponding uniformly accelerated reference frame, rather small spatio-temporal regions being taken up in a general case.[17] The principle of equivalence determines equality of the inertial mass m_u and of the gravitational mass m_T; their inequality would mean that mechanical motions in an accelerated reference frame and in a gravitational field would differ.[18] But the reverse is not true. Equality of inertial and gravitational masses ensures, of course, the principle of equivalence in classical (non-relativistic) mechanics, but it does not at all guarantee its universal correctness, e.g., for the field of optical phenomena. To show how great the difference may be here, let us cite the following example [42].

In classical mechanics the principle of relativity (that is, equivalence of all inertial reference frames) obtains where the Galilean transformations (3) are used. But the

[17] See [54, 16] on the possible expansion of this field in time. Let us note that, due to the restrictedness to small regions, equivalence of the effect of the field and of the acceleration of the reference frame does not extend to effects like tidal phenomena depending on second derivatives of the gravitational potential φ or, in a more general case, on second derivatives of the metrical tensor g_{ik}.

[18] Let us recall that inertial mass is taken to mean the magnitudes $m_i = m_{u,i}$ which figure in the equations of motion (1). According to Newton's law of universal gravitation, the force of attraction in this case is $F_{ik} = Gm_i\, m_k/r^2_{ik}$, the masses m_i and m_k being already "gravitational" masses $m_{T,i}$ and $m_{T,k}$—characteristics of gravitational interaction. Due to the equality of the inertial and gravitational mass, in the motion of any body in a gravitational field (in the absence of any other forces) the mass of the body is reduced (cancelled) out of the equations of motion. It is precisely for this reason that acceleration of all falling bodies in a given gravitational field is the same.

same principle, extended to optics and "the whole of physics", is only valid if the Lorentz transformations are applied. The transition from the equality $m_u = m_T$ to the principle of equivalence is analogous to extending the principle of relativity of classical mechanics to the whole of physics. True, the enormous exactness of the equality $m_u = m_T$ that has been proved by now (according to [43, 44] $|m_u - m_T| / m_u < 10^{-12}$ permits the indirect conclusion that the principle of equivalence also obtains in the theory of electromagnetic and strong (and also, within certain limits, in the case of weak) interactions, but that is a different matter. Besides, inasmuch as the concepts of inertial and gravitational mass are introduced in classical mechanics, they have a very limited sense for this reason, so that the equality $m_u = m_T$ can still less replace the much more comprehensive principle of equivalence. All these remarks appear to be appropriate here since the principle of equivalence is literally the foundation or physical basis of the general theory of relativity.[19] Apart from everything else, how are we to understand otherwise why the gravitational field must be described precisely with the help of the metrical tensor g_{ik} characterising the geometry and the reference frame, rather than by some other magnitudes? That is a natural way to develop theories of the gravitational field different from the general theory of relativity—by introducing other magnitudes instead of or side by side with g_{ik} (see [45, 46, 42, 47, 48]). At the same time, once the general theory of relativity has been constructed, it is guaranteed that the principle of equivalence obtains in any sufficiently small region, and the principle itself may be forgotten, the midwife can now be "buried with appropriate honours" [49, p. X] (see also [21, 22] for critical remarks concerning the principle of equivalence). It is clear from the above that the present author (as also most other physicists, see e.g. [17, 20, 50, 51-55]) in no way shares this view, adhering to Einstein's standpoint.

Let us go back to our main subject—the question of reference frames.

19 "In my view, my theory rests exclusively on this principle," thus spoke Einstein on this subject [40, S. 639].

Due to the principle of equivalence (which is confirmed by all data available, sometimes with fantastic precision [43, 44], an inertial frame cannot be distinguished from a uniformly accelerated one (with acceleration $\vec{g}$ relative to the inertial frame), in which there is a homogeneous gravitational field imparting to the bodies acceleration $-\vec{g}$. In both these cases an isolated body will move by inertia (that is, without acceleration). By dint of this, the special principle of relativity (equivalence of all inertial reference frames) is indeed expanded.[20] Or, which is one and the same in this case, inertial frames cannot be distinguished from a considerably broader class of frames having constant acceleration and also a gravitational field (inertial frames may in this connection be called "unobservable" [56]. But that is merely a beginning, since the general relativity theory, after it has been constructed, generalises classical mechanics and the theory of gravitation, incorporating them as limiting cases, and does not introduce or use inertial reference frames (for finite and still less so for infinitely great regions of space-time). The "genuine" gravitational field that cannot be removed by the choice of a reference frame, does exist, but it has the same nature as Newtonian inertial forces or the homogeneous field, and is manifested, according to the general theory of relativity, in the non-Euclidean quality of space-time (in curvature). This important point deserves, of course, a more detailed treatment, which is done in all the books (including popular-science) on the general theory of relativity. Here we shall have to give up the idea of such discussion, contenting ourselves with the remark that in a non-Euclidean (Riemannian) space the "probe" (a material point whose gravitational field is sufficiently weak) moves along the geodesic in the absence of forces—let us say, of electromagnetic ones. In spaces with varying curvature (in different gravitational fields) geodesic lines are, of

[20] A gravitational field homogeneous throughout the whole space and an infinitely extended uniformly accelerated reference frame, are abstractions whose limited significance was fully established precisely by the general theory of relativity. But from the standpoint of critique of classical mechanics, where no limitations were introduced on the size of reference frames, this remark appears to be quite convincing.

course, also different, that is, universal uniform and rectilinear motion, as that of classical mechanics, does not exist.

Thus the general relativity theory, approximate and limiting cases apart, has no favoured inertial reference frames. Accordingly, the theory develops on the basis of equations that have an identical (covariant) form for a very broad class of all possible reference frames. Insofar as not one of these frames is better (more favoured) than others, all frames prove to be equal. It is on this basis that the term "general relativity principle" and the name "general relativity theory" emerged. Equality of inertial frames (the special relativity principle) indubitably has another meaning as well—it may be said to have positive significance: under identical initial conditions a body describes an identical trajectory in all frames (let us restrict ourselves to this elementary example). In arbitrary reference frames the trajectories of moving bodies are also very arbitrary. However, inasmuch as there is no reference frame, not to mention an infinite family of reference frames, with some exceptional singled out properties, all frames again prove to be equivalent, although this equivalence is of a different, one may say, negative, character (see also [52, p. 182]. We would have liked to sum up all of this in the words of Einstein himself.

"Let K be an inertial frame without a gravitational field, K' a system of co-ordinates accelerated uniformly relative to K. The behaviour of material points relative to K' is the same as if K' were an inertial frame in respect of which a homogeneous gravitational field exists. On the basis of the empirically known properties of the gravitational field, the definition of the inertial frame thus proves to be weak. The conclusion is obvious that any arbitrarily moved frame of reference is equivalent to any other for the formulation of the laws of Nature, that there are thus no physically preferred states of motion at all in respect of regions of finite extension (general relativity principle).

"The implementation of this concept necessitates an even more profound modification of the geometric-kinematical principles than the special relativity theory... Generalizing, we arrive at the conclusion that gravitational field and metric are only different manifestations of the same physical field" [57, pp. 485-486].

The passages from Einstein quoted here show clearly the very natural origin of the name "the general theory of relativity". That is certainly a theory of the gravitational field, but a very definite theory of such field founded only on the metric tensor g_{ik} and concrete equations for g_{ik}. To distinguish this theory from many others [45, 46, 47, 48], though not so highly accomplished (not in our opinion, anyway), it would be necessary to use the term "Einstein's theory of the gravitational field" or "Einstein's theory of gravitation". That is what is sometimes done, and there can be no objections to that. We would have liked merely to stress in this connection that the name "the general theory of relativity" is quite natural, and there are no grounds for giving it up, not to mention the fact that it would be practically impossible to replace this name because of the well-established tradition.

Regrettably, questions of terminology and usage are frequently so closely interwoven with essential problems that they often interfere with the discussion of these problems, dictating the form of the debate, and compelling one to argue about words. True, the problem of a name for a theory (and concretely the question of the name "the general theory of relativity") is so purely terminological that it cannot engender any substantive divergence of opinion. But the problem of the existence of favoured or preferred reference frames in the general relativity theory is a different matter. Einstein's opinion on this subject is quite clear from the last passage that we quoted. It should only be explained that the reservation about absence of physically preferred states "in respect of regions of finite extension" is very important. Of course, there exists in the general theory of relativity a favoured reference frame for sufficiently small (formally, infinitely small) regions of space-time: we have in mind the local-inertial reference frame in free fall (the reference frame in a "falling lift"), in which there are no gravitational forces and the special theory of relativity obtains. But these frames are not merely local; they also do not coincide with the inertial frames of classical mechanics which ideally are not local and permit the existence of gravitational forces.

As for regions of finite extension in general, we do not see any genuine analogue of inertial frames—no systems that would be just as favoured. That is where the possibility of terminological controversy arises. The study of concrete physical problems involves certain simplifications, approximation, and idealisation. If we are dealing, say, with the dynamics of the solar system, it is natural, owing to the small acceleration of the Sun in the Galaxy, to small masses of planets, and to small angular velocity of the rotation of the Sun, to use the central-symmetry reference frame which is connected with the centre of the Sun, is Euclidean (Galilean) at infinity, and does not take into account the rotation of the Sun (this circumstance is, properly speaking, reflected already in the assumption of spherical rather than axial symmetry of the problem). The corresponding reference frame and the solutions of the field equations obtained in it (particularly Schwarzschild's solutions) are used very widely. Recently, the axial-symmetric reference frame and the solutions obtained in it (in the first place those of Kerr [58] are more and more used in the study of isolated rapidly rotating stars and black holes. In analysing cosmological models, mostly associated reference frames are used, in which mean large-volume distribution of matter is at rest; here matter density is averaged over volumes containing many galaxies and clusters of galaxies. All these frames may be referred to as favoured, they are actually favoured within the approximations and limitations employed. It is quite obvious, however, that this preferred status is of particular nature, quite different from the favoured status ascirbed to inertial frames by classical mechanics.

This last remark is fully applicable, in our view, to the so-called harmonic systems of coordinates, which Fok believes to be "privileged" to such an extent that, only having recognised the fundamental significance of the existence of a favoured harmonic coordinate system, "can one speak of the correctness of Copernicus's heliocentric system in the same sense in which it was possible in Newtonian mechanics. Failure to recognise favoured coordinate systems leads to the view that Copernicus's heliocentric system and Ptolemy's geocentric system are equal"[22, p. 475].

Einstein's equations for the gravitational field (for the metic tensor g_{ik}) are written in an arbitrary (within broad limits) coordinate system or, as it is said, they are general-covariant. Therefore four coordinates x_i may be subjected to arbitrary transformations; in this way four out of ten components of the tensor g_{ik} may be selected. In other words, only six components of g_{ik} are independent and, consequently, apart from the field equations, four additional "coordinate conditions" may be imposed on g_{ik} (for details see [19, p. 321, 22, 49, 51, 52, 53]. These coordinate conditions include the harmonic conditions introduced as early as 1921 [59] and often applied ever since (see in particular [22] and the references there).

These conditions have the form

$$\frac{\partial \sqrt{-g\, g^{ik}}}{\partial x_i} = 0, \tag{4}$$

where g^{ik} are contravariant components of the tensor g_{ik} (x_j), and g is a determinant out of the magnitudes g_{ik} $(i, k = 0, 1, 2, 3)$.

For an isolated ensemble of bodies under the conditions of Galilean metric at infinity and the radiation condition (that is, in the absence of gravitational waves reaching the system of bodies under consideration from outside), the equation (4) unambiguously defines the coordinate system up to the Lorentz transformation (with constant coefficients).[21] For this last reason acceleration of the particle in all harmonic systems is identical, just as in the case of all the inertial reference frames of classical mechanics. That is exactly the circumstance which brings together inertial and harmonic frames. Still, harmonic frames are merely a pale ghost of inertial frames. Indeed, the latter were introduced in all space and without any limitations. Harmonic frames, on the other hand, define the coordinate system up to the Lorentz transforma-

[21] However, it is not clear to us whether the proof [22] of the unambiguousness of harmonic frames up to the Lorentz transformations remains valid in the presence of some specific conditions in the solutions of Schwarzschild and Kerr, and also, undoubtedly, in the more general solutions which have to be considered in the case of collapsing masses.

tion first of all under the assumption that at infinity space is Galilean, that is, Euclidean or pseudo-Euclidean, with reference to space-time. But this assumption is practically identical to the assumption of the existence of inertial frames "at infinity", for which there are absolutely no grounds (moreover, cosmology usually considers models without this property). Neither are there any grounds to believe that the system of bodies under consideration is not reached by gravitational radiation from the outside. Of course, in an approximate formulation of the task this assumption, just as the Euclidean nature of the metric at infinity, is often natural and reasonable. But the whole point is that in classical mechanics inertial frames were not at all an approximate concept. Finally, inertial frames were singled out in classical mechanics according to quite definite physical features (absence of inertial forces or in some equivalent manner). And do conditions (4) have any physical meaning apart from that mentioned earlier? There are more reasons to regard as favoured in this respect those reference frames which have a static gravitational field in the case of a spheric mass (Schwarzschild's solution), or a stationary gravitational field outside a rotating mass (Kerr's solution). Let us add that the harmoniousness conditions (4) have a formal affinity with a well-known condition—the Lorentz gauge, imposed in a pseudo-Euclidean space on the potentials of an electromagnetic field $A_i = \{A_1, A_2, A_3, A_0 = \varphi\}$. This gauge has the form

$$\frac{\partial A_i}{\partial x_i} = div\,\vec{A} + \frac{1}{c}\frac{\partial \varphi}{\partial t} = 0. \quad (5)$$

Under conditions analogous to those used for the definition of the harmonic coordinate system, gauge (5) unambiguously defines a certain potential A_i given the electric field $\vec{E} = -\frac{1}{c}\frac{\partial \vec{A}}{\partial t} - grad\,\varphi$ and the magnetic field $\vec{H} = rot\,\vec{A}$. It is well known, however, that the Coulomb gauge $div\,\vec{A} = 0$ may be applied just as successfully, and it is often even more convenient. In any case, as it is possible to introduce an unambiguous potential $\vec{A}$ under condition (5) and some other additional assumptions, no one would regard this potential as the "preferred" one.

Generally speaking, if one is loath to concern oneself with wrangling about the meaning of the term "preferred reference frame", the situation appears sufficiently clear. Classical physics ascribed a certain absolute meaning to the concept of favoured inertial frame. Already in classical mechanics this absolute favouredness was metaphysical in nature but was retained for a number of reasons (among other things, in connection with the concept of immovable ether). The special theory of relativity dealt another blow to the metaphysically singled-out and favoured status of inertial frames, while the general relativity theory finally established their approximate and limited character. As is usual in such cases, no return to the past is possible here. Of the coordinate systems introduced in the general relativity theory, some are more convenient in a certain given case while others, under different conditions. Harmonic coordinates are among these widely used and often very convenient coordinate systems, but they can in no way take the place of the inertial frames of classical physics.

As for the Ptolemy vs. Copernicus controversy, it can be linked up with dynamic preferredness of certain reference frames only by a considerable stretch of imagination, as we have taken pains to show in the preceding sections. Still, if one does so, it should be remembered that neither of the two systems (heliocentric and geocentric) can be regarded as inertial, although the heliocentric system is much closer to this ideal. The general relativity theory did not introduce anything new in this respect—it only established that the ideal referred to here is in principle unattainable, for strictly inertial frames in finite spatio-temporal regions do not exist in nature at all. Corrections due to the effects of the general relativity theory within the solar system are very small even in modern terms—they are characterised by the parameter φ/c^2 which even on the Sun's surface equals

$$|\varphi|/c^2 = \frac{GM_{\odot}}{r_{\odot}^2} = 2.12 \cdot 10^{-6}. \qquad (6)$$

Here φ is the Newtonian potential of gravitational forces; $G = 6.67 \cdot 10^{-8}$ cm^3/g sec^2 is the gravitational constant, $M_{\odot} = 2 \cdot 10^{33}$ g is the mass of the Sun and $r_{\odot} = 7 \cdot 10^{10}$ cm is the radius of the solar photosphere.

The only observed relativistic effect with regard to the planets of the solar systems is the precession of the perihelions of planets, that is, of the points of their orbits nearest the Sun. This effect is the greatest for the planet nearest the Sun, Mercury, where it constitutes 43 seconds of arc in a hundred years, which is 12.5 times less than a similar precession of Mercury's perihelion as a result of perturbations caused by other planets. For the Earth, the relativistic precession of the orbit's perihelion is only 3.8 seconds of arc in a hundred years. In this time the Earth obviously makes a hundred full revolutions round the Sun, which corresponds to a precession of $1.296 \cdot 10^8$ seconds of arc. For the Earth, we are thus dealing with an effect of the order of 10^{-8} (for the Earth's orbit exactly $|\varphi|/c^2 \simeq GM_{\odot}/Rc^2 \simeq v_0^2/c^2 \simeq 10^{-8}$ where $R=1.5 \cdot 10^{13}$ cm is the orbit radius and $v_0 = 3 \cdot 10^6$ cm/sec the Earth's velocity along the orbit). This effect is so small that so far it has not been possible to single it out against the background of other perturbations to which the Earth's motion is subject. For Mercury, a certain precession of perihelion, of a nature unknown in those times, was established in the 19th century and was only explained by Einstein in 1915 on the basis of the general theory of relativity.

It is quite obvious that not only Copernicus, Galileo and Kepler, but Newton as well were concerned with coordinating the theory of planetary motion with observation at a level of precision incomparably lower than the one needed for establishing relativistic effects. Just as understandable is therefore the possibility of raising inertial frames to an absolute in those time. Finally, it is also clear why we use approximate inertial frames so widely, and why they will always be used. It is harder to explain the reasons that compel some scientists, many years after the formulation of the general theory of relativity, not only to retain reference frames favoured "in principle" (like strictly inertial reference frames), but also to link up this tendency with the long-solved question of the historical, astronomical, and physical significance of the work of Copernicus. There is just as little reason for that as for the assertion that the general relativity theory somehow changed in principle the evaluation of the substance of the controversy between Copernicans and their opponents.

In the above, we have not touched on the question of absoluteness of rotation and on Mach's principle despite their close affinity with the problems under discussion. It should be noted that Mach's principle was not only widely debated at the time of the formulation of the general relativity theory [60, 36, pp. 175-188; 61; 62] and soon after [35, pp. 121-137; 63], but it still continues to attract attention, and its evaluations still differ [46, 54, 64]. Nevertheless we shall have to restrict ourselves to just a few remarks on the subject.

In the case of the rotation of bodies, Newtonian "absolute space" acts particularly clearly as the source or cause of mechanical action. Newton discussed this question taking as his example rotation of a bucket filled with water round its axis. In his *The Foundations of the General Relativity Theory* [65], Einstein, who may be said to have completed his general relativity theory in 1916 (although all the principal results have been obtained a year before), uses a different example. He considers two liquid bodies floating in space, one of the bodies rotating relative to an inertial frame. The surface of this rotating body will be an ellipsoid, as distinct from the spherical surface of a body at rest. In the experiments with the bucket, rotation causes changes on the surface of water. In Newtonian mechanics, the cause of flattening of a rotating mass or changes in the form of the water's surface is absolute space and rotation relative to it. Of a similar kind is the Foucault experiment, in which space "confines" the plane of pendulum oscillations. Inasmuch as absolute space was not endowed with any other observed functions, its action on, say, a pendulum or rotating liquid was regarded by Mach (who has in this respect such predecessors as Leibniz or Berkeley) as an unsatisfactory and fictitious explanation. Mach also emphasised the very important circumstance, which did not follow from any known causes, that in inertial frames (fixed in terms of the laws of mechanics relative to all bodies of the solar system) remote stars are immovable (that is precisely the reason why in astronomy a reference frame is widely used with axes directed at "immovable stars")[66]. At present this fact has been established with enormous precision up to 0.4 seconds of arc in a hundred years [67]. Mach's next step was the supposition that this coincidence of reference frames singled out dynamically (the law of inertia, etc.) and kinematically (absence of rotation of remote masses in the celestial sphere) is not accidental, and that the role of absolute space was played precisely by all the remote masses (stars, galaxies). These masses create, as it were, "the field of inertia", or the "leading field" (*Führungsfeld*) ensuring the constancy of the plane of oscillations of the Foucault pendulum and the appearance of inertial forces in accelerated reference frames.

These arguments of Mach undoubtedly affected Einstein's views at the time of the formulation of the general theory of relativity [61, 68]. But gradually his positions underwent a change [39, pp. 3-95; 62; 36, pp. 175-188; 35, pp. 121-137] and in the "Autobiographical Notes" published in 1949, on the occasion of his 70th anniversary, Einstein wrote: "Mach conjectures that in a truly rational theory inertia would have to depend upon the interaction of the masses, precisely as was true for Newton's other forces, a conception which for a long time I considered as in principle the correct one. It presupposes implicitly, however, that the basic theory should be of the general type of Newton's mechanics: masses and their interaction as the original concepts. The attempt at such a solution does not fit into a consistent field theory, as will be immediately recognised"[39, p. 29].

Indeed, what we observe is not the stars themselves but what may be termed as "star compass" (*Sternenkompass*)—an aggregate of light rays emitted by the stars a very long time ago. The finite speed of light propagation (and all the other, including gravitational, perturbations), the spirit of the field theory—local propagation interaction—all of this decidedly does not permit to connect inertia (the "leading field") directly with remote masses. True, a certain connection is possible here (we shall touch on this below), but there can be only one answer to the question of the causes for the constancy of the plane of the

Foucault pendulum oscillations precisely in definite reference frames, to the question of the nature of inertial forces in accelerated frames: it is all a matter of the gravitational field, the gravitational field is, in particular, the "leading field" ensuring motion by inertia. The realisation of this was impeded (and is sometimes impeded even now) by the fact that classical mechanics is based on the concept of force, and, in particular, the gravitational field is believed to be absent in the absence of the gravity force. As for inertial motion, it is believed to be free and possible in the absence of the field. In the general relativity theory, however, the gravitational field is described by the metric tensor g_{ik}, and the motion of the "probing body" in such a field is always motion by inertia (motion along the geodesic). In the special case of the Galilean metric ($g_{00}=1$, $g_{11}=g_{22}=g_{33}=-1$) describing an inertial frame, geodesic lines are straight lines: the classical inertial motion is motion in the Galilean gravitational field, that is, the concretely given field (Galilean field) is the cause of motion by inertia, or of uniform motion in a straight line (all the other fields are of course believed to be absent).

The last formulation would be different from the old (Newtonian) one only in its form, if it were not for the fundamental fact that in the general relativity theory the field g_{ik} is not externally given and invariable: on the contrary, matter affects this field, changes it, while the field in its turn influences matter. In this connection "rotation relative to the gravitational field" is different from absolute rotation (rotation relative to absolute space), if only for the reason that there was just one absolute space while there can be an infinite number of gravitational fields. To take a concrete example, the plane of the Foucault pendulum oscillations on some "planet" or of the gyroscope axis will not be retained everywhere in one position in the neighbourhood of a sufficiently massive collapsed star (a rotating "black hole")[22]; this position depends on the coordinates of the observation point

[22] In principle, we can, of course, consider a rotating planet (say, the Earth) or a common star, but the corresponding effect would in this case be very small.

relative to the star and its rotation axis (the reason is the effect of the gravitational field conditioned by the rotation of the star). True, something similar applies to all local-inertial reference frames and rotation in these frames.

Thus gravitational field came to replace absolute space and space "in general". Einstein wrote in this connection:

"On the basis of the general theory of relativity, on the other hand, space as opposed to 'what fills space', which is dependent on the coordinates, has no separate existence. Thus a pure gravitational field might have been described in terms of the g_{ik} (as functions of the coordinates), by solution of the gravitational equations. If we imagine the gravitational field, i.e., the functions g_{ik} to be removed, there does not remain a space of the type (1)[23], but absolutely *nothing,* and also no 'topological space'. For the functions g_{ik} describe not only the field, but at the same time also the topological and metrical structural properties of the manifold. A space of the type (1), judged from the standpoint of the general theory of relativity, is not a space without field, but a special case of the field g_{ik}, for which—for the coordinate system used, which in itself has no objective significance—the functions g_{ik} have values that do not depend on the coordinates. There is no such thing as an empty space, i.e., a space without field. Space-time does not claim existence on its own, but only as a structural quality of the field" [1, p. 375] (see also the article "Relativity and the Ether" [35, pp. 121-137]).

In the framework of the field theory, the idea of Mach and others concerning the significance of remote masses can only be discussed in terms of the role of these masses in the creation of the field. In accordance with this, Einstein formulated "Mach's principle" in the 1918 article "Fundamental Aspects of the General Relativity Theory": "The *G*-field [that is, the gravitational field g_{ik} — *V.G.*] is *fully* defined by the masses of bodies" [62, S. 241].

It was further explained that "the need to adhere to this principle was not shared by all colleagues, but I

[23] Expression (1) in Einstein's article "Relativity and the Problem of Space" [1, pp. 360-377] is the Galilean metric $ds^2=dx_1^2+dx_2^2+dx_3^2-dx_4^2$.

myself believe that its fulfilment is absolutely necessary. According to (c)*, no G-field can exist without matter, in accordance with the equations of the gravitational field. Postulate (c) is most intimately connected with the question of the spatio-temporal structure of the universe; for all the masses of the world participate in creating the G-field" [62, S. 242-243].

The equations of the general relativity theory do not satisfy this principle of Mach (that came to light after the publication of the article quoted above, in which Einstein expressed the assumption that Mach's principle was satisfied by equations with the Λ term introduced in the article "Cosmological Considerations on the General Theory of Relativity" [36, pp. 175-178]. The naturalness of this result is clear from electrodynamics: here a role similar to that played by Mach's principle is played by the condition of absence of all free solutions of the field equations corresponding to electromagnetic waves. In the theory of the gravitational field, free solutions (gravitational fields and others) also exist even in the absence of matter (including the electromagnetic field). Nevertheless, as we have indicated, Mach's principle is still fairly widely discussed in various formulations as a kind of cosmological principle or principle of choosing among solutions, as a requirement imposed on the limiting conditions in the theory of gravitation, etc. (see [45 Ch. 7; 64]; the situation is rather well reflected in the title of one of the articles in [46], "The Many Faces of Mach"). But all these questions, interesting as they may be, do not appertain to our subject, and there is no reason to consider them here in detail.

Articles like the present are always superficial to an extent, for they treat of general ideas and results, leaving in the background the entire mathematical apparatus, the entire technique necessary for the materialisation of ideas and obtaining results. The role of the apparatus, of mathematics, in quantitative theories is enormous; without them, many impossible things appear to be possible, and there are no genuine criteria for selection. We therefore regard as quite true Kuhn's remark that, "had Coperni-

* (c) refers to Mach's principle.—*Tr.*

cus' cosmological First Book appeared alone [that is, unaccompanied by the other books containing astronomical computations—*V.G.*], the Copernican Revolution would and should be known by someone else's name" [5, p. 184].

The same thing may be said about the general theory of relativity. A critique of Newton's mechanics, the equivalence principle, the general idea of connection between geometry and matter, all those things that we have touched upon in the above—they are not yet the general theory of relativity, that amazingly elegant but at the same time mathematically very complicated quantitative theory of the gravitational field. The formulation of this theory in its accomplished form demanded genuinely titanic labour.

"... The years of anxious searching in the dark [wrote Einstein], with their intense longing, their alternations of confidence and exhaustion and the final emergence into the light—only those who have experienced it can understand that" [I, pp. 289-290].

As early as 1910, when the general theory of relativity did not yet exist and only the first step had been made in its direction, Einstein had done so much already that another great physicist, M. Planck, called him the Copernicus of the 20th century. After the formulation of the general relativity theory, comparing Einstein to Copernicus and Newton became a norm, so that the subtitle of our paper is not original at all.

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V. S. BARASHENKOV

THE LAWS OF THE GENERAL RELATIVITY THEORY AND THE PHENOMENA OF THE MICROWORLD

Introduction

It may seem at first sight that Einstein's theory in general has no relation at all to subatomic processes, for the magnitude of the gravitational interaction it describes is extremely small compared to all the other types of interactions playing a role in microphenomena. For example, the force of the Coulomb repulsion of two electrons is 10^{42} greater than the magnitude of their gravitational attraction, and the probability of annihilation of an electron-positron two-graviton pair, where energy approximately equals 1 GeV, is 10^{77} smaller than the probability of their photon annihilation. The differences are striking.

But the magnitude of gravitational effects grows with the decrease of distances or, equivalently, with increasing energy of interacting particles.[1] In the area $\sim 10^{-19}$ cm and $\sim 10^{12}$ GeV, gravitational interaction reaches an already measurable magnitude—approximately the same as in the process of weak interaction studied by modern experiments. Relative energy $\sim 10^{12}$ GeV may be obtained, in particular, in the colliding particle beams with energies of 10^6 GeV. These are very great energies, a thousand times greater than those used in modern accelerators (not to mention the difficulties of creating a system of colliding

[1] Let us recall that the minimal distance that can be investigated (probed) by particles having kinetic energy E, is in the order of magnitude 10^{-14}x$10/E$ (GeV). That is exactly the magnitude of the "blurring" of the trajectory of a particle conditioned by the quantum uncertainty relation $\Delta x \Delta p \sim \hbar$.

beams). And still, these are not the fantastic magnitudes of $\Delta x \sim 10^{-32}$ cm and $E \approx 10^{37}$ GeV, which one usually has in mind in referring to the essential role of gravitational effects. Unless one assumes that in the region of ultrasmall Δx an absolutely radical change takes place in the physical laws we know (reality always proves to be much more striking and rich than any fantasy), the distances in the $\sim 10^{-32}$ cm range will hardly ever be accessible to direct experimental study, whereas intervals of $\sim 10^{-19}$ cm are in principle attainable at the level of technical possibilities which science will apparently have in the remote but quite foreseeable future.

There is one more reason why Einstein's gravitational equations may play an important role for nuclear ($\sim 10^{-13}-10^{-12}$ cm) and even atomic ($\sim 10^{-8}$ cm) distances. At present, there are serious theoretical grounds to expect that there exist in nature almost closed regions of curved space-time manifesting themselves as microscopic objects. The properties of such objects must conform to the macroscopic laws of the general relativity theory and the laws of quantum theory.

Our objective will be an analysis of the philosophical aspects of application of the general relativity theory to the description of the microworld phenomena. We shall consider first the conclusions resulting from direct extrapolation of Einstein's theory to subnuclear regions; we shall then discuss the changes in these conclusions required by the quantum specificity of microphenomena; finally, we shall consider the most promising, in our view, approaches to the generalisation of the classical theory of gravitation—the attempts to go beyond the framework of this theory.

1. Micro-objects Predicted by Einstein's Theory

Already in the early 1920s A. A. Friedmann showed that the equation of the general relativity theory has a solution describing an infinite but internally closed world [1, 2]. We shall not now go into a discussion of the complex cosmological problems involved; of greatest importance here is the fundamental possibility itself of the existence of such a closed world.

It is noteworthy that a system shrinking into a closed world may in principle possess both an infinitely small and an infinitely great mass; the necessary condition is that the density of matter in the world should reach a certain critical magnitude determined only by the magnitude of the mass and universal physical constants. In other words, if for some reasons the confining forces within matter should weaken and the matter should begin to shrink under the impact of gravitational attraction, its density may gradually attain a critical value and the world will close in. That will be accompanied by a growth in gravitational mass defect, while the full mass of the system and its radius, with which it is manifested in external space, will tend to zero.

At the same time the inner radius of the system (the one seen by the observer in this system) may remain arbitrarily great (cosmic), given sufficiently great initial ("priming") mass. For example, it equals only about 300 m for a closed world that might be formed out of a system with a mass equalling the mass of the Sun. The radius of the world to which our Galaxy might collapse, is $\sim 10^{10}$ km. But the size of a closed world close to the mass of the part of the universe that we know would already be something like 10^{23}-10^{24} km. It would take a light ray more than 10^{10} years to cross this world.

If the mass and, consequently, the radius of the world is very great, its properties will not differ practically from the properties of a flat world, one without curvature. The inhabitants of such a world will not even suspect its being a closed world, they will have no inkling of the existence of many other worlds similar to their own, which appears to them infinite. These worlds exist independently of one another. For the beings inhabiting them, each of these worlds will be the entire universe, while other worlds will simply be unobservable—as if they did not exist in nature at all. One world in relation to another is a "collapsed", closed-in-itself space-time. There are not links between closed worlds. They can neither intersect nor contact one another, for they belong to different three-dimensional spaces, and their times are different too. The Friedmann solutions describe a multiply connected universe consisting of a great number of three-dimensional worlds living each in its own time rhythm. Relative to all the others, each of these worlds is an "absolute nothing", a point devoid of size, mass, and any other conceivable physical properties.

However, the general theory of relativity leads to these conclusions only in the case of an electrically neutral system. If the system has an electric charge, there is no complete collapse of space-time, and instead of a "closed world" we have a "semi-closed" one. The same thing happens if a system rotates (possesses an angular momentum different from zero [3, 4, 5]. Calculations show that a semi-closed world will be manifested in external space as a "black hole"— an object which has so great a gravitational field that it absorbs everything that falls on it but does not emit anything, not even light. All events occurring within a black hole remain unknown to the world. For an observer outside a black hole, it is an object characterised by geometrical size and three integral magnitudes—mass, electric charge, and angular momentum. All the other characteristics are "concealed" under the gravitational radius and inaccessible to external observation. In particular, it is impossible to establish what a semi-closed world is built of—matter or antimatter.

Clearly, the diversity of the properties of a material system neither decreases nor disappears in the gravitational collapse; only the effect of these properties on processes in external space is gradually weakened. For the internal world, the diversity of the system's properties is fully retained.

Black holes are very massive objects, even if they have microscopic size. For example, a black hole of the size $\sim 10^{-13}$ cm, that is, of the same magnitude as most elementary particles, will have a mass of about 10^9 tons. That is the mass of an asteroid with a diameter of about 1 km or a medium-sized mountain on the Earth's surface. Only ultramicroscopic black holes with dimensions in the region of $\sim 10^{-53}$ cm will have a mass approaching that of proton or meson.

Thus the general theory of relativity leaves room for stable microscopic particles of gravitational origin with extremely diverse magnitudes of mass and size. Being manifested as micro-objects with a minimal number of properties, these particles may contain within themselves whole worlds with immeasurably great numbers of cosmic bodies. At the level of spatial scales accessible to modern experiment ($\Delta x \geqslant 10^{-15}$ cm), the specificity of these physical objects predicted by theory consists also in that here for the first time we come across microparticles which have macroscopic mass.

We see that Einstein's theory points to the possibility of a kind of "self-closing" of the universe, when, penetrating deeper into the microworld, we again encounter objects and phenomena of cosmic order, and, passing to cosmic distances and durations, unexpectedly find that our world is merely a microparticle.[2] The correlation between the supergreat and the microscopically small becomes relative in its meaning [6, 7, 8].

In thinking of the infinity of the material world, we customarily imagine it as something like a straight line passing into the region of infinitesimal intervals, on the one hand, and into the region of unlimitedly great scales, on the other. The general theory of relativity prompts us that the infinity of the world is rather like a circle where the infinitely great is again closed in the infinitely small, while the ultrasmall is at the same time the ultragreat. It is difficult to believe, however, that the structure of the universe is an unlimited succession of identically repeated situations, where one world proves to be a microparticle in another world, and so on. The real situation must be much more complex. Proceeding from the propositions of inexhaustibility of the properties of the material world and the transition of quantitative changes into a new quality, one should expect that the self-closing infinity of the world is not a circle but, figuratively speaking, something like a spiral. The cosmos is just as inexhaustible as the microworld.

2 The question of the real cosmological structure of the world so far remains open. The solution of this question depends, in particular, on experimental precision of determining mean density of matter in the universe. The magnitude that has been measured by now is about a hundred times less than the one needed for a closed world. However, there is no certainty that all types of cosmic matter have been taken into account.

The conception that our universe is merely one of a great multitude of other universes, similar or diversely different in their properties, which appear cosmically enormous in one perspective and microscopically small in another, is probably the most important consequence of the general theory of relativity. Regardless of the concrete model realisation, its world-outlook significance and enormous heuristic charge cannot be valued too high. It forms in fact the central and most fundamental point in the revolution in astronomy (or cosmology, to be more precise) that is so often referred to in these days. The general relativity theory completes the cause begun by medieval thinkers, Copernicus, G. Bruno, Galileo, developing the idea of plurality of worlds (planets) and removing the last vestiges of anthropocentricism in the cosmological picture of the world.

However, having emerged as the necessary consequence of Einstein's theory, as a physical interpretation of some special solutions of gravitational equations, the idea of closed and semi-closed worlds leaves aside the question of how and under what conditions can nature produce objects with such unusual properties. To give an answer to this question, the general relativity theory alone is not enough, the data obtained in other branches of physics are also necessary here, including the results of nuclear physics.

A. A. Friedmann's pioneering works aroused great interest and stimulated a great number of cosmological and astrophysical studies. The process which could apparently lead to the formation of closed worlds was found fairly quickly. Computations showed that, if the mass of the body was great, the repulsion action of radiations and powerful flows of matter generated by nuclear reactions within this body might prove insufficient to withstand the contracting forces of gravitational attraction. For bodies with a mass greater than the mass of several suns, the gravitational contraction (collapse), once begun, can no longer stop, and the mass of the body will be concentrated in an increasingly smaller volume, without limit. But the shrinking of the body to a point and its complete "dropping out" of our space as a closed world will not occur, since, with the size of the collapsing body approaching its gravitational radius, gravitation grows to such an extent that a black hole is formed. At this stage, further contraction of the body stops for the external observer: the body freezes for all time as an object absorbing all radiation.

The more massive the collapsing body, the greater "hole" it forms in space. For example, a black hole into which the Andromeda nebula might drop is hundreds of times greater than the solar system; at the same time the radius of a black hole for a star with a mass equalling three solar masses, is only about 10 km. On the astronomic scale that is almost a point already, but it is a long way from complete collapse. Moreover, the gravitational fields of bodies whose masses are smaller than the mass of two or three suns, prove in general to be insufficient for crushing the forces that impede contraction and forming a black hole. Therefore 5-10 km is the smallest size of black holes that can emerge through gravitational contraction. Nevertheless it is in principle possible to indicate the conditions under which closed worlds and black holes of arbitrary size might be formed.

The solutions of gravitational equations obtained by Friedmann show that the inner size of a closed universe does not stay constant but changes with time starting from some singular state with an infinite density of matter and zero radius. The astronomical data available now point to the fact that some 20,000 million years ago there occurred an explosion of some superdense "protomatter" which produced our world, and it has been expanding ever since. The cataclysm of the "primogenital explosion", the colossal differentials of pressure and density might produce regions of small size and such an enormous mass that in their neighbourhood complete or almost complete shrinking of space and time took place and black holes were formed (the "necks" of semi-closed worlds) of extremely diverse sizes—up to the subnuclear ones, as in elementary particles.

True, this is now merely a hypothesis at the level of visual description, although very likely at the present state of our knowledge. There is no theory as yet of the superdense state of matter near the spatio-temporal singularity, and we therefore cannot give a quantitative analysis of the conditions of formation of closed worlds and microscopic black holes. A convincing argument in favour of this hypothesis would be experimental discovery of black microholes. As we shall see below, consideration of quantum-mechanical arguments prompts here some interesting possibilities.

Apart from particles that are semi-closed worlds with a complex inner structure depending on time (that is, dynamic structure), the general relativity theory also predicts the possibility of existence of yet another specific type of micro-objects which may be formed as a result of balance between contracting gravitational forces and some repulsion forces, e.g., the forces of electrostatic repulsion of like charges. In particular, if a system consists of nucleons, equilibrium between gravitational and electric forces, as calculations show [9, 10], sets in when the number of nucleons reaches $\sim 10^{18}$; that is not, of course, a "whole cosmic world", yet it is an almost macroscopic magnitude. The geometrical size of this system in a state with maximum gravitational mass defect is very small- $\sim 10^{-33}$ cm, and yet it is greater than its gravitational radius, so that no black hole is formed here.[3] In the works [8-10] it is suggested to call such particles "papapetrons", after the physicist who was the first to analyse the possibilities of corresponding solutions for the unified system of equations of Einstein-Maxwell [11, p. 191].

As distinct from the black holes, which are poor in their observable properties, papapetrons can possess an unlimited number of most diverse measurable characteristics.

2. Extended and Point Particles

One of the most fundamental difficulties of the modern field theory (both classical and quantum) is the presence in it of meaningless, divergent expressions. The reason is that in theory all particles are regarded as points having no geometrical sizes, so that processes have to be taken into

[3] This state is apparently most stable, although in a purely classical theory disregarding quantum effects much larger geometrical sizes are possible—of the order of observed radii of elementary particles [9, 10].

account which occur in arbitrarily small spatio-temporal regions, and it is these processes that contribute the infinitely great magnitudes.

From the methodological viewpoint it seems quite necessary that any theory should be built in such a way as to exclude (or make negligibly small) the effect of intervals of space and time (both very large and very small) that are far beyond our experimental possibilities. However, the attempt to "crush" the contribution of ultrasmall sizes, distributing interaction over an extended particle, immediately results in propagation of interaction at speeds greater than that of light and in violations of causality, when the order of the cause phenomenon and the effect phenomenon, divided by microscopic distances and durations, may be reversed. The image of an extended particle may be said to be alien to the modern field theory.[4]

In the general relativity theory the situation is in a sense the reverse. Strictly speaking, there is no concept of point particle—all physical objects here are extended [10]. The point is that reduction of the body's size is accompanied by an increase in its density and a corresponding growth in the gravitational mass defect, therefore as the body contracts to a point, its observed mass tends to zero, too. In other words, the region of space occupied by matter collapses, and the point object simply disappears from the field of vision of the external observer.

Owing to its non-linear nature, the gravitational field automatically excludes extremely small spatio-temporal intervals. The self-energy of a particle, which equals infinity in the classical electron theory of Maxwell-Lorentz, proves to be a finite quantity if gravitational effects are taken into account. Unified solution of gravitational, electromagnetic, and mechanical equations of motion has

[4] The spatio-extensional structure of elementary particles revealed in the experiment (e. g., in the experiments in scattering electrons by protons) has quite a different nature: it emerges as a secondary effect of the formation of a cloud of virtual particles around the initial point particle. In the modern field theory, interaction takes place exactly with these point particles before they are clothed in such virtual clouds. The theory describes the particle structure observed in the experiment and at the same time contains divergent expressions. That is precisely the basic contradiction of modern field theories.

no divergences.

It is noteworthy that extension of particles in the general theory of relativity does not cause any violations of causality since Einstein's system of equations is relativistically invariant and any solutions of it may contain only signal speeds less than the speeds of light. The theory of gravitation is in this respect a model for other field theories.

3. Quantum Effects. Friedmons

Development of a quantum theory of the gravitational field is an exceptionally hard task. With the exception of the special case of very weak fields, where linear approximations can be applied, all attempts at a more or less consistent synthesis of quantum laws with the apparatus of the general theory of relativity were unavailing. They may at best be regarded as having only a model-methodological significance.[5]

The causes of the failures lay both in the difficulties of extending the familiar methods of quantisation to non-linear fields (they are in this sense characteristic of all non-linear theories) and in the specific connection between the gravitational field and the properties of the spatio-temporal continuum, where one and the same magnitude defines both the field and the metric of space-time.

Essential progress has been achieved here only in the recent years, after non-linear fields were quantised in the light of R. Feynman's ideas that the quantum picture arises out of a specific probabilistic averaging of all kinematically possible evolutions ("trajectories") of the classical field [12]. Nevertheless we do not yet have a finished theory similar, e.g., to quantum electrodynamics, which would permit calculation of quantum effects in strong

[5] At the same time one must not underestimate the enormous methodological significance of these works. They demonstrate the fundamental possibility of a transmutation of the energy and mass of the gravitational field into electron-positron pairs and other "normal" forms of matter and thereby eliminate the sharp distinction between gravitation and other types of field so characteristic of the earlier views of the nature of gravitation.

gravitational fields, not to mention the fact that the quantum laws we know will hardly remain valid near the gravitational radii of elementary particles—for the fantastically small distances $\sim 10^{-32}$ cm. All computations based on joint application of the general relativity theory and quantum theory in the domain of strong gravitational fields and very small spatio-temporal intervals so far have any meaning only as very crude quantitative approximations of the possible effects.

The first thing that comes to light as quantum phenomena in the gravitational field are taken into account is probably the fact that black holes, despite their name, must produce some sort of emission into the surrounding space. Due to quantum fluctuations, virtual formation of electron-positron pairs, meson pairs and pairs of heavier particles takes place around black holes. These particles are spontaneously born out of the vacuum and annihilate quickly. But if that takes place near the gravitational radius of the black hole, one of the components of the pair, e.g., the positron, may be swallowed by the black hole, and then the second component, the electron, no longer has a partner for annihilation and may be emitted. If the system hidden under the gravitational radius has a great electric charge, this charge will decrease, those components of the pairs of particles which have a charge unlike the charge of the system, will be entrapped by it and decrease the charge of the semi-closed world, while particles with like charge will be pushed out into infinity. In the same way radiated into the external space will be the electromagnetic waves emitted by the virtual particles which subsequently "died" in the black hole. Figuratively speaking, vacuum "comes to a boil" around the black hole, and from the outside it all looks like gradual evaporation and contraction of the black hole.

Quantum effects result in the fact that black holes (again in sharp contrast to their properties in Einstein's classical theory) do not behave as absolutely absorbing but, on the contrary, as emitting black bodies with temperature.[6] Calculations show that a black hole with a radius

[6] The concept of temperature of black holes was originally introduced by S. Hawking on the basis of classical considerations [13],

of $\sim 10^{-13}$ cm must behave as a body heated to a temperature of about 100 million degrees. Its emissive power is about 6,000 mVt, that is, it equals the power of one and a half Bratsk hydroelectric power plants.

Only the macroscopic large black holes are indeed black, emitting nothing. Their temperature is measured in millionth parts of a degree, and the time required for their evaporation equals $10^{16}-10^{17}$ years. As for microscopic black holes, as their size decreases through evaporation, vacuum "quantum boiling" around them becomes more and more intense and their temperature and consequently power of evaporation increase. For semi-closed worlds with the size of the neck $\sim 10^{-13}$ cm this process of increasing radiation may continue for ten or twenty thousand million years, ending in an explosion.

True, the computation of the explosive phase in the life of black holes is based on an extremely problematic "tying-in" of the solutions of Einstein's equations with quantum theory, and is of merely evaluative nature. No rigorous quantum-gravitational theory of this phenomenon has been formulated, therefore there is a great deal of vagueness about the calculations. For example, we cannot say exactly what an explosion of a microscopic black hole ends in. It may be complete evaporation of its observed mass and collapse of space, but it may also happen that somewhere at the level of $\sim 10^{-33}$ cm, when quantum fluctuations of the space metric itself arise (and probably earlier), stability will be attained and an object will emerge which will have not only a microscopic size but also a microscopic mass, such as elementary particles have. Evaluations show that this outcome is in principle possible [8, p. 210]. The entire mass of the black hole may evaporate, with the exception of that part of it which is connected with the energy of zero or quantum oscillations of the matter of the black hole. These oscillations do not increase the temperature of the object, and their energy cannot be emitted. The residual mass is only about 10^{-5} g, regardless of the initial mass of the black hole and the mass of the semi-closed inner world. The magnitude

but the physical phenomena underlying the "temperature effect" are of an essentially quantum nature.

of the electric charge of the residual object also proves to be very small—of the order of an elementary particle charge, although the initial charge of the black hole may be very great.

A similar value for the mass is also yielded by a comparison of two minimal sizes of the general relativity theory: the radius of a black hole with the mass M (the radius of the Schwarzschild sphere) and the radius of the neck of a semi-closed world with a charge equalling the charge of an electron. These two magnitudes are equal only on condition that $M \sim 10^{-6}$ g.

All of this compels one to assume that the value $M \sim \sim 10^{-5}$-10^{-6} is the greatest mass of stable microscopic objects predicted by the general relativity theory. In the works [6, 8] it was suggested that these objects be called maximons. These particles are characterised by similar (and probably precisely equal) electric charges, masses, spins and geometrical sizes, regardless of the properties of their inner world.

It is not excluded that under some conditions, not yet fully understood, stable particles with a still smaller mass will be formed, up to electron mass.

All these hypothetical objects may be called *friedmons*, thus stressing the fact that "from within" each of them is a dynamic Friedmann world [6-8].[7]

Modern theory cannot tell even approximately whether friedmons are identical to any of the already familiar elementary particles (e.g., nucleons or quarks) or whether that is a completely new type of microparticles which are yet to be discovered experimentally. The latter view is apparently confirmed by the conclusion, mentioned above, that any semi-closed world, regardless of its internal properties, manifests only four characteristics in external space: size, mass, electric charge, and angular momentum; for this reason particles with a complex observed inner structure, characterised by strangeness, baryon or lepton number and other magnitudes, clearly cannot be friedmons. This is also indicated by the enormous difference in the

[7] K. P. Stanyukovich prefers to use the term planckeons, after the originator of the quantum idea Max Planck, pointing to the essentially quantum nature of such objects [14, 15].

size of friedmons ($\sim 10^{-33}$ cm) and the observed size of particles ($\sim 10^{-13}$ cm).[8] It should be remembered, however, that the conclusion of the properties of the collapsing system being "buried" was obtained without taking account of quantum factors that can substantially affect this conclusion. As for the ultrasmall size of friedmons, owing to quantum fluctuations clouds of virtual particles have to emerge round "naked" friedmons, which form the structure observed in experiments—a dense centre consisting of heavy particles (quarks, gluons, etc.) and porous and semi-transparent remote periphery. Friedmon is merely the deepest part of an elementary particle, its primal nucleus, as it were; but it is this tiny infinitesimal nucleus that may contain a new universe. However paradoxical that may appear, modern theory admits *in principle* the possibility of formation of a microscopic object "around" a cosmic object.

On the whole, the correspondence of hypothetical friedmons to the observed elementary particles remains an open question. We must not forget that the prediction of microscopic black holes of the size $\sim 10^{-13}$ cm is a direct consequence of the general relativity theory, whereas prediction of friedmons, pertaining to the region of extremely small scales, is a hypothesis that goes far beyond the framework of both the general relativity theory and modern quantum theory. Verification of this hypothesis, including the study of the mechanism of explosive radiation of black holes, is one of the fundamental problems of the quantum theory of the gravitational field. Many unexpected phenomena can be encountered here.

The friedmon hypothesis would clearly assume greater importance had it been possible to discover the radiation and explosions of black microholes.[9] The measurements

[8] Or at any rate in the sizes of baryons and mesons. The size of leptons has not yet been experimentally observed, but it may be expected, on the basis of theoretical considerations, that it must be $\sim 10^{-17}$ cm. The size of strongly interacting particles—quarks—also cannot be too small.

It is interesting that papapetrons in a state with maximal gravitational contraction have the mass $\sim 10^{-5}$ g. If such objects exist, they also must grow clouds of virtual particles.

[9] Radiation intensity and consequently life-time of a black hole

performed on artificial satellites indeed recorded radiations that can be ascribed to black holes, but this interpretation is by far not the only one, for other explanations can also be suggested. The experimental data are not yet sufficient here.

If we believe, however, that the observed radiations fully belong to black holes, an evaluation is possible of the number of such objects in space. A cube whose side equals one light year must on an average contain 200 microscopic black holes. Their number in our Galaxy's halo may be five to seven orders greater. That is a very great magnitude; one might say that the universe is literally crowded with microscopic black holes. If we accept these optimistic evaluations, the nearest microscopic hole is at approximately the same distance as the planet Pluto.

To conclude this section, we should also mention another important correction of the general relativity theory involving quantum effects. The quantum uncertainty relation may cause extremely great fluctuations in very small scale regions, including fluctuations of space-time curvature. At distances of $\sim 10^{-33}$ cm these fluctuations become so great that they may cause essential changes not only in the metric but also in the topological properties of space-time. The structure of the spatio-temporal manifold becomes in these cases very complicated [16, p. 282]. Figuratively speaking, it may be compared to a sponge or a slightly ruffled layer of foam consisting of a great number of bubbles and cavities rapidly disintegrating and forming again.

Moreover, if the now known quantum uncertainty relations can really be extrapolated to the region of so small distances, it may be shown that the intervals $\Delta x \sim 10^{-33}$ cm and $\Delta t \sim \Delta x/c \sim 10^{-43}$ sec are the minimal "portions" of length and duration with which space and time participate in physical processes [8, pp. 126-128]. Under these conditions the conclusions of the

depend on its size. For black holes with radii $\sim 10^{-13}$ cm this time is comparable with the life-time of the universe. It is these objects whose radiation must be most intense now. Black holes of smaller size have already fully evaporated or become friedmons, while the radiation of larger semi-closed worlds is very weak.

classical general relativity theory concerning possible closing of space-time no longer seem sufficiently convincing. Quite possibly, they have a meaning only up to quantum fluctuations of metric, eliminating the "absolute isolation" of Friedmann worlds.

4. The Hierarchy of the Elementary

The general relativity theory may also have a bearing on yet another methodological problem, the problem of "the most elementary".

Are there any "ultimate", further indivisible elementary objects in nature, or is our world a hierarchy, infinitely unfolding inwardly, of various structural forms? The struggle of ideas around this most important world-outlook problem permeates the entire history of science.

Anaxagoras (5th century B. C.) was apparently the first to express the idea of the unlimited divisibility of matter. The opposite view was clearly formulated in Democritus's doctrine that the world consists of an infinite number of absolutely indivisible and primordially simple particles—atoms of matter and amers, i.e., atoms of space. Further development of science, depending on the concrete attainments of natural-scientific knowledge, lent divers forms and shadings to these two basic conceptions of the structure of our world (its intensive or extensive structure) [17], but their content remained substantially the same.

Recently, quite popular in high-energy physics became yet another picture of the world's structure—the so-called bootstrap model, where each elementary particle is viewed as consisting of all the other elementary particles and the world is seen as an infinitely intricate interlacing of identical elements.[10] However, if consistently applied, this theory leads to an infinite number of elementary particles and in this sense differs but little from Democritus's

[10] It is interesting that the bootstrap idea, which is usually taken to be one of the most witty and unexpected inventions of modern theoretical physics, was conceived already by ancient scholars. It is referred to, for instance, in Buddhist texts written several centuries before our era [18, pp. 885-892].

conception of an infinite number of qualitatively different atoms.[11]

It is possible that the two principal alternative conceptions of the inexhaustibility of the microworld (an infinite "linear" hierarchy of structures or some primordial entity infinite in itself–single "protomatter" or an infinite number of simplest and equally elementary constituents) do not exhaust all approaches that are feasible here. If one assumes that all elementary particles are indeed based on friedmons, we arrive at a picture of self-closing hierarchy of material structures, where there is no "protomatter" and the number of particle elements is finite. Each particle contains in itself a whole universe, and the universe constitutes a microparticle [8]. The concept of "consisting of" assumes quite a new meaning here.

Regardless of the physical likelihood (only subsequent studies can show just how close we are here to the actual situation), the conception of a self-closing hierarchy "of the increasingly more elementary" is highly interesting from the methodological standpoint as it shows the possibility of a structure of the world fundamentally different from all that have been suggested.

5. Black Holes and Thermal Death of the Universe

One of the most important results of classical physics was that in an isolated macroscopic system entropy cannot decrease. Any processes in this system ultimately prove to

11 According to the bootstrap hypothesis, unification of any two elementary particles yields a new and equally elementary one (the individuality of component particles is entirely obliterated by great mass defect). This particle can be used in the building of other particles, etc. The number of elementary particles here grows exponentially. Calculations show, for instance, that in the interval ΔM=0.140 GeV near mass magnitude M=2.5 GeV there must be about 10^4 various elementary particles [19]. If we were to discover a new particle every day, it will take roughly 100 years to exhaust the particles only within this very small interval ΔM. Near M=5 GeV there must be already $\sim 10^8$ particles with different quantum numbers. It is hard to reconcile oneself to the idea that this structure can represent "the picture of the world at the most elementary level".

involve energy dissipation, erasing its levels, and decreasing the number of different states of parts and elements of the system. In other words, any isolated macroscopic system inevitably arrives at a steady state. This conclusion is often formulated as inevitability of thermal death of the universe, when statistical equilibrium established in its isolated regions will extend to increasingly greater volumes while the effect of surface perturbations becomes infinitesimal (inasmuch as the ratio of surface and volume effects is inversely proportional to the system's size).

This conclusion is entirely unsatisfactory from the methodological standpoint, for the assumption that in the entire time of its existence matter had only one single possibility to differentiate the whole wealth of its motion is tantamount to the conclusion that matter is mortal and its motion transitory [20, p. 36]. At the same time, all attempts to somehow restrict the action of the law of "thermodynamic degradation" of macroscopic systems invariably proved to be unavailing (a critique of some of these attempts may be found in [21, 22]): they at best showed various logical or physical difficulties involved in the application of the concept of isolated system to the infinite universe (particularly with a view to the non-stationary character of its metric). Despite the positive elements in them, none of these efforts answered the principal question raised by the thermal death paradox: in what way are the radiations, dissipated in space, again concentrated?

R. Tolman [23] was apparently the first to indicate the impossibility, within the general relativity theory, of strictly satisfying conditions under which the second principle of thermodynamics would be applicable to the whole of the evolving, expanding and contracting "universe *in toto*", but very visual and convincing examples of sharp violation of the second principle even for small macroscopic regions of space were discovered in the study of black holes.

Indeed, the very existence of objects absorbing from the surrounding space matter and radiations and concentrating them under the Schwarzschild sphere, is incompatible with the laws of classical thermodynamics. Black holes decrease the entropy of the surrounding world. In the general relativity theory, the total area of all black holes proves to be a non-reducible magnitude rather that entropy. The "area theorem" is very much like the second principle of thermodynamics. It is precise within the framework of the classical gravitational theory of black holes, but becomes immediately invalid if quantum effects decreasing their mass and surface are taken into account.

Black holes are concentrators of matter and dissipated energy returning them back into surrounding space through quantum evaporation and explosions. Neither the second principle of thermodynamics nor its gravitational analogue, the area theorem, are applicable to black holes separately. However, since reduction of entropy S is accompanied by increasing areas of black holes P, it may on the contrary be assumed that the non-reducible magnitude is actually the sum $S' = S + aP$, where a is a universal constant "levelling-off" the dimensions of S and P (this constant is expressed through other known universal constants [5, 24].

The "generalised second principle of thermodynamics" thus defined integrates three branches of physics at once: the general theory of relativity, thermodynamics, and quantum theory. The cosmological paradox of the thermal death of the universe that has troubled physicists for more than a century is thus removed; in principle, multiple processes of dissipation, subsequent concentration, then dissipation again and so on are possible. That is a most important methodological result of modern physics.

6. The Search for a Unified Theory. Geometrodynamics

Einstein's theory of the gravitational field possesses a high degree of generality and remarkable beauty and perfection of mathematical formulation. It concerns itself with the most fundamental aspects of the reality we live in. Efforts were therefore made to extend the principles inherent in it to other types of physical fields in order to obtain a unified theory of particles and the interactions connecting them.

Einstein himself believed the construction of such a theory possible through complete geometrisation of physical knowledge, through reduction of all the properties of the material world to the properties of space and time. Fifteen years after the formulation of his general relativity theory he remarked in one of his speeches: "The strange conclusion to which we have come is this—that now it appears that space will have to be regarded as a primary thing and that matter is derived from it, so to speak, as a secondary result. Space is now turning around and eating up matter" [25, p. 610]. This statement briefly formulates the programme the realisation of which occupied most of Einstein's life. Many prominent physicists contributed to the implementation of this programme—to the construction of geometrodynamics, as it is now usually referred to (see monographs [4, 26, 27] for detailed bibliographies).

Einstein's geometrodynamic programme is relevant to the fundamental philosophical concepts; its recognition even on a theoretical plane would not only essentially affect the general orientation of physical studies, first of all research in microworld physics—it would also drastically affect our world outlook.

It should be noted that the idea itself of reducing the entire diversity of the material world to geometry, to certain properties of space, is not entirely new. In 1870, long before the formulation of the general relativity theory, the English mathematician W. Clifford published a book in which he tried to substantiate the idea that matter and its motion in all their divers manifestations are merely the property of space, a manifestation of its curvature varying with time. However, until the laws of the general relativity theory were discovered, all these conceptions were in the nature of philosophical conjectures.

Einstein was the first to realise the significance of the main gravitational property of matter, which is that, as distinct from all the other fields we know, gravitation imparts identical acceleration to all bodies regardless of the magnitude of their "gravitational charge", i.e., mass. No other field possesses this remarkable property. For instance, under the impact of one and the same electric field, bodies are differently accelerated depending on the magnitude of the charge-to-mass ratio. It is this specific feature of the gravitational field, its universal nature, that permits a description of gravitation through the properties of space-time: the gravitational potential coincides with the metric tensor, while gravitational forces, defined by the potential gradient, can be regarded as a manifestation of the curvature of four-dimensional space-time expressed through the same derivatives of the potential—the metric tensor. In this case trajectories of bodies simply coincide with the geodesic extremals of curved empty space-time.

The view that gravitation is curvature of space-time appeared all the more convincing after Einstein and his co-workers Grommer, Infeld, and Hoffmann succeeded in proving that the equation of the particle's motion can be deduced as a consequence of the geometrised equations of the gravitational field, and that this equation need not be added to the theory as a postulate. The only inconsistency that remained was the need to assume the existence of the moving objects themselves—of the gravitating masses. The desire to eliminate this inconsistency was the starting point of later work by Einstein himself and other physicists on the construction of geometrodynamics.

But all efforts to extend the physical possibilities of the general relativity theory by various generalisations of the metrical elements of the apparatus of this theory were unsuccessful. Hopes for removing or at any rate somehow lessening the difficulties of the geometrodynamic approach are now placed in allowing for quantum effects in the microscopic regions of space-time.

In quantum geometrodynamics wave laws are applied to the description of the dynamics of the geometry of three-dimensional space. In normal mechanics of the particle, the dynamic variable is the coordinate of three-dimensional space, and the event is a separate point of space-time, while in quantum geometrodynamics the dynamic variable is the "whole three-geometry", and the event, a definite "value" of this geometry at a certain moment of time. The totality of all these points ("three-geometries") constitutes superspace, or the space of three-dimensional spaces—the scene of action of quantum geometrodynamics; the set of three-geometries corresponding to consecutive moments of time forms the "trajectory" of motion (change) of a three-geometry in superspace.[12] It is assumed that the probability of some "value" or other of the three-geometry is defined by a wave function subject to a generalised Schrödinger equation [4, 27]. Elementary particles are regarded here as "quantum states of an excited geometry"—something similar to the quanta of sound excitation formed in rigid bodies.

Regrettably, all of these statements are in the nature of declarative hypotheses. No computations have been made supporting the possibility of origin of particles out of "pure geometry" to say nothing of the possibility of reducing the entire diversity of all the known types of elementary particles to excitations of "empty space". The Schrödinger equation describing the motion of three-geometry, is written in symbolic notation only, and the mathematical details of its magnitudes are completely unknown.

Until recently, one of the difficulties in the way of various generalisations of Einstein's gravitational equations was the impossibility to incorporate in theory particles with fractional spin, as the spinor magnitudes describing them cannot be constructed out of tensor functions of the gravitational field. Recently, some progress was attained here thanks to the formulation of the "supergravitation" theory. This theory is based on the requirement of invariance of natural phenomena under a unified group of transformations of spatio-temporal and spin coordinates. Just as the spin variable generalisation of the Klein-Gordon

[12] As for the physical meaning of superspace, it should be remembered that the real physical space-time is the four-dimensional manifold x, y, z, t. That manifold is exactly the world in which we live (at any rate, the part of the world that we know, where space has three dimensions, and time, only one). However, this world, its metrical and topological properties may change with time; for instance, space curvature may change: somewhere in the ultrasmall region this space may become multiply connected, not singly connected, and so on. The totality of all possible spatio-temporal configurations which our world may have (the totality of all the "snapshots", so to say, of all its momentaneous positions permitted by physical laws) forms superspace.

Superspace is thus similar, for example, to the Hilbert space of quantum mechanics or the space of energy-momentum: it is an *abstract mathematical structure* reflecting certain laws of the surrounding world.

relativistically invariant equation led to the discovery of Dirac's spinor field describing electrons and positrons, taking spins into account transforms the gravitational field into a single "supergravitational multiplet", whose various states include fields of particles with the spin $s = 2$ (gravitons), $s = 1$ (of the photon type), and a certain new field with the fractional spin $s = 3/2$. Just as the Einstein equation, supergravitational equations admit of a fully geometrised interpretation.

The transition from the Klein-Gordon spinless equation to Dirac's spinor one opened up an entirely new branch of physics with a great wealth of content, where we first encountered antiparticles, annihilation, negative energy background and other essentially new and unexpected phenomena. A spinor generalisation of gravitational equations may prove even richer and more striking. However, none of this eliminates the fundamental difficulties of the geometrical approach. No self-consistent and uncontradictory theory can be built along these lines. Purely geometrical magnitudes prove to be inadequate for unambiguous description of all the properties of the electromagnetic, electron-positron, and other "non-gravitational" fields; for this purpose additional magnitudes have to be introduced inexpressible in "purely geometrical" language. The "traces" left by material processes in the properties of space and time are entirely inadequate for reconstructing in all the details the inexhaustible richness of the material world.

In general, the attempt to construct a physical picture of the world entirely from properties of space and time still remains in the programmatic stage, despite the long years of effort by Einstein himself and many other outstanding theoreticians. Moreover, the difficulties in the way of this programme grow rather than diminish in the course of time.

The programme of constructing a purely geometric world picture, when substance and matter on the whole are reduced to space, and physics to geometry, is completely untenable methodologically as well. Quite naturally, the properties of space and time, that are forms of the existence of matter, reflect certain features of material content and processes in it. The corresponding variations in the spatio-temporal form prove to be so specific that judgements may be made of the content itself from observation of form. It does not follow, however, that form has become a determining characteristic, primary with regard to its content; still less can it be asserted that content is generated by form.

The real physical situation, the actual relationship between things is actually turned inside out, or upside down, in geometrodynamics. Spatial form is here essentially ascribed the properties of the material basis determining it, and the latter, on the contrary, is viewed as an attribute of its form. In the final analysis, time also becomes an attribute of space, a form of its existence expressing the property of change or self-transformation of space.

As Einstein himself indicated, in the geometrodynamic approach "space ... appears as a reality which in a certain sense is superior to the material world" [28, p. XIV]. It is not surprising that this hyperthrophied approach does not yield a consistent and sufficiently detailed picture of the world.

There is a striking analogy between the modern geometrodynamic conception and the early 20th century energism. The assertions of the proponents of geometrodynamics concerning complete "dissolving of matter in space" are remarkably reminiscent of the well-known assertions of "disappearance of matter", "its ultimate reduction to motion", etc., current at the start of the century. A definite quantity of potential and kinetic energy corresponds to mass, and a definite curvature of space-time, to gravitation; in both cases elementary idealised physical situations can be found fully describable in terms of energy resp. spatio-temporal concept. This description, however, is purely formal and reveals its untenability in the transition to more complicated physical systems.

7. Unified Theories. An Alternative Approach

The untenability of attempts at unification of the gravitational and other types of field on a purely geometrical basis does not of course rule out other approaches to the construction of a unified theory of interacting particles. The most promising is at present an approach founded on reference to diverse symmetries and permitting to consider seemingly quite different particles as elements of a single multiplet. These multiplets are unified in supermultiplets and supersupermultiplets embracing still more different groups of particles. It proves possible to unify also various types of interaction by considering them as specific manifestations (splitting) of one or possibly two primary interactions.

The splitting of multiplets and interactions results from the fact that in the real world symmetries are not implemented precisely. The very fact of the existence of our world, in the form it has, is the realisation of only one of the equal possibilities and is thus a violation of the symmetry of natural laws. For example, the *world as a whole* can have several differing but symmetric (in some parameters) states with minimal energy. Each of these states may be "chosen" as the basic level of the *surrounding* world—its vacuum. But after the choice has been made and all the physical laws "balanced" accordingly, we may not even suspect the possibility of existence of a great number of other symmetrical worlds.

In current terminology, the existence of the real world with its concrete properties signifies a spontaneous violation of the symmetry of the universe, the breakdown of the symmetry. This breakdown could take place in the "Big Bang" epoch near the cosmological singularity, when the temperature of the extending universe somewhat diminished. The world under these conditions, just as a cooling rigid body below the Curie point, passes into some concrete "phase" state with a definite vacuum.

Since interaction velocities are finite and the size of the "cooling" universe quite considerable, it is not excluded that vacuum may vary in different regions. In other words there may be a great many worlds differing in their physical properties in the universe—not only because some of them are closed or semi-closed systems but also due to vacuum splitting.

It is hard to imagine even what unusual phenomena might be taking place on the border of such worlds differing in their vacuum.

Despite the fantastic quality of this picture, modern theoretical physics possesses models which permit computation of vacuum splitting and its consequences. There are many vague areas here, the methods of calculation are often prescriptive in character, yet exceptionally important and interesting results have already been obtained.

The first serious advance was the formulation of a unified theory of the electromagnetic and weak interactions. It was proved that the differences between these two types of interaction are not fundamental, they are quantitative rather than qualitative. At distances greater than 10^{-17} cm, the electromagnetic aspect of the phenomena prevails, while at smaller distances both aspects, the electromagnetic and weak, are of equal significance. The interaction is thus determined by a single universal constant. In this way, a hundred years ago the Faraday-Maxwell electrodynamics unified three different phenomena of nature—electricity, light, and magnetism; now the phenomenon of weak interaction has been added to them.

Even more far-reaching models have been suggested and are intensely elaborated; these unify the electromagnetic, the weak, and the strong interactions, proceeding from the idea of spontaneous breakdown of symmetry. For example, the Salam-Pati model [29, pp. 1187-1206] comprises only two types of "primary", "primordially elementary" particles: quarks (with their antiquarks) and gluons—vector particles transmitting interaction between quarks. The entire complicated spectrum of particles observed in experiment emerges through spontaneous breakdown of symmetry. In particular, the electromagnetic field (the photon) in this theory is merely a superposition of several split neutral states of the gluon field. The charges describing various types of interaction have the significance of phenomenological coupling constants expressed through the charge of the initial universal interaction and the split masses of particles.

So far the unified field theory is very ambiguous, there exist a great many variants differing in the choice of the initial symmetries, the number and type of "priming" particles, etc. Painstaking theoretical and experimental work will still have to be done here. But the very possibility of constructing such models is in principle very important (all the more so that they accord with a great number of experimental data and predict new phenomena).

The question arises: can the gravitational field be included in this scheme? Can all four now known "fundamental interactions" be described in a universal manner? This would realise Einstein's idea of a unified approach to diverse fields and interactions, although on a path fundamentally different from the one suggested by Einstein.

It is as yet difficult to answer this question. The reason is, first of all, that the gravitational field, as distinct from all known material fields, is intrinsically linked with space-time curvature conserved under all transmutations of material objects.[13]

Of course, the "primary" universal field, specifically manifested in the fields of observed mesons and photons, may be assumed to be actually closely connected with the curvature of space-time, just as the gravitational field. The only reason why it may be regarded as immersed in a flat spatio-temporal manifold is the fact that in all the cases with which we have had to deal it has proved to be weak (the theory of the weak gravitational field can also be formulated "as a flat approximation", without resorting to the concepts of space-time curvature). This viewpoint might serve as the basis for unifying all four types of interaction, but so far it has remained a hypothesis.

If we stick to the facts, however, it should be recognised that gravitation is a *property of matter*. Matter (or at any rate its kinds known at present) has this property just as it has inertia (mass). In the same way as corresponding to mass is energy—a definite characteristic of an attribute of matter, of its motion, gravitation has the corresponding feature of curvature (or, putting it more generally, geometry), that is, quite a definite characteristic of another attribute of matter—space and time. It is the material objects having mass that curve space-time around them, and not vice versa, it is not as if curvature of spatio-

[13] It should be emphasised that we are speaking only of the known forms of matter. We have no grounds at all for ascribing a universal character to such *concrete* properties of matter as gravitation, mass, energy, etc.

temporal metric were manifested as material formations.[14] The manifestations of the property of gravitation distributed in space—the gravitational field (or the field of gravitons) and the fields of other elementary particles—reflect different aspects of reality: the gravitational field is linked first of all with space and time, while the other fields, first with motion (energy) and only through the mediacy of gravitation, with space and time.

Being a property and not a variety of matter, gravitation, like mass, has a material carrier—gravitational field quanta having mass and energy. The gravitational field is in this sense quite material, just as, e.g., the photon field. At the same time it is a fundamentally different characteristic of material reality compared to other fields. The latter may be transformed into other kinds of physical matter, that is, they may disappear and emerge anew; but gravitation and space-time curvature associated with it, just as mass, energy, information, and other characteristics of matter and its attributes, are conserved in the processes of nature.[15]

The concept of gravitation, current in the literature, particularly physical literature, as curvature of space-time (or, as it is sometimes expressed, as deviation of the properties of real space-time from the properties of a flat manifold) literally means confusion of two concepts, one of which appertains to the material substratum itself, and the other, to the form of its existence. This may be avoided if gravitation is to be treated as a property of matter, and the formulations cited above interpreted in the sense of correspondence (not identity) of gravitation and curvature.

[14] Quite a definite amount of energy corresponds to definite mass, and one can speak in this sense, if *tentatively*, of the equivalence of mass and energy, but that does not mean at all that matter is reduced to energy, or motion. In the same way, the fact that gravitation is always accompanied by a strictly determined curvature of space-time does not warrant the conclusion that matter is reducible to its attributes—space and time, although *tentatively*, again, one can speak of the "equivalence" of gravitation and space-time curvature.

[15] See note 13.

8. Can Several Types of Gravitational Fields Exist in Nature?

Recently, an interesting generalisation of Einstein's gravitational theory was suggested by Salam [29], who assumed that, apart from the familiar remote-action "weak" gravitational field, whose quanta are massless gravitons, there must also exist one or more types of short-range or "strong" gravitational fields with massive quanta. All these fields go back to the "primary" field subject to the non-linear equations of the general relativity theory, having emerged through the splitting of the gravitational constant and mass of quanta in a spontaneous violation of the supersymmetry.

Analysis of experiments on the interaction of high-energy particles indeed indicates a possible admixture of tensor forces for which particles with the spin $s = 2$ and mass $M \simeq 2$ GeV are responsible. If we take these particles to be "strong gravitons", the corresponding gravitational constant proves to be 10^{37} times greater than the Newton constant. The size of "strong friedmons" with mass values equalling the masses of mesons and baryons, is here already $\sim 10^{-14}$ cm, and they may in principle be used for explaining the mechanism of confining quarks within elementary particles. "Strong black holes", whose mass is one or two orders greater, must evaporate through intense emission of particles in the nuclear traversal time 10^{-22} sec. These objects could be identified with "fireballs". Many experiments have provided indications (though not quite reliable) of the formation of such objects in non-elastic collisions of high-energy particles. "Strong black holes", if they actually exist, would provide a natural explanation why it is possible to describe, in terms of the temperature concept, a great range of experimental data on interaction of elementary particles, whereas the thermodynamic conditions necessary for the introduction of the temperature are not satisfied in elementary particle physics.

True, all these results are extremely tentative and largely hypothetical to be sufficiently convincing.

Conclusion

Only the first steps have been taken in the direction of synthesising the ideas of the general relativity theory and of elementary particle physics. There are a great many jarring contradictions and inadequately substantiated hypotheses here as yet. It is already apparent, however, that the ideas of Einstein's theory of macroscopic regions of space-time are extremely fruitful in the physics of microphenomena (although the division itself into macro- and microphenomena is in many respects doubtful).

It is obvious, though, that the general relativity theory requires further deepening and development even in the macroscopic area. The theory merely postulates or accepts as given such fundamental properties of our world as unidirectionality of time and three-dimensionality of space. The origin of these properties and their material basis remain for us just as mysterious and enigmatic as for ancient Greeks: we can only make surmises whether they are conditioned by some "quantum level" or whether their explanation requires the construction of a "hyperrelativity" theory.

Experimental verification of Einstein's theory is not sufficiently clear either. As distinct from the other three types of interaction known at present, where hundreds and thousands of *different* experiments have been performed, just a few fundamentally different experiments are so far known in the domain of gravitational phenomena, whose results may be quantitatively compared with theory. All of these experiments refer to a special case where deviation from flat space-time is not great, but even here measurement errors are of the order of several per cent. In particular, if further increase in experimental precision shows that light rays deviate in the solar gravity field by just several per cent less than predicted by Einstein's theory, that evidence will be in favour of another gravitational theory—the so-called tensor-scalar theory. As for the strong gravitational fields, all our knowledge of them is merely theoretical extrapolation, and it is not ruled out in principle that Einstein's theory will be sufficient only for their crude qualitative description.

As was stressed by A. Z. Petrov, a physicist who made a substantial contribution to the development of the general theory of relativity, it is particularly important to take into account "evolution of the theory of gravitation, the possibility of its development, the need to reject any attempts to present this theory as accomplished in its development, as one in which everything has been said and what is left are mere trifling additions, polishing the details" [30, p. 30]. Einstein was also quite convinced that "our notions of physical reality can never be final" [31, p. 266].

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V. I. RODICHEV

METHODOLOGICAL ASPECTS OF UNIFIED FIELD THEORY

Introduction

Einstein's enormous scientific heritage contains many unsolved problems, including those of gravitational field energy and momentum, analytical description of non-inertial reference frames, unified field theory and quantum theory of gravitation. Below we shall attempt a necessarily brief and incomplete retrospective evaluation of the ideas underlying the unified field theory and of the theory itself, the development of which exacted so much labour and time from Einstein and his followers.

It is sometimes said that the effort of working out different versions of a unified field theory was wasted, completely fruitless, and that the idea of a unified field theory has discredited itself. In our view, that is a profound error.

It is difficult to say who was the first to express the idea that the infinite diversity of bodies in nature and of connections between them points to the existence of a certain primary substance conditioning the diversity. It is indubitable, however, that for thousands of years this idea has been and still remains most attractive. It is of no consequence by what name we shall refer to this primary substance—the elements, as did antique philosophers; ether, as did Huygens; Einstein's fields, vacuum, or proto-matter described by a single spinor field; the point is that all of these and many other variants are realisations of one and the same idea at different times and levels. Although all the unsuccessful attempts have long receded into the past, the very idea of primary substance and its laws is still alive. The search for ever deeper laws continues, marking the transition to higher levels of scientific development.

Below we shall show that unified field theories were a natural consequence of lengthy historical development of two independent directions. The first direction is linked with concepts of a single substance as the basis of everything that is, the second, with notions of the absolute and the relative and the interconnections between them. In the unified field theories these trends were finally united, concluding the Einsteinian stage in the development of field theory.

1. The First Trend: a Single Substance Is the Basis of Everything

A. From the Antique Philosophers to the End of the 18th Century

As shown by the most ancient written monuments, the simplest laws of nature accessible to direct observation were known in China, Egypt, and India two or three millennia before our era. Later accumulation of isolated facts and special laws compelled the philosophers of antiquity to reduce everything to a single cause-and-effect chain of phenomena, thus leading to the idea of universe as a unity of all that is. Just as ancient are the attempts to understand the internal causes linking up natural phenomena, that is, to comprehend the origin of the cause-and-effect connections themselves.

During the first millennium before our era, the conviction gradually took shape that the underlying basis of the diversity of natural phenomena and of their causal relationships is a certain primary substance whose changes and transformations produce the world of visible phenomena.

There are enough historical data on the concretisation and implementation of the idea of primary substance at different epochs. Some of them are listed below.

Thales of Miletus (6th century B.C.) believed that all matter was one and all processes in the world were reducible to increased or diminished density of this single matter—the substance, which, in his view, was water.

Anaximander (6th century B.C.) posited the "unlimited" as the primary principle; it was not a substance, like water in Thales, and it was not subject to qualitative changes; it was the beginning of all that is. Here we have an example of the first abstraction, for the "unlimited" is an abstract concept designating something primary in all its manifestations.

According to *Anaximenes* (5th century B.C.), the primary substance is air: rarified air gives fire, while the various stages of its condensation, clouds, water, and earth.

Heraclitus (5th and 4th centuries B.C.) considered fire to be the primary element; fire might become air, water, and finally earth, and the transition might also proceed in reverse order. These transitions were the cause of everything that takes place in nature.

Empedocles (5th century B.C.) singled out four elements—fire, air, water, and earth, which were to a considerable extent independent and could not pass one into another, but various combinations of these elements and their motion conditioned all observable plenomena. There were "forces" acting between the elements, amity and enmity, which set the elements in motion.

Democritus (5th and 4th centuries B.C.), *Epicurus* (4th and 3rd centuries B.C.), and *Lucretius* (1st century B.C.) believed that the basis of the world of things and natural phenomena were atoms moving in vacuum. The atoms themselves were unobservable and only large and small bodies constructed out of them were accessible to observation. Expressing it in modern language, we have here the first formulation of the concepts of the micro- and macroworld.

Aristotle (384-322 B.C.) accepted the view that matter as a single entity existed in four basic forms—earth, water, air, and fire. These elements, as distinct from the Empedoclean ones, were interconnected and passed one into another. There was also a fifth form, ether, of which celestial spheres consisted.

Later, during the Roman domination and the almost thousand years of the Middle Ages, new world schemes were not worked out, particular and applied tasks were mostly solved, new results were accumulated and earlier obtained ones made more precise. It was only during the Renaissance (14th-16th centuries) that the ideas of antique philosophers were revived on a new and broader basis. The preconditions were then created for the historically more progressive mechanistic world scheme and mechanistic world-outlook.

Nicolaus Copernicus (1473-1540), *Giordano Bruno* (1548-1600), Galileo Galilei (1564-1642) regarded mechanical motion of matter as the necessary and decisive element of the world scheme. In a sense, it was given accomplished form in the works of *Rene Descartes* (1596-1650). His scheme does not envisage emptiness, space does not exist without matter, matter essentially coincides with space for it has a single property—that of extension. The observed diversity of bodies and their interactions are conditioned by mechanical motion of this primary substance.[1]

B. The Electromagnetic World Picture

The works of *Faraday* (1791-1867) and *Maxwell* (1831-1879) introduce the concept of the electromagnetic field as a definite physical reality.

The evolution from the concept of field as a convenient method of graphical representation of electric forces to the concept of field as a real physical object was long and difficult. Here for the first time scientists ran into non-mechanical laws. The laws of electrodynamics (the Maxwell equations) cannot be reduced either to the laws

[1] Descartes introduced a very important innovation. In 1637 his book *Discourse on the Method of Rightly Conducting the Reason* appeared, which introduced for the first time the concept of the orthogonal coordinate system. This concept made a very great impact on the development of mathematics and physics. The employment of coordinates, particularly in their generalised (curvilinear) form, for almost three and a half centuries greatly facilitated, on the one hand, the study of many problems of mathematics and physics, and on the other, resulted in substantive difficulties, in particular in the confusion between the concepts of coordinate system and reference system, which has persisted even into our times, as well as in the difficulties arising from the non-covariance of the gravitational field characteristics, which are combined within the unsolved problem of gravitational field energy and momentum.

of rigid body mechanics or those of hydrodynamics, although they do have some features of both.

The irreducibility of laws of electrodynamics to those of mechanics entails impossibility of constructing a mechanical (working) model of electromagnetic phenomena and consequently impossibility of visualising them.

Man's organisation (apparently owing to a certain direction in the evolution) is such that he can visualise in detail only those processes which are subject to the laws of mechanics, constructing a working mechanical model for them, if he so desires. Other phenomena are hard or impossible to visualise. Quantum physics and its laws, among other phenomena, are proofs of this.

In modern physics, mechanical visualisation in images has been supplanted by a new and higher type of visualisation, if one may put it so—the logical "visualisation" of abstract mathematical schemata of phenomena. In L.D. Landau's apt phrase, that circumstance taught us to understand things that cannot be imagined.

Interconnection between imaginative and logical visualisation as well as the problem of common sense are of great interest for modern physics in regard to both procedures and methodology, and they await a detailed elaboration.

But let us go back to electrodynamics. In the Gaußian system of units, Maxwell's equations for vacuum will be written thus:

$$rot\, \vec{H} - \frac{1}{c}\frac{\partial \vec{E}}{\partial t} = \frac{4\pi}{c}\vec{j}, \qquad (1)$$

$$div\, \vec{E} = 4\pi\rho, \qquad (2)$$

$$rot\, \vec{E} + \frac{1}{c}\frac{\partial \vec{H}}{\partial t} = 0, \qquad (3)$$

$$div\, \vec{H} = 0. \qquad (4)$$

These equations have the same significance for electrodynamics as Newton's motion equations for mechanics. A decisive role in their formulation was played, first, by the concept of displacement current, which in our case is written

$$\vec{j}_{dis} = \frac{1}{4\pi} \frac{\partial \vec{E}}{\partial t} \qquad (5)$$

and, second, Maxwell's hypothesis that the displacement current $\vec{j}_{dis}$ generates a magnetic field according to the same law as conduction current $\vec{j}$. Accordingly, the Biot-Savart law is written thus:

$$rot\, \vec{H} = \frac{4\pi}{c} \vec{J}; \qquad \vec{J} = \vec{j} + \vec{j}_{dis} \qquad (6)$$

hence equation (1), which is the differential form of the Biot-Savart law generalised for the case where there is displacement current. Equations (2) and (3) are differential forms of the Gauß theorem and Faraday's induction law respectively. Equation (4) expresses the vorticity of the magnetic field.

Equations (1)-(4) entail a very important consequence which allowed Maxwell to predict, first, the existence of electromagnetic waves (almost two decades before they were discovered by Hertz) and, second, the electromagnetic nature of light.

Let us briefly dwell on this important point. Let us ask this question: can electric and magnetic fields exist without sources? For this case, we have to assume that in equations (1)-(4) $\rho = 0$, $\vec{j} = 0$; we then obtain

$$rot\, \vec{H} - \frac{1}{c} \frac{\partial \vec{E}}{\partial t} = 0, \qquad (7)$$

$$div\, \vec{E} = 0, \qquad (8)$$

$$rot\, \vec{E} + \frac{1}{c} \frac{\partial \vec{H}}{\partial t} = 0, \qquad (9)$$

$$div\, \vec{H} = 0. \qquad (10)$$

It follows that, if free fields exist, they must be subject to equations (7)-(10). Equations (8) and (10) show that the fields $\vec{E}$ and $\vec{H}$ must both be vortices, and equations (7) and (9) both describe the mechanism through which one field supports the other. Indeed, equation (9) says that a change in the magnetic field generates a vortex in the electric field (Faraday's induction law), and on the contrary, equation (7) says that a change in the electric field generates a vortex in the magnetic field. These equations are very much like each other, so that equation (7) may well be called Maxwell's law of induction.

Eliminating $\vec{H}$ or $\vec{E}$ from the system (7)-(10), we shall obtain wave equations, respectively

$$\nabla^2\vec{E} - \frac{1}{c^2}\frac{\partial^2\vec{E}}{\partial t^2} = 0,$$
$$\nabla^2\vec{H} - \frac{1}{c^2}\frac{\partial^2\vec{H}}{\partial t^2} = 0, \qquad (11)$$

describing the propagation of fields at the speed $c = 3 \cdot 10^{10}$ cm/sec in the form of arbitrary waves.

Thus the two induction laws (Faraday's and Maxwell's) express the essence of the propagation of electromagnetic waves.

The electromagnetic field and the charges interacting across that field served as the basis on which all electric, magnetic, and optical phenomena were unified, and on which *Lorentz* (1853-1928) created the electron theory which in its turn permitted to explain a wide range of phenomena from a single standpoint. These attainments of electromagnetic theory at the turn of the century compelled many scientists to believe that the whole world, with the exception of gravitation, consists of charges and electromagnetic fields. At the same time these attainments served as one of the causes of the well-known crisis in physics which led some scientists to idealist conceptions. The nature of this crisis was first understood and explained by Lenin in his work *Materialism and Empirio-Criticism* [1].

As we now know, attempts to construct an electromagnetic picture of the world could not be successful for at least two reasons: first, this picture had no place for gravitation, and second, apart from the gravitational and electromagnetic fields, there are two more fields responsible for strong and weak interactions, for which there is no place in that picture of the world either.

Further development of the idea of a single basis for natural phenomena on a classical (non-quantum) level involved the construction of the special and later the general theory of relativity. We shall therefore end here the consideration of this direction and pass on to a discussion of the second trend in theoretical development concerned with the absolute and the relative in nature.

2. The Second Trend: the Absolute, the Relative, and Their Interconnection

A. From Ancient Greek Philosophers to Galileo

The development of notions of the absolute and the relative has been discussed in many works (see e.g. [2]), the dialectics of the links between the absolute and the relative has long been studied, so that we have no need to analyse these questions in detail. We shall therefore restrict ourselves to brief remarks which we shall need below.

The meaning of the elementary relative concepts of "up", "down", "right" and "left" was realised already by ancient Greek philosophers. Regarding the Earth as an immovable centre of the universe, that is, having selected, to put it in modern terms, a favoured reference system, they were able to attribute absolute significance to the motions of bodies—movement towards or away from the world's centre.

Aristotle introduced the concept of place, or position, of a certain body A with regard to a pre-selected reference body B, pointing out that if the distance between them changes, body A moves relative to B. He also considered the nature of the immobility of the reference body: was it relative or absolute?

Aristotle expressed ideas that were very close to what we now refer to as the law of inertia [3]. In uniform space (which he interpreted as empty space in which there were no other bodies), a body left to itself will be either at rest or continue to move. The meaning of motion or rest in emptiness (that is, regardless of any other objects) is not explicated here.

In the 3rd century B.C., *Aristarchus of Samos* expressed the idea of heliocentricity of the universe and also, in fact, the idea of the Earth's relative position of rest. Beginning with this moment, the idea began to take root that motion could with equal justification be correlated with any reference bodies.

Copernicus made the Earth's position of rest relative, quite consciously, and, choosing the Sun, that is, a more inertial system that the Earth, as the body of reference, constructed a simple picture of the planets' motion.

Galileo and later *Descartes* formulated the principle of inertia—the inertiality of rectilinear and uniform motion of a free body. But that was essentially a purely qualitative formulation of the mechanical principle of relativity. What was needed for a strict (analytical) formulation was the dynamic principle, that is, the laws of motion, which were at that time only dimly perceived.

B. The Mechanical Principle of Relativity

This defect was finally removed by Newton, who formulated the laws of motion thus concluding almost two thousand years of search. Besides, he accepted as axioms the concepts of absolute time and space, absolute and relative motions and corresponding velocities.

Now that we know the laws of motion and the Galileo transformations correlating the coördinates of two inertial reference frames, we can give a precise (analytical) formulation of the mechanical principle of relativity. In modern terms, the invariance (to be more precise, covariance) of Newton's second law under the Galileo transformation group analytically expresses the mechanical principle of relativity. That means that all inertial reference frames are mechanically equal, that is to say, in all such frames mechanical phenomena occur in an identical manner. It follows that no mechanical experiments performed within such a frame will distinguish its inertial motion from the state of rest. There are just as many "states of rest" as there are inertial frames and all of them are relative, no one single state of rest being favoured.

The conclusion is sometimes drawn that the mechanical motion of bodies is only relative and can thus be created or annihilated by a suitable choice of a reference frame, that there is no absolute velocity of motion of which Newton spoke, all velocities being relative. Despite its verisimilitude and agreement with elementary facts, this one-sided assertion is certainly methodologically untenable.

As pointed out in the above, the dialectics of the connection between the absolute and the relative, its application to mechanical motion included, has been extensively discussed in the literature, and the problem is in principle solved (see e.g. [4]). But the discussion is sometimes couched in such general terms that one gets the feeling that the author loses touch, without realising it, with the essence of the problem, hiding behind purely philosophical formulas—quite correct ones, to be sure. Let us cite some examples: "The motion of a body is absolute, inasmuch as it is self-motion, being determined by inner contradictions and the struggle of opposites, regardless of external determinant factors, of objects at rest. The state of rest is absolute to the extent in which it is determined by the unity and equilibrium of inner opposites. But motion is relative inasmuch as it is motion with respect to the state of rest, being dependent on the objects at rest. The state of rest is relative to the same extent to which it is the state of rest in regard to motion, being dependent on the moving bodies" [4, p. 192]. And then, later: "The absolute exists only in its manifestations in the relative and through the relative" [4, p. 193].

That is all, generally speaking, quite correct, but what is an unsophisticated reader to do with this correct explanation (and not just an unsophisticated reader, either)?

The defect of the statements quoted is quite obvious. They are too general: the same may be said about any kind of motion, not only mechanical. But mechanical motion has a certain specificity, which is essentially ignored in these statements.

Mechanical motion is not only relative; but what does that follow from? Cannot it be formulated with analytic precision by resorting to the reference frame concept? As these questions are very important for our further exposition, we shall consider two elementary examples illustrating the quotations cited above.

A naughty boy shoots a stone from a slingshot, which hits a windowpane and breaks it. Let us consider this "criminal" case, so to say. The stone moves relative to the window, its motion is relative. It is indeed easy to imagine a system of reference relative to which the stone will be at rest or, if you prefer, move backwards (e.g., relative to a sparrow whose flight speed is greater than that of the stone). But on the other hand a broken window is an absolute fact. You cannot find a reference frame in which the glass would be intact. The question now arises: if motion is only relative, how can it lead to absolute consequences?

Another example. A fast proton collides with an atomic nucleus and destroys it. The proton's motion towards the nucleus is relative, but the fact of the destruction of the nucleus is absolute. Here again the same question arises.

To answer it, let us consider the motion of two bodies relative to a certain reference frame. The motion of each of the two bodies A and B is relative for the reasons of which we have already spoken (the character of motion depends on the choice of a reference system). But, although that is so, the relative motion of the two bodies A and B (one relative to the other) is an absolute fact. For there is no reference frame in which both would be at rest. Therein lies an analytically precise answer to the question posed here. In other words, the absolute quality of motion is manifested in the invariance of the fact of relative motion of two or greater number of bodies. In the same way the relative state of rest of two or more bodies is an absolute fact.

This result holds in the special and general theory of relativity, and it is there given invariant significance.

C. The Velocity of Absolute Motion

The problem of absolute velocity of motion is so far unexplicated. It did not figure in our previous discourse, and it is only in the special theory of relativity that it is given a somewhat unexpected solution.

Let us now consider the interpretations of the velocity of absolute motion before the construction of the theory of relativity. Although Newton postulated the existence of absolute motion, he did not know how its speed could be determined or even recorded.

For a long time, for almost two centuries, this question did not attract any special attention, for the solution of concrete tasks did not require at that time a knowledge of the speed of absolute motion, and only in the second half of the 19th century, when optical phenomena in moving mediums were studied, it had to be seriously tackled.

In determining a body's absolute speed, the existence of a certain absolutely immovable reference system is assumed, that is, of a system whose basis is an absolutely immovable body of reference or some immovable medium. World ether was postulated as such a basis—a hypothetical medium (introduced by Huygens for explaining the wave nature of light) filling all space and immovable.

To be able to use ether as a body of reference, it is necessary to find out first how it behaves relative to the bodies moving in it. There are three mutually exclusive apriori answers to this question.

(1) Ether is absolutely immovable and unaffected by bodies freely moving through it. If that is the case, physical phenomena, including optical ones, in reference systems moving through ether must be affected by "ether wind" whose velocity must be equal in magnitude but oppositely directed to the absolute speed of the motion of the reference system.

(2) Ether is partially carried along by bodies; then the speed of "ether wind" must be less than the absolute speed of the motion of the reference system.

(3) Ether is completely carried along by bodies, just as air in an airliner; then the speed of "ether wind" is zero.

As is known, the interpretation of astronomical aberration, of experiments by Fizeau, Michelson and others, resulted in confusing conclusions confirming with great precision all three of the apriori possibilities. For this reason at the end of the 19th century, after almost 50 years of hunting for "ether wind", the same question arose again: how does ether behave relative to moving bodies?

These contradictory results in any case indicate that ether cannot be accepted as a basis for an absolutely immovable reference system, and the question of the speed of absolute motion is still unanswered.

On the other hand, when experimental results begin to contradict one another, that is a sure sign of a critical situation. There is of course no question of absence of determinism in nature: it is merely a question of crisis in the theory used to describe experiments. That means that we have moved into an area (to put it concretely, the area of optical phenomena in moving mediums) in which the given theory no longer works, where its system of axioms and concepts is in certain aspects imprecise and even incorrect.

It should be noted that that is not the only crisis that has shaken the edifice of theoretical physics since the beginning of the 20th century. In the year 1900 a crisis came to a head that was due to the impossibility of explaining, by any known means, the distribution of energy in the spectrum of emission of a black body. Further, in about 1913 another critical situation arose owing to the impossibility of explaining in contemporary terms the structure of the atom and the origin of laws of atomic spectra. Finally, at the present time a crisis obviously arises because of the inability of modern theoretical physics to explain the properties of elementary particles, that is, to construct a theory of elementary particles.

As history shows, crises have always been overcome by the introduction of more precise new concepts and ideas, and each time the overcoming of a crisis was a new leap in the development of science. For example, the overcoming of the 1900 crisis led to quantum conceptions of light, of discrete energy states, and a new world constant appeared, $h = 6.62 \cdot 10^{-27}$ erg/sec, the Planck constant. The overcoming of the 1913 crisis ultimately resulted in the creation of modern quantum mechanics. By 1905 a crisis fully matured that was due to the difficulties of various theories of the ether and failure to discover absolute motion; its overcoming resulted in the creation of the special theory of relativity.

D. The Special Relativity Theory

Let us now briefly consider the principal features of the special relativity theory with special attention to the interconnections between the concepts of the absolute and the relative.

The fact that some very precise experiments performed on the Earth failed to discover its translational movement (the Earth's orbital motion during the experiment may with great precision be regarded as inertial motion at the speed of 30 km/sec), as well as a number of other considerations indicated that the mechanical principle of relativity apparently had to be extended to electromagnetic phenomena and probably to all natural phenomena. However, it proved to be impossible simply to add the laws of electrodynamics to Newton's laws of motion declaring them to be an integral system describing mechanical and electromagnetic phenomena in any inertial reference frame. The point is that the Maxwell equations, as distinct from Newton's laws of motion, are non-covariant under the Galileo transformations. That means that the two sets of equations are formulated on different principles.

To combine mechanics and electrodynamics in an integral system satisfying the principle of relativity, we must choose one of the three ways that are possible in principle .

(1) Change the Maxwell equations (without destroying agreement with experience, of course) in such a way that they should be covariant under the Galileo transformations.

(2) Formulate anew Newton's second law of motion (leaving the Maxwell equations unchanged) and introduce new transformations instead of the Galilean ones in such a way that the whole system of equations should be covariant under the new transformations.

(3) Replace all equations by new ones.

The second possibility proved to be the correct one. Moreover, even without assuming beforehand that the Maxwell equations hold in any inertial reference system, it is possible to construct the special relativity theory, as was done by Einstein.

The works of *Hertz, Lorentz, Poincaré* and other scientists paved the way for the special theory of relativity which was formulated by *Einstein* in 1905 [6, S. 891-921]. The theory was founded on the following postulates:

(1) The relativity principle holds for all phenomena. That means that all inertial reference frames are equivalent relative to all natural phenomena.

(2) The velocity of light in vacuum is the same in all

inertial reference frames and does not depend on the speed of motion of the source.

To these two postulates must be added one more, usually implied.

(3) The geometry of three-dimensional (physical) space is Euclidean in all inertial frames.

The first and third postulates appear comprehensible or at any rate natural and well supported by experiments, whereas the second postulate runs counter to "common sense" and in particular to the familiar vector rule of addition of velocities; despite all arguments, it is difficult to perceive. To overcome this psychological barrier obviously rooted in the limitations of common sense, let us first give up the second postulate and try to consider it as a kind of corollary. (This approach is interesting not only from the methodological standpoint.) That means that the Lorentz transformations are not yet available to us and we cannot check whether the laws of electrodynamics, that is, equations (1)-(4), satisfy the principle of relativity; we cannot thus use light signals as an invariant instrument for synchronising clocks and deducing the Lorentz transformations.

We then turn to the following important circumstance: the constant $c = 3\cdot 10^{10}$ cm/sec first appears in electrodynamics in considering the magnetic effects of direct current, before the introduction of the Maxwell equations. Let us recall, e.g., the expressions for the Biot-Savart law or the Lorentz force:

$$\vec{H} = \frac{1}{c}\int \frac{I}{r^3}\,[\vec{dl}, \vec{r}\,]; \qquad \vec{F} = \frac{e}{c}\,[\vec{v}, \vec{H}\,]. \tag{12}$$

The constant c determines here the correlation of the C.G.S.E. and C.G.S.M. units, as the strength of current I and charge e are given in the S.G.S.E. system, while the magnetic field intensity $\vec{H}$ in the S.G.S.M. system.

It is easy to show that this constant must be universal, that is, the same in all inertial reference frames. Indeed, let observers in different reference systems determine the correlation of the C.G.S.E. and C.G.S.M. units. If the first postulate is correct, all observers must obtain one and the same value for c. Otherwise the reference systems are not equivalent.

The fact that c has dimensions of velocity permits the conjecture, however vague at first: can there be such "strange" fields in nature which are propagated at the fundamental velocity c? The encouraging fact here is that c coincides with the velocity of propagation of electromagnetic waves (light) in vacuum. We do not know yet, however, whether the Maxwell equations satisfy the relativity principle, and we cannot therefore say that we have found such a field. Without knowing beforehand whether any of this has any physical meaning, we can still establish that our assumption (about c) can be brought in accord with the first postulate by giving up absolute time and absolute simultaneity. Let us emphasise that this rejection is not a new postulate but a consequence of our "strange" assumption. But, having assumed that, we can immediately deduce, apriori so to speak, the Lorentz transformations with all their kinematic consequences, that is to say, we can formulate the special relativity theory as it is usually done.

Now that we have verified that the Maxwell equations are covariant under the Lorentz transformations, we can say that we have found at least one field that is propagated at the fundamental speed c—the electromagnetic field (light). Thereby the apriori construction of the relativity theory will be confirmed by experience. Further, having established covariance, under the Lorentz transformations, of wave equations for neutrino and for weak gravitational fields, we find two more fields propagated at the fundamental speed. It thus happens that there are three fields propagated at the fundamental speed; for technical reasons, only one of them—the electromagnetic field—can now be used for synchronising clocks.

Thus the special theory of relativity has been constructed without ether or Newton's absolute time and absolute speed. The apparatus of this theory, largely by the efforts of *Minkowski*, was given elegant four-dimensional form reflecting a certain equality of the temporal and spatial coordinates. The entire diversity of the mechanical, electrodynamic and other phenomena proved to be related to four-dimensional space-time with a pseudo-Euclidean metric, in which an interval (an element of proper time) will be written:

$$ds^2 = (dx^0)^2 - (dx^1)^2 - (dx^2)^2 - (dx^3)^2 = \eta_{ab}\, dx^a\, dx^b;$$
$$\eta_{ab} = diag\left\{+1,\ -1,\ -1,\ -1\right\}\ ; \qquad (13)$$
$$x^0 = ct;\ a, b = 0, 1, 2, 3$$

(the Einsteinian rule of summation is used here).

Inertial reference frames are reflected in the special theory of relativity in a four-dimensional orthogonal coordinate system (that is not quite exact but we shall not dwell on this point). Transitions between reference systems are described by the Lorentz transformations, that is, orthogonal rotations leaving the ds^2 invariant. The particle's motion is described by a world line where ds is an element of the arc length, and the world line itself is the line of the proper time of a moving particle, an invariant construction.

Let us see now how the thesis that the relative motion of two bodies is an absolute (invariant) fact is realised in the special theory of relativity. Let two particles move inertially relative to a certain reference frame (let them move away from each other, for instance). Their motion will then be represented by two diverging straight world lines. In view of the invariance of this construction, the mutual arrangement of the world lines will not change in the transition to any other inertial reference frame; and that means that relative motion of two or more bodies is an absolute fact. In particular, we have invariance in the case of two parallel world lines of two bodies, where the bodies are at rest relative to one another.

And now let us see how the special relativity theory solves the problem of absolute velocity. The velocity vector (the 4-vector) of a material point is defined in the special theory of relativity like this:

$$u^a = \frac{dx^a}{ds};\quad u^0 = \frac{1}{\sqrt{1-\beta^2}};$$
$$u^k = \frac{v^k}{c\sqrt{1-\beta^2}}; \qquad (14)$$
$$\beta = \frac{v}{c};\qquad v^k = \frac{dx^k}{dt};\quad k = 1, 2, 3.$$

If velocity v is small compared to c, we can neglect β in comparison with 1, thus finding that

$$u^k = \frac{1}{c} v^k ;$$

it follows that u^k is the expression of a component of normal (Newtonian) velocity v^k in c units.

From the geometrical standpoint, u^a is a component of the unitary vector of a line tangent to the world line, that is,

$$\eta_{ab}\, u^a u^b = 1, \tag{15}$$

which is easily found by dividing (13) by ds^2. Let us note the following circumstance: the 3-vector of velocity $\vec{v}$ with components v^k, as well as all spatial components of u^k, can be made to vanish by the choice of a reference frame, in complete agreement with the usual notion of speed as a relative magnitude. But no choice of a reference frame (in this case, of the Lorentz coordinate system) will make all the components of the 4-vector u^a ($a = 0,1,2,3$) vanish. It follows from the fact that the components of the u^a form a 4-vector and, if it is given in one coordinate system, it will be present in any other coordinate system, whatever the turn of the latter relative to the former. In particular, its modulus, according to (15), will always equal 1. Thus the 4-vector of velocity has absolute meaning. Only its components are relative, dependent on the choice of the reference frame. We have here a kind of revival of Newton's idea of the velocity of absolute motion which does not require a favoured reference frame, only not in three-dimensional space but in four-dimensional space-time with a pseudo-Euclidean metric.

Each particle "receives" its 4-vector of velocity at birth and does not part from it as long as it exists. In its own reference frame, where it is at rest ($v^k = 0$), the spatial components of the 4-vector of velocity also equal zero according to (14), but the time component $u^0 = 1$. A particle that is at rest in the usual acceptation, moves, but only in the direction of the time axis $x^0 = ct$, coinciding in this case with the line of the particle's proper time, and it moves at the speed of light.

The following curious result is also linked with the properties of the 4-vector of velocity u^a. Under the impact of any forces (of any force fields) a particle changes its usual velocity $\vec{v}$ (v^k, $k = 1,2,3$) both in magnitude and direction, as a general case. According to (14), the components of the 4-vector of velocity u^a are also changed. But, inasmuch as its modulus remains, according to (15), unchanged, always equal to 1, the 4-vector can only undergo 4-dimensional turns. In the case of speed that can only take place in uniform curvilinear motion (e.g., in uniform motion of a material point along a circle). Correspondingly, the relativistic second law of motion of a probe particle in any force field simply describes a turn of the 4-vector of velocity in its displacement along the world line.

Indeed, let a particle move in the electromagnetic field. Its law of motion has this familiar form

$$\frac{du^a}{ds} = \frac{e}{m_0 c^2} F^a_b u^b, \tag{16}$$

where

$$F_{ab} = \frac{\partial A_b}{\partial x^a} - \frac{\partial A_a}{\partial x^b} \tag{17}$$

is an antisymmetric tensor of the intensity of the electromagnetic field, A_a being components of the 4-vector of the potential. In geometric terms F_{ab} is a matrix describing the turn of, generally speaking, any 4-vector. Therefore, whatever the nature of the force field, the law of the particle's motion can always be presented in the form of (16).

In conclusion let us list a system of equations of mechanics and electrodynamics satisfying all the requirements of the special relativity theory:

$$m_0 \frac{du^a}{ds} = f^a;$$

$$\frac{\partial F^{ab}}{\partial x^b} = \frac{4\pi}{c} j^a, \tag{18}$$

$$\frac{\partial F_{ab}}{dx^c} + \frac{\partial F_{bc}}{\partial x^a} + \frac{\partial F_{ca}}{\partial x^b} = 0.$$

This system could be complemented by the equations of relativistic hydrodynamics, the Dirac equations, and others which also satisfy the special relativity theory, but we shall not dwell on them.

3. The General Theory of Relativity and Unified Field Theories

A. Gravitation and Non-Uniform Space-Time

The gravitational field theory, or the general relativity theory, is at the same time a theory of space-time and a basis of modern cosmology. In small spatio-temporal domains it is transformed into the special relativity theory and is in this sense a generalisation of the latter. Further we shall briefly dwell on the physical principles of the general relativity theory in order to make as natural an approach as possible to such an unusual property as space-time curvature.

A remarkable characteristic of the gravitational field established already by Galileo is equality of accelerations of any bodies moving in identical gravitational fields. That means that a body's inertial and gravitational masses expressed in identical units are equal. This fundamental fact, which is now established to an accuracy of 10^{-11}, is the first postulate of the theory of gravitation.

Equality of accelerations of all bodies in identical gravitational fields makes motion in the latter analogous to motion relative to non-inertial systems. Similarity between the kinematic results of the action of the forces of inertia and of gravitation is so great that they are locally indistinguishable: both forces are proportional to the body mass. This fact is referred to as the principle of local equivalence. It entails local equality of two statements: (a) the inertial reference frame possesses a gravity field; (b) there is no gravity field, but the reference system is a non-inertial frame. Consequently, in the presence of the gravitational field the laws of nature must be covariant not only relative to the choice of the inertial system, as in the special relativity theory, but also relative to the choice of the non-inertial system. Moreover, since the non-inertial system need not be necessarily connected with the gravitational field (the non-inertial motion of the reference system may be conditioned by other force fields as well), the laws of nature must be covariant relative to the choice of a non-inertial system without the gravitational field, too.

Transition to a non-inertial system, that is, to a reference system in non-rectilinear and non-uniform motion, involves, generally speaking, a transition to a certain curvilinear coordinate system (the reverse statement is not true). Then permissibility of any reference systems, according to Einstein, must analytically be expressed by the requirement of general covariance of the laws of nature. The equations of the gravitational and other fields must retain their form in any curvilinear coordinate system.[2] The general covariant form of some law, however, does not yet indicate the presence of a gravitational field. It would indicate such a field in the case of complete identity of gravitation and inertia, and that not under all conditions.

The world line of a particle in the special relativity theory, that is, the line of its proper time describing the history of its motion, is an invariant construction not only under the Lorentz transformations but also under the transition to any curvilinear system of coordinates x^μ connected with the Galilean coordinates x^a by a certain law of transformation

$$x^a = x^a(x^\mu); \quad x^\mu = x^\mu(x^a); \qquad a, \mu = 0, 1, 2, 3. \tag{19}$$

Transforming interval (13) with the help of (19), we shall obtain

$$ds^2 = g_{\mu\nu}\, dx^\mu\, dx^\nu, \tag{20}$$

[2] It should be noted that a system of reference as a kind of physical object must be geometrically reflected by an invariant object and not a coordinate system. Although the requirement of general covariance is absolutely necessary, it follows from other considerations. We shall not, however, dwell on this question in order not to deviate from the orthodox course of exposition.

where the metric tensor components have the following special form:

$$g_{\mu\nu}=\eta_{ab}\frac{\partial x^a}{\partial x^\mu}\frac{\partial x^b}{\partial x^\nu} \tag{21}$$

Since transition to a non-inertial system involves, as we have indicated already, transition to a certain curvilinear coordinate system, the metric tensor $g_{\mu\nu}$ which now depends on all four coordinates x^μ, must contain, according to the orthodox view, physical information about inertial forces (for instance, about centrifugal forces and Coriolis forces), apart from the purely geometric information about the nature of the coordinate system.

The second postulate of the gravitational theory may now be formulated in the following way: inasmuch as the fields of forces of inertia and gravitation are locally indistinguishable, the information about the gravitational field, just as about the forces of inertia, must be contained in the metrical tensor $g_{\mu\nu}$, which plays the role of the potential in the theory of gravitation. If there is no gravitational field, the components of the metric have the special form (21), which permits the transition from (20) back to the interval expression (13), that is, from a non-inertial system to an inertial one, thereby eliminating the forces of inertia in all space. In the presence of the gravitational field the components of $g_{\mu\nu}$ no longer have their special form (21), and in that case no coordinate transformations will reduce the expression (20) in entire space to expression (13), that is, it is impossible to introduce a single Lorentz coordinate system, an inertial system. Geometrically that means that space has ceased to be flat.

As a result, we arrive at a conclusion that is decisive for the gravitational theory: space in which there is a gravitational field is not flat. Gravitation is manifested in space curvature, and that sharply distinguishes the gravitational field from all other fields.

The source of the gravitational field, that is, the cause producing curvature of space-time, are moving masses and any fields. The distribution and motion of masses as well as the dynamic characteristics of any fields are described, as we know, by the energy-momentum tensor $T_{\mu\nu}$. The component T_{00} determines the density of energy (mass), and the rest describe the density of the flow of energy (mass), the quantity of motion.

We thus see that, as distinct from electrodynamics, where the source of the field is the 4-vector of current density j^a $(a = 0,1,2,3)$ combining the density of the charge ρ and the density of normal current $\vec{j}$, the source of the gravitational field is a much more complicated magnitude[3]; the potential of this field is described by ten components of the tensor $g_{\mu\nu}$.

After nearly eight years of agonising search and study Einstein gave a final formulation of the gravitational field equations:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi\kappa}{c^4} T_{\mu\nu}. \tag{22}$$

These equations express in general covariant form the idea that distribution and motion of any kinds of matter produce curvature of space-time. The right-hand side of equation (22) contains the density of source distribution—the energy-momentum tensor $T_{\mu\nu}$ including all kinds of energy with the exception of gravitation; the latter is implied in the left-hand side of the equation, which contains the characteristics of space-time curvature, namely the Ricci tensor

$$R_{\mu\nu} = R^{\sigma}_{\mu\sigma\nu}, \tag{23}$$

which is the sum of the components of the curvature tensor $R^{\lambda}{}_{\mu\sigma\nu}$; the latter depend on a rather complicated manner on $g_{\mu\nu}$ and their first and second derivatives.[4] Further, the left-hand side of (22) also includes scalar curvature R connected with the tensor (23) in the following manner:

$$R = g^{\mu\nu} R_{\mu\nu}. \tag{24}$$

In the case of two-dimensional space of constant

[3] According to the Einstein rule, identical indices imply summation from 0 to 3.

[4] See any monograph on the general relativity theory.

curvature (e.g., a sphere) it equals $1/r^2$, where r is the radius of the sphere.

At present, a great number of solutions for Einstein's equations have been obtained. Of these the most important, in terms of experimental verification, are the well-known solutions of Schwarzschild and Friedmann.

In the case of the Schwarzschild solution the interval has the following form:

$$ds^2 = \left(1 - \frac{2r_0}{r}\right) c^2 dt^2 - \frac{dr^2}{1 - \frac{2r_0}{r}} - r^2 \left(d\theta^2 + \sin^2\theta \, d\varphi^2\right); \qquad r_0 = \frac{\kappa M}{c^2}. \tag{25}$$

This solution describes the geometrical properties of space-time conditioned by the point mass M at the beginning of the "spherical" system of coordinates. At great distances, where the magnitude r_0/r may be neglected in comparison with 1, the expression (25) becomes the special relativity theory interval written in the spherical coordinate system. The Schwarzschild metric (25) describes, in fine agreement with experiment, three well-known effects: the displacement of the planet's perihelion, the deflection of a light ray by the sun, and the gravitational red shift of spectral lines.

Thus the properties of the gravitational field are such that it can only be described in curved space-time, the curvature varying from point to point. These spaces are called heterogeneous.[5] Space is made heterogeneous by the presence of a physical field, the gravitational field. The characteristics of the gravitational field become at the same time geometrical characteristics of heterogeneous space-time.

Despite its depth and elegance, this idea of Einstein leads, as we have already indicated, to a number of well-known difficulties which come under the general heading of the problem of gravitational field energy-momentum

[5] There are curved but homogeneous spaces, e. g. constant curvature spaces.

[5]. The origin and nature of these difficulties are not yet fully clear: they may arise out of our failure to grasp something essential about the situation, and they may also have deeper roots. Most physicists active in the field of gravitation theory are apparently inclined to accept the second possibility. In any case, the transition to the study of heterogeneous spaces opens up great possibilities and at the same time leads to serious difficulties.

Let us point out in conclusion that in the general theory of relativity the concepts of the absolute and the relative may be said to reach their highest development, being profoundly and consistently incorporated in the fabric of the theory. On the one hand, such constructions of the special relativity theory as world lines, velocity 4-vectors, various Lagrangians, etc. retain their significance in the general relativity theory; merely the form of notation is changed in accordance with the requirement of general covariance. On the other hand, the acceleration 4-vector, which was an absolute (invariant) construction in the special relativity theory, loses its invariant meaning in the general relativity theory, becoming relative, for acceleration, by the principle of equivalence, may be eliminated at any world point by a suitable gravitational field.

B. Unified Field Theories

Einstein envisaged the unified field theory as a colossal theoretical construction incorporating all known physical fields as more or less independent parts of a certain primitive structure. The field equations of such a theory (general covariant equations, of course), just as the other equations of this theory, had to have normal solutions everywhere, but in a certain small region, comparable in size with elementary particles, the intensity of fields, just as energy concentration, had to be very great. These solutions must describe elementary particles, if only approximately, without the familiar difficulties with diverging self-energy.

What grounds were there, and are there now, for developing this scheme? The answer to this question was in fact given at the very beginning of the article where we considered the two-thousand-year long history of the idea of primary substance. What we said there might be translated into modern terms as follows: the diverse "elementary" particles and connections between them observed in nature must necessarily have some common basis—unitary primary matter whose various degrees of excitation produce elementary particles and zero state probably corresponds to vacuum. If there were no such primitive basis, the particles would not "know" how to behave in their encounters, that is to say, they would be unable to interact, being completely unconnected objects. The existence of the primitive basis makes all particles cognate, as it were, ensuring their mutual transformations.

However, to develop these assumptions into a theory, they must be reflected in a suitable mathematical (geometrical) scheme. The decisive step along this path is the following proposition: space in which there is any physical field, not necessarily gravitational, becomes heterogeneous! The next question is, what geometrical object should be used to reflect this heterogeneity? Some relevant experiences have already been accumulated, and they point to the fact that heterogeneity of space-time conditioned by the gravitational field should be reflected in a non-trivial metric, that is, one that is not due merely to coordinate transformation and is thus irreducible to the form (21). To find out what other possibilities there are here, let us consider in the most general terms how space geometry is constructed.

The background against which space in the geometrical sense of the term is constructed is the so-called elementary manifold (see e.g. [5, p. 13]). In terms that are not quite rigorous, an elementary manifold is a certain abstract set in which all elements are numbered in a definite order, the numbering being mapped onto a suitable numerical region as a coordinate system (network). The elements of the set are not ascribed any properties beforehand, so that they may have diverse interpretations depending on the task being solved. They may be events in physical space-time, states of the dynamic system, points on the surface of a body, etc. Inasmuch as the numbering of the elements of the set is formal, it can be varied within very broad limits, satisfying only one requirement—that of non-ambiguity. In the mapping, the corresponding procedure will be coordinate transformation. At this stage in the construction of geometry, when we have points and coordinate systems at our disposal, curved lines and surfaces may be formed in the manifold as well as tensors with the usual law of transformation, all operations on tensors can be performed that do not require transition to neighbouring points, that is, addition, multiplication, and convolution.

However, this manifold cannot as yet be called space. From the geometrical standpoint it is something very indefinite and amorphous. There is no metric in it so far, and the arc length of a curved line cannot therefore be calculated. There is no connection here as yet and, consequently, tensors given at different points of the manifold cannot be compared, and the covariant derivative cannot thus be defined. Therefore two possibilities are open to us:

(1) One is to define the metric $g_{\mu\nu}$ and its own symmetric connection $\Gamma^{\lambda}_{\mu\nu} = \Gamma^{\lambda}_{\nu\mu}$, that is, the kind of connection where $\nabla_{\sigma} g_{\mu\nu} = 0$ (the covariant derivative of $g_{\mu\nu}$ equals zero). We shall then obtain Riemannian geometry used by Einstein in the general theory of relativity.

(2) The other is to define the metric $g_{\mu\nu}$ and an arbitrary connection ${}^{*}\Gamma^{\lambda}_{\mu\nu} \neq {}^{*}\Gamma^{\lambda}_{\nu\mu}$ independent of $g_{\mu\nu}$. Assignment of these magnitudes transforms the elementary manifold into space in the geometrical sense of the term.

Let us analyse the second possibility (the analysis will of necessity be quite superficial in the framework of this article).

If the metric $g_{\mu\nu}$ is given, arbitrary connection ${}^{*}\Gamma^{\lambda}_{\mu\nu}$ may be resolved into the following three more or less independent parts:

$$ {}^{*}\Gamma_{\mu\nu,\sigma} = g_{\lambda\sigma}\, {}^{*}\Gamma^{\lambda}_{\mu\nu} = \Gamma_{\mu\nu,\sigma} - S_{\mu\nu,\sigma} + Q_{\mu,\nu\sigma}, \tag{26} $$

where

$$ \Gamma_{\mu\nu,\sigma} = \frac{1}{2}(\partial_{\mu} g_{\nu\sigma} + \partial_{\nu} g_{\mu\sigma} - \partial_{\sigma} g_{\mu\nu}) \tag{27} $$

are Christoffel's symbols of the first kind, representing the metrical part of connection and themselves forming the object of connection,

$$S_{\mu\nu,\sigma} = \frac{1}{2}({}^*\nabla_\mu g_{\nu\sigma} + {}^*\nabla_\nu g_{\mu\sigma} - {}^*\nabla_\sigma g_{\mu\nu}) \tag{28}$$

are the so-called Weylian terms, while

$$Q_{\mu\nu\sigma} = C_{\sigma\nu,\mu} + C_{\sigma\mu,\nu} + C_{\mu\nu,\sigma} \tag{29}$$

is the tensor determined by space torsion; the torsion is determined by connection in the following manner:

$$C^\lambda_{\mu\nu} = \frac{1}{2}\left\{{}^*\Gamma^\lambda_{\mu\nu} - {}^*\Gamma^\lambda_{\nu\mu}\right\}; \qquad C_{\mu\nu,\sigma} = g_{\sigma\lambda} C^\lambda_{\mu\nu}. \tag{30}$$

It is clear from (26) that Riemannian geometry is a very special case of a more general geometry, where the tensors (28) and (29) vanish.

If connection ${}^*\Gamma^\lambda_{\mu\nu}$ is given, "parallel" translation of a vector (or any other tensor) is thereby defined. That means that the law is given of the change of vector components in its "parallel" translation

$$d_P A^\lambda = -{}^*\Gamma^\lambda_{\mu\nu} A^\nu dx^\mu. \tag{31}$$

The character of vector change in this translation cartainly depends on the structure of connection, the following three cases being possible.

(1) If connection is produced by the metric of flat space in which a curvilinear coordinate system is introduced and the tensors (28) and (29) equal zero, "parallel" translation, according to (31), may be written without quotes: the vector is not changed in parallel translation, just as it should be. In the transition to the Lorentz coordinate system all components of the connection ${}^*\Gamma_{\mu\nu}$ will vanish, and neither the vector nor its components will change in parallel translation owing to the homogeneity of the coordinate network.

(2) If a non-trivial metric is assigned but (28) and (29) still equal zero, we have connection of Riemannian space (27). In "parallel" translation the vector changes its direction because of space curvature, but its length remains the same.

(3) If, apart from (27), there is the Weylian term (28) in the connection, the length of the vector in "parallel" translation is retained.

(4) Finally, if there is a torsion member (29) in the connection, the parallelogram rule is violated in "parallel" translation.

Having elucidated the geometrical meaning of various structural items in the connection, let us consider unified theories. We shall only discuss the most general principles of the construction of such theories, analysis of concrete variants being beside the scope of our task. Besides, we shall mostly restrict ourselves to the ways of unifying the gravitational and the electromagnetic fields.

We must thus formulate analytically the principal idea of unified theories. In terms of our task it sounds as follows: the presence of the gravitational and electromagnetic fields make space-time heterogeneous.

Space heterogeneity is described by the curvature tensor which is expressed in the following manner through connection (26):

$$R^{\lambda}_{\mu\nu\sigma} = \partial_{\mu}\,{}^{*}\Gamma^{\lambda}_{\nu\sigma} - \partial_{\nu}\,{}^{*}\Gamma^{\lambda}_{\mu\sigma} + {}^{*}\Gamma^{\lambda}_{\mu\tau}\,{}^{*}\Gamma^{\tau}_{\nu\sigma} - {}^{*}\Gamma^{\lambda}_{\nu\tau}\,{}^{*}\Gamma^{\tau}_{\mu\sigma} \quad (32)$$

It is clear from this that the primary cause of heterogeneity is connection. We shall therefore concentrate on the latter.

It was indicated above that the metrical part of connection (27), that is, the Christoffel symbols, have already been used by Einstein for describing the gravitational field. It follows that what is left for the electromagnetic field are the tensors (28) and (29).

For example, H. Weyl considered space without torsion and concretised the tensor (28). That can always be done, for the covariant derivative $\nabla_{\sigma} g_{\mu\nu}$ has not yet been assigned a value. If we accept that

$${}^{*}\nabla_{\mu} g_{\nu\sigma} = A_{\mu} g_{\nu\sigma} \quad (33)$$

we shall obtain Weyl's gradient-invariant theory of gravitation. Here A_{μ} functions as the 4-vector-potential of the electromagnetic field. The whole system of equations is thus resolved into the Einstein equations (22) and the

Maxwell equations (18).

Another possibility of constructing a theory assumes the use of torsion (29), as in the case of the Einstein-Cartan theory. The torsion tensor may be concretised in different ways, each time obtaining different variants of the unified theory of the gravitational, electromagnetic and, generally speaking, other types of fields. For example, in his 1925 work [7, S. 417] Einstein concretises torsion by assigning a non-symmetric metric, which in linear approximation is written like this:

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} + \varphi_{\mu\nu}, \tag{34}$$

where the antisymmetric tensor $\varphi_{\mu\nu}$ functions as the intensity of the electromagnetic field, determining space torsion.

The next trend in the development of variants of a unified theory consists in increasing the number of space-time dimensions to five and more, Riemannian connection being mostly used. Field characteristics connected with the fifth coordinate pertain to the electromagnetic field. The entire system of equations, just as in the previous cases, is resolved into the equations of Einstein and those of Maxwell.

The fifth coordinate is not, as a rule, ascribed any physical meaning, and one usually tries to get rid of it—e.g., by imposing the requirement of cylindricity, but the number of tensor components, corresponding to five-dimensional space, is left intact. The fifth coordinate is sometimes ascribed the meaning of action (Rumer) or the proper time of the field (Rodichev). In both cases a unification of the gravitational and electromagnetic fields is attained.

Thus we see that a unified system of equations of gravitation and electromagnetism can be obtained by complicating the structure of space.

Conclusion

Consideration of various formulations of unified theories shows that the basic idea (that the presence of any field makes space-time heterogeneous) has indeed been given an analytical formulation. We can say quite definitely that the more fields we shall want to unify, the more complicated will be the structure of space.

Despite the elegance of some of four-dimensional and five-dimensional variants of the theory, quite justified questions arise: does any of these introduce any novelty into physics? Have the solutions been obtained, as expected by Einstein, for the description of the structure of elementary particles? Regrettably, the latter expectation was not justified, and it becomes clearer and clearer why not. First of all, for all situations in which the system of equations of a unified theory is resolved into the Einstein equations and the Maxwell equations, we cannot, quite obviously, hope to obtain any new results, for gravitation and electromagnetism prove to be independent. In situations analogous to [7, S. 417-418], where the system of equations is resolved only in weak fields, while in strong ones there is a certain connection between the gravitational and the electromagnetic fields which, it is to be hoped, will bring about non-trivial results, this connection has not yet been explored because of mathematical difficulties or ambiguities in the choice of Lagrangians. Unified field theories have not yet solved this most important problem. Moreover, even if such studies were taken to their conclusion, there are grounds to believe that the results obtained would not be satisfactory. The most important reason is that all the Einsteinian unified theories ignore the spinor field (first used in physics by Dirac), which is now believed to be the most suitable object for describing primitive states of matter.

Indeed, spinors are more elementary formations than vectors or tensors in higher dimensions. A tensor in any dimensions may be constructed out of spinors (but not vice versa); in particular, Einstein's equations may be written in spinor form. Spinors are very well adapted to the description of spin, or rotational, properties of matter. The spinor field cannot obviously be ignored. Modern attempts at constructing a theory of elementary particles begin with the formulation of spinor field equations in flat or, more precisely, curved space; the cause or source of the curvature being the spinor field.

It is curious to note that the system of equations of the spinor field written in space with torsion and Galilean metric η_{ab}, the torsion being specified as a fully antisymmetric tensor in three dimensions, contains the familiar non-linear pseudovector addition transforming the Dirac equations into the non-linear Heisenberg-Ivanenko equations. The latter were made the basis of Heisenberg's interesting attempt at constructing a model of strong and electromagnetic interactions.

It may be said in conclusion that the idea of unified field theories continues to develop on a higher and more profound basis—as various modern attempts at constructing a theory of elementary particles.

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PROBLEMS IN THE SUBSTANTIATION OF PROBABILISTIC RESEARCH METHODS IN PHYSICS

Introduction

The fundamental nature of probabilistic ideas and research methods in modern physics has now been widely recognised. The elaboration of statistical methods based on the theory of probability and their fruitful application in all areas of physical study, rapid and insistent spreading of quantum ideas have graphically revealed the invaluable role and significance of probability in physics.

Probabilistic and statistical conceptions in physics emerged in the middle of the 19th century in the course of development of the molecular-kinetic theory, of cognition of the nature of thermal phenomena in gases. Since then, the deepening of the conceptions about the structure of matter and substance has involved application and development of theoretical ideas and methods of research based on probability theory. The works of Einstein have made the greatest contribution to the statistical mode of thinking in physics at the turn of the century. Classical statistical physics was given accomplished form in these works. The studies of Einstein and Smoluchowski in the theory of Brownian motion actually signified final assertion of materialist conceptions of the reality of atoms and molecules. On the basis of statistical conceptions and methods, Einstein conducted profound studies in quantum light theory which explained the photoeffect properties, the laws of the chemical action of light, the quantum properties of rigid bodies (the theory of heat capacity of rigid bodies) and many other physical phenomena.

When probabilistic and statistical methods and conceptions were introduced into physics, the questions arose directly of their substantiation, evaluation, and place in the overall system of physical cognition. How can the significance and efficacy of probabilistic and statistical ideas in physics be explained from the most general positions—in terms of conceptions of the nature of being and cognition? Both philosophers and physicists took part in the discussion of these questions from the very beginning.

Einstein was invariably interested in these questions, taking a sufficiently concrete view of them. As a rule, natural scientists consider the fundamental questions of being and cognition in terms of the leading questions of their science. Analysis of the nature of statistical laws came to be closely linked with the analysis of the essence of probability distributions, the study of the nature of entropy, the interpretation of the second law of thermodynamics, and a number of other problems. Particular attention was paid in the initial phase of the debate to the historical place of statistical conceptions in the system of physical knowledge and, first and foremost, to the correlation of classical statistical physics (statistical mechanics) and classical mechanics. After the construction of quantum mechanics, the interconnections between quantum mechanics and classical physics came to be regarded as a problem of great, if not decisive, significance. Einstein also paid special attention to the analysis of the general structure of quantum mechanics as a physical theory, and in particular to the completeness of this theory.

At present, the role and significance of probabilistic conceptions and methods have gone far beyond the framework of physics. Probabilistic ideas underlie the main trends in modern scientific research, beginning with physics and biology and ending with sociology. At the same time the data of physical cognition continue to serve as a basis for revealing the nature of probability and the causes of its intense application in modern science. Particular attention is paid to the comparative analysis of the foundations of probability in classical and quantum physics. It is natural to assume that the development of physics, its transition from the classical to the quantum stage permits a fuller elucidation of the basis for application of probabilistic methods, inasmuch as this transition was based on probabilistic notions.

These questions however, remain largely unclarified, and there are different views of the correlation of probability in classical physics and in quantum physics. Feynman and Hibbs write, for instance: "The concept of probability is not altered in quantum mechanics. When we say the probability of a certain outcome of an experiment is p, we mean the conventional thing, i.e., that if the experiment is repeated many times, one expects that the fraction of those which give the outcome in question is roughly p. We shall not be at all concerned with analyzing or defining this concept in more detail, no departure from the concept used in classical statistics is required. What is changed, and changed radically, is the method of calculating probabilities" [1, p. 2].

V.A. Fok and M.E. Omelyanovsky express different views. "The concept of probability was also considered in classical physics [writes Fok], but had a different meaning there. In classical physics, probabilities were introduced when the conditions of the task were not fully known, and one had to perform averaging of unknown parameters...

"Probabilities in quantum physics are of quite different nature. There they are essentially necessary, and their introduction reflects the potential possibilities objectively existing under given conditions rather than incompleteness of conditions" [2, p. 173]. This statement obviously opposes the signification of probability in classical and quantum physics. Omelyanovsky develops similar views: "Probabilities differ radically in quantum mechanics from those in classical theories. In the latter they express the existence of circumstances that are random for the phenomena being studied and therefore do not enter directly into the laws of these phenomena... Things are quite different in quantum mechanics: in it probabilities are considered as occurring in the basic laws of nature, and their introduction reflects the potentially possible objectively existing in certain real conditions" [3, p. 136].

C.F. von Weizsäcker takes a very radical view of probability: "quantum theory is nothing but a general theory of probability" [4, p. 334].

The following statement by J.M. Jauch reflects a widely current view: "The probabilities which occur in classical physics are interpreted as being due to an incomplete specification of the systems under consideration, caused by the limitations of our knowledge of the detailed structure and development of these systems. Thus these probabilities should be interpreted as being of a *subjective* nature.

"In quantum mechanics this interpretation of the probability statements has failed to yield any useful insight, because it has not been possible to define an infrastructure whose knowledge would yield an explanation for the occurrence of probabilities on the observational level. Although such theories with 'hidden variables' have been envisaged by many physicists, no useful result has come from such attempts.

"We therefore take here the opposite point of view which holds that the probabilities in quantum mechanics are of a fundamental nature deeply rooted in the objective structure of the real world. We may therefore call them *objective* probabilities" [5, pp. 2-3].

Thus there exist quite different evaluations of the role and meaning of probability in classical and quantum physics. Let us consider the historical development of the discussions on philosophical substantiation of probabilities in physics.

1. Classical Physics: Probability and Chance

Atomistic conceptions were the starting point of the development of classical statistical physics. General notions of molecular structure of substances, and in particular of gases, were expressed a long time ago in science. Their development can be traced in the works of Boyle, Newton, Bernoulli, Lomonosov and other scientists who were active at the time of elaboration of classical physics. But the assertion in physics of statistical concepts as working physical ideas is first of all due to the studies of Clausius, Maxwell, Boltzmann and Gibbs. As he worked on the kinetic theory of gases, describing gas as a system consisting of an enormous number of particles, Clausius conceived the idea that these studies required a change in methods. An indication of this is introduction of "mean magnitudes" for characterising the states of motion of gas molecules. This permitted a transition from the mechanics of particle systems to the study of the physical state of systems formed by an enormous number of molecules. In Maxwell's words, Clausius's main attainment was that he "opened up a new field of mathematical physics by showing how to deal mathematically with moving systems of innumerable molecules" [6, p. 427]. However, it was Maxwell who clearly realised that in the course of development of the molecular-kinetic theory of gases a transition takes place from the strictly dynamic methods of mechanics to theoretical-probabilistic methods. From the conception of mean values of magnitudes characterising molecular motion in macrosystems, he moved to the conception of probability distributions for the values of these magnitudes. The concept of probability distribution came to be used for describing the properties and laws of material systems; it is the central concept of the numerous and varied applications of probability theory.

Classical statistical physics was given relatively general form in the works of Boltzmann and Gibbs. The basic law of thermodynamics, its second principle, was given a statistical interpretation in the works of Boltzmann (in his famous H-theorem). The works of Einstein, Smoluchowski, and Perrin concluded the formation of classical statistical physics, revealing its objective basis.

The formation of classical statistical physics involved a discussion of its foundations and significance. The notion emerged at once that science was compelled to employ the ideas and methods of probability theory because of the impossibility of rigorous solution of a number of complicated problems, that is, that probability in physics was the consequence of incompleteness of our knowledge. These assertions were justified by the fact that historically (in its origin) statistical physics was elaborated as the mechanics of an enormous number of particles. Inasmuch as direct solution of the appropriate equations of mechanics was in this case rejected, and mean values of magnitudes characterising particle motion were introduced, it was asserted that probabilistic methods were the consequence of simplification of the research task. All of this essentially affected the formulation of the principal task of statistical theory in physics. At the stage of initial formation of statistical physics this task was regarded as that of reducing all observed macrolaws of the systems under study to the laws of classical mechanics. It was thus assumed that statistical laws would be given a more profound theoretical substantiation, and a deeper insight into the essence of the physical processes being studied would be attained. Indeed, the classical mechanical conceptions and images played a great heuristic role in the formation of statistical ideas in physics. Without such concepts and images, neither the development of the language itself of statistical theory, nor especially the development of its mathematical apparatus are conceivable. In his first fundamental works on kinetic theory, Einstein adhered to this view of the principal task of statistical physics. In 1902 he wrote: "However great might be the attainments of the kinetic theory of heat in the field of the theory of gases, mechanics has still been unable to provide a satisfactory foundation for the general theory of heat, for it has not been possible so far to deduce the propositions on heat equilibrium and the second principle [of thermodynamics] only in terms of mechanical equations and probability theory, although the theories of Maxwell and Boltzmann came very near this goal. The objective of subsequent reasoning is to fill this gap" [7, S. 417]. This idea was also repeated in later years. For instance, in 1915 Einstein wrote: "But today it is more difficult than earlier to negate that a great part of physical phenomena may be traced to mechanical processes in a very satisfying manner. We owe, in the first place, the kinetic theory of heat to this conviction of the fundamental meaning of mechanics for theoretical physics..." [8, S. 283].

The present situation in the study of these problems is definitively summed up in the works of N.S. Krylov containing an overview of these studies. "The concept of *probabilistic* laws of distribution *necessarily* accompanying the realisation of a given macroscopic state [he asserts] cannot in principle emerge in a theory based on classical mechanics; that is to say, the concept of statistical, and in particular thermodynamic, law cannot in principle arise here" [9, p. 67]. The conclusion that "classical mechanics cannot form the basis for the construction of statistical physics", as Krylov specially indicates, "must not be interpreted in the sense that classical mechanics cannot give us all that we need for substantiating statistics and has to be supplemented by elements of probability conceptions.... That conclusion means something much more important: in no logically possible combination of probabilistic conceptions and classical mechanics can the goal of substantiation of physical statistics be attained; in other words, classical mechanics cannot serve as the micromechanics on the basis of which statistical physics can be built" [9, p. 92].

It is now widely recognised that the purpose and meaning of probabilistic methods is greater than to be merely the scaffolding. This resulted in a substantial reformulation of the principal task of statistical physics. In the new formulations, the reduction of laws of one level to those of another no longer figures. Characteristic in this respect are the works of Uhlenbeck. In his works on the fundamental problems of statistical mechanics he especially stresses that "the basic task of statistical mechanics ... is ... the elucidation of the *relation* between the microscopic, molecular description and the macroscopic description of the physical phenomena" [10, p. 501]. The question of this correlation is the key question for the analysis of the role of probability in classical physics.

Statistical physics studies macroscopic bodies consisting of immense numbers of particles, that is, macrobodies as certain material systems. Statistical physics attained the most essential results, we repeat, in the study of gases and similar systems. As for the study of liquid and rigid bodies, statistical methods began to play a substantive role here only quite recently.

Historically, the working out of the statistical theory of gases was preceded, on the one hand, by the formulation of the laws of their thermodynamics (that is, of a macroscopic theory independent of atomistic concepts), and on the other, by the elaboration of the theory of mechanical motion of the simplest objects (classical mechanics). The development of atomistic ideas in the study of gases led to a kind of synthesis of the macroscopic laws of gases and of classical mechanics, that is, it posed the task of studying the properties and laws of gases taking into account their inner differentiation and integration. To understand the essence of this synthesis, it is important to remember that it was made possible by the use in physics of probabilistic methods of research. Probability was the scientific concept which permitted a unification of two principal and independent directions in the study of the systems in question—the direction which proceeds from the properties of the system as a whole to the properties of elements, and the direction proceeding from the properties of elements to the general properties of the system.

Central to the cognition of statistical systems is the conception of probability distributions on the basis of which the physical characteristics and laws of these systems are expressed. "*A property, is pr.-theoretical if, and only if, it is describable in terms of a distribution*", states Michel Loève [11, p. 171]. Elements, their interconnections and systems as a whole are characterised in the language of distributions. Distributions express the unity of continuity and discreteness, the synthesis of the integral and differential aspects of the structure of statistical systems, that is, their structure. In other words, probability in classical physics is the structural characteristic of physical systems or, to be more precise, of those systems whose specificity of inner structure is characterised in terms of the category of chance.

The category of chance plays the decisive role in bringing out the specificity of statistical systems. Chance and probability have become practically inseparable in the scientists' conceptions. The philosophical substantiation of probability and statistical methods was from the very beginning built on the basis of this category. A broad philosophical interpretation of these methods naturally depends on the interpretation of the category of chance which has undergone certain changes in the course of the development of modern knowledge. In the classical period of the development of natural science the category of chance was interpreted in a purely subjective manner—as a characteristic of phenomena and processes whose cause and necessary connections we simply do not know. Holbach wrote: "Nothing in nature can take place by chance; everything follows fixed laws; these laws are nothing but necessary connection between certain effects and their causes. To speak of fortuitous *collision of atoms* or to attribute certain effects to chance means to say nothing more but that one does not know the laws by which bodies act, meet, combine or separate" [12, pp. 29-30]. In accordance with this view, application of probabilistic methods was believed to be founded on the incompleteness of our knowledge; where the processes under study are complicated and we are unable to follow the concatenation of all causes or simply do not know them, we resort to probabilistic methods. These methods were attributed temporary and secondary status. But, as applications of probabilistic methods developed, particularly in physics, their objective character and independent value became increasingly clear. This view was held by materialist philosophers and natural scientists themselves—those who applied the probabilistic methods.

"As far as application to theoretical physics is concerned, [wrote Smoluchowski]*all probability, theories which regard chance as an 'unknown partial cause'* must be regarded as *unsatisfactory* from the very outset. *The physical probability of an event can only depend on the conditions which affect its emergence, and not on the degree of our knowledge!* " [13, S. 254].

The view has become established in our philosophical literature that the category of chance characterises first of all a definite class or type of connections in the material world. The main meaning, and the main difficulty, lies in the question: what is the specificity of the given class of connections? At present, the specificity of those connections which are characterised as accidental, is fairly often defined as something external, secondary, and incompatible with the intrinsic essence of the process under study. On the contrary, the inner connections determining the essence of the process are usually characterised in terms of the category of necessity.

The assertion that chance is not connected with the essence and describes merely the external, inessential, and secondary aspects of processes, is tantamount to the assertion of secondary status and temporary nature of the ideas and methods of probability theory. But the latter assertion is completely at variance with reality: the theory of probability is the royal road of the development of generalising ideas and concepts of modern natural science.

Wherein lies the defectiveness of the definition of chance as something unconnected with the inner essence of the process under study, characterising merely its external, secondary, and inessential properties? Is that definition false? Propositions like these must be handled carefully. We apply the concept of chance in precisely this meaning in the interpretation of very numerous scientific results, particularly in our everyday language. Let us consider in greater detail, however, what is described in terms of the conception of chance in the simplest applications of classical statistical theory—in the analysis of the properties and laws of gases. In theories of gases, the concept of chance is used for characterising the relations of molecules to one another, that is, for characterising their inner structure. In other words, the concept of chance is used here to express the inner essence of the given material systems rather than to characterise something external and secondary. In other applications of probability theory, the concept of chance is used for revealing the specificity and, consequently, the essence of the processes under study. For example, in genetics these concepts are used to characterise the relationships between mutations in their definite systems, that is, to characterise the inner structure of the mutation process.

Along with the development of science, our conception of the category of chance is also developed and enriched. Of great importance in the discovery of its essence is analysis of the generalising ideas of modern science. Accordingly, the greatest attention in the study of the nature of chance is paid to the role and significance in cognition of the concepts of independence, autonomy, substantiation of goal-directed choice and other fundamental categories expressing the structure and behaviour of complex systems. Accidental relations are those relations between objects, events, or elements of a set in which there are practically no direct mutually conditioning connections and dependencies between elements, or else they play an insignificant role.

Independence means that the state or behaviour of the object of study does not depend upon and is not determined by the state and behaviour of other objects that are congeneric to it or surround it. But how is this independence possible? How is independence possible in a world where the very origin and being of each object and phenomenon is impossible outside their interaction and connection with material environment?

The concept of independence characterises first of all certain mass phenomena, certain systems formed by an exceedingly large number of objects. It expresses a certain structure of these systems. But the mass phenomena themselves depend on the conditions of their existence or origin. In other words, independence has a meaning only in the presence of certain integral characteristics of systems expressing the unity of these systems. It is important to stress that, in speaking of the unity of such systems, we actually characterise a certain new level in their structure and organisation. If one bears in mind the independence of levels and the conceptions of them one can speak of a profoundly dialectical content of the category of chance.

Thus the significance of probability in classical physics is first of all manifested in the fact that it is a structural characteristic of a definite class of physical systems. Its methods permit the discovery of interdependence and mutual transitions between the micro- and macrocharacteristics of the systems in question.

2. Quantum Theory and Its Possibilities

The elaboration of quantum mechanics in the 1920s may be said to be the climax of the development of probabilistic methods in modern physics. In Victor Weisskopf's words, quantum theory is "a field of human thought that, more than any other scientific achievement, has deepened and broadened our understanding of the world in which we live" [14, p. 24]. Many philosophical trends regard quantum mechanics as a model for the construction of scientific knowledge in general. The neopositivism of the 1920s-1940s bloomed, in our view, mostly on the basis of the raising to an absolute of its origin and inner structure.

Quantum mechanics formulated in a new fashion a number of methodological problems of cognition, including the problem of the nature of probabilistic methods.

The significance of probabilistic ideas in quantum mechanics was largely brought out in the debate between Einstein and Bohr on problems of quantum theory. It is a well-known fact that most of the theoretical physicists who took a direct part in the development of the ideas and methods of quantum theory and its applications to diverse physical problems, took Bohr's side in this debate. The reason for that is the general approach to quantum theory. Niels Bohr insisted that it should be substantiated by modified epistemological approaches. The appeal for a new style of thought in physics found a response amongst scientists. What changes took place in the epistemological approach to the interpretation of probability?

As distinct from classical physics, the fundamental nature of probabilistic notions was widely recognised in quantum physics practically from the very outset: probability is from the start considered here as one of the most important foundations of the very structure of physical theory. That is due to a change in the very formulation of the main task of studies: in quantum theory, probabilistic methods are used first of all for cognising the properties and laws of individual, separate quantum particles—the micro-objects. Transition from the study of systems formed directly of an immense number of particles to the study of separate particles is indicative of exceptional flexibility and fruitfulness of probabilistic methods. This transition became possible owing to essential changes in the mode of specification (expression or characteristic) of probabilistic concepts. In classical physics, the properties and laws of physical systems were expressed directly in the language of probability distributions. In quantum physics the states of microparticles are expressed in terms of a special characteristic, in the first place, in terms of the wave function. Historically, wave functions were introduced into quantum theory in a purely formal manner and only asserted themselves in physics when it became possible to link them up with probability distributions: the square of the modulus of a wave function in a certain representation defines the probability of the corresponding physical magnitude. The connection between wave functions and probability is, generally speaking, a justification for their use in quantum theory; only the establishment of this connection gave profound real meaning to the entire mathematical apparatus of quantum mechanics, and that was done only after the latter had been constructed.

Changes in the formulation of the principal tasks of research pose a very important question: how is it possible to study, on the basis of probabilistic methods, the properties and laws of isolated, individual microparticles, if the theory of probability is, according to the most recent definition, the science of mass (accidental) phenomena? It was this question of the possibilities and value of probabilistic methods in the analysis of the properties of individual physical objects that determined Einstein's approach to quantum theory. As a matter of fact, Einstein refused to accept that probabilistic methods could be effective enough for describing the properties and laws of separate physical systems. It was for this reason that he regarded a quantum-mechanical description of systems as an incomplete one. "Quantum mechanics [Einstein asserted] describes ensembles of systems, not the individual system. A description through the Ψ-function is in this sense an incomplete description of an isolated system, not a description of its real state" [15, p. 38]. The same idea can be found in his last published reference to quantum theory evaluation: "It is further difficult to escape the suspicion that the statistical nature of the theory is conditioned by the incompleteness of description and has nothing to do with the things as they are" [16, p. 10].

What are then the objective foundations of the application of probabilistic and statistical methods to the cognition of isolated physical objects—the microparticles? What are the indications for that in the very structure of quantum mechanics? It should be admitted that there are considerable difficulties, vagueness, and divergence of opinion involved in the search for the answers to these questions, but there is also quite a definite and increasing tendency in the works on this subject.

Just as in classical physics, probabilistic methods in quantum mechanics are founded in mass phenomena. The latter, however, are of a different nature than in classical physics. Quantum physics is based on the statistics of mass observations, of manifestations of the properties of the micro-object being analysed under some standard conditions. Conclusions as to the object's properties are drawn from stable diversity in the results of such observations. "A micro-object [writes V.A. Fok] manifests itself in the interaction with the measuring device.... The result of the interaction between an atomic object and a classically described measuring device is the basic experimental element, the systematisation of which accordingly (on the basis of appropriate suppositions as to the properties of the object) is the aim of the theory: from the consideration of such interactions the properties of an atomic object are deduced, while the predictions of a theory are formulated in terms of the interaction results to be expected" [17, p. 215]. And further: "For given external conditions the result of the interaction of the object with the measuring instrument is (in the general case) not predetermined unambiguously, but has only some probability. A series of such interactions leads to a set of statistics that corresponds to a definite probability distribution.

"This probability distribution reflects the potentiality existing in the given conditions" [17, p. 217].

"...What is to be verified is ... a probability distribution" [17, p. 218].

In referring to series (collectives, ensembles) of observations (manifestations of the properties of micro-objects), one should stress that they have the basic characteristics inherent in the probability systems of classical physics. In the first place, the results of individual observations do not depend on each other: the result of one observation does not determine the result of another (subsequent) observation. In other words, the inner structure of mass phenomena formed by observation results is random in its nature, being defined in terms of the category of chance.

Further, in classical physics any statistical collective (probability system) also had integral characteristics, since otherwise probabilistic methods could not be applied to these systems. These integral characteristics are also inherent in series (collectives) of observations in quantum theory. "Wave mechanics [indicated Mandelshtam] is a statistical theory. But we can only speak of statistics and probability if we have a definite ensemble of elements to which this statistics applies. In wave mechanics this ensemble is made up of repeated experiments (each individual experiment being its element), and repetition must take place under identical conditions...

"Let us call this statistically processed ensemble a collective. The collective must be in some way singled out, otherwise formulation of any questions about it is meaningless. Now, it is said that $[\psi]^2$ is a probability. But in what collective? Unless we indicate that, all kinds of vagueness and paradoxes are possible...

"Of course, we encounter the same question in classical physics. We can speak of Maxwell's distribution of speeds only under constant temperature. If temperature changes, the distribution will be quite different. The same thing happens in classical problems which do not involve collectives... Thus in any theoretical consideration, experimental conditions must be defined, and this definition may always be reduced to fixing certain parameters.

"Here we arrive at a point that I believe to be the most important and essential. Namely, wave mechanics asserts that, to define the micromechanical collective to which the ψ-function refers, it is sufficient to indicate (specify) the macroscopic parameters" [18, pp. 332-333].

The existence of integral characteristics of micromechanical collectives (ensembles of repeated experiments) directly determines the existence of natural boundary conditions imposed on wave function. These conditions include normalisation of wave functions (integration of the square of the modulus of the wave function in the case where the system's energy levels are discrete), their finiteness, non-ambiguousness, and continuity in the whole of space. These limiting conditions are necessary for the apparatus of quantum mechanics.

Thus the general features and the substantiation of probability which were characteristic of classical physics hold for the substantiation of statistical collectives of observations (experiments) in quantum mechanics. But quantum mechanics does not simply study the results of such observations *per se*. Conclusions about the properties, structure, and laws of microparticles are drawn from these observations. Accordingly, the categories of necessity and chance are no longer sufficient for substantiating probability in quantum theory: the category of the potentially possible is added here. The properties of micro-objects are determined on the basis of observational data. Their physical state is characterised by the wave function. But that is a characteristic which permits the determination of all possible manifestations of these properties which may be observed under certain permissible conditions. It is therefore said that the wave function (and quantum mechanics in general) characterises the potential possibilities of the behaviour of objects under concrete conditions. The category of possibility enabled scientists to describe and substantiate the utilisation of the language of probability theory in quantum physics. Merely saying that quantum mechanics (as a theory of microprocesses) simply expresses the possibilities of the behaviour of micro-objects would not be the whole truth. In considering the spectrum of possibilities of the behaviour of micro-objects, quantum mechanics reflects the existence of certain order or regularity in the mass of such possibilities; its principal propositions are essentially founded on the existence of such order. It also becomes clear that the laws themselves in the spectrum of possibilities are conditioned by the deeper properties of micro-objects, and these are studied in the first place in quantum theory. It is extremely essential that in theory these deep characteristics are not defined as potential possibilities corresponding to a situation where the result of observation is not unambiguously predetermined, depending not only on the object but also on its macro-environment. The formulation of quantum-mechanical problems, as V.A. Fok points out, "permits the introduction of quantities describing the object itself irrespective of the measuring device (such quantities as charge, mass, spin of a particle, and other properties of the object described by quantum operators); at the same time it allows various approaches to the object: the object may be characterised by those of its properties (e.g., wave-like or corpuscular), that manifest themselves under external conditions created by the given measuring device" [17, p. 215].

Accordingly, it is very essential for the analysis of quantum-mechanical knowledge that its concepts are divided into levels, into two classes: the first class is made up of "directly observable" concepts, as it were (e.g., coordinates and momentum), which are viewed in theory as typically random (in the probability-theoretical sense) magnitudes; the second class is formed by quantum numbers (of the spin type). The differences between these two classes of concepts consist first of all in the degree of closeness to the immediately given in the physical experiment. The magnitudes of the first class express the more external characteristics, the magnitudes of the second class, the deeper and more internal ones. The former permit an individualisation of quantum processes, the latter are general in nature. The former gravitate in their character towards classical concepts, while the latter express, first of all, the specificity of quantum phenomena. The former change continually, while the latter are more stable. The former are closer linked with the phenomenon, while the latter, with the essence, although, undoubtedly, the essence is phenomenal and the phenomenon is essential. The fulness of theoretical expression of quantum processes is naturally attained when the concepts of both classes are used belonging to different logical levels.

The establishment of the interconnections and synthesis within a unified theory of these two classes of magnitudes of different nature was made possible by probabilistic concepts. In the process, the modes of characterising the states of microparticles are essentially altered. In defining these states, the main attention is paid to concepts of the second class (quantum numbers), as expressing the deeper essence of the micro-objects. These characteristics, depending on their numerical values, quite rigorously and unambiguously define each of the types of elementary particles, serving as the basis for the identification of particles of a certain kind in experimental research. In characterising the states of microparticles, these parameters (or magnitudes) are defined sufficiently unambiguously. But their specification does not define unambiguously the values of the parameters of the first class: it rather defines the entire field of the possible manifestations of the latter. In a similar way, in defining the character of a person, we do not predict his or her concrete behaviour in a concrete situation but rather the field of possible modes of behaviour in different life situations.

It is now generally recognised that the possibilities of a certain type of behaviour of some material objects are first of all conditioned by their inner structure. The inner structure always defines a mass of possibilities, and the deeper the properties described, the broader the field of possibilities. The realisation of a given possibility is conditioned by the inner state of the object and the conditions of its external being. The transition from possibility to reality possesses, as a general case, some features of irrationality, to some extent reminiscent of the transition between two points on the number axis. The latter feature is reflected in the nature of interconnections between concepts of different classes in quantum theory. The concepts expressing the deeper essence of objects (the specificity of quantum processes, properly speaking) can be called integral-generalised. The significance of such concepts depends on their role in relatively closed theoretical systems; they are not simply added to the other, primary concepts of the same systems but express a certain order in the relations between such primary concepts. The elaboration of such concepts was begun already in the theoretical systems of classical physics (centre of mass and moment of inertia, in simple mechanical systems; vector field rotor, in electrodynamics). The essence of integral-generalised concepts is directly linked with the nature of the general: the general is not a certain mechanical unification of individual terms but rather expresses the structural organisation through which each individual term is included in a system. In other words, the dependences between these two classes of concepts are not of the coordinative but of the subordinative type. Subordination also includes a certain independence or autonomy: characteristics of a higher level do not determine unambiguously characteristics of the lower, initial level but rather the spectrum of their permissible values.

The following conclusion may be drawn from the above: the significance of probability in quantum physics lies first of all in that it permits the study and theoretical expression of the laws of objects with a complex, two-level structure including certain features of independence or autonomy. The principal meaning of probability lies in this connection with structure and methods of its expression. This required new theoretical forms for the expression of probabilistic notions: a transition from probability distributions as basic characteristics to wave functions. In this way the synthesis was realised of the continuous and discrete, of stability and mutability, rigid conditioning and independence, elementarity and integrality, thus expressing the profound inner dialectics of the world of atomic processes.

Conclusion: Probabilistic Methods in the Light of the Laws of Development of Cognition

A philosophical evaluation of the role and significance of probabilistic and statistical methods of cognition should be approached from a historical standpoint, from the standpoint of a general conception of the development of cognition. One of the most important laws of the development of cognition is that, once having emerged, cognition moves along the path of working out more and more generalised and meaningful forms. In discussing the problems of the relativity theory, Einstein indicated that "no fairer destiny could be allotted to any physical theory, than that it should of itself point out the way to the introduction of a more comprehensive theory, in which it lives on as a limiting case" [19, p.7]. That is exactly the angle from which he viewed the formation of the theory of relativity. Einstein's views of the value of probabilistic methods were all his own.

In considering the nature and significance of probabilistic and statistical ideas and methods, scientists often compare them with historically preceding notions and methods. The principal problems here are those of correlation between rigidly determined (dynamic) and probabilistic (statistical) laws and theories. In the light of the general laws of the development of cognition the conclusion must be drawn that probabilistic conceptions and methods are more advanced and have a more general nature than the ideas and methods based on the principle of rigid determination.

What are the features of generalisation processes? What are the traits of the more generalised forms and methods of cognition? What does the new as the more generalised mean? The elaboration of more generalised conceptions means, first of all, the expansion of the cognised sphere of reality: new ideas and methods are based on a broader sphere of material practice. The content of generalised concepts is rooted in a new sphere of material reality, but at the same time they lead to a deeper comprehension of earlier cognised phenomena. The mathematical forms and methods of expression of new ideas are more abstract, being represented by more advanced mathematical disciplines. They are characterised by a more mediated connection with the "immediately given" in scientific experiment. Finally, a most important feature of generalised forms and methods is that they possess a greater inner wealth and greater inner possibilities for the cognition and expression of the individual, the singular.

The content of our discourse proves that probabilistic forms and methods are more generalised than those based on the principle of rigid determination. That is first of all shown by the wide use, in revealing the essence of probability, of the idea of levels in the inner structure of systems containing relative independence and autonomy of subsystems. The existence of levels within theoretical systems makes probability structures more flexible. If flexibility in the connections between levels and mobility of one level relative to another in probability structures are removed, the result will be a return to rigidly determined structures.

The approach to the interpretation of probability developed here permits to show more clearly the differences between the views, quoted at the beginning of the article, of the role of probability in classical and quantum physics. When Feynman and Hibbs say that the concept of probability does not undergo any changes in the transition from classical to quantum physics, they refer to interpretation of probability at the basic empirical level. At the level of "direct observation" a frequency interpretation of probability is valid, and in this sense the transition from classical statistical physics to quantum physics did not introduce any essential changes in the interpretation of probability. But the significance of theoretical notions does not consist in merely describing and bringing in agreement direct experimental data, as the positivist programme of analysing knowledge insists. The general concepts and categories of a science (and that is the core of theoretical notions) express a certain aspect, a given cross-section of material reality which reveals the inner essence of the objects of this science. As our analysis shows, the concept of probability is linked with the discovery and expression of the inner structure of the physical systems under study. The complexity of the situation, the principal difficulties and debate are mostly due to the establishment of the nature and foundations of probability at the theoretical level.

Analysis of probability at the theoretical level is most interesting and complex, and here essential changes took place in the transition from classical to quantum physics, as indicated in the quotations from Fok and Omelyanovsky above. Quantum theory has shown clearly that the strength and significance of probability lies in its connections with such generalising ideas and concepts of modern natural science as system and structure, levels of inner organisation of material systems, independence (autonomy) and connectedness of elements within integral systems.

The statement by Weizsäcker is important in that it directs the attention of scholars to the importance of "feedback" relations between probability and its applications. It is often implied that the development of probabilistic research methods and the expansion of the sphere of applications of probability do not affect in any substantive way the understanding and interpretation of the nature of probability itself. But the development of applications does not leave the conception of probability unaffected. It is widely recognised that probability in quantum physics is its natural and immanent part. But the materials of quantum physics and analysis of its structure are practically not used for revealing the meaning of probability. However, a dialectical view of the nature of cognition means that the more developed cases of application of probability theory correspond to a deeper penetration into and expression of the essence of probability.

Jauch's statement is interesting in that it stresses the essential difference between probability in classical and in quantum physics. Intuitively that is accepted quite frequently but it is not always logically comprehended. The statement that probability in classical physics is subjective in nature has become a kind of prejudice accepted without question. But the proposition that probabilities in quantum mechanics are objective in nature and deeply rooted in the very structure of the material world have great heuristic force. In the present article we have endeavoured to elucidate the modern state of studies in this question.

It follows from the above that the efficacy and fruitfulness of probabilistic methods of research are due to the fact that they express some fundamental traits of the structure of the material world. That is why most physicists who actively developed quantum ideas in the 1920s and later disagreed with Einstein's view expressed in the quotation above—to the effect that the statistical nature of quantum theory has no relation to the nature of things. The development of probabilistic methods signified increased flexibility and scope of physical thinking of our times, which were largely facilitated by the works of Einstein himself.

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S. V. ILLARIONOV

THE EINSTEIN-BOHR CONTROVERSY

It is difficult to put into words the feeling of being in the presence of something titanic, which envelops a researcher analysing one of the most outstanding intellectual battles in the history of scientific knowledge—the Einstein-Bohr controversy on problems of quantum mechanics. There have been scientific debates before and after it, but not one of them had the same far-reaching consequences and attracted such general attention.

How is one to explain the special place which this debate occupies among other scientific debates? One reason certainly was that its subject was quantum theory, one of the most revolutionary physical theories in the entire history of knowledge. But that is not the only point. As a rule, discussions of the truth of theories ended when one of the theories was confirmed better than others and were immediately relegated to history. The Einstein-Bohr controversy, however, touched on the deepest aspects of the scientific cognition of the world and its basic principles. The scope and significance of this controversy are determined by the choice of the ways of development of scientific cognition implied in the controversy. The debate ranged over a number of interconnected problems: the general principles from which a concrete type of physical laws may be deduced as against obtaining these laws by generalisation of experimental data; clarity and distinctness of knowledge as against its contradictoriness; continuity of processes and discreteness of the world; universal causality and chance.

All these problems are most intimately connected with a scientist's general world outlook, with epistemology. That is why the Einstein-Bohr controversy has not only special scientific but, in the first place, general philosophical content.

Several stages may be singled out in the development of the debate. At each of the stages the debate centred on a certain part of the problems outlined above, but invariably the first terms in the oppositions listed above represented Einstein's position, and the second, Bohr's. Let us consider in greater detail the individual problems that were the content of the controversy—in the form they assumed relative to quantum mechanics in the interpretations of Einstein and Bohr respectively.

One of the most important constituents of Einstein's world outlook was the conviction that the task of physics is the search for fundamental principles of great degree of generality which would permit to deduce concrete laws of the given class of phenomena under minimal assumptions and recourse to experimental facts (see his work "Principles of Research" [1, pp. 224-227]). That was reflected in Einstein's conception in the interpretation of scientific theory as free invention of the human intellect (see the paper mentioned above and the work "On the Method of Theoretical Physics" [1, pp. 270-276]), as well as in his unitary field-theory programme where Einstein took the view that the very existence of the electron was sufficient for the construction of a unified field theory of matter. Adhering to this view, he insisted that quantum mechanics as a theoretical system was too firmly tied to the empirical data it described, and that it lacked a general principle ("Considerations concerning the Fundamentals of Theoretical Physics" [2, pp. 487-492]).

As opposed to Einstein, Bohr and his school (Heisenberg in particular) regarded the "empiricity" of quantum mechanics as an achievement rather than a drawback of the theory. Indicative in this respect is the principle of observability on which Heisenberg relied in constructing quantum mechanics [3, S. 1-3] and Einstein's negative attitude to it. The principle of observability registers the specificity of empirically observed objects characteristic of the fragment of reality under study, theory thus being ried down to experiment. This linking-up of theory to experiment may go far beyond the framework of the fundamental principles established by the previous development of physics, and may even contradict them. From Einstein's view, this contradiction is at least a descriptive anomaly indicative of the incompleteness of theory.

The problem of obtaining a concrete theory from general principles or generalisation (in the broadest sense of the term) of empirical material is thus naturally transformed into the problem of clarity and distinctiveness of knowledge and the relation of this clarity to real being.

The requirement of clarity and distinctness, which goes back to the Cartesian tradition, directly follows from the requirement of the existence of a general principle which contains no inner contradictions. Einstein consistently adhered to this tradition, in developing the special and the general relativity theory and in arguing with Bohr, whose thinking radically went beyond the tradition of clarity. Bohr's style of thinking involved a feeling for the paradoxical nature of being, its inner contradiction that had to be irrationally reflected in thinking. Bohr's conception of the quantum object as "fuzzily defined in space and time" naturally leads to the opposition of the categories of continuity and discreteness and of rigorously defined causality and chance.

The clarity and distinctness of the theoretical scheme in Einstein's interpretation reflects the fundamental structure of reality. Hence his conception of simplicity of nature and the requirement of continuity: "field-theory does exist as a program: 'Continuous functions in the four-dimensional (continuum) as basic concepts of the theory' " [4, p. 675]. Continuity of any aspect of existence is in principle opposed to discreteness and chance. Only quasidiscreteness in the form of pseudosingular solutions of some (generally speaking, nonlinear) system of field equations is allowed. The same is true of chance. Chance is opposed not only to the rigorous determinism of continuous solutions of field equations but also to continuity as such. Chance introduces an element of discreteness in existence: in the realisation of a certain possible situation all other possibilities cease to exist, that is, continuity is violated.

The paradoxical nature of being and discreteness and chance connected with it were just as fundamental features of Bohr's worldview as clarity, continuity, and rigid determination were the features of Einstein's worldview. All of this taken together and interpreted in terms of a concrete theory (quantum mechanics) gave rise to the controversy that is the object of our analysis.

The Einstein-Bohr controversy is thus not so much a conflict of the personal worldviews of two most outstanding scientists of our times as a conflict of two fundamental conceptions each of which possesses a certain inner integral quality and goes back to the traditions of the previous development of science. It can be noted that the worldview represented by Einstein has deeper roots in the classical period of physics than Bohr's view, in which the traditional aspects of physical world outlook, namely, close links between physical theory and experiment, are interwoven with new, non-classical tendencies. Bearing this in mind, one must certainly give up the primitive idea that Einstein represented only the obsolete, conservative tendencies in this controversy. Many elements of the Einsteinian conception of physical reality have played and will play an important role in the world outlook of scientists, even those of them who on the whole adhere to Bohr's positions.

Let us consider the course of the discussion more concretely. We do not aim to describe it in detail, the more so that that is the subject of a well-known article by Bohr himself, "Discussion with Einstein on Epistemological Problems in Atomic Physics" [4, pp. 199-241]. We shall mostly be interested in those aspects of the controversy which are vital for the present.

As indicated above, the entire course of the debate can be divided into three stages. The first stage involved the discussion of the uncertainty relation and the content of quantum mechanics. That stage was connected with the international congress of physicists at Como (1927) and the Solvay conference of 1930. The beginning of the second stage may be tentatively dated 1935, when the well-known article by Einstein, Podolsky, and Rosen appeared under the title "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?"

[5, pp. 777-780]. This stage is mostly characterised by the discussion of the problem of completeness of quantum mechanics and, more generally, of the requirements imposed on a scientific theory. The third stage has to do with the present times already. It is very important for us, as it was in the recent decades that the depth and fundamental nature of problems constituting the content of the debate became clear. This stage may be said to have begun in 1949 and to be continued into present. Its main content relates to the problem of hidden parameters, that is, the problem of completeness of quantum mechanics, which can mostly be traced to the general problematic of the article by Einstein, Podolsky, and Rosen.

Let us consider the course of the discussion in accordance with the division into periods suggested. At first Einstein, dissatisfied with the direction of development of quantum mechanics, endeavoured to demonstrate its inner contradictions using the fact that the content and the mathematical apparatus of this theory in the Copenhagen interpretation is intrinsically characterised by ambiguity in the description of the state of the micro-object due to the Heisenberg uncertainty relation. In a series of highly original mental experiments Einstein showed that in idealised situations information about the quantum object could be obtained which contradicted the uncertainty relation. He substantiated his models by the idea that the limitations imposed by the uncertainty relation could be avoided by taking into account the interaction between the micro-object and the device in greater detail than in the usual mental experiments of the Heisenberg type.

In his reply to Einstein's critical analysis Bohr showed that when it was desired to take into account the interaction between the micro-object and the device, it was necessary to bear in mind the uncertainties inherent in the device itself, as well as the fact that a change in the type of interaction between the micro-object and the device can drastically affect the result of the experiment. The first aspect of Bohr's counterargument, namely, the requirement that uncertainty in the device itself should be taken into account, is important for the analysis of mental experiment problems and of the conditions of the consistency and inner agreement of such an experiment. Bohr's detailed elaboration of these questions proved to be extremely important for the further development of mental experiments. This manifested itself most clearly in the initial formation of the quantum field theory, when an analysis of measurement of fields conducted by Bohr and Rosenfeld in the work "On the Question of Measurement of Electromagnetic Field Magnitudes" [see 6, S. 3-65] established the conditions for the absence of contradictions in this theory.

The second aspect of Bohr's counterargument is even more important, for, in point of fact, it laid the foundation of the complementarity concept, which is not only one of the essential components of the conceptual system of quantum mechanics but, as Bohr himself and some other scientists assumed, a general methodological principle of natural science as a whole (see Niels Bohr's article "Biology and Atomic Physics" [7, pp. 6-15] and the book [8]).

Let us take a closer look at this aspect of Bohr's reply to Einstein's critical remarks. Einstein's line of reasoning is clear from an analysis of the following mental experiment (see Fig. 1).

In performing an experiment on interference in the usual situation (without the movable shutter *z*) we cannot ascertain through which of the two slits (1 or 2) the particle passes. But we can do it by introducing the shutter *z* and watching its movement (up or down). At the same time the diffraction picture on the screen *e* provides information of the wave length (particle momentum). In analysing this mental experiment, Bohr showed that the interaction of the particle with the screen e_1 destroys the diffraction picture that may be observed if *z* is not moved.

This argument by Bohr expresses the whole of the complementarity principle: corpuscular and wave measurements cannot be combined in one device; corpuscular and wave properties of the micro-object are manifested only under different situations (they are relative to the means of observation). The establishment of this principle was of immense significance for the development of quantum mechanics. Along with the statistical interpretation of wave function it forms the basis of what may be referred to as "interpretation" of this theory. After the fundamental elements of the conceptual system of quantum mechanics were formulated, the possibility arose of interpreting the theory on its own logical basis.

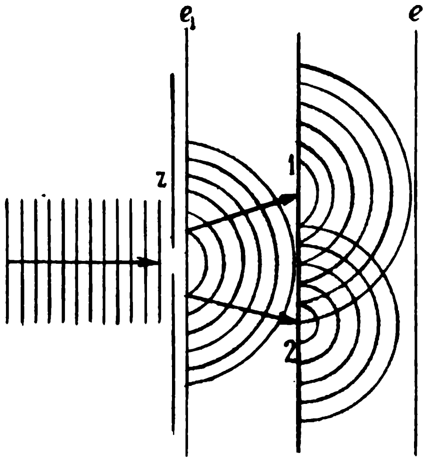

Fig. 1

Complementarity thus emerged due to the need for solving the paradoxes found by Einstein. The first stage in the discussion resulted not only in proving the consistency of quantum mechanics and recognition of this consistency by Einstein himself, but also in a more consistent interpretation of this theory as compared to the one before the discussion. It was made clear that the indeterminacy and paradoxical nature of the existence of micro-objects did not result in logical contradictions, that is, they could be perceived by human consciousness as the content of being itself rather than a defect in its understanding.

However, this result was completely unacceptable to Einstein. His conception of clarity and distinctness prompted quite a different approach to the interpretation of the situation. Since it was proved that Bohr's interpretation of indeterminacy and inner contradictions in the existence of micro-objects did not lead to logical inconsistency of theory, he concentrated on another fundamental requirement imposed on scientific theories, namely the requirement of completeness.

The fundamental nature of the requirement of completeness appears to be almost self-evident. We say "*almost*", for it has become clear after the formulation of the Gödel theorem that it is impossible to satisfy this requirement in Gilbert's strict interpretation. But physics does not require that degree of strictness. Einstein's interpretation of completeness consisted in the requirement that a theory should give an unambiguous answer to the question of the state of reality at any point of the spatio-temporal continuum. This is more concretely expressed in the juxtaposition of continuous functions in space-time with reality and more concretely still, in the field-theoretical programme [4, pp. 674, 675].

Quantum mechanics with its inherent uncertainty, statistical and discrete nature of physical reality, apparently did not satisfy this requirement. In the article "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete? " Einstein raised directly the question of completeness of quantum mechanics. He suggested the following criterion of physical reality: "If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity" [5, p. 777]. The article further analysed a mental experiment which showed the possibility of reliable prediction, "without in any way disturbing a system", which follows from quantum mechanics itself. The gist of the phenomenon which is now called the Einstein-Podolsky-Rosen paradox consists in the fact that a quantum system is considered consisting of two micro-objects which at a certain moment in the past interacted with each other, forming a single system. It is then assumed that the micro-objects, owing to the type of interaction, are divided in space in such a way that they may be viewed as non-interacting. Certain conservation laws are observed (momentum, spin, etc.). Now, if measurement of a certain magnitude in one micro-object is performed, the value of the respective magnitude of the second one may be reliably predicted from the result of the first measurement and the law of conservation.

In his article, Einstein considered a mental experiment situation, but it can also be reproduced in a real experiment, and in several variants. In Einstein's view, the situation described here means that either there is a certain reality determining the values of measured magnitudes for both micro-objects, or else a paradox arises. Indeed, if the micro-objects are sufficiently remote from each other, none of them can "learn" of what has happened to the other until an exchange of signals takes place propagated at the speed of light or less than the speed of light. Inasmuch as the first case is rejected in the orthodox interpretation of quantum mechanics, the whole situation was called the Einstein-Podolsky-Rosen paradox, or EPR paradox.

In principle, the EPR paradox is related to the familiar Schrödinger paradox (the "cat" paradox) and that of de Broglie. For instance, in the de Broglie paradox a box in which there is one particle is divided by a partition into two, and the two halves are taken sufficiently far apart. An observation of only one of these two halves instantaneously makes the wave function in this half vanish (if there is no particle here), and makes it into a unity in the other, or vice versa [9, pp. XII-XIII]. In these situations the wave function (wave packet) is said to be reduced.

Thus the class of paradoxical situations was known before Einstein already. But Einstein was the first to observe that the real (in terms of the classical approach) paradox arises when we consider a multi-particle quantum system rather than in the case of one particle (as in de Broglie's example). Indeed, in the one-particle case the wave function may be interpreted as "an observer's notebook", that is, on a purely informative plane. Generally speaking, no subjectivistic conclusions that observation (taking the reading) changes the state of the object, follow from this fact. In the many-particle experiment (two-particle experiment, in the simplest case) the reduction of the wave function takes place in performing the act of measurement on one particle, whereas an unambiguous prediction about the second one is obtained "without in any way disturbing [the] system". In accordance with

Einstein's criterion that means that there is a certain element of reality of which we only obtain information in the form of the wave function using the measurement.

The EPR paradox was the most serious challenge to quantum mechanics. Einstein's mental experiments of the first stage mostly required a more accurate analysis of processes, while now the blow was aimed at the fundamental elements of the conceptual system—the content of the concept of wave function and the principle of superposition. Publication of the article by Einstein, Podolsky, and Rosen meant that a black cloud appeared against the background of the immense successes of quantum mechanics—much like the clouds which had destroyed the edifice of classical physics at the start of the 20th century.

Einstein's view of quantum mechanics was that it was merely a phenomenological description of the microworld phenomena which did not reveal the physical nature of microscopic reality. The genuine theory of the microworld was as yet awaiting its formulation [10, p. 318]. This position did not affect the results attained, but it cast a doubt over the further development of the physics of the microworld based on the extrapolation of the principles of quantum mechanics to deeper levels.

In a certain sense that was a pivoting point: would physics develop along the path of quantum mechanics, retaining the ideas of indeterminacy, discreteness, and paradoxical nature of being, or would it go back to the "Cartesian" path? "To be or not to be—that is the question..."

Bohr's reply was not long in coming (see the articles "Quantum Mechanics and Physical Reality" and "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete? " [11, p. 65; 5, p. 696]). In analysing the EPR paradox, Bohr paid attention to the meaning of Einstein's expression "without in any way disturbing a system". For Einstein, any particle figuring in his mental experiment was a system. Bohr pointed out that in quantum mechanics a system was made up of the two particles connected by a single wave function. By affecting one of the particles, we thereby influence the system as a whole. Thus Bohr formulated a new conception of wholeness in quantum mechanics: a strict division of a quantum-mechanical system into separate systems corresponding to individual particles was impossible before the act of interaction.

This proposition signified, in fact, the logical conclusion of quantum mechanics, it became a logically complete theory (complete in the physical sense). The new conception of wholeness cannot be said to be something radically new in quantum mechanics. Rather, it was the culmination of development during the previous decade. The idea of wholeness irreducible to classical forms is contained in the principle of indistinguishability of particles, in the Pauli principle, and in the many-particle equation of Schrödinger. For example, the Schrödinger equation for a system of many micro-objects is not written for each of them but for a general wave function defined in the space of the configurations of all particles. The idea of wholeness specific for quantum mechanics is thus contained in the Schrödinger equation for many particles. Bohr's argument made this idea absolutely transparent, taking it to the level of an element of a conceptual system.

Bohr's arguments were perceived by the world scientific community as an almost ideal triumph of quantum mechanics. In any case, there were no more doubts about the inner completeness and consistency of the theory. Einstein himself admitted as much: "To believe this is logically possible without contradiction; but, it is so very contrary to my scientific instinct that I cannot forego the search for a more complete conception" [10, p. 318]. Einstein thus clearly resorted to physical intuition, that is, to a system of the principal propositions of the physical worldview which we considered at the beginning of the article.

Yet this admission on Einstein's part did not mean the end of the polemics. The main elements of his worldview—the desire for clarity, completeness, and unambiguousness—are so important for any physicist that their rejection is an extremely difficult psychological process. We may put it even stronger: these propositions are an almost ineliminable premise of scientific cognition. It would therefore be more correct to speak not so much of rejection as of re-interpretation of the terms clarity, completeness, and unambiguousness.

However, even a re-interpretation of such fundamental elements of the physical worldview is by no means a rapid or painless process. It is therefore quite natural that the controversy, interrupted by the tragic events of the Second World War, was renewed as soon as the circumstances became more propitious. The third stage in the Einstein-Bohr controversy may be said to have begun in 1949 with the publication of the book *Albert Einstein: Philosopher-Scientist* [4] containing articles by Bohr and other eminent scientists developing quantum physics, on the one hand, and Einstein's reply, on the other (see [4, pp. 665-688]).

In his reply Einstein went back to the arguments of 1935 and of his subsequent works (see "Physics and Reality" [10, pp. 290-323]; *The Evolution of Physics* [12]; "Quantum Mechanics and Reality" [13, S. 320-323]), that were based on the conception of reality as existing independently of any act of observation, "reality as such" [13, S. 321], on a rejection of probabilistic description of a micro-object [4, pp. 668-669; 12, p. 297]; and the assertion that statistical quantum mechanics cannot be the starting point of the entire subsequent development of the physics of the microworld [1, pp. 318-319; 4, pp. 671-672]. Thus the question again arose of the basic concepts, as was stressed by Einstein himself in the title of his 1953 work "Introductory Remarks Concerning Fundamental Concepts" [14, pp. 4-14]. Here Einstein repeated his arguments that statistical descriptions cannot be viewed as "complete" descriptions of reality.

It is thus clear that the third, postwar stage in the Einstein-Bohr controversy is characterised by a deeper understanding of its inner content. It is no longer a question of consistency or completeness of a theory (of quantum mechanics), but of physical reality itself, of the relation of the concept of probability to it and, as a result, of the entire future of physics.

This fundamental formulation of the problem naturally increased the world scientific community's interest for it, the more so that the difficulties of the development of the microphysics that became apparent already before the war (divergencies in the quantum field theory) remained. In the first and second stage of the discussion the main participants were Einstein and Bohr themselves and very few other scientists (Max Born, von Neumann), whereas the third stage attracted the attention of a much greater number of scientists.

The most characteristic features of the third stage are as follows: on the one hand, the probabilistic interpretation of quantum mechanics was given greater depth in connection with the problem of reality, and on the other hand, attempts were made to revise the content of the theory and its apparatus in accordance with Einstein's understanding of reality.

Let us consider in some detail the first trend. Deeper insights in quantum mechanics were attained as a result of rejection of such elements of its positivist interpretation as the theory of interphenomena (Hans Reichenbach), the insistence that the statistical quality is "created" by uncontrolled interaction, the interpretation of the indeterminacy relation as indicating certain boundaries of cognoscibility of the micro-object (W. Heisenberg). Bohr's works after the war ("On the Notions of Causality and Complementarity" [15, pp. 312-319], "Quantum Physics and Philosophy" [16, pp. 308-314], "Discussions with Einstein on Epistemological Problems in Atomic Physics" [4, pp. 199-241]) emphasised quite definitely the limitations of application of classical concepts (coordinate, momentum) in the description of micro-objects and the immanent probability of the very essence of the phenomena of the microworld.

A most consistent interpretation of quantum mechanics and of the essence of the phenomena of the mircoworld was attained in the works of the Soviet physicist V. A. Fok [17, 18, 19, 20]. Fok developed Bohr's ideas and freed them from unfortunate terminology, explicitly formulating the principal elements of the interpretation of quantum mechanics. We shall discuss Fok's interpretation, opposing its main propositions to those of Einstein. Einstein believes that "quantum physics formulates laws governing crowds and not individuals. Not properties but probabilities are described..." [12, p. 297], while Fok defines probability as a fundamental property of the micro-object [17, p. 12; 18, pp. 13-14; 20, p. 95]. "The state of the object described by the wave function is objective in the sense [states Fok] that it is an objective (independent of the observer) characteristic of the *potential possibilities* (italics mine—*S. I.*) of a certain result of the interaction between the atomic object and the device. That is also the sense in which it refers to the given individual object" [17, p. 12].

Thus the concept of reality in physics is changed: probability is no longer interpreted as the measure of human knowledge or ignorance but as the very essence or content of the phenomena of the microworld: the difference between probability as a characteristic of individual objects and the mode of their cognition is also taken into account here [20, p. 95]. If that is not done, certain aberrations arise in the perception and interpretation of statistical experiments. Among other things, failure to draw this distinction results in the so-called ensemble interpretations of quantum mechanics which are not, in actual fact, interpretations but a statement of the empirical level of statistics.

However, changes in the conception of reality in quantum mechanics are not limited to those in the status of the probability concept. They are deeper than that, affecting the basic concept of "reality as such", to which Einstein frequently turned in the discussion of quantum mechanics. The concept itself of "reality as such" is one of the fundamental abstractions of classical physics [20, pp. 9-11]. Exactly this abstraction was the target of Einstein's critics in [4] who insisted on the classical quality of his worldview. Rejection of this abstraction and the need for taking into account the effect of the mode of observation of the nature of the process itself is one of the most important features of quantum mechanics recorded in Bohr's complementarity conception. In the works of Fok this conception was discussed and formulated as the principle of relativity with regard to the means of observation [17, pp. 7-8; 20, pp. 14-15]. This principle requires that physical reality should be considered as given in a definite concrete situation rather than "by itself". Its further generalisation was formulated by B. Ya. Pakhomov as the principle of relativity with regard to the type of interaction [21].

It may be noted that the problem of the status of the concept of probability and that of physical reality are closely interwoven. Indeed, the classical abstraction of "reality as such" owes its origin to the fact that classical physics operates with truths rather than probabilities, the classical concept of reality being merely one of the expressions of the assertion on the existence of true knowledge about all physical magnitudes. Introduction of probability as an objective characteristic of microworld phenomena naturally leads to the need to take into account the device (or, in broader terms, the type of interaction) for establishing the way in which the potential possibilities produced by the micro-object will be realised.

Fok endeavoured to interpret the special form of integrality in the microworld discovered by Bohr as a manifestation of a certain kind of "non-force" interactions, in a way similar to generalisation of the basic elements of the probabilistic interpretation of quantum mechanics [17, p. 5]. This concept was used to interpret the EPR paradox and various quantum-mechanical correlations, e. g., the correlations conditioned by the Pauli principle.

We believe, however, that the introduction of the "non-force" interaction concept is a kind of tribute to the language of classical physics. Bohr's idea of specific quantum-mechanical wholeness seems to reflect the essence of microphenomena in a deeper manner. The realisation that probability is an objective characteristic of the microprocesses, that these processes are relative with regard to the type of instrument (or kind of interaction), and the conception of specific wholeness, create a complete interpretation of quantum mechanics in the spirit of Bohr's ideas devoid of any ambiguity or subjectivity. The controversy considered here played an enormous role in the establishment of such an interpretation.

Apart from establishing a consistent interpretation of quantum mechanics in an "orthodox" sense, the third stage in the Einstein-Bohr controversy also had other consequences. A number of scientists, inspired by Einstein's ideas, attempted a return to the classical mode of description on the basis of the idea that "hidden parameters" constitute elements of reality (in Einstein's sense) and are responsible for the statistical nature of microphenomena. Of these attempts, the best known are the works of

David Bohm (see [22, pp. 359-381; 23, pp. 139-168; 24, pp. 93-109], as well as [25]). All these attempts reject von Neumann's theorem (or rather thesis) of the impossibility to combine the results of quantum mechanics with "hidden parameters" [26, pp. 323-327].

Since neither Einstein nor Bohr took part in the latter stages of the discussion, we shall not analyse them in detail. What is important to note is the fact that 25 years of effort in this direction have not brought any tangible success. On the contrary, J. S. Bell obtained important results [27, pp. 195-201; 28, pp. 447-452], confirmed by experiments, which strengthened the position of quantum mechanics.

It can be noted that all attempts to implement Einstein's programme of revising quantum mechanics were built on purely classical foundations and proved to be fruitless. However, what was the attitude of Einstein himself to them? On the one hand, they may be said to follow, quite obviously (probably too obviously), from Einstein's programme of 1935 and 1949 and from the conception of reality envisaging continuous functions in space-time. On the other hand ... The whole point, however, is that there is nothing "on the other hand" apart from their fruitlessness, now almost obvious. In any case, Einstein's attitude to them was wary enough [29, S. 258]. The reason for this attitude might be that all attempts to modify quantum theory were (and still are) based on the empirical material at which they were oriented, that is to say, "under the insuperable pressure of facts", rather than on a broad generalising principle. But that is merely our assumption.

Now that we have considered the entire course of the controversy and the underlying principles of the views of its main participants, Einstein and Bohr, it is time to sum up—if it can in general be done, for the argument continues even in our days.

It can be stated that for almost half a century (since 1935) physics has developed mostly along the path suggested by Bohr, and serious results have been obtained within this approach. It naturally follows that Einstein was mistaken in his controversy with Bohr. But the very concept of "mistake" ceases to be categorical when applied to such a thinker and scientist as Einstein. Einstein's impact on the whole of modern physics was so profound and all-embracing that we must find some other definition for his role in the debate.

This fact was probably most clearly realised by Einstein's chief opponent, Bohr. In his work on the history of the controversy, he comments on the fundamental role of Einstein's critique in the formation of a consistent interpretation of quantum mechanics. Einstein grasped the very essence of the new theory and pointed out those main points where it diverged from the established propositions of the scientific worldview, so that his critique pointed to the need for their detailed analysis and interpretation. In essence that meant that what was required was not a mere rejection of those principles which underlay Einstein's physical worldview but rather their re-interpretation in a new cognitive situation.

Let us consider again the fundamental tenets of Einstein's worldview in the light of their revision in quantum mechanics and, in a broader sense, in modern physics. The requirement of clarity and distinctness of knowledge, so important for Einstein, was transformed into the requirement of the possibility of non-contradictory thinking about the feasible results of interaction of quantum objects, as registered in Bohr's complementarity principle. This requirement, applied to the microworld, resulted in a consistent interpretation of quantum mechanics achieved, as has been indicated, in the course of the controversy with Einstein. The concept of reality was revised in a similar way. Reality did not disappear from quantum mechanics nor was it replaced by an "interphenomenon" conception—it came to be comprehended in a way different from classical physics. The place of reality as an ensemble of point events was taken by the reality of potential possibilities. One may even refer here to "reality as such" *in the sense of independence of an ensemble of potential possibilities from the act of observation,* but not of course in the sense of independence from the surrounding macro-or even microsituation.

However, the greatest impact on physics was made by Einstein's conception of the unity of the world. In Einstein himself this conception has two aspects, ontological and epistemological. The ontological aspect consists in the idea of a single basis of the world, and the epistemological one, in the requirement of a search for a unifying general principle from which the special cases may be deduced as particular ones.

This conception was also revised. Few scientists now hope to find a general principle, fewer still hope to do so by a flight of imagination, but the search for unity is one of the most important motive forces of modern science. The main trend in physics is finding unity through experiment rather than formulating a general principle as a free invention of the intellect.

This idea of unity can also be traced in Bohr's conceptions of quantum-mechanical wholeness and in all the attempts at constructing a unified theory of elementary particles and their interactions. Not only the general direction of the search but also many details of the theories go back to Einstein's ideas—non-linearity of the principal equations, the fundamental role of the invariance principle, particle-like solutions of non-linear equations, and others.

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EINSTEIN AND MACH

The fundamental physical theories of the 20th century greatly affected the intellectual climate of the epoch. The epistemological and philosophico-methodological debates caused by the relativity theory and quantum mechanics deal with such profound matters that they continue in these days, too. The realisation of the general cultural value of the new physical theories, their increased impact on cognition and society's life led to the need for elucidating the philosophical content of the non-classical conceptions of reality, causality, space, and time, and to a greater urgency of this problem: what philosophical ideas had facilitated the appearance of the relativity theory and quantum mechanics? Is there a link, if only a mediated one, between the philosophical concepts dominating the scene at the time of the formulation of the new theory and its basic propositions?

The present article suggests definite answers to the questions formulated above. It does not discuss, however, the whole range of the philosophical premises of the relativity theory and the impact of the philosophico-methodological views, dominating the cultural environment in which the scientific revolution took place, on the developing scientific knowledge, but only one aspect, namely: what is the relation of philosophical positivism in general, and Machian positivism in particular, to Einstein's relativity theory?

Modern physical theories can only be understood in their entirety if one takes into account the history of their emergence and initial development as well as the influence of various philosophical schools on the formulation and solution of the properly physical problems that led to fundamental results. The reason for the truth of this thesis is that any new fundamental scientific theory, "sublating" the existing system of conceptions of the world, faces the need to take upon itself all the functions, including that of the leader in a given area of knowledge with all its consequences, which had previously been performed by the preceding system of knowledge. Hence the problems of the philosophical-worldview foundations of the new theory: just how deeply substantiated are the principles of the new theory? do they follow from the entire previous culture, the quintessence of which is philosophy? can the new theory deepen philosophical, not only physical, knowledge? And so on. All these problems face the relativity theory, too. As distinct from problems of the physical content of the new theory, the solution of the above tasks takes a longer time. The realisation of the profound physical content of the relativity theory and of its impact on other branches of natural science in general and physics in particular, and further, on the philosophical worldview, compelled the representatives of most philosophical systems to try to "assimilate" the relativity theory by proving that its ideas followed from the works of Kant or Hume or some other philosopher. The question of Mach's ideological role was particularly vital here. Without going into the causes of this phenomenon, let us point out that the philosophical premises of the new theory of space, time, and gravitation, in our view, can only be successfully elucidated in the analysis of the epistemological situation in science at the turn of the century, when the special relativity theory was formulated.

A new cognitive situation arose at that time, in which the epistemological analysis of the principal system-forming concepts of physical knowledge became part of the activity of a scientist. This situation did not arise overnight, for physicists displayed an interest for the philosophical foundations of their field of knowledge before the relativity theory as well. However, that interest was mostly episodic in nature and depended on many attendant circumstances. There was no explicit and direct link between physical studies and philosophical ratiocination. The situation changed essentially late in the 19th and early in the 20th century. As Einstein remarked, "the present difficulties of his science force the physicist to come to grips with philosophical problems to a greater degree than was the case with earlier generations" [1, p. 279]. Relying not only on Einstein's authority but also on the history of physics in general, we can say that the growing complexity of physical knowledge, changes in the status of logico-mathematical abstractions, etc. resulted in the need for solving philosophico-methodological problems. Analysis of epistemological problems was a novel feature and was naturally attended by certain losses. In asserting new ideas, scientists also endeavoured to find out what philosophical ideas contributed to the origin of the new theory and in what relation the new conception stood to traditional philosophical directions. The latter does not mean that philosophical interpretations only emerged when the physical theory itself was already formulated. Debates concerning the role of philosophical ideas in the development of scientific knowledge had taken place earlier, too. But at the turn of the century the situation became more acute due to the crisis of the methodological foundations of physics.

The fact that the mechanistic-metaphysical methodology widely current among natural scientists cannot help in the solution of the new epistemological problems of science, was understood in the 19th century. Mechanistic materialism was thus proved to be narrow and limited, and it became clear that a higher form of materialism was needed, one that did not raise to an absolute mechanical laws but developed materialism on the basis of dialectics. That was the path followed by the founders of dialectical materialism. However, apart from this scientific direction in overcoming the difficulties facing the natural-philosophical form of problem-solving, there also emerged another, subjective-idealist, philosophical direction developed by Auguste Comte. Comte and his followers declared war on philosophy in general, taking a strictly phenomenological view of the existing knowledge.

In the years preceding the formulation of the relativity theory, widely current were the ideas of Mach, Ostwald and their followers, who essentially continued the line of Berkeley and Comte. In characterising the influence of Mach's ideas on the minds of his contemporaries, primarily on natural scientists, Gerald Holton, an American historian of science, writes: "The influence of Mach was enormous... At least since 1880, his ideas and philosophical attitudes were so much part of the intellectual baggage of his contemporaries that much later Einstein had every right to speak of those who fought Mach's ideas which, without knowing it, they had 'imbibed with the milk of their mothers' " [2, p. 100]. Let us also quote in this connection Einstein's article "Ernst Mach", where he wrote: "of myself I know, at least, that I was particularly strongly helped by the works of (Hume and) Mach, directly or indirectly" [3, S. 102].

Why did it happen so? What could be so attractive to Einstein in Mach's philosophy of pure description? To answer these questions, one must bear in mind several important interconnected circumstances.

First, the basic propositions of dialectical materialism, which overcomes the dogmatism of metaphysical materialism, Kantian apriorism, and philosophical relativism, for various reasons were not widely known among natural scientists.

Second, there was a need in science for a critical attitude to the basic principles of classical mechanics, which had assumed the character of philosophical tenets. Scientists needed a certain epistemological basis for a critical revision of the existing physical conceptions. In this situation, the work of Ernst Mach *Mechanics in Its Development* became widely known, and Mach's name became associated with a critique of the foundations of Newtonian mechanics.

Third, philosophers and scientists sharing the basic propositions of Machist epistemology (Duhem, Ostwald, Poincaré and others) did indeed point out certain weaknesses in the substantiation of classical mechanics. In particular, they correctly showed the non-absolute nature of classical conceptions and the impossibility of realising the mechanistic philosophical programme. They also admitted the impossibility of explaining all natural phenomena on the basis of mechanics. That was the reason why they won authority in the scientific and philosophical circles.

However, in endeavouring to find new ways of studying objective reality and to formulate non-classical requirements to the structure of scientific knowledge, all these scientists and philosophers took the path of rejecting the objective nature of the laws of physics. For example, Duhem wrote: "When the inanity of these efforts [of mechanical explanation of all natural phenomena—*K. D.*] clearly showed that such an explanation was a chimera, physicists, convinced that it was impossible to satisfy at once the exigencies of reason and the needs of imagination, had to make a choice; strong and just minds, subject before anything else to the dictates of reason, ceased to demand an explication of natural laws from physical theory, to safeguard its unity and rigorousness"[4, p. 152]. But too high a price was paid for formal unity and consistency of theories—a rejection of explaining nature, which essentially signified a rejection of science.

As was noted by Max Planck, one of the better-known opponents of positivism, Mach "overshoots his goal, degrading, along with the mechanical world picture, the physical world picture in general" [5, S. 27]. During the debate on the relativity theory organised by the French philosophical society in Paris, Einstein thus replied to the question about his attitude to Mach asked by the well-known philosopher Meyerson: "Mach's system studies relations existing between experimental data; the sum total of these relations is, for Mach, the exact science of nature. That is a bad viewpoint; on the whole, what Mach did is a catalogue, not a system. Mach was a good mechanist but a poor philosopher" [6, p. 111].

As Fr. Herneck correctly indicated, "this annihilating evaluation of Mach the philosopher by Einstein ... fully and almost literally coincides with Lenin's pronouncements in his work *Materialism and Empirio-criticism* directed against Mach and Machism" [7, S. 564]. We do not believe that this coincidence is accidental. Einstein's critique is directed essentially against the raising of the sensually given to an absolute, which leads to subjective idealism. That is why one cannot explain Einstein's evaluation merely as a mood, as Herneck does in the article quoted above: this evaluation follows from Einstein's entire scientific programme. In his 1955 "Autobiographical Notes" Einstein thus analysed the ideas which led him to the new theory of space and time:

"Reflections of this type made it clear to me as long ago as shortly after 1900, i.e., shortly after Planck's trailblazing work, that neither mechanics nor thermodynamics could (except in limiting cases) claim exact validity. By and by I despaired of the possibility of discovering the true laws by means of constructive efforts based on known facts. The longer and the more despairingly I tried, the more I came to the conviction that only the discovery of a universal formal principle could lead us to assured results... After ten years of reflection such a principle resulted from a paradox upon which I had already hit at the age of sixteen: If I pursue a beam of light with the velocity *c* (velocity of light in a vacuum), I should observe such a beam of light as a spatially oscillatory electromagnetic field at rest. However, there seems to be no such thing, whether on the basis of experience or according to Maxwell's equations. From the very beginning it appeared to me intuitively clear that, judged from the standpoint of such an observer, everything would have to happen according to the same laws as for an observer who, relative to the earth, was at rest...

"One sees that in this paradox the germ of the special relativity theory is already contained. Today everyone knows, of course, that all attempts to clarify this paradox satisfactorily were condemned to failure as long as the axiom of the absolute character of time, viz., of simultaneity, unrecognizedly was anchored in the unconscious. Clearly to recognize this axiom and its arbitrary character really implies already the solution of the problem" [8, p. 53].

Everyone familiar with Mach's basic philosophico-methodological propositions will understand that the epistemology of the Viennese philosopher was powerless to offer a positive solution of this task of discovering a general formal principle. But the construction of new mechanics was preceded by an important phase—the realisation of the fact that the system of physical knowledge contained the axiom of absolute nature of time and simultaneity that was arbitrary and insufficiently confirmed by facts. In Einstein's view, the realisation of this circumstance essentially gives the key to the solution of the problem. Mach's critique of the basic concepts of classical mechanics could be helpful exactly at this stage—in the establishment of experimental untenability of the classical conceptions of time, motion, and space. As distinct from many positivistically minded natural scientists, Einstein believed the works of scientists in the field of epistemology to be extremely important and valuable. This was reflected in the obituary for Mach written in 1916.

These concepts "easily achieve so much authority over us that we forget their earthly origin and take them for something immutably given. They are then stamped as 'necessities of thought', 'a priori given', and so on. The path of scientific progress is often obstructed by these errors for long periods of time. It is therefore no idle amusement at all, when we are preoccupied with analysis of concepts that have been current for a long time and with showing upon what circumstances are dependent their justification and utility and how they emerge, individually, from experiential data. Thereby their excessively great authority is broken down. They are omitted, if they cannot be made properly legitimate; corrected, if their coordination with the given objects was too carelessly established; or replaced, if it is possible to construct a new system which we, for some reason, prefer" [3, S. 102].

Despite the fact that Einstein's statements were quite unambiguous and anti-empiricist in their spirit, the adherents of Mach's philosophy began to spread the idea that the new theory of space and time had been stimulated by the Viennese philosopher's epistemology. Thus Hans Reichenbach, one of the most influential representatives of neopositivism, wrote: "It is the philosophy of empiricism, therefore, into which Einstein's relativity belongs... In spite of the enormous mathematical apparatus, Einstein's theory of space and time is the triumph of such a radical empiricism in a field which had always been regarded as a reservation for the discoveries of pure reason" [8, pp. 309, 310]. The idea that the relativity theory is a concrete implementation of the principles of radical empiricism, was not new. It was asserted by Mach's followers as early as the 1920s, despite Mach's skeptical attitude to the theory of relativity. Philosopher Petzoldt in an article entitled "The Relation of Mach's World of Ideas to the Relativity Theory" published as an appendix to the seventh edition of Mach's *Mechanics in Its Development,* wrote: "The relativity theory is not in conflict with Mach's worldview in any of its significant propositions. It is a golden fruit of his deeply rooted and wide-spread tree of thought..." (quoted from [9, S. 517]).

Mathematician A. A. Vasiliev developed similar ideas in the work *Space, Time, Motion* (1922). He endeavoured to prove that "Einstein's theory of relativity is built on epistemological premises coinciding... with Mach's ideas; however, for this theory to be constructed and accepted by a majority of outstanding scholars and thinkers of our times, two requirements had to be satisfied: *first,* the evolution of ideas about space had to change the dominant view of the relation between physics and geometry, between space and the phenomena taking place in it, the view of space as "rooms to let", in Weyl's witty phrase; *second,* the place of two distinct notions of three-dimensional space and time, a manifold in one dimension had to be taken by a general concept of the world, of an ensemble of events, a manifold in four dimensions. The former was made possible by the attainments of non-Euclidean geometry, the latter, by the development of physical experiment" [10, p. 63]. Vasiliev was one of the first to develop the idea that the English philosopher George Berkeley was the ideological, philosophical precursor of the relativity theory. In his view, "the immortal attainment of Berkeley was that he decisively rejected external reality of space, recognising it as an entirely subjective result of an association of visual, tactile, and kinetic sensations" [10, p. 55].

This kind of judgements about the relationship between the relativity theory and Mach's philosophical doctrine are also widely current in modern Western philosophy of science and in physical literature. Thus D. W. Sciama, an English physicist, in his work *The Physical Foundations of General Relativity* considers the views of Berkeley and Mach on gravitation and the nature of the forces of inertia, endeavouring to prove that they had a decisive impact on the formulation of the general relativity theory. The basic principles of the critique of absolute space by Berkeley and Mach are indeed identical, their philosophical positions having a great deal in common. The fact that the basic principles of Machist philosophy essentially do not differ from the principles of Berkeley's philosophy was shown by Lenin in *Materialism and Empirio-criticism*. Sciama is right in stating that "Berkeley... objected to the idea of absolute space because it is unobservable" [11, p. 17]. Continuing the analysis of the philosophical premises of the new theory of gravitation in the section on "Mach's Principle", Sciama writes: "Mach's approach to the problem of inertia was only a slight elaboration of Berkeley's, and it is important largely because it stimulated a rediscussion of the problem at a time when Newton's authority was unquestioned. Mach's criticisms of Newton's laws of motion are more detailed than Berkeley's, but in regard to centrifugal force his standpoint is the same" [11, p. 18].

Indeed, Mach's critique of the basic propositions of Newton's gravitational theory was not a simple matter. Sciama is absolutely right on this point. He is also correct in saying that Mach's criticism of Newton's doctrine was more profound than Berkeley's. However, this depth is due to Mach's physical rather than philosophical arguments. In this respect Mach's principle as a physical principle which played a definite role in the formulation of the general relativity theory clearly cannot be identified with his philosophical assertions. One cannot therefore accept Sciama's logic according to which the philosophical standpoint of Berkeley and Mach is obligatory for all physicists, since they criticised from identical epistemological positions the principles of classical mechanics, later essentially revised in its foundations and claims. This logic simplifies and distorts the real picture, for it completely eliminates the question of differences in the critique of the foundations of classical mechanics and the question of whether the philosophical propositions of Machism were realised in the new theory. This logic also loses sight of the complexity of the relations between philosophy and physics in general and between the subjective-idealist epistemology of Berkeley and Mach and the relativity theory in particular. The gist of this relation lies precisely in that in the existing epistemological situation some aspects of Machist epistemology were used in the critique of old concepts of space and time. Of greater importance here was not their positive content but their critical orientation and the ignorance of scientists about other, more scientific methodological ideas better answering the needs of developing physical knowledge. The logic of Machist philosophy, being consistently empirical-phenomenological, could not by its very essence be of any real use in building a new edifice of physical theory. As was correctly noted by Omelyanovsky, "what attracted Einstein in Mach were most likely the critical aspects of his analysis of Newton's mechanics and those arguments of Mach which Einstein took to be a critique of the mechanistic dogmatism of physicists" [12, p. 106].

At the same time Fr. Herneck, a German specialist in the history of science, is quite right in saying in his analysis of this problem that "the significance of Mach's critique for the history of science is not diminished by the fact that Mach made fundamental and fatal mistakes in the area of philosophy, rejecting philosophical materialism along with the mechanistic picture of the world and the mechanistic-materialist dogmas based on it" [13, S. 55]. B. G. Kuznetsov [14] and P. V. Kopnin [15] also pointed out this fact. In particular, Kopnin wrote that "the influence of Mach's ideas on the natural scientists of those times cannot be gainsaid. Such physicists as Einstein and Planck, whose worldview and mode of thinking were indubitably different from those of Mach, repeatedly admitted their ties with Mach" [15, p. 131]. His explanation for this fact was that "the opposition to mechanism brought Mach the renown of a fighter for new physics", and that natural scientists saw Mach, first of all, "as a critic of the mechanistic world picture" [15, p. 131].

Finally, let us point the view of Max Born who, while thoroughly criticising the positivist conception of scientific cognition for its anti-rationalism and dogmatism, still believed that "this standpoint has proved itself productive by inducing physicists to adopt a critical attitude towards traditional assumptions, and has helped in the building of relativity and quantum theory" [16, p. 49].

Thus Mach's philosophy, being purely phenomenological and empiricist, could not serve as the methodological instrument of elaborating the foundations of the new conception of space and time. On the other hand, being critical towards existing knowledge, it facilitated the realisation of the need for destroying dogmatic natural-philosophical constructions based on classical mechanics.[1] For this reason, to understand and explain the positive attitude of various natural scientists to Mach's philosophical ideas, one must, apart from the facts pointed here, take into account that those scientists who constructed new physics mostly did not go in for a systematic conceptual analysis of Machist epistemology or a critique of the subjective-idealist essence of this philosophy but rather accepted Mach as an anti-dogmatist and critic of the foundations of classical natural science. As V. S. Ukolov writes in an article on the evolution of Einstein's world-view, "Einstein singled out elements of dialectics in the philosophy of Hume and Mach, ignoring their philosophical context" [18, p. 18].

Some aspects of Mach's teaching can undoubtedly be given dialectical interpretation, but, as we shall show below, they did not express the essence of his philosophy. In particular, in the obituary for Mach quoted above, Einstein wrote that the positive role of the Viennese philosopher lay in that he had attacked those metaphysically (in the Hegelian and dialectical sense of the term) thinking philosophers and scientists who "declared the fundamental immutability" of certain concepts of mechanics [3, S. 102]. Natural scientists were also attracted to Mach's philosophy by his wide use of natural-scientific data in constructing his system and emphasis on real problems facing physical science.

Thus, Mach was dissatisfied with the constructions of absolute space and absolute time introduced by Newton, as they could not be in principle juxtaposed with experimental data. Mach correctly pointed out the experimental nature of spatio-temporal characteristics: "Motion can be uniform relative to some other motion. The question

[1] See also the section on "The Controversy about the Philosophical Premises of the Relativity Theory. The Mach-Einstein Problem" in our work [17].

whether motion is uniform by itself has no sense" [9, S. 217]. In another passage Mach wrote: "We must not forget, however, that all things are interconnected and that we ourselves, with all our thoughts, are merely a bit of nature" [9, S. 217]. These dialectical *motifs* (rather numerous in the works of Mach) were naturally perceived by scientists as unconnected with his idealist assertions. But these ideas, correct in themselves, did not play a decisive role in the works of Mach himself. The essence of his views is expressed in the following words: "Unbiased contemplation teaches us that every *practical* and *intellectual* need is satisfied as soon as our ideas can fully reproduce the sensuous facts. This reproduction is therefore the *aim* and *purpose* of physics, and atoms, forces, and laws are, on the contrary, only the *means* which facilitate that reproduction" [19, S. 257]. "My viewpoint completely *excludes* all *metaphysical* [that is, philosophical—*K. D.*] questions [wrote Mach in the same work], irrespective of whether they are regarded as unsolvable only at present or as meaningless in general and for all time" [19, S. 300]; "the *sensuous* world belongs *simultaneously* both to the physical and psychical domains" [19, S. 253].

The subjective-idealist statements quoted here were not apparently perceived by most natural scientists as organically linked with the critical aspects of Machian philosophy. Characteristically, Mach's clearly formulated subjective-idealist views of the elements of the world, of "complexes of sensations" of which the world consists, and so on, were largely ignored by natural scientists. Only later (some time after 1910), when the question of the philosophical premises of the relativity theory came to be widely discussed and there appeared special works on the epistemological aspects of the new theory, physicists had to study the philosophical interpretations of the new stage in the development of physical science. As a result, most scientists, including Einstein, took a negative view of the interrelations between the relativity theory and various idealist philosophical schools, including Machism. In particular, the founder of the theory of relativity criticised Mach, "for he did not place in the correct light the essentially constructive and speculative nature of thought and more especially of scientific thought" [8, p. 21].

This remark of Einstein touches on the most essential weakness of Mach's epistemology as an empiricist platform in philosophy—underestimating the role of theoretical, rational, creative element in cognition. It was Mach's fundamentally negative attitude to the products of logical theoretical knowledge that led him to the idea of untenability of the relativity theory. The same cause rather than mood or age underlay Mach's negative attitude to atomism and his appraisal of atomic-molecular theory as "mythology of nature", and of atoms, as "witches' Sabbath" [20, S. 104]. Therefore the attempts of Mach's pupils, in particular of Frank, to prove that a historical mistake is often made when the struggle of Mach and Duhem for positivist philosophy is linked up with their aversion for atomism and the victory of atomism is thereby regarded as a defeat of positivism, are historically untenable. Incidentally, the divergence between Mach's philosophical ideas and the new physics was so obvious that it had to be recognised even by Mach's followers, and that gave a stimulus to attempts at modernising Machism.

Thus the emergence of the relativity theory was not due only to scientists coming across experimental facts that could not be squeezed into the old conceptual scheme: it was also due to previous critical philosophical analysis of many self-evident and at the same time fundamental concepts of classical mechanics. The influence of positivist aspirations, including Mach's ideas, among some natural scientists is partially explained by the fact that many other contemporary philosophical schools and sects in the West were clearly irrational, aprioristic, and subjectivist in nature, ignoring the attainments of natural science and taking a negative or skeptical attitude to the development of scientific knowledge.

In discussing the impact of some philosophical system on the worldview of a natural scientist or sociologist, one must bear in mind that philosophical systems are perceived by natural scientists differently from sociologists. Moreover, there is a certain difference between the perception of the same epistemological ideas by theoreticians and experimenters in physics. The process of interpretation of philosophical ideas by natural scientists (just as specialists in other concrete areas of knowledge) directly depends on the tasks which they solve at the given period and on the categorial scheme which they employ. Having studied various philosophical interpretations of his theory in the work devoted to his contribution to science, Einstein characterised the situation in the following words: "The scientist... appears as *realist* insofar as he seeks to describe a world independent of the acts of perception; as *idealist* insofar as he looks upon the concepts and theories as the free inventions of the human spirit (not logically derivable from what is empirically given); as *positivist* insofar as he considers his concepts and theories justified *only* to the extent to which they furnish a logical representation of relations among sensory experiences. He may even appear as *Platonist* or *Pythagorean* insofar as he considers the viewpoint of logical simplicity as an indispensable and effective tool of his research" [8, p. 689]. The specificity of perception of philosophical ideas is one of the causes of different interpretation of identical propositions, say, of Hegel or Kant.

One may cite in this connection the following fact from the history of science. As we know, Einstein analysed the problem of correlation of many philosophical doctrines and the theory of space and time. In particular, he expressed a negative attitude to Kant's interpretation of the correlation of space, time, and moving matter in the framework of science: "Kant's attempt to remove the embarrassment [the reference is to the difficulties of the classical approach to the correlation of space and time—*K. D.*] by denial of the objectivity of space, can ... hardly be taken seriously" [21, p. 137]. However, some physicists (not to mention neo-Kantians of the Cassirer type), who share relativist concepts, hold the opposite view of the Kant-Einstein problem. Thus Max von Laue writes: "I arrived at an understanding of the relativity theory which satisfied me only when I succeeded in connecting it with the Kantian teaching of space and time" [22, S. 159]. Such judgements of the role of Kant's philosophy in the interpretation of the relativity theory prove, in our view, the following point: there is a certain specificity in the perception of a given philosophical system, its basic principles and methodological postulates by natural scientists, sociologists, writers, and so on; this specificity depends on the scientist's level of culture, his social position, and the problems that he works on. These circumstances explain why Mach had a certain influence on the worldview of contemporary scientists; especially, they help to understand what they sought in the epistemological constructions of the Viennese philosopher to solve their own problems.

The error of Mach, Ostwald, Duhem and their followers did not of course lie in that they criticised the metaphysical and essentially anthropomorphic elements in the system of Newtonian physics, and by the same token certain principles of the metaphysical method of thinking: their error lay in that they criticised them, as shown by Lenin, from the positions of subjective-idealist philosophical empiricism. As Karl Marx indicated, "Crass empiricism turns into false metaphysics, scholasticism, which toils painfully to deduce undeniable empirical phenomena by simple formal abstraction directly from the general law, or to show by cunning argument that they are in accordance with that law" [23, p. 89]. That is why the attempt at relativisation of the categories of space, time and motion ended in negation of the objective content of these concepts. In the final analysis, Machism failed to give a philosophical-critical interpretation of the foundations of Newton's physics. Epistemological subjectivism underlying these attempts led his adherents to idealism of Berkeleyan type.

Empiricism restricts the subject matter of scientific knowledge to the sense data and their systematisation. It is incapable of answering the question of how one is to proceed from one categorial system to another. Moreover, a consistent empiricist platform underlying the logic of scientific cognition, rules out the very possibility of considering the transition from one theoretical system of knowledge to another. At best, it can only specify the existing system of knowledge by eliminating its hypothetical elements, as well as the directly unobservable magnitudes and generally everything that is not immediately given. This purely phenomenological viewpoint does little to facilitate the solution of the tasks facing science. The actual problem that worries scientists was not removed: new requirements had to be imposed on the categorial apparatus of physics; the content of some fundamental categories of Newton's mechanics had to be changed, the sphere of action of other concepts had to be restricted by the domain of low speeds and great masses, and theoretical substantiation had to be given to the new categories reflecting newly discovered connections and relations which had no mechanical analogues.

The new theory of space, time, and gravitation is linked with diverse variants of the epistemological conception of Mach and his followers mostly historically rather than conceptually or through common origin. The relativity theory could not in principle be methodologically stimulated by Machism, still less could it consistently implement its philosophical principles. Therein lies apparently the explanation of the fact that in 1922, when Einstein began to pay attention to the philosophical problems of physical science, he criticised Mach as a philosopher very sharply. Einstein not only expressed his negative attitude to Mach, but also pointed to the weakest element of his theoretical constructions—the raising to an absolute of sensory data and underestimating the active creative role of the subject in cognition. He explained the negative attitude of Mach and Ostwald to atomism by their failure to understand the creative role of the subject: "The antipathy of these scholars towards atomic theory can indubitably be traced back to their positivistic philosophical attitude. This is an interesting example of the fact that even scholars of audacious spirit and fine instinct can be obstructed in the interpretation of facts by philosophical prejudices. The prejudice—which has by no means died out in the meantime—consists in the faith that facts by themselves can and should yield scientific knowledge without free conceptual construction" [8, p. 49].

The realisation of the role of the imagination was probably the reason why the founder of the new theory of space and time later valued more highly the methodological possibilities of Kant's philosophy, towards which he held a negative attitude immediately after the formulation of the relativity theory [24, pp. 50-51]. However questionable, Einstein's assertions that theories are free inventions of human reason and that there is no way from experience to theory etc., are directed against the Machist and generally against the positivist line in philosophy.[2] The raising of empiricism to an absolute led Mach not only to a lack of faith in the truth of the relativity theory because of its alleged dogmatic character but also to a decisive stand against atomism. Defending himself against Planck's materialist criticism, Mach wrote that the main difference of opinion from modern physics consisted *in the belief in the reality of atoms.* The physicists apparently had all the premises for founding a church; they began to assimilate the procedures customary in the latter. And Mach added that if belief in the reality of atoms was so essential, he would give up the physicist's mode of thinking, he would not want to be a real physicist, he would give up any claims to the title of a scientist for freedom of thought was dearer to him [see 25].

No comment is needed here, apparently. Mach's erroneous philosophical positions made him reject the leading physical theories of the 20th century. Therefore Bergmann's statement that Mach's attempt to analyse physical theory relative to observation rather than within its metaphysical superstructure proved to be triumphant [see 26, S. 80] is strange, to say the least. Characteristically, in the article "Ernst Mach and Modern Physics" Bergmann cannot point a single fact to show the positive influence of Mach's philosophical ideas on the contemporary methodological search in physics. That is not accidental. The reason lies in the fundamental difference between the mode of development of natural science in the 20th century and the basic methodological principles of Mach and his followers. Therefore there is more truth in the critique of Mach's empiricism by the American philosopher Robert S. Cohen: "His program for philosophical analysis of science is thereby close to seeing it as a programmed high-speed computer" [27, p. 144].

The development of modern science brought the realisation of the untenability of the basic principles of traditional positivism. Not only Mach but also, later, Carnap, Reichenbach and others lost their authority in modern

[2] The possibility of different interpretations of these assertions and their debatable quality follow from their indefiniteness or their philosophical nature, if you like.

science. The problems of the growth of knowledge, the mechanism of development of knowledge, the role of socio-cultural factors—all these problems alien to traditional positivism are widely discussed in modern methodology of science. That is evidence of profound and fundamental difference between the basic principles of Machist philosophy and the main trends in 20th-century scientific cognition. Science has overcome the "fateful 'fear of metaphysics' " which, in Einstein's words, "has come to be a malady of contemporary empiricistic philosophizing" [1, p. 289]. The history of cognition confirmed the prediction of the founder of relativistic mechanics "that one can, after all, not get along without 'metaphysics' " [1, p. 291], thereby proving the incompatibility of the theory of knowledge of Mach and Einstein.

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EINSTEIN AND BRIDGMAN'S OPERATIONALISM

A critical analysis of the philosophy of operationalism is of great importance for a deeper understanding of Einstein's philosophical worldview and in the first place of his conception of the method of scientific cognition. This philosophy was worked out by P.W. Bridgman (1882-1961), an outstanding American scientist, specialist in high-pressure physics, awarded the Nobel Prize for studies in this field. Bridgman undertook an attempt to critically revise, from the positions of operationalism, the content of modern physics and in particular of Einstein's relativity theory. In 1949, Einstein and Bridgman were engaged in a controversy reflected in two articles published in the book *Albert Einstein: Philosopher-Scientist* [1, pp. 333-354; pp. 663-688].

The main problem tackled by operationalism is the definition of the content of physical concepts. Physics differs from mathematics in that the magnitudes of the equations of physical theory are linked with the results of observations and experiments. Physics requires an empirical interpretation of its formalism. It is usually assumed that corresponding to the physical concepts are the properties of real physical objects established by physical experiments. It is these properties that determine the content of physical concepts.

Bridgman believes the solution outlined here to be unsatisfactory. In his view, the content of physical concepts is not determined by the properties of things but rather by operations performed on these concepts. "The fundamental idea back of an operational analysis [he writes] is simple enough; namely that we do not know the meaning of a concept unless we can specify the operations which were used by us or neighbour in applying the concept in any concrete situations" [2, p. 7].

Bridgman believed that the special relativity theory fully satisfies the principles of operationalism and, moreover, is one of the weightiest proofs in its favour. The principal attainment of Einstein's theory was, according to Bridgman, as follows: "In the first place, he recognized that the meaning of a term is to be sought in the operations employed in making application of the term. If the term is one which is applicable to concrete physical situations, as 'length' or 'simultaneity', then the meaning is to be sought in the operations by which the length of concrete physical objects is determined, or in the operations by which one determines whether two concrete physical events are simultaneous or not" [1, p. 335].

Operationalism was directed against the contemplative interpretation of physical knowledge which underestimated the role of measurements. However, operationalism itself did not yield a correct evaluation of the role of measurements in physics, the special theory of relativity included. From the operationalist standpoint, the special relativity theory does not at all describe the physical world but merely the measurement operations and apparatus readings. For instance, length relativity has a purely operational rather than objective basis. "...The precise way in which the length varies from the motion [Bridgman explains] will be a function of the definition of the length of the moving object" [1, p. 336].

Operationalism appears untenable already from the standpoint of the materialist principles spontaneously followed by any physicist. In particular, measurements according to this view merely manifest relativistic effects—they do not create them. They are a means of cognition of the properties of the objective world and not of creating them.

Then there is this essential point. The development of the special relativity theory yielded an interpretation that had no place not only for observers but also for devices and measurement operations in the sense accepted in operationalism. We refer to the interpretation in terms of the Minkowski space. In this space, differences in the length of the measuring rod and correspondingly of the time interval in different reference frames are not linked with any measurement procedure, appearing as simple consequences of the fact that one and the same spatial or temporal interval has projections varying in length in different coordinate systems. Characteristically, this interpretation, which contradicts operationalism, is rejected by its followers as operationally untenable. However, in actual fact it was of great importance for the development of the special relativity theory and for the transition from the latter to the general relativity theory.

Operationalist methodology displays features not only of subjectivism but of empiricism as well. Rigid limitations imposed on the physical concepts used follow from it. If we are not in a position to indicate the operations in which a concept is to be used, the latter is empty, from the operationalist viewpoint, and has to be excluded from physics. The consequences of applying this methodology to the general relativity theory are not hard to imagine. This theory, with its abstract mathematical formalism, contradicts the operationalist ideal of scientific knowledge, for many of its concepts are not directly connected with physical operations.

Beginning a critical analysis of the general relativity theory, Bridgman makes the reservation that he is not going to criticise the physical-mathematical aspects of this theory and that he is much more interested in its philosophical foundations: "Two general aspects of the general theory of relativity may be recognised. Firstly, there is the mathematical edifice of the system of equations and the rules by which the symbols of the equations are to be correlated with the results of physical operations; and secondly, there is the attitude of the mind, or what I may call the philosophy, that leads to the arguments used in deriving the equations and to the expectation that the equations so derived will have physical validity... In this paper we are concerned with the philosophy of Einstein rather than with the equations which he deduced by the philosophy" [1, p. 347].

But this reservation proved to be a mere declaration.

Einstein's philosophy is closely connected with his equations. Bridgman is therefore compelled to argue not only with the philosophical postulates but also with the physical-mathematical content of the general relativity theory. A number of fundamental concepts of this theory turn out to be unacceptable from the operationalist standpoint. In the first place, that applies to the concept of event. An event that is a point characterised by three spatial coordinates and one temporal coordinate is devoid of any physical meaning, according to Bridgman. Coordinates are always coordinates of some real physical object. Outside of a physical substratum we cannot single out in space anything that may be characterised by coordinates. Therefore the concept of event as a point in empty four-dimensional spatio-temporal continuum turns out to be fictitious, on the physical plane.

Just as strongly does Bridgman object to the concept of an arbitrary coordinate system. It has no operational meaning either. Only that coordinate system is physically meaningful with which an observer and his instruments are connected.

The concept of covariance of laws employed by Einstein in the general relativity theory has a similar fate: it is also rejected by Bridgman as devoid of operational meaning.

We know, however, that the concepts of event, arbitrary coordinate system, and covariance are the fundamental notions of the general relativity theory. A rejection of these concepts leaves the general relativity theory in ruins. Bridgman concludes his paper with the following words: "That in his conviction of the possibility of getting away from any special co-ordinate system, in his conviction of the fruitfulness of so doing, and in his treatment of the event as something primitive and unanalyzed, he [Einstein—*Ed.*] has carried into general relativity theory precisely that uncritical, pre-Einsteinian, point of view which he has so convincingly shown us, in his special theory, conceals the possibility of disaster" [1, p. 354].

Einstein read Bridgman's paper, just as the other articles of the book *Albert Einstein: Philosopher-Scientist,* when it was at the proof stage. His reply was included in the work "Remarks Concerning the Essays..." which appeared as an appendix to the book. That reply did not contain a detailed criticism of Bridgman's views, yet he succeeded in expressing, in an extremely brief but pithy passage, the difference between his interpretation of the relativity theory and that of operationalism: "In order to be able to consider a logical system as physical theory it is not necessary to demand that all of its assertions can be independently interpreted and 'tested' 'operationally', *de facto* this has never yet been achieved by any theory and can not at all be achieved. In order to be able to consider a theory as a *physical* theory it is only necessary that it implies empirically testable assertions in general" [1, p. 679].

These quotations from the works of Einstein and Bridgman show quite transparently the difference between the creative methods and the views of the nature of physical knowledge of these two scientists. Einstein believes the so-called hypothetical-deductive scheme of cognition to be most adequate for the purposes of physics. According to this scheme, theoretical principles are formulated first and then empirical consequences are drawn from them in a deductive manner, the basic theoretical principles being "free inventions" of the scientist's reason.

Einstein expresses the idea of free invention of theoretical principles in many of his works. Thus, in the article "On the Method of Theoretical Physics" he wrote: "A complete system of theoretical physics is made up of concepts, fundamental laws which are supposed to be valid for those concepts and conclusions to be reached by logical deduction. It is these conclusions which must correspond with our separate experiences... The structure of the system is the work of reason; the empirical contents and their mutual relations must find their representation in the conclusions of the theory. In the possibility of such a representation lie the sole value and justification of the whole system, and especially of the concepts and fundamental principles which underlie it. Apart from that, these latter are free inventions of the human intellect, which cannot be justified either by the nature of that intellect or in any other fashion *a priori*" [3, p. 272].

However, Einstein does not interpret the term "freedom" in the sense of subjective arbitrariness of formulating theoretical principles. He explains that freedom in this case has a specific meaning: "The liberty of choice, however, is of a special kind; it is not in any way similar to the liberty of a writer of fiction. Rather, it is similar to that of a man engaged in solving a well-designed word puzzle. He may, it is true, propose any word as the solution; but, there is only *one* word which really solves the puzzle in all its parts" [3, pp. 294-95].

Freedom is interpreted by Einstein mostly in the sense of anti-inductivism, as the possibility of formulating, on purely logical grounds, theoretical principles that do not directly follow from experience. That was the kind of freedom that was manifested in the emergence of the general relativity theory. It is appropriate to emphasise here that this theory does not follow from a single empirical fact—the equivalence of gravitational and inertial masses. In itself, this fact does not yet lead to the general relativity theory. It is only connected with it under the condition of a definite interpretation. If the interpretation is altered in a certain way, this fact may be regarded as the empirical basis of a competing theory rather than of the general theory of relativity—e.g., the scalar-tensor theory of gravitation. Even if the equivalence of gravitational and inertial masses is given an interpretation which leads to the general relativity theory, it cannot be viewed as a sufficient basis for it. Neither the conclusion that gravitation is geometrical in nature nor the covariant equations of the gravitational field can be obtained from this fact. To obtain these conclusions, additional hypotheses of mathematical nature are needed. In particular, the deduction of gravitational equations requires that certain formal conditions be postulated: the four-dimensional quality of space-time, symmetry of the metric tensor, invariance of equations under the groups of continuous transformations.

The hypothetical-deductive scheme and the closely related principle of freedom of constructing the basic theoretical principles are not, in Einstein's view, the property of relativistic physics alone. The whole of physics from the very outset followed that scheme, and it is also characteristic of the development of modern physical thought.

The hypothetical-deductive method in the Einstein version is unacceptable for operationalism. This method assumes the possibility of global empirical substantiation of physical theory as a whole. According to Bridgman, however, the task consists in empirical verification of local elements of the theory—concepts and principles considered separately. Only this kind of analysis, he believes, can bring out the meaningfulness and empirical substantiation of a theory.

Bridgman's desire for determining the destiny of each proposition of a physical theory by separate empirical verification is untenable. The point is that physics always contains, along with concepts amenable to direct empirical interpretation, abstract theoretical constructs that are not directly linked with experience. Following the logic of operationalism, they would have to be excluded from physical theory. But the latter cannot exist and function without them, and such an elimination is therefore impossible.

In an attempt to find a way out of this logical *cul-de-sac*, Bridgman suggests an expanded interpretation of operations responsible for the content of physical theories by allowing not only instrumental but also mental operations: "It is often supposed that the operational criterion of meaning demands that the operations which give meaning to a physical concept *must* be instrumental operations. This is, I believe, palpably a mistaken point of view, for simple observation shows that physicists do profitably employ concepts the meaning of which is not to be found in the instrumental operations of the laboratory... All these non-instrumental operations we may loosely lump together as 'mental' operations" [2, p. 8]. Mental operations include, according to Bridgman, paper-and-pencil operations and verbal ones.

However, Bridgman's extension of the concept of operation does not solve the problem. On the one hand, since no clear boundaries or criteria of application of mental operations are indicated, some theoretical constructs are arbitrarily permitted (e.g., the wave function in quantum mechanics) while others rejected (e.g., the arbitrary coordinate system in the general relativity theory). On the other hand, despite the declared admissibility of mental operations, Bridgman comes in the final analysis to the conclusion that only real physical operations determine the content of concepts. This is clear from the following remark: "the operations which give meaning to our physical concepts should properly be physical operations, actually carried out" [4, p. 9].

A clear manifestation of Bridgman's empiricism is his negative attitude to idealised experiments. These experiments introduce, in his view, a speculative element in the solution of the problems of observables, which is unacceptable in physics. Idealised experiments must therefore be banished from physics and replaced by real, actually performed experiments, and the problem of observables must be reformulated to satisfy the conditions of the latter.

Bridgman connects idealised experiments with the work of Einstein, mostly with his general theory of relativity. Indeed, Einstein widely used the method of idealised experiments in the formulation of the general relativity theory, but this method is not characteristic of Einstein only. Its employment goes back to the beginning of physics as a science. Even the first law of mechanics, the law of inertia, could not have been established without idealised experiments [5, p. 8]. At present, idealised experiments are employed not only in relativistic physics but also in quantum mechanics and elementary particle physics. It is hard to imagine the development of physical cognition without them.

Idealised experiments in themselves do not introduce a speculative element in the solution of the problem of observables. On the contrary, they permit a more rigorous solution of this problem. It is on the basis of these experiments that the concept of *observability in principle* is introduced.

In physics, an object is recognised as observable if it is measurable. Observability is thus identical with measurability. In many cases, however, what is important is not the actual measurability but the possibility of measurement in principle. That means that we can ignore the technical difficulties of the procedure of measurement due to the imperfection of instruments and the influence of other phenomena on the measured magnitude. This kind of abstraction is realised in the transition from a real to an idealised experiment. That which may be measured under the conditions of an idealised experiment is called observable in principle.

Idealised experiments also make more precise the concept of objects unobservable in principle, which must be excluded from theory. Objects unobservable in principle are divided into two classes—abstract theoretical constructs that have a significance within science, and empirical objects. Theory forbids only those objects which are ascribed empirical status, not all objects unobservable in principle.

Now, what are the objects of the former type? These are apparently objects that cannot be registered even in an idealised experiment, let alone an actual one. The impossibility of discovering them is due to physical laws rather than technical difficulties. Idealised experiments thus permit an abstraction from all the technical details that interfere with the elucidation of the observability or non-observability of empirical objects in principle and with the formulation of the following clear-cut criterion of unobservability in principle: the admission of the reality of objects unobservable in principle contradicts the established physical principles and laws.

The solution of the problem of observables in the relativity theory, both special and general, does not make this theory a speculative scheme. On the contrary, relativistic physics, as distinct from classical physics, offered a rigorous empirical definition of spatio-temporal concepts. Thus the special relativity theory revealed the physical meaning of the concept of simultaneity of events occurring in different places, which was believed to be intuitively clear in classical physics and perceived in a purely speculative fashion. The general relativity theory implemented the transition from abstract geometry to physical geometry. Besides, the Einsteinian conception of observables permitted to exclude from physics fundamentally unobservable objects, such as Lorentz's ether.

The view is sometimes expressed that after formulating the special and general relativity theory Einstein's attitude to the problem of observables changed, and that he held the opinion that that problem was inessential for physics. Indeed, in a letter to the well-known English philosopher Karl Popper Einstein wrote that altogether he did not "at all like the now fashionable (*modische*) 'positivistic' tendency of clinging to what is observable" [6, p. 458]. Yet this statement could hardly be interpreted as a manifestation of Einstein's negative attitude to the principle of observability. Einstein did not at all reject the principle of observability as such but rather its positivist interpretation which identified that principle with reduction of theories to protocol sentences. As distinct from logical positivists, he believed that the empirically observable depends on theory. Heisenberg quotes the following words as expressing Einstein's view on this question: "whether you can observe a thing or not depends on the theory which you use. It is the theory which decides what can be observed" [7, p. 37]. The assertion of the dependence of the observable on theory does not eliminate, however, the principle of observability but merely explains it, revealing the nature of the observable in principle, which constitutes the essence of that principle.

Bridgman believed that the methodology of operationalism brought greater strictness to physics. This confidence stemmed from the fact that operationalism, removing arbitrary constructions from physics, ensured closer links between theory and experiment. In this case, greater strictness was not attained through impoverishment of the science. "I can see no reason [wrote Bridgman] why the operational method should have any inhibiting effect on any legitimate theorizing, and in so far as it has any effect at all, it can be only beneficial because it increases precision" [8, p. 32].

The real situation differs essentially from this appraisal. The requirement of operational definition of physical concepts under conditions of an actual experiment imposes serious limitations on physics as a science. Consistent implementation of this requirement can in general destroy physics as a theoretical science. That is why Bridgman did not insist on a full implementation of the operationalist programme. However, even where this programme is implemented only partially, it results in the exclusion from physics of a number of important problems and areas. Bridgman himself insisted, for instance, that a researcher would never be able to learn what is inside stars or what happened millions of years ago [8, p. 192]. Astrophysics and cosmology are, from this standpoint, a set of speculative hypotheses outside science.

We would have liked to point out the similarity between operationalist principles and mathematical intuitionism of Brouwer—a direction in the foundations of mathematics which emerged early in the 20th century. Brouwer and his followers believed that the cause of the crisis of classical mathematics manifested in the antinomies of Kantor's set theory, was the employment by mathematicians of constructively uncontrolled abstractions based on the concept of actual infinity. To overcome the crisis in mathematics and provide a more reliable basis for the latter, it was suggested to restrict mathematics to constructive objects only, that is, to those objects for which an algorithm of their construction can be indicated. The intuitionist revision of mathematics did indeed result in the removal of antinomies, but that was attained by essential impoverishment of the content of mathematics—by exclusion of a number of important branches.

Bridgman was apparently familiar with the programme of mathematical intuitionism. At any rate he mentions this trend and expresses an approval of it [4, p. 41]. One gets the impression that he set himself the task of carrying out the same kind of revision in physics as was carried out by intuitionists in mathematics. Just as the adherents of mathematical intuitionism, he sacrifices the wealth of content of scientific theories for the sake of their more rigorous substantiation that proves a mere phantom.

The principal object of operationalist revision are fragments of the empirically uninterpreted mathematical formalism of physics. Bridgman intended to free physics from mathematical "excesses", tying the mathematical apparatus down to the real empirical situation. Yet this methodological programme did not prove fruitful for physics.

Einstein's approach to mathematical formalism is different. He did not believe it expedient to introduce from the beginning the restrictions which Bridgman considered necessary. On the contrary he was in favour of free development of mathematical formalism in a more or less abstract form. This approach made it possible to use more fully the heuristic functions of mathematics in empirical sciences.

The fruitfulness of Einstein's method manifested itself not only in the very fact of formulating the equations of the general relativity theory but also in their subsequent development. These equations proved to possess a much richer content than Einstein himself had supposed, as illustrated by the following familiar fact. Originally Einstein believed that his equations permitted only static solutions. Proceeding from this assumption, he obtained a cosmological model whose spatial metric did not change with time. On this basis he drew the conclusion that a spatial structure with an immutable metric is the only possibility permitted by the theory. But this conclusion proved to be incorrect. In 1922 A.A. Friedmann found that not only static spatial structures but also structures with metrics varying with time satisfy Einstein's equations. Moreover, after Hubble's discovery of the red shift it was established that dynamic rather than static models describe the structure of the real world. Equations thus proved to be "cleverer" than their creator.

This example is not unique. Similar facts can be observed in other physical theories permitting a certain freedom from operationalist restrictions in the development of mathematical formalism. We could cite here Maxwell's purely mathematical anticipation of electromagnetic waves, Dirac's prediction of anti-particles, and a number of other facts.

It would appear that Bridgman's empiricist principles would lead to a more "realistic" interpretation of physics as a science. In accordance with these principles, physics was to be freed from abstract theoretical constructions, generalisations which go beyond the framework of experience, as well as any ideas which have no direct empirical substantiation. All of this would have certainly narrowed down physics, reducing it to the status of a mere phenomenological description, a kind of catalogue of facts. To make up for that, physics would retain absolutely "reliable" truths offering objective conceptions of the physical world. This type of revision of physics from empiricist positions is, generally speaking, logically permissible. But

Bridgman's empiricism does not contribute to greater objective value of physical knowledge but, on the contrary, introduces elements of subjectivism in their interpretation.

Two circumstances condition Bridgman's subjectivist interpretation of physical science.

The first is the operationalist interpretation of the content of physical concepts. As we earlier pointed out, Bridgman opposed the epistemological theory of concepts, according to which the latter have referents in the objective world. In his view, the content of concepts is determined by our operations on them rather than by the properties of things in the objective world. Concepts are in this case divorced from objects and are closed in themselves.

On the whole, one can understand Bridgman's motive for emphasising the role of the operational element in the formation of the content of concepts. He opposes the naive contemplative interpretation of the relation of physical knowledge to its object. That is clear from the following argument, for instance: " 'Property' is an invented concept, defined itself by the property that things have properties in and of themselves, independent of what we do or think. But it is always dangerous to define concepts by their properties, and in this case we have obviously attempted the impossible, for we have neglected to remember that 'property' must find its meaning in operations" [4, p. 43].

This passage combines Bridgman's dislike for naive contemplative interpretation of physical concepts and his subjectivism. We certainly cannot say anything about the properties of the physical world outside of operations, their actual measurement and theoretical description. These operations impose an imprint on the content of concepts. Bridgman is quite right in this respect. Moreover, he should be given credit for drawing the attention of physicists to the role of the operational element in the formation of the content of concepts. It would be a mistake to assert, however, that the properties of things are created by operations. The experimenter's instrumental operations do not create the properties of physical objects, they only facilitate their manifestation.

Second, Bridgman's subjectivism is also manifested in constant stress on the individual and personality-oriented element in scientific activity, in rejecting the general validity and social character of science. "There is no escaping the fact [he writes] that it is I who have the experiences that I am trying to coordinate into a physical theory, and that I must be the ultimate center of any account which I can give... It seems to me that to attempt to minimize this fact constitutes an almost wilful refusal to accept the obvious structure of experience" [4, p. 83].

In developing his conception of the individual quality of scientific activity, Bridgman comes to reject the fact that science studies objective laws which have general validity for all researchers. He criticises the standpoint of Einstein, who postulated the existence of general physical laws expressible in covariant form outside man's consciousness. "Perhaps the most sweeping characterization of Einstein's attitude of mind with regard to the general theory [writes Bridgman] is that he believes it possible to get away from the special point of view of the individual observer and sublimate it into something universal, 'public', and 'real'. I on the other hand would take the position that a detailed analysis of everything that we do in physics discloses the universal impossibility of getting away from the individual starting-point" [1, p. 349].

Physicists, who mostly accept the materialist view of the world, regard all these arguments by Bridgman as untenable. The value of science lies in providing objective knowledge of the world that is not reducible to the personal viewpoint, to the individual perceptions of individual scientists. The fact that Einstein emphasised this point shows the strength of his philosophical position rather than its weakness.

It would of course be incorrect to idealise Einstein's creative method, to insist that Einstein was always right. There is a one-sidedness in his method which prevented his evaluating correctly quantum mechanics. We know that he criticised the interpretation of quantum mechanics given by Heisenberg and Born. He did not accept the very method of cognition that asserted itself in quantum mechanics, according to which physical theory should describe the object in the form it takes in physical measurement rather than the object as such. Einstein believed that physical objects could be cognised more or less "speculatively", through construction of a corresponding mathematical model whose correctness could only be proved after the fact, by verification of the empirical consequences which follow from the theoretical description. However, Einstein's rationalism and his belief in the possibility of purely intellectual cognition of the microprocesses do not accord with the nature of quantum-mechanical cognition.

Despite this shortcoming, Einstein's views of the essence of physical cognition and of methods of empirical substantiation of physical theories are undoubtedly superior to Bridgman's operationalism.

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THE THEORY OF RELATIVITY AND SOVIET SCIENCE

(A Historico-Methodological Analysis)

By the time when the relativity theory emerged, Marxist philosophy had accumulated considerable experience in the methodological analysis of scientific theories. Engels's dialectical-materialist studies in the problem of correlation of space, time, and moving matter in *Anti-Dühring* and *Dialectics of Nature* are widely known. The dialectical-materialist investigation in the philosophical problems of developing natural science was continued by Lenin in *Materialism and Empirio-criticism* and *On the Significance of Militant Materialism*, where he analysed the revolution in physics at the turn of the century. Lenin's analysis of the scientific revolution served as the methodological basis for overcoming the difficulties which physical thought encountered in its progressive development.

Elaboration of the philosophical problems of the relativity theory from the standpoint of dialectical materialism went through several stages. Just as studies in all the other spheres, it was linked with complex socio-economic and ideological processes in this country. The nature of many discussions of the philosophical problems in the relativity theory cannot be fully understood outside this context. On the whole, the following stages can be singled out in the analysis of the philosophico-methodological problems of the relativity theory from the standpoint of philosophical materialism: (1) the 1920s—the years of search and considerable achievement (the works of A. F. Ioffe, A. A. Friedmann, Ya. I. Frenkel, V. K. Frederiks, S. Yu. Semkovsky and B. M. Gessen); (2) the 1930s—defence of the foundations of the relativity theory from metaphysically- and nihilistically-minded physicists and philosophers and further deepening of the philosophico-methodological problems (the works of S. I. Vavilov, A. F. Ioffe, S. F. Vasiliev); (3) the end of the 1940s and the first half of the 1950s—further elaboration of these problems in the works of M. E. Omelyanovsky and I. V. Kuznetsov and at the same time defence of the actual scientific-materialist content of the relativity theory (the works of V. A. Fok, A. D. Alexandrov, G. I. Naan, and others); (4) the first All-Union conference on the philosophical problems of natural science (1958) to the present time, when the studies in the philosophico-methodological problems of the relativity theory have reached the greatest depth and scope.

The present brief historico-methodological review lays particular stress on the first two stages singled out above, although we shall briefly dwell on the latter two as well. The justification for such an approach is that the discussions of the early 1950s were mostly concerned with critique of idealist interpretation of the relativity theory, while the studies of the last two decades require an independent all-sided and systematic analysis.

1. The First Stage (the 1920s)

The need to defend the scientific-materialist content of the new theory of space and time arose earlier than did the entire problem of the correlation of dialectical materialism and the relativity theory. This defence involved an analysis of separate important philosophico-methodological problems in the works of such leading physicists as Ioffe, Vavilov, Frenkel, Friedmann, and others. The properly philosophical aspects of the relativity theory were studied more deeply in the works of Semkovsky, Gessen, Vasiliev, and others. Let us analyse these works in the historico-methodological aspect.

Ioffe, the prominent Soviet physicist and one of the leading organisers of science in this country, always paid great attention to philosophical problems of natural science, defending the fruitfulness of the methodology of dialectical materialism in the study of the laws of the objective world. In characterising the changes that took place in physics since the beginning of the 20th century, he wrote in 1921: "Physics now goes through its heroic period each year brings a whole stream of new facts and ideas anticipating our boldest expectations... We all remember the physics of the 19th century with its immutable and continuous laws of nature expressed in the laws of thermodynamics and Maxwell's equations, and with the mechanical picture of the world built on matter and ether. Now we have physics in which nothing is impossible and all things are more or less probable, physics without ether. Once it was said that nature did not know leaps, now it is all the other way round: matter, electricity, and probability itself abound in discreteness" [1, p. 16]. The changes that took place in the structure of physical knowledge are essentially directed against common sense and the epistemology of phenomenologism: "in epistemology, the assertion of the reality of the atom and the electron destroys the good old peace concluded on the basis of phenomenology and permission to use working hypotheses... Physics also undermines the basis of common sense through its theories of relativity and quanta" [1, p. 17]. In physics, "the last bulwark of mechanistic worldview, ether, disappeared when it became clear that all bodies, on the one hand, do not carry it along in their motion and at the same time do not manifest their motion relative to ether. Devoid of all its concrete properties, ether was also deprived of reality in the relativity principle" [1, p. 19]. The reality of ether was rejected because of inobservability in principle of a state of matter which would have the mechanical properties ascribed to ether: "The impossibility of discovering the motion of the body relative to ether is a fact, and one of the most firmly established facts, at that" [1, p. 19]. Einstein's solution of the problem was that, rather than "multiplying entities" by inventing new properties for each given case, he "suggested that this fact [of impossibility in principle to discover ether experimentally—*K.D.*] should be taken as basic, and nature should be ascribed all those properties which follow from it" [1, p. 19].

Despite the unfortunate terminology, Ioffe correctly indicated the methodological advantage of Einstein's approach to the problem of ether: taking into account the negative result of numerous experiments intended to discover ether as well as more general contradictions between mechanics and electrodynamics, Einstein suggested that classical notions of space and time should be revised.

The radical changes in the foundations of physical knowledge resulted in a "shift in the physicists' psychology"; physicists "ceased to trust the so-called common sense, when it led into a *cul-de-sac* of contradictions" [1, p. 21]. The realisation of the limitations of common sense and of past experiences made physicists more "sensitive" to new ideas: "We are willing to test any theory if it illumines our path and eliminates obstructions... What we demand from a theory is correct prediction of experiments and absence of inner contradictions" [1, p. 21].

This interpretation of cognition relying on more general philosophical premises ("we believe that our world and our logic do not contradict each other, that an explanation of nature is possible" [1, p. 21]) was the methodological basis for evaluating the revolutionary upheaval in the structure of physical knowledge. Ioffe wrote that "this our only faith [the faith in the unity of the world and logic and the possibility of explaining nature—*K.D.*] came to no harm in the whirlwind of new ideas and facts" [1, p. 21]. New discoveries, however, are not indifferent to epistemological directions, for, having proved the correctness of the above-mentioned philosophical direction based on the recognition of the objective nature of the real world and its cognoscibility, new physics proved the anti-scientific nature of phenomenological empiricism and agnosticism: "Having broken away from the phenomenological pessimism, whose forebodings proved void, modern physics is full of faith in the reality of the world and its accessibility to our analysis" [1, p. 22].

Ioffe consistently defended the thesis of the fruitfulness of the dialectical-materialist approach to the world in his later works, too. In the article "The Continuous and the Atomic Structure of Matter" that was first published in the collection of articles *Karl Marx in Memoriam* on the occasion of the 50th anniversary of Marx's death, he wrote that "the history of the problem of the structure of matter is one of the most striking illustrations of the Marxist conception of science" [2, p. 22]. In comparing different periods in the development of science with the development of Marxist-Leninist philosophy, he stressed this point: "The time of Marx was the epoch of the theory of continuity, Lenin's time is the period of the triumph of atomism. The theory of Marx and Lenin, the philosophy of dialectical materialism, foresaw their inevitable synthesis that could not be predicted either by Boltzmann or Lorentz" [2. p. 26]. Ioffe saw the truth and scientific quality of dialectical materialism in its heuristic possibilities enabling it to predict the direction of the development of cognition. "A most certain feature of a correct theory is its ability to provide an integral and consistent picture of the already known and, moreover, to foresee correctly the future paths. For the philosophy of dialectical materialism, this feature is fully justified at every new stage in cognition, at every new phase of history. History fills the correctly formulated dialectical forms of development with continually changing new content and new traits" [2, p. 26].

The philosophico-methodological significance of Einstein's theory was also discussed in the first monograph published in Russian which studied the problems of the theory of relativity, written by Ya. I. Frenkel, an outstanding Soviet theoretical physicist. "From the methodological viewpoint [wrote Frenkel], the relativity principle may be regarded as the fountainhead of the basic physical laws that may be deduced from it in a purely speculative way. The radical transformation of the usual spatio-temporal conceptions, which is a most characteristic feature of the relativity theory, calls for as thorough a substantiation as possible" [3, pp. 3-4].

In Ya. I. Frenkel's view, the relativity theory "is an extremely remarkable and original interpretation of the entire ensemble of physical phenomena. Its originality lies in that, having established the impossibility of interpretation of all these phenomena within the framework of our usual conceptions of space and time, the theory of relativity transforms these conceptions, adapting, as it were, the logic to the facts rather than the facts to the logic" [3, p.

5]. This approach, proceeding from the very outset from the need to transform logic rather than adapting the facts to the logic, is essentially materialist. Analysing from these positions the philosophico-methodological content of the new theory, Frenkel suggested that two aspects should be distinguished in the relativity theory, namely the negative critical and the positive methodological one: "On the one hand, the relativity theory destroys the old dogma of the absolute meaning of such concepts as space, time, force, etc.; along with velocity, acceleration, and other magnitudes characterising motion, all other directly measurable electromechanic magnitudes (including distance and time intervals) become relative or, to be more precise, variable, depending on the standpoint of the observer and determined by his motion relative to the objects considered" [3, p. 6].

The relativity theory is not limited, however, to destruction of old concepts that have become classical. The negative critical work prepares the ground for asserting new, non-classical conceptions. The relativity theory, "proceeding from the principle that the laws of phenomena must be invariant correlations between variable magnitudes characterising these phenomena, and making use of the fact that these invariant correlations may be established, generally speaking, unambiguously, discovers in a purely speculative mathematical way all the laws of electromechanical phenomena... Therein lies the enormous methodological value of the relativity theory" [3, pp. 6-7].

Relying on this interpretation of the content of Einstein's basic principles, Frenkel opposed the raising of the variable to an absolute, which leads to philosophical relativism. In concluding the section on "The Logical Significance of the General Principle of Relativity of Motion", he wrote: "We would be fully justified to say that the relativity theory is at the same time the theory of the absolute—in the sense that it determines invariant or absolute physical laws" [3, p. 102].

Consistently opposing the retaining of the term ether in the physical vocabulary in any shape, manner or form, Frenkel wrote: "Lorentz's transformation of Maxwell's electromagnetic theory to make it conform to the actual existence and atomic structure of electrical substances, showed ether to be pure fiction" [3, p. 83]. Therefore "the essence of Lorentz's electrodynamics will remain absolutely unchanged if the quite meaningless ether concept (on which it is allegedly founded) is replaced by the just as meaningless but less vague concept of absolutely immovable coordinate system" [3, p. 33]. This interpretation of the status of Lorentz's ether, identifying it with the immovable empty space of Newton's mechanics, naturally led to the inevitable requirement of eliminating it from the structure of physical knowledge.

The struggle against ether as a universal mechanical medium was in those years topical both from the physical and philosophico-methodological standpoints. Although we are dealing here with an experimental science of nature, elimination of ether encounters not only problems of a purely physical nature but also the force of traditions and habits. It "proves to be unacceptable to persons brought up in the appropriate [classical–*K.D.*] traditions" [4, p. 136]. The latter leads to the search for ether based on old habits of thought that "have an extraordinary power over human minds. These habits are as often as not stronger than logic or even facts, interfering not only with correct interpretation but also with simple comprehension of the latter" [4, p. 145].

"In the field of physical science [wrote Frenkel in the article "The Mystique of World Ether"], the hotbed or focus of mysticism is, in our view, the concept of world ether. Even nowadays many scientists regard this concept as the foundation of the physical structure of the world" [4, p. 136]. For them, the role of this concept in the structure of physics is comparable "with the role of divinity in a religious conception of the universe" [4, p. 136]. "It may be said without exaggeration [Frenkel continues] that for the physicists and natural philosophers of the old school ether is what divinity is for believers. A comparison of the evolution of these concepts reveals striking similarities between them–similarities that sometimes border on identity" [4, p. 136].

Frenkel believed that ether in physics and divinity in theology were analogous not only in being a kind of unifying factor but also in their inaccessibility in principle for experiment, and also in the fact that they were both ascribed new properties when researchers came too closely to the dangerous border of empirically establishing their fictitious nature. However, the banishment of ether from physics is just as inevitable as the triumph of the materialist worldview rejecting the existence of any supernatural entities. "In both cases this evolution ends in a complete negation and elimination of ether on the one hand and divinity on the other" [4, p. 136].

Analysing the various historical stages in the development of the doctrine of ether (the ether of Huygens and of Fresnel, the ether of Faraday and Maxwell, Lorentz's ether), Frenkel shows the inevitability of eliminating the absolute, immovable, all-pervading mechanical world substance which lost all "physical meaning and along with it any right to further existence" [4, p. 145].

Frenkel opposed philosophical relativism which became widespread through a subjectivist interpretation of the new theory of space and time, and endeavoured to show the anti-scientific nature of the assertion that everything is relative. "One of the widely current prejudices connected with the relativity theory [he wrote] is the notion that everything is relative according to this theory. This notion is quite erroneous" [5, p. 148]. Einstein's theory certainly asserts that "many events and properties believed to be absolute are in actual fact relative; on the other hand, it destroys the old conceptions of the absolute only to replace them by new ones" [5, p. 148]. Stressing the concept of absoluteness rather than relativity therefore corresponds to the content of the new theory : "It would probably be more correct to call it the theory of absoluteness rather than the relativity theory" [5, p. 148]. This is how Frenkel substantiated this idea: the relativity theory "introduces relative magnitudes in order to construct with their help absolute magnitudes and to establish rules connecting these magnitudes—rules that are absolute and express physical laws" [5, p. 148].

Critique of philosophical relativism endeavouring to make its basis the relativisation of many classical concepts in the relativity theory, was an urgent philosophical worldview task. Credit should be given to Frenkel for consistently defending the thesis of the unity of the absolute and the relative in the relativity theory and for stressing the primacy of the absolute. "I would have liked to point out again [he wrote] what the principal significance of the relativity theory for physics consists in. What is essential here is not only the 'relativisation' of the concepts which we have considered absolute. Much more essential is the other aspect of the theory—the establishment of new absolute concepts, or invariant magnitudes and invariant correlations between the 'variable' magnitudes, for physical laws must be immutable or 'invariant' correlations correct regardless of the definition of the state of rest, that is regardless of the choice of a system of coordinates relative to which we consider various physical magnitudes" [5, p. 148].

Another prejudice which Frenkel criticised was the thesis that the "theory of relativity was entirely created by Einstein" [5, p. 148]. This assertion often led to underestimating the role of other physicists in preparing the new doctrine, and to opposing the relativity theory to classical mechanics. Pointing to the erroneous isolation of relativistic conceptions of the world from the preceding scientific thought, Frenkel wrote: "In actual fact it [the relativity theory—*K.D.*]. was prepared by the works of Newton. The concept of relativity of space was contained already in the works of Newton. Einstein generalised that concept, adding to it the relativity of time" [5, p. 148].

The problem of continuity of scientific knowledge which Frenkel here touches upon was at that time extremely topical because of the then current exaggeration of the novelty of relativist conceptions and underestimation of connections and correlations between the classical concepts of space and time and the interpretation of these categories in the relativity theory.

There are also interesting philosophico-methodological remarks in the works of A. A. Friedmann *The World as Space and Time* [6], V. K. Frederiks and A. A. Friedmann *Foundations of the Relativity Theory* [7], and S. I. Vavilov *Experimental Foundations of the Relativity Theory* [12].

Pointing out the indubitable philosophical significance of the relativity theory, Friedmann at the same time warned against exaggerating that significance. He stressed that it was erroneous to identify the world of the relativity theory with objective reality constituting the subject matter of a philosopher's cogitations: "The world whose schematic picture is created by the relativity theory is the natural scientist's world—it is an ensemble of only those objects that can be measured and numerically evaluated, therefore this world is infinitely narrower and smaller than the philosopher's world; if that is so, the significance of the relativity principle for philosophy must not of course be exaggerated" [6, p. 6]. However, "the other extreme view should not be drawn from this either, completely negating the significance of the world scheme suggested by the relativity principle for philosophy" [6, p. 6]. In Friedmann's opinion, "the titanic and bold scope of thought characterising the general concepts and ideas of the relativity principle concerning such objects as space and time (true, only measurable space and time) must indubitably produce a certain impression, exert a certain influence probably, on the development of the ideas of modern philosophers, who all too frequently stand too high above the 'measurable' universe of the natural scientist" [6, p. 6].

In analysing problems in arithmetisation of space, Friedmann indicated the error of identifying geometrical and physical space: "Physical material space may correspond to geometrical space in the sense that each thing of geometrical space may be correlated with some image from physical space... The relativity theory is also a grandiose interpretation of four-dimensional geometrical space which operates with extremely complex physical objects rather than simple ones" [6, p. 17]. He emphasised especially that "physical space is material space, and that all images of geometrical space are interpreted in physical space either by material objects or material actions with these objects" [6, p. 17].

These remarks concerning the importance of the distinction between the mathematical (geometrical) and the physical (meaningful), and particular emphasis on the geometrical spaces being interpreted in physical space over the set of actually existing material objects, show that already in the 1920s Friedmann paid great attention to the philosophico-methodological aspects of the problem, approaching them from materialist positions. For instance, in defending the basic materialist principles in the analysis of space metric, he wrote: "Concerning the problem of physical space, I believe it useful to draw attention to the fact that physical space as material space is in its very essence inconceivable without matter ... for in this space not a single thing from geometrical space could be interpreted or represented, as we have agreed to interpret the things of geometrical space by material objects in physical space" [6, p. 32].

Proceeding to the analysis of the problem "time and the world", Friedmann remarks that our concepts of space are much clearer than those of time, although the role of time in cognition and practice is very great, and conceptions of it are attributive in character [6, p. 49]. He discusses the specificity of stellar, gravitational, and light time, showing that the physical world should be considered in terms of the unity of space and time. The special relativity principle in his opinion realised this idea, "viewing for the first time a combination of space and time in the form of the physical world rather than space and time separately" [6, p. 65]. The doubts about the truth of the special theory of relativity were unjustified, for "the special relativity principle yielded a number of consequences whose interpretation in the physical world was subjected to experimental verification and stood the test superbly" [6, p. 65].

Friedmann also proves the untenability of the interpretation of space and time in the sense of the conception of time as a fourth coordinate of space and absolute identification of space and time. "A more careful consideration of the question will show [he writes] that the subsequent conclusion ["time is in no way different from other coordinates"—*K.D.*] cannot be regarded as quite correct, and that certain limitations must be imposed on the invariance postulate as well as on the modes of arithmetisation of the physical world, to restore the exclusive position of time" [6, p. 67]. In Friedmann's view, the need for solving this little-studied question is determined by its importance and fundamental nature: "The pretext for the restoration of the exclusive significance of time is the principle of causality, one of the requirements of which is that cause and effect cannot change places whatever the changes in the arithmetisation of the physical world" [6, p. 67].

In analysing the theoretical and experimental foundations of the general relativity theory, Friedmann commented on the error of enshrining the results attained: "There are several other experimental facts confirming the correctness of this hypothesis of gravitation and, consequently, of the correctness of Einstein's theory known as the general relativity principle. It should be noted, however, that the correctness mentioned here has only been confirmed very roughly; the relativity principle should not be regarded as something fully established; many details of Einstein's theory, particularly those pertaining to the establishment of world laws, may and certainly shall be modified both under the impact of new experimental facts and that of the continually perfected mathematical analysis" [6, p. 92].

Let us note that Friedmann did not merely emphasise the possibility of further development of the relativity theory—he also made a significant contribution to this development. In his studies he suggested a number of simplifying assumptions, arriving at the idea of a variable-type universe. A variable universe differs from a stationary one in that in the first case space curvature varies with time: "The second type of universe [a variable universe—*K.D.*] can be represented by a continually changing sphere—now expanding, now reducing its radius and contracting, as it were" [6, p. 100]. Proceeding from this hypothesis, which was brilliantly confirmed by Hubble's observations in 1927, Friedmann criticised the idea of finiteness of the universe.

Even this brief exposition of Friedmann's views shows that his approach to complex physical, mathematical, and cosmological problems was a materialist and dialectical one.

Philosophico-methodological problems were also discussed in the book by Frederiks and Friedmann *Foundations of the Relativity Theory* (first part, 1924), particularly in the Introduction. The authors express the opinion here that the questions raised by Einstein in the general relativity theory are of great significance. That is in the first place true of the problem of the nature of gravitation which once seemed incomprehensible. The theory of relativity, "in considering the question of gravitation, used instruments that went beyond anything that had been regarded, before its emergence, as applicable and meaningful in physics. In tune with its concepts of time and space, the new theory employed mathematical disciplines in a purely experimental science, which were connected with systems of geometries different from Euclidean geometry and previously regarded as almost the highest stage of abstraction from everything real and actually existing" [7, p. 6]. Thus the general relativity theory made an important step forward in changing the conception of the epistemological status of mathematical knowledge, which became an instrument in the cognition of directly inaccessible regions of the real world. This theory showed that geometrical constructions, earlier regarded as abstract entities without any relation to objective reality, had real content. Particularly interesting is the formulation of the problem of correlation of geometry and physics in the relativity theory. The latter took a new approach to this theory, demonstrating that "physics" does not exist without geometry. But geometry exists in physics insofar as physical things are given a non-geometric interpretation [7, p. 23].

Many critics of the new theory disagreed with its basic propositions and conclusions, believing that it was divorced from the practical needs of physical knowledge and overmathematised. At first sight, these objections were justified. First, the mathematical apparatus employed in the relativity theory (calculus of tensors, the theory of invariants, differential geometry, calculus of variations) is so abstract that its links with the real world are indeed problematic. Second (and this reproof is largely methodological in nature), Einstein's new theory is more complicated than Newton's old theory. Frederiks and Friedman analysed the arguments mentioned here and widely used by the antirelativistically-minded physicists and philosophers, showing them to be untenable. They noted in particular that "simplicity may sometimes be a seeming one, a purely external one, as for instance in the question of the inertial systems of classical mechanics" [7, p. 24].

It would be wrong to think that the methodological strength of the relativity theory lies only in its logic and elegance: just as any other physical theory, it must be first and foremost confirmed empirically. But in this respect, too, Einstein's theory is not inferior to classical physics, as it was empirically confirmed and, moreover, it explained some theretofore unexplained facts without resorting to *ad hoc* hypotheses, predicting also some new ones, which is heuristically very important: "The new theory, without any hypotheses for the nonce, has apparently explained one astronomical phenomenon (which was inexplicable before)—the too fast motion of Mercury's perihelion, and it also correctly predicted another phenomenon, never observed earlier and now discovered, the deviation of the light ray in a sufficiently strong gravitational field" [7, p. 24].

In the view of Frederiks and Friedmann, the gap between classical and relativistic mechanics on which various authors insist is also untenable: "Einstein's theory does not at all exclude classical mechanics; on the contrary, it formally includes the latter as a first approximation, generally speaking" [7, p. 24].

Not only absolute opposition of classical mechanics to the general relativity theory, but also the opposition of the special relativity theory to the general relativity theory, is not corroborated by the real facts: "The special relativity principle is not annihilated by the general one—it is only ascribed an appropriate area of application... Historically and logically it is the link between classical mechanics and Einstein's theory [the general relativity theory—*K.D.*]. Einstein and Newton do not oppose each other—Einstein continues Newton, as it were" [7, p. 24].

These quotations are evidence of the profoundly dialectical quality of the arguments of Frederiks and Friedmann; implicitly relying on the dialectics of absolute and relative truths and the principle of correspondence, they defended the unity of physical knowledge in general and of classical mechanics, the special and general relativity theory in particular. The philosophical value of this position is clear in the light of the approaches of various authors to the correlation of classical mechanics and the new stage in the development of physical knowledge at the time discussed here. The fact is that the triumph of the special and later (after 1919, when experiments by Eddington and his colleagues confirmed one of the predictions of Einstein's theory) the general relativity theory made the adherents of the new theory "forget" the correctness of classical mechanics in its own field, stressing the correctness of Einstein's ideas only and the errors of Newton's mechanics with its absolute motion, absolute time, etc. At the time of such all-out criticism of classical physics the dialectical thesis that Einstein and Newton were not opposed to each other was very valuable.

It is also interesting to note, in the light of modern methodological discussions, that Frederiks and Friedmann, while pointing to the "inclusion" of classical mechanics in the relativity theory as a first approximation, drew the attention, quite correctly, to the fact that this inclusion was to some extent formal, hinting at the incompatibility of these theories.

The works of Ioffe, Frenkel, Friedmann, and Frederiks treated the philosophico-methodological aspects in the framework of developing physical knowledge as a whole—they were not special studies in the problem. The first systematic analysis of the philosophical problems of Einstein's theory from the positions of dialectical materialism was undertaken by S. Yu. Semkovsky.

In the work *Dialectical Materialism and the Relativity Principle*[1] [8] published in 1926, Semkovsky endeavoured to prove, relying on the Marxist tradition of analysis of philosophical problems of natural science, that "the relativity theory marks a radical upheaval in the established views of the relation of space and time to matter in motion. It thus touches on the very basis of dialectical materialism" [8, p. 9]. He believed that the necessary condition for a genuine analysis of the problem was separating idealist schools trying to "exploit" the relativity principle "from the essence of Einstein's theory itself" which, in his view, "far from refuting dialectical materialism, is a brilliant confirmation of its correctness" [8, p. 11].

To prove this thesis, Semkovsky considers such problems, important from the physico-mathematical and philosophical aspects, as the content of the relativity prin-

[1] This work was first published in 1924 under the title *The Relativity Theory and Materialism.* The edition analysed here is a deeper and expanded discussion of the problem of interconnection between the relativity theory and dialectical materialism.

ciple, the correlation and meaning of relative and absolute motion, the law of causality in the light of the relativity theory, the physical and philosophical status of the absolute world, the question of ether, and finally, the experimental foundations of the relativity theory. Apart from these fundamental natural scientific problems, which undoubtedly have an important philosophico-methodological content, he undertakes a special analysis of the relation of various philosophical schools to the relativity theory, in particular the relation to it of Mach, Kant, and Hegel.

In the section analysing the relativity principle, Semkovsky shows that the postulate underlying this principle follows from experience, which proves that "there is nothing that would be in a state of absolute rest and that therefore there is no absolutely preferred coordinate system" [8, p. 27]. This principle is therefore within the ideological confines of dialectical materialism, "being in complete accord with the materialist dialectics which is the revolutionary focus of Marxism" [8, p. 27].

Semkovsky pays great attention to the dialectics of the absolute and the relative in the relativity theory. The explanation is that for many natural scientists and philosophers the most difficult conceptual point was the transition in the new theory from the relative to the absolute and objective. Semkovsky shows that "Einstein was no relativist in the philosophical sense, as many have regrettably endeavoured to prove either from a lack of understanding or for their own ends"; "taking relativity as his starting point, Einstein arrives at an extra-relative objective world which he himself calls an absolute world" [8, p. 40]. In the relativity theory, relativisation is linked with objectification, and that is quite naturally and logically incorporated in the general historical cognitive process. For "the exact sciences have continually evolved towards exclusion of the subjectivity of the cognising 'ego' (in old physics, for instance, optics was still connected with the perception of light, whereas in new physics it became a chapter of the science of electricity and magnetism)", while "Einstein's discovery is, in brief, that the concepts of space and time, as they were traditionally established in mechanics since Newton, are still tied to the subjectivity of the perceiving 'ego' and must be still more objectified" [8, p. 40]. The relativity principle thus only confirms the materialist notion that "the world of nature exists independently of the process of cognition" [8, p. 40].

The conclusion that the relativity theory is based on the dialectics of the absolute and the relative, which leads to the objective, is specially substantiated in the section on "The Absolute World" against a broad scientific (Newton, Helmholtz, Lobachevsky, Riemann, Gauß) and historico-philosophical (Lucretius, Diderot, Lafargue, Karl Marx, Friedrich Engels) background, including also the latest works of Minkowski, Einstein, and Friedmann. Relativistic mechanics discovers laws which do not depend on the observer's relative viewpoint. In Semkovsky's opinion, the new world picture is materialistically more concrete than the old Newtonian world scheme of abstract materialism. Newton viewed space, time and matter as three separate self-sufficient essences. Newton's space and time did not depend on variously moving matter, retaining their invariance and homogeneity. The theory of relativity, however, showed that the structure of space and the flow of time are not at all invariantly homogeneous, changing with gravitational fields. Thus the relativity theory inseparably "linked space and time with matter. It confirmed the truth of materialism, presenting space and time as forms of the existence of matter in motion" [8, p. 82].

Analysing the methodological aspects of the relativistic approach to the status of the absolute, the relative and the objective, Semkovsky proves that "the objectivity of motion in space and time, that is, the fact that motion takes place outside and independently from the subject's consciousness, is recognised by both Einstein and Newton. Yet the basic difference between them is that Newton builds his system on absolute motion, and Einstein, on relative motion" [8, p. 82]. Einstein's main idea that "from the physical viewpoint there is no 'preferred' (favoured) state of motion", is ideologically in line with the concept of relativity of motion which follows from the basic propositions of dialectical materialism. Therefore "the argument between Newton and Einstein, between absolute and relative motion, is not at all about objectivity. According to Einstein, space exists just as objectively, that is, outside and independently of our consciousness, as according to Newton; Einstein speaks of various 'observers', but such 'observers' may be physical devices objectively recording data, and the structure of space is not at all determined, according to Einstein, by the properties of the subject's cognitive apparatus but rather by the properties of the objective world—moving material masses" [8, p. 88]. The development of the relativity theory continues the mainline in the development of cognition, for "the inner development of the Copernican idea leads to the recognition of relativity of motion", while Einstein's theory, "taking to the logical conclusion the critique of geocentric absoluteness and immobility begun by Copernicus, quite consciously and with a clear realisation of the previously traversed path chooses relative motion as its basis constructing on it a materialist system of the world" [8, p. 101].

Semkovsky's work for the first time considered the specificity of the relativistic solution of the problem of causality. In the section on "The Relativity Theory and the Law of Causality" the author showed that "the law of causality, far from being rejected by the theory [of relativity—*K.D.*], is implemented in it even more rigorously, as it eliminates the basically mystic conception of extratemporal, momentaneous nature of causal action" [8, p. 75]. He noted correctly that in its foundations the relativity theory is not directed against causality in its classical formulation but rather deepens the perception of the problem through the postulate of the speed of light propagation being finite.

In this connection Semkovsky points to the untenability of the critique of the relativity theory for allegedly positing a metaphysical absolute in the form of the postulate that light velocity is the greatest velocity possible: "Einstein believes that light velocity, which is at the same time the velocity of electromagnetic processes in general, is the greatest possible velocity among all the processes existing in the world. In this case the fact that *c* is the limiting case does not at all signify the establishment of some metaphysical absolute but rather the recognition of the physical fact which follows from the material unity of the world" [8, p. 80].

The elucidation of the philosophico-methodological content of the new theory led researchers to the question of relations between the relativity theory and various philosophical schools. Particularly topical were the themes "Kant and Einstein", "Machism and the Relativity Theory", and, in the context of the relations between dialectical conceptions of space and time and the relativity theory, the theme "Hegel and Einstein". In discussing them, Semkovsky considered a set of problems involved in the relations between the relativity theory and the leading philosophical schools of the West, showing their ideological incompatibility.

Discussing, in particular, the relations between Machism and the relativity theory, Semkovsky asserted that the philosophical inclinations of the founder of the new theory of space and time should not be confused with the immediate content of the relativity theory: "Three questions should be distinguished: (1) Einstein's personal philosophical likes and dislikes, which are by no means necessary for substantiating the relativity theory; (2) the historical influence of Mach's *Mechanics* on the elaboration of Einstein's relativity theory; (3) the substance of the relations between the relativity theory and Machist philosophy (empirio-criticism)" [8, p. 122]. In Semkovsky's opinion, "the relativity theory is decidedly in conflict with 'Machism', for it is founded on matter rather than 'sensation elements'" [8, p. 122].

Semkovsky completes the analysis of the basic propositions of Einstein's theory that have some philosophico-methodological significance, with a thorough study of the problem of ether and experimental substantiation of the relativity theory. In his view, "dialectical materialism cannot link its destiny with the problematic destiny of ether" [8, p. 121], for the question of ether is connected with the relativity theory only from the point of view of "the ability of ether to take the place of Newton's 'absolute space' as an absolutely favoured coordinate system rejected by the relativity theory" [8, p. 173].

As far as the problem of experimental substantiation of the relativity theory is concerned, Semkovsky shows the untenability of the attempts of the critics of this theory to prove its alienation (due to lack of experimental substantiation) from science. He considers the latest experiments of D. C. Miller, which were taken as proofs of the existence of mechanical ether, showing the problematic and debatable character of the interpretation of their results.

In 1925, Engels's *Dialectics of Nature* was published in Russian for the first time. It immediately became the focus of attention of philosophers and scientists. In the section "The Controversy about the Relativity Principle in the Light of *Dialectics of Nature*" Semkovsky analysed the basic ideas of the relativity theory with reference to the ideas of Engels. "Needless to say [he wrote], Engels could not refer to Einstein's theory as such. It is all the more striking that Engels, in outlining in the fragments of his *Naturdialektik* the main features of the dialectical-materialist philosophy of natural science, from the methodological standpoint came very close to those points out of which the principle of relativity later developed" [8, p. 202]. The conclusion, thoroughly substantiated by Semkovsky, is this: "the relativity theory does not refute dialectical materialism for the simple reason that, despite the attempts at interpreting it in the spirit of idealism, Machism and relativism, it is basically materialist, and dialectical materialism is confirmed by it in a truly remarkable fashion, just as it is confirmed by all materialist science" [8, p. 201].

The philosophico-methodological analysis of the theory of relativity given by Semkovsky shows the heuristic possibilities of materialist dialectics, which made it possible to grasp the essence of the new ideas already at the time of the initial formation of relativistic mechanics. This analysis was important not only for revealing the philosophical significance of these ideas but also for opposing their idealist interpretations. The results obtained by Semkovsky were also important for the struggle against the metaphysical and nihilistic attitude to the relativity theory on the part of some natural scientists and philosophers who questioned not only the philosophical but also, in fact, the physical significance of the relativity theory (see [11]).

The study of the philosophico-methodological status of the relativity theory continued. In 1928 B. M. Gessen's work *The Basic Ideas of the Relativity Theory* [9] appeared, which considered the little-studied logico-epistemological and philosophico-methodological problems of the relativity theory. In the same year 1928 S. I. Vavilov's monograph [12] was published, the first work in Russian devoted to experimental foundations of the relativity theory; it touched on interesting methodological questions.

Gessen's book considered philosophically the most significant results of the special and general relativity theory, with particular emphasis on the fundamental methodological aspect of the problem. His contribution to its solution was mentioned by O. Yu. Schmidt in his report at the Second conference of Marxist-Leninist scientific institutions in 1929. Pointing to the works where for the first time the materialist analysis of the relativity theory was given, Schmidt said: "Of greatest interest in this respect was the book by Semkovsky—one of the first attempts in this field.[2] Recently Gessen, approaching the matter from a different side, also revealed the materialist kernel of the relativity theory. This question may now be regarded more or less solved. In the relativity theory elements of dialectics are more obvious than in any other modern theory" [10, p. 9].

Gessen believed that "any fundamental physical theory involving our basic views of nature always has a methodological substratum" [9, p. 5]. Starting from this premise, he set the task of "establishing the methodological conceptions underlying the physical and methodological constructions [of the theory of relativity—*K.D.*]" [9, p. 5]. Gessen deemed it necessary to warn against two approaches, both of them methodologically erroneous, in the analysis of the philosophical content, methodological foundations, and consequences of the relativity theory: (1) the identification of the new theory of space, time and gravitation with its numerous idealist interpretations; (2) exaggeration of the worldview significance of the relativity theory, which leads to the interpretation of this theory as a philosophical

2 Apparently S. Yu. Semkovsky's work *Dialectical Materialism and the Relativity Principle* [8] is meant here.

system.

In analysing the materialist content of the new theory of space, time and gravitation, Gessen relied on Marx's thesis of the active character of the cognising subject, criticising the contemplative approach to cognition. Proceeding from the first thesis of Marx on Feuerbach, he proved the following propositions: "Recognition of the objective nature of the world in the sense of its existence independently from us is a materialist premise, but it must not be interpreted in the sense that genuine materialism consists in the elimination of the subject in principle. That is not so", for "the difference of any other type of materialism from dialectical materialism is precisely this metaphysical raising of the objective to an absolute. That is why Marx in his first thesis on Feuerbach points out that the active (subjective) side of cognition was developed by idealism. But it was developed in an abstract fashion, too, which led to the elevating of the subject to an absolute" [9, p. 107].

Dialectical-materialist critique of the classical conceptions of space and time proceeds from the assumption that "Newton's conception is a metaphysical one", and that "Newton's conception is unsatisfactory and undialectical in that it *objectifies* the abstract concepts of space and time ascribing to them independent, separate, real existence", forgetting that space and time are forms of the existence of matter, and that "there is no space by itself and pure duration by itself into which matter is introduced from the outside" [9, p. 60]. Critique of the Newtonian conception of space and time from the dialectical viewpoint, begun by Hegel and continued by Marx and especially by Engels, was scientific in nature and philosophically anticipated the new ideas.

Critical analysis of Newton's conception of space and time leads Gessen to the conclusion that "space and time do not exist outside matter but rather in matter; matter is their genuine reality, their objective synthesis" [9, p. 64]. The unfortunate use of the term "synthesis" to describe the new relationship between space, time, and moving matter in Einstein's theory, later, at the time when the mistakes of Deborin's school in various areas of philosophical knowledge were criticised, led to a negative evaluation of the views expressed in the book *The Basic Ideas of the Relativity Theory*. Yet this usage, as it is easy to see from the previous analysis, was not of conceptual nature. Gessen made a significant contribution, particularly significant for his time, to the study of the actual philosophical content of the relativity theory, to the defence of this theory from its nihilist mechanist rejection by some physicists and philosophers [11].

The emergence of the relativity theory and the difficulties involved in elucidating its genuine physical content as well as philosophical conclusions, resulted in a revival of various idealist philosophical schools, particularly those of philosophical relativism. Criticising the attempts to use relativist mechanics for developing idealism, Gessen remarks that "the views of the dialectical materialism of the correlation between absolute and relative truths differ radically from the views of many adherents of the relativity theory who posit the relativity of our knowledge as a general principle of cognition and thereby negate the possibility of unlimited approximation to absolute knowledge" [9, p. 67]. Relying on the thesis that the spatial and temporal characteristics depend on the state of the system in which measurements are made, he tackles, in the chapter on "Philosophical and Physical Relativism", the question of whether this relativity of our knowledge is in principle insuperable or whether there is a possibility of eliminating the influence of the observer's state, thereby taking a step towards absolute cognition of nature. He solves this question in the framework of the dialectical-materialist approach to the correlation of absolute and relative knowledge, showing that, although "the form of perception of objective reality undoubtedly depends not only on the state of the perceived object of the external world but also on the structure and state of the perceiving subject", and although "we arrive at the cognition of the object only through the subject", our knowledge does not for this reason become "purely subjective cognition" [9, p. 105]. The thesis that "the subject is a necessary condition of cognition" does not entail the conclusion that "the entire content of our knowledge is subjective" [9, p. 106]. Our cognition, "being expressed in the forms of the cognising subject, possesses objective content, which is a genuine reflection of the properties of external reality" [9, p. 106]. This general philosophical position enables Gessen to criticise the principles of philosophical relativism, which views the subject "not only as a condition of cognition but also as an insuperable barrier on the road to absolute knowledge" [9, p. 106].

It is a well-known fact that at the first stage in the development of the relativity theory its experimental basis was not great as compared to that of classical mechanics. This situation, rather rare in science, was exploited by the opponents of the relativity theory, who endeavoured to prove that science did not need such "strange" and not easily visualised concepts as the four-dimensional world, curved (non-Euclidean) space, relativity of simultaneity, etc. Gessen objected to these reproofs, pointing to the advantages of the relativity theory over classical mechanics on the physical plane, too, "for classical physics does not provide a correct result for all the phenomena that are fully explicable in terms of the relativity theory", since "classical physics explained the qualitative aspects of the phenomena but in most cases failed to provide a precise quantitative coincidence, where the relativity theory offers quite a satisfactory coincidence" [9, pp. 170-171]. Another argument in favour of the relativity theory was, in his view, the methodological advantages of the new mechanics. "In explaining a number of phenomena from the classical standpoint [he wrote], one has to formulate *ad hoc* assumptions, whereas in the relativity theory explanation and interpretation of the same phenomena follows as a consequence from the general propositions of the theory" [9, p. 171]. Another proof of the truth of the new theory is the fact that "the relativity theory includes classical Newtonian mechanics as a limiting case" [9, p. 183].

Thus already at the first stage of philosophical interpretation of the relativity theory, a number of important philosophico-methodological problems were formulated and partially solved on the basis of the classical principles of the analysis of the data of natural-scientific knowledge.

2. The Second Stage (the 1930s)

In analysing the experimental foundations of the relativity theory, S. I. Vavilov expressed interesting methodological ideas about the structure of theory, correlation of theory and experience in physical cognition, and the role of mathematical abstractions and physical concepts in relativistic physics. He wrote, among other things, the following: "A great advantage of the relativity theory is precision and clarity of its structure. It is based on generalised experimental facts that at first sight contradict one another. Mathematical elimination of this contradiction necessarily leads to changes in the physical concepts of space and time and to a number of consequences accessible to experimental verification. If the postulates and consequences are experimentally confirmed, and the intermediate calculations are correct and not arbitrary, the equations of the theory are unquestionable for the natural scientists" [12, p. 9]. At that time it was necessary to stress the fact that the postulates underlying the new theory are experimental in nature, for one of the most debatable problems then was experimental substantiation of the basic postulates of the theory. Vavilov believed that before the relativity theory, physicists had dealt with imaginary space, for Newton's absolute space was inaccessible to experimental study. The superiority of the new theory in the physical and methodological aspects seemed to him to be indubitable, as "Democritus's empty Euclidean space and unknowable ether were replaced by the complex but physically accessible space-time of Einstein" [12, p. 13]. In Vavilov's view, the methodology of the relativity theory is based on the method of Newton's *Principia.* The relativity theory has the same structure as Newton's theory of gravitation and the theories of the electromagnetic field and electrodynamics: "At the beginning of the theory are generalised facts—the axioms, the theory itself is a number of consequences from these axioms and at the end are facts again, old or new ones" [12, p. 15].

In the article "Physics" written for the *Great Soviet Encyclopedia,* S. I. Vavilov, drawing on the developments in the relativity theory and quantum physics, showed the changed role of mathematics in the insights into the new and directly inaccessible levels of reality. He studied the way in which "mathematics plays a heuristic role as a means of finding new physical laws in a purely logical fashion", and he also showed that mathematics "not only makes the reasoning more rigorous but also points the direction of experimental search" [13, p. 51]. Vavilov was thus one of the first to indicate, on the basis of analysing the movement of knowledge to new results in the regions of great velocities and small masses, the qualitatively new role of the mathematical apparatus, revealing the heuristic possibilities of mathematical hypotheses.

The methodological status of mathematical hypotheses was also considered by Vavilov in the article "Old and New Physics", published in the book *Karl Marx in Memoriam. A Collection of Articles on the Fiftieth Anniversary of His Death. 1883-1923* (Leningrad, 1933). Vavilov thus explained the content of the new methodological principle: "The new method may be called a mathematical hypothesis or the method of mathematical extrapolation. Its essence consists in the generalisation of partial empirical mathematical correlations, in the search for mathematical forms which, including all separate cases found directly in experience, would simultaneously provide a much richer content" [14, p. 11].

In Vavilov's opinion, the essence of the new stage in the development of physical knowledge cannot be understood without grasping the nature of employing mathematical apparatus in cognition, for, beginning with Maxwell, "mathematics assumed an incomparably greater significance for the physicist than in classical physics. Formerly an auxiliary instrument for quantitative calculation and formulation, mathematics became a heuristic method enabling the theoretician to anticipate experiments, indicating fundamentally new experimental facts" [14, p. 11]. In his view, "the development of the relativity theory and quantum mechanics are striking examples of the power of the method of mathematical extrapolation. Deprived of concrete images and models in the world of new dimensions, the physicist found in mathematics an unlimitedly powerful method for formulating a new theory" [14, pp. 11-12]. Further development of science confirmed

Vavilov's methodological prediction that, on the basis of mathematical hypotheses, physics "may develop unlimitedly, relying on experience and mathematical thinking" [14, p. 12].

A shrewd thinker, Vavilov understood that it would be erroneous to raise the method of mathematical hypothesis to an absolute. He indicated that mathematical extrapolation could be unjustified, too, for insights into a qualitatively different structural level of reality, which has no analogue in the macroworld, inevitably involve a certain measure of risk that mistakes will be made. Therefore in new physics, too, the final word is with experiment. "The physicist is of course often mistaken [wrote Vavilov], choosing the wrong path in the limitless sea of possible mathematical forms", but the result and direction of search are "set right by experiment", for "the only justification of the correctness of a selected mathematical form is its subsequent confirmation by experiment" [14, p. p. 11-12].

Methodological problems of the relativity theory were also discussed in L. I. Mandelshtam's lectures on the physical foundations of the relativity theory delivered in the years 1933-1934 and published for the first time in the 1950s. Mandelshtam considered the history of various problems in the origin of the relativity theory, combining this study with a very fine epistemological analysis of the scientist's operations and basic concepts. Mandelshtam stressed the experimentally verified, rather than speculative, nature of the relativity theory, which is the only way out of the difficulties of classical physics: "The relativity theory is a physical theory. This theory was formulated to embrace a greater class of physical phenomena which (and this should be stated quite definitely) for a long time consistently refused to be squeezed into the framework of existing views" [15, p. 83]. The methodological advantage of the new theory consists first of all in that it is based on meaningful and physically definite concepts (as distinct from classical mechanics), for many concepts with which classical physics operated were either vaguely defined or not defined at all: "The apparently simplest and most elementary concepts were not clear" [15, p. 85].

Having analysed the specificity of employing concepts describing spatio-temporal relations in physics, as well as the experiments intended to determine the effect of ether, etc. Mandelshtam showed the inevitability of the conclusions of the relativity theory, despite their seeming paradoxicalness from the classical standpoint. The new theory did not result in a more complex structure of physical knowledge. Moreover, it significantly simplified the latter and served as the nucleus of a new world picture. The removal of Galilean transformations, introduced into physical theory dogmatically, resulted in a solution of the contradictions involved in the attempt to give up other basic physical propositions—the relativity principle and the principle of constancy of light velocity. The way out of the difficulties suggested by Einstein was thus justified both physically and methodologically.

Mandelshtam paid particularly great attention to the analysis of the epistemological status of measurement procedures and definition of concepts. His arguments, not always aptly expressed, caused a discussion of his philosophical position in the 1950s. Some scholars accused Mandelshtam of operationalism, which was not at all true, for he had never negated the objective nature of concepts studied with the help of operations. He attempted to discern between some fine epistemological shadings which were not noticed by other researchers. In his opinion, "a number of concepts are defined for cognising nature, they are not cognised" [15, p. 167], and in physics "a bridge should be built between the concepts with which mathematics works and the real objects" [15, p. 169]. To achieve this, we must define the basic physical concepts. The difficulty lies in the possibility of different definitions due to the differences in the standards and procedures of measurement. Recognising some elements of conventionality in definitions does not entail conventionalism, however, for these conventions do not determine the entire epistemological system. At the same time the measurement procedures, however important they may be, do not create the lengths and durations being measured, in Mandelshtam's theory. Fok was quite right therefore when he defended the materialist character of Mandelshtam's epistemological principles in the 1950s controversy.

The philosophico-methodological problems of the relativity theory were also discussed in the debate that centred on V. F. Mitkevich's book *The Principal Physical Views.* Ioffe, Vavilov and other scientists opposed the attempt of Mitkevich to take physics back to the positions of classical physics in the spirit of Maxwell and Faraday. The arguments of the critics of the relativity theory and quantum physics found no support in the articles and speeches of most scientists.

Vavilov thus defended the relativity theory: "Einstein should be given full credit for proving, not merely indicating, that our space is living physical space (whose properties are conditioned by matter, in its turn affected by space), genuine moving matter, whose geometrical properties are continually changing–they do not remain abstractly permanent, as in the static receptacle of Newton and Mitkevich" [16, p. 60]. The development of science, in Vavilov's opinion, showed the absence of an objective counterpart of Newton's absolute space. Absolute space, performing "the honourable but meaningless role of a favoured coordinate system", was invariably and absolutely inaccessible to studies by physical means; but "a materialist cannot consent to the possibility of existence of something inaccessible to any influences, something absolutely immovable and having no properties other than being a 'receptacle' for ether or anything else" [16, p. 60]. The physical and methodological superiority of the relativity theory is indubitable, for "Einstein's physical space eliminated Newton's difficulty, replacing formal action at a distance by short-range interaction" [16, p. 60].

The idea of the dialectical-materialist nature of relativistic spatio-temporal conceptions was also defended by Vavilov in the article "New Physics and Dialectical Materialism" published on the occasion of the 30th anniversary of Lenin's book *Materialism and Empirio-criticism.* In Vavilov's opinion, "the recent decades fully revealed the limitations of the metaphysical, mechanist materialism in physics, the materialism of Newton, Kelvin, and others" [17, p. 28]. The limitations of metaphysical-mechanist methodology were manifested first of all in the fact that "to explain the atomic structure, it was impossible to apply the classical laws of mechanics on the basis of which the physics of large bodies and small velocities has been built with enormous success since Newton's times" [17, p. 30]. Einstein's teaching is more dialectic in nature, for it sets in motion the basic concepts of physics, considering in their interconnections those properties and relations which had formerly been considered in isolation from each other: "In Einstein's theory space-time is an inalienable property of matter itself; it depends on matter, changes with matter, and does not exist without matter. We know of no space outside matter, outside material force fields. That is the principal idea of Einstein's general relativity theory, which was also given concrete physical forms" [17, p. 30].

Vavilov's position was supported by A. F. Ioffe.

In his analysis of the main arguments of Mitkevich against the new theory of space and time Ioffe wrote that "in the Michelson experiment the idea of immovable ether was defeated after the rejection of the conception of ether being carried along by a moving body. Einstein found a way out of these contradictions in his relativity theory: in the process, ether was sent to the same wastepaper-basket of history where earlier phlogiston (heat liquid), magnetic liquids, and other naive mechanist fictions had gone. The relativity theory showed how various physical magnitudes could be measured in a moving system and how the laws change in a system moving relative to the observer" [18, pp. 131-132]. In Ioffe's view, the struggle against the relativity theory dragged physical theory backwards, for the attainments of the new theory were demonstrated in practice in the same way as the conservation law: "... in 1905 Einstein headed a whole revolution in physics by formulating the relativity theory, the theory of light quanta and the theory of Brownian motion. Of these, the relativity theory met with a particularly fierce opposition. Some physicists could not reconcile themselves to the conceptual re-structuring inevitably involved in a consistent relativity theory. Its experimental verification and further application to atomic physics phenomena made it just as firmly established a principle of modern physics as the law of conservation of energy" [18, p. 134].

A number of interesting and little-studied methodological aspects of the relativity theory were considered in the mid 1930s in the works of S. F. Vasiliev.

His article "On the Problem of Observability in Principle" was the first work in which the methodological status of the principle of observability was philosophically analysed. Here Vasiliev studied its role in the emergence and interpretation of the relativity theory. In his opinion, the insistence that magnitudes unobservable in principle should be excluded from physics was quite justified. What was unscientific was merely its subjectivist interpretation: "This step ('exclusion of magnitudes unobservable in principle') was later subjectivistically interpreted as ... the programme of limiting oneself to the observable only. Einstein was presented as a Machist, although there was nothing that opposed the letter and spirit of Mach more than the invariant formulas of the relativity theory" [19, p. 10].

Vasiliev was also one of the first to study the methodological status of the principle of correspondence in scientific knowledge. In his critical analysis of Emile Meyerson theory of science he showed the continuity in the development of scientific theories: "A subsequent theory does not simply destroy the previous one but 'sublates' it, that is, conserves some elements of its content without changes. Relativistic mechanics did not eliminate Newtonian mechanics, it only showed the boundaries of its application" [20, p. 66].

In the article "On Some Features of the Evolution of Scientific Theories (On the 40th Anniversary of F. Engels's Death)" Vasiliev made a more thorough study of the correspondence principle, taking into account the urgency of the problem of correlation of classical and non-classical conceptions. He thus explained the motives of his analysis: "the relativity theory is often presented as a theory which hit classical physics the first mortal blow, and was the first to show complete untenability of the old conceptions of the structure of the physical world" [21, p. 9]. Vasiliev did not reject the specificity of the new theory and its difference from classical physics, but at the same time he correctly drew attention to the unity and integral nature of knowledge and the relative character of negation: "We are not going to question the fact that the relativity theory did indeed signify a radical upheaval in the classical conceptions, we are compelled to insist, however, that the blow struck by the relativity theory on classical physics did not at all destroy completely the classical laws, at least as far as the special laws rather than the general methodological constructions of the latter are concerned" [21, p. 9]. The assertion of complete destruction of classical mechanics is false because "classical mechanics, for instance, was not simply destroyed by the relativity theory but only limited" by it, for, "revealing the limitations of classical mechanics, the relativity theory nevertheless retained the significance of this mechanics for a certain area of phenomena" [21, p. 9]. The truth of the laws of classical mechanics was proved by numerous practical and experimental examples. There exists therefore an area which corresponds to the true part of this theory. The mistake lies in the raising to an absolute and a universal of laws that have a limited sphere of application.

The general relativity theory, which emerged later as a generalisation of the special relativity theory, despite its fundamental differences from the previous theoretical schemes (classical mechanics and the special relativity theory), is subject to the correspondence principle in the same degree, for, "just as classical mechanics is a particular case of the special theory or its first approximation, the special theory is in its turn a particular case of the general onc. The general theory becomes the special theory wherever the gravitational field may be regarded as homogeneous and so weak that it may be ignored" [21, p. 15]. The same law is observed in the mathematical correlations underlying the special and general theory of relativity: "The equations of motion of the special relativity theory are constructed in such a way that for small speeds they become practically equivalent to the equations of the usual classical mechanics. The situation is quite similar in the case of the equations of the general relativity theory, which become the equations of the special theory in the presence of homogeneous gravitational fields and for relatively small regions of space" [21, p. 15]. We can thus assert the existence of "continuous links between classical mechanics, the special relativity theory, and the general relativity theory"; their development did not take "the form of simple rejection of the content of the previous theory by the subsequent one but that of limitations imposed on the significance of the former and its further generalisation" [21, p. 17].

This interpretation of the mechanism of development of physical knowledge, based on a recognition of the dialectical structure of reality which includes a unity of evolution and revolution, enabled Vasiliev to refute philosophical relativism in a convincing manner. An analysis of the development of physics led him to the conclusion that "the history of development of scientific thought, reflected in the formulation of the relativity theory, cannot by any means be used as a source of arguments in favour of philosophical relativism" [21, p. 17]. On the contrary, a study of the formation of the basic ideas of the relativity theory convincingly confirms the truth of the dialectical approach to the developing knowledge. In the course of the development of the relativity theory, the approximate but nevertheless objective nature of previous knowledge was shown clearly at every subsequent stage of this development. "Gradual approximation of an increasingly more complete and all-sided reflection of the natural course of the objective world was here revealed with striking clarity and convincingness" [21, p. 15].

Having thus analysed the dialectics of the correlation of classical and relativistic mechanics, of the special and general relativity theory, and later of classical and quantum mechanics, Vasiliev showed that the development of physical knowledge was in accord with dialectics in general and its theory of truth in particular. "The truth of the previous stage in the development of scientific thought [he correctly concluded] is not destroyed by the latest results but conserved and raised to a higher level. The development of physical theories may and must be represented as progressive development of the truth. Herein is revealed the real dialectics of the cognitive process" [21, p. 18].

However, apart from declaring the unity of knowledge and the unity of continuity and discreteness, dialectics, proceeding from the fundamental thesis of the unity of the world, also includes recognition of the irreducibility in principle of qualitatively different levels of reality. Doesn't the above interpretation of the correspondence principle contradict this proposition?

In discussing this problem, Vasiliev showed that the properly evolutionary character of the development of knowledge is in evidence only if a phenomenological approach to the problem is taken, in those cases where we are compelled to restrict ourselves to "mere phenomenological comparison of laws formulated by the three theories analysed here [classical mechanics, the relativity theory, and quantum mechanics–*K.D.*]" [21, p. 24]. Within a broader approach, the problem of incomparability of theories arises: "The real pictures of the physical world furnished by each of these theories differ of course greatly from one another, having specific and even incompatible features. Therefore it is much more difficult to outline an evolution of the world picture corresponding to these three theories in the same consistent manner as in the phenomenological analysis of laws" [21, pp. 24-25].

An analysis of Vasiliev's works thus shows that he was the first to consider from the dialectical-materialist positions important philosophico-methodological problems of the relativity theory, demonstrating the heuristic nature of materialist dialectics. These works continued the systematic elaboration of the philosophical aspects of new physics begun by Semkovsky and Gessen.

Relying on the classical ideas of the founders of dialectical-materialist philosophy, all these authors made the first and the most difficult step in the philosophico-methodological analysis of the leading 20th-century physical theories. Although at the next stage some of their valuable methodological innovations were not developed and the emphasis in studies in this problematic was for various reasons shifted towards critique of the idealist interpretations of the relativity theory and quantum mechanics, Marxist philosophical science continued to advance in the sphere of the methodology of natural science. Thus at the 1942 Jubilee Session of the USSR Academy of Sciences it was stated that the relativity theory "by no means entailed a negation of the existence of nature; and neither did the relativity theory negate absoluteness of space and time, of matter and motion in the sense of their objective existence irrespective of human consciousness" [22, p. 134].

This theory undermined the metaphysical conception of classical mechanics which regarded space, time, and motion as absolutely immutable and independent entities. Instead, the relativity theory "offered a dialectical doctrine of the unity of space and time, of matter and motion" [22, p. 134]. For this reason, the physical essence of the relativity theory, far from contradicting the dialectical approach to the world, was on the contrary "a step forward in the spreading of the dialectical laws of nature" [22, p. 134].

3. The Third Stage (the late 1940s to the mid 1950s)

The most pithy works of this stage were Omelyanovsky's book *Lenin and 20th-Century Physics* (1947) and I. V. Kuznetsov's *The Principle of Correspondence in Modern Physics and Its Philosophical Significance* (1948), which stand out among other studies of those times as they provide a positive analysis of a number of complex problems of physical science.

In his monograph, Omelyanovsky considered several approaches to the correlation of matter, motion, space and time, causality and interaction, with reference to physical knowledge; and he also showed the significance of Lenin's philosophical ideas, in the first place those formulated in *Materialism and Empirio-criticism*, for the philosophical interpretation of the recent developments in physics.

In analysing the philosophical problems of the relativity theory, Omelyanovsky endeavoured to prove the objective character of the "new physical conception of space and time" suggested by Einstein. Characterising the new elements introduced by the relativity theory in the physical comprehension of the world he emphasised in particular that the relativity theory "developed an entirely consistent doctrine of the relativity of spatial formations", "revised also the concept of simultaneity accepted in classical physics", and "established the relativity of lengths and durations" [23, p. 77]. "The general relativity theory [he went on to say] continued the revolution in physics begun by the special theory, and demanded a still more radical transformation of the physical views of space and time" [23, p. 79].

In considering the philosophical aspects of the new theory of space, time, and gravitation, Omelyanovsky showed the scientific untenability of the attempts of the adherents of philosophical relativism to exploit the variability of our notions of space and time for proving their absolute relativity. The relativity theory "does not at all discard in its conceptual content the idea of the absolute in solving the problem of space and time", for "a distinction should be made between the concept of the absolute in the epistemological sense of absolute truth in which this concept is used in philosophy, and the concept of the absolute as used in physics" [23, p. 81]. This confusion between the two aspects of the concept of the absolute underlies many "theoretical misadventures of idealists in the problem area of space and time" [23, p. 81]. The relativity theory does not entirely reject absolute magnitudes, for "invariant properties, invariant expressions, etc. in the relativity theory play the role of the absolute (in the physical sense)" [23, p. 82]. Thus "the relativity theory, in studying physical phenomena, finds the absolute in the invariant properties of the geometry of the Minkowski four-dimensional world rather than in relation to the imagined absolute space and time of Newton" [23, p. 82].

I. V. Kuznetsov studied the methodological and epistemological status of the correspondence principle. He demonstrated the universal nature of this principle within the framework of physical knowledge and defined it as follows: "in its most general form the correspondence principle may be formulated in this way: the theories whose truth was experimentally verified for a certain group of phenomena, are not discarded with the appearance of new theories but retain their significance for the former sphere as a limiting and particular case of the new theories. The conclusions of the new theories become the conclusions of the classical theory for that sphere in which the latter obtains. The mathematical apparatus of the new theory, containing a certain characteristic parameter, whose values differ in the new and the old spheres of phenomena, becomes the mathematical apparatus of the old theory given the appropriate value of the characteristic parameter" [24, p. 8].

The methodological significance of the correspondence principle lies in that developing physical knowledge appears, owing to this principle, as an integral whole in which all elements are necessary and do not exclude one another absolutely. The collapse of a theory is therefore always relative, it prepares the basis for a subsequent, more general, theory. The correspondence principle reveals the actual mechanism of continuity of knowledge. It obtains both in the transition from quantum mechanics to classical theory and from the relativity theory to Newton's mechanics. In particular, "Einstein's relativity theory is a rational generalisation of classical mechanics, and the latter becomes a special case of relativistic mechanics" [24, p. 24]. The correspondence principle can be fully explicated only within the framework of dialectical materialism in general and the theory of absolute and relative truth in particular.

Still, in the early 1950s there was less attention paid to the positive elaboration of the philosophical problems of physics than to critique of idealist interpretations of the relativity theory. Certain mistakes were made in this critique, involving identification of the physical content of the theory with its philosophical interpretation. That was the case with the book *The Philosophical Problems of Modern Physics* (1952) and with the discussion of G. I. Naan's articles in the *Voprosy filosofii.* During this polemics some philosophers and natural scientists, to defend their erroneous and largely obsolescent metaphysical mechanist conceptions, again took up long-solved problems, ignoring at the same time the unsolved complex philosophico-methodological questions of the relativity theory and quantum mechanics.

However, the debate put an end to the nihilist attacks on the relativity theory. An important role in this was played by the articles by Fok, Alexandrov, and Naan, who cited Lenin's appraisal of Einstein as one of the great transformers of nature. Fok showed, among other things, the unity of materialism and new physics. The relativity theory and quantum mechanics, he wrote, "have fundamental significance. They were remarkably confirmed by an enormous amount of experimental data, permitting a number of very important and fully justified predictions of new physical phenomena and laws" [25, p. 168]. From the outset Fok proceeded from the fundamental thesis that "the relativity theory and quantum theory, correctly reflecting objective reality, are a splendid confirmation of the basic propositions of dialectical materialism" [25, p. 168].

Of great significance for further progress of the branch of philosophy dealing with the philosophical problems of natural science was the article "On the Results of the Discussion of the Relativity Theory" published in the *Voprosy filosofii* (1955, No.1). It stated, quite properly, that the relativity theory "is necessary for a correct description of processes having speeds comparable with the speed of light", and that this theory "is one of the foundations of the modern theory of elementary particles. It constitutes the physical foundation for a number of new areas of technology" [26, p. 135]. Apart from the editorial board, this appraisal of the relativity theory was shared by most of the participants in the debate: "analysis of the numerous contributions, partially reflected in the journal, shows that the absolute majority of those taking part in the discussion evaluate the relativity theory as one of the major attainments of physics" [26, p. 135]. The review noted especially that "the correctness and value of the mathematical apparatus of the relativity theory was not questioned by any of the participants" [26, p. 136]. And further it was stated: "There are no convincing objections to the postulates of this theory either, as the sphere of its application is limited, just as that of any other physical theory. The development of science may result in the establishment of new facts, which will require a revision of the views of the relativity theory, but its conclusion will still hold for those phenomena of nature where they were confirmed by a wealth of practical demonstrations in physical experiments and technology" [26, p. 136].

Finally, of considerable significance for further elaboration of the philosophical problems of the relativity theory was an unambiguous negative evaluation of the position of A. A. Maximov, which was termed "vulgarising and nihilistic". That put an end not only to natural-philosophical attempts to question the scientific quality of the leading physical theories of the 20th century: it also meant a rejection of the style of polemics relying mostly on discussion of quotations outside their context rather than on an integral conceptual analysis of developing knowledge.

Further analysis of the philosophical problems of the relativity theory invariably took into account, implicitly or explicitly, the outcome of the debate summed up in the article "On the Results of the Discussion of the Relativity Theory". This was the case, for instance, in the works of V. I. Svidersky on space and time [27, 28].

Svidersky analysed the interrelation of space, time, and moving matter historically, considering the evolution of spatio-temporal conceptions at various stages in the development of cognition and of men's production activity throughout history. Svidersky stated that "modern natural science and in the first place the relativity theory enriched our conception of the essence of space and time, confirming at the same time the correctness of the dialectical-materialist view of the world" [28, p. 4]; drawing on the materials of physics and taking the above as his premise, he studied the problems of objectivity, absoluteness, relativity of space, showing the specific features of space as extension, order, principle, and the law of coexistence of phenomena, and of time as duration and the law of variability of phenomena, and he also considered the problem of continuity and discreteness of space and time. He paid great attention to the philosophical problems of infinity of space and time, and to the specificity of the methodological level of studying the infinity of space and time. In Svidersky's view, solution of all these problems was impossible unless philosophical ideas were resorted to, for space and time in their real being are linked with change, conservation, stability, quantity, quality, and other basic aspects of reality.

A number of philosophico-methodological problems were also analysed in collections of papers on the philosophical problems of natural science published at that time [29-31]. The results of the relativistic approach to the world were also widely used in the works on the philosophical analysis of the concepts of mass, energy [32], causality [33, 34], etc.

We cannot analyse here in detail the approaches to and proposed solutions of the philosophical problems of the relativity theory in these works; we can merely state that these studies were in a sense transitional, for, on the one hand, they criticised, sometimes from natural-philosophical positions, certain physical propositions and questioned some fundamental principles of new physics, and on the other hand, they offered a much deeper and many-sided analysis of the philosophical problems of the relativity theory, quantum mechanics, and elementary particle physics. This transitional process was completed in 1958, when the First All-Union Conference on the Philosophical Problems of Natural Science was held.

4. The Fourth Stage (since the mid 1950s)

That Conference opened up a new and important stage in the philosophico-methodological studies in natural science. It summed up previous work in this area and, formulating new problems, exerted a strong influence on further development of physical and philosophical thought. The reports and speeches by prominent physicists (V.A.Fok, A. D. Alexandrov, D. I. Blokhintsev, M. A. Markov, and others) and philosophers (P. N. Fedoseyev, B. M. Kedrov, M. E. Omelyanovsky, G. I. Naan, and others) summed up the work that had been done on the philosophical questions of physics [35]. Among the results of the First Conference was one organisational step—the founding of the Scientific Council on the interdisciplinary theme "The Philosophical Questions of Modern Natural Science".

An analysis of further work on the philosophical problems of physics (see [36]) shows that the union of natural scientists and philosophers has been strengthened, that studies in the urgent problems of developing knowledge have become deeper and more comprehensive, and that critique of the idealist interpretations of the attainments of physics has become more conceptual and constructive. Systematically analysed were the philosophical problems of the now classical relativity theory and non-relativistic quantum mechanics and even elementary particle physics. The results of the philosophico-methodological studies of elementary particle physics were summed up in the work *The Philosophical Problems of Elementary Particle Physics* (ed. by I. V. Kuznetsov and M. E. Omelyanovsky) published in 1963, translated in the USA, and discussed in *Physics Today* (see [37])

A generalised expression of the results of further studies in the philosophical questions of physics was a series of works under the general title "Dialectical Materialism and Modern Natural Science" (editorial board: V. A. Ambartsumyan, D. I. Blokhintsev, Ya. I. Gerasimov, V. M. Glushkov, B. V. Gnedenko, B. M. Kedrov, I. V. Kuznetsov, M. E. Omelyanovsky, V. N. Stoletov, V. A. Fok, Ye. V. Shorokhova). All works in this series [38-44] were written by prominent philosophers (P. N. Fedoseyev, B. M. Kedrov, the Bulgarian philosopher Todor Pavlov, M. E. Omelyanovsky, P. V. Kopnin, G. A. Svechnikov, and others) jointly with physicists (D. A. Alexandrov, V. A. Fok, D. I. Blokhintsev, and others). Well-known foreign physicists also took part in the works of this cycle, like John Bernal, Cecil Powell, and Seiichi Sakata. We cannot offer here a substantive analysis of the ideas on the philosophical problems of physics expressed by the authors of this series (see review [45]); let us point out merely that this series was characterised by creative development of the conceptual apparatus and methodological instruments of the philosophical science on the basis of physical knowledge, as well as by a deep and convincing theoretical analysis of the problems considered. This series drew on the history of science and philosophy and generalised a great number of facts from the natural sciences, confirming the fruitfulness of Lenin's idea of the union of philosophy and natural science, showing the unity and mutual conditioning of the natural-scientific and philosophical levels of cognition, and the methodological role of dialectical-materialist philosophy. Philosophers and physicists, analysing concrete methodological, logico-epistemological, and worldview problems of physics, have proved the creative nature of materialist dialectics, the growing interdependence between the physical and philosophical levels of research and subsequent increased complexity of the structure of science and greater role of abstract-theoretical and mathematical principles in cognition. Resorting to the conceptual apparatus and methodological instruments of philosophical science on the part of natural scientists is all the more necessary when complex systems become the objects of science and the non-trivial character is recognised of the problem of interpreting the data of experiments, the correlation of empirical and theoretical aspects, etc. In analysing these and other problems relative to physical science, philosophers and physicists showed the specificity of concrete application of philosophical ideas in the solution of vital problems of physics.

Philosophical problems of the relativity theory were also analysed at conferences and symposia on various logico-epistemological and philosophico-worldview problems of elementary particle physics, cosmology, field physics, etc. The papers reviewing these discussions [46-53] are an important part of the scientific literature on the philosophical problems of the relativity theory.

Questions of the logic and methodology of scientific cognition have also been comprehensively studied in the last 10-15 years [54-58]. Research in this area of the philosophical science has been essentially based on the analysis of the specificity of the structure of physical knowledge. Being the best developed theoretical system among the natural sciences, physics offers a wide problem range for the study of the laws of scientific knowledge as a whole. The logico-methodological problems of relativistic mechanics have naturally been studied from various viewpoints here as well.

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