M.E. Omelyanovsky

DIALECTICS IN MODERN PHYSICS

Progress Publishers

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PREFACE TO THE ENGLISH EDITION

This is an English translation of my monograph *Dialectics in Modern Physics* published in Russian by Nauka Publishers in 1973. Its substance remains, for the most part, as in the Russian original, except for the addition of a short chapter 'In Lieu of a Conclusion', which represents a sort of philosophical summing up.

I do not propose to speak here about the book's substance. The reader will perhaps tell me that there are repetitions in it. My reply would be that such repetitions are frequently necessary, especially when one allows for the fact that each time they express a new shade of meaning in the appropriate context.

I would like to thank Progress Publishers for the work they have done in translating and publishing my book. I am the more pleased to do so since some of the material of the Russian edition had been published abroad in the form of articles and papers. In particular I would mention the following: Das Problem des elementaren Charakters der Teilchen (*Physikalische Blätter*, 1966, *22*, 8); a paper on the absolute and the relative in the *Proceedings of the XIVth World Congress of Philosophy* (Vienna, 1968); an article on the principle of observability in modern physics in *Foundations of Physics*, 1972, *2*, 2/3; a paper on elementary particles and the universe in the *Proceedings of the XVth World Congress of Philosophy* (Varna, 1973); and a report Objektives und Subjektives in der Quantentheorie to the 'Connaissance scientifique et philosophie' colloquium of the Belgian Academy of Sciences (Brussels, 1975).

It is my hope that the material presented here has not become out of date, since the Russian original was published in 1973, and that the book will prove useful to those who are interested in the philosophical problems of modern physics.

M. E. Omelyanovsky

PREFACE TO THE RUSSIAN EDITION

This monograph brings together into a unified whole the ideas and problems that have been considered in many of my published works (articles in *Voprosy filosofii* and papers in collective works devoted to the philosophical problems of science, published in Russian, for instance, in the series *Dialectical Materialism and Modern Science.* Most of the problems or the aspects of them that are treated here have been discussed in my earlier work, but the present book contains new material, additions, and more precise definitions, and also a number of new conclusions. I have been especially interested to show that dialectics and its very important requirement of applying the all-round universal flexibility of concepts objectively is the logic of modern science.

The basic substance of the book (as its title says) is Marxist-Leninist dialectics in modern physics. Dialectics is not a formal mental construction but rather a living method of cognising nature and of searching for new truths in modern science, and in physics in particular, as far as this book is concerned.

It is undoubtedly simpler to talk about this than to apply the propositions involved in basic research. It is not up to me to decide how far I have managed to cope with the problems arising. One must, however, emphasise the following specific feature of Marxist-Leninist dialectics today. It is an essential element of the contemporary scientific and technical revolution. Only through creative development of dialectical materialism can we reap the rich results of solving the philosophical problems posed by this revolution. It takes its own course in socialist society, in a form that distinguishes it from the scientific and technical revolution in capitalist society. Only when one has an advanced revolutionary theory can one foresee the course of today's very complex processes; only advanced Marxist-Leninist theory and its integral component—materialist dialectics—enable us to deal properly with the new problems posed by the evolution of scientific knowledge in our day.

Conscious dialectics, it seems, makes a scientist really free in his scientific creative work; its consistent application in science is typical of the work of scientists in socialist countries.

Lenin's idea that modern physics gives birth to dialectical materialism has been profoundly developed in the theory of relativity, quantum theory, and other branches of modern physics in the broad sense of the term. Without dialectics one cannot deal correctly with problems of the clarity of representation or visualisation of physical concepts and theories, relativity and absoluteness, discontinuity, elementarity, and all the other philosophical problems posed by modern physics. The very methods of theoretical thinking, like those of mathematical hypothesis, fundamental observability, stochastic and structural approaches, and so on, are foreign in their methodological essence to the old philosophy, in which metaphysics and idealistic speculation have, in the last analysis, gained the upper hand. In our book we treat a number of special matters, in particular the degree to which dialectics and materialism (the methods and the world outlook) are applied in the work of those scientists who have created modern physics (scientists who, it would seem, were subjectively remote from dialectics); they applied the laws of materialist dialectics unconsciously and were successful precisely where metaphysics suffered fiasco.

It may be worth noting, in connection with the issues of dialectics considered here, that several of the ideas and statements in this book, which were formulated in my earlier work, have been supported by others than physicists who consciously hold the principles of dialectical materialism. (I refrain from citing the relevant statements.) Max Born, for instance, in a letter to the author of 18 November 1966, gave a positive estimate of the idea of the special relativity of the concepts 'elementary', 'complex', and 'structure' in transatomic physics, and called it 'most interesting'.*

Our monograph does not set out all the important philosophical problems of modern physics in any systematic way. Our analysis is limited to a few fundamental problems of materialist dialectics in modern physics; that is done, how-

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* This problem is treated in several of my publications: *viz.* The Problem of the Elementary Character of Particles in Quantum Physics (in *Philosophical Problems of Elementary-Particle Physics* edited by I. V. Kuznetsov and M. E. Omelyanovsky, Progress Publishers, Moscow, 1968); The Elementary and the Complex in Quantum Theory (in: *Struktura i formy materii* edited by M. E. Omelyanovsky, Nauka Publishers, Moscow, 1967); M. E. Omeljanowski und G. B. Rumer. Das Problem des elementaren Charakters der Teilchen (*Physikalische Blätter*, 1966, *22*, 8: 337-346).

ever, so that the reader can get an overall picture of the dialectical spirit of physics today.

We assume that the reader is familiar with the philosophical ideas of the founders of modern physics (the literature is rich; that published recently, especially, provides a quite complete idea of them). We have avoided a didactic presentation with word for word citations of authors' statements on certain matters, page reference to the relevant publications, and so on.

Our book has quite a few shortcomings; the author is usually more aware of them than the reader, of course. One of them, however, needs to be mentioned here.

We have not, by a long way, taken into account the rich Marxist literature on the philosophical aspects of physics that has appeared in recent years. This shortcoming also applies to the Soviet philosophical literature. I had to finish the book while seriously ill and therefore had to omit many interesting, important topics.

In conclusion, I would like to express my sincere thanks to my friends and colleagues, students and comrades, who helped me with the book, above all Professor V. A. Fock, Member of the USSR Academy of Sciences, an outstanding physicist, man of principle, and kind friend of everyone who takes the philosophical issues of science as his basic field of research. The crispness and clarity of his formulations of the philosophical propositions of modern physics, his discussion of major problems of modern science at our meetings, the constant attention he has given to my work and that of other Marxist philosophers, and his deep dialectical insight helped create that atmosphere in which—and only in which—creative work is possible.

I would also like to thank Professors Ya. F. Askin and I. S. Narsky for their valuable remarks and kind comments on my book, which they read in manuscript. In addition, I should like sincerely to thank my colleagues in the department of philosophical problems of science at the Institute of Philosophy of the USSR Academy of Sciences for their stimulating influence and creative contributions when we discussed the themes treated in this book.

M. E. Omelyanovsky

I

DIALECTICAL MATERIALISM IN MODERN PHYSICS

Since natural philosophy became the scientific, systematic study of nature, it has striven to construct connections between the established facts and the separate relations and patterns discovered by it. This special feature of science is expressed most fully in physics, which by virtue of its fundamental spirit, content, and methods of cognition has been and most probably will remain a kind of a control centre of the sciences about nature.

Physics deals with more general, fundamental laws of the material world than any other branch of the natural sciences; hence the breadth of its content and its corresponding very deep influence on the other natural sciences, and its particularly close relation to philosophy. Since it deals with inanimate nature and comprehends its laws, physics studies problems of matter and motion, space and time, regularity and causality, and the picture of the world as a whole by its own techniques; in short, it strives to understand the nature of things in its own way. Its philosophical significance can hardly be overestimated, and its connection with philosophy is intimate. It was not by chance that scientific problems were closely interwoven with those of philosophy in the work of Galileo, Descartes, Newton, Lomonosov, Faraday and Maxwell, Helmholtz, Mendeleev, and other great scientists of the classical period of science. And in modern, non-classical physics the connection of its content with philosophical problematics has become even stronger. According to Max

Born, for instance, the physicist's whole work is devoted to creating the basis for a philosophy of nature. 'I have always tried,' he says, 'to think of my own work as a modest contribution to this task.'[1] Einstein's comment is also typical: 'Epistemology without contact with science becomes an empty scheme. Science without epistemology is—insofar as it is thinkable at all—primitive and muddled.'[2] In this connection the book *Nature of Matter. Purposes of High Energy Physics*[3] published in the USA in 1965 which included some 30 papers by famous contemporary physicists, has special significance. Its contents speak clearly in favour of the comprehension of the deepest laws of nature being closely associated with the philosophical problems of reality, space and time, symmetry, causality, and necessity.

Although the relation between physics and philosophy has always been intimate, its meaning and forms have altered in the course of the historical development of science and philosophy.

The special feature of the association between classical physics (eighteenth and nineteenth centuries) and philosophy was that the former spontaneously accepted the materialist theory of knowledge. Philosophy's conscious influence on classical physics did not affect its content in any serious way while the development of the latter, as far as the fundamentals of physical science were concerned, did not then face philosophy with any major problems of vital significance for physics itself.

The development of classical physics was, so to speak, an extensive development, an ever greater coverage of natural phenomena in breadth based on the principles of classical Newtonian mechanics. This situation only began to change in the second half of the nineteenth century, in connection with the rise of thermodynamics, the Faraday-Maxwell theory of electromagnetism, and statistical mechanics; at that time, too, however, Newton's scheme of isolated space and time with bodies moving in them appeared unassailable. In the classical period of its development physics could satisfy its philosophical needs through a mechanistic world outlook and through a methodology whose principles did not, on the whole, go beyond the framework of formal logic.

All that, of course, does not mean that there was no dialectics in classical physics. On the contrary, the basic concepts and principles not only in relatively complex classical physical theories (the theory of heat and classical electrodynamics) but also in classical mechanics (the law of inertia or the principle of action and reaction) cannot be comprehended without the idea of dialectical contradiction. But the paradoxical situations—and they are the touchstone of dialectical thinking—that arose in classical theories remained within classical physics and did not call its foundations in question, i.e. the Newtonian schema of space—time—motion mentioned above. Classical physics grew and became consolidated as a direct generalisation of everyday experience; that is the explanation of why the fundamentals of classical physics remained unaltered throughout its development and were even converted in the works of Kant and other philosophers into the *a priori* foundation of human knowledge.

The relationship between physics and philosophy is being altered radically in the present period of scientific development. Modern physics, materialist in its fundamental spirit, is becoming more and more intimately linked with dialectics. Lenin formulated and demonstrated this idea back when non-classical physics was only beginning its development. 'Modern physics is in travail; it is giving birth to dialectical materialism.'[4] In these words Lenin summed up, in *Materialism and Empirio-criticism*, his philosophical analysis of the epoch-making achievements of physics at the turn of the century, which included, above all, the discovery of electrons and radioactivity and without which there would have been no non-classical physics.

The natural sciences, and physics in particular, have undergone enormous change since then and have moved far (by no means in any trivial sense) from classical science. Modern physics differs radically in its theoretical content, structure, and style of thinking from the physics of Newton and Maxwell. The most important discoveries and underlying ideas of twentieth century physics that are particularly essential are the following:

1. the motion of electrons in the atom (and other phenomena on an atomic scale) follows the laws of quantum mechanics, which are qualitatively different from those of Newtonian mechanics that govern the motion of macroscopic bodies (motion characterised by velocities small in comparison with the speed of light);

2. the particles of matter and immaterial light have a dual corpuscular-wave nature;

3. space and time are linked in a single four-dimensional manifold (in which time preserves its qualitative difference from space);

4. the mass and energy of any material real object (body or field) are inseparably linked by a definite law;

5. the bodies now known are based on a host of types of elementary particles of matter that have a unique structure and correspond to a certain field;

6. elementary particles are transformed into each other, observing certain conservation laws and principles of invariance.

All these statements are concrete proof of the limited nature of classical physics and the relative character of its conceptions, principles, and theories. Nature is much richer than it appears from the standpoint of classical physics. The new physics emerged and developed as a result and expression of the human knowledge's penetration into the sphere of the most refined electro-magnetic phenomena, into the atomic and subatomic world, and into the field of immense cosmic phenomena while covering the objects comprehended by classical physics from an already new angle. It emerged and developed having created the 'bizarre' (as Lenin said) ideas and theories just because everything cognised by it differs profoundly from the commonplace macroscopic world though related to it through diverse transitions. The discoveries and theories of non-classical physics, being the product of its contradiction-ridden development, have brought about the need and task to reflect nature's comprehensive, universal patterns in concepts that would, in Lenin's expression, be 'flexible, mobile, relative, mutually connected, united in opposites, in order to embrace the world'.[5]

The idea of the variability and mutual transformation of all material realities, including elementary particles, is characteristic of the physics of our day. Recognition of the unity of the opposing corpuscular and wave conceptions of matter is a necessary element of quantum physics. Without acceptance of the idea of an internally necessary connection between time and space concepts the theory of relativity would not have existed. Probability, according to quantum theory, is a direct ingredient of the basic laws of nature. The concept of structure, in contradistinction to the mechanistic atomistic view, has become very widely used in natural science, including the physics of elementary particles.

Non-classical physics itself is developing in such a way that different and opposite concepts, principles, and theories are being synthesised. These and similar dialectical ideas are arising and becoming established within physics itself in the present period of its intensive and extensive development, stimulating its progressive development. By the essence of their philosophical interpretation they mean that physics is moving forward and arriving at dialectical materialism regardless of the personal philosophical views of the scientist, and that conscious application of dialectics in physics is becoming a vital necessity in our day.

Furthermore, in present-day conditions of the rapid development of pure and applied science paradoxical situations have become an ordinary phenomenon in physics, a circumstance that again and again emphasises the spirit of thinking characteristic of it. The special theory of relativity was born through resolution of the paradoxes that had arisen at the junction of classical mechanics and classical electrodynamics. Quantum mechanics also began with a paradox when the experimental data led to a need of sorts to unite the corpuscular and wave pictures of the motion of atomic objects. The development of quantum field theory and relativistic cosmology also consists of a chain of paradoxes, solution of which may radically alter existing fundamental theories.

These paradoxes in physics, their rise and the need to resolve them, clearly indicate that there are limits to the applicability of established theoretical notions and even theories, that theoretical ideas and theories should not be converted into dogmas, that new theoretical conceptions and new methods of describing cognised phenomena should be sought for; and that means that the old physics' spontaneous materialism is quite inadequate for a solution of the epistemological and methodological problems advanced by physics' contemporary development that ignores philosophy. The physics of our time requires conscious application of the laws of theoretical thinking, and knowledge of them, of course, comes from that philosophy which does not counterpose itself in one way or another to concrete sciences but is consonant with them.

Dialectics is an adequate form of thinking for modern physics and science as a whole that completely corresponds to the character and constantly varying content of modern science. The idea of the need for internal unity of the dialectic philosophy of Marxism and science used to seem a remarkable scientific prediction of Marx, Engels, and Lenin; now it is a portentous fact of twentieth century culture to which the development of the Soviet Union and the victory of socialism in other countries has made a significant contribution.

In his book *Patterns of Discovery*, the British author N. R. Hanson stressed, in his terminology, 'philosophical aspects of microphysical thinking' and called for the 'perennial' philosophical problems to be viewed through the lens of the modern physical theories. One should not, in his view, construct the physical explanations from 'standard' philosophical elements; in his view microphysics has philosophical independence and its conceptual structure is accepted as logic in itself.[6]

Hanson is not original. The same motif can be heard from such Western scientists as, say, Born or Heisenberg for whom the Copenhagen interpretation of quantum mechanics is the philosophy of modern science. The striving of some Western scientists to turn certain interpretations of the modern physical theories into a kind of philosophy is evidence not only of total or partial ignorance (or ignoring) of dialectical materialism but also expresses their lack of satisfaction with traditional philosophical doctrines and modern positivism. Heisenberg, for instance, disagreed with positivists' statements about the logic of science and said directly that the most precise science cannot avoid using imprecise concepts (such as the concept of infinity in mathematics which leads to contradictions but without which 'it would be practically impossible to construct the main parts of mathematics').[7] We would add, for our part, that there are plenty of such dialectical contradictions in modern physics, and that it is impossible to understand them without dialectical logic.

The development of contemporary physics is its ever deeper penetration into phenomena that lie at qualitatively different levels of developing matter, yet which are, at the same time, related to each other. In the most sophisticated experiment that is generalised by modern physics relying on extremely delicate instruments, and dealing with the finest phenomena of the microworld or immense phenomena of a galactic scale, nature is not perceived directly, but rather in a very complicated way through concepts of the most varied levels of abstraction. Theory interacts with experiment in modern physics and is not expected just to explain the phenomena of reality. It is acquiring enormous heuristic significance; its main task is becoming the search for possible new forms of phenomena and new possibilities potentially existing in nature.

Modern physics thus demonstrates with all certainty that cognition is not the contemplative, passive perception of nature (as it was understood by metaphysical materialism), but is an active process in which the subject of cognition (the observer or researcher) plays a decisive role. At the same time one must remember that nature, in answering the questions put to it within the limits of existing knowledge, frequently poses problems on her own to the researcher that are completely unexpected and which call for new ideas and notions or a new method of description. Such a dialectic of the interaction between the cognising subject and the cognised object has found a characteristic expression and development in modern physics, which will be discussed below. Here we would simply like to note that Niels Bohr's well-known words to the effect that to have a chance of being true a really new theory should be quite 'crazy', speak of the essentially new style of thinking of contemporary physics. Unconventionality and oddity from the 'commonsense' point of view is an indispensable feature of modern physical theory.

Objectively applied dialectics, and its very important requirement of all-round, universal flexibility of concepts[8] is thus the logic of modern science. Now, with the scientific and technical revolution it is particularly important that the transition from principles and categories of dialectical materialism to the methodological paths and propositions that lead to scientific results should be brought out in study of the philosophical problems of science, and that these results in turn should promote the enrichment and further development of dialectical materialism.

* * *

Dialectics and its principles are discussed, without using the term (there are exceptions, however), by the very scientists who created non-classical physics (although they cannot be regarded as conscious adherents of dialectical materialism). Max Planck's remark about the corpuscular and the wave hypotheses of light, which, in his words, 'oppose each other as two fighters of equal strength', is typical. 'Each of them is well-armed,' he continues, 'but each of them also has a vulnerable spot. What will be the outcome of the struggle? It is most likely, today, that neither of these two hypotheses will win outright. More likely the verdict will be that the advantages and also the one-sidedness of each of them will be brought out from a higher standpoint.'[9] Let us note that the 'higher standpoint' mentioned by Planck with such dialectical penetration has been realised in modern quantum electrodynamics.

In his discussion with Albert Einstein on epistemological problems in atomic physics, Niels Bohr wrote about the existence of the so-called 'deep truths' which are 'statements in which the opposite also contains deep truth'. 'The development in a new field,' he remarked, 'will usually pass through stages in which chaos becomes gradually replaced by order; but it is not least in the intermediate stage where deep truth prevails that the work is really exciting and inspires the imagination to search for a firmer hold.'[10] We hardly need to stress that in this case Bohr essentially characterises the process of cognition that occurs through the struggle of the opposites, in complete agreement with dialectics.

In this connection it is worth mentioning Heisenberg's opinions on the dialectical approach to understanding phenomena of nature in his book *Der Teil und das Ganze*.[11] In it, in particular, he discussed the problem of the elementary particle and continuity, having in mind only the dialectics of Plato and, especially, of Hegel. Of interest are his observations on the Hegelian thesis, antithesis, and synthesis and his statements concerning formal logic in the chapter on 'elementary particles and Plato's philosophy'; they are far removed, however, from the physical concreteness, and a Marxist cannot on the whole agree with them.[12]

If we turn, say, to Max Born, one of the founders of quantum mechanics, we find that the interpretation of quantum mechanics that was correct for him, was that which tried, in his words, to 'reconcile both aspects of the phenomena, waves, and particles'. According to him broader use of the concept of particle 'must satisfy two conditions: First it must share some (not in the least all) properties of the primitive idea of particle (to be part of matter in bulk, of which it can be regarded as composed), and secondly, this primitive idea must be a special, or better, limiting case'.[13]

There are many remarks of this kind in the works of other outstanding physicists, which witness, in essence, that dialectics is not in the least an exotic element in modern physics. In this respect Einstein's statement about the relation between epistemology and physics referred to is significant. Let us discuss it further here.

When a philosopher manages to develop a consistent system, in Einstein's view he begins immediately to interpret the content of science in the light of his system and to reject everything which does not fit into it; the scientist, on the other hand, Einstein said, 'cannot afford to carry his striving for epistemological systematics that far. He accepts gratefully the epistemological conceptual analysis; but the external conditions, which are set for him by the facts of experience, do not permit him to let himself to be much restricted in the construction of his conceptual world by the adherence to an epistemological system'.[14]

He went on to draw an important conclusion: the scientist therefore must appear to the systematic epistemologist as a type of unscrupulous opportunist: he 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'.[15]

In this extract Einstein essentially (if one overlooks the inaccuracy of individual terms) speaks *in favour of the many-sidedness* of cognition (as personified by the scientist) and against the one-sidedness and rigidity of the systems of traditional philosophy and philosophical relativism. One cannot help agreeing with Einstein; *Marxist* philosophy, however, expresses this thought incomparably more precisely and profoundly. In Lenin's fragment 'On the Question of Dialectics' dialectics is characterised as '*living*, many-sided knowledge (with the number of sides eternally increasing), with an infinite number of shades of every approach and approximation to reality (with a philosophical system growing into a whole out of each shade)'. Lenin emphasised that the major *misfortune* of 'metaphysical' materialism is 'its inability to apply dialectics... to the process and development of knowledge'.[16] The same fragment presents a remarkable analysis of epistemological roots of idealism which, according to Lenin, 'from the standpoint of *dialectical* materialism, ... is a *one-sided*, exaggerated ... development (inflation, distention) of one of the features, aspects, facets of knowledge into an absolute, *divorced* from matter, from nature, apotheosised'.[17]

Einstein's statement above demonstrates yet again that the dialectics of scientists who are not conscious adherents of dialectical materialism, like, in general, the dialectics of representatives of spontaneous scientific materialism, is inadequate to solve the philosophical problems of science. The vulnerable spots in their ideology are used by spokesmen of reactionary philosophy for their own purposes: one can find as many corresponding facts pertaining to the philosophical statements of Einstein, Bohr, and others of the founders of modern physics as one wants.

Only conscious application of materialist dialectics really frees the scientist of one-sided approaches and preconceived ideas of one sort or another in studying philosophical problems of science by opening up a correct perspective in the quest for their solution that corresponds to the experimental data. In the forming and consolidation of a materialist and dialectical understanding of the theory of relativity and quantum mechanics as new landmarks (compared with classical physics) in the cognition of nature by the progressively developing science, dialectical materialism's ideas and conceptions about the philosophical category of matter, space, and time as objectively real forms of being, about causality and necessity in nature, the absolute and the relative, dialectics of the cognitive process, and so on, have played a definite role.

The dialectical idea of the inexhaustibility of the electron, which was first expressed by Lenin, is more and more becoming part of the theory of modern physics; this is recognised by the outstanding scientists, including the American physicist F. J. Dyson, the British physicist C. F. Powell and others. The dialectical idea of the unity of possibility and actuality underlies V. A. Fock's standpoint on quantum mechanics.[18] In Peter Kapitsa's view the physicist should be guided in his methods of studying nature by an understanding of a phenomenon arising from itself; by the determining role of the experiment; by the requirement of unity of theory and experiment for the harmonious development of science; by a negative attitude to dogmas in science and the need for new ideas; and by recognition of the inexhaustibility of matter.

These propositions clearly express the materialist and dialectical nature of methodology in modern physics.[19] A rich Marxist literature on the philosophical aspects of science, including publications of scientists themselves, has developed, especially in recent years. The works of the scientists bring out sharply that conscious application of dialectical materialism encourages faster development of science; and they analyse their own discoveries in that light.[20]

We must stress that since the triumph of the October Socialist Revolution Soviet scientists have approached dialectical materialism as the only true philosophy and methodology of modern science. During the first years after the Revolution the young Soviet country's science developed at an accelerated pace, and the philosophy of Marxism became ever more significant in its progress. This is clearly to be seen, if we consider physics, from the work of that time by S. I. Vavilov, D. S. Rozhdestvensky, A. F. Ioffe, I. E. Tamm, and others. In those years quantum mechanics was only beginning, and the strangeness of the new ideas connected with discovery of the corpuscular properties of light and wave properties of matter gave rise to conclusions about the collapse of causality in the microworld, about its being necessary to reject objective reality in atomic physics, and so on. From the very beginning Soviet physicists resolutely opposed the idealistic and positivist interpretations of quantum and relativist theories that were fashionable in the West. Thus, I. E. Tamm drew attention in his papers of that period to the fact that there was no need whatsoever to reject the principle of causality in the name of quantum theory. The laws of the microworld are paradoxical from the standpoint of conventional macroscopic conceptions, but 'are there any grounds for believing', he asked, 'that the laws of microscopic phenomena should be identical to the laws of the macroworld that we are accustomed to?'[21] V. A. Fock also opposed an idealistic approach to quantum mechanics.[22]

When one considers how dialectical materialism, created in the nineteenth century, in the steam era, can correspond to modern science which is developing in the epoch of mastering the atomic world and interplanetary space, the answer must be sought in the essence of dialectical materialism.

An advanced philosophy has always given science leading generalising ideas application of which made empirical study of nature truly scientific cognition and in general performed a methodological function in science, encouraging the rise of scientific concepts, principles, and disciplines hitherto unknown. Suffice it to mention Descartes' philosophical system and the analytical geometry created by him, the teaching of Francis Bacon, whom Marx called 'the real progenitor of *English materialism* and all *modern experimental* science',[23] the rules of philosophising of Isaac Newton, the great founder of classical physics, directly related to it, Leibniz's dialectical ideas and his development of differential and integral calculus simultaneously with Newton; not to mention that this philosopher-encyclopaedist anticipated many subsequent scientific discoveries.

There are more than enough such examples in the history of philosophy and science: one need only recall the idea of the atom, which had been known for thousands of years before the discovery of chemical atoms and elementary particles, or the principle of the conservation of motion, which had been formulated by Descartes, Leibniz, and Lomonosov long before discovery of the law of the conservation of energy, and other conservation laws.

The facts collected by science call for systematisation and generalisation, and that cannot be done without scientific thinking that objectively reflects the real world, and without application of its laws, which are studied by philosophy. The development of philosophy which has been going on for thousands of years, is the history of quests for its own subject-matter and at the same time the history of the freeing of its content from the mythology and metaphysics that were associated in one ratio or another with the elements of scientific thought in every philosophical system existing before Marxism. Only Marxism, as we know, turned philosophy into a science; Marx and Engels, for the first time in the history of human culture, combined conscious dialectics with a materialist understanding of nature.

Dialectical materialism does not function as a philosophy that stands above other sciences, and rejects philosophy as an absolutely complete system. By its very essence it is not a numbing philosophical doctrine isolated from the development of other sciences. With each epochal discovery in both the natural and the social sciences dialectical materialism perfects its form and enriches its content. Its creative character, which excludes a one-sided, dogmatic approach to cognition of man's environment, determines its correspondence to contemporary science.

At the same time the deep revolutionary transformations and constant progress in modern science, its features and peculiarities mentioned above, its ever-growing significance in the life of the modern society, and above all the contemporary scientific and technical revolution, of necessity link science with materialism and dialectics.

Dialectical materialism, which was created by Marx and Engels as a science of the general laws of development of the material world, and of its cognition, and raised by Lenin to the level of the great achievements of twentieth century science, is the philosophical source and foundation of the progress of modern physics and of science as a whole, the logic and the theory of knowledge of the sciences of nature of our time.

We are also convinced of this by a circumstance of no little significance, that analysis and solution of epistemological and methodological problems in modern physics given by scientists do not diverge in their basic materialist and dialectical character from the philosophical ideas formulated in their time by the founders of Marxism-Leninism. The fact mentioned above, that the great physicists of the twentieth century have not been conscious adherents of dialectical materialism, is revealed, of course, in their philosophical reasoning and conclusions.

* * *

It is not fortuitous that the relation between philosophy and science occupies a leading place in the international philosophical discussions of our time. The development of the modern science is continually raising philosophical problems not only of world outlook but also of methodology and logic. The theoretical methods developed by modern physics (mathematical hypothesis, the principle of observability), for instance, or the structural and stochastic approaches in modern science, cannot be explained by traditional philosophical systems. On the other hand, philosophy has had to open to cognition previously unknown ways of comprehending a new sphere of reality lying outside the competence of already established knowledge.

The philosophy of dialectical materialism makes it possible to solve the problems arising in this connection from the standpoint of science. Evidence of this is the work of scientists and philosophers who take a Marxist stand.

Interest in the philosophical problematics of science, as we know, has grown sharply in the West in recent years. Special seminars on the methodology of knowledge have been held by scientific societies and universities in the United States on a big scale. The Solvay meetings, which enjoy very great authority in the field of physics, are now frequently devoted to the methodological and philosophical problems of physics, as happened before, when quantum theory was being established. The most outstanding contemporary physicists (not to mention Einstein, Bohr, and Born) like Heisenberg, de Broglie, Dirac, Weisskopf, Dyson, and Wigner, have frequently published works devoted to philosophical analysis of the situation in the present-day science.[24]

The reason for this heightened interest of distinguished Western scientists in philosophical problems of science is that the leading branches of modern natural science—the physico-mathematical and biological sciences—began a radical transformation of their principles and main concepts in connection with deep penetration into the atomic and subatomic world and the need to take in theoretically the phenomena of outer space discovered in the twentieth century and the achievements of molecular biology and genetics. The existing theories and conceptions were proving less and less adequate to interpret the epochal discoveries of recent times from a single, monistic point of view.

As to the opinions of Western scientists on the relationship of science and philosophy, they now represent quite a mixed bag (these views do not necessarily form a system of any sort, but are rather of the nature of trends).

Many scientists in the West are now experiencing certain philosophical doubts and are going through a kind of re-evaluation of philosophical values; positivism is no longer as attractive as it was earlier, while other anti-materialist trends, though being galvanised by individual researchers, are also, on the whole, suffering fiasco. We have not the space to dwell in greater detail on the issues arising, but we must say, however, that many scientists in the West now do not ignore the work of Marxists. Some of them, while not accepting dialectical materialism as the philosophy of modern science, treat it with due respect and recognise its cognitive value (a striking example of such a natural scientist is the distinguished German physicist Max Born); others, however, actively oppose dialectical materialism.

These scientists suggest that the general conceptions of non-classical physics determine the essence of the philosophy of modern science which, as they see it, is not idealism, or positivism, or materialism, although it includes elements of these philosophical systems. In views of this kind one can trace dissatisfaction with the one-sidedness and rigidity of idealist and metaphysical philosophy, and also a distorted notion of dialectical materialism, which they actually identify with pre-Marxian materialism. One can also include scientists in this circle who assume that the philosophy's role in science now belongs to cybernetics or general systems theory.

The scientists described above are close to those researchers in the West whose stand on the relationship of philosophy and science can be called a certain 'neutrality' towards philosophy. Some idea of this 'neutrality' can be got from Prof. J. M. Ziman's *Public Knowledge.*[25] According to him, 'the objective of Science is not just to acquire information nor to utter all non-contradictory notions; its goal is a *consensus* of rational opinion over the widest possible field'.[26]

Prof. Ziman actually believes that scientific truth is revealed through agreement among scientists. It is understandable that in defending such a standpoint, which implies rejection of study of the relationship between a scientific theory and objective reality, he considers philosophy something alien to physics. Similar views have been expressed by Prof. Laurie Brown in his review of the book by Soviet authors *Philosophical Problems of Elementary-Particle Physics.*[27] In his opinion physics manages to cope with its difficulties without philosophy, including Marxist philosophy.

Without making a critical analysis of these standpoints, we would like to note that Faraday's discovery of electromagnetic induction, von Mayer's discovery of the law of the conservation of energy, Einstein's formulation of the theory of relativity, or the construction of quantum mechanics as a physical theory were 'brought' to their authors by philosophical considerations in which materialism and dialectics were far from the least.

In spite of the inconsistency, contradictoriness, and sometimes seriously mistaken character of the philosophical views shared by contemporary scientists in the West, there is no little evidence indicating that a tendency of major scientists to come over to the position of dialectical materialism is becoming more and more definite and marked. It is particularly significant that very distinguished modern scientists—the physicists Paul Langevin, Frédéric Joliot-Curie, J. D. Bernal, C. F. Powell, and S. Sakata—did not simply say, but demonstrated concretely in their work, that materialist dialectics, and only materialist dialectics, could and does offer philosophical help in solving the most important scientific problems of our time.

One can cite other facts showing the growing, serious interest of scientists in the West in Marxist-Leninist philosophy and its application to science. The speeches and papers of Marxists at the international and national philosophical congresses and symposia arouse great interest and are very favourably received by most participants. Translations of Soviet work in the USA, West Germany, Italy, Mexico, and other capitalist countries, and papers by Soviet philosophers are appearing in Western publications ever more frequently. Work of this kind is only beginning, but it is a successful beginning, and it has a great future.

Strengthening of the position of materialism and dialectics in modern science is giving rise to a tendency among the ideological opponents of Marxism-Leninism to distort the true facts of the historical development of Marxist-Leninist philosophy and its application in science. This is aided by specially founded institutes, chairs, and journals; and numerous publications are devoted to this purpose in capitalist countries. Bourgeois ideologists ascribe rejection of the theory of relativity and other leading theories of modern science to Marxists as allegedly idealistic constructions, ascribe an ignoring of modern formal logic to them, and so on and so forth. They try to show that materialist dialectics has not led to a single scientific discovery, that modern science is allegedly alien to materialism and dialectics, and so on. The reality of the progress of science, however, disproves all these and similar statements.

To sum up briefly, whereas in the nineteenth century, during the creation and consolidation of Marxism and its philosophy, conscious adherents of dialectical materialism among scientists could be counted on the fingers of one hand, now, in the age of the great victories of socialism and communism, there are many of them. The dialectical materialism developed by Lenin is taking ever stronger hold in modern science, because it is the most adequate method and the most adequate philosophy of science. Its consolidation is based mainly on cooperation between Marxist philosophers and scientists directed at philosophical interpretation of everything advanced in science, at fighting Marxism-Leninism's opponents' attempts to force obsolete philosophical systems onto science. Only through dialectical materialism and its creative development is it possible successfully to deal with the philosophical problems posed by the contemporary scientific and technical revolution.

In the chapters that follow it will be demonstrated more concretely that the path being followed by modern physics in trying to solve its epistemological, methodological, and logical problems is the philosophy of dialectical materialism.

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II

THE PROBLEM OF OBJECTIVE REALITY IN QUANTUM THEORY

1

The Methodological Significance of the Idea of Objective Reality in Physics

The problem of objective reality has been frequently treated in the work of Max Planck, Albert Einstein, Niels Bohr and other great reformers of science. It was dealt with, in particular, in Max Born's paper *Symbol und Wirklichkeit* which very definitely expressed a philosophical position typical of many contemporary scientists in the West.[1] Physicists who are the conscious adherents of dialectical materialism have also occupied themselves with the problem of objective reality and its various aspects.[2]

The philosophical needs of science have thus turned out to be stronger than the statements of the modern positivists who declared objective reality to be a pseudoproblem. By its fundamental spirit science cannot consider nature other than as it is, without arbitrary additions by the cognising subject that are alien to it, and this means that it cannot help being materialist. This is the reason for the ineradicability of scientific materialism and indestructibility of the spontaneous, philosophically unconscious belief of most scientists in the objective reality of nature reflected by human consciousness. There is no need to cite here the many statements of distinguished contemporary scientists about the objective nature of science, and that a physicist, say, is dealing with objective reality and should consider his sense impressions as messages about this reality and not as illusions.[3] Humanity's belief in the objective reality of the external world reflected by science is a conviction of twentieth century scientists that is necessarily becoming stronger.

Scientists' spontaneous, philosophically shapeless materialism is inseparably connected with philosophical materialism; but it cannot, precisely because of its lack of philosophical shape, cope with the philosophical problems posed by the development of modern physics, and that is made use of by trends opposed to materialism. These philosophical problems include, above all, the problem of objective reality itself.

The point is that the question of the objective reality of matter in motion and its particles, of space and time, of the regularity in nature could only be formulated and considered *consistently* from the point of view of materialism by *dialectical* materialism. All materialist theories before Marx and Engels brought to the fore in philosophy not so much the question of the objective reality reflected by the human consciousness but that of the *ultimate* reality, like the 'final' atoms, the 'absolute substance' (compare Democritus' differentiation between the existence of colour, heat, bitterness according to opinion, on the one hand, and of atoms and the void, according to truth, on the other hand, Locke's and Hobbes' distinguishing between primary and secondary qualities, and the 'constant masses' or particles of the mechanistic picture of the world in physics). Pre-dialectical materialism unjustifiably raised one property of matter or another, which was characteristic only of certain states of matter, to the level of an absolute, a universal property of matter, so turning it into an 'invariable element', the 'invariable essence' of things. Lenin criticised this metaphysical position as follows: 'From Engels' point of view, the only immutability is the reflection by the human mind (when there is a human mind) of an external world existing and developing independently of the mind. No other "immutability", no other "essence", no other "absolute substance", in the sense in which these concepts were depicted by the empty professorial philosophy, exist for Marx and Engels. The "essence" of things, or "substance", is *also* relative; it expresses only the degree of profundity of man's knowledge of objects; and while yesterday the profundity of this knowledge did not go beyond the atom, and today does not go beyond the electron and ether, dialectical materialism insists on the temporary, relative, approximate character of all these *milestones* in the knowledge of nature gained by the progressing science of man.'[4]

'Invariable elements' and other metaphysical 'invariabilities' thus represent the purest subjective constructions, alien to nature. Objectively real nature itself is both diverse and united, complex and simple. By isolating classes of natural phenomena, by formulating concepts and categories of various degrees of generality man pursues a goal—to catch the many-sided phenomena of nature in the net of knowledge. But that means this, that the cognising person connects up the field of experience isolated by him in a single totality of phenomena or wholeness that appears before the mind cognising it in its most varied aspects. How do we know that nature is united in its diversity and diverse in its unity? That it contains no 'ultimate realities'? We know this from the development of human knowledge, the history and logic of which demonstrates that the simple in nature passes into the complex, and the complex into the simple, that everything different in nature merges, that in the course of development of knowledge man cognises nature more deeply and more fully without exhausting it completely. Cognition of nature's objective reality is cognition of nature as it is, in other words, cognition of nature as matter in motion.

* * *

Let us first recall certain definitions and formulate the problem itself. The 'objectively real' or the 'objective' or the 'objectively existing' means what 'exists regardless of human consciousness and (in certain conditions) reflected by it'. Unlike the objective, the 'subjective' means what 'exists in consciousness'. The concept of the objective (from the point of view of materialist philosophy) coincides with that of matter from the aspect of the theory of knowledge; according to Lenin, 'the concept matter ... epistemologically implies *nothing but* objective reality existing independently of the human mind and reflected by it'.[5] In accordance with that (materialist) understanding of the objective and subjective, cognition is a process of reflection of the objectively real world in man's mind. By creating concepts, theories, and a picture of the world, man takes in an approximate, relatively universal pattern of constantly moving and developing matter through them.

It follows from what we have said that the 'objectively real' (or 'objectively existing') is not equivalent to what 'exists' since 'existence' is also possible in the mind. The confusion of these concepts and the issues related to them—which is wrong in itself—opens the road to an idealist outlook. A vivid example of this is provided by the ideas of Rudolf Carnap, one of the leading spokesmen of positivism in the twentieth century. According to him, if one accepts the language in which statements about objects that are dealt with in physics are formulated, then whether phlogiston, say, or ether exists has to be answered by empirical research. But to ask about the existence of a system of physical objects as a whole, i.e. of the physical world, is meaningless, as Carnap sees it, since the answer cannot be formulated in terms of the accepted physicalist language. 'To be real in the scientific sense,' he wrote, 'means to be an element of the system; hence this concept cannot be meaningfully applied to the system itself.'[6]

Carnap's very posing of the question of the real (or the existing) presupposes a non-materialist answer. In his argument he started from the ready-made knowledge expressed in language and ignored the problem of the origin, source, development, etc., of knowledge from the very outset, in other words, he considered knowledge (and language, since the latter is used to express knowledge) in fact as the primary element and, therefore, supported an idealist point of view (which he appeared to disown). In reality Carnap dealt with the problem of the meaning of subjective constructions (expressed in language) and wrongly substituted it for that of objective reality. How do we know, however, that things do exist independently of our consciousness? According to Lenin, this knowledge springs 'from the development of our knowledge, which provides millions of examples to every individual of knowledge replacing ignorance when an object acts upon our sense-organs, and conversely of ignorance replacing knowledge when the possibility of such action is eliminated'.[7]

In Marxist-Leninist philosophy the materialist solution of the major problem of philosophy is thus inseparably linked with the dialectics of the process of cognition in contrast to metaphysical materialism.

The philosophical problem—i.e. whether the statements of physics expressed in mathematical formulas have objective meaning, or from what one can deduce that the statements of physics are not pure subjective constructions, or how objective knowledge is achieved—had already appeared in classical physics. And it is the problem of objective reality in the physical sciences in its most general form.

In the science of the classical period, the solution of this problem did not seem particularly difficult, though it had its complex elements. Most naturalists then, as now, did not rack their brains over philosophical niceties. For them acceptance of the objective reality of the external world reflected in our mind was common sense. The phenomena observed were explained by a mechanical macroscopic model. The observation of motions of macroscopic bodies (including the motions of the celestial bodies then known) did not call for particularly precise special equipment. The degree of abstractness of the concepts which expressed the measurable characteristics of these motions (velocity, acceleration) was not very different from that of notions developed in everyday experience.

Classical theory, however, could not by-pass the problem of objective reality. How could one know that the 'green' one saw was the same 'green' seen by another observer? This was an example from everyday experience, but classical physics frequently based its conclusions on such experience. Our analysis will begin exactly with just this example.

The question posed is, as a matter of fact, the question whether the sensation 'green' corresponds to something objective. The answer given by practice is positive: to answer it, it is sufficient to imagine a driver who is daltonian or colour-blind. The fact that we know about colour blindness and can avoid its undesirable qualities to some extent, moreover, only confirms another fact, that the sensation 'green' corresponds to objective reality.

As for the problem of reality, analysis of such cases does not differ essentially from analysis of measurement procedure and of experiment in general, the direct task of which is the recording of macroscopic parameters. All physical theories, both classical and non-classical, grew from measurements and experiments through study and thinking (when the cognitive power of abstraction becomes greater and greater). If we generalise what we have said, taking into account data from the most varied branches of science and practice, we come to the well-known premises of materialism (formulated by Lenin with classical clarity): the sole source of our knowledge is sensation; objective reality is the source of human sensations or, which is in fact the same thing, the external cognisable world exists independently of human consciousness.[8]

Max Born, in his work already mentioned, does not agree with this fundamental statement of materialist epistemology. True, he does not express himself against it in essence; on the contrary, he criticises idealism and apriorism, especially the views of Kant, Machists, and logical positivists. He does not consider Lenin's statement to be proved, however, and wants to justify his own position by relying, as it seems to him, on modern physics. (Born's paper has a typical subtitle: 'An attempt to philosophise in a scientific way is not a philosophy of natural science.') Is he right?

According to Born, the impossibility of answering whether the 'green' I see is the same 'green' that he sees rests on the fact that in this case 'one is trying to understand a single sensation'.[9] Such an 'understanding' is, indeed, impossible; Born sees the way out as follows. 'Even for two impressions of the same sensory organ, for instance, for two colours, the communicated, objectively verifiable statement is specified—which rests on comparison, first of all, on the judgment concerning identity or non-identity (in other words, indistinguishability or distinguishability...). I cannot transmit my feelings to another person when I call something green, but I can, and he, too, establish that when the green of two leaves appears to me identical, it also appears identical to another person.'[10]

Born is saying here essentially that objective knowledge is not what corresponds to the objectively real but rather to the common meaning. After Lenin's criticism of the views of Bogdanov, who defined the objective as the common meaning, there is no need to discuss the erroneousness of Born's idea further. On the other hand, the example of 'green' serves Born to stress the idea of invariance, use of which, in his view, makes it possible to solve the following problem: how is the passage from subjectivity to objective knowledge made? (Born developed his understanding of this matter in greater detail in other works.)[11] From this last standpoint the idea of invariance presents great interest, but before we discuss it let us consider whether Lenin's statement above on the fundamental premise of the materialist theory of knowledge is, in fact, not proved, as Born suggests.

In trying to resolve how the passage is made from the subjective to objective knowledge, Born did not see the question behind it of objective reality being the source of sensation (and therefore of subjectivity). In Born's work one can read: 'Subjectivity as primary and the possibility of objective statements as a problem.'[12]

This statement of Born's agrees with science only when it is associated with another to the effect that 'subjectivity' itself is generated by objective reality; but this last statement cannot be found explicitly in Born's works. In short, his argument by-passed the basic question of philosophy (or, more precisely, its primary aspect) of the relationship between mind and matter and its solution by materialism. In Lenin's *Materialism and Empirio-criticism* (Section I of Chapter III, which is entitled 'What Is Matter? What Is Experience?') there are epistemological and logical proofs of the need to accept the fundamental propositions of materialism.

The problem of objective reality became more and more confused in physics from the time it began to leave the macroscopic objects perceived in everyday experience for the sphere of phenomena whose cognition called, in addition to very refined, specialised experimental equipment, for non-classical theories with their abstractions unknown to classical physics.

Even before non-classical physics had been created, Engels remarked that 'atoms and molecules, etc. cannot be observed under the microscope, but only by the process of thought'.* The deep insight of his words became completely apparent when physics began, so to say, to come closer and closer to the foundation of matter. It is impossible to manage in physical theories without abstractions and mathematics. In Boltzmann's kinetic theory, and in Einstein's theoretical work on molecular theory, the heuristic significance of mathematics was revealed with all clarity: their works led

* Frederick Engels. *Dialectics of Nature* (Progress Publishers, Moscow, 1976), p 205. Use of the Wilson cloud chamber and other such devices emphasises the correctness of the fundamental meaning of Engels' remark. If, for example, it is stated that the cloud chamber enables individual atomic particles to be observed, the word 'observed' is not by any means understood in its direct sense. In this case the physicist 'observes' the atomic particles in fact rather by thinking than by seeing.

to Perrin's decisive experiments, and the molecular-atomic structure of macroscopic bodies became a demonstrated fact. What was the situation here with the problem of objective reality?

In classical physics (and that includes the studies of Boltzmann and Einstein mentioned above) it was sufficient, in order to explain the phenomena observed in the instruments, to link the observed data by chain of appropriate reasoning (with the addition, where necessary, of assumptions of one sort or another) with the system of basic concepts and axioms of classical mechanics. As for the problem of objective reality, it meant that the transition from what had been observed in the apparatus to knowledge about the objects being studied could be reduced to the construction of some mechanical macroscopic model. Classical statistical physics, as we know, rests in fact upon the fundamental notions of classical corpuscular mechanics.

In the science of today the problem of objective reality has assumed a form differing from that it had in classical physics. At the turn of the century paradoxical situations emerged in physics when the data of observations could not be fitted into the theoretical schemes and conceptions then existing. Such were the situations encountered by physicists in connection with the Michelson-Morley experiment, in connection with the facts that were called the 'ultraviolet catastrophe', in connection with Rutherford's planetary model for the atom (1910-12), and at the end of the twenties in connection with certain facts, including direct experiments, that made it necessary to ascribe properties to electrons (which no one had seen) that were mutually exclusive from the standpoint of classical physics. As a matter of fact, it was only then that the problem of objective reality took on the form in which it appears in modern physics (these situations were, of course, the starting points of non-classical physical theories).

It is possible, of course, generally speaking, to try and interpret paradoxical situations by varying the schemes of classical explanations in one or another way. Such attempts are still being made; one can cite as an example Jánossy's interpretation of the theory of relativity, or the interpretations of quantum mechanics of, say, Schrödinger or David Bohm. On the abstract level there is nothing unjustifiable in such attempts. But still, the problem of the truth of the relevant interpretations is decided according to the fruitfulness of the results obtained, and here the development of physics has a weighty word to say: the theory of relativity and quantum mechanics have become established as non-classical theories, i.e. as theories that employ mathematical abstractions inapplicable in classical physics and also basic concepts and principles that differ from classical ones.

It appeared to many at one time that the problem of objective reality in physics had been removed by positivism, whether that of Mach or of modern logical positivists, which declared only the world of sensations to exist, so to say, without objective reality. From that point of view, nature for Margenau, for instance, ceases to exist beyond the experiment, and proves to consist of sensory data and conceptual 'constructions' (things from everyday life, atoms, electrons, etc.) since they emerge through experiment from 'chaos or non-being'.[13] According to him, the real is only that which acts either on the objects or on the human psyche; outside that action it is not real. 'What is not real in the Roman sense,' he says, 'may well be real in this. God, according to this version, is real to the person who believes in Him.'[14] The only way out of this situation is to join Born who said, in criticising the ideas of this kind of positivists and other anti-materialists: 'Whoever believes that the only important reality is the realm of ideas, of the spirit, should not occupy himself with science.'[15]

* * *

The development of modern physics occurs through the passage of some fundamental theories into others, more general (and deeper) and differing qualitatively from the former. The disappearance of certain basic concepts (that figure in the original theory) and the formation of new basic concepts (without which the new theory is not a theory) is necessarily associated with generalisations of this sort. The disappearance of old concepts and the appearance of new basic ones is a single process in which the old concepts (in the original theory they were absolute concepts or invariants of sorts) undergo a kind of relativisation and become aspects of new absolute concepts or the invariants in a more general theory. In the theory of relativity, for instance, the concepts of absolute length and absolute duration accepted in classical mechanics disappeared, and relativistic concepts of length and duration became established; they represent the aspects of one of the most important invariants in the theory of relativity—the four-dimensional interval which represents a special 'combination' of length and duration. In quantum mechanics the absolute nature of the corpuscular and wave concepts inherent in them in classical theory is lost; these concepts become relative ones, as aspects of a broader concept (than the classical one) of a particle with certain invariant characteristics, which is applied to atomic objects.

Those two examples help express certain considerations on the epistemological plane about the idea of invariance. First of all, one cannot agree with Born, who ascribes reality in essence only to invariants and, so to say, denies reality to aspects of invariants. The justification for recognising the objective significance of physical concepts or statements does not consist in the idea of invariance. Suffice it to recall that the relativistic concepts of length and duration correspond to objective reality (this has now been confirmed by direct experiments) and are not invariants of the theory of relativity. In other words, both invariants and their aspects are images of objective reality.

At the same time, the idea of invariance plays a major role in the question of the transition from subjectivity to objective knowledge. The concepts of classical mechanics and the science as a whole, for instance, are, of course, essentially approximate. This was demonstrated concretely from various aspects by the theory of relativity and quantum mechanics when they determined the limits of applicability of classical mechanics itself and of its concepts. Thus, the uncertainty principle in quantum mechanics established the limits of applicability of the classical concept of a particle (absolute in a certain sense). In this case in determining the limit of applicability of the classical concept of a particle, attention was given to the fact that, let us say, electrons and protons possess wave properties as well as corpuscular properties. To put it differently, the establishing of a limit to the applicability of the classical concept of a particle meant deeper knowledge of the particles of matter than was possible in classical mechanics. Beyond these limits, of course, the classical concept does not 'work', i.e. has no objective meaning and represents a subjective construction.

In general, when one bears in mind a number of major modern physical theories of an increasing degree of generality (classical mechanics—quantum mechanics—quantum electrodynamics—quantum field theory or the theory of elementary particles) one can say that the relativisation of old absolute (invariant) concepts, and the introduction of new ones, during the generalisation of a theory mean progressive movement from the subjective to objective knowledge, deeper and deeper cognition of objective reality in which the one-sidedness (and subjective constructions inseparable from it) of individual physical theories is obliterated, as it were, and the theories themselves, while preserving their content which corresponds to objective reality, acquire a higher integrity.

That, it seems to us, is the philosophical significance of the idea of invariance in the problem of objective reality in modern physics. In non-classical physics, which poses the question of the reality of its objects, Lenin's ideas on the relation between the objective and the subjective find expression. The objective and the subjective, matter and mind oppose each other and preserve their absolute opposition only within the limits of the main question of philosophy: namely, that of the relation between mind and matter since no mind exists or can exist outside and independently of matter. 'To operate beyond these limits', said Lenin, 'with the antithesis of matter and mind, physical and mental, as though they were absolute opposites, would be a great mistake.'[16] The situation is also exactly the same in modern physics when the question of the objective nature of its statements is discussed; a striking example of this is the application of the idea of invariance in it.

Bohr's concept of complementarity acquired essential significance for the problem of the objective and the subjective in modern physics. We shall discuss it separately in the following sections and in other chapters; here we shall make only a brief comment about the problem involved.

Complementarity has frequently been regarded as referring to the subjective observer, which is incompatible with the objective nature of the scientific description and the cognition of the phenomena of nature. This applies both to physicists who share Bohr's ideas, and those who do not, especially to idealist philosophers, and positivists in particular. Bohr himself, Heisenberg, and many other distinguished scientists spoke against such a view.

In his essay 'Atoms and Human Knowledge' (1955), Bohr mentioned that it was necessary, of course, in every field of experience to 'retain a sharp distinction between the observer and the content of the observations'. But 'discovery of the quantum of action' had 'revealed hitherto unnoticed presuppositions to the rational use of the concepts on which the communication of experience rests'. And he posed the question of whether one could draw a sharp line in experience between the cognised object and the cognising subject, the observed system and the instruments used for observation. 'In quantum physics,' he said, 'an account of the functioning of the measuring instruments is indispensable to the definition of phenomena.'[17]

Bohr did not employ the term 'initial-state preparation' which would have clarified his idea in this case; he also did not use the term 'relativity to the means of observation'. These terms would have helped clarify more deeply the meaning of his main ideas and make the general line of his reasoning easier to understand. They have been used by other authors.[18]

In his works on quantum mechanics and its philosophical problems Bohr, as a matter of fact, demonstrated that the concepts of the subjective and the objective, which were interpreted in classical physics as separate concepts with an absolute difference between them, required revision. With deeper analysis of this problem in terms of the content of quantum mechanics, the difference between the subjective and the objective proved to be relative. This analysis also made it possible to establish that classical physics' understanding of the objective and the subjective was not rejected, generally speaking; it remained valid, but within certain limits that could be and are being made more precise as physics develops.

Materialist dialectics opens up the necessary paths here for resolving the paradoxes emerging. We would like to emphasise once more that the significance of Lenin's ideas on the relation between the objective and the subjective is especially great in this case for physical problematics. The following remark of Lenin's is very important in this connection: 'There is a difference between the subjective and the objective, BUT IT, TOO, HAS ITS LIMITS.'[19] We shall return to the questions raised here in the appropriate places in subsequent chapters.

To conclude this section, we would say a few words about a fact that can, in particular, illustrate a well-known thought: if a physicist ignores materialist dialectics during his analysis of his science's philosophical problems in certain conditions this science will turn in his hands into an ally of sorts of reactionary philosophy. In Heisenberg's *Der Teil und das Ganze* he presents the following point of view: whereas it used to be difficult to find a place for religion in the conceptual system of classical science the situation is now different. This is because, according to him, of 'the emancipation of our thinking' that has resulted from the 'development of physics in recent decades', which has demonstrated 'how problematic the concepts "subjective" and "objective" are'.[20]

Heisenberg had in mind the alteration and refinement of these concepts in the theory of relativity and especially in quantum mechanics (compared with classical theory) discussed above, which are evidence of a new triumph of materialist dialectics in physics. He, however, interprets this change as physics' rejection of materialism.

In what follows we shall continue our discussion of the questions raised above.

2

Observation, Complementarity, and Dialectics

The discovery of the corpuscular properties of light and the wave properties of matter in phenomena on an atomic level made it necessary for physics to combine the corpuscular and wave conceptions of matter and field as applied to atomic processes. It proved far from simple to resolve the theoretical problems that emerged in physics in this connection, the main reason being that, from the standpoint of classical physics (with its notions of particle and wave), an object could not exist simultaneously in those processes as a particle and as a wave. The difficulties emerging, it seemed, were coped with by the Copenhagen interpretation of quantum mechanics.

The last expression (Bohr does not use it) is often used by Heisenberg. In his view 'the Copenhagen interpretation of quantum theory starts from a paradox': it assumes that any experiment (regardless of whether it refers to the everyday phenomena or those of atomic physics) 'is to be described in the terms of classical physics', which cannot be replaced by any other concepts; at the same time it affirms that their applicability 'is limited by the relations of uncertainty'.[21] Heisenberg goes on to explain Bohr's idea of complementarity by the particle and wave characteristics of atomic objects being mutually exclusive, since'a certain thing cannot at the same time be a particle (i.e. substance confind to a very small volume) and a wave (i.e. a field spread out over a large space)'. These two characteristics, he says, complement each other.[22]

We would like to note two aspects of the Copenhagen interpretation. The first, developed by Heisenberg, can be formulated as follows. Where it is possible, in principle, in classical physics to eliminate the effect of observation (or measurement) on the object, it is impossible, in principle, in quantum mechanics, since the latter contains an uncertainty relation that causes inaccuracies in measurements (the idea of uncontrollability in principle).

The second aspect, developed by Bohr, can be represented as follows. Micro-objects cannot be regarded either as particles or as waves in the sense of classical physics. In some experimental conditions the most natural description of micro-objects is that based on corpuscular conceptions, in other conditions it would be most natural to describe micro-objects in terms of waves. Both descriptions are complementary to each other, and this relation ensures consistent application of the classical concepts in the realm of microphenomena.

It is usually assumed that these aspects are equivalent. Heisenberg, for instance, frequently employed the idea of complementarity in his arguments; Bohr, too (especially in his work of the thirties and forties), often resorted to the idea of an 'uncontrollable interaction between object and instrument'. All these aspects are far from identical, which can be seen quite well in Bohr's last works.

In the aspect of the Copenhagen interpretation developed by Heisenberg attention is drawn not so much to the fact that the properties and behaviour of macro-objects should not be ascribed to micro-objects as to the idea of the inaccuracies associated with applying classical concepts to micro-objects. These inaccuracies and the corresponding interpretation of the uncertainty principle are given (as we shall show later) a fundamental importance in the physics of quantum mechanics that is quite untypical of them. Heisenberg also resolved the paradox above in the spirit of just this interpretation.

Why do the classical concepts by which experiments with atomic objects are described not correspond precisely to these objects? According to Heisenberg, the answer is that 'the observation plays a decisive role in the event and that the reality varies, depending upon whether we observe it or not'.[23]

From this standpoint (if it is consistently held), momentum or energy, for example, are not so much objectively real as that they appear and disappear depending on the choice of one method of observation or another. The mathematical apparatus of quantum mechanics is not so much objective as symbolic in nature (needed only for agreeing the readings of the instruments). The uncertainty relation is becoming the absolute boundary of human knowledge; no new fundamental physical concepts have been developed in quantum mechanics.

One must emphasise that Heisenberg's view formulated above (again, if it is held consistently) on the uncontrollability principle leads to non-materialist philosophical conclusions. In fact, however, Heisenberg himself by no means employed it consistently. When he considers philosophical questions inseparable from the theoretical content of modern physics, its basic materialist and dialectical spirit is revealed, often quite clearly, in his statements. When, on the other hand, he moves away from physics into the realm of general philosophical problems, the idealist and metaphysical line gains the upper hand in his reasoning.

Consider his standpoint relative to the cognition of nature which underlies, as could be expected, his philosophical reasoning about quantum mechanics.

According to Heisenberg, man describes and explains 'not nature in itself but nature exposed to our method of questioning' and our techniques of research.[24] Heisenberg highly appreciated the idea of the German physicist Carl von Weizsäcker that 'Nature is earlier than man, but man is earlier than natural science'. 'The first part of the sentence,' he wrote, 'justifies classical physics, with its ideal of complete objectivity. The second part tells us why we cannot escape the paradox of quantum theory, namely, the necessity of using the classical concepts.'[25]

From that point of view it would appear that the transition of science from classical physics to quantum physics, instead of strengthening the bonds between man and science, separated them from each other. The point is that, according to Heisenberg, experiments with atomic processes are as real as any phenomena of daily life to describe which classical concepts are employed. Atomic or elementary particles, however, are not as real. They form a world of potential possibilities rather than a world of observed things or facts and can only be represented symbolically by mathematical signs. In other words, according to him, atomic and other micro-particles prove to be in a sort of realm of things-in-themselves. 'The "thing-in-itself" is for the atomic physicist, if he uses this concept at all, finally a mathematical structure; but this structure is—contrary to Kant—indirectly deduced from experience.'[26] On the other hand, the classical concepts (and they include, according to Heisenberg, space, time, and causality) have to be interpreted in a certain sense as *a priori* in respect to the theory of relativity and quantum mechanics.

Is it true that there are adequate grounds in modern physics to revise the concept of objective reality?

Quantum physics appeared and developed, of course, through acceptance of the objective reality of the physical world, including the atom and the elementary particles; Heisenberg, for example, noted that 'quantum theory does not contain genuine subjective features, it does not introduce the mind of the physicist as a part of the atomic event'.[27] On the other hand, quantum theory has to take into account the conditions of observation (recorded by instruments) in which the objects of its research are found, because of their dual particle-wave nature (relativity to the conditions of observation),[28] whereas classical theory had every right to ignore them. The description of physical phenomena by the idea of relativity to the conditions (or means) of observation means that quantum theory has made a new advance in cognition of the objective reality of nature and not that this objective reality is limited by the boundaries of classical physics, as Heisenberg asserts.

One also cannot agree with Heisenberg when he says that only classical theory idealised nature as such, while the rise of quantum theory was accompanied with the establishment of another point of view, namely, that science describes nature not as it is in itself but as subjected to human methods of research. In classical physics the picture of nature is not completely adequate to nature; it is a rough approximation and simplification, as is proved by both the theory of relativity and quantum theory. But then the statement to the effect that classical physics describes and explains nature without taking us ourselves into consideration is wrong. Much the same thought is to be found in Heisenberg's remarks about the limited character of classical concepts. He does not, however, follow up these remarks, narrowing the philosophical concept of objective reality down in his argument to its presentation in classical theory.

If one bears in mind that the reflection of nature through observation and thinking idealises, simplifies, and roughly approximates the reflected object, and that at the same time the progress of cognition, theory, and science on the whole overcomes this simplification, which is inevitable in each individual cognitive act, it becomes clear that the development from classical to relativistic and quantum theories reflects nature more completely in the system of concepts and at a deeper level, without exhausting it. The forward movement of physical knowledge is thus accompanied with the introduction of new methods of describing the phenomena of nature, developing new fundamental concepts and principles, constructing new theories, and creating the scientific picture of the world. It is understandable that this development of knowledge, which implies ever newer alteration of nature by the person cognising it, in no way resembles a one-sided increase of subjective elements in science through cognition of its objective content; but Heisenberg holds the opposite view.[29]

Thus, in the process of cognising (objectively real) nature the objective and the subjective should not be opposed and separated from one another, as has been done in his own way by Heisenberg, in whose view the difference between the subjective and objective in classical physics is only absolute, and in quantum physics only relative. The constant advance of science, which reflects the material world, reduces the one-sided elements of the objective and the subjective to nothing. In Lenin's words, the 'logical concepts are subjective as long as they remain "abstract", in their abstract form, but at the same time they express also the Things-in-themselves. Nature is *both* concrete *and* abstract, *both* phenomenon *and* essence, *both* moment *and* relation. Human concepts are subjective in their abstractness, separateness, but objective as a whole, in the process, in the sum-total, in the tendency, in the source'.[30] The development of physics—from classical science to that of today—confirms these ideas of Lenin's in a remarkable way.

One can suppose that Heisenberg's statements above are not so much a revision of the concept of objective reality in modern physics as the fact that the subject plays an active role in cognition. According to him, the passive role of the subject in classical physics, and its contemplative attitude to cognised nature, are quite natural: physics studies the objective world without violating its state in the course of observation. In modern physics (in quantum theory it is expressed with extreme clarity) it is accepted to speak of the observer and the object, as we know, as opposites. Hence it would seem to follow that Heisenberg's argumentation deserves the closest attention and support from the standpoint of dialectical materialism, which rejects *contemplative* materialism.

We would like, however, to stress that the subject-object relation (the objective and the subjective) in classical physics is the same in principle as in quantum theory. Man cognises nature only when he changes it, i.e. when he isolates some phenomena of nature from others (such isolation occurs already in the act of observation); when he conducts experiments in which he alters and controls the conditions under which these events take place; when he reconstructs the object in thought and approximates or simplifies concepts of it, etc., etc. The alteration of nature by cognising man is both inevitable and necessary since it is only it that creates opportunities for man to cognise nature as it is and to understand it as a unity of the diverse.

This character of the alteration of nature, without which there is no cognition of it, has an essential special feature. The more man changes nature, the deeper and more completely he cognises it. Nature then appears more and more diversified and united to him, more 'wonderful' and richer in its manifestations and patterns, more and more different from the nature to which he was accustomed in the conditions of the 'conventional' experience.

From the ordinary point of view, however, man's 'stronger' alteration of nature in order to cognise it or, as some authors put it, the subject's greater activity in cognition, is only the reverse of cognising man's movement forward from ignorance to knowledge, from shallow knowledge to deeper knowledge. On the other hand, the relation itself between cognising man (the subject) and cognised nature (or rather, its fragment, i.e. the object) does not change in principle: both at the level of shallow knowledge (in physics, say, classical mechanics) and at the level of deeper knowledge (e.g. quantum mechanics) nature exists before it is cognised by man, to whom it tells its secrets when he alters it and to the extent that he alters it.

There are statements in the literature that at the level of physics described by quantum mechanics the subject of cognition is taken, so to say, beyond the bounds of its 'classical' passive state, since the interaction between the atomic object and the instrument is regarded as 'disturbance of phenomena by observation' or as the 'creation of physical attributes of objects by measurements'.[31]

Such statements now lack conviction. They were used to be common in the literature on quantum theory; now, if they are found at all, it is rather as relics. In his last works Bohr (and many other outstanding scientists) began to oppose the use of such expressions, which led to erroneous philosophical conclusions. One must remember that from the time when quantum mechanics was created to the end of his life Bohr kept returning to the philosophical questions of this theory, refining his terminology and perfecting his argumentation; this, as we shall show later, yielded significant positive results, one of which was his idea that the words 'phenomenon' and 'measurement' should be used in matters of quantum mechanics in the direct sense in which they are employed in classical theory.[32]

The ideas and concepts developed and refined in recent years in quantum mechanics: viz. the proposition that 'the interaction between object and apparatus ... forms an inseparable part of the phenomenon'[33]; the notion of relativity to the means of observation; the idea that a particle is a relative concept in respect to phenomena on the atomic level, or that the concepts of particle and wave make sense in atomic physics not so much as the concept of a particle in itself and the concept of a wave in itself, as in internal interconnection, and the idea of potential possibility and probability in quantum mechanics—are all convincing evidence of how far human thought has advanced by virtue of abstraction, its analytical and synthetic power since the times when classical mechanics was constructed and other classical theories arose.

At the same time, the laws of cognition operating in classical physics and in quantum physics, or in any other scientific discipline and theory, are the same; otherwise there could be no unified science, and in general no united human knowledge reflecting the objectively real world. It is for that reason that science has followed the path of materialism, still does, and will, and why there is no place in its system of concepts for idealism and religion.

To conclude our discussion of certain epistemological issues of quantum mechanics, let us dwell briefly on the fact that classical mechanics is much closer to it epistemologically than certain authors think. In classical mechanics, for example, the inertial motion of a particle cannot be thought of independently of the inertial frame of reference. This 'relativity' very much resembles the 'relativity' of the particle in quantum mechanics, although the content of these 'relativities' by no means coincides. We shall return to this point, and to other topics discussed above, in the next sections of this chapter and in Chapters V and IX on dialectical contradictoriness in modern physics and philosophical aspects of the theory of mensuration.

Let us now turn to the conception of complementarity, which we shall take as presented in Niels Bohr's essay on quantum physics and philosophy.[34] There is no concept 'uncontrollable interaction' in it. The term 'complementarity' used by Bohr denotes a novel kind of relationship between the different experimental data about atomic objects obtained by means of various experimental apparatus. Although these data, says Bohr, appear contradictory when combination into a single picture is attempted they in fact exhaust all conceivable knowledge about the object.[35]

The description of atomic phenomena, Bohr stresses, 'has in these respects a perfectly objective character, in the sense that no explicit reference is made to any individual observer'.[36] In quantum mechanics, in his view, we are not concerned 'with a restriction as to the accuracy of measurements, but with a limitation of the well-defined application of space-time concepts and dynamical conservation laws'.[37]

In quantum mechanics, Bohr writes, the word 'measurement' should be used in its direct sense of quantitative comparison (comparison with a standard). He is against using expressions like 'disturbance of phenomena by observation' or 'creation of physical attributes of objects by measurements.'[38]

Summarising, Bohr concluded that 'far from involving any arbitrary renunciation of the ideal of causality, 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'.[39]

Thus, one can find explicit expression in Bohr's essay *Quantum Physics and Philosophy* of a position that is basically materialist and dialectical. By linking the mathematical apparatus of quantum mechanics with visualisable notions and classical concepts he reveals, as a philosopher would say, the antithetical character of the corpuscular and wave conceptions. Contrasting these ideas as a certain antinomy always played a decisive role in Bohr's notion of complementarity. In his early work on quantum mechanics, however, this antithesis was masked by the idea of 'uncontrollable interaction'; in *Quantum Physics and Philosophy*, however, this drawback is eliminated.

The considerable philosophical significance of the idea of complementarity for physical theory is that, according to it, the application of opposite concepts to the same objects under study is not simply possible but even necessary in certain conditions. As Bohr demonstrated (especially in his discussions with Einstein), this does not lead to any formal logical contradictions in physical theory, but enables the mathematical apparatus of quantum mechanics to be interpreted in accordance with the experimental data and a whole picture to be given of atomic phenomena that classical theories could not cope with.

We limit ourselves here to a brief outline of complementarity, allowing for the fact that Bohr's ideas will be discussed almost throughout the present book.

The complementarity principle, as a conception of quantum mechanics (taking it in its mature form), is distinguished by a harmonious fusion of its philosophical and physical content. Although we have not touched on the other concepts of quantum mechanics in our presentation we shall make an exception for one of them, viz. Reichenbach's conception, which seems to us as a matter of fact to contain almost no physics but a great deal of philosophy. In his analysis of quantum mechanics and its philosophical aspect Reichenbach employed his theory of equivalent descriptions (the essence of which will be brought out below).

In discussing quantum mechanics, Reichenbach speaks of phenomena and interphenomena. The physicist draws inferences about phenomena (e.g. about the electrons striking photographic film) from macroscopic events (tracks in emulsion; instrument readings), relying on a theory that contains no quantum laws. His conclusions about interphenomena (e.g. about the motion of an electron before it strikes a screen) are deduced from phenomena relying on quantum theory. Inferences about interphenomena, Reichenbach notes, assume certain definitions or rules that make it possible, not being either true or false, 'to extend the language of phenomena to that of interphenomena'.[40]

For a description of interphenomena in terms of 'particle' and 'wave', Reichenbach says, the following definitions are adopted. 'When we lay down the rule that the quantity had the same value *before* the measurement, we have introduced the particle interpretation.' But if we assume that the quantity has all possible values simultaneously before the measurement this introduces the wave interpretation.[41]

In certain conditions the particle and wave interpretations, Reichenbach notes further, are 'equivalent descriptions; both are admissible, and they say the same thing, merely using different languages.'[42]

If certain definitions are postulated and the question of the physical properties of interphenomena is posed, Reichenbach states, one finds that 'the behaviour of interphenomena violates the principle of causality', i.e. the principle of short-range interaction fails and an anomaly arises. Reichenbach thinks that the existence of such anomalies is an inevitable feature of quantum mechanics, and therefore introduces a 'principle of anomaly'.[43]

The following examples will help explain these ideas of Reichenbach's and to draw certain inferences. If the *particle* interpretation is applied to the diffraction of electrons by a single aperture, the principle of causality is satisfied, since the electron-particles hitting the screen produce scintillations on it. When, on the other hand, one employs the *wave* interpretation, an anomaly arises, in other words the principle of *short-range effect* is violated, since the electron-waves contract incomprehensibly into points on hitting the screen.

When electron diffraction by two apertures is observed and the *particle* interpretation is used, an anomaly arises (we omit the appropriate argument). When, on the other hand, this phenomenon is subjected to the *wave* interpretation, the principle of causality is satisfied, i.e. the principle of short-range interaction is not violated.

It follows from Reichenbach's argumentation about the various interpretations or equivalent descriptions applied to the atomic world that for him a physical theory is simply a means of systematising of the observed in one way or another, and that the question of objective reality's being reflected by the theory is thought to be deprived of meaning. This idealist interpretation of physical theory by Reichenbach is closely related to his neglect of the real dialectical unity of the particle-wave properties of matter.

3

The Philosophical Evolution of the Copenhagen School

The terms 'Copenhagen school' and 'Copenhagen interpretation' are usually employed to denote a certain community of physical and philosophical views typical for that trend in modern physics represented by Niels Bohr, Werner Heisenberg, and other scientists. This school advanced new fundamental ideas relating to quantum theory that arose from discovery of the corpuscular properties of fields and the wave properties of matter, discoveries that classical physics could not explain.

The philosophical views of the physicists of the Copenhagen school used to coincide on the whole with the line of positivism, but it would now be wrong to characterise them in that way. The influence of positivism among the Western scientists has diminished considerably in recent years. As we have already mentioned, Bohr, Heisenberg, and Born have spoken out against positivist trends in science. Probably only P. Jordan, among the distinguished members of the Copenhagen school, now clings to positivist dogmas.

The Western physicists who have opposed positivist philosophy in their latest works hold essentially different ideological points of view, though this difference is not too clear on a number of matters and rather resembles a trend. Niels Bohr, for instance, made a definite advance towards a materialist approach to quantum mechanics. Heisenberg, on the contrary, inclined in his objections to positivism towards views close to Plato's objective idealism. Max Born has spoken out particularly sharply against positivism.

In this section we shall discuss the evolution of the philosophical views of quantum theory shared by the leaders of the Copenhagen school, Niels Bohr and Werner Heisenberg. The facts given below witness to the bitter philosophical struggle in modern science and once more demonstrate that materialist dialectics is at the centre of the philosophical issues of modern physics. Without in any way giving a full picture of the evolution of the Copenhagen school's philosophical ideas we shall touch simply on how Bohr and Heisenberg treat the problem of reality in quantum theory.

As we have seen, the Copenhagen school essentially faced the problem of giving meaning to, i.e. expressing in physical concepts, the objective dialectics of atomic processes.

Were they successful in doing so? History indicates that this problem was frequently resolved by physicists in spite of their personal philosophical inclinations. Because of certain circumstances, above all social factors, many physicists of the Copenhagen school either ignored dialectical materialism or directly opposed it.

The ambivalence of the Copenhagen interpretation was already there in embryo in Heisenberg's formulation of the task of quantum theory. 'Our actual situation in science is such,' he said, 'that we do use the classical concepts for the description of the experiments, and it was the problem of quantum theory to find theoretical interpretation of the experiments on this basis.'[44]

This problem was resolved by adherents of the Copenhagen interpretation by introducing the idea of the uncontrollability in principle which can be formulated as follows: in order to employ classical concepts without contradictions in the description of atomic experiments, the interaction between the atomic object and the measuring instrument was regarded as uncontrollable in principle.

The term 'uncontrollable interaction', taken in its literal sense, is wrong: all phenomena of nature are cognisable and hence controllable in principle. This philosophically erroneous term expresses the truth that modern physics has discovered new forms of matter and motion (for which the notions of classical physics about matter and motion proved to be narrow); that the objectively real connections are much more diverse than it was admitted by classical theories; that the laws of microphenomena cannot be reduced to those of classical mechanics, i.e. the latter are not absolute. This truth could not be philosophically comprehended by physicists who were not conscious adherents of materialist dialectics, and contemporary positivism played up the term 'uncontrollable interaction' in the spirit of subjectivism.

The idea of uncontrollability in principle led to idealist and metaphysical philosophical conclusions that were supposedly confirmed by quantum mechanics but in reality had nothing in common with its scientific content.

A philosophically erroneous thought was associated with this idea, to the effect that one could only employ the concept of objective reality in classical physics in the sense that nature existed independently of the human mind; in quantum theory, however, the situation was such that the atomic object allegedly had a different 'degree of reality' than the macroscopic instrument.

The idea of uncontrollability in principle replaced the problem of the dual particle-wave nature of atomic objects by that of whether the experimenter could decide which properties were manifested and which eliminated during observation, by selecting one method of observation or another.

The idea of the uncontrollability in principle did not, in fact, break with the notion of an atomic object as a particle in the classical sense. An atomic object was represented as possessing both classical position and classical momentum, which could not be cognised simultaneously because of the uncertainty relation. This relation was in fact converted into a kind of agnostic enigma, and the problem of qualitatively new quantum concepts (compared with classical ones) was completely excluded from atomic physics.

The materialist criticism of the Copenhagen interpretation was directed mainly against the idea of uncontrollability in principle, which was counterposed to the idea of unity of the opposite corpuscular and wave properties of matter and fields. Among the papers devoted to this issue we would cite that of V. A. Fock, *A Critique of Bohr's Views on Quantum Mechanics*,[45] in which he justly drew attention to the fact that there cannot in general be any fundamentally uncontrollable interaction. When speaking about uncontrollability in principle, Bohr essentially considered the question not of the impossibility of full analysis of the interaction between object and measuring instrument but of this interaction being expressed in the admittedly incomplete language of classical mechanics. From the very beginning he formulated an unresolvable problem: to follow the simultaneous changes of the position and momentum of an atomic object while remaining faithful to classical mechanics. When, however, it proved that this was impossible, the result was ascribed not to the wave properties of matter but to the presence of supposedly uncontrollable interaction between the object and the instrument. Fock said this approach to the problems of quantum theory was an echo, perhaps, of the long abandoned view that position and momentum were always 'in reality' allegedly characterised by certain values, but because of some whim of nature would not be observed simultaneously.

Bohr needed the concept of uncontrollability in principle in order to hide the logical inconsistency resulting from the concepts of classical mechanics being used outside their field of applicability. The introduction of this idea into quantum theory once more confirmed the profound correctness of Lenin's words: 'It is mainly because the physicists did not know dialectics that the new physics strayed into idealism.'[46]

The development of the physics of the microworld and the discovery of the contradictory and yet united opposite aspects of the micro-objects coincided with a very heightened wavering of some scientists between idealism and dialectical materialism. The discovery of the wave properties of matter and corpuscular properties of a field, i.e. discovery of the fact that matter and field have a dual particle-wave nature, stimulated scientists' recognition of dialectical contradictions in natural phenomena. Many physicists, including those whose philosophical views diverged from Marxism, began to talk about dialectics. But, through ignoring materialist dialectics they were unable to explain the contradictory nature of micro-particles or to understand the objective character of the contradictions. In that lay the source of their idealist errors.

Wolfgang Pauli, for instance, agrees to apply 'dialectical' to the joint play (*Zusammenspiel*, his expression) of the typical aspects of the Copenhagen interpretation of quantum mechanics[47]; his interpretation of the dialectic nature of atomic phenomena in accordance with the idea of the fundamentally uncontrollable interaction between the instrument and the observed system is, however, subjectivist.

When Heisenberg discusses the relations between various philosophical systems, on the one hand, and quantum theory, on the other, he finds that 'the theory of knowledge analysis of quantum theory, moreover, especially in the form Bohr gave it, contains many features that resemble the methods of Hegelian philosophy'.[48]

All modern physics and its theoretical foundations are riddled with dialectical contradictions. The opponents of dialectical materialism, however, try to draw the unjustified conclusion from their existence that there can allegedly be no objective meaning independent of the human mind in physics' concepts and statements, as if truth were something conditional, determined simply by the point of view of one researcher or another, and erroneously state that the concept of objective reality should be revised in the light of the new discoveries in physics. This is the main line of reasoning of all contemporary positivism and 'physical' idealism, whatever 'scientific' terminology their spokesmen hide behind.

The very essence of modern positivism and idealism excludes recognition that there are contradictions inherent in every object and phenomenon in the material world, that the concepts reflecting matter, which develops through contradictions, must necessarily be flexible, mobile, and relative, united in their opposites, and that dialectical logic with its mobile categories is incomparably more definite, consistent, and convincing than formal logic with its invariable categories.

To cognise all nature's phenomena as they are, without subjectivist and other idealist additions, means to cognise them as a unity of opposites. This also applies to the problem of reality in quantum theory. Physicists approach this problem in exactly such a dialectical way, although many of them gropingly, spontaneously, inclining towards idealist and metaphysical views. This is obvious, in particular, from the facts of the evolution of the Copenhagen interpretation.

* * *

Let us consider Bohr's essay *Quantum Physics and Philosophy* again, in which, as we know, he presents the conception of complementarity without the idea of 'uncontrollable interaction'. In this exposition complementary concepts (particle and wave, position and momentum) are juxtaposed in the form of an antinomy which is then resolved. Such a juxtaposition always played a decisive role in Bohr's conception. Let us dwell on the antinomy of complementarity in greater detail.

We introduce this expression here in order to stress the definite similarity between Kant's antinomies and the concept of complementarity.

An antinomy asserts two mutually exclusive, opposite judgments about the same object, each of them (thesis and antithesis) being stated with the same necessity. As we have remarked more than once, employment of the corpuscular and wave concepts of classical physics to describe atomic objects created contradictions in physical theory; those contradictions could be given the form of antinomies. Bohr demonstrates this convincingly when discussing numerous concrete examples in his work. Let us take one of them.

'If,' he writes, 'a semi-reflecting mirror is placed in the way of a photon, leaving two possibilities for its direction of propagation, the photon may either be recorded on one, and only one, of two photographic plates situated at great distances in the two directions in question, or else we may, by replacing the plates by mirrors, observe effects exhibiting an interference between the two reflected wave-trains. In any attempt of a pictorial representation of a behaviour of the photon we would, thus, meet with the difficulty: to be obliged to say, on the one hand, that the photon always chooses *one* of the two ways and, on the other hand, that it behaves as if it had passed *both* ways.'[49] Bohr sees the way out of this difficulty in the conception of complementarity. One should not, in his view, isolate the behaviour of the photon in itself from the conditions in which the phenomenon takes place: in some experimental conditions it will behave as a particle, in others as a wave.

If we consider the application of the concept of complementarity, or rather the arguments about it employed in individual cases as they are presented in the literature, we can see quite clearly that both the conclusion and the premises contain mutually exclusive statements about one and the same thing which are formulated with the identical necessity. For example, the conclusion obtained in the imaginary experiment with a microscope for gamma-rays (a description of this imaginary experiment can be found in many publications on quantum mechanics), namely, that the greater the accuracy of the determination of the electron's position the lower is the accuracy of the determination of its momentum, means essentially that the electron possesses both the property of a particle and the opposite property of a wave. But this latter is also confirmed by the fact that in the corresponding reasoning the essence of quantum mechanics is expressed by the formula $p = hk/2\pi$, where p is the momentum of the micro-object, h is Planck's constant, and k is the wave vector. This formula demonstrates that both particle and wave quantities apply to the same micro-object, since p characterises a point particle, and k a spatially infinite sinusoidal wave. Each of these mutually exclusive statements about the micro-object corresponds to the experiment.

The same must be said about complementarity as such, regardless of the individual forms in which the idea of it is employed. When it is said that the study of so-called complementary phenomena requires mutually exclusive experimental conditions and that only the whole totality of these phenomena can provide complete knowledge of an atomic object, this means, as a matter of fact, that from the standpoint of complementarity we can express two mutually exclusive opposing opinions about one and the same atomic object which would be equally correct.

Thus, when the contradiction between the particle and wave concepts as applied to atomic objects is resolved, the complementarity principle emphasises the cognoscibility of the atomic world and not Kant's point of view, who, in 'resolving' his antinomies in his own way, introduced the unknowable 'thing-in-itself'.*

And yet Bohr's complementarity principle does not finally resolve the problem of particle-wave dualism. According to his ideas, the contradiction between the particle and wave properties of atomic objects is supposedly frozen in the form of an opposition of two classes of mutually exclusive experimental situations with which the 'complementary phenomena' are associated. The true solution of the 'antinomy of complementarity', however, consists in considering the particle and wave properties of an atomic object as a unity of opposites. That is why quantum theory concepts reflecting the dual nature of atomic objects must differ qualitatively from classical ones.

The drawback of the complementarity principle in Bohr's exposition of it, namely that it concentrates attention mainly on going into the limitations of the old classical concepts instead of on philosophical comprehension of the new concepts introduced by quantum mechanics, stems from the weakness noted above. This was very clearly demonstrated by V. A. Fock: 'Bohr does not say what these new primary concepts are (physical, visualisable, pictorial and not simply symbolic) that should replace the classical ones, and does not emphasise the unlimited possibilities of making the description of atomic objects more precise by means of new concepts. For not only do the limitations proper to the description of phenomena 'in themselves' in isolation from the means of observation ('complementarity') have philosophical significance but also the constructive part of quantum mechanics and the new primary concepts associated with it.'[50]

Complementarity is undoubtedly a form of dialectical contradiction and, as Bohr, his supporters and followers who

* According to Kant there are only four antinomies that the mind gets involved in when it attempts to cognise the world as a whole. It follows from his reasoning about them that he accepted the dialectical nature of human thought, and that is the great merit of his philosophy. The dialectics of the objective world, however, remained outside his philosophy with the unknowable thing-in-itself. Kant's theory of antinomies was corrected, extended, and generalised by the subsequent development of dialectics. In criticising Kant, Hegel rejected his agnosticism and noted that there were not just four antinomies, but that every concept was a unity of opposite elements that could be given the form of an antinomy.

developed his ideas have pointed out, the logic of this dialectical contradiction is also the logic of the development of atomic physics.

From the angle of the questions discussed above Heisenberg's *Physics and Philosophy* also presents great interest. Like Bohr's work, it contains certain new elements relating to philosophical views on quantum theory.

Unlike Bohr, Heisenberg actively opposed the principles of materialism. When speaking of 'materialistic ontology', however, he essentially had metaphysical, mechanistic materialism in mind. He did not reveal in his book that he was very familiar with dialectical materialism although one can find attacks on Marxist philosophy in places in the book that are hardly of serious philosophical significance.

Heisenberg stressed that the Copenhagen interpretation of quantum theory was 'in no way positivistic'. Positivism, he said, was 'based on the sensual perceptions of the observer as the elements of reality', while 'the Copenhagen interpretation regards things and processes which are describable in terms of classical concepts, i.e. the actual, as the foundation of any physical interpretation'. It was thus recognised, he continued, that 'the statistical nature of the laws of microscopic physics cannot be avoided, since any knowledge of the "actual" is—because of the quantum-theoretical laws—by its very nature an incomplete knowledge'.[51]

The Copenhagen interpretation is also not materialist, as Heisenberg has more than once pointed out. In this case he counterposed the Copenhagen interpretation to materialism. But as regards philosophy, the point is not what Heisenberg personally thought of this interpretation but how he dealt with the basic problem of philosophy. In his own words, 'the ontology of materialism rested upon the illusion that the kind of existence, the direct "actuality" of the world around us, can be extrapolated into the atomic range. This extrapolation is impossible, however'.[52]

According to Heisenberg physics is not so much concerned with nature itself, reflecting it in its concepts and theories, as it is concerned with the 'actual', i.e. nature transmitted as it were through man's perception, and which has already been subjected to certain methods of research.[53] In classical physics study of the 'actual' does not lead to difficulties of any kind, but in quantum theory, he says, these difficulties are unavoidable since the uncertainty relation limits the applicability of classical concepts to nature.

The need for a dialectical approach to atomic physics, evident in connection with the discovery of the unity of the particle and wave properties of atomic objects, is thus considered by Heisenberg as a need to revise the concept of objective reality in physics. One cannot, of course, disagree with Heisenberg when he says that expressing the achievements of modern physics in the concepts of the old philosophy can hardly yield any advantages, but he contradicts himself when he 'pours' the young wine of quantum physics into the old bottles of metaphysical and idealist philosophical systems.

In Heisenberg observed phenomena, things, and the actual are described by means of classical concepts; atomic and other micro-particles are characterised in terms of mathematical abstractions; both these aspects are in a mutually exclusive but complementary relationship which is the quintessence of the philosophy on which he bases quantum theory. In this respect he gives epistemological significance to 'complementarity', trying to resolve the problem of reality in physics in an allegedly new way. (It must be noted that the meaning of the term 'complementarity' in Bohr's essay *Quantum Physics and Philosophy*, as we have seen, is quite different.) Heisenberg's standpoint on reality is expressed particularly plainly in his polemic with opponents of the Copenhagen interpretation, including those scientists who defend the position of dialectical materialism in physics.

In Heisenberg's view the merit of the Copenhagen interpretation was that it 'led the physicists far away from the simple materialistic views that prevailed in the natural science of the nineteenth century'.[54] He disapproved of those who tried 'to return to the reality concept of classical physics or, to use a more general philosophic term, to the ontology of materialism. They would prefer to come back to the idea of an objective real world whose smallest parts exist objectively in the same sense as stones or trees exist, independently of whether or not we observe them'.[55]

Heisenberg thus identified, in fact unjustifiably, the philosophical concept of matter with classical physics' notion about it, and also failed in essence to notice the difference between 'objective reality' and the 'actual' or 'real'. Dialectical materialism, on the other hand, discriminates between them: e.g. the category of possibility, which plays an important role in philosophical questions of quantum theory, has (like the category of reality), an objective character from the standpoint of dialectical materialism. On this point dialectical materialism differs fundamentally from metaphysical, mechanical materialism, but Heisenberg did not notice this very essential difference.

Heisenberg perpetuated the language of classical concepts in physics and retained it to describe instrument readings, the actual, and the world of phenomena. As regards the essence of these phenomena, they appear, according to him, as peculiar Kantian 'things-in-themselves'—the mathematical abstractions of quantum theory are precisely such in his conception. It is not fortuitous that he believed the classical concepts to be somehow *a priori* with regard to the domains of the theory of relativity and quantum theory in which they were applied with the appropriate restrictions.

We noted above that the problems of quantum mechanics cannot be reduced to explaining the limited nature of classical concepts. Heisenberg's argument about the *a priori* character of the classical concepts ignored the dialectics of concepts, which reflects the dialectics of objective reality. The idea of the variability and evolution of concepts had already been current in science for a long time (although not all the scientists drew the appropriate philosophical conclusions from it). The development of non-classical physics has thus been accompanied with a change in the original meaning of concepts like mass and energy; they still have something in common with the original concepts but at the same time have acquired a deeper content.

The radical revision of classical concepts made by quantum mechanics indicates that our knowledge of objective reality, nature, and matter has become deeper. Fock, in reproaching the Copenhagen interpretation of this theory for its one-sidedness, justly noted the importance of the 'new primary concepts', which in his view were relativity in respect to the means of observation, the distinction between the potentially possible and the realised, and the concept of probability as a numerical measure of the potentially possible.[56]

Quantum theory confirms dialectical materialism and differs with metaphysical materialism. As for mechanical materialism, Heisenberg was right in a certain sense when he criticised 'materialist ontology'. His criticism, however, had nothing to do with dialectical materialism. It is impossible to take his words seriously that, since dialectical materialism was created in the nineteenth century, its 'concepts of matter and reality could not possibly be adapted to the results of the refined experimental technique of our days'.[57] (1) The very essence of dialectical materialism excludes dogmas of all kinds and inevitably alters its form with every fundamental discovery in science—both Engels and Lenin spoke directly about this very important feature of Marxist philosophy, drawing the appropriate conclusions in their philosophical works. (2) Heisenberg never analysed the dialectical materialist conception of matter and reality, which differs sharply from those of the old materialism. His statement that the concepts of Marxist philosophy 'could not possibly be adapted' to the results of modern pure and applied science is not supported by any arguments.

Heisenberg wrongly presented the objective dialectics of the particle-wave properties of atomic objects, which is demonstrated in the well-known experiments, as 'complementarity' of the mathematical symbolics relating to these objects and of the description of the atomic experiments in classical concepts. That is why the transition of physics from cognition of macro-phenomena to cognition of atomic, and in general microscopic, events is treated by Heisenberg not as a deepening of the human knowledge of matter and objective reality but as dissolution of the 'objectively real' world 'in the transparent clarity of a mathematics whose laws govern the possible and not the actual'.[58]

We must also mention, however, Heisenberg's wobbling between idealism and dialectical materialism. His reasoning about the 'complementarity' of particle and wave, the possible and the real, and the mathematical apparatus as form, and about the physical content of scientific theories certainly shows signs of his coming near to an understanding of the significance of the unity of opposites that is the nucleus of dialectics. The same needs be said about his ideas about the relativity of physical theories and matter.

In this connection Heisenberg's statements about the unity of matter deserve mention. Having presented the experimental data on elementary particles, and the discovery of the many forms of these particles, etc., Heisenberg concluded: 'These results seem at first sight to lead away from the idea of the unity of matter, since the number of fundamental units of matter seems to have again increased to values comparable to the number of different chemical elements. But this would not be a proper interpretation. The experiments have at the same time shown that the particles can be created from other particles or simply from the kinetic energy of such particles, and they can again disintegrate into other particles. Actually the experiments have shown the complete mutability of matter. All the elementary particles can, at sufficiently high energies, be transmuted into other particles, or they can simply be created from kinetic energy and can be annihilated into energy, for instance, into radiation. Therefore, we have here actually the final proof for the unity of matter. All the elementary particles are made of the same substance, which we may call energy or universal matter; they are just different forms in which matter can appear.'[59]

If we bear the philosophical aspect in mind and ignore certain inaccuracies in terminology, this statement undoubtedly expresses a materialist point of view.

Heisenberg, however, followed it up with: 'If we compare this situation with the Aristotelian concepts of matter and form, we can say that the matter of Aristotle, which is mere "potentia", should be compared to our concept of energy, which gets into "actuality" by means of the form, when the elementary particle is created'.[60]

In this regard, we may recall Heisenberg's words about the young wine of science and the old philosophical bottles. He does not see the new philosophy—dialectical materialism, which fully corresponds to the new physics.

The philosophical evolution of the Copenhagen interpretation still continues. The dialectical and materialistic elements in it have been strengthened in struggle with the metaphysical and, in particular, mechanistic ideas in atomic physics; the 'uncontrollability in principle' appears less and less frequently in the reasoning and arguments of the Copenhagen school. That this is how matters stand can be seen from the discussion on quantum theory between Alfred Landé, on the one hand, and Max Born, Walter Biem, and Werner Heisenberg, on the other hand, in 1969.[61]

Landé opposed Bohr's ideas and denied the interpretation of quantum theory by Born and Biem who, according to him, regarded matter and field as having equally a particle and a wave nature. He considered the Copenhagen interpretation to be positivist (introducing a new term 'dialectical positivism'). In Landé's view there is every reason to regard matter as simply a discontinuous formation and field as simply a continuous one.

In summarising the discussion Heisenberg disagreed with Landé, suggesting that it had not been about the physical content of quantum theory itself but had been dealing with the language that should be used to describe quantum-theory phenomena. He noted, in particular, that Landé's criticism of 'sloppy' formulations in the earlier literature on quantum theory was correct.

How can the problem of the language of quantum theory be solved? Neither the experimental facts nor logical considerations provide a criterion for answering this question. In that case, Heisenberg says, it is necessary to resort to historical arguments. A language has become established among physicists that had taken shape during the development of quantum theory. The concepts 'particle' and 'wave' borrowed from classical physics and the natural language had been equally employed to describe atomic phenomena regardless of whether formations with a non-zero rest mass (electrons, nucleons, mesons) were being described, or ones with zero rest mass (photons, neutrinos, phonons). The physicist, Heisenberg stressed, did not consider a quantum-mechanical description as dualistic. He had become accustomed to the fact that when this monistic description was translated into natural language various additional pictures might appear; the question, which picture was correct—the corpuscular or the wave—then had no meaning.

Heisenberg also concluded that the interpretation of quantum theory employed by Born and Biem was the historical product of physicists' forty-year experience with atomic phenomena that were explicable by quantum theory, rather than the result of dogmatic statements or agreement of some kind.

In our view, Heisenberg's argument essentially emphasises the dialectics of concepts in physics that was left out by Landé in trying to interpret quantum theory in the language of the concepts of classical physics.

4

Physical Reality

The question of physical reality arose and was developed in modern physics. In classical physics it was never actually formulated, or rather, it coincided with the question of objective reality. If the concept of physical reality was used in classical physics at all, it meant nothing other than acceptance of the objective reality of the physical world, which developed in accordance with one and the same invariable laws. Why, as we shall now see, has the question of physical reality now acquired special significance in arguments of a philosophical character about the theory of relativity and quantum theory?

The most important reason is that the phenomena and processes with which the modern physics is concerned are covered by its theories by means of methods and abstractions that appear strange from the point of view of the notions of classical physics. No physicist has ever seen an electron as he sees, say, a stone rolling down a mountain, or a sea wave. Ultraviolet light, however, is also invisible to man, and there are sounds that cannot be heard, but in these cases no special questions arise!

To put it briefly, let us recall simply that the observed phenomena by which the physicist forms judgements (draws inferences) about the electron and its motion in the atom, about the atomic nucleus, or, let us say, about objects moving with velocities close to the speed of light, create paradoxical theoretical situations in physics when it is attempted to interpret them in terms of the ideas and schemes of classical theories.

Generally speaking, modern physics does not generalise everyday experience but the experience pertaining to very refined phenomena that do not fit into classical physics' notions about nature. In such a refined experiment, for which high precision instruments are used, the physical facts are grasped by the cognising mind in a very complex way, through concepts of very different levels of abstraction (that appear strange from the angle of classical physics). As an example we can take the discovery of resonances (as extremely unstable elementary particles with a half-life of 10^{-23} second are called), which could not have been done without a whole chain of theoretical considerations that have nothing in common with classical ideas.*

So the physicist, who is not prepared to discard his belief in the objective reality of the external world and its knowability by man, becomes an eye-witness of the following situation: objective reality seems to escape cognition, while the concepts which, if one can so express it, helped to cognise the physical world, now refuse to serve. In Einstein's theory of relativity, for instance, space and time proved relative in contrast to the corresponding concepts of classical physics, according to which space and time are absolute. In quantum mechanics, in accordance with its central idea of Bohr's complementarity, something similar happened with the terms 'particle' and 'wave', which lost their significance of absolutes and acquired the sense, unusual for classical physics, of 'relativity to the means of observation'. The most typical feature of the relativistic quantum theory of elementary particles is the absence from it of the principle of constancy of the number of particles and recognition of the fact that particles appear and disappear during interaction.

The fundamental propositions of modern physics are necessarily bizarre, strange, and unconventional from the point of view of common sense and classical theory.

In the new circumstances of the development of physics of this kind the concept of physical reality ('the physically real') began to acquire a new meaning for physicists that it did not have in classical science. In order to identify and determine this new element, let us first briefly consider statements about physical reality of the founders of modern physics.

In Einstein and Infeld's *The Evolution of Physics* we read: 'We have seen new realities created by the advance of physics.' 'Physics really began with the invention of mass, force and an inertial system. These concepts are all free inventions.' 'For the physicist of the early nineteenth century,

* Resonances, let us note, even when they are moving with a velocity close to that of light, can cover a distance of an order of 10^{-13} centimetre during their life, and not more. They may thus be born and decay at almost one point. They cannot, therefore, be discovered by the conventional methods of nuclear physics (from visible traces of the trajectories of the passage of high-energy charged particles in a Wilson cloud chamber); the existence of resonances was discovered by indirect methods, through observation of their breakdown products.

the reality of our outer world consisted of particles with simple forces acting between them and depending only on the distance.' 'The difficulties connected with the deflection of the magnetic needle, the difficulties connected with the structure of the ether, induced us to create a more subtle reality. The important invention of the electromagnetic field appears.' 'Later developments both destroyed old concepts and created new ones. Absolute time and the inertial co-ordinate system were abandoned by the relativity theory.' 'The quantum theory again created new and essential features of our reality.' 'The reality created by modern physics is, indeed, far removed from the reality of the early days.'[62]

It does not follow at all from these statements that Einstein denied the objective reality of the physical world and suggested that the physicist's sole reality is allegedly his free inventions.

We could have wished, of course, that Einstein's remarks about reality have been more precise and unambiguous. There is no doubt that he adopted a materialist standpoint of recognising the objective reality of the external world cognised by physicists, although he did not always express it clearly and distinctly enough. Here, however, is an extract from his paper *Quantum Mechanics and Reality*, which no longer leaves any doubt: 'If one asks what are the typical features of the world of physical ideas, regardless of quantum theory, the following above all strikes one: physical concepts pertain to a real external world, i.e. they imply ideas about things that require a "real existence" (of a body, a field, etc.) that is independent of the perceiving subjects; on the other hand, these ideas are transformed to correspond as exactly as possible to the sensual impressions.'[63]

We must recall that Einstein thought quantum mechanics (as understood by Bohr and Heisenberg) to be incompatible with the fundamentals of physics formulated by him. He opposed the Copenhagen interpretation of quantum mechanics, considered it (bearing in mind the philosophical aspects of the discussions that arose in his time) as positivistic, and suggested that a complete and direct description of reality would be found, which in his view quantum mechanics in Bohr's interpretation did not give.

This matter has been discussed in the literature[64]; without going into details, we shall simply note that Einstein approached the physical meaning of quantum mechanics from the standpoint of the basic ideas of classical physics, i.e. in much the same way as his theory of relativity was approached by opponents of physical relativism. Let us return to his remarks about physical reality.

In making his objections to Einstein, Born believed that the latter borrowed his point of view on physical concepts' being free inventions of the human mind from conventionalists' opinions on concepts.[65] In fact, however, Einstein, in stating that physical concepts were free creations of human mind, was stressing (as he himself said) simply that they were 'not logically derivable from what is empirically given'.[66] This is a profound dialectical thought: the transition from the perceived results of observation to theoretical judgements about the observed phenomena, and also to the theory of these phenomena itself, is not by any means made through logical inferences of a formal character. As a matter of fact, Born was also saying the same thing when he analysed the method of mathematical hypothesis and the synthetic forecasts associated with it.[67]

What then was Born's standpoint on physical reality? At bottom it did not differ from the views of Bohr and Heisenberg (which were considered in detail in sections 2 and 3).

The main point of Born's argument about physical reality is that this question should be approached in terms of the concept of invariance taken from mathematics.

Born did not consider 'very apt' a statement common in the literature in connection with Bohr's ideas that it is impossible in quantum mechanics to speak of an objectively existing external world, or of a 'sharp distinction between subject and object'.[68] At the same time, he said, 'the naive approach to the problem of reality which was so successful in the classical or Newtonian period, has proved to be not satisfactory'.[69]

On the other hand, Born disagreed with positivists' understanding of reality according to which the concept of reality was either applied to atoms and electrons with a meaning other than to perceptible phenomena or its use was forbidden in general in science (as, for instance, the British positivist Herbert Dingle poses the matter). The microscope makes it possible to observe colloidal particles, the electron microscope, even large molecules. 'Where does that crude reality, in which the experimentalist lives, end, and where does the atomistic world, in which the idea of reality is illusion and anathema, begin?' Born asked, criticising contemporary positivists.

But although the boundary between the 'world of atoms' and 'macroscopic reality' established by positivism does not exist, they still differ from each other as quantum physics has demonstrated. Born asked whether 'any philosophy can give a definition of the concept of reality that is untainted' by 'the realities of a peasant or craftsman, a merchant or banker, a statesman or soldier'.[70] He answered his question positively and considered the key to it to be in the idea of invariance.

Born gave an example from the 'pre-scientific field': when a person sees a dog sitting beside him or jumping about or disappearing in the distance, all these different perceptions are unified in his subconsciousness as one and the same dog. 'I propose,' he said, 'to express this by saying that the mind constructs, by an unconscious process, invariants of perception, and that these are what ordinary man calls real things.'[71]

The same thing essentially happens, in Born's opinion, at the level of scientific cognition when instruments are used. Here 'the innumerable possible observations are linked again by some permanent features, invariants, which differ from those of ordinary perception, but are nevertheless in the same way indicators of things, objects, particles'.[72] In the theory of relativity, for example, such reality is the interval—the invariant of the spatial and temporal aspects; in quantum mechanics, the electrons and other atomic objects are the invariants of the corpuscular and wave aspects, which allows one to ascribe reality to them.

The views of the American physicist Richard P. Feynman are close to Born's opinions on the invariance. In the first volume of *The Feynman Lectures on Physics*, devoted to the special theory of relativity, one comes across various versions of the idea that the four-vector momentum is more 'real' than either the momentum or the energy alone, since the momentum (represented by the space components of the four-vector arrow) and the energy (represented by its time component) depend on the observer's point of view, i.e. on the frame of reference.[73] This statement does not differ essentially at all from the proposition (which can often be met in the literature) that Minkowski's interval is more real than its components—the spatial distance and the temporal duration.

When this material on the views of physicists on physical reality is compared with the way the problem of reality was treated in the history of philosophy, points of intersection of the lines of development of the corresponding ideas can be found. Let us just sketch it briefly.

The concept of reality is usually not separated from the more general concept of being and coincides with the concept of existence in historically known systems of philosophy, including contemporary philosophical theories, the content of the reality concept bearing the stamps of the basic assumptions of the corresponding system. For our theme the idea of 'degree of reality' first clearly formulated by scholastics, who ascribed the 'highest degree of reality' to God, who possessed the whole 'completeness of being', is important. In the fourteenth century dispute between the so-called realists and nominalists over the concept of reality occupied the foreground. The realists, whose conception originated in Plato's principles of idealism, said *universalia sunt realia*, i.e. that the existence was inherent in the universal as independent being above and independent of the individual. The nominalists raised objections to the realists, who most fully expressed the traditional scholastic philosophy; in the nominalists' view nothing existed in the real world except individual things that had certain general properties. Marx called nominalism 'the *first form* of materialism'.[74]

The realist and nominalist concepts were reborn in the subsequent historical development of philosophical thought, including modern bourgeois philosophy. Without making the relevant analysis we shall simply note that the ideas of realism are also manifested in special form in modern physics in the works of certain scientists.

In every outstanding philosophical system of modern times, materialist and idealist, the idea of degree of reality has been expressed and developed in one form or another. It can be found in the systems of Descartes, and of Spinoza, according to whom substance possessed the highest degree of reality. Locke believed that the so-called primary qualities of things (length, impenetrability, motion) had a greater degree of reality than secondary ones (colour, sound, smell).

According to Leibniz monads had the highest degree of reality. Hume supposed that impressions, either renewed by the consciousness or stable, had a greater reality than any others. In Kant we find a distinction between the 'empirical reality' of phenomena and categorial (abstract) reality. In his *Science of Logic* Hegel differentiated reality (*Realität*) from actuality (*Wirklichkeit*) as a unity of essence and existence, or of the internal and external. Contemporary bourgeois philosophy (e.g. logical positivism, critical realism) contains nothing new, compared with classical philosophy, on the question of reality.

* * *

Let us summarise what we have said about reality in physics and formulate certain statements relating to this concept that appear important to us.

The term 'reality' (the 'real') is used with several meanings. The most general of them is that of existence: the perceptible ball exists and the perception of the ball exists; a particle exists and a material point exists; a billiard ball exists and an ideal ball exists; an electron diffraction pattern exists and electron diffraction exists; matter exists and spirit exists; truth exists and error exists; they are all real in this sense of the term.

There is a difference between the 'real' in the sense of existence and the '*objectively real*'. The 'objectively real' or the 'objective' or the 'objectively existing' means existing independently of the human mind and reflected by it under certain conditions. In opposition to the objective the '*subjective*' means 'existing in consciousness'. The subjective or spiritual* (sensations and perceptions, concepts, judgments, etc.) can and do reflect the objectively real in certain conditions. This subjective functions in scientific theories and science as a whole, which objectively reflect the real world; it therefore also figures in physics and its theories. The subjective, however, may not reflect the objectively real because of errors and illusions; it appertains to man's subjective world. The natural sciences, of course, are not concerned with this world, or rather physics is concerned with material realities and not with spiritual ones. That is why, when we speak of 'the physical reality

* We abstract from the ambiguity of the term 'spirit'.

of a certain something', we mean that somehow or other the concept of this something does or should correspond to the objectively real.

The term 'real' ('reality') has another meaning of the 'actual' (or 'actuality'). It derives from the Latin *res* (thing, object); while the term 'actual' comes from 'act' (Latin *actus*) (German *wirklich* from *wirken*; Russian *deistvitel'nyi* from *deistvovat'*). The concept 'physical reality', as we shall see later, is closest of all to the concept 'actuality' (*Wirklichkeit*) in content and meaning.

The 'existing' and the 'actual' are by no means identical, and this difference is literally tangible in modern physics. With a Wilson cloud chamber, for instance, which was designed for observing the tracks of fast-moving, electrically-charged particles (electrons, protons, etc.), one can draw inferences about the nature and properties of these particles from the parameters of the visible tracks of their trajectories. But have we the right to infer from the data obtained that an electron moves 'in actuality' in the way a macro-particle does? Quantum theory, as we know, has given an answer to that; and it follows from this answer that (1) the 'existing' and the 'actual' in physics are by no means the same; and (2) that every 'objectively real' in physics is not thereby 'actual' in a certain theory, but every 'actual' in a physical theory is 'objectively real'.*

The question of physical reality, as it is considered at present, cannot be comprehended outside the 'epistemological lesson' (Bohr) that the development of modern physics has given scientists. What is the essence of this lesson? In classical physics the observed phenomena made it possible to obtain information (at least in principle) about the behaviour of objects regardless of their interaction with the means of observation (measuring instruments). In quantum physics the observed phenomena also provide information about the experimental conditions, which can no longer be ignored in principle, in other words, quantum phenomena characterise the properties of the 'whole experimental situation' rather than those of the object 'by itself'. In short, from the point of view of quantum physics the experimental physicist has proved to be, figuratively speak-

* It must be remembered that physics, as a natural science, deals with material realities.

ing, not simply a spectator but an actor in the drama of cognition, so it is put in the literature on quantum theory as is well known. Hence corresponding problems of physical reality arose.

It seems to us, however, that the content of the 'epistemological lesson' that Bohr spoke about is much broader. Classical science considered it its job to find the universal constant laws of nature. Modern physics has rejected such an approach from its very inception: classical mechanics is a limiting case of the special theory of relativity and quantum mechanics, i.e. of the more general and deeper theories; the special theory of relativity is the limiting case of Einstein's theory of gravitation; quantum electrodynamics has developed and quantum field theory is being built; and ideas are voiced about the future of physics belonging to even more general and profound fundamental theories than those now existing. In other words, for modern physics it is essential not only to find the laws of the phenomena existing in a certain system (circle) of interrelations, but it is also important (this question arises sooner or later in one form or another at a certain stage of its development) to find the laws of the transition from the laws of one sphere of phenomena to the deeper, more general laws (which must and will be found) of a new, wider circle of phenomena.

Modern physics thus undermined the prejudice of the old contemplative materialism, according to which cognition, i.e. reflection of nature by the human brain, should be understood 'abstractly', 'devoid of movement', 'without contradiction',[75] a philosophical prejudice that in essence was supported by classical science. With the creation of the theory of relativity and quantum theory Lenin's idea of cognition found expression in physics: 'Man cannot comprehend=reflect=mirror nature *as a whole*, in its completeness, its "immediate totality", he can only *eternally* come closer to this, creating abstractions, concepts, laws, a scientific picture of the world, etc., etc.'[76]

That spatial and temporal quantities prove to be dependent in the theory of relativity on the frame of reference chosen by the observer, or that in quantum mechanics, in Bohr's words, 'any observation of atomic phenomena will involve an interaction with the agency of observation not to be neglected'[77] does not in the least mean that the theory of relativity and quantum mechanics in addition to employing their principles and concepts allegedly imply some degree of subjectivity, some reference to the observing subject, some special activity of the observer. On the contrary, these and similar features, which are typical of the relativistic or quantum method of describing phenomena mean that the physical knowledge has penetrated deeper, that the new concepts and principles developed by modern physics reflect nature's patterns more correctly and completely than those of classical theories.

When we turn, say, to quantum mechanics, the wave and particle pictures of the behaviour of electrons* observed through the appropriate set-up; the concept of relativity with respect to the means of observation plus the complementarity principle interpreted in the sense that only the aggregate of 'complementary' phenomena can provide complete information about the behaviour of a micro-object; the concept of the electron as a physical substance possessing certain invariant characteristics; and the Schrödinger equation which is invariant with respect to unitary transformations—all these are levels of cognition of the moving electron which combine to form an integral theory embracing the experimental data.

On this plane the concepts and statements of the quantum theory listed above reflect the objectively real. In exactly the same way 'probability' in quantum mechanics, mathematically represented by the square of the modulus of the wave function, is physically real, i.e. its physical concept reflects the objectively real and is by no means just a 'pure' construction of the physicist's.

These considerations concerning quantum mechanics, and similar arguments about Einstein's theory (we neglect them here), have a direct bearing on the problem of physical reality. Construction of a theory of a certain circle of phenomena solves the problem of the reproduction in thought of the object of this theory as it exists in actuality, i.e. as a concrete integrity of phenomena and substance (the causal relation, basic laws), of the external and the internal, or as a unity of the diverse.

The construction of a theory provides the most complete knowledge of its object, and from that point of view, if we

* The term 'electron' is used here for brevity's sake to denote any quantum object.

consider the examples above, physicists' statements that the space-time continuum is 'more real' than either space or time separately, are logically justified.

From the same point of view the hypertrophy of any one aspect of the cognition of something, and neglect of the fact that unity exists in its many-sidedness, leads in the final analysis to subjectivism and conclusions of an idealist and metaphysical character. A similar situation arises in the theory of relativity if 'relativity' is absolutised and one is abstracted from the fact that space and time are aspects of a single space-time.[78] An analogous situation arises in quantum theory when the idea of interaction of atomic objects and the measuring instruments (which causes the 'uncontrollability in principle') is overemphasised and it is forgotten that complementary experiments 'only in combination with each other disclose all that can be learned about an object'.[79]

In connection with what has been said one cannot help agreeing with Bohr who raised objections to Heisenberg and Dirac on how one should speak of the emergence of phenomena that permitted only predictions of a statistical character. According to Dirac, we are dealing here with choice by 'nature' when the point in question is the realisation of one individual effect (from the number of possible ones); according to Heisenberg, with choice by the 'observer' who built the measuring instruments and took the readings. 'Any such terminology,' Bohr said, 'would, however, appear dubious since, on the one hand, it is hardly reasonable to endow nature with volition in the ordinary sense, while, on the other hand, it is certainly not possible for the observer to influence the events which may appear under the conditions he has arranged.' Bohr believed that 'there is no other alternative than to admit that, in this field of experience, we are dealing with individual phenomena and that our possibilities of handling the measuring instruments allow us only to make a choice between the different complementary types of phenomena we want to study'.[80]

The rise of new relative concepts in science, and at the same time of new, more profound and more general theories in which they figure (e.g. the concepts of relative space and time in the theory of relativity, which is a new theory in regard to classical physics) does not mean the increase in elements of subjectivity (since the new types of reference system appear that have not been known before); it means a new step in understanding nature. Indeed, first, the new relative concepts reflect the objectively real; second, the appearance of new 'relativities', more meaningful than those known before, means the finding of limits of applicability of the absolute (invariant) concepts of the old theory (from which the new one was developed).

The concept of physical reality thus comes into modern physical literature also as a kind of synonym of the philosophical concept of actuality in the sense of dialectical materialism. It seems to us that it is logically legitimate to employ the terms 'empirically real' ('empirical reality') and 'abstractly real' ('abstract reality'). The first of these denotes that which exists independently of the human mind (the objectively real) and is embraced by that stage of cognition which is called living contemplation and without which there can be no observation. The second term denotes the objective reality that is reflected at a deeper level of human understanding—the abstract thinking that reveals the essence of cognised phenomena, the laws of nature. But the deepest and the most complete cognition of an object that exists independently of the human mind is achieved by combining observation and abstract thinking (we could rightly use the term 'dialectical thinking' here) when a scientific theory reflecting its object as reality, i.e. as a united whole of numerous aspects and their relations, is constructed logically on the basis of practice and acquires certain integrity and relative validity.

Physical reality is thus the objective reality cognised in a physical theory, the content of the concept of which becomes definite depending on the definiteness of the theory itself as such and the stages (elements) of its structure.

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III

CAN WE FORM MENTAL PICTURES OF THE CONCEPTS AND THEORIES OF MODERN PHYSICS?

Visualisation is a problem of considerable philosophical significance in modern physical theory, especially in quantum theory. Suffice it to recall that the absence of a mental picture in quantum mechanics, as it seemed (unlike classical theory), used to be employed by individual physicists as a proof of sorts simply of the tentative nature of those of its general ideas that gave it a revolutionary character. The problem could not help occupying a prominent place in the work of the founders of quantum theory.

Dirac, for instance, said that nature's 'fundamental laws do not govern the world as it appears in our mental picture in any very direct way, but instead they control a substratum of which we cannot form a mental picture without introducing irrelevancies'. Quantum theory, moreover, according to him, is built up 'from physical concepts which cannot be explained in terms of things previously known to the student, which cannot even be explained adequately in words at all'.[1] We shall return to these ideas of Dirac's below.

Let us also note Niels Bohr's analysis of issues relating in one way or another to this problem. One must agree, in particular, with his statement that '*however far the phenomena transcend the scope of classical physical explanation, the account of all evidence must be expressed in classical terms*'.[2]

At the same time, according to him, 'an adequate tool for a complementary way of description is offered precisely by the quantum-mechanical formalism which represents a purely symbolic scheme permitting only predictions, on lines of the correspondence principle, as to results obtainable under conditions specified by means of classical concepts'.[3] This apparatus, Bohr says, is an appropriate means of describing 'complementary phenomena', i.e. phenomena observed in mutually exclusive experimental set-ups permitting the particle and wave properties of atomic objects to be discovered.

The idea of complementarity thus served Bohr as the key to the visualised interpretation of atomic processes. That this is the case is strikingly clear in his essay 'Quantum Physics and Philosophy', in which he wrote in particular: 'the limited commutability of the symbols by which such variables are represented in the quantum formalism [i.e. the quantities that characterise the state of a physical system in classical mechanics—*M. O.*] corresponds to the mutual exclusion of the experimental arrangements required for their unambiguous definition.'[4]

The problem of forming a mental picture is directly related to the trends in philosophy. The concept of visualisation, which arose on the soil of everyday experience and is linked with common sense, is not accepted by idealism, which disclaims its significance in man's cognitive activity. Materialism, on the contrary, accepts it and develops it in depth (which also applies to dialectical materialism).

An example of a point of view on visualisation in quantum physics that is close to the views of objective idealism is provided by Heisenberg's considerations on the complementarity of the mathematical symbolics relating to the atomic world, and its description in terms of the concepts of classical physics, which were discussed in Chapter II.

Positivists, if they are consistent, do not think in the least how to connect the content of the mathematical concepts of quantum theory with those of the natural language. The mathematical apparatus of quantum mechanics makes it possible to give order to the observed results, e.g. to predict the possible results of some observations from those of other observations, and that quite suits positivists.[5]

The line of materialism on the problem of a mental picture of a physical theory implies recognition of the dialectical unity of sensuous knowledge and abstract thinking reflecting objective reality. The combination in a single whole of the mathematical formalism of the physical theory and the experimental data and results relating to this theory and expressed in the concepts of classical physics corresponds to the point of view of dialectical materialism on the problem of visualisation. One must bear in mind that the nature of this combination differs from how it is presented from the standpoint of non-dialectical materialism, as will become quite clear from the exposition that follows.

Born, incidentally, when discussing this problem and analysing various philosophical approaches in that connection, did not expound the point of view of Marxist philosophy on this problem in an adequate way. He stated that, according to dialectical materialism, it was sufficient to limit oneself to 'the objective world of formulas without relation to sensual intuition'.[6] As has already been said above, the point is quite different: this chapter is devoted to elucidating issues relating to the problem of visualisability in physics from the point of view of dialectical materialism.

* * *

In our view, quantum mechanics reflects exactly, in precise concepts, the motion of atomic objects that resembles the motion of particles in some experimental conditions and in others the spread of waves and that differs radically from them both (with which classical theory is concerned). At the same time—and this has to be emphasised in every possible way—this motion is not picturable, i.e. it cannot be expressed in a visual picture like that in which the motion of a macroscopic body or the 'wave motion' of a certain continuum is represented. In this sense it is said that quantum theory cannot be visualised. As the German physicist Gerhard Heber puts it: 'Although we describe the nature of atomic objects mathematically, we cannot understand it on the model level. It is usually said in this connection that the nature of quantum-mechanical objects is "not obvious". I would assume that our inability to construct a visual model of the microworld is not final, and that it will be possible in the future to build a visual model of atomic objects, because our power of sensual intuition is as capable of development as our power of abstraction.'[7]

That atomic objects are only described mathematically by modern quantum mechanics, and that there are not as yet the appropriate words and images for them, is only partially, so to say, true. One has to bear in mind that quantum theory, like the other 'not visualisable' theories of modern physics, is being confirmed by experiment and has grown up on that basis. And that means that quantum mechanics employs visualisable concepts (and others directly related to them) in one way or another, because its truth is verified by means of instruments that are macroscopic bodies, and their readings, from which inferences about atomic objects are drawn, are perceived by man. If this question is posed more broadly it cannot be otherwise: the atomic objects are material realities, and matter is not simply and only that which exists objectively independently of the human mind, but is the objective reality acting on the human sense organs and producing sensations in them. Man would have known nothing about the atomic world existing independently of his mind if this world, so to say, had not given signs of itself through macroscopic phenomena perceived by him which are related in a regular manner with atomic and microscopic phenomena in general.

Thus, visual concepts are one way or another inevitable in quantum theory. The question is, however, how and in what form do they come into quantum theory. To answer that let us first consider the definition of the concept of a mental picture or visualisation.

A theory is most frequently called easy to visualise if it employs habitual concepts. The concept has been defined in roughly this way by the Austrian physicist Arthur March.[8] Such a rather psychological definition can hardly, because of its extremely arbitrary nature, be accepted as satisfactory. Many authors add that a picturable theory is one that deals with phenomena that can be perceived directly.[9]

This last criterion of visualisation or obviousness of a theory, though to some extent satisfactory in itself, was not, in practice, separated in physics from certain other requirements of principle that in fact confused the matter. Thus, when mechanistic views were dominant, it actually meant a requirement for all physical phenomena to be reduced to mechanical ones. In this case Maxwell's electromagnetic theory, for example, proved not to be 'visualisable' as Boltzmann, in particular, suggested. In our day, when physicists have become accustomed to the fact that electromagnetic phenomena cannot be reduced to mechanical ones, Maxwell's theory has come to be called obvious.[10]

When we turn to quantum mechanics, it would seem that the same situation as with Maxwell's theory has developed in it. It has become quite clear that macroscopic phenomena cannot be reduced to atomic ones, and vice versa. Quantum mechanics has also become a 'normal' theory, but it is regarded, as we know, as a theory about which we cannot form a mental picture. L. I. Mandelstam, in particular, stressed this; March, too, drew attention to it in his many discussions of the philosophical problems of science. He called a theory obvious or visualisable (*anschaulich*) that employed 'only concepts ... borrowed from the world of everyday experience', but quantum mechanics 'forbids the use of certain concepts, in which we are accustomed to think, as misleading'.[11] Then why, in his opinion, is Maxwell's electromagnetic theory visualisable?

So, we have not yet advanced a single step in our reasoning about 'mental picturing' (*anschaulichkeit*). What theory is easy to visualise? Let us return to this question.

Man in his historical practice has had to deal millions upon millions of times with macroscopic phenomena that occur at relatively low velocities. This practice also led to the theories and concepts of classical physics, the first scientific generalisation of notions about the inanimate nature perceived by man (historically the first such theory was Newton's mechanics), acquiring a visual form in his mind. It meant that it was possible to imagine, on the basis of the propositions and concepts of the theory of an object, the sensual impressions and perceptions produced in man by the object being studied.

When, for instance, starting from the concept of a moving particle in classical mechanics (an object characterised simultaneously by its position and by its momentum) we state that the particle is a visual concept, we associate notions of a stone, a pellet, a bullet, a grain of sand with the concept 'particle'. In fact, we picture, say, that a bullet flying from the muzzle of a pistol passes through a thin cardboard disk leaving a hole in it.

On the other hand, we have every reason to believe that the pistol bullet is exactly a particle. Let the flying bullet pass through two disks rotating at a high angular velocity around a common axis, at a short distance from each other (with such a system one can measure the bullet's velocity).[12] In this example the holes in the disks represent coordinates (position); the bullet's momentum can be determined from its mass, the distance between the disks, and the time it took to cover this distance. In general the classical notion of a moving particle is the physical generalisation of notions of the mechanical behaviour of a stone, a grain of sand, a bullet, and other similar objects that man has to do with in everyday life. This concept, when considered from the formally theoretical aspect, corresponds to the system of axioms (basic principles) of Newton's classical mechanics.

One should not, however, confuse the 'mental picture' of concepts and theories in classical physics with the 'mental picture', say, of the concepts of common sense that had been developed by man in his everyday experience even before there was any science, or to confuse it with the imaginability of the objects being studied. One cannot, for instance, imagine a motion with a velocity of 300,000 kilometres per second as one can imagine motion with a velocity of five kilometres an hour (the motion of a pedestrian) or with a velocity of 100 kilometres an hour (the motion of a motor car). Ultraviolet radiation (a traditional example) cannot be imagined either.

And at the same time the concepts with which classical physics operates are easy to visualise. Thus, the concept 'motion with a velocity of 300,000 kilometres per second' is associated with the idea of a certain solid (a scale) that is laid a certain number of times along a straight line, and the idea of the time during which the hand of a watch passes through a certain interval on a certain line. The same can be said *mutatis mutandis* about the 'mental picture' of many other concepts and statements of classical physics. The concepts 'force' or 'mass', for example, do not coincide with the corresponding ideas from everyday life; the law of inertia is by no means a commonsense statement.

What we have said should illustrate the idea that 'visualisation' is not identical with the 'representability' or 'imaginability'. Classical physics takes from 'sensuous representation' (living contemplation) the appropriate material to be worked on by thought. Non-classical physics does the same thing but in its own manner. Classical theories, however, do not move as far from 'representation' as non-classical ones do. The problem is to determine how the concepts and abstract notions of classical and non-classical physics are related.

In dealing with this problem Lenin's following note concerning Hegel's arguments about the relation of idea to thought is of decisive philosophical significance: '"Come before consciousness without mutual contact" (the object)—that is the essence of anti-dialectics. It is only here that Hegel has, as it were, allowed the ass's ears of idealism to show themselves—by referring time and space (in connection with sensuous representation) to something *lower* compared with *thought*. Incidentally, in a *certain* sense, sensuous representation is, of course, lower. The crux lies in the fact that thought must *apprehend* the whole "representation" in its movement, but *for that thought* must be dialectical. Is sensuous representation *closer* to reality than thought? Both yes and no. Sensuous representation cannot apprehend movement *as a whole*, it cannot, for example, apprehend movement with a speed of 300,000 km per second, but *thought* does and must apprehend it. Thought, taken from sensuous representation, also reflects reality; time is a form of being of objective reality. Here, in the concept of time (and not in the relation of sensuous representation to thought) is the idealism of Hegel.'[13]

In this note of Lenin's the statements that are especially important for our topic are those from which it follows that sensuous representation and thought are interrelated, that thought, growing from sensuous representation and reflecting reality more deeply and completely than sensuous representation, embraces all sensuous representation in its movement as though making it an element of itself. From this point of view the abstractions and the relations between them that are contained in a physical theory in the form of a mathematical apparatus must necessarily be connected with the directly perceptible material provided by experiment. In classical physics, for instance, the values of its variables and functions, and in quantum mechanics the eigenvalues of its operators, correspond to the values of the corresponding physical quantities observed in the experiment.

In general, no theory in physics, if it is to and does grasp objective reality, can avoid establishing a connection between its mathematical concepts, on the one hand, and the perceptible readings of the experimental set-ups that inform about this reality, on the other. It is only this connection that makes a theory in physics a truly physical theory. In this sense, no non-classical theory can be substantiated without classical physical theories, since it is impossible to describe the experimental results without employing classical concepts. The philosophical roots of all this are that nature, with which physics deals, represents moving matter, and that cognition of matter (of any of its forms and structures) is impossible without its (direct or indirect) effect on the human sense organs. In this case it is appropriate to quote the words 'the sensuous, physical (excellent equating!)' that Lenin uttered in connection with certain ideas of Feuerbach's.[14]

* * *

How are sensuous representation and thought related and connected in physical theory?

If we take a physical theory in its developed form—not simply in its aspect of formalism, but as a physical theory—it treats its subject-matter simultaneously as it were in its aspects of sensuous representation and thought. The experimental set-ups provide sensually perceptible data about phenomena being investigated by the physical theory, while the mathematical apparatus, which represents a system of abstract concepts, makes it possible to raise these data to the level of theoretical generalisation and so to reflect the laws of the phenomena concerned. In accordance with what we have said a physical concept appears as a result of a dual sensuous and abstract thought process of understanding objective reality. The transition from the perceptible readings of an instrument (which inform about the phenomenon concerned) to mathematical concepts, and the reverse transition from mathematical concepts to instrument readings are effected by certain rules and imply the existence of laws of the phenomena being studied. These rules of the connection or relationship between mathematical concepts and perceptible instrument readings should (and in reality do) reflect these laws, and find expression depending on the specific nature of the regularities of the field of the phenomena being investigated.

Quantum mechanics broke with the mechanistic prejudice that the laws of macroscopic phenomena also operate in the microworld. This circumstance, however, only explicitly affected the mathematical apparatus of the theory; as for the rules of the connection between mathematical concepts and instrument readings, this matter is frequently either presented in the literature of quantum mechanics in an uncertain way (without answering whether or not the corresponding rules in classical and quantum theory should coincide) or is posed in such a form that fundamental concepts of classical theory are only 'limited'. Heisenberg, for instance, says that 'the first language that emerges from the process of scientific clarification is in theoretical physics usually a mathematical language, the mathematical scheme, which allows one to predict the results of experiments'.[15]

The converse of this statement, as we know, is Heisenberg's own statements that the classical fundamental concepts are in some sense *a priori* with respect to Einstein's theory and quantum theory, i.e. that no new primary physical (and not just mathematical) concepts have allegedly been introduced by the theory of relativity and quantum theory. In order to follow through a point of view consistently that holds that the laws of macroscopic phenomena are qualitatively different from those of the microworld, it is necessary to follow this same point of view in matters relating to the combination of experimental facts and theories, to the combination of the sensually perceptible and mentally abstract in the understanding of physical phenomena, and to the connection between physical notions and mathematical concepts in the physical theory.

Let us consider these questions in greater detail.

A child who plays with a cat for the first time combines individual sensations (through the action of the first signalling system) (it sees the cat and hears its mewing) into an impression of a definite cat. At the same time a kind of 'generalisation' of the acquired conditional reflex occurs: the child reacts in the same way to similar cats with whom he happens to play. The general concept 'cat', however, only develops in the child's mind when he learns about cats from grown-ups' stories, reading of the appropriate books (in transfer of the results of mankind's centuries-long practice the second signalling system plays the main role), and now every individual cat for him is a member of the genus 'cat'. In that way, even first acquaintance with the objects surrounding man contains embryos of the connection between and unity of the sensually perceptible and mentally abstract. The unity of sensual and abstract cognition (underlying which is man's practical relation to nature) reflects the dialectics of the objectively real world.

This example, which is unrelated to physics, can help us in considering the problem posed above, since the process of forming a physical concept does not differ essentially, from the logical aspect, from the process of forming the concepts of everyday life.

In classical theories physical concepts for the most part represent a direct generalisation of notions that are employed by so-called common sense. The physical concept of length, for instance, represents a generalisation of the fact that perceived things possess various extensions. The comparisons of dimensions made billions of times by man in practice before systematic scientific investigation of nature led to the development of scientific concepts of a constant scale and units of length, and through the latter to rules of the correspondence between the lengths of perceived things and certain numbers. The length of every perceived thing could thus now be measured precisely, i.e. generally speaking, the concepts developed in everyday experience and mathematical abstractions could now be unified in that profound synthesis of sensual and abstract cognition without which physics as a science does not exist.

It would be the purest pedantry, of course, to demand that all the physical concepts figuring in classical and non-classical theories should arise in exactly this way, i.e. in a way by which a physicist always proceeds from the perceptible readings of an instrument to mathematical abstraction. That way is typical of the concepts of classical mechanics, for the reason that the latter arose directly from everyday experience and took shape before the other theories of classical physics, serving for some time as their model of scientific cognition.

The mathematical apparatus of a physical theory (which is interpreted here as a theory *at the stage of formation*), which represents a certain system of abstractions, possesses relative independence and has its own logic of development; by virtue of that certain concepts appear initially in certain conditions in a physical theory, which is becoming established, as a mathematical abstraction; only later is the physical meaning of the mathematical concepts revealed, i.e. they find, as one says, their physical or empirical interpretation. Discovery of the physical meaning of mathematical abstractions is a most important necessary aspect of the development of a physical theory. Without it the theory is, after all, a mathematical scheme and not a *physical* theory. Only this aspect gives mathematical abstractions physical flesh; consequently, only by taking it into account is it possible to formulate the laws of those physical phenomena that must be reflected by the theory; which means to give the physical theory a really developed form.

In modern physics, which deals with phenomena that are not directly perceptible, the second way of forming physical concepts is typical, i.e. when the physicist proceeds from mathematical abstractions to perceptible instrument readings (which inform of the things being studied). This is shown convincingly by quantum mechanics.

How were quantum concepts developed?

Planck's hypothesis about the discontinuity of the possible values of an oscillator's energy, which diverged in principle from classical notions, made it possible to explain the laws of thermal radiation. Even at the first stage of quantum theory the development of this hypothesis led to outstanding discoveries: e.g. Einstein's discovery of photons; creation of the theory of the heat capacity of solids; Bohr's atomic model; and the explanation of Ritz's empirical rule followed by the spectral lines of atoms, etc.

One must note that even at the initial stage of quantum theory the physical content of the assumptions made remained unclear: the heuristic role of the mathematical form was pushed to the foreground (an example of that is scientists' numerous attempts to comprehend physically Planck's formula $\varepsilon = h\nu$ at the dawn of quantum theory).

The further development of quantum theory consisted, above all, in finding the mathematical apparatus to express the statement of the discontinuity of energy. Only then did it become possible to bring out the physical sense of all the quantities involved in the mathematical apparatus, and consequently to carry solution of the problem of creating atomic mechanics through to completion. All this equally applies to the matrix mechanics of Heisenberg and Born and to the wave mechanics of de Broglie and Schrödinger, the two roots, as Born put it, of quantum mechanics, which was given contemporary form by Dirac. Schrödinger, for instance, compared the hypothesis about the discontinuity of energy states in micro-objects and the mathematical equation he had formulated, which he had obtained by employing the mathematical apparatus of the classical theory of vibrations assuming that the quantities describing the behaviour of micro-objects were associated with relationships of this apparatus that had been altered in a certain way. He supposed, further, that some operator of a certain class corresponded to energy, and its eigenvalues to the energy values observed in the experiment.

This assumption together with the established equation already made it possible to obtain fruitful results, e.g. to substantiate the Balmer series and explain the Stark effect.

An important role has been played in the development of quantum mechanics by finding the physical meaning of the wave function which figures in the Schrödinger equation. This wave function characterises the state of a micro-object in certain macroscopic conditions. It is it that makes it possible to effect the transition from operators to the values of quantum quantities observed in experiment.

If the wave function is the eigenfunction of an operator of a physical quantity (say, of position), then, according to the basic postulates of quantum mechanics, the operator's eigenvalue corresponding to this function is a possible value of the quantity (in an experiment with electrons it corresponds to the position of the spot observed on the screen).

If the wave function is not an eigenfunction of the (physical) quantity's operator (assuming, again, a quantum position) this quantity (in the state characterised by this wave function) has no definite value (in the experiment with electrons it corresponds to the distribution density of the observed spots on the screen). Max Born suggested interpreting the square of the modulus of the wave function $|\psi(x)|^2$ as the probability of an electron's hitting a point with a coordinate x. In accordance with this interpretation of the wave function it is stated that a quantity in a state characterised by a wave function that is not an eigenfunction of its operator has only an average value. The value can be computed from the mathematical apparatus of quantum mechanics if the wave function characterising the state of the micro-object is known.

Generally speaking, only some of the quantities appertaining to a micro-object in a given state have definite values in quantum mechanics; all other quantities (in the same state) have only average values and not definite ones. This is closely related to the specific feature of the wave function which consists in its coinciding with the eigenfunctions of some operators and not with those of others.

This last feature of the wave function follows from the central point of quantum mechanics, viz. the so-called commutation relation. From this relation it can be deduced that the state of a micro-object is a common eigenstate of any two quantum quantities only if the operators corresponding to these quantities are commutative. Thus, from the commutation relation for the operators of momentum and position $\hat{P}_x\hat{X} - \hat{X}\hat{P}_x = \frac{\hbar}{i}$ one can derive that momentum and position cannot have definite values simultaneously in quantum mechanics.

The commutation relation expresses the unity of the opposite particle-wave properties of micro-objects in the form of mathematical abstractions. The establishing of this relation and the finding of its connection with the particle and wave pictures formed by micro-objects and observed in experiment are an excellent example of the dialectics of nature and its cognition by man.

* * *

We can now bring together our discussion of the problem of the visualisation of classical and quantum concepts, including the question of the role of classical concepts in quantum theory.

There is an element of imaginability in both classical and quantum physical concepts: if there is no connection between the perceptible readings of instruments and the values of variables (in the case of classical theory) and the eigenvalues of operators (in the case of quantum theory), there would be no physical concepts in either classical or quantum theory. In classical theory, however, concepts are a direct generalisation of the observation data; the concepts in quantum theory are not such a direct generalisation, but instead generalise the observation material in a mediated way through classical concepts.

The eigenvalues of quantum operators correspond to observation data (the readings of instruments) in exactly the same way as the values of classical variables correspond to the data of observation; for example, the position of a spot on the screen in an electron diffraction experiment and the position of the hole in a disk pierced by a bullet are measured by a constant scale with appropriate divisions. In other words, it is never possible in measuring quantum quantities to do without classical concepts.

At the same time the dual particle-wave nature of micro-objects is reflected in the mathematical apparatus of quantum mechanics and this puts its stamp on the classical concepts used in quantum theory. Thus one can infer from the commutation relation $\hat{P}_x\hat{X} - \hat{X}\hat{P}_x = \frac{\hbar}{i}$ that eigenvalues of the momentum and position operators do not exist for one and the same state. It follows from this that the classical concept of a moving particle cannot be employed in quantum mechanics in exactly the same way as in classical theory (as we noted above the term 'moving particle' is applied in classical mechanics to an object that simultaneously has position and momentum). In other words the particle and wave characteristics, when applied to atomic phenomena, lose their 'classical' independence and become connected as it were, implying one another.

This means that the so-called relativity of the state of a micro-object (i.e. the fact that the state of an object is not determined in quantum mechanics regardless of the experimental set-up by which the object is being studied but only in connection with this set-up, in connection with the conditions fixed by it) is a manifestation of the dual particle-wave nature of micro-objects.

Micro-objects do not behave in a single experiment in the same way as waves or particles of the macroworld. At the same time, since only classical concepts can be employed to describe the observed phenomena, the classical particle and wave concepts should be treated in experiments with micro-objects as mutually exclusive, and the experimental conditions under which corpuscular phenomena are observed as incompatible with the conditions in which one observes wave phenomena, and vice versa. The contradiction is resolved by introducing new physical quantum concepts that have features similar to those of the corresponding classical concepts but differ radically from them.[16]

In conclusion we shall try to answer the following question. In which precise language can one speak about the micro-objects themselves? Is the refined and developed natural language appropriate for this or is such a language unsuitable for this purpose?

According to positivists, this question has no meaning; many scientists, however, including those whose philosophical sympathies are far from materialism, do pose it.[17]

From the foregoing discussion we find that such a precise language does exist and that it has developed from the language of classical theories; the job of constructing such a language was solved by Bohr's complementarity principle, which was developed further by his successors. The corresponding classical concepts (e.g. the concept of a moving particle), which proved to be imprecise when applied to phenomena on an atomic scale, were radically transformed and defined as concepts relating to the system of concepts and principles of quantum mechanics, which system differs radically from the system of concepts and principles underlying classical theories. This found expression in a new formalism and correspondingly new rules of the relation of mathematical concepts and the observed results in quantum mechanics (described in the language of classical notions), compared with the formalism and rules of connection in classical theories.

An element of visualisation is present in quantum physical concepts and quantum theory but the concepts themselves and the theory are not easily visualised. Here a very important role was played by the development of the concept of relativity to the means of observation, without which it would have been impossible to comprehend quantum mechanics as a physical theory, and which is a further generalisation and development of the concept of relativity with respect to frames of reference in the theory of relativity and classical mechanics.

The physical concepts in any physical theory, either classical or non-classical, are thus not the instrument readings and not mathematical abstractions; in physical concepts reflecting objective reality the two are combined, and it is they that are precise physical concepts; they are precise because they correspond to objective reality.[18]

There are other conceptions in the literature of the matter under discussion. We shall only mention the attempt to formulate an exact language corresponding to the mathematical formalism of quantum mechanics but having nothing to do with 'visualisation' and suggesting a change in the laws of conventional formal logic.

So-called quantum logic (Reichenbach, Weizsäcker) ascribes not two values of truth to statements ('truth' and 'falsity'), as conventional logic does, but three—'truth', 'falsity' and 'uncertainty'. This 'uncertainty' is not equivalent to 'ignorance'; rather it characterises a special type of situation. The principle of the excluded third ('a statement is either true or false, *tertium non datur*') does not operate in quantum logic. The following example is quite demonstrative in this respect: if one says that an electron passing through a screen with two apertures 'has not passed through a certain aperture', it still does not follow that 'it certainly passed through some other aperture'; there is a third possibility: 'the electron's passage through the aperture is uncertain' (this possibility is by no means equivalent to our ignorance of which hole the electron has passed through).

From the point of view of 'quantum logic' in Weizsäcker's presentation of it, it follows that any visualisation is excluded from quantum mechanics, and that there is a logical and epistemological gap between it and classical theory. This follows if only because ordinary logic is the logic of the everyday, refined natural language that is the language of the concepts of classical physics.

The question is whether deviations from everyday language and ordinary logic like Weizsäcker's quantum logic are still needed if one has in mind explanation of the phenomena on an atomic scale that quantum theory deals with.

The content of what we have said provides an answer to this question. Here we would only add that Bohr, Pauli, and other physicists have disagreed with employing a multivalued logic in order to get a more 'precise' representation of the situation that has built up in quantum mechanics.[19]

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[3] *Ibid.*, p 40.

[4] Niels Bohr. *Essays 1958-1962 on Atomic Physics and Human Knowledge* (N. Y., London, Interscience Publ., 1963), p 5.

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[13] V. I. Lenin. Philosophical Notebooks. *Collected Works*, Vol. 38 (Progress Publishers, Moscow), p 228.

[14] *Ibid.*, p 75.

[15] Werner Heisenberg. *Physics and Philosophy* (George Allen & Unwin, London, 1959), p 145.

[16] The matter posed here about the dialectical contradiction in quantum mechanics is considered in greater detail in Chapter V.

[17] See, for instance, Werner Heisenberg. *Op. cit.*, pp 154-155.

[18] These points are developed further in Chapter X.

[19] Niels Bohr. *Essays 1958-1962 on Atomic Physics and Human Knowledge*, p 5.

IV

THE PRINCIPLE OF OBSERVABILITY IN MODERN PHYSICS

1

Formulation of the Question. The Significance or Meaning of 'Observability'

There is a quite rich literature on the principle of observability in physics. Physicists and philosophers have published much analysing, on the philosophical plane, matters pertaining to this principle.[1] Their work draws attention to aspects as yet little studied of the principle of observability. We should perhaps recall here that several authors associate this principle with Mach's philosophy. Is that right? We shall discuss the point below. Here we shall just note that the 'principle of observability' has to some extent become similar to the affirmation of the 'disappearance of matter' that diverted many scientists, at the time of discovery of radium and electrons, from the materialist path, the real meaning of which was revealed by Lenin in *Materialism and Empirio-criticism.*[2]

In this chapter we shall consider the theory of knowledge and methodological problems that are associated with the principle of observability. Let us begin with some definitions.

Observation, of course, is a cognitive activity of man associated with purposeful perception of objectively real objects and phenomena; in other words, observation of the objects and phenomena of nature would be impossible without their direct or mediated (through devices or means of observation) effect on the human sense organs. From this materialist point of view the concept 'observability' means the possibility of observing objects and phenomena of nature that exist objectively and independent of the human mind. Objects exist objectively, of course (and are therefore cognised), in various relations to other objects and in their development, but we shall leave issues of the cognition of these relations and of the role of observation in cognition.

The concept of observability is also employed in modern physical literature with a more special meaning, namely, in the sense that physical statements about objects, phenomena, properties, and magnitudes that are recognised as observable must satisfy certain requirements (which will be discussed below). Our job is to analyse and substantiate these requirements, since the principle of observability means just them. Let us consider the statements of authors in which the principle of observability is formulated in one way or another.

According to Einstein, the concept 'simultaneous' 'does not exist for the physicist until he has the possibility of discovering whether or not it is fulfilled in an actual case'.[3]

Paul Langevin wrote that 'theory should not, as far as possible, introduce anything that has no experimental significance and that does not correspond at least to an imaginable if not easy experiment'.[4]

In *The Feynman Lectures on Physics* one can find the following statements: 'Another thing that people have emphasized since quantum mechanics was developed is the idea that we should not speak about those things which we cannot measure. (Actually, relativity theory also said this.) Unless a thing can be defined by measurement, it has no place in a theory.... Just because we cannot *measure* position and momentum precisely does not *a priori* mean that we *cannot* talk about it. It only means that we *need* not talk about them.'[5]

F. A. Kaempffer has written: 'Quantum mechanics purports to be a description of physical reality which deliberately eliminates from theory all features not demanded by experiment.'[6]

Some authors confuse the epistemological question of objective reality and its cognition by man with the content of the principle of observability. This strikes one sharply in Eddington's works. He stated, for instance, that when the physicist formulated the laws of mechanics, he was dealing not with 'wholly objective particles and wholly objective behaviour (of these particles) but with their observed behaviour, with 'properties imposed by our procedure of observations'.[7] For Eddington physical knowledge was essentially 'observational knowledge' allegedly obtained by 'scrutinising the frame of thought', 'by the observer's sensory and intellectual equipment'[8] used for observation (and not through deeper and deeper generalisation of facts obtained by means of observation). It was by this *a priori* way that we allegedly obtained knowledge of the fundamental laws and constants of physics (e.g. the speed of light in vacuum) which, in Eddington's view, were 'wholly subjective' and 'can be discovered *a priori*'.[9]

The principle of observability actually has nothing in common with the problem of the relation between the subjective and the objective as resolved in the idealist manner. In a (closed) physical theory only those statements are admissible that are substantiated in one way or another or can be substantiated by experiment (observability in principle); those statements that cannot be substantiated by experiment are excluded from the theory. That is the meaning of the principle of observability.

It is customary to cite the following confirmations of the usefulness of this principle. The critical analysis Einstein made of simultaneous events observable in principle in various places enabled him to arrive at relativistic conceptions of space and time. Similarly, Heisenberg overcame the difficulties in Bohr's atomic model when he excluded the position of the electron in the orbit and its angular momentum as unobservable; he created matrix mechanics, the preliminary form of quantum mechanics, relying solely on the frequencies and intensities of spectral lines observable in experiment.

Is it true that both leading theories of modern physics owe their origin just to the observability principle? The answer to that must be above all sought within the frame of physics itself and not on the basis of speculative conjectures as Eddington in essence suggested.* One must not confuse the observability principle with the epistemological

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* Sir Arthur Eddington. *The Philosophy of Physical Science* (CUP, Cambridge, 1949), p 39. In Eddington's view we can, for example, learn that a quantity is possibly an 'unobservable' 'from a scrutiny of its definition, which is found to contain a self-contradiction or vicious circle or other logical flaw'.

statement about the relation between the subjective and the objectively real.

Dirac wrote that 'science is concerned only with observable things'.[10] Schrödinger expressed the same idea, but with a reservation, writing: 'We can never say what *actually* is ... but simply what will be observed in a particular concrete case. Must we be always satisfied with that...? In principle, certainly. In principle the demand that exact science should in the last analysis strive only to describe the actually observed is not at all new. The question is simply whether we must, from now on, renounce linking the description we used to use to a lucid hypothesis about how the world is really constituted. Many would already proclaim this rejection today, but I believe that we would thereby make things a little too easy.'[11]

Dirac himself, strictly speaking, did not attach any epistemological meaning to his statement. This can be seen from his continuation of the citation above: 'We can observe an object only by letting it interact with some outside influence.'[12]

Schrödinger, on the other hand, already ascribed an epistemological meaning to his statement, although he did not develop the appropriate argument.

Heisenberg expressed himself clearly and unambiguously on the epistemological plane. According to his point of view, when we speak of modern exact science's picture of nature, it is no longer a matter of 'a picture of nature, but of a picture of our relations to nature'.[13] He assumed that when man observed nature, he was dealing not with nature itself but with nature considered through the prism of problems posed by man.

We discussed Heisenberg's point of view in detail in Chapter II, and are not going to dwell on it again here. We would simply like to stress that in their statements of a philosophical character both Eddington and Heisenberg in essence separated observation as a necessary aspect of the cognitive process from cognition as a whole, making an absolute of abstract thought, isolating it from objectively real nature and matter. When man observes nature and creates scientific theories he is, in fact, dealing with nature; human knowledge is relative, but this relativity is not absolute and is overcome to a greater and greater extent as cognition (knowledge), reflecting eternally developing nature, progresses.

In a complete physical theory verified by experience its statements and concepts reflect the material world; these concepts and statements, having been verified by experience, are true and correspond to objective reality. In the development of physical science, however, situations arise such that in certain conditions (e.g. when the researcher comes across a new sphere of phenomena in his experiments to which a given physical theory is not in essence applicable, but that has not yet been brought out by physics) some of the concepts and statements of the given complete theory do not correspond to objective reality. A new experiment disproves the assertion that a certain concept or statement of this theory corresponds to objective reality; which means that this concept or statement ceases to be true.

The question is asked whether physics is right to admit statements and concepts on which experiment seems to give a dual answer as to whether they correspond to objective reality; and if it is right what is the epistemological content of this 'admission'? Physics faces such questions when a new theory grows out of an old one, and the latter becomes a special, limiting case of this new, more general theory.

The observability principle, as we shall see later, has something to do with the question posed; it also correspondingly concentrates the necessary material for answering it. If the question is formulated more rigorously, then it is a matter of paradoxical situations and of how to resolve the emerging paradoxes. The principle is also one of the methods of resolving paradoxes of this kind. The results of applying it do not so much reinforce statements (and theories) already known in physics as lead to new statements (and theories) not yet known to science. There were no such theoretical methods in the science of the classical period, and could not be, at least in their explicit form, because observed phenomena were explained in the final analysis at that time by a mechanical macroscopic model, and such an explanation was regarded as the only one possible that did not give rise in principle to any logical ambiguities, although engendering practical difficulties in complicated cases.

Even now individual authors voice serious doubts with respect to the objective substantiation and heuristic value of the principle of observability.[14] It is said, in particular, that the principle does not answer why, in some cases, the unobservables (like the trajectory of an electron in an atom) have to be excluded and in other cases are permitted (for example, wave functions); in some cases they are harmful (e.g. absolute simultaneity), and in other cases may play a necessary and positive role (e.g. this same wave function)?[15]

It will become clear from what follows, however, that the situation is not quite that hopeless. As we see it, the epistemological and methodological aspects of the principle of observability should not be considered independently of the questions associated with the application of dialectics to cognition and its development.

2

What Is an Observable (or a Non-observable)?

An 'observable' (about which we spoke in the first section) is a concept that has experimental meaning, or one based on experiment, or something that a statement about can be verified experimentally. One can often read in the literature that 'only thoroughly empirically based concepts' should be employed to describe physical phenomena.[16]

This last requirement seems quite reasonable from the standpoint of physics, but it is in fact ambiguous and therefore nearly useless in that form. The symbols which form the mathematical apparatus of any physical theory (without them there is no theory) do not as yet constitute a *physical* theory. For a theory in physics really to be a physical theory, concrete measurement formulae have to be provided for the symbols of its mathematical apparatus that relate these symbols to physical objects. In quantum mechanics, for example, the wave function *in itself* does not yet have a physical meaning, and is therefore not an observable quantity until a concrete formula is given that relates it to something physical. From that point of view Born was right when he said that the wave function was not an observable quantity.[17]

The concept of observability (or non-observability) should not, in fact, be applied to the wave function as such: the latter is a *mathematical* quantity, while the observability concept applies only to the *physical*. Wave functions, or the vectors in Hilbert space, are mathematically quantum states (just as the operators that act on these functions are mathematically quantum physical quantities, or 'observables'). At one time, when quantum mechanics was acquiring the developed form we now know, the job was to determine the physical agent of the wave function (and if it was a question of an operator, to find its physical realisation). This was done by a probability interpretation of quantum mechanics: for given values of the variables that are the arguments of the wave function the square of its modulus equals the probability density at which the variables obtain their selected values during measurement.

It was in this way that the physically realised wave function is an observable quantity in quantum mechanics, representing the most important physical characteristic of a system. Similarly, the properties of a quantum quantity are brought into correspondence with an operator in such a way that the possible values of a certain quantum physical quantity correspond to the eigenvalues of the operator representing this quantity.

Thus, when it is a matter of the observability of a quantity, reference to the experiment, although necessary, is far from sufficient to solve the problem of this observability.

Let us take some other, different examples. The concept of *absolute* simultaneity employed in classical mechanics agrees beautifully with a certain group of experimental mechanical data; sophisticated experiments relating to electromagnetic phenomena in moving bodies, however, do not correspond to this concept and form the basis for the concept of *relative* simultaneity of Einstein's theory.

Or take the concept of the atom. Strictly speaking this concept had not been substantiated experimentally before Perrin's experiments. It had a hypothetical character; the atomic hypothesis, however, as we know, played an outstanding role in the development of physics.

The appeal to experiment as the sole substantiation, in the final analysis, of physical knowledge thus still leaves too many uncertainties for unambiguous answers to be given relating to the description of physical phenomena and knowledge of the laws of nature. In matters of this sort physical theory also plays an important role, and therefore the requirement for a corresponding (logical) analysis of the statements of natural science. Even when quantum mechanics was taking its first triumphal steps, Max Planck drew attention to this circumstance.

In Planck's opinion the fact that quantum mechanics dealt with quantities observable in principle and problems having physical meaning was not its special advantage over other theories. The problem of observability in principle, he stressed, can never be solved *a priori*; it has only to be solved from the angle of a certain theory. 'The distinction between the different theories,' he said, 'consists precisely in the fact that according to one theory a certain magnitude can in principle be observed, and a certain question have a meaning as applied to physics; while according to the other theory this is not the case. For example, according to the theories of Fresnel and Lorentz, with their assumption of a stationary ether, the absolute velocity of the Earth can in principle be observed; but according to the Theory of Relativity it cannot.... The choice between these two opposed theories depends not upon the nature of the theories in themselves, but upon experience.'[18]

It is worth adding to Planck's example that the negative result of the Michelson-Morley experiment substantiated to some extent (as far as absolute velocity was concerned) not only the theory of relativity but classical mechanics as well. This issue was resolved in favour of the theory of relativity by postulating the principle of the independence of the velocity of light of the motion of the source (a principle that accorded with Lorentz's theory of motionless ether). The principle was not, however, postulated by itself but in a peculiar combination with the principle of the relativity of uniform, rectilinear motion, which contradicts it.

By this addition, we would like to stress not only that the experimental basis of the theory of relativity is incomparably broader than the experimental basis of classical theories but also that the spread (generalisation) of established principles and basic concepts to a new field of phenomena means, in certain conditions, their alteration at certain points. Such generalisations are closely related to our theme.

Let us consider the problems arising here. The concept of the observable in principle is not simply compatible with a certain theory. It is necessarily connected by a chain of corresponding conclusions with the theory's basic concepts and principles. The definition of the observable in principle provides a method that allows us, on the basis of experiments, to say whether the observable in principle corresponds to the objectively real. Examples of the observable in principle were given above; they provide an opportunity of clarifying that the observable in principle coincides in essence with the operationally definable.

Operational definitions have long been in use in physics, especially in connection with the employment of mathematical concepts and methods in it and, accordingly, with the appearance of abstractions of an ever higher order. They were also dealt with in classical physics, but, remembering its history, they were not used explicitly in it. Their systematic application and development in explicit form one finds in non-classical theories.

Operational definitions have advantages—in certain circumstances—over verbal ones. When the point concerns physical quantities and, in general, physical characteristics relating to idealised objects in the broad sense of the term (on the plane of logic of science they include, for instance, so-called constructs), and it is necessary to solve problems about these objects (finding, say, their physical characteristics) from instrument readings, operational definitions may be the only useful ones. From that point of view it is clear that the method of an operational definition has nothing to do with definitions of matter, a law of thought, and other philosophical concepts or, as we remarked above, either mathematical or biological concepts. For them there are other methods of definition.

It is difficult to agree with Born who, while justly opposing the epistemological line of operationalism, suggested, however, that the domain of operational definitions was solely classical physics.[19] Of course, one cannot, as we noted above, define a wave function or operator by an empirical 'operation', but the operational definition is not 'responsible', so to say, for the 'philosophy' of operationalism and its metaphysical, *a priori* ideas. The operational definition of a physical quantity thus means that it is defined by describing the operations needed to measure it *within the limits of a certain theory.* What we have stressed, however, is exactly what is ignored in the corresponding arguments by operationalism (and, in general, by positivism), which regards operations not as a means of reflecting the objectively real in the human brain but as the real itself. That is why operationalism even does not pose the question of the conditions and limits of the applicability of operational definitions or of their variability.

The applicability of any operational definition is in fact limited not simply in the trivial sense by the boundaries of the object being defined but also by the limits of the theory in which the definition occurs. In classical theory, for example (as became clear with the development of physics), the simultaneity of events at two points A and B removed from one another is defined by taking a clock from A to B, when it is affirmed that it goes synchronously at A and at B (after being brought there). In Einstein's theory, however, simultaneity at two different points is defined as follows: (1) points A and B are connected, according to a certain rule, by a light signal; (2) the frame of reference to which the simultaneity argument applies is indicated. When formulating his theory of relativity Einstein thus altered the definition of simultaneity accepted in classical theory.

A similar picture exists in quantum mechanics as well, when it is compared with classical theory. Not only is the mathematical apparatus of quantum mechanics different from that of classical theory, but also the rules for linking its concepts with the instrument readings or experimental data (without such a connection the concepts of its mathematical apparatus have no physical meaning), in other words, there are operational definitions of quantum quantities that do not coincide with operational definitions of analogous classical ones.* In general, if a field of new fundamental laws has been discovered and a theory covering it established, the operational definitions of the corresponding objects should also be new. In short, in contradiction to the operationalist point of view, there is no universal criterion, the same for all theories, of when an assertion should be regarded as having (or not having) empirical meaning. Nature is infinitely richer than any of its domains and any of its aspects reflected in experience and the theories grown on it. As physical knowledge develops, penetrating phenom-

* The first person to draw attention to the need to distinguish between the rules for the transition from the concepts of the mathematical apparatus to the experimental data in classical and quantum theories was apparently L. I. Mandelstam [see his *Lectures on the Fundamentals of Quantum Mechanics* (in *Polnoye sobranie sochinenii*, Vol. 5, Moscow, 1950, p 354)].

ena and processes of nature that have not been studied by earlier experience, peculiar situations can arise in which we have somehow or other to use concepts of the old theory that are losing their meaning, and at the same time to construct a new theory, selecting concepts corresponding to it.

From the standpoint of a certain theory it would be useful to compare the observable in principle with the experimentally observable and hypothetical for a more definite identification of their specific nature.

When, given the appropriate necessary and adequate conditions the observable in principle is still not observed in the experiment, this often has far-reaching consequences for the theory. That is how the hypothetical classical ether became obsolete in modern physics, and the corresponding theory (in one version or another) was preserved only as a historical relic if one disregards some of its 'revivals' through *ad hoc* hypotheses. The observable in principle may prove (in certain conditions) to be observable in experiment, or experimentally observable. Formally that means confirmation of the theory at a definite (and sometimes decisive) point. From this seemingly trivial point of view, Hertz's discovery of electromagnetic waves was a most important confirmation of the validity of Maxwell's theory of electromagnetic field; or J. G. Galle's discovery of the planet Neptune after it had been 'discovered by pen' (i.e. predicted) by J. C. Adams, and independently of him by U.J.J. Leverrier, became proof of the validity of Copernicus' system, which had, strictly speaking, before that, to be considered a hypothesis. Frederick Engels wrote about this in his *Ludwig Feuerbach and the End of Classical German Philosophy.*[20]

On the other hand if the experimentally 'observables' figure in a certain system of concepts (which by itself is not a closed physical theory), i.e. are only experimentally 'observable' in the given system, they are simply the scaffolding for a possible closed theory. The mechanical characteristics of electron motion, for example, such as the electron's position in an orbit or its period of revolution, were 'expelled' from Heisenberg's matrix mechanics, and matrices put in their place. Matrix mechanics yielded fruitful results *confirmable by experiment*; the question of what it meant to use matrices instead of position and momentum in this theory remained, however, outside its field of view. The mechanics of the atomic world had to deal with problems of this kind when it decided to be a really physical theory and not just empirical magic. That happened with discovery of the uncertainty relation and the formulation of Bohr's complementarity principle, as is now well known.

While the observable in principle and the experimentally observable thus may exist separately in certain systems of concepts, they tend towards each other, as it were, as these systems develop, and after certain theoretical 'adventures' they combine to form 'normal' physical concepts in a closed physical theory. The '*observables*' in quantum mechanics, represented mathematically by corresponding operators, can serve as an example of such 'combinations'.

To conclude this section, let us take a remark of Arnold Sommerfeld's so as to stress the need to distinguish between the observable in principle, the observable in experiment, and the hypothetical, although these concepts, as follows from what has been said, do have undoubted points of contact. Sommerfeld, who made a great contribution to the development of quantum theory, wrote: 'The declared intention of Heisenberg's first work on quantum mechanics (i.e. on matrix mechanics—*M. O.*) was to develop a method that would be based exclusively on the connections between quantities observable in principle.'* Such concepts as 'the position of an electron', 'period of rotation', 'the shape of the orbit' were to be excluded from consideration. 'This restriction to the directly observable is based, in the last analysis, on Mach's philosophy.'

Sommerfeld noted further that Wilhelm Ostwald's energetics that Mach and his supporters had propagandised also stemmed from a striving to limit himself to the directly observable. But, Sommerfeld concluded: 'energetics could be counterposed to the very fruitful kinetic theory of gases in which the positions and velocities of gas molecules, though not observable in detail, could not be left out as entropies of the theory. In the same way we can counterpose to Heisenberg's point of view the wave mechanics in which eigenfunctions can just as little be checked in detail through experiment as the earlier electron orbits.'[21]

* From the citation that follows one can see that Sommerfeld interpreted the observable in principle essentially as the directly observable, or the observable in experiment.

In this comment of Sommerfeld's correct ideas are mixed with statements with which we cannot agree in such a way that the latter set the tone. First of all, it is wrong to say that the observable in principle in physics rests on Mach's philosophy. That is not only made clear by the whole content of our book, but also by Heisenberg himself who, having paid tribute to positivism in the twenties, pointed out in his *Physics and Philosophy* that positivism and the principle of observability differed from one another.[22]

Furthermore, Sommerfeld apparently does not draw a sufficiently clear distinction between the 'observable in principle' and the 'observable in experiment'. Quantum mechanics, as we know, has its own observables in principle. Suffice it to recall—and Sommerfeld is wrong here, too—that the wave function in its *probability interpretation* is a *physical* characteristic. Heisenberg adopted it as a concept needed by quantum mechanics. These facts, incidentally, disprove the view that there is a philosophical similarity between Heisenberg's standpoint, which rejects electron orbits, and that of Mach who did not recognise atoms.

Finally, the position and velocity of an individual atom, treated by Sommerfeld as unobservables, should be rather classed as hypothetical; they may be included, moreover, among the observable in principle from the standpoint of classical mechanics, since the kinetic theory of gases is very closely associated with the latter.

3

The Heuristic Role of the Observability Principle

We cited above statements by distinguished scientists on the methodological value of the principle of observability in physics. Let us add that Max Born included this principle in one of his last papers among modern physics' most important methods of thought, because in his view the methods of thought dealt with in traditional philosophy had ceased to operate in the practice of modern physics.[23] V. A. Fock also spoke about the great positive role of this principle in establishing the laws of quantum mechanics.[24]

Before turning to the theme of this section let us note (which can be seen from the above) that the term '*observability* principle' does not altogether adequately reflect its content. Max Born in particular speaks, in the paper mentioned above, not of 'observability' but of 'decidability' or 'determinability' (*Entscheidbarkeit*), and formulated the principle as follows: not to use any concept for which it is undecidable in principle whether it corresponds or not to reality.[25]

From the angle of the true content of the observability principle, Heisenberg's reminiscences about the time when what is now known as the Bohr-Heisenberg interpretation of quantum mechanics was created, present considerable interest.[26] After the paper read by Heisenberg in 1926 in which the idea of describing phenomena solely by means of observable quantities played a major role, Einstein asked him: 'What did you mean by only observable quantities?' Heisenberg's reply was that he 'did not believe any more in electronic orbits, in spite of the tracks in a cloud chamber'. He felt it necessary to 'go back to those quantities which really can be observed' and that this had been exactly Einstein's view in the theory of relativity 'because he also had abandoned absolute time and introduced only the time of the special coordinate system'.

Heisenberg then continued: 'Well, he laughed at me and then he said: "but you must realize that it is completely wrong ... it is nonsense".'

Heisenberg gives Einstein's explanation: 'Whether you can observe a thing or not depends on the theory which you see. It is the theory which decides what can be observed.' 'Einstein,' he continued, 'had pointed out to me that it is really dangerous to say that one should only speak about observable quantities. Because every reasonable theory will, besides all things which one can immediately observe, also give the possibility of observing other things more indirectly. For instance, Mach himself had believed that the concept of the atom was only a point of convenience, a point of economy in thinking, he didn't believe in the reality of the atoms. Nowadays everybody would say that it is nonsense, that it is quite clear that the atoms really exist. These were the points [Heisenberg stressed] which Einstein raised.'[27]

Later, when Heisenberg discussed the interpretation of quantum mechanics with Bohr, he remembered Einstein's remark: 'It is the theory which decides what can be observed.' 'In this way,' Heisenberg said, 'things became clear ... so finally we all agreed that now we had understood quantum theory.'[28]

Perhaps we have cited Heisenberg's remarks at too great length, but we have done so deliberately. We want to show the reader with his own eyes, so to say, that the authors of the observability principle did not associate it at all with positivist and idealist principles. That is the first point. The second point is that the 'exclusion' of a certain concept from a new theory as 'unobservable', and without meaning, is not simply a consequence of this new theory but that it helps construct the new theory. Einstein's explanation, as a matter of fact, means that when one has to pass, and is passing, from one fundamental theory to another, more general and deeper one, the old theory must necessarily be altered at certain points: new, more meaningful concepts are developed in place of some basic concepts or other of the old theory that reflect the sphere of phenomena with which the old theory could not cope. It is this thesis that is also employed in the search for a new theory by means of the observability principle. What follows is devoted to concrete analysis of this idea.

How and why does the question of the observability in principle or non-observability of a quantity arise? To bring out the methodological role of this principle it is essential to determine that *such and such* quantity precisely is not observable in principle. If, for example, it had been assumed, before the theory of relativity, that ether was not observable in principle, that assumption would not have affected the meaning of the principles of classical physics in any essential way: the concept 'ether' did not figure in classical mechanics, as we know, and classical electromagnetic theory would have become more rigorous and would have better reflected its object, because the concept of field would have had an appropriate place in it (as a matter of fact, that is exactly what happened in the electromagnetic theory after Maxwell). The history of the creation of relativity theory witnesses that establishment of the non-observability precisely of absolute simultaneity was the methodological starting point from which the development of non-classical theories began. In general it was establishment of the non-observability of that quantity and no other, and the extraction from it of everything needed to build a new theory diverging in its fundamental content from the principles of known theories, verified by experiment, that constituted the element that was unknown earlier from the angle of the cognising mind's approaches to the phenomena of nature, which was 'alien' to the 'style of thinking' of physicists of the classical period of the development of science.

Thus, one cannot answer the question of the heuristic value of the observability principle in any concrete way without a methodological analysis of the appearance of the theory of relativity and, if we pose the question on a broader scale, without a methodological analysis of the rise of non-classical theories in physics.

How did Einstein's special theory of relativity come about, remembering the methodological aspect of the question? Classical mechanics (with the notions of absolute space and absolute time, characteristic of classical physics), in accordance with experience, affirmed the relativity of the uniform, rectilinear motion of bodies (Galileo's principle of relativity)*; this, however, contradicts the fact that the velocity of light is independent of the motion of the source. On the other hand, classical electromagnetic theory assumed ether, but this assumption contradicts Galileo's principle of relativity although it agrees that the velocity of light is independent of the frame of reference.

The contradictions that arose here were resolved by Einstein who extended the statement about the relativity of uniform, rectilinear motion to electromagnetic phenomena and adopted it as the first principle of a new non-classical theory, the theory of relativity. As the second principle of his theory he put forward the proposition that the velocity of light is independent of the motion of the source, expressing it as the principle of the constancy of the velocity of light. It proved—and here the dialectics in Einstein's reasoning was revealed especially clearly—that these prin-

* Galileo's principle is expressed in classical mechanics in Galileo's transformations. In the theory of relativity they are replaced by the Lorentz transformations (and Galileo's principle of relativity, accordingly, by Einstein's).

ciples did not contradict each other *if the classical concepts of space and time were altered.*

It would have been possible not so much to resolve the contradiction between Galileo's principle of relativity and the fact that the velocity of light is independent of the motion of the source (as permitted by the hypothesis of ether) as, it seemed, to eliminate it. For that some hypothesis in the spirit of classical conceptions could have been added to these statements.* Einstein did without these arbitrary hypotheses, and this opened the way to him to create the first non-classical theory.

The idea of changing the classical concepts of space and time was thus the turning point in the genesis of the theory of relativity, but the source of this thought in Einstein's reasoning was his rejection of the concept of absolute simultaneity in the content and structure of the theory. Or rather, when he excluded absolute simultaneity and introduced relative simultaneity, he reached a higher synthesis of two mutually contradictory statements: namely, that of the relativity of uniform, rectilinear motion and that of the velocity of light being independent of the motion of the source. On that foundation the theory of relativity was consolidated.

Quantum mechanics arose in a similar way, although the way it came into physics was much more complicated and confusing than the birth of the theory of relativity. We shall not dwell on this, but shall just make the following general observation. When Heisenberg assumed the non-observability of an electron's position and velocity on its orbit in the atom, he opened the first door, by his matrix mechanics so to speak, for Bohr's complementarity principle (with its 'relativity with respect to the means of observation' and the other basic concepts unknown to classical theories) which underlies modern quantum mechanics; the 'second' door for the complementarity principle was opened by Schrödinger's wave mechanics.

When one examines the process of cognition in physics, or cognition as a whole, one finds it has a very peculiar

* The negative result of the Michelson-Morley experiment, for instance, and the independence of the velocity of light from the motion of the source, can be made to agree with the ether hypothesis if it is assumed that ether is completely carried during the motion of a body. The facts, however, do not confirm this assumption.

dual nature. (1) In cognising something, i.e. in going beyond the limits of the already known, we extend to this something the established concepts, laws, and theory that are treated as known. (2) This process of extension does not exclude but, on the contrary, implies that in doing so one may have to alter (revise) some established basic concepts and principles or other of the theory qualitatively and therefore, as a result, to construct new concepts and principles and a new theory. These two elements of cognition, in spite of their being opposite, pass into each other and are in fact one; depending on the conditions, however (which above all include the cognised object itself with its specific features), one or another of them is pushed to the fore.* Here we are interested only in the second element because it is exactly when a theory new in its fundamental content is born that 'non-observables' appear.

From this point of view the revision of a concept (quantity) in physics can be reduced to the following: it is assumed (on the basis of certain considerations) that this concept (quantity) is regarded as observable in principle (it can often be determined experimentally) from the standpoint of the established theory extended to the unknown (new) field of research; it is stated that experimental determination of this concept (quantity) in regard to the unknown field of research will either not yield a positive result or at least sow doubts about its objectively real existence; and a mental equivalent of the concept (quantity) so experimentally rejected is established. This mental equivalent is unobservable in principle from the angle of the theory embracing the new field of research, a theory that still has to be crystallised out from the established one.

Thus, when a new theory (which still has to take shape) may and does grow from an already formulated (old) theory *on a new foundation*, the introduction of something 'unobservable in principle' is inevitable in certain circumstances. In this respect one has to agree with Heisenberg, to whom 'it is more advisable initially to introduce a great wealth of concepts into a physical theory [he does not specify whether he means a *developing* theory or one *already devel-*

* The point is that, when physical knowledge is extended, it is impossible to know the limits of the established theory in advance. These limits are determined along with the creation and shaping of the new theory, for which the old one becomes a limiting case.

oped—M.O.] without consideration of their rigorous justification by experiment [he does without the needed addition: by a *new* experiment—*M.O.*] and to leave the decision to nature, in each case of any theory, whether and at what points a revision of the basic principles is necessary'.[29]

Every step in extending an established theory to an unknown field of research should, of course, be subjected to experimental verification. That applies equally to our first and second elements (above) of the expansion of physical knowledge, and before this verification these elements should therefore be considered as hypotheses. Here Engels' words that the form of development of science, in so far as it thinks, is the hypothesis are particularly appropriate[30]: without a hypothesis, this necessary element of scientific knowledge, there would have been no progress in either classical or modern physics; the development of the latter completely disproves the inventions of positivists, who reject the scientific hypothesis and consider the physical theory only as systematisation of the 'observable' and not as the ever more accurate and complete reflection of the material world.

In modern physics it is not so much the hypotheses which, being confirmed by experiment, reinforce already established theories as the assumptions that lead to the creation of new theories and a radical restructuring of science that are most important. The assumption of the non-observability of a certain quantity as the starting point of a theory being created is just such a hypothesis.

This assumption is neither a descriptive nor an explanatory hypothesis. Unlike the latter, it does not see the explanation of new facts as its task; rather it leads to an operational definition of new concepts in the developing new theory. Like descriptive and explanatory hypotheses, the assumption of the non-observability of such and such a quantity is also 'evoked' by an experiment. In that lies the source of its cognitive force. Thus, the exclusion of absolute simultaneity and introduction of relative simultaneity in studies of electromagnetic phenomena in the moving bodies are a schematised, idealised expression of the negative result of the Michelson-Morley experiment. The same has to be said also about the exclusion of the classical trajectory and introduction of the concept of relativity to the means of observation into studies of phenomena on the atomic scale:

they were 'evoked' by the experimental data on the particle and wave properties of one and the same micro-objects.

The non-observability of a quantity in principle is thus not revealed as a result of elucidating the fact that the corresponding statements about the quantity are incompatible with the principles of the theory; it had been assumed before these principles (and therefore the theory itself) received the right to exist and their explicit formulation. The process of excluding the non-observable quantity, however, is at the same time, in its developed form, the process of crystallising the theory's principles and concepts on the basis of certain experimental observations. To put it more definitely, the establishment of non-observability is an indication that the old theory is no longer effective in some respect (as regards the new sphere of phenomena) and that a new theory needs to be created.

It is exactly these fundamental features that determine the heuristic value of the principle of observability. As a method of finding the laws of nature the principle not only does not reject other methods of theoretical and practical research, but, on the contrary, presupposes their use. Only then can one expect fruitful results from it.

In order to picture more concretely what this last remark means, let us consider the creation of wave mechanics and discovery of positron from the angle of our present theme, and also the proposition about the non-observability of the details of elementary particles' behaviour when the distances between them become ultra-small.

Schrödinger created his wave mechanics independently of Heisenberg's matrix mechanics, as we know, and, as he demonstrated, it was mathematically equivalent to the matrix mechanics. Schrödinger arrived at wave mechanics by analysing the connection that he had found between de Broglie's idea of 'waves of matter' and Hamilton's work on dynamics and geometrical optics. Thus, it was not the principle of observability that played the methodological role in the formulation of the wave mechanics, but an explanatory hypothesis, concretely the hypothesis of 'waves of matter'. To put it more accurately, however, the mathematical hypothesis served as the method here,[31] while the 'waves of matter' helped represent the matter more 'visually' rather than determined the quest.

That visual models played no decisive role in the creation of wave mechanics stands out particularly clearly in its further development, which led (along with the development of matrix mechanics) to modern quantum mechanics in which the concept 'waves of matter' is not preserved literally, while the concept of a wave function in its probability interpretation is a basic one. The enormous heuristic significance of the method of mathematical hypothesis came out even more clearly in Dirac's brilliant prediction of the positron, which was not only not governed by visual models of any kind but was rather made in defiance of them.*

In the literature 'waves of matter', 'wave function', and Dirac's 'holes' are frequently called 'unobservables', and attempts are made to draw conclusions against the principle of observability from the corresponding discoveries made by applying the technique of mathematical hypothesis. In fact, however, the principle of observability and the mathematical hypothesis mutually mediate and complement each other. Here are some considerations *apropos* of that.

The appearance of the 'unobservables' to which mathematical hypothesis leads is nothing other than the process of creating (or rather one of the elements of creating) a new theory in which these 'unobservables' (as they are regarded from the angle of the old theory) become observables. The exclusion of an 'unobservable' (from the angle of the new theory), however, as we have already made clear, is also a process of creating (or rather an element of the creating) of the new theory. Without going into details of the relevant argument here, we may note that if, let us say, the wave function in its probability interpretation and the positron are observables from the standpoint of quantum mechanics and quantum electrodynamics, respectively, that only confirms the idea of an inner connection between the principle of observability and the method of mathematical hypothesis. Bearing all these circumstances in mind, we must stress the great progressive significance for the development of new theories of the introduction of 'unobservables' in this sense of the term into science.

* The 'negative energies' and 'holes' in a 'vacuum', i.e. the notions that Dirac employed when he formulated his theory of a relativistic electron, cannot in the least be classed as visual entities. Interestingly, Dirac himself assumed that the 'hole' was a proton, and only Anderson's experimental discovery of the positron established the meaning of his theory: the positron is the antiparticle of the electron.

Finally, let us briefly comment on the proposition about the non-observability in principle of the details of elementary particles' behaviour when they come within ultra-small distances of one another (i.e. high energy particles[32]), a proposition being employed in the theory of elementary particles that is now taking shape.

The fact that this theory treats elementary particles (and there are the necessary experimental grounds for doing it) as transformable into each other according to the conservation laws and the principles of symmetry (we would be justified in saying that mutual transformability is the mode of existence of elementary particles) makes this proposition very plausible. In particular, it accords with the accepted view that interactions between high energy particles cannot be described by such quantum-mechanical concepts as wave functions and operators.

There is no closed theory of elementary particles, however, that would resolve the contradiction between quantum mechanics and the theory of relativity, one of the crucial contradictions of the modern physics, in a higher synthesis. This situation in the modern physics of elementary particles resembles that which built up when quantum mechanics was taking shape soon after the creation of matrix and wave mechanics, but with quite serious differences. (1) The conception of the theory of elementary particles (represented by G. F. Chew) that expresses the principle of observability in its pure form (rejecting the idea of a space-time continuum)* does not yet have a developed mathematical formalism. (2) The other conception of the development of the modern theory of elementary particles (represented by Heisenberg), i.e. the theory of quantised fields based on the idea of a space-time continuum, is not sufficiently 'crazy' for a new theory, to use Bohr's expression. In any event, Chew's and Heisenberg's different conceptions are evolving and perhaps, in coming closer together, may lead to the formulation of a closed theory of elementary particles.

There is the possibility, of course, of a theory of elementary particles being formed in another concrete way. Prob-

* According to Chew 'there is no experimental way of checking up on the space-time continuum', but 'a continuum in momentum variables has experimental significance' (*International Conference on High Energy Physics. Geneva, 1962*, Geneva, 1963).

lems of this kind, it seems to us, can hardly be solved in general if one does not take into account the profound meaning of Niels Bohr's observation 'that the reason why no progress was being made in the theory of transformations of matter occurring at very high energies is that we have not so far found among these processes any one exhibiting a sufficiently violent contradiction with what could be expected from current ideas to give us a clear and unambiguous indication of how we have to modify these ideas'.[33]

In examining the heuristic value of the principle of observability we have tried to indicate clearly that the method based on this principle presupposes a necessary connection with the other methods of physics and that it is employed not according to a known scheme, given once and for all, but concretely, in various ways, developing new schemes of application each time during the study of new spheres of phenomena.

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V

DIALECTICAL CONTRADICTORINESS IN MODERN PHYSICS

1

Introductory Remarks

The presence of materialist dialectics in the theoretical content of modern physics discussed in the preceding chapters is now an unquestionable fact. This applies not only to the results obtained by physics, which confirm the principles of dialectics, but also to the process of obtaining these results, to theoretical thinking of scientists. That this is the situation follows not only from the research into the philosophical problems of science by conscious adherents of dialectical materialism, but also from analysis of the works of the scientists who created and developed modern physical theories, including ones whose personal philosophical views do not coincide with the propositions of Marxist-Leninist philosophy.

That dialectics as a method and philosophy of science is not something external to modern physics but is born, so to say, within it, makes the latter dissimilar in a certain sense from the old, or classical physics. It does not, however, follow from this that classical physics was metaphysical in character. We would like to draw attention here simply to the following feature of the historical development of physical science: classical physics was satisfied in its day to recognise certain fixed schemes and stable fundamental concepts (Newton's conception of space—time—mass—force; the constant atoms), whereas modern physics excludes immovable schemes and eternal basic principles from the start. The state of the science in the past, above all of physics, encouraged to a certain extent the predominance of a metaphysical way of thinking among scientists of the eighteenth and nineteenth centuries, although science had already by then demonstrated by discoveries and the accumulated facts that everything in nature happens in the end dialectically. From that angle, it seems to us that Engels' words about the conflict between the results obtained by science and scientists' preconceived mode of thinking, which explained the confusion in theoretical science in the nineteenth century,[1] apply to twentieth century science with major reservations.

Dialectical contradictions permeate modern physics, including its holy of holies, its theoretical foundations. The law of the unity and struggle of opposites makes it possible to express the change and development of objectively real nature in the logic of concepts. Development as a unity of opposites is a splitting of the whole into mutually exclusive opposites (aspects, tendencies), and the relationship between these. This applies to all the phenomena and processes of the material world, and to their reflections in the form of concepts in the human brain, i.e. to their cognition.

If we take physical knowledge as knowledge abstracted from its origin, movement, and development, it appears to be deductive knowledge. In that case, it is usually (when physics is considered as theoretical physics) in the form of a deductive theoretical system (or several deductive systems), e.g. classical mechanics, thermodynamics, relativistic mechanics, quantum mechanics. The laws of formal logic (traditional or modern) are then sufficient to solve the problems of cognition relating to physics that arise.

If, on the other hand, we take physical knowledge as it exists in reality, i.e. from the point of view of its origin (from experience) and development, then formal logic proves to be limited when used to solve cognitive problems. Such physical knowledge already appears as a succession of theories, as the emergence of a new theory, with new principles and basic concepts, from an old one. Here materialist dialectics comes on the scene as dialectical logic, which is concerned with developing knowledge and the laws of development of scientific cognition.

From this point of view a proposition (let us take a nonphysical example: 'the house exists') and its negation ('the house does not exist') cannot be regarded as true in one and the same theoretical system, i.e. a proposition and its negation cannot be proved in it; they can have, so to say, only parallel existence; they coexist in different theoretical systems. This circumstance is expressed in formal logic in its most general and complete form by the law of contradiction, by which a proposition and its negation in a formal or formalised theoretical system cannot be true simultaneously; in other words, the opposition between them is absolute (in our example of a house this means that the statement 'the house exists' and its negation 'the house does not exist' cannot be regarded as true at the same time in one and the same theoretical system if one has one and the same house in mind at one and the same time).

This is not the place to enlarge on the subject of formal logic's serving the cognition of truth when it is not called on to perform tasks not proper to it.* From the angle of the formal-logical system the elements of stability in connections and transitions that are united in the objective world by diverse relations between developing things are fixed (conditionally). Dialectical logic points out the relative nature of the abstract isolating lines; by assuming the existence of the limits to the applicability for established concepts, principles, and theories, it unites various, opposite concepts, principles, and theories through mediating logical links in higher synthetic constructions.

It is important to note, for the theme of this chapter, that dialectical logic does not merely reject the absolute significance of the opposition between a statement and its negation. It preserves the actual content of this opposition as an *absolute value within certain limits*, which are determined by the conditions in which a certain theory is applicable, but the opposition becomes relative beyond these limits. It is this kind of 'maintenance' of the value of concepts, and not some other kind, that ensures, on the one hand, precision of the language of concepts employed and, on the

* Niels Bohr's student Léon Rosenfeld wrote: 'In speculating about the prospects of some line of investigation, he would dismiss the usual considerations of simplicity, elegance or even consistency with the remark that such qualities can only be properly judged after the event.' In: S. Rosental (Ed.). *Niels Bohr. His Life and Work as Seen by His Friends and Colleagues* (North-Holland Publishing Co., Amsterdam, 1967), p 117.

other hand, gives these concepts the flexibility needed when science embraces a wider circle of phenomena that the existing theory cannot explain.*

In our view this is the most important feature of the dialectics and logic that guided Marx in *Capital* and brought brilliant results to science. In this connection suffice it to recall his reasoning, say, about how the transformation of money into capital is disclosed on the basis of the immanent laws of the exchange of commodities, and the money-owner is turned into a capitalist; the role of such a special commodity as labour power (a use value that has the property of being a source of value) in this transformation brought out by Marx, and of the various historical conditions that must be met for the money-owner to be able to find labour power on the market as a commodity. Marx's thought, formulated in the course of the reasoning, to wit, 'it is therefore impossible for capital to be produced by circulation, and it is equally impossible for it to originate apart from circulation. It must have its origin both in circulation and yet not in circulation'[2], opened the necessary perspectives for understanding the logic of the solution of the problem.

The analysis of corresponding points of a logical character bearing on Marx's argument has introduced the term 'antinomy problem' into Marxist literature.[3] We will not go into these topics here, however, though they are very important and interesting for dialectics, and refer the reader to the available literature. Our brief remarks about dialectical contradiction should help towards a clearer understanding of the logical essence and conceptual language of the theory of relativity and quantum mechanics, which developed from classical physics. We shall try to show that the idea of dialectical contradiction, and only it, made it possible to construct the theory of relativity and quantum mechanics in the forms now known, in which they work fruitfully.

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* In our example about the house the meaning of the context is that if the house in question is one 'being built', the concepts 'exists' and 'does not exist' are compatible with respect to it. The opposition between them is then no longer absolute and becomes relative. Different, though mutually related meanings appear for them (the house 'exists', because it is partially there and will be finished; it 'does not exist', because it still has to be completed).

2

The Theory of Relativity and Dialectical Contradiction

On the plane of quantum conceptions the theory of relativity did not introduce any significant changes into the scheme of classical mechanics, since it preserved the classical concept of the trajectory of a moving particle (in this sense it can be viewed as a classical theory), whereas quantum mechanics transformed Newton's laws of motion radically at just this point.

The theory of relativity, however, began in physics that which quantum mechanics has continued. Its radical revision of the notions of space and time in the physics of Newton and Maxwell awakened physicists (to use rather metaphorical language) from their metaphysical (dogmatic) dream. The idea of the variability of basic physical principles that is now usual among scientists was first used by the theory of relativity.[4]

The theory of relativity, as regards its philosophical and methodological aspects, plays an important role in modern physics also because it demonstrated for the first time the inner necessity of the idea of dialectical contradiction in theoretical development of the content of physics. The application of this idea to the fundamental principles of physics distinguishes classical theories sharply from modern physics, and this was demonstrated quite convincingly for the first time in the theory of relativity.

The rise of the theory of relativity itself cannot be understood without, and independently of, the idea of dialectical contradiction. We spoke about this in general form in Chapter IV; here we shall stress certain aspects of this question.

According to classical mechanics, absolute rest and absolute uniform, rectilinear motion do not exist. Being relative, they are correlative concepts; this is expressed in Galileo's principle of relativity, which affirms the impossibility of identifying a separate system inside a class of inertial reference frames on the basis of the laws of classical mechanics.

Galileo's principle of relativity, however, proved incompatible with the laws of classical electrodynamics, in particular with the experimental corroboration of the independence of the velocity of light of the motion of the source, This became evident when points about the application of Maxwell's electrodynamics to phenomena in moving bodies were raised. Classical electrodynamics admitted 'luminiferous ether', which accorded with the independence of velocity of light; this assumption, however, introduced concepts of absolute rest and absolute motion into physics, which contradicted Galileo's principle of relativity.

The logical conflict arising at the juncture of classical mechanics and classical electrodynamics could not be resolved directly by experiment. The unsuccessful attempts to detect motion of the Earth with respect to the ether, i.e. to measure its absolute velocity (the Michelson-Morley experiment and the like), given the assumption of certain legitimate premises, led to diametrically opposite conclusions: 1) if classical mechanics was applied to a moving source of light, the velocity of light proved to be relative; 2) if the same phenomenon was treated from the angle of Lorentz's hypothesis (which originated from electromagnetic theory), the negative result of the Michelson-Morley experiment had to be interpreted in such a way that the velocity of light was absolute (since, according to Lorentz's hypothesis, the absolute velocity of the Earth cannot be detected experimentally).

The conflict between classical mechanics and electrodynamics took the form of a contradiction between the principle of relativity and the proposition that light is propagated in a vacuum with a certain velocity that does not depend on the state of motion of the radiating body. Although both had been convincingly confirmed by experiments, they appeared logically incompatible.

The contradiction was resolved by Einstein, and that was the logical foundation on which the theory of relativity was built. The principle of relativity in which the idea of all inertial reference frames' being equivalent was generalised for electromagnetic phenomena (Einstein's principle of relativity) was taken as the first premise of the theory. As the second and last premise of his theory Einstein employed the independence of the velocity of light of the motion of the source, expressed as the principle of the constant velocity of light. He combined both principles and succeeded in doing so by altering the physical concepts of space and time. The simultaneity of two differently located events lost its absolute nature, the spatial intervals between bodies and the temporal intervals between events also proved to be relative, i.e. dependent on the bodies' state of motion with respect to the frame of reference. The relativistic kinematics that emerged led to the transformation of classical physics. In the theory of relativity a new law of motion was formulated for particles moving at high velocities; the law of the interconnection of the mass and energy of a material system was discovered; the law of the conservation of mass proved to be closely associated with the law of the conservation of energy.

The logic of Einstein's resolution of the contradiction between classical mechanics and electrodynamics, discussed above, is essential to the theme of this section.

First and foremost, and this is the main point, Einstein did not get rid of the contradiction between the principle of relativity and the principle of the velocity of light being constant by introducing some additional hypothesis that would have preserved these principles together with the foundations of classical physics. Such a 'resolving' of this contradiction would not have removed it but just brushed it aside, because the principle of relativity and the principle of the constancy of the velocity of light would have proved to be isolated, existing parallel within a certain classical scheme. Einstein resolved the paradox in a truly dialectical manner. He combined the two mutually contradictory principles, but not at all in the sense of the conjunction of formal logic; that meant abandoning certain basic concepts of physics that appeared established forever, and also the forming of new fundamental physical concepts, and consequently the constructing of a new fundamental physical theory, in which the principle of relativity and that of the constancy of the velocity of light figure as necessarily related to each other.

Physics abandoned absolute space and time and introduced relative space and time precisely in the theory of relativity; this is expressed adequately by the Lorentz transformations by which the transition is made in the theory of relativity from one inertial reference frame to another. At the same time the theory of relativity does not discard the concepts of absolute space and time completely but preserves them when the conditions of the problem permit certain circumstances to be ignored. If, for instance, it is possible to neglect the duration of the time light takes to pass between the points where the events occur, the concept of the absolute simultaneity is employed. In other words, the theory of relativity brings out the approximate nature of classical physics' concepts of space and time and indicates the limits of their applicability.

The theory of relativity thus reflects objective reality more accurately and more profoundly than classical physics, i.e. it embraces phenomena and processes that for some reason or other seemed too 'refined' for classical physics. The latter *directly* generalised notions arising in everyday experience and relating to space and time. The theory of relativity, which is based on experimental study of electromagnetic phenomena, develops its conceptions and notions indirectly through the ideas and concepts of classical physics. No other concepts than classical ones are used to describe the results of any experiments, including those with electromagnetic phenomena on moving bodies, and the physical interpretation of observations in each given inertial reference frame assumes the classical isolation of space and time.

The need to relate phenomena that occur in various inertial reference frames, however, and to find concepts and laws common for all inertial systems, increases the degree of abstractness of the physical concepts. The classical concepts are generalised and transformed into new relativistic ones, the classical concepts appearing as aspects of more meaningful and general relativistic concepts.

We shall see that the idea of dialectical contradiction of cognition is most important in metamorphoses of this kind.

In classical mechanics space and time are unified by Newton's laws of motion, and according to these same laws they do not depend on each other in the context of this unification, and exist separately, in mutual isolation. Galileo's transformations used in classical mechanics to pass from one inertial reference frame to another are just those that leave the expressions for spatial distances and time intervals invariant for all inertial reference frames (in classical theory, these expressions reflect the main properties of space and time). The situation is quite different in the theory of relativity. In it space and time are unified by laws of motion that differ from those of Newton; and in accordance with these new laws they prove to be interrelated by their nature. In the theory of relativity space and time are regarded as forming an integral system each component of which is objectively impossible and unimaginable without the other. The Lorentz transformations leave invariant the expression for the square of the interval that, according to the theory of relativity, defines the main properties of space and time, and this interval, or four-dimensional distance, is a special unification of the spatial distance and the temporal interval between the events. The matter of the unification of space and time, and of the specific character of this unification, is thus central to the theory of relativity.

If the point were the four-dimensional nature of an event, in the sense that it is characterised by three spatial quantities and one temporal one that is different from them, there would be no difference whatsoever between classical physics and the theory of relativity. Minkowski correctly stressed that 'the object of our observation is always only positions and time joined together. Nobody has observed a position other than at some time, or a time other than at some location'.[5] And although the concepts of space and time in classical physics are more 'abstract' than those developed by normal perception, classical physics also rests on acceptance of the idea of four-dimensionality, i.e. of an aggregate of spatial and temporal characteristics of physical objects. In Einstein's words: 'Classical mechanics, too, is based on the four-dimensional continuum of space and time.'[6]

The difference between classical mechanics and the theory of relativity on four-dimensionality begins with the solution of the problem of passing from one inertial reference frame to another one. In classical mechanics the spatial quantities vary separately during this transition from the temporal quantity, which remains constant (Galileo's transformations). In the theory of relativity when there is a transition from one inertial reference frame to another (the Lorentz transformation) time does not remain invariant but varies together with the spatial quantities. In other words, an unambiguous separation of the four-dimensional manifold into space and time is impossible in the theory of relativity, since it depends on the frame of reference in which the transition takes place, i.e. spatial three-dimensionality and temporal one-dimensionality form a truly single space-time four-dimensionality in this theory.

According to the theory of relativity, space and time thus do not have an independent existence; they are a single formation, something, so to speak, greater than space and time separately, which are simply added together, as it were, in classical theory. This understanding of space and time is already clearly depicted in the Lorentz transformation formulas. The most complete, concentrated expression, however, of the theory of relativity's understanding of space and time is to be found in its concept of interval. This concept, formulated by Minkowski, and his ideas of a four-dimensional world in general, plus the corresponding mathematical construction, gave the notions about relative space and time discussed in Einstein's paper *A Contribution to the Electrodynamics of Moving Bodies*[7] (this was the paper from which the theory of relativity began as a developed theory) their needed theoretical completion.

The most essential thing in the theory of relativity is not so much the discovery (or introduction into physics of the idea) of relativity of spatial distances and time, as the fact that it reflects in the appropriate concepts a united, necessarily connected space and time. The interval that combines spatial distance and the temporal interval is invariant relative to the Lorentz transformation, i.e. it is the same whatever inertial reference frame is considered; it is by virtue of this that spatial distance and the temporal interval will be different in different frames of reference.

The interval squared can be written as

$$S^2 = c^2T^2 - l^2,$$

where l is the distance between the points at which events took place (in some given inertial reference frame), T is the temporal interval between these events, and c is the velocity of light.

The difference in the signs of the two terms in this expression is a specific feature of Minkowski's four-dimensional geometry (or geochronometry) that distinguishes it from Euclidean geometry; it reflects the different nature of space and time, while the expression for the interval itself, in this case, conveys that in the unified space-time of the theory of relativity the radical difference between space and time is preserved. Following Minkowski, one can introduce a notation $\sqrt{-1}\,T$ so as to make the expression for the interval completely symmetrical (then the interval acquires the meaning of a four-dimensional distance between two points), but the imaginary sign before T also stresses, in this case, that time and space are not identical from the standpoint of the theory of relativity.

Let us assume that the interval corresponds to certain two events. For a given frame of reference there is a square of the spatial distance between the points at which these events occur, and a square of the temporal interval between them; in other frames of reference they will be different, but whatever system is taken the value of the interval will be the same. Suppose, now, that $S^2 > 0$. Since S^2 is invariant, we have $S^2 > 0$ for all frames of reference. If $S^2 < 0$, then $S^2 < 0$ for all frames of reference.

Intervals are thus divided into two classes according as their squares are negative or positive. The condition $cT > l$ defines the second class, and $cT < l$ the first.* In the first case the intervals are called timelike, in the second spacelike. These terms are associated with certain circumstances. If, say, a reference frame can be found for two events such that they occur at the same point, then the temporal interval between them $T \neq 0$, and $l = 0$, i.e. S^2 is reduced to its temporal term c^2T^2, hence the name 'timelike interval'. The origin of 'spacelike interval' can be explained in a similar way.

It must be remembered that an interval is by no means a mathematical abstraction but a concept of modern *physical* theory, and the theory of relativity expresses this definitely and convincingly. Without Minkowski's four-dimensional geometry, of course, the theory of relativity would not have achieved the status of a highly perfected theory; his ideas, however, as he pointed out, arose 'on an experimental-physical' basis' and 'therein lies their force'.[8]

This circumstance was reflected above all in the concept of the interval.

To sum up, what is the physical realisation of the interval? Or how is the interval that figures in Minkowski's geometry defined physically? Let us first consider the timelike interval. Let an event A and then an event B occur within a certain frame of reference at the same place. What is the interval between these two events? We would be justified in saying that within this frame of reference the

* We do not consider the case here when $c^2T^2 = l^2$, i.e. $cT = l$, $S = 0$ (the condition of the light cone).

distance between the points at which A and B occurred is zero ($l = 0$); therefore the interval $S = cT$. If another frame of reference is considered (moving with respect to the first one), the time interval between the two events will be different, and the distance l will be also different (no longer zero); the interval, however, remains constant. It turns out that the interval is defined physically as the difference between two clock readings that are at rest in the system in which the events occurred at the same place (i.e. in terms of the theory of relativity the physical meaning of the interval is that of the *intrinsic time* between the events).

One can show in a similar manner that the spacelike interval is physically determined by the so-called *intrinsic length.*

If we put what has been said in more general form, then, from the angle of the theory of relativity, it is not time itself that is measured by the clocks, but the time aspect of the interval, it is not distance itself that is measured by a ruler, but the spatial aspect of the interval. In the extreme limiting cases the clocks at rest measure a timelike interval, and a ruler at rest a spacelike interval. In the theory of relativity the concepts of space and time thus have meaning not so much as concepts of space by itself and time by itself as in their deep essential interrelation.

As a summary of sorts of the exposition in this section, we may cite Minkowski's words with which he began his famous paper *Space and Time* at a meeting of German naturalists and doctors in Cologne on 21 September 1908: 'From now on space in itself and time in itself are reduced to the role of shadows, and only some form of combination of the two should remain independent.'[9]

These words vividly expressed the dialectical spirit of modern physics when its first leading theory was nearing completion.

3

Dialectical Contradiction and Quantum Theory

The experimental data about corpuscular and wave properties of micro-objects (particle tracks in a cloud chamber and the diffraction of particles, e.g. electrons or molecules) are beyond doubt and are not rejected by any physicist. But how can these data—the particle-wave duality—be interpreted in a theory? This point is by no means trivial, because classical physics considers corpuscular and wave theoretical constructions as mutually exclusive. On the philosophical plane, the question of the ontological status of 'waves' and 'particles' arises first of all: does objective reality correspond to the experimental data on the micro-objects, which we denote by words classed as 'particles' and 'waves'? Is Philipp Frank, say, right when he states that 'the "electron" is a set of physical quantities which we introduce to state a system of principles from which we can logically derive the pointer readings on the instruments of measurement'?[10]

One can speak of a certain analogy between Zeno's paradoxes relating to motion and the particle-wave duality. In the first case the point is not so much the sensual certainty of the motion, of whether there is motion, as how to express it in the logic of concepts.[11] In the second case one also has in mind the need to understand the empirical certainty of corpuscular and wave properties of the micro-objects because the certainty alone is not enough. The corresponding problems in the two cases are solved by dialectics; the cases differ, however, as regards the nature of the dialectical unities that emerge. In the case of motion (mechanical displacement) the latter does not directly lead to the idea of contradictoriness, and even now one cannot help feeling amazed at the virtuosity of Zeno's dialectical mind (a virtuosity not yet conscious in many modern scientists),[12] when he, so to say, 'divided the single into two'. In the case of particle-wave duality, on the contrary, the 'split' is usual and it is the empirical fact of electron diffraction that causes surprise, or visual experiments with light of low intensities, which mean that the particle and wave aspects *merge together*.

How can the mutually contradictory particle and wave aspects be combined? More than one approach to a solution of this problem is possible.

Attempts used to be made to treat the wave phenomenon as one in a medium formed of particles. J. J. Thomson's theory, according to which 'the electron behaves as if it were within an atmosphere containing charges of electricity', can serve as an example.[13] Such a theory, in which only the particle is ascribed fundamental meaning and the waves are represented as something derivative, is being reborn in modern physics in one form or another.

When quantum mechanics was being created Schrödinger tried to interpret particles as 'wave packets'. This interpretation did not agree with the facts (it can be shown that 'wave packets' should 'spread' in the course of time, which does not happen to micro-particles); in addition it came up against insuperable difficulties when it had to explain the interaction between two 'wave packets, in physical, three-dimensional space.

Of late theories are being offered (David Bohm and others) that treat particles and waves as equally fundamental aspects of matter, emphasising primarily the idea of the joint existence of corpuscular and wave properties of moving objects in a certain classical type of model. This model preserves the classical concept of a trajectory, and in essence eliminates the symmetry between particles and waves that is inherent in quantum theory.

Those interpretations and other like them are typically based on the application of certain classical concepts and schemes to phenomena of atomic scale. In this way the classical concepts and schemes are understood in the corresponding conceptions as invariable and absolute. On the methodological plane, this feature is the main source of weakness of these conceptions: in the last resort they 'explain' *post factum* results that have already been obtained on the basis of Bohr's conception which rests on non-classical principles. Let us turn now to a point of view on the unifying of the particle and wave aspects that differs in principle from those noted above.

Bohr called the method of unifying the corpuscular and wave aspects based on the idea of transferring the concept of wave from classical optics to particle mechanics an *irrationality*. Although the attacks on his conception of unifying the corpuscular and wave points of view, and on his use of the term *irrationality* in this case not only still continue but have also become unjustifiably bitter,[14] one must nevertheless agree with Bohr about the essence of the matter. The method of unifying the particle and wave aspects in quantum mechanics resembles to some extent the introduction of irrational and imaginary numbers into mathematics, or the concept of the interval into the theory of relativity. One cannot get far in analysing issues related to such unification on the basis of any system of formal logic. Dialectical logic, which may appear, and actually seems irrational to the metaphysical mind, but which is in fact beyond reproach on the plane both of formal logic and of its own dialectics, appears on the scene.

In each of the 'rational' approaches noted above a segment of the line of cognition that reflects the state of things as it is is stressed in a one-sided way. Materialist dialectics, on the contrary, excludes one-sided cognition. It provides everything necessary and sufficient to clarify whether the supposedly absolutely incompatible particle and wave pictures of the behaviour of the micro-objects have objective meaning.

Matter, i.e. substance and field, is not, on the whole, particles or waves in the sense of classical theories, or unification of the two in a certain macroscopic (classical) model. Particle and wave properties are united in their opposition. In other words, matter simultaneously has the properties of particles and waves, but only in the sense that the motion of micro-objects can only approximately be regarded as translation of particles and propagation of waves. When the limiting cases are taken into account, micro-objects behave approximately like waves in some experimental conditions, and approximately like particles in others. The so-called relativity with respect to the means of observation (which realise the conditions in which the mutually exclusive properties of the micro-objects are manifested) is a typical feature of the description in quantum theory that follows from acceptance of the dual particle-wave nature of micro-objects.

These ideas have been developed in their clearest and most systematic form by scientists who are conscious adherents of dialectical materialism.[15] Idealist and metaphysical views primarily influenced a certain interpretation of the problem of uniting the particle and wave pictures of the behaviour of micro-objects, viz. by denying the objectively real nature of the unity of the particle and wave properties of matter at its atomic level and by subjectivising relativity to the means of observation. This interpretation is expressed most clearly in the idea of the uncontrollability in principle of the interaction between the microscopic object and the means of observation.

'Uncontrollability in principle', in the proper sense of the term, contains no truth, because processes and phenomena in nature are in principle cognisable, and, therefore, in principle controllable. Among the physicists who used this term, however, it frequently had no definite meaning and played the role of a kind of notation for the fact that quantum laws are qualitatively different from the laws of classical mechanics. The opponents of materialism, however, used this philosophically mistaken term in a subjectivist manner.

The concept has disappeared from the scientific literature of late, especially in the works of those physicists who oppose the principles of positivism in science (i.e. not only those scientists who are the conscious adherents of dialectical materialism). Niels Bohr, for example, in his last works on the philosophical aspects of atomic physics (as mentioned in earlier chapters), did not employ the concept and made it clear that the description of atomic phenomena had 'a perfectly objective character'.[16] The term 'complementarity', which he retained, signifies a novel kind of relation of the experimental evidence about micro-objects, obtained by mutually exclusive means of observation. This evidence, Bohr remarked, though it appears mutually contradictory, in fact 'exhausts all conceivable knowledge about the object'.[17]

Let us now go into greater detail about certain aspects of the meaning of a conception that stems from recognition of the dual particle-wave nature of micro-objects.

The particle—a basic notion of classical mechanics (like its other basic notions) — can be defined indirectly by Newton's law. Such a definition signifies that a particle has both momentum and position.* The classical concept, however, cannot be applied on the atomic scale because it does not correspond to the quantum laws established by experiment that are expressed by quantum formalism. In this case the uncertainty relation plays a most important role not only determining the limits of the applicability of the *classical* concept of particle, but also allowing us to generalise the particle concept and make it more profound by giving it a new content unknown to classical theories.

* We are dealing with the particle concept here solely from the standpoint of classical mechanics.

This new content follows from the need to allow for the wave properties of micro-objects in the theory.

In the definition of a particle of classical mechanics, of course, its momentum and position are unrelated to each other by their very nature, and must be considered separately. In quantum mechanics it is impossible to consider the position and momentum of a particle separately; they have to be understood in their deep interrelation, because micro-objects have wave properties that are inseparable from their corpuscular ones. This becomes clear, in particular, from the imaginary experiments that accompany the exposition of the uncertainty relation; they provide obvious evidence that one cannot isolate the particle's position from its momentum in quantum mechanics precisely because of the dual particle-wave nature of micro-objects.

In quantum formalism, which differs qualitatively from the formalism of classical theories, the state of things in physics internally linked with recognition of the dual particle-wave nature of micro-objects is described mathematically. In it symbols figure that denote not numbers (as in classical formalism) but more abstract mathematical concepts (operators) that are not, generally speaking, governed by the commutative law of multiplication. Each physical quantity in quantum mechanics corresponds to its operator in such a way that the eigenvalues of the latter give the possible values of the former, and its eigenfunctions describe the corresponding states of the object (system). Even the definitions of the operators of momentum and position potentially contain the uncertainty relation (for momentum and position), which means that in no quantum state (mathematically described by a wave function) there exist the eigenvalues of the operators of position and momentum at the same time together, i.e. it is affirmed in essence that quantum mechanics does not deal with the 'classical' particle.

In quantum mechanics (and this is demonstrated above all by its mathematical apparatus) corpuscular and wave notions thus cannot be combined in the manner of classical physics. From the standpoint of classical physics the expression 'particle-wave dualism' can be used, as follows from what has been said, in the following senses: 1) *either* a particle *or* a wave, 2) *both* a particle *and* a wave. From the standpoint of quantum formalism, however, both these meanings lose significance. It remains to find, as Bohr put it, the 'irrational' form of uniting the particle and wave concepts. If such a form exists, what is its logical meaning?

The novel form of the combination of the particle and wave concepts in quantum mechanics is concentrated in the novel feature of *quantum* probability, one of the fundamental concepts of quantum theory. This concept, introduced by Born and developed further by Bohr, means that the processes in material systems are governed by probability (stochastic) laws. According to this interpretation, the translation of a particle is associated with a wave process that represents the propagation of a probability wave.

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. The hypertrophy of this state of affairs that is typical of metaphysical ideology leads to a subjectivist interpretation of chance and probability (Laplacian determinism). 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. The probability laws of quantum mechanics are the laws of behaviour not of 'classical' particles and not of 'classical' fields, but of material systems that combine the properties of particles and waves in a novel way.

The idea of the 'probability wave' of quantum mechanics as a mode of uniting the particle and wave concepts may appear artificial, but when one analyses certain experiments that are by no means imaginary, its naturalness is obvious.

In an experiment, say, with a machine gun, we can judge the statistics of the bullets by their pattern on the target. In an experiment on the diffraction of successive electrons we learn about the statistics of electron behaviour on the basis of the specks on a screen (traces of the electrons hitting it), which form a diffraction pattern in a sufficiently long experiment. Comparing these two experiments, we are justified in saying that the probability behaviour of the electron is governed by the wave law (which cannot be said of the behaviour of the bullet). The diffraction pattern formed by the traces of electrons hitting the target is evidence that the electron moves not as a 'classical' particle but as one possessing both corpuscular and wave properties. Indeed, we conclude from a spot on the screen that the electron possesses particle properties; from the diffraction pattern formed by the spots we infer that the electron that has passed through a diffracting system has interacted not with a single atom, or a small number of them (as a 'classical' particle would have done), but with the diffracting system as a whole (i.e. it behaves as a wave). Thus, an electron passing through a diffracting system moves neither as a 'classical' particle nor as a 'classical' wave but as an object that has inseparable particle-wave properties.

It is very important to clarify what the inseparability of the electron's particle-wave properties means or what is understood by dialectical unity of the particle and wave properties of matter when the question is posed more broadly. It can be demonstrated by the following example. By performing Young's interference experiment (assuming that the screen used is made of material that emits photoelectrons easily) we can observe the particle nature of light. Born denied that in this experiment light appears in its two forms simultaneously as particles and as waves.[18]

When one thinks over Born's arguments, however (he says, in particular, that 'to speak of a particle means nothing unless at least two points of its path can be specified experimentally; and similarly with a wave, unless two interference maxima are observed'[19]), it becomes clear that he essentially had in mind the 'classical' particle and wave. Indeed, in order to understand the corresponding phenomena in Young's experiment one must not employ the classical concept of particle and wave—it was just that which Born's argument demonstrated, as a matter of fact, although he meant to show something else. Here one must already employ the concepts of *quantum* theory which differ qualitatively from the classical ones. The concept of particle in quantum theory undoubtedly differs from its classical analogue, and in its own way Young's experiment demonstrates this circumstance.

The difference between the *quantum* concepts of particle and wave and the analogous *classical* ones is that the quantum concepts are relative within the limits of their theory, while the classical ones are absolute within the limits of their theory. This means that it is necessary, in order to describe the behaviour of a micro-object, to consider the means of observation (relativity with respect to them), whereas this consideration can be omitted in the description in classical physics.[20] This difference rests on recognition of the fact that in quantum theory the moving objects are regarded from the standpoint of the unity of their opposing particle and wave properties, while in classical theory the unity of waves and particles, if permitted at all, is only so from the standpoint of their coexistence or parallel existence in a certain model governed by the laws of classical theory.

We are justified in inferring that the dialectical unity in which relative opposites must be and are combined differs radically from the uniting of opposites in the sense of their conjunction, when they remain absolute and immobile. The combination of opposites in a dialectical unity does not lead to a formal-logical contradiction (as follows from the definition of dialectical unity). Such a combination implies that a more profound theory than that in which absolute opposites figure is being, or has been born, a theory with corresponding new basic concepts and principles. The opposites combined in this theory become aspects of a new concept. The quantum-mechanical concept of particle thus 'preserves' the element of discreteness of the classical concept but 'loses' the properties of motion along a trajectory and of individuality. These 'losses' actually mean that, whenever it is a matter of quantum-mechanical objects, wave properties are combined with particle ones (which is expressed in quantum mechanics itself concretely by the uncertainty relation for momentum and position).

Summarising what has been said on the logical plane about dialectical unity, we can note that this unity is governed, generally speaking, by the formula 'both yes and no', reand as regards particle-wave duality by the formula '*both* particle *and* wave', but posed as an antinomy problem.* This formula neither can nor does lead to a formal logical misunderstanding, because, when the antinomy problem is resolved, the quantum mechanics means by 'particle'

* Here we are using terms of the type of contradiction category that is called contradiction-antinomy or the antinomy-problem.

and 'wave' mutually relative concepts, while in classical physics they are absolute concepts. In the terms of modern logic it becomes especially clear that the formula 'both particle and wave does not lead to any logical nonsense. This expression belongs to the metalanguage, while the expression 'either particle or wave' belongs to the object language, and moreover to the language of classical theories, and this is admissible only on condition that the problem is formulated in the metalanguage and resolved in the object language. From that point of view quantum mechanics is also, in a certain respect, the metatheory of classical mechanics. It is quantum mechanics that enables the limits of applicability of classical mechanics and of its principles and basic concepts to be established, and other matters relating to classical mechanics as a whole as a theory to be considered (e.g. the matter of the adequacy of the concepts admissible in classical mechanics to objective reality).

The limitations imposed in quantum mechanics on the classical concept of particle are neither a limitation of knowledge, nor confirmation of the positivist thesis that the objective significance of the empirically observed is a question quite without scientific meaning. This 'limitation' is in fact a deeper understanding of the corpuscular properties of matter allowing for the wave properties that are inherent in it and that are neglected by classical theories of matter in their study of particles. The concept of particle is generalised and deepened in accordance with this 'limitation' when it drops its classical form, so to say, in this generalisation.

Let us sum up. When physics comes to understanding the world of atomic phenomena and of the subatomic world, or when it passes to cognition of the world of stellar systems and galaxies, it has to take into account the all-round, universal flexibility of concepts reflecting the eternal development of the objectively real world when synthesising in the truly philosophical sense of the term the physical knowledge gained about the macroworld and the microworld. Lenin's fragment *On the Question of Dialectics* which is extremely 'coimpressed' and very profound in its content, and which summarises everything basic that he said in his *Philosophical Notebooks*, clearly indicates that such an all-round flexibility of concepts is inherent only in dialectical thinking.

The splitting of a single whole and the cognition of its contradictory parts is ... the *essence*... of dialectics,' he said. 'The condition for the knowledge of all processes of the world in their "*self-movement*", in their spontaneous development, in their real life, is the knowledge of them as a unity of opposites. Development is the "struggle" of opposites.'

'The second *alone* [the conception of development as a unity of opposites—*M. O.*] furnishes the key to the "self-movement" of everything existing; it alone furnishes the key to the "leaps", to the "break in continuity", to the "transformation into the opposite", to the destruction of the old and the emergence of the new.'[21]

It is as if this fragment had been intended by Lenin for the new physics, for the quest for a solution of the philosophical problems arising in it. Striking confirmation of this is the transformation of the original quantum ideas into a logically consistent, developed physical theory—quantum mechanics.

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VI

DETERMINISM IN QUANTUM THEORY

1

The Objective Reality and Determinacy of Phenomena

In dealing with the connection between the phenomena of nature and its regularity, necessity, and causality, there are, as Lenin pointed out, two major philosophical lines, materialist and idealist. Recognition of the objective reality of the phenomena of nature and of the external world leads to recognition of an objectively real connection, necessity, causality, and determinacy in natural phenomena, i.e. materialism, which, when consistently followed, cannot be separated from determinacy. On the other hand, a consistently followed negation of the objective reality of the external world, and acceptance of nature as derived from mind, consciousness, and experience leads to a view that consciousness 'creates' laws, and mind introduces order into nature's 'primary chaos', and leads to acceptance of indeterminism, i.e. idealism, which, when it is consistent, is inseparably connected with indeterminism.

It is not by chance that those scientists who tend toward idealism, i.e. who see only symbols, signs, and logical constructions serving to 'systematise the observed' in scientific concepts and theories, instead of a reflection of objective reality, conclude that determinism either plays no scientific rôle whatsoever or has only limited significance as regards cognition of nature and that the principle of causality operates only in the sphere of the ideal, which has no relation to the real world. Ideas like this have been turned into whole philosophical conceptions in the work of modern bourgeois philosophers[1] as a reaction to physics having penetrated into the atomic and subatomic worlds, and having begun to study processes that are not perceived directly but are learned about only from the readings of instruments, statements about these readings, moreover, not being classifiable within the theoretical schemes of classical physics.

Dialectical materialism, like non-dialectical materialism, recognises the objectively real world connection, but its understanding of this connection, and of objective reality, is much deeper and broader than that of metaphysical mechanical materialism. In mechanical materialism objective reality is reduced to absolute, invariable substance, to constant particles that move according to laws established once and for all, and the world connection is correspondingly likened to a direct, necessary connection, representing the whole world after the manner of a gigantic mechanism. Engels called this kind of determinism 'mechanical determinism'. For mechanical determinism the connections existing in nature are reducible in the final analysis to the connections that are studied by classical mechanics, rejecting the objective reality of chance, and recognising necessity, identified with causality, only in its direct, simple, abstract form. Kant and Hume, who are frequently cited by the modern idealists, who consider these philosophers' theory of causality matchless, developed a mechanistic approach to the world connection, depriving it, however, of its materialist foundation.

Marxist philosophy has developed a quite different view on the objectively real connection, necessity, regularity, and causality. In accordance with dialectical materialism's rejection of metaphysical 'invariabilities' of all kinds and recognition of only one thing as invariable, viz. the existence of the eternally developing external world, matter, reflected by human consciousness (when the latter exists), Marxist philosophy considers the objectively real world connection as inexhaustible and comprehensive by its actual nature, revealing to cognising man ever new, more meaningful forms and aspects; causality is one of these forms, cognised, like all other forms of connection, more and more completely and precisely with each step of science and practice. Dialectical materialism pays special attention to the reciprocal transitions of cause and effect and to the relation of causality to other forms of the world connection. Although causality does not exist outside necessity, it is not identical with the latter. It causes chance phenomena that exist objectively as a manifestation and complement of necessity. The problem of causality is related to that of the infinity of matter deep in the depths and infinity of its cognition.

Quantum mechanics is once more confirming all these statements of dialectical materialism. It owes it to dialectical materialism that it has emerged from the indeterminist impasse into which modern idealism tried to force it; dialectical materialism helped it resolve the philosophical problems before which mechanical materialism came to a halt.

Heisenberg's uncertainty relation, Schrödinger's wave equation, and the novelty of the statistical (probability) laws of quantum mechanics are a new landmark in man's progressing knowledge of the objectively real, regular, causal connection. The concepts 'order', 'regularity', and 'causality' in physics do not necessarily have to be expressed solely by the quantities and relations of classical mechanics. They can, in particular, be expressed by means of the quantities and relations of quantum mechanics, which reflect moving matter more deeply and accurately; these concepts thereby acquire a new content that classical theory could not know; in other words, quantum mechanics reflects connections that classical mechanics could not embrace. The further penetration of human knowledge into matter is now, undoubtedly, revealing, and will do so in the future, ever deeper and more general connections that do not come into quantum mechanics' field of applicability, as the developing science of elementary particles witnesses; and the content of the concepts of causality, order, and law in physics will correspondingly undergo a new change.

The progress of atomic physics led to the spread in modern non-Marxian philosophical literature of an idealist point of view on necessity, law, and causality in nature, viz. to an affirmation that determinism is allegedly bankrupt as regards atomic phenomena, and the principle of causality, if it remained at all, did so only in the sphere of mathematical ideas about the atom. In this case 'physical idealism', to paraphrase Langevin's expression, repaid what it had borrowed from philosophical idealism with interest. In this connection let us compare the views of certain modern Western physicists and philosophers on causality with dialectical materialism.

Heisenberg, for instance, considers the concepts of the objective reality and causality (taken together) as ones that are inherent solely in classical physics. As for quantum mechanics, he thinks that 'the objective' and 'the real' are isolated from one another in it; the 'objective' is retained only for symbolic representation of the atom by the (mathematical) wave function, and 'the real' only for describing atomic processes in terms of classical concepts (or in terms of space and time)[2]. In accordance with this point of view, determinism or causality (Heisenberg does not distinguish between them)[3], instead of governing events in space and time, operates formally in the mathematical scheme of the atom, events in space and time being governed solely by statistical laws.

Heisenberg's ideas about the 'objectivity' of the atom are very close to Plato's philosophy, as their author said more than once.[4] At the same time the following aspect of his outlook is important. According to him, symbolic representation by the wave function (and causality) exclu des description of atomic processes in terms of classical (corpuscular) concepts (and statistical laws). They represent complementary aspects in the sense that only their combination makes it possible to solve problems relating to atomic theory. But then Heisenberg's ideas (which are summed up in the complementarity conception formulated and developed by Niels Bohr) include a grain of a dialectical approach to analysis of atomic processes. We shall return to this point in the sections that follow.

The positivist philosopher Hans Reichenbach disagreed with Heisenberg; he suggested that, if causality existed, then it did so really rather than formally, governing events in space and time. In his opinion 'a causal supplementation of observable data by interpolation of unobserved values can be consistently done'.[5] In classical physics, he said, such causal supplementation existed; in quantum mechanics, however, it did not exist, for the reason that the principle of causality allegedly meant the possibility of predicting the future with arbitrary accuracy, but, by the uncertainty principle, 'we cannot expect to be able to make strict predictions of future observations'.[6] Reichenbach made a step backward compared with Heisenberg, because, from his point of view, the antithesis of statistical and dynamic patterns, which is quite clear in Heisenberg's reasoning, had been reduced to nought.

The American physicist P. W. Bridgman holds a similar idealist position, but he is far from the dialectical guesses that abound in the statements of Bohr, Heisenberg, Born, and many other representatives of the Copenhagen interpretation. According to him, the conclusion that causality does not exist in the microworld 'is to be accepted without prejudice or passion just as any other experimental result is accepted'.[7] This conclusion, he assumed, corresponded completely to the 'new understanding of the experimental situation', in the domain of experimental investigation of atomic phenomena, which was expressed in the statement that 'events are not predictable in the realm of small things'.[8]

The American physicist and philosopher Henry Margenau stood for recognition of causality in classical and quantum physics, but for him it was just a connection between 'constructs', 'a metaphysical requirement' presented to scientific 'constructs'; these 'constructs' were built by the intellect in such a way 'as to generate causal laws'.[9]

Margenau rejected the concept of objective reality that appears in one form or another in the publications of physicists of the Copenhagen school, and also opposed the idea of complementarity or rather the antithesis of its aspects. Bohr, he wrote, condemned himself to 'an eternal dilemma': either to reject causality for describing nature in terms of classical observables or to describe it only in terms of 'abstract states, such as ψ-function', the second choice allowing 'causality to be retained'.[10] In Margenau's opinion, science chose the second path.[11]

Max Born's statements about causality and determinism are of special interest. He rejected determinism for microphenomena and said that it 'is an *idol*, not an *ideal*, in the investigation of nature and, therefore, cannot be used as an objection to the essentially indeterministic, statistical interpretation of quantum mechanics'.[12] At the same time, as if contradicting himself, he supported causality in quantum mechanics. 'The deterministic mechanistic view,' he wrote, 'produced a philosophy which shut its eyes against the most obvious facts of experience; but a philosophy which rejects not only determinism but causation altogether seems to me just as absurd. I think that there exists a reasonable definition of the cause-effect relation which I have already mentioned: that a certain situation depends on another one.'[13]

The following common features are inherent in these statements and in the views on causality of other authors who reject the objectively real connection because of the advances of atomic physics. (1) Causality is isolated from the objectively real external world and becomes a kind of supernatural principle (and the real external world either proves to be a derivative of the mind, spirit, or experience, or is declared to be essentially unknowable); accordingly causality is identified in one way or another with the predictability of what is observed. (2) The difference between mechanical determinism and determinism as understood by dialectical materialism, as a theory of the universal connection of phenomena that discloses new aspects of itself in the infinite process of its cognition, is ignored. (3) Causality is confused with dynamic regularity, being either opposed to statistical regularity or regarded as a statistical average of disordered elementary phenomena.

In what follows we shall consider points related to this issue. Here we shall simply outline the trend which should determine our critical analysis of these non-materialist and metaphysical views of causality.

Isolation of causality from the objectively real world, i.e. rejection of an objectively real causal connection, is an idealist line of argument about the principle of causality. Every law is incomplete, narrow, and does not exhaust the whole of phenomena; the concept of causality reflects the universality of the world connection in only a fragmentary way, but for all that laws and the causal connection exist objectively, independently of the mind cognising them; the all-sidedness of the world connection cannot be exhaustively expressed, once and for all, by a single theoretical scheme of determinism, and it is in this, in particular, that the objective character of the universal connection between phenomena is revealed. It is here that physicists who ignore dialectical materialism sink into idealism.

Born, for instance, did not agree with mechanical determinism. He supported indeterminism, understanding this term in the sense of statistical regularity. He, however, either did not want to, or could not, reject regularity, necessity, and causality in nature and called for a new definition of the relationship of cause and effect. Such a seeming inconsistency of Born's as acceptance of indeterminism and retention of causality can be explained by the fact that the spontaneous materialism and its rejection of the 'traditional' idealist and metaphysical philosophy, which pushed Born to retention of the objective causal connection, could not solve the problem of the dialectical contradiction associated with problems of the synthesis of particle and wave notions, the combination of dynamic and statistical regularities, etc. These problems can only be solved from the standpoint of dialectical materialism, which Born ignored as the philosophy of modern science.

Dialectical materialism, as we know, provides a philosophical answer to the problem of causality in quantum mechanics. 'Causality, as usually understood by us, is only a small particle of universal interconnection, but ... a particle not of the subjective but of the objectively real interconnection.'[14] In these words of Lenin's is said what Born was looking for but did not find.

The problem of determinism in quantum mechanics cannot be solved without a dialectical analysis of necessity and chance, possibility and reality, cause and effect.

2

On the Relationship Between Determinism and the Principle of Causality in Physics

On the point in the title of this section there is no unanimity among scientists. If that is a minus from the standpoint of the strictness of a system of ideas, it is a plus from the standpoint of the history of views on the problem of causality and determinism, a plus in that the various statements about the problem cover diverse aspects of the universal connection in nature. Philosophy once experienced something similar. In ancient philosophy, for instance, the concept of cause was more general and undefined than it is in our day, and Aristotle, that great encyclopaedic mind of antiquity, distinguished four kinds of causality: *causa formalis*, *causa materialis*, *causa efficiens*, and *causa finalis*.

The concept *causa finalis* was used in particular by Engels in his *Dialectics of Nature*, though in another sense than Aristotle's. In general, all these terms can be found in modern philosophical literature, but the meanings given to them by Aristotle are now referred to other, more accurately defined categories. Only the term *causa efficiens* (the efficient cause) has to some extent retained its meaning, which corresponds approximately to the modern meaning of the word 'causality'.

In the first section of this chapter we considered the relationship of determinism and the principle of causality in its general form. Here we shall add some details and definitions in connection with our theme.

Causality is a category for denoting a necessary connection in time for processes occurring in it. If in given constant conditions phenomenon A generates, causes, or determines (in this context these concepts are identical) another phenomenon B, then the connection between the two phenomena is a causal one in which phenomenon A is the cause and phenomenon B is the effect.

A causal connection is a necessary connection between different phenomena precisely in time. There are the most varied connections between the phenomena of nature, including a necessary connection in the space in which various phenomena occur at one and the same time. The statement 'a charge is the source of an electromagnetic field', for example, expresses a necessary connection between the values of certain quantities existing simultaneously; in other words, the connection between the electrical and magnetic fields is a necessary one but, like the connection mentioned in the first example, it does not represent a causal connection. An infinite number of such examples can be adduced; they illustrate the idea that a causal connection is only a tiny part of the world connection between phenomena.

The categories of cause and effect have an inherent meaning only as applied to phenomena that in given conditions are regarded independently of the phenomena around them and in that sense represent an isolated system. As soon, however, as these phenomena are considered in connection with the phenomena around them, cause and effect are united with each other in the notion of universal interaction in which they never remain the same: what is the cause in some conditions becomes the effect in others, and vice versa.

The category of causality implies a connection between two phenomena. A certain phenomenon M can be a cause of a certain phenomenon N and an effect of phenomenon K; no phenomenon, however, can be the cause of itself. Engels, it is true, said that matter and its inherent motion were *causa finalis* (the final cause), but did not do so in the ordinary meaning of the term 'cause'.[15]

A change of any object or phenomenon, and its transformation into 'its other', is a splitting of the whole into contradictory parts, into mutually exclusive opposites, and the unity of these opposites is sometimes called the cause of change and development. That is done, however, so as to make the argument easier to follow, and the term 'cause' is not used here in its proper meaning; the category of dialectical contradiction underlies the other categories of logic and dialectics, including that of causality, so that it is wrong to explain the category of contradiction by the category of causality.

At the same time we must not ignore the fact that a phenomenon can change and at the same time remain basically the same; in this case the concept of state is used. This concept plays an important role in physics, especially in matters relating to causality. Without it, it is impossible to solve problems relating to the theme of this section.

Many physicists, regardless of their philosophical views, understand by the principle or law of causality in physics a proposition about a necessary connection between a system's state (an isolated system is implied, which may be a single particle) at an initial moment of time and its state at any other succeeding moment of time. The Austrian physicist Arthur March, for instance, who said that 'the spirit of materialism' and 'the materialist mode of thought' were 'bankrupt',[16] at the same time has written that 'in quantum mechanics, too, there is causality, and this, as in classical physics, consists in the basic proposition that it is possible to deduce the future state of a system from its state at a given time and under given influences'.[17]

From this point of view the principle of causality is valid in quantum mechanics because in it, the initial value of the state of a system characterised by a wave function allows one to determine the state, i.e. the wave function ψ, at any other moment of time by means of the so-called wave equation $i\hbar \frac{\partial\psi}{\partial t} = \hat{H}\psi$, where $\hat{H}$ is the energy operator, or Hamiltonian.

This understanding of the principle of causality, however, actually means an extension of the concept of causality, its incorrect identification with the idea that phenomena are mutually connected and reciprocally caused. It seems to us that one cannot agree with that interpretation of causality, when it performs the function of other categories reflecting aspects of the universal world connection. The principle of causality, of course, consists only in the following: under certain conditions a phenomenon (cause) generates another phenomenon (effect). In the case of causal relation between phenomena we ignore their connection with the world whole and consider them independently of it. Consequently, as we have already noted, the infinite diversity of necessary connections cannot be reduced to just one causal connection, i.e. the connection between cause and effect.

Let us turn to classical mechanics. In the case of uniform motion in a straight line the change in a particle's position at a certain moment of time is not the result of the action of a force. Newton's first law directly expresses the connection between phenomena relating to uniform motion in a straight line and therefore it makes it possible, given knowledge of the initial position and the velocity of a particle moving uniformly along a straight line, to calculate its position at any other moment of time.

In the case of non-uniform motion, however, a change in a moving particle's velocity results from the action of a force that functions in this case as the cause; Newton's second law expresses this causal connection. In classical mechanics, however, the state of motion of a particle at a certain moment of time is not a cause of its state at a subsequent moment of time. If the initial state allows one to calculate the particle's position and velocity at any other moment of time, this circumstance is evidence only that the particle's state of motion at a given moment and its state at any other moment are necessarily connected with each other, and this connection is a regular pattern of the phenomena of motion studied by classical mechanics and expressed in Newton's laws.

The problem of causality and determinism is similarly solved in quantum mechanics. If the value of the wave function at any moment of time can be calculated from its value at any initial moment, this means only that the connection established by quantum mechanics between the values of the wave function at different moments of time is a regularity of quantum mechanics, and this regularity is expressed by the wave equation (which was formulated by Schrödinger).

Quantum mechanics thus resembles classical mechanics in the sense that they both unambiguously determine the connection between a state at time t_0 and a state at time t.

Although in both classical and quantum mechanics the state of a system at a future moment can be determined unambiguously from the state of this system at a given moment, the nature or type of the connection between the two states differs fundamentally in classical and in quantum mechanics.

The connections between a particle's states at two different moments of time that are considered by classical mechanics resemble the connections of the states, say, of an electromagnetic field to which Maxwell's theory applies, in this respect, that value of the quantities describing the state of an object at any moment of time can be calculated from the values of the quantities describing its state at an initial moment. This common feature of the given connections exists, in spite of Newton's laws being different from Maxwell's equations, and in spite of the states of an electromagnetic field being characterised by quantities other than position and momentum. Such connections have something to do with dynamic regularity, and many authors believe the latter to be the sole, so to say, representative of determinism and causality in physics.

In quantum mechanics, as follows from what has been said, the type of connection between the values of a particle's state in time is different in principle from that in classical physics. The wave function describing the state of a particle describes not the particle 'by itself' but the potential possibilities of its interaction with instruments, i.e. definition of the wave function at the initial moment of time makes it possible to obtain probabilities of results of measurements of each quantity, measurements that can be made of a particle in a given state.*

We would be justified to draw the following general conclusion from what has been said: the wave function determines the probabilities and at the same time satisfies the Schrödinger equation; this means that there is an inner necessary connection in quantum mechanics between its probability (statistical) and dynamic regularities.

The connections between the quantities of quantum mechanics relating to the time variation of a state thus do not have solely a statistical or solely a dynamic regularity. This is the novel feature of the statistical (probability) laws of quantum mechanics. Its laws inseparably combine the statistical and dynamic aspects of the mechanism of atomic phenomena (which is most adequately expressed in the operator equations of quantum mechanics).

It follows from everything said above that quantum mechanics, like every scientific theory, is deterministic, although its determinism differs from the Laplacian determinism of classical mechanics and from the wave determinism of classical field theory. And as regards the question of causality in quantum mechanics, i.e. whether quantum mechanics is a, so to say, causal theory, the answer suggests itself. Quantum mechanics recognises force effects on micro-objects; it is therefore a causal theory, since these effects or actions necessarily generate corresponding changes in the objects' further motion. These force effects are therefore a cause. The temporal connections (i.e. the course of atomic processes in time) that are reflected by the wave equation also include these causal connections.

To conclude this section, let us consider the statements of contemporary physicists about the relation between determinism and the principle of causality.

In Heisenberg's view the principle of causality gradually, as philosophy and physics developed, proved to be 'tantamount to the expectation that the event in nature is uniquely determined, that exact knowledge of nature or of a certain sector is sufficient in principle at least to predict the future'.[18] He believed that this was exactly the situation in Newtonian physics, in which a system's state at

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* For details of the analysis of the problem of measurement and interaction in quantum mechanics, see Chapter IX, sections 6 and 7.

a certain time makes it possible to calculate its future motion. 'If we interpret the word "causality" so narrowly, we also use "determinism" and mean by it that there are firm laws of nature by which the future state of a system can be predicted unambiguously from its present state.'[19]

Heisenberg thus did not distinguish between causality and determinism, and understood the latter in the spirit of a mechanistic outlook.

Max Born drew a line between causality and determinism in physics. According to him, determinism coincided with Laplacian determinism. Hence one can understand why Born fought for indeterminism in quantum mechanics, as we said in the first section.

There is much in common between Born and Leon Brillouin in their understanding of causality and determinism. In Brillouin's opinion, '*determinism* assumes a "must": the cause must produce such and such effect (and very often one adds, "right away"!).'[20]

'*Causality*,' he continues, 'accepts a statement with a "may": a certain cause may produce such and such effects, with certain probabilities and certain delays.'[21]

Brillouin thus rejects dynamic regularity (and the mechanical determinism associated with it) and accepts statistical regularity only, formulating the concept of causality accordingly.

And yet, Brillouin's probabilistic formulation of causality not only does not disprove determinism (which, of course, cannot be reduced to mechanical determinism, i.e. to a determinism such as corresponds, in spite of its limitation, to a certain domain of connections between the phenomena of nature) but, on the contrary, enables one to comprehend it deeply. Indeed, his formulation essentially does not cancel the *genetic* connection between cause and effect, as would appear at the first glance; this idea remains, but effect appears in it as a multitude of certain potential possibilities that are realised in certain conditions. Interpreted in this way causality is close to the idea of transformability in the modern theory of elementary particles.

March understood by causality in physics 'the concept of order in application to natural processes'.[22] In his interpretation a causal relation connects a present event not with a past *event* as its cause but connects it, in his words, 'with the whole past of the world'.[23]

This understanding of causality led him to accept causality in both classical theory and quantum mechanics. 'Every physicist,' he wrote, 'must believe in the possibility of drawing inferences about the future from the present; abandonment of this principle would be tantamount to an interpretation that natural events take place quite anarchically, which would deprive physics of any content. A causality also exists in quantum mechanics, and it consists in the principle, as in classical physics, that it is possible to infer from the state at the moment of a system that is under a given influence what its future state will be. The difference from classical physics lies solely in the interpretation of the concept "state", which quantum mechanics does not understand in the same way as classical physics.'[24]

Consideration of the concept of state led March to conclude that there is 'strict causality' in classical mechanics and 'statistical causality' in quantum mechanics with no essential difference between the two and statistical causality including the strict one as its special case.[25] He did not use the concepts of determinism and indeterminism.

March's reasoning, which touches in one way or another upon the question of the relation between determinism and causality in physics boils down, as a matter of fact, to his calling statistical regularity in the processes of nature causality and assuming that probability underlies all laws of phenomena occurring in time.

With physicists who hold to dialectical materialism the matter of the relationship between determinism and causality is also not quite determined. They have demonstrated the incorrectness of mechanical determinism as applied to the processes of nature, emphasised the acceptability of Laplacian determinism for phenomena within the domain of classical mechanics, and rejected it for the atomic processes with which quantum theory is concerned. As for the terms for denoting objectively real, necessary connections in time between atomic phenomena, however, they have not yet developed a generally accepted point of view. Langevin, for example, preferred the term 'determinism' to describe the temporal course of the atomic phenomena that are reflected by quantum mechanics, drawing attention to the various forms of determinism in various physical theories and to the need for new concepts and new formulations of the problem when new phenomena were being studied.[26]

Fock, Blokhintsev, and Terletsky prefer the term 'causality' to denote necessary connections in time, and point out the need for new forms to express causality in nature and, correspondingly, for new concepts.

Fock, for instance, says: 'We need to introduce two terms, for example, "Laplacian determinism", which means a conviction of the possibility in principle of infinitely precise forecasts, and a more general term "causality" in the sense of the existence of laws of nature. Laplacian determinism is actually disproved by quantum mechanics, but causality is fully retained, only with its expression acquiring new forms.'[27]

The question under consideration was treated quite clearly in Terletsky's *Dynamic and Statistical Laws of Physics* (1950). He distinguished between a general law of *causality* that manifests itself in the 'existence of an objective reciprocal connection and the conditionality of phenomena and objects' and the *two main forms of its expression in physics*: (a) *classical determinism* understood 'as a notion of the full reflection of a physical process by a certain set of quantities that are completely determined at any moment of time when the initial conditions are given', and (b) a *statement* to the effect that 'every successive event is always a consequence of certain preceding events, or causes'.[28]

It will readily be noted that Terletsky used the term 'causality' in the sense of 'determinism'. And when he uses the term 'general law of causality', he means by it what we, following the philosophical tradition, have called 'determinism'. In this case it would be better to use 'the law or principle of causality' to denote what figured with Terletsky as the second main form of manifestation of the 'general law of causality'.

Which terminology is more appropriate and accurate? That can only be answered correctly in connection with the history of philosophy and the development of its concepts, which have found their highest result and summary in dialectical materialism. The term 'determinism' signifies *determinacy*, reciprocal conditionality, an all-sided connection between phenomena of the material world; the term 'causality' signifies a certain part of the world connection; the terms 'dynamic regularity or laws' and 'statistical regularity or laws' signify various manifestations of the world connection in the sphere of phenomena studied by physics.

3

Statistical Laws and Determinism

Statistical conceptions are inseparable from the atomistic picture of the world. The development of atomistic views of matter involved and more and more brought out the idea of statistical laws.

Even the atomists of antiquity held concepts in embryo which, in developed form, contributed to the notion of statistical law in classical physics. Democritus made external necessity the most important principle of atomism; the atoms, which moved initially in all directions, collided with each other forming vortexes that generated countless worlds in the infinite void. The chaotic motion of atoms in all directions, according to him, was the basis of everything that happened in the great world, whose phenomena did not resemble the motion of atoms in the void.

Epicurus modified Democritus' atomistic teaching substantially. The famous *declinatio atomorum a via recta* ('*declination* of atoms from the straight line') introduced by him represents an inner necessity inherent in atoms. As Lucretius correctly said, it violated the 'laws of fate', Democritus' fatal necessity. Whereas the 'vortex of atoms' (or the 'motion of repulsion') in Democritus' theory was an act of external, 'blind' necessity, Epicurus saw in the 'motion of repulsion' a synthesis of inner and external necessity, external motion and the motion inherent in the atom.[29] As we shall see later, the question of the synthesis of external and inner necessity is decisive for a correct solution of the relation between dynamic and statistical necessity.

The idea of random motion of infinitely small particles underlies classical physics' explanation of phenomena in the macroworld. It comes out in Democritus' well-known dictum: 'cold exists only according to opinion, heat exists only according to opinion, but in reality there are only atoms and the void'.[30]

Democritus' necessity is essentially the same, abstract, simple necessity as that with which Laplace's superintellect deals, or rather, it represents the hypostasis of the latter. L t us consider what that means.

It is usually said that statistical laws are laws of mass random phenomena. This statement opposes statistical laws to dynamic ones and at the same time, in fact, records that the random is necessary, since regularity does not exist without necessity. When, however, statistical laws are studied, various points of view on chance arise.

(1) It can be assumed (as mentioned above) that elementary processes are indeterminate (nature decides with respect to elementary phenomena). The determinacy of phenomena that exists in the macroscopic world can be explained, on this assumption, by the law of large numbers. But the law of large numbers itself applies to mass random phenomena and therefore does not explain the determinacy of macroscopic phenomena but only their statistical characteristic. The law of large numbers, which means that in certain conditions the sum total of the effect of a huge number of random factors yields a result that is nearly independent of chance, in fact expresses the organic link between chance and necessity that we shall discuss later in more detail.

Moreover, the justification of statistical regularity by the law of large numbers disagrees with the history of its origin. Thus, in Democritus, the originator in natural philosophy of the concept of statistical regularity, atomic collisions were inevitable because atoms could not independently change the very different directions of their motion. Moving atoms would thus collide with the same necessity as that of the intersection of an infinite number of straight lines with different directions in space. In other words, every event in the life of an atom and therefore of everything in the world without exception was predetermined for eternity: 'everything (occurs) because of necessity' (Democritus).

(2) It can be assumed that the elementary phenomenon is determined but, for some reason or other, the factors determining it remain unknown (e. g. the observer does not know whether a molecule is moving a bit to the right or to the left before colliding with another molecule, which would strongly affect the result of collision); on this assumption, such incomplete knowledge also leads to statistical conclusions.

Mechanical materialism (as mentioned above in another connection) takes this assumption to be true. Representatives of 'physical' idealism, who have taken on the job of disproving determinism, also accept it in their own way. The standpoint of mechanical materialism on statistical laws, which means in principle acceptance on the whole of necessity in nature, in practice rejects necessity for each individual phenomenon and leaves it at the mercy of pure chance. That the situation is just so is confirmed specifically by Max Born's views on law in physics. Pleading that determinism allegedly implies the existence of an initial state with absolute accuracy, Born rejects it in physics in general, and in classical mechanics in particular.[31] We shall consider his views on this point below.

(3) It can be assumed that each elementary phenomenon occurs independently of every other one while, at the same time, in their aggregate they determine macroscopic phenomena. It is this aggregate of elementary phenomena that is the substance of statistical regularity. Natural philosophy's surmise about this, as we mentioned above, was expressed by Democritus; the assumption found adequate form in the hypothesis of the total randomness of statistical physics according to which the individual elements with which statistics operates are completely independent of each other. This understanding of statistical regularity links the chaotic motion of primary particles with necessity in nature, but what had been a conjecture in Democritus gradually received systematic development on the basis of the data of natural science in the work of Robert Boyle, M. V. Lomonosov, Leon Boltzmann, and Josiah Willard Gibbs.

Thus, necessity, according to Democritus, existed in nature only in the form of external, abstract necessity: in his view, randomly moving atoms could not spontaneously change their motion, and from that aspect the Democritean chaotic motion of atoms was the expression of external necessity.

At the same time, in antique philosophy, as noted above, Epicurus expressed in his 'declination of atoms from the straight line' a conjecture about the inner necessity inherent in atoms; he also synthesised, in his 'motion of repulsion', the external and inner necessity, the forced motion *and* the motion inherent in the atom. This feature of his atomistics, which remained beyond the understanding of all non-Marxian philosophers, was first brought out by the young Marx in his doctoral thesis. Marx then, on the whole, of course, held an idealist point of view and accordingly criticised the atomistics of Democritus; he was deeply interested, however, in a dialectic understanding of motion, and this approach enabled him to determine the difference between the atomic theory of Democritus and that of Epicurus.

As we see it, the difference established by Marx is very important for elucidating the philosophical sources of modern scientific atomism—a question that has engaged the attention of many researchers. Heisenberg, for example, when considering the philosophical problems of atomic theory in connection with quantum physics, and rejecting invariable atoms, stated in particular that 'the development of recent years . . . has very clearly been—if we draw a general comparison with ancient philosophy—the turn from Democritus to Plato'.[32] In reality, as we have shown here, if a comparison is to be made at all with ancient philosophy, the development of quantum physics has made a step forward from the materialist Democritus to the materialist Epicurus. This also finds expression in the problem of statistical regularity.

Scientific conceptions of statistical regularity, in contrast to the natural-philosophical conjectures of the Greek atomists, have developed since systematic study of nature began, when quantitative methods of understanding matter evolved, and physics (above all mechanics) reached preliminary completion. If Newton, whose atomistic views played an important role in his theory of matter, had not yet arrived at statistical ideas, his older contemporary Boyle who, as Engels put it, made chemistry a science, explained the properties of matter by the statistical behaviour of atoms; he demonstrated that the relation between the pressure and volume of a gas in a vessel could be understood if one assumed gas pressure to be the result of vast number of atomic collisions with the vessel's wall. The ideas of the great Russian scientist M. V. Lomonosov are particularly remarkable in this connection. Drawing on 'corpuscular philosophy', he gave a first sketch of a physical explanation of thermal phenomena, and built a molecular-kinetic theory. When it is said, for instance, that the concepts 'temperature', 'pressure', and the 'amount of heat' are inapplicable to individual atoms or molecules, the origin of this statement can be traced to Lomonosov, according to whom 'the property of elasticity [as regards gas—*M. O.*] is not manifested by individual particles devoid of any physical complexity and organised structure but is produced by their aggregate'.[33]

From the time of Maxwell, who introduced probability conceptions into the kinetic theory of gases, and especially of Boltzmann and Gibbs who created statistical mechanics, statistical concepts began to be employed systematically in problems of the structure and properties of matter. In statistical mechanics the motion of individual particles is regarded as subject to the laws of classical mechanics with the addition at the same time of statistical postulates to the latter's propositions.

According to Boltzmann and Gibbs, the need to introduce statistical probability concepts into physics could be explained as follows: the mechanical properties of a complex system consisting of a vast number of particles are not fully known because of the crudity of the human sense organs and measuring instruments employed. From this point of view, the concept of gas temperature would not be needed if, for instance, the positions and velocities of gas molecules were known. Boltzmann and Gibbs thus interpreted statistical laws as a result of our ignorance of fully determined but seemingly chaotic, extremely complex motions of a vast number of particles forming a system (whole). In reality, to come back to the example of temperature, the behaviour of a gas cannot be reduced to the cumulative behaviour of the individual molecules composing it; the gas and its behaviour are a new quality, and this fact is reflected in thermodynamic concepts and laws. The dialectical thought that the concepts that apply to an element of a set (whole) are by no means applicable to the set (whole), and vice versa (an idea shared by Lomonosov, as we have seen), has become widely accepted today, and many authors who are subjectively remote from dialectical materialism hold it.

We must now define several of the concepts discussed above, and make the appropriate generalisations.

The necessary is that which in given conditions can be and cannot fail to be, which can be only such-and-such and not something else, whose being or a kind of being has its basis in itself.

The random or accidental (chance), on the contrary, is that which in given conditions may or may not be, which may be such-and-such or something else, whose being or non-being, or being of one kind or another has its basis not in itself but in something else.

In accordance with these definitions every something, representing a certain whole and at the same time regarded as an element of a certain other whole, has its basis in itself and at the same time in another, i. e. something is neither necessary nor random, but both random and necessary at the same time. An inner necessity thus appears on the scene that is not opposed to chance as something external (the latter being inherent in abstract necessity) but considers it an element of itself.

From the point of view of everything said above about the necessity and chance, dynamic and statistical laws are internally connected with each other, and represent a single pattern of nature in which neither the dynamic nor the statistical aspect can be reduced to the other. Dynamic and statistical laws—forms of a necessary, regular, causal connection between phenomena of nature—are not only linked by transitions from one to the other but are united in their opposition. A dynamic law expresses a change in time of the state of a material system considered in certain conditions in isolation from other systems; it is realised as a direct necessity. A statistical law applies to a set or aggregate of material systems taken in certain conditions as independent of each other. A statistical law is realised as an internal tendency making its way through a mass of random events and manifesting itself in them as an average of numerous random deviations. When the number of systems constituting a set (statistical ensemble) is sufficiently large the generic properties inherent in all the systems, i. e. the properties essential for a given set (which are expressed by statistical averages, their study leading to statistical laws), come to the fore. When, on the contrary, the number of systems forming the set is smaller, the generic properties appear less definitely and properties typical of the individual systems, i. e. the inessential, random properties of the given set, are revealed more definitely.

The concept of statistical law thus actually has nothing to do with the incompleteness or insufficiency of knowledge when very complex systems are studied or with the assumption of the 'lack of cause' (pure chance) of elementary phenomena. A statistical law exists in objective reality just like a dynamic law, and it is neither 'worse' nor 'better' than the latter in terms of its truth, definiteness (accuracy) and validity. The concepts of statistical and dynamic regularity taken by themselves always simplify the objectively real connection between phenomena; in certain circumstances of research, however, each of them corresponds to the real situation.

4

Statistical Laws, Determinism, and the Uncertainty Principle

Although Boltzmann and Gibbs considered statistical law and chance in a subjectivist manner, their studies actually included the concept of chance in the category of a physical law; or rather they abandoned the concept of necessity as a category in physics isolated from chance and came to regard chance itself in connection with necessity, in spite of their mechanistic views on causality. The dialectical process of the approximating of the concepts of necessity and chance in physics that had begun with the creation of statistical mechanics was developed further in quantum theory. It was at the level of quantum physics, when non-classical atomism became established, that the transitions between and the unity of statistical and dynamic laws were discovered, and the idea of quantum determined new approaches to statistical regularity. We shall leave discussing of the relevant points to the next sections, and consider here certain aspects of the problem of the nature of statistical laws.

A mechanistic view according to which statistical laws were subjective in character was common among physicists of both the classical period in science and in modern times. This view was quite consistently applied by Heisenberg to both classical and quantum mechanics (his relevant statements were cited above). Max Born supported this view; he overstressed the idea of the subjective nature of statistical laws and rejected 'determinism' even in classical mechanics (let us recall that he employed the term 'determinism', like many other physicists, to denote the dynamic regularity that these physicists usually identify with objective regularity in general). It is of interest to consider his argument.

From his analysis of the concept of determinism in physics Born concluded that the possibility of determinism is defined by our precise knowledge of state (taking it in the sense of classical mechanics). He tried to show that the situation in classical mechanics, contrary to the commonly held opinion, was also such that precise definition of state had no physical meaning and that the statistical method had therefore always to be used, even in the case of a single particle;[34] in other words, that classical mechanics was indeterminist (Born, of course, identified statistics with indeterminacy).

His reasoning boils down to the following. Let us assume that a mass particle moves without friction along a straight line (the x-axis) under no forces, and is elastically reflected at the termini. In order to say where it will be at any moment of time, it is assumed that its velocity (and co-ordinate) are exactly known. If, however, there is even the least inaccuracy in the determination of velocity, the inaccuracy of the prediction of co-ordinate (Δx) will increase with time and may attain a very large value. Thus, at time $t_c = l/\Delta v_0$, where l is the distance between the termini, and Δv_0 is the inaccuracy in the determination of velocity, Δx becomes equal to l. From that he inferred that if there was the least inaccuracy in the determination of velocity, determinism turned into indeterminism.[35]

One cannot agree with Born. Strictly speaking it is a matter here of the transition from a dynamic form of regularity to a statistical one, and that happens, according to him, because there is no absolute accuracy of measurement.

In this case Born is saying in fact that whether a regularity is dynamic (when the measurement is accurate) or statistical (when the measurement is inaccurate) depends on the accuracy of the measurement. This approach, however, does not agree with the content of physics. Both dynamic and statistical regularities are objective, and the fact that a falling of a stone is governed by a dynamic law and the Brownian motion of particles by a statistical law does not depend at all on the accuracy of the measurement of the quantities that characterise the object of measurement. It would be nonsensical, for example, to make the measurement of quantities describing the motion of a stone so precise that the precision exceeded the limits of a certain microscopic scale, because beyond that limit a qualitative change occurs in the quantity and it already acquires another physical content. The concept of absolute accuracy of measurement is meaningless if it is employed without taking the concrete content of the measured quantity into account. When this content is allowed for, however, absolute accuracy of measurement becomes a concept with a definite meaning, and it is infinitely extensible refinement of the values of a quantity that gives an absolute, infinitely precise value to the measured quantity built up from an infinite number of values each of which is characterised by limited accuracy.

To illustrate our point, let us consider Born's example above. In it the inaccuracy in prediction of co-ordinate at a certain time grows with time and is $\Delta x = t\Delta v_0$, where Δv_0 is the inaccuracy in the determination of the initial velocity (which, according to Born, cannot be eliminated). After the critical moment $t_c = l/\Delta v_0$ is reached, where l is the distance between the termini, the inaccuracy or deviation Δx becomes greater than l, and the particle is located somewhere in the interval $0 < x < l$ (where 0 is the initial point of the interval, and x is the particle's co-ordinate). When Δv_0 decreases, the critical moment t_c is only moved back, but remains finite for each finite Δv_0. Born notes that $t_c = \infty$ only for $\Delta v_0 = 0$, but he excludes an absolutely accurate value of velocity. In reality, however, $\Delta v_0 = 0$ means passage of Δv_0 to the zero limit, so that his interpretation of the absolutely accurate value of a quantity and his conclusion about the indeterminacy of the final position lose their point.

Let us now consider the uncertainty principle from a different angle: does it actually disprove determinism, as certain authors state (examples have been given above). To make our discussion more specific, let us consider the uncertainty relation for position and momentum.

The uncertainty principle is a relation between quantum momentum and quantum position. This relation is a fundamental quantum mechanical law and, like every fundamental physical proposition, has great heuristic value. It was possible, by means of it, for instance, to establish that there are no electrons in the atomic nucleus, and that particles are not in a state of rest at a temperature of absolute zero. Modern experimental technique is sufficiently refined to confirm the truth of this relation, as Blokhintsev has pointed out.[36]

The fact that the uncertainty principle is a relation between quantum momentum and quantum position seems to us to be a crucial point in quantum mechanics for correct interpretation of its physical meaning. The various real and imaginary paradoxes associated with it are then automatically removed. As L. I. Mandelstam stressed: 'the uncertainty relation troubles us just because we call x and p position and momentum and think that it is a matter of the corresponding classical quantities. Let us call x and p quasi-position and quasi-momentum. Then the relation between them will trouble us as little as that between ν and t' (frequency and time in wave optics).[37]

The Copenhagen interpretation of course makes use only of classical concepts in describing atomic phenomena. According to Heisenberg it is impossible in general 'to construct the whole physical description from a new "quantum-theory" system of concepts'.[38]

The question arises: why is it impossible? Heisenberg, citing Weizsäcker (as was mentioned in Chapter II in connection with another matter), points out that the role of classical concepts in the interpretation of quantum theory is similar to that of the *a priori* forms of contemplation in Kant's philosophy. Just as Kant declared the concepts of space, time, and causality (which are a prerequisite of every experience in his philosophy) to be *a priori* concepts, so (Heisenberg says) the concepts of classical physics are the *a priori* basis of a quantum-theoretical experiment. At the same time, in his opinion, the *a priori* concepts of classical physics can be employed to describe quantum-mechanical experiments only with a certain inaccuracy. He arrives, as a result, at the conclusion that it is a question of not nature itself in quantum mechanics but of nature comprehended and described by man through classical concepts that are either innate or obtained through contemplation.

In this case Heisenberg ignores in his reasoning the dialectics of concepts, which reflects the dialectics of things. The dialectical idea of the mobility and development of concepts has already been employed in science for a long time (unconsciously in the past). Whereas the concept of number used to mean what is now called 'a positive integer', it was extended and its content enriched by the development of mathematics, which introduced negative numbers, rational numbers, irrational numbers, real numbers, and imaginary numbers. The same thing is happening in physics; its development, for instance, altered an initial meaning of the words 'light' and 'sound': there is invisible light, and sounds that cannot be heard, the concepts of mass and energy have also been altered, retaining something in common with the initial concepts while acquiring a deeper content.

Non-classical physics is no exception. As physics penetrates into the realm of phenomena occurring at enormous speeds approaching the velocity of light, and into the atomic world, the classical concepts are necessarily being altered and becoming subject to new, broader, more meaningful concepts expressing the fact that another step has been taken along the path of understanding nature. A well-known example is the behaviour of an electron in an atom, which to some extent resembles the motion of macro-particles; the electron, however, at the same time has wave properties that make it on the whole dissimilar either to a moving macro-particle or a propagating wave.

When non-classical physics was being constructed and its concepts formed, the following feature acquired essential significance. In a non-classical theory, say quantum theory, the classical concepts are not excluded but are retained; they figure, however, not like those in the conceptual system of classical physics but as an element of a quantum concept being formed. The concept of quantum momentum, for instance, retrospectively, so to say, retains classical momentum in the form of the eigenvalue of the momentum operator.

This kind of law of the moulding of concepts when a theory that is broader and more meaningful grows out of another one is valid not only for the transition from classical to non-classical physics but also within classical physics itself (development of the concepts of radiation and mass), in mathematics (development of the concepts of number and set), and in many other sciences.

It is not the business of this chapter to go fully into this question.* What we have said is enough to conclude that quantum concepts, as new ones reflecting laws of the atomic sphere, assume the existence of corresponding classical con-

* Light is thrown on various aspects of this matter in other chapters.

cepts as an element of them; the link between the concepts of quantum theory and instrument readings that inform about real atomic objects is effected through classical concepts. Heisenberg's argumentation above about classical concepts as the *a priori* basis of quantum theory in fact records the same thing, but in a mistaken, idealistically Kantian form.

Let us consider in greater detail whether the uncertainty relation confirms or disproves determinism in physics.

By itself this relation elucidates the connection between certain quantum quantities and consequently confirms determinism. When, however, it is said that it disagrees with determinism it is not this aspect of the relation that is implied, but something else, namely, that the uncertainty relation renders Laplacian determinism meaningless when the behaviour of atoms is being considered, and that because of this determinism is allegedly bankrupt in quantum mechanics.

Determinism, however, does not only have a Laplacian form (which corresponds to the motion of macro-particles according to the laws of Newton's mechanics). Furthermore, neither rejection nor confirmation of Laplacian determinism, which is associated with the concept of dynamic regularity in classical mechanics, follows from the uncertainty relation. The latter clarifies the content of the concept of quantum state, i. e. it states that a quantum state is such that the eigenvalues of operators of momentum and position do not exist simultaneously in it. And the quantum state itself, of course, is described mathematically by a wave function that satisfies the Schrödinger equation, and this signifies in the final count that quantum state at a certain moment of time is necessarily connected with a preceding quantum state (i.e. that determinism is valid in quantum mechanics).

The uncertainty relation would only violate Laplacian determinism in the case when it were instrumental in proving the following: viz., that the initial state (characterised by position and velocity) of a system subject to forces does not unambiguously, in accordance with the laws of Newton's mechanics, determine the state of the system at any other moment of time. Such proof, however, has nothing to do with the uncertainty relation in the same way as the latter has nothing to do with demonstration of the validity of

Laplacian determinism (within the limits of classical mechanics).

A typical feature of quantum state, namely, its radical difference from classical state, is thus expressed in the uncertainty relation (principle). Although quantum mechanics is a determinist theory, its determinism is not identical with Laplacian determinism or in general with the determinism of classical physics. The uniqueness of the laws and relations of quantum mechanics is determined not by the behaviour of micro-objects excluding determinism and causality but by their dual particle-wave nature.

The interpretation of the uncertainty principle (relation) considered here, which assumes acceptance of determinism in quantum mechanics, rests on the fact that quantum-mechanical concepts are new ones differing qualitatively from those in classical physics. If, on the other hand, it is interpreted from the classical point of view (which is often met in the literature), then grounds are created for idealistic ghosts in quantum theory, including indeterminism. Let us dwell, in conclusion, on this point.

According to Heisenberg, the uncertainty relation establishes the impossibility of simultaneous determination of the position and momentum of an atomic particle with an arbitrary accuracy. Either its position can be measured with great accuracy, but then knowledge of its momentum is lost to some extent because of the interference of the instrument; or, on the contrary, knowledge of position is lost because of the measurement of momentum. There is therefore a lower boundary of the product of the two inaccuracies, which is determined by Planck's constant.[39]

By interpreting the uncertainty relation in this way Heisenberg reached the conclusion that 'incomplete knowledge of a system must be an intrinsic ingredient of every formulation of quantum theory' and because of that 'quantum-theory laws must be of a statistical nature'.[40] Furthermore, he stated, the statistical element of atomic physics is incompatible with determinism.[41] This interpretation of the uncertainty relation, which starts from the idea that *new quantum* concepts do not, in principle, exist in quantum mechanics, cannot be regarded as consistent, as was brought out in the foregoing exposition. Let us now summarise the position.

(1) The uncertainty relation does not so much establish the limit of errors in simultaneous measurements of the position and momentum of a micro-particle as the boundary of the applicability of simultaneously the concepts of position and momentum (or of the concept of a classical particle) to (say) the electron. This boundary exists not by virtue of the uncontrollable interaction of the micro-object and the macroscopic instrument, but because the uncertainty relation is a relation between quantum momentum and quantum position. In fact, it follows from it in operator form that there is a limit to the applicability of the classical particle concept (from the commutation relation $\hat{P}_x\hat{X} - \hat{X}\hat{P}_x = \hbar/i$ one can mathematically deduce a relation $\Delta x \Delta p_x \geqslant \hbar$).

(2) To cite the fact that the data discovered by atomic experiments do not fit into the theoretical schemes of classical physics in order to assert that knowledge of a micro-particle is incomplete (in principle), that the behaviour of a micro-particle is without cause, and so to revise the concept of objective reality, means to commit a philosophical error. The content of the concepts of objective reality, determinism and causality, and cognition cannot be reduced to the content these concepts are associated with in classical theory, or in general in any physical theory whatsoever. These philosophical concepts are immeasurably broader, and no single scientific theory, or science as a whole, can do without them. Niels Bohr, who in one of his last articles did not use the concept of 'uncontrollability in principle' that he had employed in his earlier work, was inclined in his own way to support this idea. It is relevant to cite again here his idea that we quoted in Chapter II in another connection: 'It may be stressed that, far from involving any arbitrary renunciation of the ideal of causality, 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.'[42]

(3) The novel statistical nature of quantum-mechanical laws is by no means the result of our incomplete knowledge of the system being an inseparable part of the formulation of the laws of quantum mechanics (differing in this respect from statistical mechanics, which, according to the erroneous subjective view discussed above,recognised incomplete

knowledge of a system only in practice but not in principle). Quantum statistical laws, like those of statistical mechanics, are objective laws. The connections between quantum quantities relating to change of state in time do not have simply a statistical character or only dynamic regularity; and that constitutes the novel feature of the statistical (probability) laws of quantum mechanics. It is incorrect to reduce the laws of quantum mechanics just to statistical laws. The point here is not one of accepting some hidden aspect of statistical laws that are governed by a dynamic regularity. That (i.e. recognition of the primacy of dynamic laws) is as wrong as recognition of the primacy of statistical laws. In quantum mechanics there is a synthesis of statistical and dynamic conceptions of atomic laws, and not their reduction to each other. This feature of quantum laws finds adequate expression in the mathematical apparatus of quantum mechanics. In quantum mechanics it makes sense, for instance, if the eigenvalue of the operator of an electron's position is determined with absolute accuracy. This also means that the electron (in such and such conditions) occupies a certain position. It would be wrong to consider such examples as only special cases of a more general statistical relation. Without them the very concept of a quantum quantity represented by a mathematical operator would become quite meaningless.

The uncertainty principle, by bringing out the content of the concept of quantum state, thus poses the question of the statistical nature of physical laws and the nature of probability in physics on a much deeper level than they were posed and solved after its fashion in classical physics. In quantum mechanics the concepts of possibility, probability, and chance are included in the category of the fundamental law, and became integrally interwoven with the concepts of reality, necessity, and regularity.

5

The Concepts of Actuality and Possibility in Classical Physics

Works have appeared of late by physicists in which the meaning of the concepts of actuality and possibility as employed to deal with the philosophical problems of quantum theory is clarified. Heisenberg has written much—in the spirit of Plato's idealism, however —on possibility as an objective category and on its important role in analysis of the concept of quantum state.[43] There are several important statements by Max Born about actuality and possibility as applied to atomic physics.* A major role in understanding the significance of the idea of possibility for quantum mechanics was played by V. A. Fock's paper *On the Interpretation of Quantum Mechanics*,[44] and by his more recent publications discussed in other chapters of our book (they indicated from various aspects that it was impossible, without the category of objective possibility as it is understood by dialectical materialism, to deal properly with the philosophical problems posed by quantum mechanics).

Different meanings are often attached to the concepts of actuality and possibility, and to many other general concepts used in philosophy and science. Max Born, for instance, drew attention to the fact that the concept 'actuality' is often used with the meaning of 'truth'. This concept also has other meanings. Much confusion rises from the multiple meanings of concepts, about which more than enough has been said in the philosophical literature. We shall consider 'actuality' and 'possibility' as categories that reflect objective reality and material objects and processes from certain definite aspects (the specific nature of these aspects will be defined later). In this way we emphasise, first of all, that we do not intend to identify the concepts 'objective reality' and 'actuality'; cognition of actuality is a higher stage in the cognition of phenomena and processes of objective reality.**

Let us look more closely 'actualiuy' and 'possibility'.

Hegel defined actuality as the unity of essence and existence, or of the inner and the outer, that has become immediate.[45] This contains the profound idea that immediate or direct phenomena and the essence, law, etc., found in them are in fact inseparable, that cognition of objects, processes, etc., in their actuality, is cognition of the unity of their essence and existence. The actuality of an object combines in itself both the mediation of its essence and the immediacy of its being.

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* See Max Born's papers cited above.

** These problems were discussed in Chapter II, Section 4.

Possibility is a moment of actuality, the inner of actuality; whether it or the other is possible, i. e. the possibility of the one or the other being realised, is determined by the whole aggregate of the moments of actuality. In the appropriate conditions possibility passes into actuality, and this means disappearance of one actuality and at the same time the birth of another actuality, with its possibilities. Generally speaking, the categories of actuality and possibility come to the fore when one studies the development of an object, the passing of a certain something into a different something, the process of the disappearance of the old and simultaneous origin of the new.

The possibility of something (an object, event, property) is such a being of something as is equivalent to its non-being. The concept of the possibility of an event implies that this event may occur in one way or another but not just in the one way and not in another. Otherwise possibility would not be a moment of actuality but actuality itself; in other words, realisation of a possibility in just this way and not in another one, in exactly such a form and not in another one, would have been predetermined for ages. It follows from this that the possible and the chance are connected with one another, because, as we know, the existence of objective chance reduces acceptance of the fatal necessity in nature to nought.

The concept of probability developed by the physical and mathematical sciences has a major role in understanding objective, law-governed, necessary connections in nature. It is a concept of the same order as that of possibility; it is not one that characterises the degree of our knowledge; similarly, possibility is not a concept that characterises conceivability, though just these meanings can and should be ascribed to the concepts of probability and possibility in certain cases. The probable is an objective category representing the possible in its, so to say, quantitative aspect; probability is the measure of the possibility of a certain event's taking place in such and such definite conditions, which can be repeated as often as you wish.

In classical physics whose object of study made it possible within certain limits to ignore the transformability of material realities into one another, the concepts of possibility and actuality could be treated as independent of each other. Theoretically this meant that only one actuality was recognised as an object of science; in scientific practice this led to possibility existing alongside actuality and being opposed to it.

Thus, there was a thesis in classical mechanics that events in the future were predetermined by events in the present, and possibility consequently should be realised exactly in the form in which it was realised. The possibility of an event's occurring did not differ in classical mechanics from necessity; probability, consequently, was out of the question on the plane of principle in classical mechanics (compare Laplacian determinism). On the other hand, the impossibility of predicting events in classical mechanics beyond certain limits, including temporal ones, was interpreted as due to the incompleteness of our knowledge of the initial conditions; random events were therefore admitted in practice and probability concepts introduced.

The statistical theories of classical physics also presented no exception. Gibbs, for example, believed that the application of probability concepts in physics was due to the crudity of the human sense organs and of measuring instruments. On the other hand, when problems relating to mass phenomena of a certain type were being dealt with, they could not be solved without employing probability concepts. Ideas associated with these concepts arose inevitably in classical physics, but in the form of assumptions supplementing the principles of a, so to say, dynamic type on which a given theory rests. The kinetic theory of gases, for example, added the hypothesis of molecular chaos to the principles of classical mechanics.

In summing up our brief analysis of the problem of the possibility in classical physics, we would like to emphasise the fact that in classical physics this question could not be answered in the aspect of its connection with actuality, since from the angle of classical physics probabilities could not be included in basic laws but developed in theory independently of them.

The coexistence within classical theories of assumptions associated with the notion of probability and dynamic principles, determined to some extent the content of the so-called theory of levels (Louis de Broglie, David Bohm, J. P. Vigier), the philosophical ideas of which were developed by Bohm.[46] Let us briefly consider these ideas.

It is well known that the irregular fluctuations of the Brownian motion of a particle have their basis in the effect of chaotic molecular motion. Bohm stated that '*all* the factors determining the irregular changes in the Brownian motion were not assumed to exist at the level of the Brownian motion itself, but rather, most of them were assumed to exist at the level of atomic motions'. If, therefore, the level of the Brownian motion itself were considered, only statistical regularities would be treated, 'but for a study of the precise details of the motion this level will not be sufficient' (p 80).

To explain 'a very strange combination' (as Bohm put it) 'of determinate and statistical aspects' (p 78) that physics encountered in the atomic domain, a similar assumption was introduced. In order, for instance, to consider all the details of the motion of an individual electron or quantum of light, we would transfer to a certain, deeper level as yet unknown, the relation of which to the atomic level is the same as the relation of the latter to that of Brownian motion. In that case it would be quite possible that those properties which are determinate at the atomic level are determined by factors existing at the atomic level itself, while other properties of a statistical nature are determined by factors existing at an even deeper level. From this angle, for instance, one could 'conceive of the division of these "indivisible atoms of energy" at a more fundamental level' (p 81).

Thus, according to Bohm, there is a 'sub-quantum mechanical level of continuous and causally determined motion, which could lead to the laws of quantum mechanics as an approximation holding at the atomic level' (p 94). If only those entities are considered that can be defined at one quantum-mechanical level, their motion will be indeterministic in the full sense, 'because determining factors that are important . . . simply cannot be defined at this level' (p 106).

From the standpoint of the statement of Bohm's 'causal laws' and 'laws of chance' coexist, representing two aspects of one and the same real process. Or, as Bohm put it: 'The various kinds of things . . . have been found to be organised into levels. Each level enters into the substructure of the higher levels, while, vice versa, its characteristics depend on general conditions in a background' (p 140). That is why the system of purely deterministic laws cannot be absolutely valid, because it covers only a finite number of objects and does not take into account the infinite number of factors contained at levels below and above that which includes these objects. As a result, 'causal laws' and 'laws of chance' should be regarded 'as effectively furnishing different views of any given natural process, such that at times we may need one view or the other to catch what is essential, while at still other times, we may have to combine both views in an appropriate way' (p 143).

Although the theory of levels is free from such a radical drawback of mechanical determinism as the denial of objective chance (in spite of the fact that this theory criticises indeterminism and develops an important dialectical idea about the qualitative infinity of nature), there are serious flaws in it, in the form it is expounded by Bohm.

First of all, Bohm isolates necessity from chance and in fact opposes them to each other. He says, in particular, that 'it is not the existence of indetermination and the need for a statistical theory that distinguishes our point of view from the usual one [meaning the Copenhagen interpretation—*M.O.*].... The key difference is that we regard this particular kind of indeterminacy and the need for this particular kind of statistical treatment as something that exists only within the context of the quantum-mechanical level' (p 106).* One cannot be agreed with all that. Dynamic and statistical regularities operate in their inseparable connection at the levels of macroscopic processes, atomic phenomena, and subatomic processes, and physics reflects them in their unity with one degree of completeness and depth or another depending on the specific nature of a given level, allowing for its connections with other levels, the research conditions, and the special features of the objects studied.

Furthermore, from the standpoint of Bohm's theory of levels the chance is not by any means explained by the necessary. According to this theory an approach to a phenomenon from the aspect of the category of chance is only corrected and supplemented by allowing for the necessary connection, and vice versa, an approach from the aspect of the category of necessity should be corrected and supplemented by allowing for the random insignificant factors. Bohm writes, for example: 'A causal law can arise as a

* We ignore the inaccuracies in Bohm's terminology. He uses 'indeterminacy', for example, to denote statistical nature.

statistical approximation to the average behaviour of a large aggregate of elements undergoing random fluctuations, a law of chance can arise as a statistical approximation to the effects of a large number of causal factors undergoing essentially independent motions' (p 143).

When it is a matter of a 'causal law', however, the question arises of explaining the basis of the random fluctuations, i.e. to accept either the primary determinacy or the primary indeterminacy of elements. When, however, it is a matter of a law of chance, it is necessary to remember that 'a large number of causal factors undergoing essentially independent motions' represents a statistical ensemble, i.e. the same dilemma arises again: the elements of a statistical ensemble are either primarily deterministic or primarily indeterministic. The theory of levels, instead of resolving this dilemma, sidesteps it, since, according to Bohm, although the necessary and the random are mutually connected, this connection is exclusively external and represents only a coexistence of the random and the necessary.

Certainly, Bohm's statement that 'actually neither causal laws nor laws of chance can ever be perfectly correct' (p 143) is valid, but its validity follows not from the fact that 'each inevitably leaves out some aspect of what is happening in broader contexts' (p 143), but from the necessary being as chance as chance is necessary.

Finally, the theory of levels does not contain the idea of objective possibility, and in that respect does not differ from the conception of mechanistic determinism. In classical physics the fact that the apparatus of the theory of probability is accepted not so much from the angle of reflection of objective reality by probability concepts as from the angle of its serving statistical regularities was also validated by this, that classical theory studied the patterns of mass random phenomena on the assumption that the individual particles forming statistical ensembles moved according to the laws of Newton's mechanics. The theory of levels endeavours in fact to extend the same approach to include the laws of quantum mechanics, and quantum physics in general, although, as is clear from the content of quantum theory (with which we are concerned throughout our book), there are actually no grounds for such an approach to atomic phenomena. Micro-particles are not the corpuscles of classical mechanics; their dual particle-wave nature means that the problem of the probability and statistics in quantum theory cannot be solved in the spirit of classical notions.

In this case Bohm holds another point of view, which can be formulated as follows. It is assumed that every elementary particle is connected with a body that 'in most applications at the atomic level ... can be approximated as a mathematical point' (p 111). The body is associated with a wave that 'is assumed to be an oscillation in a new kind of field' described by the ψ-function; 'the ψ-field and the body are interconnected in the sense that the ψ-field exerts a new kind of "quantum-mechanical" force on the body, a force that first begins to manifest itself strongly' only at the atomic level but that 'has not previously turned up in the study of the large-scale domain'. The body in turn acts on the ψ-field, and this reciprocal action, which may be significant 'in the sub-quantum mechanical domain', is 'small enough to be neglected in the quantum-mechanical domain' (pp 111-112).

It is assumed, furthermore, that the ψ-field undergoes 'random fluctuations about an average that satisfies Schrödinger's equation and that these fluctuations communicate themselves to the body. The details of these fluctuations would then represent properties of the field associated with a sub-quantum mechanical level (p 113), while at the quantum-mechanical level the behaviour of micro-particles would be regarded only statistically. The assumed fluctuations 'produce a tendency' for more or less random motion of the body, a tendency opposed by the 'quantum-force', 'which pulls the body into the places where ψ-field is most intense'(p 113). In the end 'a mean distribution in a statistical ensemble of bodies' results 'which favours the regions where the ψ-field is most intense, but which still leaves some chance for a typical body to spend some time in the places where the ψ-field is relatively weak' (p 113).

Thus, in any process 'both wave and particle could be present *together* in some kind of interconnection', as Bohm writes (p 111).

The 'interconnection of waves and particles' in the theory of levels is thus not a dialectical unity of the opposite particle and wave properties of matter but a certain 'combination of particle and field' (p 116), a coexistence of waves and particles in a certain mechanical picture. It is understandable that such an interpretation of a micro-particle inevitably leads to the already known notion of the coexistence of 'causal laws' and 'laws of chance'. Hence the natural absence of possibility and probability from the theory of levels as objective categories.

In summarising Bohm's point of view on probability and statistics in physics, we must add that it opens up the way to identifying probability with the statistical concept of 'frequency', the illegitimacy of which is well known. He considers probability and statistics in quantum physics in the aspect of mechanical classical concepts, and says, for instance, that the results of the theory of levels show 'that mechanical concepts can go further in the quantum domain than had hitherto been thought possible' (p 128).

In our view one cannot agree with statements of that kind. The theory of levels does not reflect what in quantum mechanics is called the symmetry of particles and waves, and, in particular, an essential feature of quantum mechanics is left out: namely, the quantum state is described by a wave function in a coordinate representation, and with the same justification by a wave function in a momentum representation, while in fact only the particle interpretation, 'corrected' in the spirit of the mechanical ideas of classical physics, is legitimated.

To sum up, Bohm's theory of levels solves the problem of the nature of probability in quantum mechanics in the spirit of classical ideas, which contradicts the content of quantum theory.

6

The Concepts of Reality and Possibility in Quantum Physics

In quantum mechanics probability as a measure of possibility is numbered among the main laws, i.e. possibility is integrally linked with actuality, while probability cannot fail to be objective, and reflected in the corresponding concepts of quantum mechanics. It is possible in quantum mechanics, of course, to indicate the eigenvalues of the operators of quantities from the wave function if this wave function is the eigenfunction of the operators, and to calculate the mean values of operators or the probabilities of their eigenvalues, knowing the wave function, if it is not their eigenfunction. This also means that probability should not be approached in quantum mechanics as something subjective and isolated from reality. Let us consider this last point in greater detail.

Imagine a flux consisting of a large number of electrons hitting a screen with two slits from the left; the electrons passing through the slits then form a diffraction pattern on the right on a photographic plate. The essence of this well-known imaginary experiment is this: the components of the flux passing through the slits interfere with each other. If one assumes that the electrons are classical particles, the diffraction pattern would mean that electrons sometimes annihilate one another and at other times arise from nothing, but that is excluded by the laws of conservation. It remains to assume that the electron interferes with itself,[47] in other words that the electron possesses wave properties simultaneously with particle ones. But then the probabilities of an electron hitting such-and-such places of the photographic plate cannot be interpreted in the sense that they are the result of ignorance of certain details of its motion: from the point of view of classical theory it is absurd that the probability of an electron reaching a certain spot on the photographic plate through two apertures is zero, while for one aperture (it is irrelevant which one) the probability of an electron hitting the same place has a definite non-zero value.

The dual corpuscular-wave nature of micro-particles determines that probability in quantum mechanics is by no means the result of mere application of the propositions of the theory of probability to the motion of particles of classical type. Quantum mechanics resembles statistical mechanics in that both theories accept probability in the initial state. Quantum mechanics also resembles the general theory of stochastic processes since both theories accept probability when there is a transition from one state to another. As regards its theoretical foundation, however, quantum mechanics is by no means identical to the statistical theories of classical physics, and the wave function used in it to calculate the probabilities of the eigenvalues of the corresponding operators differs radically from the probability distribution function in classical statistical theory.

What is the nature of quantum probabilities? Or what are the grounds for probability in quantum mechanics?

From what we have said above, the answer suggests itself. The grounds for the probabilities of the values of quantum quantities are in the unity and identity of the opposing particle and wave properties of micro-objects. These probabilities are not therefore something alien to the laws of atomic phenomena, arising as a result of ignorance of certain circumstances, but are a necessary element of these laws. From that angle the wave function pertains to a single micro-object; at the same time it characterises those properties that a micro-object possesses in the given conditions and those properties that it will possess in other conditions which exclude the given ones. This fully accords with the concept of quantum probability, since the probability of one behaviour of a micro-object, or another, is not brought in from outside but is internally connected with the properties the micro-object possesses at a given moment of its existence.

In studying laws of atomic motion that involve probabilities, quantum mechanics, of course, solves the problem of the transition of possibility into reality and of the realisation of probability laws. This question cannot be side-stepped in quantum mechanics, if only because experimental determination of the numerical values of probability becomes necessary, without which quantum mechanics would not be a physical theory.

As concerns the philosophical aspect of the matter, possibility is not cognised directly but in a mediated way, through the cognition of reality. The mediated way of cognising possibility corresponds to the possible's being the inner of actuality, i.e. exists owing to actuality, its other, and not in itself. From the standpoint of physics this means that, for the passing over from possibility to reality, from the probability of a process or of the value of a physical quantity to the realised, either unlimited repetition of the conditions in which realisation occurs or an unlimited number of phenomena representing the possibilities being realised in the given conditions are necessary; in short, it is necessary to introduce the concept of statistical ensemble into quantum theory. This is justified by the fact that quantum theory deals with physical phenomena that arise not as a result of the action of separate individuals but of vast aggregates of them (spectra, α-radioactivity).

Dialectical ideas of the unity of actuality and possibility, and also of transformation of possibility into actuality, have thus found broad application in quantum mechanics, which cannot be understood correctly without them.

Let us now summarise Heisenberg's point of view on possibility and actuality in quantum mechanics by means of the following scheme:

Symbolic Representation of Atomic Processes	*Physical Knowledge of Atomic Processes*
Symbolic representation of state by means of the wave function	Description of state by means of classical concepts
A wave equation of dynamic type	Statistical laws
	Knowledge of 'actuality' is incomplete knowledge
The wave function governing possibility symbolically characterises the state of an atomic particle completely	A description by means of classical concepts inevitably contains a 'subjective' element, i.e. a statement about the observer (instrument)
The characterisation of atomic processes by means of the wave function is a complete, objective one, i. e. contains no references to the observer (instrument).	

The transition from possibility to reality (actuality), or from the mathematics of the atom to its physics, is made by introducing classical concepts or references to the observer (instrument) into quantum theory.

Thus, according to Heisenberg, the possibility of an event is something lying between the idea of an event and the actual event. The statistical element, however, is introduced simply because atomic processes cannot be described by any means other than classical concepts, which are only applicable to atomic processes with limited accuracy. In other words, Heisenberg believed that quantum theory dealt not with nature as such but with nature subjected to the effect of human methods of investigation; that is why statistics comes into quantum theory.

For a critical review of these views of Heisenberg's we refer the reader to the preceding sections; here we should discuss other topics of our theme.

In analysing determinism in quantum physics the thesis of the infinity of nature, the inexhaustibility of matter and of any of its particles, and the infinity of matter in depth and breadth is very important. This infinity is composed of an infinite number of finite objects at various stages (elementary particles, atomic particles, macroscopic bodies, cosmic formations—to sketch the division roughly), the transition from one stage to another being transitions of quantity into quality and vice versa.

Taking this thesis as our guide we can say that knowledge of an object (or process) is knowledge of it as an element of a certain whole (e.g. the atom is an element of the molecule) and at the same time knowledge of it as a certain whole (the atom consists of a nucleus and electrons). One-sided development of the first aspect leads to a tendency to explain all nature's phenomena from knowledge of elementary phenomena (the atomistic approach). One-sided development of the second aspect leads to a tendency to explain elementary phenomena from knowledge of the whole (the integral approach).

In classical physics the atomistic approach came to the fore and found its extreme expression in the mechanistic picture of the world. In relativistic physics an integral approach began to arise though it did not receive final expression. Both approaches are interwoven in atomic and quantum physics, the link between the atomistic and the integral aspects in investigating nature becoming more and more organic and inseparable with the development of quantum physics. Thus, in modern conceptions, the atom not only cannot be reduced to the sum of nucleons and electrons but these structural units of it themselves differ in many of their properties from electrons, protons and neutrons in the free state. The modern theory of elementary particles provides even more striking examples of unity of the atomistic and integral approaches (see Chapter VII).

In the transition from the whole to its elements and vice versa, when the appropriate round of phenomena is studied, it becomes crucially important whether the whole is an aggregate of a large number of objects to which the statistical method can be applied. If the situation is such, statistics and its related theory of probability are necessarily brought into the theory of the sphere of phenomena being studied, with all the conclusions and generalisations following from this. The transition from macroscopic phenomena to molecular or atomic ones, for example, and to elementary processes, and the reverse transition from elementary phenomena to macroscopic ones are impossible without statistics and the theory of probability. Philosophical problems of law and causality, necessity and chance, actuality and possibility therefore inevitably arise in both macroscopic and microscopic physics (which we discussed above).

Let us note, in connection with the question raised about the atomistic and integral aspects of the approach to cognising physical phenomena, that both of them affect understanding of statistical regularities. Let us also recall that the atomistic approach leads in its extreme expression to mechanistic Laplacian determinism and the denial of objective random events. The truth, however, as follows from the laws of dialectics, lies at the juncture of the two approaches, and consists in the fact that dynamic and statistical regularities are actually inseparable, that macroscopic and microscopic phenomena are linked by transitions and are in fact united. Our whole book is essentially concerned with this point; here we shall consider its related topics from the standpoint of this section.

It would be trivial to state that it is impossible to extract information about the behaviour of an individual molecule or a single atom from phenomenological (classical) thermodynamics. On the other hand, knowledge of the positions and momenta of all the molecules of a gas would not by any means lead to or be a substitute for knowledge of the gas's temperature. The truth was found (and its discovery marked a great advance in physics) when the thermodynamic internal energy of a system, which depends on temperature and other macroscopic parameters, was identified with the mean statistical value of the kinetic energy of microscopic particles, which depends on their velocities and mutual position. This identification of the dynamic and the statistical, which combined the properties and microstructure of macroscopic bodies into something united, made it possible to validate thermodynamics in a profound way, to overcome the drawbacks of classical thermodynamics (including such a philosophical flaw as the formal possibility of assuming 'thermal death'), and to explain and discover new facts (e.g. the fluctuation of thermodynamic quantities).

Within the limits of classical physics, however, the principles relating to probability concepts are, of course, only an addition to the basic laws, and the probabilities of various possible events do not figure in the content of these laws. It cannot be otherwise from the angle of classical mechanics since, in it, a particle that moves with constant velocity in space and time remains everywhere and always identical to itself and alters its velocity only when acted on by other particles (when the number of such actions is large enough and they are mutually independent, we have movement similar to Brownian motion). The theory of relativity did not add anything new, compared to classical physics, on the nature of statistical laws and of probability in physics, and only quantum theory, as we know, introduced radical changes into this problem.

This can be explained as follows. Quantum theory posed the task of revising the concept of a particle identical to itself—the most important concept of pre-quantum physics. In quantum mechanics a moving particle is no longer considered identical to itself since it has not merely particle properties but dual particle and wave ones. The relativity of the concept of a particle identical to itself becomes more definite in relativistic quantum mechanics according to which matter and field do not exist separately, and the law of conservation of the number and kind of particles ceases to operate. The concept of the inseparability of particles and fields accordingly becomes filled with new meaning, which is expressed by the wave function, which becomes an operator in quantum field theory. In quantum field theory, of course, the probability interpretation of the wave function is not only not removed but undergoes further development (which we will not discuss).

As quantum field theory develops, the boundaries of the applicability of the concept of a self-identical particle are being made more precise, the relativity of the concept is being brought out more completely and more deeply, and the idea of the reciprocal transformability of particles is coming to the fore and subordinating the idea of the self-identity of a particle to itself.

The statement that the idea of transformability does not exist in classical and relativistic theory is not, of course, true; to disprove such statements, it is sufficient to give an example from the law of the conservation and transformation of energy. It was assumed in pre-quantum theories, however, that the matter studied by physics ultimately consisted of constant elements of one kind or another (the material points and empty space of classical mechanics; the continuous field of Maxwell's theory and the theory of relativity). Quantum physics eliminated the idea of the ultimate invariable bricks of the Universe; it regards elementary particles as mutually transformable, and the law of reciprocal transformation of elementary particles forms the foundation of the theoretical building of modern physics.

The theory of elementary particles has not yet been built, and the job of building it is at the centre of attention of present-day physics. There are still only the sketches of a theory; we shall recall here Heisenberg's programme for a unified theory of matter, but shall not go into it. Let us just note that it would have to remove the difficulties of quantum relativistic physics (the divergent expressions that figure in it in place of finite values observed in experiment for a number of quantities), unify microscopic particles and fields, theoretically deduce the properties of elementary particles known from the experiment and the types of transformation of elementary particles. Let us, in conclusion, consider certain aspects of the problem of causality and determinism in connection with the theory of the so-called scattering matrix formulated by Heisenberg, in particular, to eliminate divergencies in the theory of particles and fields.

Heisenberg suggested a new formalism—a scattering matrix for the subatomic spatial and temporal domain with its extremely short distances and durations—instead of the Schrödinger equation which determines the values of the wave function at an arbitrary moment of time from its values at the initial moment of time (the so-called Hamiltonian formalism, which assumes the continuum of space and time). The scattering matrix is an operator that transforms the wave function of particles before scattering into their wave function after scattering. If the scattering takes place in the subatomic domain, the state corresponding to the first wave function and that corresponding to the second wave function should be separated by a time interval greater than the temporal subatomic domain. Then the equation $\psi_{+\infty} = S\psi_{-\infty}$ (where ψ is the wave function and S is the scattering matrix) expresses the connection between the values of the wave function at a moment of time remote in the past $t = -\infty$ and its values in the remote future $t = +\infty$.

From this point of view the transfer of the interaction in such subatomic space and time domain occurs at a velocity greater than that of light and the time sequence of events, it would seem, and the connection of cause and effect are violated (as was assumed by Heisenberg).

There is no need, however, to draw odious conclusions against materialism from such an interpretation of processes occurring in the subatomic domain. Several authors, and Heisenberg himself (in his programme for a unified theory of matter) assume the existence of a minimum length (of the order of the radius of a light atomic nucleus 10^{-13} centimetre), a universal constant that is part of the basic laws of nature. This assumption may mean that a geometry founded on the principle of continuity alone (mathematical continuum) is insufficient for describing the spatial properties of matter at subatomic level (the same must also be said about the temporal properties of subatomic processes, which, it must be assumed, cannot be described just by the continuity of time). As a result, we arrive at the following conclusion: discontinuity, being intrinsically connected with continuity, must come into the space and time concepts that relate to the subatomic domain, and the space and time concepts of physics should be revised accordingly.

But in that case the concept of velocity for subatomic domain would also need to be altered. It will have to reflect the discontinuity of space and time, and will therefore receive a new content compared to the concept of velocity employed for the macroscopic and atomic domains. Then the concept 'a velocity greater than that of light' may have a sense that is by no means relativistic. What we have said does not cancel the proposition of the theory of relativity that the value of the velocity of light is a limiting value; it only expresses the idea that the future theory will give a deeper substantiation of this fundamental proposition of the theory of relativity by determining the boundaries of its applicability.

The theory of the scattering matrix, incidentally, should not necessarily pose the problem of causality on the plane discussed above. A scattering matrix can be constructed in such a way that the construction assumes a condition of microscopic causality by which the physical action, i.e. signal, cannot be propagated at a velocity greater than that of light in ultrasmall spatial and temporal domains (just as in the domain of large space-time scales). This construction could be used to deduce the so-called dispersion relations, study of which provides important information on the nature of reciprocally interacting elementary particles.

Since dispersion relations contain directly observable quantities, they make it possible to examine a large deal of experimental material. Checking their validity at high energies enables us to determine the limits of applicability of the notion about point interaction and consequently to confirm or disprove the validity of the condition of causality in the special form we are concerned with here. Such verification of the validity of dispersion relations is understandably of enormous significance for both physics and philosophy.

We would like to add that the most general formulation of the condition of causality employed in quantum field theory is that given by Bogolyubov and Shirkov: 'Any event occurring in a system can influence the system's evolution only in the future and cannot influence its behaviour in the past.'[48] This formulation leaves a possibility for generalising the Lorentz transformations, not to mention that it excludes the assumption of velocities higher than that of light.

In connection with what has been said above, the concept of a particle identical to itself should also undergo radical change in as much as its transformability is beginning to play a main role. From this angle a particle before scattering is not identical with a particle after scattering. A theory that has to reflect the processes allowing not only for the continuous nature of space, time and motion but also for their discontinuous nature, the appearance and annihilation of elementary particles, the transformation of matter into field and vice versa undoubtedly cannot make do with the concepts and principles of classical and modern physical theories; it must develop new concepts and principles, preserving the results of all the preceding work of physics as a limiting case.

In quantum field theory and the physics of elementary particles, in which the idea of the reciprocal transformability of elementary particles engenders (or rather should engender) their whole theoretical content, new physical concepts and statements are thus needed, and not rejection of the objective reality of the physical world, and objective necessity and causality in nature. The so-called virtual processes, which witness in fact not to an imaginary violation of, say, the law of the conservation of energy but to the need for a further development of the basic physical concepts and principles about the deeper levels of infinite matter, point in their own way to the same thing.

7

A Contribution to the Problem of Causality in Non-Local Quantum Field Theory

Causality or a causal relation, as noted above, is an objectively real genetic connection between (at least) two events or phenomena occurring in different places. If it has been determined that, in such and such conditions, event A is the cause and event B is the effect, it is concluded that event B occurred after event A. In classical mechanics it is assumed that the changes in a system produced by an external factor may (but not necessarily because of long-range forces) form a causal chain. If one allows for the fact that a causal relation is by necessity a connection in time, then this thesis about causality is expressed in the form known in physics: namely, a signal cannot be transmitted to the past but only to the future. The laws of classical mechanics, however, since they describe reversible mechanical processes, do not contain any statement about causality pertaining to the signal. This statement is an addition to the laws of classical mechanics, which by themselves do not determine the direction of time.

The situation is quite different in the theory of relativity and in quantum mechanics, which accept the thesis about causality in the sense above but with a new element that is essential to the theory of relativity, namely, that in it the velocity of light in a vacuum is the limiting velocity of a signal.

The separation of events into those consecutive in time and the quasi-simultaneous, which is closely related to causality, follows as a consequence of the existence of a limiting velocity in the theory of relativity. As it turns out, if two events are connected with each other by a causal relation, only then is their sequence absolute, i.e. the temporal sequence of these two events is preserved in all inertial reference frames. As to quasi-simultaneous events, i.e.

events that cannot be connected through interaction, their sequence is relative, i.e. it depends on the frame of reference. The well-known philosophical dictum '*post hoc* can never justify *propter hoc*' is thus given a novel and clear expression by the theory of relativity.

In this connection Einstein's remark about events connected by a signal with a velocity greater than that of light ($W > c$, where W is the velocity of propagation of a certain signal, and c is the velocity of light) and the time T necessary for transfer of the signal from A to B, presents interest. Einstein wrote: 'The velocity v [i.e. the velocity of the observer—*M.O.*] can assume any value less than c. If, therefore, $W > c$, as we have assumed, v can always be so selected that $T < 0$. This result means that we must take a transmission mechanism as possible by which the effect obtained precedes the cause. If this result also does not, in my view, contain any contradiction, taken purely logically, it still contradicts the character of our whole experience to such an extent that the impossibility of the assumption $W > c$ seems adequately proved thereby.'[49]

The question of causality in quantum field theory, it seems to us, should be considered from a rather different plane than in pre-quantum physics and (non-relativistic) quantum mechanics.

With the so-called axiomatic approach to the construction of quantum local field theory, the latter adopts the principle of relativistic invariance and the unitariness and locality principles (let alone certain other requirements that we ignore). Quantum fields are associated with elementary particles, and the process of interaction between (very high energy) elementary particles is described by the so-called scattering matrix, which is an operator translating the wave function (state) of particles before the reaction (scattering) into their state after the reaction.

In descriptions employing the scattering matrix, it is important to remember (and this is the source of the new approach to causality in quantum field theory compared with classical physics) that the point consists not in elucidating the behaviour of particles when they are brought very close together but in the problem of the final (post-reaction) states, and the probabilities of their arising.

From this point of view the concept in the theory of high energy particle interaction (only now being constructed) of details of behaviour of particles when the distances between them are small does not make sense (is unobservable in principle).[50]

The assumption that this concept is unobservable in principle opens up certain perspectives for non-local quantum field theory (this theory has developed in its initial form soon after physics came up against the paradoxes of the divergencies inherent in modern quantum theory with its postulate of the localisation of field interaction). In 'normal' quantum theory, in fact, the postulate of an interaction's localisation is borrowed from the classical theory of point particles. It requires that field interactions pertain to one and the same point of space-time. This requirement accords with the theory of relativity, which rejects an assumption about the dimensions and structure of elementary particles because it has to be supposed otherwise that a signal can be propagated at a velocity greater than that of light, and therefore (as was noted above) to assume that the effect-event could precede the cause-event.

It is thus impossible to separate the postulate of an interaction's localisation from the thesis of causality that the cause-event cannot follow the effect-event.

Non-local quantum field theory was intended to rid modern quantum physics of difficulties with divergencies. It abandons the postulate of locality of field interaction and tries to do so in various ways; consequently more than one variant of non-local theory is being developed. We shall not dwell on these variants or forms or on the difficulties of non-local theory (it now appears that the last are not so fundamental).[51] We are interested in the philosophical essence of the theory: is it true that there is nothing left of the principle of causality in it, and that it leads to a need to reject the space and time concepts as applied to the world of elementary particles, as some authors assert? Or rather, how do things stand with the principle of causality and with space and time at that level of matter known as the elementary particle?

Let us recall that, from the standpoint of materialist dialectics, causality is only a tiny part of the objectively real universal connection. Lenin gave a very positive estimate of the fact that Hegel had paid comparatively little attention to the theme of causality so dear to Kant's followers. For Hegel as a dialectician, Lenin wrote, 'causality is only *one* of the determinations of universal connection, which he had already covered earlier, in his *entire* exposition, much more deeply and all-sidedly; *always* and from the very outset emphasising this connection, the reciprocal transitions, etc.'[52] It is on this plane that the problems posed in regard to non-local theory incorporate something unusual.

This theory, first of all, should satisfy the possibility of meeting the condition of macroscopic causality, i.e. it should not lead to experimentally observable consequenceo disagreeing with the statement of causality on the macroscopic (including atomic) scales of space and time. This means, in essence, that when non-local theory is generalised for the large scales of space and time it turns into 'conventional' local quantum theory (in accordance with the correspondence principle).

A new universal constant appears in non-local theory, that of the dimension of length (or elementary length), which 'separates' (as it were) the domain of ultra-small dimensions in which causality is 'violated' and perhaps a radical revision of physical notions about space and time is called for, from the space-time domain in which the principle of causality and the laws of geometry hold. A specific constant for high energy physics is thus added to the universal constants c and h on which quantum field theory is based; it links (or should link) short-range and long-range interactions into something united.

The introduction of elementary length,* with certain assumptions, puts the question of revising geometry in its usual form on a physical basis; metric space-time geometry ceases to exist; the concepts 'nearer' and 'more remote', 'before' and 'after', 'length' and 'duration' lose their macroscopic meaning in the ultra-small. The separation of phenomena into cause-events and effect-events should, of course,

* The point is that the concept of local interaction can be revised in various ways in relation to the 'ultra-small'. One way is to regard the very concept of point interaction as unobservable in principle, by analogy with the fact that the classical concept of trajectory itself is meaningless in principle in quantum mechanics. Another possibility is associated with the assumption of the unobservability in principle of the concept of a definite space-time point (which leads to the theory of quantised space-time). We shall not consider the concrete issues relating to these possible ways of constructing a non-local theory in this book.

also become invalid, and the theory's mathematical apparatus should reflect this situation.

Does this mean that the philosophical foundation of non-local quantum field theory contains a certain idealist and fideist line on causality? The answer to that question becomes quite clear as soon as we consider how materialist dialectics understands the causal relation.

In its usual interpretation the causal relation does not exhaust the forms of connection and mutual dependence. The present-day development of quantum physics is leading to the discovery of new forms of connection and mutual dependence between the phenomena of inanimate nature which cannot be fitted into the schemes of existing physical theories. This once more confirms, in particular, the objective nature of the universal connection, its inexhaustibility, the transformation of some of its forms into others that are deeper and more general. Causality, as it is usually understood, may have no meaning in the ultra-small; in this domain a deeper, more general form of connection—interaction—comes into prominence in conditions of mutual transformation according to certain laws of the fundamental particles of matter. It appears, however, not as a constant change of cause and effect but as their foundation and the whole generating them.

In abstract reasoning one is not forbidden, of course, to regard interaction as cause[53]; in this case, however, we are not dealing with cause as it is conventionally understood. The latter is an individual cause which acts at an individual moment of time and at individual location, i.e. such form of connection which was called *causa efficiens* (efficient cause) in the old philosophical systems. But interaction as a cause is not a *causa efficiens* but rather, to use the old philosophical concepts, *causa finalis* (final cause); Spinoza's well-known dictum *substantia est causa sui* is concerned with 'final cause'.

There is no reason, however, to pour the wine of modern science into old philosophical bottles. It was Engels who noted that 'already in Hegel the antithesis of *causa efficiens* and *causa finalis* is sublated in reciprocal action'.[54]

In the world of the large (including atomic dimensions) the abstraction of individual phenomena taken out of their universal connection and consequently considered separately (with respect to space and time) is internally justified; as we can see from what has been said, the principle of causality implies the legitimacy of this abstraction. In the ultra-small world, however, or the world of high energy elementary particles interacting with and transforming into one another, such abstraction loses its meaning and the thesis of causality in its usual understanding is also deprived of confidence and status.

Experiment undoubtedly has the last word in clarifying these points, which are very important for high energy physics; at the same time one must not neglect the fact that objectively applied, comprehensive, universal flexibility of concepts is of great importance in the quest for their correct solution.[55] Strictly speaking, it is experiment also that confirms that the flexibility of concepts has been objectively applied, i.e. is a correct reflection of the eternal evolution of the world.

The development of quantum physics and theory of elementary particles is opening up new forms of the universal connection, that are not covered by the schemes of existing physical theories. The points discussed above reflect the round of ideas of the transition from one form of connection and reciprocal dependence to another that is deeper and more general. On that plane the work of Tamm, Bogolyubov, and Blokhintsev devoted to space-time and causal relations in the microworld, various aspects of which have been discussed in this chapter, present special interest from the angle of dialectics.[56] Modern physics is providing remarkable confirmation of Lenin's words: 'From coexistence to causality and from one form of connection and reciprocal dependence to another, deeper and more general.'[57]

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VII

THE PROBLEM OF THE ELEMENTARY AND THE COMPLEX IN QUANTUM PHYSICS

1

On the Concepts of the Simple and the Complex in Philosophy and Physics

The concepts of the simple and the complex or compound are usually associated with that of development. In Marxist philosophical literature one finds definitions of development as a transition from the lower to the higher, from the simple to the complex.[1]

Such statements, it seems to us, do not so much define development as express one of its many aspects; development itself still has to be defined. Indeed, if the complex is the developed simple—and the concept of the 'complex' should not, it seems, be defined except through 'development'—then the content of this concept is elucidated through understanding of development as such. Let us assume that development is understood as diminution and increase, as repetition (the metaphysical conception of development); then the complex is just the 'augmented simple'; now let us suppose that development is understood as a unity of opposites (the dialectical concept of development); then the complex differs qualitatively from the simple and at the same time repeats the simple in some way. All this follows from Lenin's analysis of the concept of development in his famous fragment *On the Question of Dialectics.*[2]

In the history of philosophy the problem of the simple and complex in application to the Universe appears as the problem of the substance of the world from which the concrete diversity of things is formed. Two main tendencies are to be observed in study of this problem in the history of materialism and of science. The first (which in essence presupposes a dialectical understanding of development) regards the world as regularly developing matter that is one in its diversity. The second (in its complete form it is the trend of mechanical materialism) recognises only external combination and dissociation of the constant elements underlying the Universe.

Before the rise of Marxism the mechanistic conception seemed to be the fuller, and related to the concrete tasks of science. The atomistics of Leucippus and Democritus, Descartes' physics in the new philosophy, Newton's *Principia*, the philosophical theories of the eighteenth century French materialists, Lomonosov's scientific work and his 'corpuscular philosophy', the notions about matter and its structure of the coryphaei of classical physics—such are the landmarks in the history of the mechanistic doctrine. At the same time we must not forget that the work of these thinkers devoted to the 'structure of the Universe' or 'the world order' contains many elements of dialectics: suffice it to recall Descartes' cosmological theory, the ideas of an internal connection between matter and motion of the atomists of antiquity and of the French materialists, and Lomonosov's thesis of the conservation of matter and motion—although it is impossible to separate their philosophical views from their metaphysical understanding of nature as something basically constant and invariable.

In the history of philosophy the dialectical conception as applied to problems of the Universe is represented by the teaching of Heraclitus, the atomistic ideas of Epicurus and Lucretius, the natural philosophy of Giordano Bruno, and the philosophical views of Alexander Herzen, as regards the materialist trend. The dialectical conception developed spontaneously in natural science, and in the classical period (the seventeenth to nineteenth centuries) it was not fully expressed: the law of action and counteraction in Newton's mechanics, the differential and integral calculuses devised by Newton and Leibniz, which made it possible to depict the processes of nature mathematically, Kant's and Laplace's cosmogonic hypothesis, the law of the conservation and transformation of energy, and classical electromagnetic theory did not shake classical physics' scheme of space-time-matter.

The theories of idealist philosophers contain many dialectical constructs relating to the philosophy of nature. They often brilliantly guessed the dialectics of modern science. In this connection Aristotle's analysis of the relationship of matter and form as that of possibility and actuality, or, say, Leibniz's theory of monads, which considered individual monads as closed yet at the same time connected with the whole world, are of considerable importance for the modern theory of elementary particles. The idealists' natural-philosophical, dialectical constructs, however, did not directly yield science any new scientific results; having grown out of 'pure' thought they, like all idealist philosophy in general, were isolated from the concrete concerns of science, and the atomistic ideas of Democritus-Newton-Dalton dominated classical science.

These ideas and classical physics' scheme of space-time-matter were struck a crucial blow from the positions of science itself by relativistic and quantum physics, which made a further advance in the cognition of nature. The deep transformations and progress of modern science are integrally linked with dialectical materialism, as Lenin had already demonstrated at the time when the new physics was being created, and as has been confirmed by its subsequent development.

What are the simple and the complex as applied to matter?

The simple (we do not distinguish it from 'elementary') and the complex (or compound) cannot be defined by the difference between genus and species. They are defined, like other opposite philosophical categories, by analysing their reciprocal connection. In one way or another the simple and the complex resemble the individual and the general, the discontinuous and the continuous, the chance and the necessary, the possible and the actual. Lenin's ideas about the individual and the general or universal are of the greatest importance for the theme of this section. Let us recall them here: 'the individual exists only in the connection that leads to the universal. The universal exists only in the individual and through the individual. Every individual is (in one way or another) a universal. Every universal is (a fragment, or an aspect, or the essence of) an individual. Every universal only approximately embraces all he individual objects. Every individual enters incompletely into the universal, etc., etc.'[3] 'Every individual is connected by thousands of transitions with other *kinds* of individuals.'[4]

It follows from this statement of Lenin's, in particular, that knowledge of the laws of nature enables us to discover new phenomena, i.e. the laws make it possible to identify the reciprocal connection between many phenomena; every law is narrow, incomplete, approximate[5]; the laws of nature are reciprocally connected. This same statement of Lenin's leads one to the idea that objects united in a certain whole (and appearing as elements of a system) exist as elements only within the connection that makes them a whole, and the system exists only through its elements. In abstraction, however, the system and the element are separated and opposed to each other.

We have come close to a definition of the elementary (simple) and the complex (compound), but to make the last step we must define such concepts as a thing or object (which are treated here as equivalent), property, and relation.

We shall omit the appropriate argumentation and give the following definition: a thing is an aggregate of properties.[6] The essential element of this definition of a thing through its opposite is that a thing is interpreted as constant and invariant with respect to the variation of properties, since one property differs from another. Our definition corresponds approximately to Ashby's interpretation of a system as 'a list of variables'.[7]

A thing's diverse relations to other things reveal its properties, i.e. they are relative, although the metaphysical mind frequently ascribes the same absolute meaning to a property as it does to a thing. Discovery of the relativity of one property or another of an object in physics more than once constituted an epoch in its development (the relativity of mechanical motion in classical mechanics; the relativity of the extension and duration of events in the special theory of relativity; the relativity of the particle and wave properties of micro-objects in quantum mechanics). Things themselves are dialectically contradictory; each thing is connected with every other thing, each property passes into every other property; the development of a thing is an endless process of discovering new properties, relations, etc., etc.[8] We shall not go into details here of the dialectics of things, properties, and relations.

Now let us consider the definition of a system and of structure. If objects are linked through relations with one another into a single whole, these objects become the elements of a system that possesses structure. The following examples are well known: atoms can form a molecule, an atomic nucleus and electrons an atom, neutrons and protons an atomic nucleus. In this case the atoms, the atomic nucleus and the electrons, the neutrons and protons, which are connected by certain interactions, are elements of corresponding systems—the molecule, atom, and atomic nucleus, which have a structure. Every system has a structure, which remains unchanged in certain transformations of this system; from that angle structure is an invariant of a system.

This definition of system and structure accords with the view of these concepts that has become established in the contemporary mathematical literature. 'To define a structure,' we read in Bourbaki, 'one takes as given one or several relations into which these elements [of a set—*M.O.**] enter ... then one postulates that the given relation, or relations, satisfy certain conditions (which are explicitly stated and which are the *axioms* of the structure under consideration)'[9] (my italics—*M.O.*).

A *system* of objects, which has structure, is something complex in relation to the objects that are its elements. *Systems* of objects, or complex objects, in turn, may be elements of a system of a higher level with respect to the initial systems. The elements of a system, on the other hand, may be objects that have been formed from objects of a deeper level. A hierarchy of various levels of systems or structures thus emerges. In the next sections we shall consider the relations between the levels of structures and whether there is a finite or an infinite number of such levels. As modern science has demonstrated, the world is a hierarchy of material structures.

In the same way that a thing's properties are revealed in its relations with other things, so the elements (and their relations) of a system of a certain level are revealed in its relations with systems of other levels. In that sense a mate-

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* A set is also called a class, system, complex, family, domain (S. C. Kleene. *Introduction to Metamathematics* (New York-Toronto, 1952)). We do not distinguish between the terms 'set' and 'system'.

rial system's structure is something relative. Here are a few comments on this relativity.

First of all, there are systems of varying degrees of complexity in nature, in addition to simple ones. The great complexity of these systems depends (1) on their embodying some part of the hierarchy of material systems (a macroscopic body, for example, consists of crystals, which consist of molecules, which consist of atoms, and so on); (2) on the fact that the number of a system's elements may be very great, and so may be their connections. Macroscopic bodies, for example, with typical dimensions of the order of 10^4 to 10^{-2} centimetres include molecules and atoms with typical dimensions of the order of 10^{-8} centimetre; the atom includes the atomic nucleus with typical dimensions of 10^{-12} centimetre, while atomic nuclei are formed of protons and neutrons, which are elementary particles with even smaller typical dimensions. One has to remember here that the elements of a system and their various combinations regarded as systems of the same level as the initial one (e.g. at molecular level there are mono-atomic molecules) represent the parts, while the initial system represents the whole. Parts are independent in relation to each other to the extent that they constitute a whole (which is opposed to the parts). This dialectic of the whole and its parts also finds application in study of the problem of the structure of matter.

When very complex systems are cognised, the principle known as the law of the transition of quantity into quality (and vice versa) operates. As the system becomes more complex, i.e. as the number of elements and the connectedness of the system increase, the properties of the whole differ qualitatively from those of its parts. Generally speaking, an object as a system is exactly a connected unity and not an agglomerate, and this unity is a new quality formed as a result of the combining of a large number of the system's various interconnected elements. From this angle there is no need, for instance, to employ the laws of atomic physics when designing a locomotive; for that purpose the laws of classical physics dealing with macroscopic phenomena are quite adequate.

Knowledge of the properties and behaviour of structures of a deeper level provides the key to explain phenomena and laws that belong to a higher level, but not at all in the sense that the laws of chemistry, for example, can be reduced to the laws of quantum mechanics and the Pauli principle. The laws of structures of various levels differ qualitatively from each other; and at the same time they are related through transitions (quantum mechanics, for instance, is related to classical mechanics through the correspondence principle).

A decisive methodological role is played in analysis of the problem of the simple and the complex in relation to matter by the idea of the infinite diversity of nature, the inexhaustibility of matter in any of its parts, the infinity of matter in depth and breadth. This infinity is composed of many finite objects of various levels of a single matter, and the transitions from one level to another represent transitions of quantity into quality and vice versa. Definition of a system consists in essence (1) in separating the part from the whole, and (2) in unifying the parts into a whole.

From this position one can say that knowledge of an object is knowledge of it as an element in a certain system and at the same time knowledge of it as a certain system. The first aspect was predominantly developed in classical physics, which led to a tendency to explain the phenomena of nature in terms of elementary phenomena. The second aspect is typical of relativistic theory in which a tendency to explain elementary phenomena from the standpoint of knowledge of the whole finds a certain expression. Quantum physics unites both aspects, and this connection is getting closer and closer as quantum theory develops. When an object representing a very complex system is cognised and the mental transition is made from the elements to the system and from the system to the elements, a need arises to employ statistics and the theory of probability. That is how matters stand in the transition from macroscopic phenomena to molecular and atomic ones, and in the reverse transition from elementary phenomena to macroscopic ones.

The question of the system and structure of matter thus cannot be separated from the philosophical problems of regularity, necessity and chance, possibility and actuality. We shall discuss this more concretely in the sections that follow.

2

Classical Science on the Elementary and the Complex

The atomistics of Leucippus and Democritus was applied and developed in classical physics and chemistry. Not only was the basic idea of invariable fundamental particles of matter moving in empty space taken into the arsenal of natural science in the seventeenth to nineteenth centuries but concepts of the atomistics of antiquity are also met in the theories of classical science that appear naive even from the standpoint of those theories (let alone of modern science). Democritus' atoms, for instance, were furnished with hooks so as to combine by means of them into sensibly perceptible bodies; the same idea in rather modified form was held by Boltzmann, although Lomonosov had already criticised the theories of his day for their 'wedges, needles, hooks, rings, bubbles, and numerous other figures of particles created in the head with no foundation of any kind'.[10] According to Boltzmann an atom resembled a sphere with a sensitive process (each atom having a definite number of processes); atoms were repelled when they collided with one another, except when the processes overlapped; then a molecule was formed.[11] We shall consider Boltzmann's atom again below; the ideas of classical chemistry on the eve of its transformation into modern chemistry found visual expression in it.

In classical science, which (as we know) began the systematic scientific study of nature, the idea of atomism had already been expressed quite fully and with the greatest clarity by Newton. Although the author of the *Philosophiae Naturalis Principia Mathematica* held strictly to his dictum *hypotheses non fingo*, he created remarkable hypotheses when the tasks of investigations required it. His idea of atomism, which he set out in detail in his *Optica* and related works, and also in his short memoir *De Natura Acidormu* (1692), was just such a hypothesis.[12]

Although Newton's *Principia* did not explicitly contain the concept of the atom, it is impossible without it to comprehend correctly the definition of the 'quantity of matter', which (according to Newton) was measured by its density and volume conjunctly.* One can get an idea of Newton's atomism from the following extract from his famous '31st optical problem', which is often cited: 'God in the beginning formed matter in solid, massy, hard, impenetrable, movable particles, of such sizes and figures, and with such other properties, and in such proportions to space, as most conduced to the end for which he formed them; and ... these primitive particles being solids, are incomparably harder than any porous bodies compounded of them; even so very hard as never to wear or break in pieces.'[13]

For Newton, as for the atomists of antiquity, matter was discrete, but unlike them he put forward a conception of a hierarchy of systems of successively diminishing solidity containing indestructible, absolutely hard particles only at the deepest level. In place of the kinetic conceptions of the ancient atomists about direct collisions as the sole cause of a change of atoms' state of motion (in the new philosophy these notions were shared by Descartes), Newton employed a dynamic scheme: particles moving in a vacuum became a sort of focus of forces acting at a distance.

Newton thus arrived at a hierarchic scheme of the structure of matter. The foundation of the hierarchy consisted of absolutely hard, invariant particles. Being connected with one another by great forces they formed systems of great strength and very small dimensions. These systems, being linked by interactions of less force, formed new (more complex), less strong systems of larger size, and so on, up to the bodies observed in everyday life, which could be broken up relatively easily.

As Vavilov convincingly demonstrated, one can say with great certainty that the founder of classical science arrived at an atomic conception that retained its significance fully for the whole period of classical physics.[14] The development of physics after him, down to the twentieth century, added nothing essential to this conception. It has also passed, in a transformed version, and on a new basis, into modern physics. Let us consider the atomic conception of classical physics in greater detail.

The atomism of classical science rests on Newton's scheme

* One cannot, therefore, agree with Sommerfeld, who calls this definition of Newton's meaningless (Arnold Sommerfeld. *Mechanics. Lectures on Theoretical Physics*, Vol. 1 (Academic Press, New York, 1952), p 4).

of space, time, and moving matter. According to him space and time have no internal connection either with each other or with the matter moving in them; the motion of matter itself is understood as the displacement of particles, which is changed by the effect of forces acting between particles and dependent solely on distance. Newton's theory of matter was the pinnacle of the view on matter developed in classical science. It explained a certain circle of thermal phenomena in accordance with experience and provided a consistently mechanical picture of the structure of matter.

A kinetic conception developed alongside Newton's dynamic scheme in classical physics, and in struggle with it, a conception based on Descartes' ideas of natural philosophy and Huyghens' related physical ideas (the ether as a continuous medium; the wave theory of light). The contradictions between these two conceptions, which led through their development to the Faraday-Maxwell theory of an electromagnetic field, were resolved by Einstein's theory of relativity, which arose from the problem of field and was the last theory of classical physics and at the same time the first theory of non-classical physics. It created a new physical doctrine about space, time, and moving matter in which these concepts lost their 'classical' isolation.

Within classical physics itself there were the premises for its transition into deeper, non-classical theories. The idea of forces acting at a distance in empty space thus potentially included the concept of field (in Newton, though, in the form of a mathematical presage). From the point of view of mechanism, indeed, action at a distance without the mediation of a substance filling space is meaningless. The idea of mutual contact between particles, however, preferred by the kinetic conception, did not differ essentially from the idea of action at a distance. There can be no absolute contact between particles; otherwise they would merge together and matter would not be discrete. It was left to assume that particles had forces that did not allow them to merge with one another. Contradictions of this kind were resolved with the development of field theory in physics.

Although the idea of a hierarchy of structural levels of matter was first legitimated in classical science, the principle of development that goes with such a scheme and cannot be separated from it did not receive consistent application. From the standpoint of classical science the same mechanical laws operated, in the final analysis, at all rungs of the hierarchic ladder, and the job was to explain all non-mechanical phenomena and regularities exactly, or to subordinate them to the laws of mechanics (as fundamental laws). Mendeleev, for example, had no doubt that chemical processes would be explained in terms of Newton's mechanical laws.[15] Boltzmann and Gibbs explained the need to introduce statistical concepts into physics by the circumstance that the mechanical properties of a complex system consisting of an enormous number of particles were inaccessible to cognition because of the crudity of the human sense organs, measuring instruments, etc. Maxwell's electromagnetic theory was long misunderstood by physicists because it could not be reduced to mechanics (such reduction had to be abandoned in physics, of course).

Classical atomistics is thus inseparable from the mechanistic rejection of qualitative transitions in the development of matter. This development is interpreted, in the last analysis, simply as quantitative growth, and the complex as the augmented simple. From this position matter is governed everywhere and always, at all levels, by the same laws of mechanics.

The natural form of determinism for classical science and its theory about the structure of matter, and the only one, was mechanical determinism (most clearly represented by Laplacian determinism in classical mechanics). Much has been written in Marxist philosophical and physical literature about its being impossible to reduce determinism, i.e. the theory of the objectively real, universal connection, to mechanical determinism, about causality (as conventionally understood) being only a small part of the universal connection, and about statistical and dynamic laws being of equal value in the pattern of nature.[16]

According to classical mechanics, a material object is a dynamic system governed by the laws of mechanics, i.e. a determined system in the sense of Laplacian determinism. The theory of relativity left the foundations of mechanistic determinism undisturbed, but quantum mechanics demonstrated its inconsistency and connected dynamic and statistical laws into a single whole, which made it possible to get a deeper understanding of determined systems. Quantum physics brought complex objects (especially those of great complexity), before which, as a matter of fact, classical theories had come to a halt, into the sphere of deterministic analysis.

Classical science, in explaining the development of nature, ultimately stressed constancy in transformations, repetition in natural processes, and renewal of one and the same forms in the phenomena of nature. The facts of the relativity of such constancy and repetition, and the need to explain this relativity, were ignored. Accordingly the idea that universal change was based on constant, eternal primary particles incapable of transformations and moving by one and the same laws, appeared absolutely correct. The indestructibility and constancy of the moving primary particles should, from the standpoint of classical scientific conceptions, determine the constancy of everything happening in nature and the repetition and recurrence of its phenomena.

Another characteristic idea of classical notions about matter was that of the separation between matter, on the one hand, and motion, space, and time, on the other. Matter was discrete particles whose combination into systems of various complexity, and the dissociation of the latter into their components, determined the diversity in nature. Motion, space, and time, however, are represented in classical science as continuous entities. With this is associated the fact that various absolutes are often encountered in classical physics, e.g. mechanical ether, absolute motion, absolute time, etc.

Finally there is a typical tendency in classical science (expressed in its notions about the structure of matter) to consider that it is possible in principle to calculate and cognise the parameters of material systems of any degree of complexity, i.e. of any material objects, from the properties of primary particles. This classical tendency also operates to some extent in modern physics, when the idea is expressed that it is possible to explain the properties (and behaviour) of any material system in the universe in terms of elementary particles and the laws of their behaviour. The development of the theory of relativity and of quantum field theory, however, has advanced an opposite tendency, namely to explain the properties of particles by those of the systems formed by them. We shall consider the problems that arise in analysis of these tendencies later.

3

The Problem of Simplicity in Microscopic Physics

Physics, like its mother, philosophy, has always striven, but in its own ways, to penetrate the most fundamental laws of nature. Its founders, Galileo and Newton, and the physicists of the classical period who continued and developed Newton's main ideas, assumed that science had cognised the laws underlying the universe. Lagrange aptly expressed this typical feature of classical physics when he called Newton the happiest of mortals since he had discovered great truths which, Lagrange considered, could only be discovered once.

Had classical physics, however, comprehended the most fundamental laws of nature? The development of twentieth century physics has given an answer to that question which does not agree at all, of course, with Lagrange's view: fundamental laws of nature in the sense that this was understood by the creators of classical physics, were not discovered by classical science and its understanding of the structure of matter, nor by all the developed versions of the system of principles of classical mechanics, nor by classical field theory, nor by Lorentz's theory of electrons.

The problem of studying the laws of nature that underlie all the physical phenomena now known is resolved by quantum theory. It emerged and developed on a broad empirical foundation; that is its strength and the guarantee that its principles and concepts are not in the least *a priori* constructions, in spite of their being far removed from the 'visualisable' ideas and theories of classical physics.

Even in its historically first forms (Bohr's atomic model, modern quantum mechanics), quantum theory successfully resolved many of the problems that confounded classical science (though by no means in the 'classical' spirit). When chemistry was establishing itself as a science, for instance, the concept of a chemical element (with its smallest part, the atom) and the law of the conservation of mass linked chemical phenomena into a single chain. But is there a connection between chemical elements? This question, which is very important for the theory of the structure of matter, came to the fore in the nineteenth century when a great many elements were discovered.

Mendeleev's periodic law linked all chemical elements together; it received deeper substantiation, however, in the nuclear model of the atom, by which it was possible to explain exactly why chemical elements (resp. atoms) are the elementary structural units in chemistry, and to understand that chemical properties are associated with electron shells and are determined by the electrical charge of the atomic nucleus.

The nuclear model of the atom in the original form in which it was proposed by Rutherford served in physics rather as a scout than as an established theory: the atom, regarded as a classical electromagnetic system, could not exist as a stable material formation. The stability of atoms (preserving the nuclear model) was explained in terms of quantum laws (Niels Bohr). The principles of quantum theory as applied to the forces of electrical origin that connected atoms also made it possible to explain the various connections between atoms and the formation of molecules and crystals. Thanks to quantum theory, chemistry became an exact science in the full sense of the term; at the same time it became clear (and no longer simply on the basis of general considerations) that chemical laws cannot be reduced to mechanical ones, as was assumed by nineteenth century scientists.

On the other hand, the classical approach to the relationship between matter and field remained to some extent unaltered in chemistry, or rather in the theory of the structure of matter transformed in accordance with quantum laws. From the angle of quantum mechanics, fields still remained 'classical' but the behaviour of particles acquired features of wave motion which created an affinity between matter and field.

This last circumstance found reflection in quantum mechanics' understanding of structure. On the one hand, quantum mechanics radically revised the concept of physical system (structure) as a system of particles capable of strict localisation and connected by forces, the behaviour of which was governed by the principle of Laplacian determinism. On the other hand, quantum mechanics preserved the classical separation of matter and field, and accordingly the kinds and number of elementary particles were regarded as invariable.

Quantum mechanics, it is true, following the theory of relativity introduced a new element (compared with classical mechanics) into the question of the extension of fundamental particles. Whereas fundamental particles could be regarded as absolutely solid bodies according to classical mechanics, from the standpoint of the theory of relativity there are no such bodies, and elementary particles therefore had to be regarded as points. Although quantum mechanics has altered the situation, it too approaches the problem of the extension of fundamental particles in accordance with the principles of the theory of relativity.[17]

New possibilities of solving this problem have been given by the latest development of quantum theory and experiment (this point will be discussed below; here we would note once more that, according to quantum mechanics, elementary particles are stable formations whose number and type are invariable during their interaction).

The problem of the elementarity of particles in quantum physics was radically altered with the development of quantum field theory (which, like quantum mechanics, originated from Planck's quantum hypothesis). This branch of quantum physics combines the ideas of quantum mechanics and the theory of relativity and in essence is a relativistic quantum theory of elementary particles. In its general form quantum field theory is still far from complete; it has already, however, reached a most important position, the experimental conclusions from which are now well known, and the philosophical implications of which can hardly be exaggerated.

Quantum field theory considers elementary particles from the angle of their emergence and disappearance and of their reciprocal transformations in accordance with certain principles (conservation laws). It contains no statement about invariance of the number of interacting particles. Fundamental particles are produced and annihilated during interaction with each other. In other words, modern atomism which has grown on the soil of quantum physics, is something new in principle compared with the atomistics of classical science.

The ideas and methods of quantum electrodynamics, i.e. the quantum theory of electromagnetic field, led quite a long time ago to the discovery of anti-particles and mesons. Hyperons were detected for the first time in cosmic rays. The establishing of various types of interaction between elementary particles during their transformations (strong, electromagnetic, weak), and the discovery of certain symmetries and conservation laws that govern the scattering, creation, annihilation, and reciprocal transformation of particles were of great significance.

Research in the field of high energy physics has added new knowledge and posed new problems in the theory of elementary particles. Without going into an analysis of the many points relating to this, let us consider those that are directly concerned with our theme.

Not so long ago (1960) about 30 particles were known (among them, the electron, proton, neutrino, and photon were classed as stable; the rest were unstable). Now, since the discovery of groups of so-called resonances (particles with an extremely short half-life, even in terms of nuclear time), the number of known types of elementary particles considerably exceeds 100, and physicists suggest that this is not the limit. New, unexpected properties of strong interactions have been discovered, and the new data on weak interactions may possibly lead to a radical change in physical notions about the symmetry of space and time that once seemed unshakable. The concept of the structure of an elementary particle is becoming more and more important, with a content unusual from the standpoint of classical theory; physics is now more and more departing from the notion of a point particle.

One of the most significant problems posed by all these discoveries and others is that of elementarity. How do matters stand with the elementarity of the particles that are usually called elementary, if there are so many of them? Are they indeed elementary? Is their number finite? What is the relationship between the elementary and the complex (if there is one) in the world of fundamental particles? Is the posing of the question of structure to be preserved in this world in the form in which it was expressed before the theory of elementary particles?

In pre-quantum physics the problem of the elementarity of particles was solved, of course, in the following way: matter consisted at bottom of stable, indivisible particles capable of quite accurate localisation in space and time, which formed the structure of the more complex forms of matter. This idea was realised to some extent in chemistry: Prout's hypothesis that chemical elements consisted of hydrogen is realised in one way or another, only the role of hydrogen is being played by the charge of the atomic nucleus, which determines the number of electrons in the atomic shell, and the element's place in Mendeleev's periodic system. It must be remembered, however, that the atom as a system (its structure and properties) is governed by quantum laws: the parameters of the simplest atoms are calculated by means of quantum mechanics, while those of complex atoms are calculated by approximate methods.

The problem of elementarity has arisen again in connection with the discovery by modern physics of a great number of elementary particles and their various types of interaction and a whole set of diverse quantum properties. Can it be solved as was acceptable before the discovery of elementary particles? Or are new approaches needed? In order to clarify the situation, we must allow for its being impossible, for instance, to consider stable particles that do not decay without an external influence (the group includes, as was noted above, the proton, electron, photon, and neutrino) as truly elementary and to regard all the remaining elementary particles (metastable ones and resonances), which decay spontaneously, as compound. Thus, a neutron does not consist of a proton, an electron and an anti-neutrino, although in its free state it decays into these three particles.

It would seem reasonable to reduce the problem of elementarity to the existence of a certain sequence in the levels of matter in which each of them is an 'elementary' stage for the next higher level and a 'compound' stage for the preceding deeper level. This idea of the hierarchy of elementarity found one of its embodiments, in particular, in the Newtonian conception of matter as a system of particles of a mounting degree of complexity; it also finds expression, to a certain extent, in the contemporary understanding of the structure of matter (the level of elementary particles—the level of atomic nuclei and atoms—the molecular level, the series being continued toward the macroscopic world and, in the opinion of some authors, toward the microscopic world).[18]

Will the idea of a hierarchical system really serve as the key to solve the problem of elementarity in modern physics?

Assume that the sequence of levels begins from the 'elementary' side. Then matter will be represented as an ordered set of elementary particles and systems (particles) of various degrees of complexity that consists ultimately of these same elementary particles. Thus, we face a version of classical atomistics. The scheme of the Japanese physicist Sakata, which consists of three fundamental particles, namely, the proton, the neutron, and the lambda-hyperon (together with their anti-particles), from which all strongly interacting particles are constructed, can serve as a novel expression of this version among contemporary conceptions of elementary particles.[19] We must, however, remember (1) that in Sakata's scheme it is not so much, in fact, a matter of three particle-bricks as of the three laws of the conservation of the electric charge, of the baryon charge, and of strangeness being valid in the processes of strong interaction; and (2) that the choice of the three main particles is not unambiguous—they may be xi-hyperons (Ξ-$^{-}$) and (Ξ-^{0}) or lambda-hyperons (Λ). These peculiar features of Sakata's scheme diverge from classical atomistics.

More recently other physicists have returned again to the notion of three fundamental particles, having altered and refined Sakata's scheme. It has been established that the quantum numbers of these particles (known as 'quarks') have to be represented by fractions. Only experiment, of course, can settle the matter of the existence of quarks. Yet another scheme has been suggested, according to which all particles are constructed of four fundamental particles.

Now let us assume that the sequence of the levels of matter is infinite (i.e. has no beginning) from the 'elementary' side, this infinity representing a constantly recurring transition from the compound to the elementary and vice versa. According to this assumption, the 'elementarity' of objects is only relative, and the objects themselves are something compound (complex). We arrive at the idea that there are no 'elementary' objects as such, i.e. that matter does not consist of elementary particles.

Many physicists today hold this view of matter in one way or another. Hofstadter, for instance, who discovered the structure of the nucleon, suggests that 'the search for ever smaller and more fundamental particles will go on so long as man is thirsty for knowledge'.[20]

In their logical essence the remarks above on the elementary and the compound resemble Kant's second antinomy: there exists nothing that is not either itself simple, or composed of simple parts (thesis); in general there does not exist in the world any simple substance (antithesis).[21] From his argumentation Kant drew agnostic conclusions. A dialectical critique (Hegel, Marxist philosophy) corrected his argument and resolved his antinomies.

Dialectical principles, it seems to us, make it possible to outline an approach to the problem of elementarity that excludes both the concept of purely relative elementarity and the point of view of classical atomism. This approach (matters relating to it will be analysed in the next section) wholly corresponds, in our view, to the trends of development of the physics of elementary particles.

4

The Concept of the Elementary and Structure in the Physics of Elementary Particles

The infinite sequence of levels of matter, as Engels pointed out, is 'various *nodal* points which determine the various *qualitative* modes of existence of matter in general'.[22] From this standpoint matter is not just elementary particles and their combinations and is also not just substance that does not consist of elementary particles; matter in general has simultaneously the properties of both the elementary and the compound or complex.

There are grounds in classical physics for abstracting the unity of the elementary and the complex and considering them in isolation from one another (and this understanding is confirmed by experiment). In quantum physics the situation is fundamentally different, the reason being that the further physics penetrates into the heart of matter the more strongly its theory is bound to be affected by discovery of the reciprocal transformability of all elementary particles. In modern atomistics the concept 'transformation of the one into the other' has come to the fore, to the plane on which the problem of elementarity and complexity is posed and solved in a way quite different from that in classical atomistics (in which transformation is understood in the final analysis as 'the combination and dissociation of certain constant particles').

The concepts of the elementary and the complex, as applied to elementary particles, have lost their abstract opposition to one another and so their literal meaning. Elementary particles are not elementary in the classical sense; they resemble but are not classical complex systems. The properties of the elementary and the complex are united in them, i.e. an elementary particle is simultaneously both an elementary entity and a system.

The concept 'to consist of' has accordingly also changed its meaning as regards elementary particles. It had already undergone a certain metamorphosis in nuclear physics. In the statement 'an atomic nucleus consists of neutrons and protons', the concept 'consists of' has a meaning rather different from that in the statement 'a molecule of water consists of oxygen and hydrogen atoms'; the neutron and proton are considered as two states of the same particle, the nucleon, while it is quite a different matter with oxygen and hydrogen atoms.

The change in the concept 'consists of' is especially striking as regards resonances. A lambda (1520)-particle can decay into a sigma-particle (Σ) and a pion (π), or into a neutron (N) and a kaon ($\varkappa^-$), or finally, into a lambda-particle (Λ) and two pions (π); but that does not mean that the lambda (1520)-particle literally 'consists of' the particles into which it 'decays'.

These examples emphasise that 'elementarity' and 'complexity' are not inherent in the interacting elementary particles by themselves, irrespective of the conditions in which their transformations occur, but in their intrinsic link with these conditions.

For a particle involved in an interaction to decay, certain conservation laws have to be observed, which in this case operate as the conditions of the possibility of decay. In strong interactions, for example, only those decays can occur the initial and final particles of which have identical values of all the quantum numbers conserved. For the possibility of decay to become actual, the initial particle must have total energy (rest energy plus kinetic energy) at least equal to the sum of the total energies of the particles into which it should decay, i.e. the law of the conservation of energy must be observed.

The above may be illustrated in a certain sense by the set of experimental data from which it was possible to infer the existence of the omega-hyperon (Ω^-). A high energy kaon colliding with a proton produces an omega-hyperon (Ω^-), and two kaons (a K^+-meson and a K^--meson); then the omega-hyperon decays into a pion (π^--meson) and a xi-hyperon (Ξ°); the last decays into two gamma-quanta and a lambda-hyperon (Λ°), which in turn decays into a proton and a pion (π-meson).

In this reaction the kaon and the omega-, lambda- and xi-hyperons (Ω^-, Λ°, Ξ°) behave as compound systems only because the total energy of each of them is sufficient for them to decay into the corresponding particles without violating certain conservation laws. In other reactions the total energy of one or more of these particles may not satisfy this requirement; the corresponding particles are then no longer compound formations.

An interacting particle thus cannot be regarded as elementary or complex without mentioning the total energies of all the particles involved in the reaction. In that sense the concepts of 'elementary' and 'complex' are relative as regards elementary particles.

This understanding of elementarity has nothing in common with its understanding in the sense of pure relativity. 'Purely relative elementarity' is unimaginable without a supplementary statement that the object by itself is complex. From the point of view developed here the situation, as we have seen, is quite different. The relativity of the 'elementarity' and 'complexity' of elementary particles is similar to the relativity of size of a body and duration of a process in Einstein's theory, or the relativity of particle and wave characteristics in quantum mechanics, in spite of the different content of these 'relativities'. Without relativity in this sense, it would be impossible to employ classical concepts with the necessary refinement to describe those phenomena of nature that do not fit into, or cannot, in general, be made to fit into classical theories.

In conclusion, let us consider the notion of structure in elementary-particles physics. If a fundamental particle can be complex, it can consequently have a structure. And as the concept of the 'complex' has no 'classical' meaning as regards elementary particles, the concept of 'structure' should not be identical in relation to elementary particles to the classical understanding of structure. Since Hofstadter's experimental proof of the structure of a nucleon, the existence of structure in elementary particles has ceased to be a matter of debate and has become an object of research in modern physics.

The concept of structure is inseparable from those of set and element, i.e. from the concept of discontinuity. As materialist dialectics has demonstrated, however, the concept of discontinuity is one with its opposite, continuity, i.e. the opposition between these concepts is not absolute, as metaphysical philosophy considers. On this fundamental question quantum theory has followed the path of dialectics: in quantum mechanics the corpuscular concept (pertaining to discontinuity) and the wave concept (pertaining to continuity) are considered in their internal connection. Niels Bohr developed this interpretation of quantum mechanics most fully; it has been developed further in quantum field theory.

The specific quantum concepts of virtual process, virtual state, and virtual particle also have a direct bearing on the problem of the structure of elementary particles.

On this plane Berestetsky's remarks on the composition of strongly interacting particles are of great interest. He distinguishes between the concepts 'consists' and 'composed of'. If, for example, it is said that 'the nucleus *consists* of nucleons' it is implied (1) that a nucleus with quantum numbers A and Z can be formed of Z protons and A-Z neutrons and (2) that its mass defect is small. There are systems, however, for which the first proposition is true and the second is not. In that case, according to Berestetsky, we should say 'may be composed of' or 'is composed of' instead of 'consists'; for instance, non-strange mesons are *composed of* nucleons and anti-nucleons.[23]

In this scheme the particles of which a system is composed are virtual. For them the law of the conservation of energy, it is said, does not hold or rather it is meaningless to apply the law of conservation of energy to them. From this angle elementary particles constitute a part of other elementary particles not in their real form but in a virtual state; in other words, elementary particles have virtual structure.

The concept of a particle's virtual structure was developed in quantum theory quite long ago. Underlying it is the idea that an interacting particle is the source of a field whose quanta transfer interaction. In an interaction particles exchange virtual quanta of the field; a nucleon, for example, with a baryon charge produces and absorbs virtual π-mesons, quanta of the nuclear field.

It can be shown that the probability of two or more π-mesons being produced at the same time in strong interaction is quite big. As a result, the nucleon proves to be on average (in time) in an atmosphere consisting of virtual π-mesons. This atmosphere of virtual mesons (which has certain dimensions) cannot be separated from the nucleon, and from this angle it must be said that the latter has a π-meson structure.

A nucleon is a source of K-mesons or kaons, in addition to π-mesons or pions. The corresponding argument leads to the conclusion that a nucleon engenders kaons when hyperons are formed. It is also possible for a nucleon to engender virtual nucleon-antinucleon pairs. They, too, contribute to the general virtual structure of a nucleon.

Thus, a nucleon has virtual structure as a consequence of its interaction with other elementary particles. Virtual processes occur within it: the nucleon spends part of the time in the state of a nucleon with pions, part of the time in the state of a hyperon with kaons, and part of the time in the state of a nucleon with nucleon-antinucleon pairs. The superposition of sets of virtual particles of different kinds (various virtual structures) also gives the nucleon's general structure that can be observed in the experiment.

The structure of the nucleon was first observed in Hofstadter's experiments on the scattering of fast electrons by protons. Its structure becomes real after being virtual through the transfer of energy to it by the moving electrons. It has been demonstrated in experiments that the proton scatters electrons as if its charge were distributed in space and not as if it were a charged point particle.

Hofstadter's experiments, in particular, left no stone standing of March's philosophical construction, by which an elementary particle is quite without structure so that, therefore, the concepts of extension and shape are inapplicable to it. March said that there was no experiment that would resolve whether an elementary particle was point-like or had extension, since all the relevant data were based on hypotheses. Analysis of these hypotheses led March to infer that the application of conventional spatial concepts to elementary particles resulted in contradictions; the way out of these contradictions March saw in the thesis that modern physics excludes the concept of matter.[24]

Hofstadter's experiments were the experiments whose possibility March had denied. They showed that the elementary particles do possess structure but that this structure is not the 'classical' structure of normal bodies.

In the light of these ideas about the structure of elementary particles, the 'bootstrap' hypothesis put forward by Chew and Frautschi is of great philosophical interest.[25] According to this hypothesis every strongly interacting particle helps create other particles which in turn form the particle itself.

Chew and Frautschi's hypothesis, according to which no single particle can exist without the existence of other particles interacting with it, is interesting philosophically in that it puts forward the idea of freeing fundamental theory of purely empirical quantities not related to its postulates, and tries to connect these quantities with the postulates of the theory and so explain them and understand the necessity of their existence. In short, this hypothesis has a resemblance to the ideal of a perfect physical theory, in which, as Einstein thought, there would be no purely empirical constants and all the physical constants would admit of theoretical definition and follow from a theoretical principle reflecting the harmony of the universe.[26]

Modern atomistics thus does not at all require the diversity of known particles to be reduced to a few elementary entities or, on the contrary, elementary entities to be excluded in general from scientific use. Elementary particles, which form the deepest level of matter at present known, unite the properties of the discontinuous (particles) and the continuous (fields). The number of the various types of particles is unlimited; at the same time they are one; this feature of the level of elementary particles distinguishes it from the higher levels of matter, in the consideration of which the intrinsic unity of the discontinuous and continuous can be abstracted in certain conditions.

Heisenberg held the view that '*there is no difference in principle* between "*elementary*" and "*non-elementary*" microparticles'.[27] From everything said above about the elementarity of particles it is clear where one can agree with Heisenberg and where one cannot. There is a difference between the 'elementary' and the 'non-elementary' in the world of elementary particles but it is *relative* in nature and not absolute (as in the sphere of macroscopic phenomena).

As noted above in Section 2, classical atomism linked the fact that there is a constancy in the development of nature (sameness of its forms; recurrence of its phenomena; repetitions) with its basic propositions (in particular, with that about the finite diversity of types of elementary entities). From that angle there could be no constancy in nature if the number of types of elementary particles were infinite.

This line of reasoning of classical atomism, however, has no justification in the light of the modern data on elementary particles. The latter are transformed into one another in accordance with certain laws of conservation (which do not permit arbitrary reactions between elementary particles). It is on these conservation laws, which at the same time are laws of the transformation of elementary particles, that constancy in nature rests (and also the relativity of this constancy).

In conclusion we would like to draw attention to the following. The concept of the relativity of the difference between the 'elementary' and the 'complex' or, say, the radical alteration of the classical concept 'to consist of', etc. (discussed above), from being a kind of a regulative idea, has now become an idea of action leading the theory of elementary particles to new advances.[28] This can be seen from the work of Soviet scientists, in which dispersion relations for the photoproduction of mesons were first formulated and demonstrated (in terms of the fundamental principles of quantum field theory). The physical characteristics of the processes of photoproduction of pions were linked with those of the strong interaction of pions and nucleons, and reliable quantitative results were obtained for photoproduction processes in a quite wide energy range.

This work was discussed in an article in *Pravda* by N. Bogolyubov and Bruno Pontecorvo (members of the USSR Academy of Sciences), 'A Major Contribution to Particle Physics'. It is of interest to note that, analysing the present-day development of the physics of elementary particles, they wrote: 'The old naive conceptions about matter's being divisible into parts and the very concept "consists of" thus prove to be inconsistent.'[29]

In summing up this section we would like once more to stress that the concepts of discontinuity and continuity, possibility and actuality, and the infinite and the finite are becoming closely interwoven within the problem of the elementarity and structure of matter in contemporary physics. Physics, which reflects eternally developing nature, has followed the path of materialist dialectics in solving this problem. New perspectives in understanding the structure of matter are also being opened up on this path. Modern quantum field theory is full of difficulties and paradoxes. It was not possible to unite the various types of interaction, and the particles involved in them, on its basis, although physicists have not given up looking for approaches to a solution. Modern physics is also far from linking the world of cosmic dimensions and the atomic and subatomic world up into a single theory. The problems emerging, one must suppose, will necessitate new physical principles and basic concepts, and that will lead to deeper knowledge of the structure of matter. The idea of the inexhaustibility of the electron expressed by Lenin long before discovery of the abundance of the elementary particles and of the laws of the microworld is also stimulating the development of physical theory today.

5

The Elementary Particle of Matter and the Universe

The title of this section cannot now appear as extravagant from the standpoint of exact science as it undoubtedly would have been in the first twenty or thirty years of this century, let alone in past centuries. The problems of the relationship between the fundamental particle and the Universe have now left the unsure philosophical ground that at one time engendered them and have become burning issues in physics and astronomy.

The reasons for this can be found in the development of science itself. The discovery of the electron and of radioactivity created real grounds for the solving of two of the great enigmas pertaining to the problem of matter in its micro- and mega-states, namely, atomic structure and the source of solar (stellar) energy. Discovery of the quantum of action gave rise to non-classical atomism and to a new understanding of the relation, internally connected with it, between the fundamental and the complex, the part and the whole, the element and the system, which was unknown to the old science, and which could not help but embrace the problems of elementary particles and problems of the Universe, so combining them in one way or another.

Major philosophical problems began to emerge in physics (now one can speak rather of the posing of them; they are still very far from being solved) and, as always in such cases, the posing of questions of the history of philosophical thought may prove useful here, in the sense that one might be able to extract pointers to possible solutions from it, though not, of course, in a concrete form.

When we consider the great philosophers of the past who studied problems of the Universe when there was no science as such, we can, as a matter of fact, easily find ideas in them that are in the forefront of the modern science about nature.

An outstanding philosophical predecessor of Giordano Bruno, the dialectician Nicolas of Cusa, with his theory about the coincidence of opposites (*coincidentia oppositorum*) expressed the proposition that the absolute 'minimum' (any, even the most insignificant object) coincided with the 'absolute maximum' (the whole world).[30]

According to Leibniz, the monads that he believed to form the basis of everything were both closed and connected with the whole world, themselves representing, as he put it, 'compressed Universes'.

And for Democritus, the great materialist of Ancient Greece, one of the founders of atomism, atoms figure not only as indivisible microscopic formations but also as whole vast worlds. In their own way they very much resemble Markov's 'friedmons' — the fruit of ultramodern notions about the microworld and the Universe that have grown on the soil of the general theory of relativity (we shall discuss them below).

Let us now consider ideas relating to the theme of this section more systematically. To that end, let us return to Berestetsky's comment about the composition of strongly interacting particles (see Section 4 above).

Let us assume that a strongly interacting particle (a hadron) A turns ('decays') into a combination (becomes a system) of hadrons B and C:

$$A \to B + C,$$

the probability of such a transformation being very close to 1. Then, in accordance with the conservation laws, the sum of the corresponding quantum numbers of hadrons B and C should coincide with the quantum numbers of hadron A; this is a necessary condition of the above transformation of hadrons.

Another condition, of course, is the existence of a mass defect. If the defect of particle A is small, i.e. if it has enough energy for the transformation ('decay' into particles B and C) in fact to take place, it is said that particle A *consists* of particles B and C. Let us assume that particles B and C consist, in turn, of particles with still smaller mass, and that these consist of particles of even smaller mass; then how far can this process of constructing a particle of a given mass out of particles with smaller and smaller masses be continued? An answer is provided by the uncertainty relation; it turns out that there is a limit to the process beyond which the total mass of the particles forming the structure of the initial particle begins to exceed the mass of that particle.

If, on the other hand, the mass defect of the particle A is great, i.e. its energy is not sufficient for the transformation in fact to occur, it is said that particle A is *composed* of particles B and C. What, however, does that statement mean?

In this case B and C appear as virtual particles, and the particle A has virtual structure. A particle of given mass is constructed, as it were, out of particles of larger mass. How is this to be understood?

(1) If the process of combining particles B and C is accompanied, because of energy release, by a decrease in the sum of their masses, that is evidence precisely of the formation of a system $(B + C)$ that differs qualitatively from the simple combination of particles B and C. (2) Although, during the formation of system $(B + C)$ the energy radiated diminishes the sum of the masses of particles B and C according to Einstein's equation of the relation of mass and energy, only strong interactions can lead to a big release of energy and, therefore, to a big mass defect of the system $(B + C)$. In this case particles B and C cannot really exist

in the structure of particle A, and do not; they exist only virtually, in a possibility that becomes actuality in certain new conditions when particle A receives a corresponding amount of additional energy.

Such is the necessary concretisation of the material about the concepts 'consist', 'elementary', 'complex', etc., that were discussed in the preceding sections.

Let us recall from this angle that any elementary particle can be regarded as complex, and a complex fundamental particle as an elementary one: the answer depends on the existence of the appropriate conditions for the transformation of the particles (the relativity of the concepts of elementary, complex, and structure in the world of elementary particles). From the same angle it is held that hypothetical quarks have a mass exceeding that of nucleons. In general, all such assumptions are based on the idea that strong interactions are responsible for the relevant mass defect created in particle systems.

Let us now assume that known elementary particles are 'composed' of quarks, and the latter, of yet heavier particles, etc.; what conclusions would such reasoning lead to? Would we have to recognise the existence of fundamental particles of infinitely large mass?

This problem was studied by M. A. Markov, who demonstrated that there is an upper limit for the masses of fundamental particles; he used the term 'maximon' to denote the heaviest fundamental particles. According to Markov, maximons, which are gigantic particles (on the microworld scale), are combined in smaller particles, a new mechanism beginning to operate in this combination, namely, gravitational collapse, by which astronomic phenomena are already explained.

Gravitational collapse (increase of a system's spatial density through the effect of the gravitational forces between the bodies composing it), which almost instantaneously increases the energy of particle coupling, leads to an enormous mass defect, to a tremendous difference between the sum of the masses of the maximons and the mass of the particle to which they are condensed by gravitational collapse. For the collapse to begin, there has to be a colossal density of matter that does not now exist in the part of the Universe known to us. Such density could have existed when the Universe (according to Friedmann's theory) once began to expand. From the angle of the idea of maximons the beginning of the appearance of the elementary particles now known thus coincides with the beginning of expansion of the Universe, which is still going on.[31]

It was not our intention to go into the details of the maximon hypothesis, especially in view of its presentation here being very sketchy. Let us simply stress that it developed on the basis of the notions and principles of modern physical theories. Problems of this sort, it seems to us, will be solved more accurately on the basis of fundamental physical theories that are more general and profound than contemporary ones, and that do not contain the contradiction between quantum and relativistic physics existing at present. We would like to stress the idea that modern physical theories pose the problem of the unity of the elementary particle and the Universe, of the ultimately simple and the ultimately complex, in a quite concrete way. Research on the relevant plane continues and will do so in the future; new truths will undoubtedly be discovered along this path, which science is still only approaching without yet knowing how close it has come to them.

Markov's quite recent hypothesis of 'friedmons' provides confirmation that this is precisely the way matters stand. Let us consider it briefly.

According to the general theory of relativity, there could be cases when gravitational interaction would lead to a large mass defect, i.e. play the role of strong interaction in the appropriate systems. Because of the large gravitational mass defect, for example, the total mass of a closed Universe is zero; to put it differently, the mass of all the bodies of the Universe is reduced to nothing by the gravitational interaction between them.

If, on the other hand, Friedmann's Universe is considered as not completely closed ('nearly' closed), its total mass, depending on the degree of this 'nearly', can be arbitrarily small, in particular, it can equal to the neutron's mass, and for the external observer its behaviour will not differ from that of an elementary particle like the neutron (although it may contain a whole system of galaxies).

Note the following fundamental property of such universes: if a semi-closed universe emerged with an arbitrarily large electric charge, it would prove to be unstable; it would tend to reduce its total mass (by giving rise to various kinds of pairs of charged particles and decreasing its total electric charge) and so to close as fully as possible. It turns out that the system tends to a certain identical limiting system with a total electric charge of a definite value regardless of the magnitude of the initial electric charge, which can be of any size.

It is assumed that the final value of the limiting system's electric charge may be close to that of an elementary particle. In its final state this system is called a friedmon. Markov points out that friedmon with its amazing properties is not a figment of poetic imagination; the Einstein-Maxwell system of equations contains friedmon solutions.[32]

Contemporary physical theories thus make it possible to interpret the Universe as a micro-particle, while the microparticle may contain the whole Universe. In other words, modern physics unites the opposite properties of the superlarge and ultrasmall worlds.

For all the hypothetical nature of these propositions and arguments, especially if we remember that they take only partially the quantum character of the laws of the microworld into account and regard the laws of the theory of relativity as applicable without limit to very small distances, it is still possible, in the present state of science, to consider it proved that the gulf created by the mind between the Universe and the microworld does not really exist, and that the problems of the Universe and those of the elementary particle are closely linked with one another. Besides, let us note once more that such a unity and connection are not the result of 'foggy' philosophical reasoning but are referred to by such a very rigorous science as physics in the precise language of its concepts.

In conclusion let us discuss a statement of Zelmanov's that is closely related to our theme. According to him, three concepts of the Universe should, apparently, be distinguished in cosmology, and the following expressions used to denote them: 'the Universe in general', 'the Universe as a whole', 'the whole Universe'. The first of these concepts, Zelmanov says, denotes the whole irrespective of its parts, the second the whole in relation to its parts and all the parts in their relation to the whole, and the third, finally, denotes all parts irrespective of the whole. Confusing of these concepts can lead to very serious misunderstanding.[33]

What Zelmanov has written about the relation between the whole and the parts in application to the Universe, it seems to us, can also be applied *mutatis mutandis* to the elementary particle.

In our view one should distinguish between three concepts of the elementary particle, for which we suggest the following labels: 'the elementary particle as an elementary particle' (this resembles Zelmanov's first concept of the Universe); 'the elementary particle as a system' (this resembles the second concept of the Universe); 'the elementary particle as an elementary particle and at the same time as a system' (this is a concept of the elementary particle which means that the existence of each elementary particle leads inevitably to the existence of others — hadrons are implied—and resembles the third concept of the Universe).

There is thus yet another aspect of the unity between the Universe and the elementary particle, which finds expression in their concepts.

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VIII

QUANTUM PHYSICS AND THE TRANSFORMABILITY OF FUNDAMENTAL PARTICLES. THE ABSOLUTE AND THE RELATIVE

1

The Transformability of Elementary Particles

If one takes it that the qualitative diversity and variability of the phenomena of the observable world are not an illusion, then knowledge of observable phenomena implies motion of the substance underlying them. This applies both to continuous substance (the material primary elements of the Ionian philosophers, Aristotle's matter, Descartes' matter, the ether and field of classical physics) and discrete substance (the atoms of the ancients, Newton's hypothetical, absolutely solid particles, Hertz's material points). The diversity and variation of the observable were explained from the standpoint of antique and classical atomism by the combination of moving 'indivisibles' and the dissociation of bodies into primary particles. On the other hand, if bodies consisted of an infinite number of infinitesimal parts, the manifest repetitions and relative constancy of nature would be impossible.

Motion was thus considered an inalienable property of matter even by the atomistics of antiquity, although it interpreted motion, and matter, in a one-sided way that was later expressed very concretely in the mechanistic views of classical physics.

The development of classical physics itself, in spite of its additions and innovations, did not change the essence of the ancient atomists' mechanistic understanding of motion. Newton was an adherent of ancient atomism and, while refining the notion of the particles composing bodies, did not go beyond the framework of the mechanistic idea of motion. The discovery of the law of the conservation of energy and creation of the classical theory of field and statistical physics could, seemingly, have destroyed the notion of invariable particles given once and for all, moving in space, and forming the foundation of the Universe, but the physicists who discovered this law and created the classical theory of field and statistical physics thought differently: the views about matter and motion, which fell within the stream of classical atomism, held by the outstanding physicists of the nineteenth century like Helmholtz, Maxwell, Gibbs, and Boltzmann, who completed the classical period of development of physics, are well known.

At the same time, it must be acknowledged that this situation could not be avoided; there were not yet sufficient experimental data in classical physics to pose the question of the motion occurring at the very foundation of matter in a new way and in a spirit quite different from the mechanistic tradition. Such data were accumulated much later: the theory of relativity and the development of quantum theory prepared the necessary premises, on the basis of experimental data that no one had even dreamed of in the nineteenth century, for a solution of this physical problem gravitating towards the idea of the reciprocal transformability of elementary particles.

Philosophy had already, long before, created a doctrine on the development of matter that accords with the experimental data on the transformability of elementary particles. Progressive philosophical thought, which has always fertilised science with seminal ideas (atomistic views; Descartes' and Lomonosov's ideas on the conservation of matter and motion; Kant's cosmogony), is now giving science an understanding of development in its deepest form, free of one-sidedness, in the form of dialectical materialism.

The two following features of the dialectical understanding of the motion and development of matter must be stressed.

(1) The motion and development of the world's phenomena and processes is a struggle of opposites, the division of unity into the mutually exclusive and at the same time reciprocally connected elements. In his fragment 'On the Question of Dialectics' Lenin defined the splitting of a single

whole and the cognition of its contradictory parts as the essence of dialectics.[1] Each contradictory part of the whole develops into its opposite and the opposites pass into one another; in this way a given contradiction is resolved, giving rise to a new phenomenon, a process with a new inherent contradiction. Without unity of opposites there is no evolving phenomenon or process; without the struggle of opposites there is no development or transformation of a given phenomenon into a new one.

(2) Development, as a unity of opposites, implies that the unity is relative, while the struggle of opposites is absolute.

The dialectical understanding of the development of phenomena is not compatible either with the subjectivism and relativism that turn the world into a chaos of empty changes, or with the metaphysical outlook in general that immortalises constancy and rest in one way or another.

Does the dialectical interpretation of development cover the data on the transformability of the elementary particles that, in the notions of modern physics, form the foundation of the matter known to us? All our subsequent exposition will be devoted to this question.

Let us point out once more that, in accordance with the experimental data of modern physics, reciprocal transformability is an inalienable property of elementary particles. Motion is a mode of existence of matter, motion being not only change of place but also of quality. The experimental data on elementary particles convincingly confirm this very important proposition of dialectical materialism and give it new content.

Elementary particles like, say, photons, can be engendered during quantum transitions in atoms, accelerated motion of charged particles, and the decay of a pion and certain other particles, or during the annihilation of an electron and a positron, or, in general, of a particle and an antiparticle. They can also be absorbed and 'disappear' in interactions with molecules, atoms, and atomic nuclei; they can be scattered by other particles, and can form so-called electron-positron pairs. Photons themselves exist only in motion with the velocity of light; their 'stopping' means either their absorption or transformation.

All other kinds of elementary particles are also capable of being transformed, and are actually transformed into one another in the appropriate conditions; this has been proved in experiment, but we shall not go into the relevant data.[2] Let us just note two moments relating to the discovery of the law of the universal transformation of elementary particles. (1) This law was partially expressed, in essence, in Dirac's theory that synthesised quantum and relativistic ideas in regard to the electron. (2) The beginning of its experimental proof was the discovery of the positron (1932), and its completion the discovery of the antiproton (1955). Discovery of the positron led to discovery of the transformation of the electron-positron pair into photons and vice versa. With discovery of the antiproton (and later of the antineutron) the proposition, which was to some extent justified and had a touch of classical atomism in it, that existing heavy particles (the proton, etc.) always remained heavy particles and could not be transformed into lighter ones (and conversely, that light particles always remained light ones) collapsed.

Reciprocal transformability is inherent in all known elementary particles, the transformations of which are governed by certain conservation laws. The view has been expressed that these laws limit the possibilities of the transformations of elementary particles. This assertion in fact states that these transformations are not a chaos of arbitrary changes but are regular ones governed by law.

The conservation laws ensure transformations of elementary particles in accordance with their general and specific nature. We are obliged to conclude that the transformations of elementary particles and the conservation in them of certain quantities are two aspects of one and the same phenomenon. The conservation laws (some of which were discovered long before modern physics) reveal what is constant and preserved during transformations of studied objects. If a certain quantity in a physical process remains constant according to such-and-such conservation law, the process itself and the conserved quantity are regarded as something united. Before going more closely into the relationship of conservation and transformability in elementary-particle physics, let us consider this question from the historical aspect.

The understanding of the variation of bodies according to which the basis of this variation is the combination and dissociation of fundamental, discrete particles, assumes conservation of the number of these particles (only their configuration and relation to one another changes). In correspondence with this understanding, the conservation of matter in its transformations was interpreted ultimately as conservation of the number of these particles, in other words, the development of uncreated, indestructible matter was reduced to the motion (behaviour) of the initial discrete particles.

This mechanistic interpretation of the development of matter, which prevailed in classical physics, could not in fact be finally exploded by quantum mechanics: it could be assumed that fundamental particles (the kind and number of which do not vary according to the notions of quantum mechanics) moved according to this theory's laws. The subsequent development of quantum physics (quantum field theory; the theory of elementary particles) finally buried the idea of the 'bricks of matter'; a profound understanding of the development of matter at its very foundations became established in physics, an understanding that is inseparable, on the philosophical plane, from the conception of dialectical materialism.

The mechanistic understanding of the development of matter led to a mechanistic interpretation of such a fundamental conservation law as the law of the conservation of energy. Helmholtz, who shares credit for the discovery of this law with Mayer and Joule, considered the law of the conservation and transformation of energy in the spirit of mechanism, in particular as proof of the reducibility of all physical processes to mechanical motion. Engels criticised this mechanistic interpretation, pointing to the transformability of the forms of motion as the essence of Mayer's, Joule's, and Helmholtz's discovery, linking the law of the conservation of energy and the law of the conservation of matter together in one law.[3] These ideas of Engels' have found fruitful application in modern physics.

The conservation laws that figured in classical physics have been enriched in content and have acquired certain new aspects in contemporary physics, especially in connection with discovery of the reciprocal transformability of elementary particles; conservation laws unknown to classical physics have been discovered. The new element introduced into the interpretation of these laws by modern physics consists in constancy and conservation being regarded in intimate connection with the development of matter, while this development is understood as the transformation of the various forms of matter into one another (contemporary physics provides no grounds for the idea of reducing physical changes to the motion of certain eternal constant elements).

In modern physics the conservation law asserts that a certain physical quantity remains constant during a physical process. It is important to mention here that immutability and variation are regarded by the conservation law as something united, internally connected with each other; from this angle unchanged quantities remain even during the transformations of fundamental particles (there was no concept of 'particle transformation', of course, in classical physics), and are used to describe the world of elementary particles.

This feature of the conservation laws is also reflected in their very content compared with the understanding of them in classical physics. From the standpoint of the latter fundamental laws determine what *should* or what *will necessarily* happen to matter; they order the particles that form the basis of the Universe, as it were, to behave in a certain way and not in some other one (the abstract imperative of the Laplacian superintellect dominates the scene).

The situation is quite different from the angle of modern physical conceptions. The conservation laws limit the possibilities of the transformations of elementary particles; they define which events may and may not occur, and the probabilities of the possible events in the world of fundamental particles. Necessity remains operative in them, but it figures in them not in abstract form but as an actual necessity leading to multiple-valued results and associated with the probabilities of possible events and the conditions of the possibilities being realised.

In present-day views, elementary particle interactions are governed by the following conservation laws, which can be divided into two groups: (a) *exact* or *rigorous* or *strict* conservation laws, which include the laws of the conservation of energy and momentum, and of angular momentum, the laws of conservation of electric, baryon and lepton charges (these laws are valid for all interactions of elementary particles, strong, electromagnetic, and weak, and are not violated in any of them, which is why they are called rigorous), and (b) *conditional* or approximate laws which include the laws of conservation of strangeness and parity, the law of conservation of isospin, temporal parity, charge parity, combined parity.

The development of modern physics indicates that the conservation laws are not absolute in character. Each of them, as is becoming more and more clear, turns out to be valid, not in general, but in certain conditions, determination of the boundaries of which means the cognition of a new stage in the development of matter with the laws inherent to that stage. The conservation laws consequently change as regards their content and form, becoming deeper and more concrete; the class to which they belong also changes.

Thus, the law of conservation of baryon charge was modified until it took on its present form. This law, which speaks of the impossibility of transformation of the nucleons within an atomic nucleus into leptons and photons, had the following form before the relevant discoveries: in particle transformations the number of protons remains constant before and after interaction; in symbolic form: $N_p = \text{const}$.

After the discovery of the neutron, antiparticles, and hyperons (and, correspondingly, of their decay reactions) the law of conservation of baryon charge is now written as follows:

$$N_p + N_n + N_\Lambda + N_\Sigma + N_\Xi - (N_{\tilde{p}} + N_{\tilde{n}} + N_{\tilde{\Lambda}} + N_{\tilde{\Sigma}} + N_{\tilde{\Xi}}) = \\ = \text{const},$$

where N denotes the number of particles, and the subscripts p, n, Λ, etc. denote the proton, neutron, various hyperons and, correspondingly, their antiparticles.

Let us consider another example. The law of the conservation of energy and the law of the conservation of momentum, which existed separately, so to say, in classical physics, were unified in the theory of relativity and enriched in content in the process by acquiring new aspects; they were converted into a broader law than the classical ones. The concepts of energy and momentum were altered correspondingly: they relinquished their 'classical' independence and formed two, internally connected aspects of one and the same essence (expressed mathematically by the concept of a four-dimensional energy-momentum vector). The concept of rest mass, unknown in classical physics (which is important in the theory of elementary particles), emerged; mass and energy accordingly proved to be intimately connected with each other, which led to important theoretical and practical conclusions.

The law of conservation of parity is of special interest from the angle of these ideas. The quantum concept of parity is inextricably linked with the principle of mirror symmetry, which we shall dwell on later. Before the experiments suggested by Lee and Yang, the law of the conservation of parity was regarded as a strict one. Its violation in weak interactions gave rise to serious difficulties. The ways they were resolved led to Landau's hypothesis and a new law, thought strict at the time, which was called the law of the conservation of combined parity.

Anticipating a little, let us make the following assumption: every conservation law at present known as strict can (and in certain circumstances does) turn into an approximate one, but that serves as a prerequisite and reason for the discovery of a new, broader and more concrete strict law, i.e. the difference between the concepts of strict and approximate conservation laws is relative, and these laws are connected by transitions. It cannot be otherwise, since the individual laws discovered by man are various manifestations of the universal law of the conservation of matter and motion.

The conservation laws governing the transformations of elementary particles express the uncreatability and indestructibility (conservation) of eternally evolving matter at its deepest level at present known. The uncreatability and indestructibility of evolving matter is a necessary condition of its objectivity and reality; therefore, the conservation laws discovered and discoverable by science again and again confirm the objective reality of the developing world, and science, in turn, in discovering conservation laws, is based on acceptance of its objective reality, i.e. on acceptance of an external world that exists and develops independently of human consciousness.

Modern physics has not simply connected the ideas of conservation and transformation in regard to the fundamental particles of matter. Its concepts and statements relating to the transformations and interactions of particles clarify the basis of this unity and bring out the reciprocally determining connection between the conservation laws and the so-called symmetry principles. Many types of symmetry were discovered by classical physics (some were known even earlier); they did not, however, play an important role in the understanding of physical phenomena and their laws. In modern physics not only have new types of symmetry not known before been discovered, but, and this is the main point, the close connection between the symmetry principles and conservation laws, and their important role in physical theory, have been clarified. If we approach the symmetry principles of modern physics (and the theory of elementary particles) from the philosophical aspect, the deep truth of Lenin's words becomes clearly apparent: 'Dialectics in the proper sense is the study of contradiction *in the very essence of objects*: not only are appearances transitory, mobile, fluid, demarcated only by conventional boundaries, but the *essence* of things is so as well.'[4]

The symmetries in the theory of elementary particles are precisely 'contradictions in the very essence of objects' 'translated' into the language of modern physics. We shall now take this point up, leaving aside, however, important aspects of the problematics of the symmetry of the laws of physics (in particular, the so-called dynamic or non-geometric symmetries; when physicists, as Wigner put it, 'deal with the dynamic principles of invariance [they] are largely on *terra incognita*')[5].

As we noted above, there is an internal connection between the conservation laws and symmetry principles. A certain symmetry leads to a certain conservation law corresponding to it; such-and-such a conservation law entails a corresponding symmetry, although the link connecting the symmetry and the conservation law is not always simple, and much experimental and theoretical work is required in order to determine the connection between them. The internal relation between the two makes it possible to get a better understanding of the content of the conservation laws and at the same time to determine the great heuristic role of symmetry principles in cognising the laws of nature. Let us consider the philosophical points appertaining to this theme.

The properties of symmetry in nature are expressed mathematically by transformations of the space and time coordinates. The equations that express the laws of nature have to be invariant with respect to the corresponding transformations. The invariance of equations expressing the laws of nature or, in short, the invariance of the laws of nature in respect of transformations of one kind or another, also leads to a conservation law of one kind or another.

The symmetries and connections between them known to modern physics do not exhaust the wealth of symmetries and connections existing in nature. Let us consider certain most important symmetries.

Symmetries of classical physics. In classical mechanics there are transformations of translation, shift of time scale, rotation, spatial inversion, temporal inversion, and Galileo's transformations.

Transformations reflect symmetries; transformations of spatial inversion, for example, reflect right-left or mirror symmetry; Galileo's transformations reflect the symmetry of rest and uniform motion in a straight line, and so on. Symmetries lead to conservation laws (the conserved quantities are invariants of the corresponding transformations); invariance of the physical laws with respect to spatial translation, for example, leads to the law of the conservation of momentum, while invariance of the physical laws with respect to shift of the time scale leads to the law of the conservation of energy. In classical physics not all symmetries entail corresponding conservation laws. Thus, the principle of right-left symmetry in classical physics does not lead to a conservation law, but a law corresponding to this symmetry arises in quantum theory: namely, the law of the conservation of parity.

Symmetries of the theory of relativity. This theory does not simply take over the symmetry principles of classical physics; it introduces new symmetries, or new invariances, corresponding to regularities that cannot manifest themselves within the limits of applicability of classical theories. In that connection the classical principles of symmetry are altered at the appropriate points in the theory of relativity. Thus, the Lorentz transformations reflect not just the symmetry between rest and uniform motion in a straight line (like Galileo's transformations in classical mechanics), but also, at the same time, a symmetry between space and time that is alien to classical physics. In the theory of relativity physical laws are invariant in respect to transformations of the rotation of the four-dimensional space-time continuum (these transformations can be broken down into transformations of spatial rotation and Lorentz transformations).

Symmetries of quantum theory. This theory introduces new symmetries corresponding to the microworld regularities discovered by it, about which pre-quantum physics could not have an adequate notion. They are the symmetries of particle and wave, charge symmetry, or the symmetry of particles and antiparticles, and invariance with respect to isotopic spin. The laws of conservation of nuclear and lepton charges, and of strangeness, are manifestations of deep symmetries. Quantum theory also subjected the symmetry principles of pre-quantum physics to profound reconsideration; the new conceptions of right-left symmetry can serve as a striking example of this.

The discovery of quantum symmetries meant that physics had begun to study the contradictions in the very foundation of matter. In modern physical theory symmetries have acquired great heuristic significance and play a particularly important role in its development. Suffice it to recall that discovery of the symmetry between particle and wave determined, if one can express it so, the main axis of quantum ideas: the laws of quantum mechanics are, of course, invariant with respect to the symmetry between particle and wave, i.e. quantum mechanics reflects this symmetry.

Of vital interest, however, is approach to the symmetry problem that is becoming more and more defined in modern physics and which, as it seems to us, acquires the total clarity from the philosophical aspect in the light of the dialectical principle of contradiction. In this respect discovery of the breach of the conservation of parity and the interpretation of this violation provide the necessary point of support.

We shall not go into the physical details associated with the quantum concept of parity. This concept characterises how the wave function describing the state of a micro-particle will change with mirror reflection of the spatial coordinates (coordinates x, y, z being replaced by $-x$, $-y$, and $-z$). The concept of parity makes it possible to express mirror symmetry, or the symmetry between left and right, mathematically, in the form of a conservation law. The fruitfulness of the concept of parity became clear during the development of quantum mechanics, and it was demonstrated that conservation of parity was a consequence of the Schrödinger equation being invariant relative to inversion of left and right. For each state of an atomic system it is possible to determine its 'mirror state', which is connected with the first one in the same way as any object is connected with its reflection in a mirror.

The law of conservation of parity or, correspondingly, the principle of mirror symmetry, operated, it was once thought, in all regions of the macro- and microworlds. The experimental data on weak interactions, however, posed new problems of the principle of mirror symmetry. As Lee and Yang showed, it followed unambiguously from experiments with K-mesons that the law of conservation of parity did not hold for weak interactions, i.e. instead of symmetry, there was asymmetry between right and left in weak interactions.

A situation thus developed in which the law of conservation of parity was valid for strong and electromagnetic interactions but ceased to hold for weak interactions. In other words, one had to assume that space was homogeneous and isotropic and at the same time asymmetric with respect to left and right. It did not hold together.

Among the possible solutions for the difficulties, the greatest philosophical interest attaches to the idea put forward at one time by Landau and independently of him by Lee and Yang.

In order to consider this idea and the consequences flowing from it that are essential for the problem of symmetry in nature, we must discuss the matter of the symmetry between particles and antiparticles.

It used to be assumed that there was a substantial asymmetry between positive and negative electricity, which did not manifest itself in electromagnetic phenomena but the basis for which lay in deep laws not yet discovered, pertaining to elementary particles. The first decisive blow to this assumption was struck by the discovery of the positron, which was the direct opposite of the negative electron; now (since the appropriate theoretical research and discovery of the antiproton and other antiparticles) the principle of the symmetry between particles and antiparticles, or the principle of invariance with respect to charge conjugation, has become a leading proposition of the theory of elementary particles.

It became clear, however, that the situation with the principle of charge symmetry was far from simple and was to some extent similar to that with the principle of mirror symmetry. Beta-decay experiments indicated that, in weak interactions, not only was the law of conservation of parity violated, but also invariance with respect to charge conjugation, i.e. the principle of symmetry between particles and antiparticles. It could appear that it was necessary to return to the initial idea of the asymmetry of positive and negative electricity, appropriately modified.

Reality, however, proved to be 'smarter'. Landau's idea gave a possibility of a better understanding of symmetry in nature than that existing before it.

In strong and electromagnetic interactions, as experiment witnesses, the principle of the symmetry between particles and antiparticles and that of symmetry of right and left operate independently of each other, i.e. both charge and parity are conserved. As for weak interactions, Landau assumed that for them the conservation laws did not hold when taken separately, but that a law, called the law of conservation of combined parity, did. This law is as follows: an antiparticle with mirror-symmetrical spatial properties is associated with every particle; the transformation of charge conjugation and of spatial inversion were accordingly unified by Landau in a new transformation that he called combined inversion; physical laws were invariant with respect to combined inversion, i.e. with respect to charge and mirror symmetry simultaneously. Landau's idea thus excluded mirror asymmetry of space and charge asymmetry of matter; at the same time it did not allow the principles of mirror and charge symmetry to be converted into certain absolutes.

Landau's approach thus, in essence, posed the question of the symmetry and invariance of the laws of nature in a quite new way. Those symmetries that had seemed exact, in fact proved to be approximate and relative; at the same time a new exact symmetry was discovered which turned out to represent a novel unity of the old symmetries that had become approximate. One is led to think that the difference between exact and approximate symmetries or, correspondingly, between exact and approximate conservation laws is due to our reflection and is not absolute; approximate and exact symmetries are inseparable, like relative and absolute in dialectics.

From this angle the concept of symmetry in physics is, so to say, fluid. The different symmetries cease to lead a separate existence; they are bound together by transitions, more and more deeply and completely covering the phenomena and processes of nature, and their essence and laws. The discovery of combined inversion is an important step towards establishing a universal, concrete connection between symmetries in nature. When physics resolves this problem more completely, it will be possible to determine, in particular, why some symmetries have a broader character than others, why such-and-such symmetries exist precisely in certain interactions and not in others, in short, it will provide a chance of identifying the kinds of symmetry more clearly and will lead, in general, to solution of the problem of the relations between, and hierarchy of, symmetries. We shall consider certain details of the problem posed here in the next section.

On the plane of what has been said, the following point is of philosophical interest: is it possible to arrive at a really unified picture of moving matter that would reflect both the microworld and the vast regions of the Universe?

Dialectical materialism gives a positive answer to this question. The world is single, and its actual unity consists in its materiality; the world, i.e. moving matter, is cognisable. From these propositions of dialectical materialism there follows the possibility of a picture of the world that reflects ever-evolving matter, and this picture must include knowledge, when such is obtained, of the subatomic and atomic worlds, the macroworld, and the world of cosmic scale, because these worlds are ultimately one and the same world of evolving matter, in spite of their qualitative differences.

As for inorganic nature, physics has, at one stage or another of its historical development, put forward a fundamental physical theory that was the most mature one for its time and should, it seemed, lead to a unified picture of the then known world. The achievements of classical mechanics, for example, made it possible for the mechanistic picture of the world to emerge in the old physics, in accordance with which the phenomena in nature were reduced to the motions of eternally given particles of matter governed by Newton's laws. The attempt to understand the world on the basis of classical mechanics proved (as was demonstrated by the theory of relativity and quantum theory) to be a relative truth valid only within certain limits.

For the same reasons the attempt to construct a unified picture of matter in motion on the basis of classical electromagnetic theory also failed. In our day we face the task of building a single theory of moving matter in terms of the theory of relativity and quantum theory. Let us note the following philosophical aspect of this task, which applies to any scientific picture of the world.

A scientific picture of the world is impossible that remains unshakeable not only in its details but also in its main features and does not change with the progress of science. The modern physicist accepts this idea in one way or another; for the dialectical materialist it was clear from the very beginning. We would remind the reader of an idea that has been referred to more than once in our book on the appropriate plane. At the turn of the century, when the electromagnetic picture of the world was established in physics, Lenin wrote, disagreeing with the spiritualist-philosopher James Ward, who ascribed a 'mechanistic' picture of the world to materialism: 'It is, of course, sheer nonsense to say that materialism ever maintained ... a "mechanical", and not an electromagnetic, or some other, immeasurably more complex, picture of the world of *moving matter.*'[6]

It is this immeasurably more complex picture of the world compared with the mechanistic or electromagnetic picture that is being created in contemporary physics, which could be called a relativistic quantum picture since it is built on the basis of the achievements of both relativistic and quantum physics.

It is now only being built and is very far from that harmonious whole, from that single, consistently developed picture that the mechanistic picture once was. This is due mainly to there still being no unified relativistic quantum theory of elementary particles free of internal contradictions, but several theories relating to individual types of particle and their interactions (e.g. quantum electrodynamics deals, in spite of the difficulties in it, with questions of the interactions of electrons and positrons with photons; the meson theory, which is not related to quantum electrodynamics, studies the meson-nucleon interaction). Analysis of the difficulties and contradictions of the modern theory of elementary particles would lead us away from our theme. Let us simply stress that the creation of a unified relativistic quantum theory of elementary particles and an associated scientific picture of the world has great progressive significance, because it would mean a new step forward in understanding the material world.

Among the attempts to create a picture of the world as moving matter in terms of quantum physics, the programme for a unified theory of matter (it is a matter mainly of a programme, since there is as yet no theory that is in any sense complete) suggested by Heisenberg, taking some account of the related work of Dirac, de Broglie, and others, is of great philosophical interest.

The great plus of this programme compared with the mechanistic and electromagnetic pictures of the world that now belong to the historical past is that it is based on the idea of the reciprocal transformability of all elementary particles rather than on certain constant elements or invariable substance. Since, from this point of view, which rests on experimental material, elementary particles represent a single whole that is internally connected, the foundation of all physical phenomena should contain 'primordial matter', so to say, a single field whose quanta are elementary particles of all kinds. This field is characterised by the operator spinor wave function, and the elementary particles correspond to combinations of the latter's base components. It is non-linear, i.e. its equation reflects the fact that this fundamental field interacts, engendering elementary particles, not with other fields but with itself.

Heisenberg's non-linear fundamental field is thus a kind of illustration of Engels' philosophical remark: 'Spinoza: *substance is causa sui* strikingly expresses the reciprocal action'.[7]

According to Heisenberg, the equation that describes motion (interaction) of 'primordial matter' should be invariant with respect to all known transformations with which the theory of elementary particles deals. Having found this equation, Heisenberg obtained information from it about the masses of elementary particles and the elementary electric charge that agreed more or less with their experimental values, and other data about elementary particles.

In spite of the definite positive results of the theory, mainly qualitative, the attitude of theoretical physicists to it 'fluctuates extraordinarily', as Tamm put it. Its mathematical basis is recognised as far from satisfactory. In addition the indefinite metric introduced by Heisenberg, and the 'negative probabilities' associated with it (they were to help the modern theory of elementary particles get rid of the divergencies, i.e. of infinite values for the mass, charge, and other constants of elementary particles figuring in the theory, instead of the finite values known from experiment), still leave certain essential matters appertaining to this problem obscure, as Tamm has shown. Finally, Bohr's well-known statement that Heisenberg's theory is not 'crazy enough' for a new theory throws into relief the fact that the theory is vulnerable as regards its methodology. In this case Bohr stressed the fact that the ideas of Heisenberg's theory, like his 'negative probabilities', are not yet 'bizarre' enough to build a really new theory with.

Heisenberg himself affirmed that the equation he obtained possibly adequately described the law of nature relating to matter. But there was no answer to this question as yet, he continued; it would only be obtained in the future on the basis of more accurate mathematical analysis of the equation and its comparison with the experimental data being accumulated in ever growing quantities.[8]

In our view it is necessary, in creating a unified theory of matter, (1) to take account *inter alia* of the possibility of a radical revision of ideas about symmetry and invariance in the spirit of the views considered above, and (2) to be guided not only by the methodological principle of explaining the whole by means of its parts, but also by the principle, dialectically connected with it, of explaining the parts by the whole. It is necessary, in particular, to consider the existence of gravitational fields, without which it is hardly possible to construct a really unified theory of matter in the proper sense of the term.

It must be assumed that such a theory would provide a positive solution of the problem of revising space and time ideas in relation to the scale of elementary particles. The need for such a revision follows not only from general considerations but also from special ones that it would be out of place to discuss here. There is the problem of quantising space and time, i.e. the question of their possibly being discrete. Democritus, for instance, ascribed an atomistic structure equally to space and time as to motion: there existed tiny bits of space and time that were sensibly imperceptible, and also discrete units of motion that could only be comprehended by scientific thought. These ideas of Democritus' are little known to scientists.

The conception of abstract, pure discreteness of space, time, and motion, and also the abstract, atomistic interpretation of matter do not accord with the facts; its one-sidedness was overcome during the history of philosophy and science. The dialectical materialist point of view on the problem of the discontinuity and continuity of space and time is briefly expressed in Lenin's following words: 'Motion is the essence of space and time. Two fundamental concepts express this essence: (infinite) continuity (*Kontinuität*) and "punctuality" (= denial of continuity, *discontinuity*). Motion is the unity of continuity (of time and space) and discontinuity (of time and space). Motion is a contradiction, a unity of contradictions.'[9]

From the philosophical aspect, the various approaches to resolving the problem of quantising space and time cannot avoid dealing in one way or another with this statement of Lenin's. Thus Heisenberg postulates a third universal constant (in addition to those already known, i.e. Planck's constant and the velocity of light)— 'fundamental length' of an order of magnitude of 10^{-13} centimetre (the same order of magnitude as that of the radius of the lightest atomic nucleus), below which present-day quantum field theory is inapplicable, i.e. he postulates a length below which distances are meaningless. He introduced this third universal constant from considerations of dimensionality in an endeavour to overcome difficulties with divergencies.

It is hardly possible to solve the problem of fundamental length in a purely atomistic, formal way. In order to solve this problem, it is necessary, it seems to us, to unite the general theory of relativity and the quantum theory of field, because the problem of quantising (real) space and time cannot be solved outside and independently of that of the discontinuity-continuity of moving matter.

2

On the Absolute and the Relative in Modern Physics

In modern physics the concept of the absolute, which was brought down from the Olympus of the speculative constructions of traditional philosophy, 'works' effectively. This concept, one of the 'loftiest' ones in the old philosophy, turned out in fact to be quite 'earthly' in its content. True, in order to become 'earthly', it had to undergo thorough transformations and to become linked with its antipode, the concept of the relative; the old philosophical notion of symmetry then appeared once more on the scene of physics, To put it briefly, the ideas of the absolute and the relative (moreover, exactly in their materialist and dialectical interpretation) have full force in non-classical physics and play a tremendous heuristic role in it. The theory of relativity and quantum mechanics, and also the modern theory of elementary particles, are inconceivable without the concepts of absolute and relative.

What then are the absolute and the relative? We will not recall the numerous definitions of these concepts in the philosophical literature, since most of them are not employed in science at all. By 'absolute' is meant that which exists (or makes sense—in this case one has in mind a concept, and not the objectively real) through or in itself. By 'relative' is meant that which exists (or makes sense) through or in relation to an other. Dialectics assumes a profound connection between the two; in that regard Lenin's idea is very important: 'In life, in movement, each thing and everything *is usually* both "in itself" and "for others" in relation to an Other, being transformed from one state to the other.'[10]

In modern physics the concept of the invariant has the meaning of the absolute (with no metaphysical overtones). It arose in mathematics and found embodiment in physics above all through the work of Einstein. It was not fortuitous that some authors suggested interpreting the theory of relativity as 'the theory of the absolute world'. What, then, should we understand by invariance?

By 'invariance' is meant the property of immutability in respect of a certain class of changes of physical conditions. If, for instance, a working mechanism is loaded onto a train moving at constant speed along a straight line, the processes in the mechanism will go on in just the same way as if it were standing in one spot, i.e. all the laws of mechanics will remain the same (the invariance of mechanical laws with respect to motion at a constant velocity along the straight line).

Here is another example. If an instrument works in a certain place and is then transferred to another, similar place (from Kiev to Moscow, say), then (if the instrument is not altered during the transfer) it will work in exactly the same way at the other place, according to the same laws (invariance of the laws of physics with respect to spatial translations).

The mathematical sense of invariance is immutability or constancy with respect to a group of transformations. Various quantities and equations expressing the laws of nature can have this property. Moreover, in classical mechanics, in the theory of relativity, in quantum mechanics, in any logically closed physical theory in general—and this is very important—there are invariants and relative transformations proper to them. Lengths and durations, for example, are invariant in classical mechanics but are relative in the theory of relativity, and only their special combination in the form of an interval (the most important concept of the theory of relativity) is an invariant of this theory.

It will be clear from what we have said about invariance that invariant formations are independent of the so-called frames of reference in which the physical conditions are realised (in which the physical phenomena occur).

There are inertial reference frames in classical mechanics, i.e. ones in which the law of inertia holds (they are connected through Galileo's transformation.)

In the theory of relativity the frames of reference are systems in which the law of inertia holds, and the velocity of light (in a vacuum) is independent of the velocity of its source (they are connected by the Lorentz transformation).

In quantum mechanics the frames of reference are the means of observation (instruments). One can say that the laws of one physical theory or another are invariant with respect to transition from a frame of reference appropriate to a given theory to another one.

An invariant formation is therefore a certain independent formation in the context of a given theory whose interpretation does not necessitate the existence of other formations. Minkowski stressed this brilliantly in his own way when he said: 'From now on space for itself and time for itself must sink into the shadows and only a kind of union of the two will prove independent.'[11]

In an analysis of the absolute and relative in physics it cannot be ignored that the class of reference frames includes elements that appear opposite in respect to one another. When the transition is made in classical mechanics, for instance, from one inertial reference frame to another moving at a constant velocity with respect to the first, these two inertial frames are thereby treated as opposites. The same can also be shown *mutatis mutandis* for other classes of reference frame. In quantum mechanics, for instance, when a state is expressed in representations of position and momentum, the existence of mutually exclusive types of means of observation (which fix the state) is thus recognised.

The crux of the matter here is that rest and the uniform motion in a straight line are not isolated opposites but are one and the same in certain conditions (in an inertial reference frame, and in a frame of reference moving without acceleration in respect to it, all mechanical phenomena are governed by the same laws, although the kinematic aspects of the reference frames are different). In quantum mechanics, similarly, the opposite particle and wave properties of matter are regarded as inseparable, which is expressed in Bohr's complementarity principle. The position with regard to frames of reference is more complex in Einstein's gravitational theory according to which gravitating matter is inseparable from the space-time continuum (we shall not dwell on this point).

The principle of invariance means in essence that the laws of nature (physical laws in particular) remain constant with respect to certain variations of physical conditions. Depending on the features of the class of variations a whole set of the principles of invariance arises (some of which have been discussed above): namely, uniform motion in a straight line (the Lorentz transformation),* displacement in space, displacement in time, rotation by a fixed angle, reflection of space (mirror invariance), time reversion (T-invariance), and replacement of a particle by its antiparticle (charge invariance). The concepts listed signify that invariance of the laws of nature is understood as their symmetry.

The idea of invariance has a very concrete significance in the development of modern physics. This development occurs through the passing of certain theories into others that are more general (and profound) and differ qualitatively from them. This kind of generalisation of a theory is necessarily associated with loss of certain concepts (that figure in the initial theory) and the formation of new ones (without which the new theory is not a theory).

Let us now draw certain epistemological conclusions about the idea of invariance. The concepts of classical mechanics

* In the example of the working mechanism cited above it was a matter of the laws of mechanics. In it the appropriate transformation was Galileo's, which is a limiting case of the Lorentz transformation,

(and the discipline on the whole) are in essence, of course, approximate. This was demonstrated concretely and in various ways by the theory of relativity and quantum mechanics when they determined the limits of applicability both of classical mechanics itself and of its concepts. The uncertainty principle, for instance, established the limits of applicability of the classical concept of particle (absolute in a certain sense). In this case, with the limit of applicability of the classical concept of particle determined, it was taken into consideration that, say, electrons and protons have wave properties in addition to corpuscular ones. In other words, establishing of the limits of applicability of the classical concept of particle meant deeper study of the particles of matter than was possible in terms of classical mechanics.

Bearing in mind a number of modern physical theories of the increasing degrees of generality (classical mechanics—quantum mechanics—quantum electrodynamics—the quantum theory of field—the theory of elementary particles) we can say in general that the relativisation of old absolute (invariant) concepts during the generalisation of a theory means an ever-deepening cognition of objective reality in which the one-sidedness of the individual physical theories disappears (and the subjective constructions associated with it), and the theories themselves, while retaining their content corresponding to objective reality, acquire a more integrated character.

We must not, when analysing the concept of invariance, ignore that domain of physical laws and phenomena in relation to which the principle of invariance (or group of principles) is valid. Defining of this domain, i.e. defining the limits of the applicability (initially in experiment) of a fundamental physical theory, is an essential moment in the development of physical knowledge; it allows knowledge of nature to rise to a higher level of abstraction and to comprehend the object of study more deeply. Einstein's gravitational theory (or the general theory of relativity), for example, having identified the limits of applicability of the special theory of relativity, overcame them by advancing new principles and basic concepts, and making the special theory of relativity its limiting case.

The principle of relativity and the principle of the constancy of the velocity of light of the special theory of relativity do not hold beyond the limits of its applicability (i.e. invariance with respect to the Lorentz transformations is violated), but that does not mean at all a return to pre-relativistic ideas about absolute nature of simultaneity, space, and time as isolated entities.

This dialectical law of negation not only operates when it is relatively easy to compare the old and new theories that have already developed, as with Einstein's theories, but also operates when new facts that supposedly should completely eliminate invariances already known to physics are being discovered or just beginning to be interpreted. This 'negation' is not stark negation but an element of the profound development of a theory, and modern physics disposes of very rich material in this connection. Let us consider, for example, the principle of mirror invariance already discussed in the previous section. This principle, called for short the principle of P-invariance, can be formulated as follows: the laws of nature are invariant when 'right' is replaced by 'left' and vice versa. It appeared to be an absolute principle, but in 1956 it was discovered that it was violated in weak interactions of elementary particles. A paradoxical situation developed: it turned out that there might have to be internal anisotropy of space.

Things, however, proved different. In order to demonstrate this, let us note that the situation with the principle of mirror invariance was rather like the principle of invariance with respect to charge conjugation or, in brief, to the C-invariance according to which the laws of nature are invariant with respect to particle-antiparticle transition; it was found that the latter principle did not hold for weak interactions, and this also gave rise to certain difficulties. The way out of this impasse was indicated by Landau. According to his idea (although the principles of mirror symmetry and charge conjugation taken separately did not apply in weak interactions) physical laws were invariant with respect to combined inversion, i.e. a transformation that united transformation of charge conjugation and that of mirror reflection (so-called CP-invariance). The principle of combined inversion excludes mirror asymmetry of space, and at the same time does not allow the principles of mirror invariance and charge conjugation to be turned into metaphysical absolutes.

We have the right to ask: are the principles of invariance a kind of metaphysical absolute or is the situation different? The material already discussed makes it possible to answer it to some extent, and now, since experiments that demonstrated that invariance with respect to combined inversion is violated in nature, the answer becomes quite definite.

The invariance principles do not have the absolute character of final, unquestionable truth in the metaphysical sense. They are absolute only within certain limits which are expanded or narrowed as physics develops. In other words, the laws of nature are invariant not in a strict, absolute sense but in an approximate, relative way. To restrict ourselves to C-, P-, and T-invariances and their combinations in the theory of elementary particles, we can say today that only CPT-invariance out of all invariances appears not to be violated. The violation of CP-invariance leads to rejection of invariance relative to time reversion, which is regarded as a cornerstone of physics. If we disregard the violation of T-invariance, then the paradoxical conclusion can be drawn from violation of C-, P-, and CP-invariances that the laws of nature prefer either 'left' or 'right'. There are other possibilities, also paradoxical. A final answer can only be given by experiment, of course, and that is reflected in the deepening and possible fundamental restructuring of existing theories.

As for CPT-invariance, which (as we noted above) remains the sole one today that is not, in principle, violated, this is evidence only of the truth of the general foundations of quantum electrodynamics and the (special) theory of relativity. Naturally, when a logically closed theory of elementary particles is created and the future synthesis made of Einstein's gravitational theory and quantum physics, new and even more spectacular 'surprises' may emerge.

Modern physical theories, by reflecting in their development nature ever more fully and deeply, are thus enriching our picture of the material world. One can find a varied expression in modern physics of Lenin's dialectical idea that there is an internal connection between the absolute and the relative, that the absolute exists in the relative, and that the difference between the two is relative.[12]

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IX

PHILOSOPHICAL ASPECTS OF THE THEORY OF MENSURATION

1

Preliminary Remarks

It has long been known that a natural science is converted into an exact study of nature through measurement. Progress is also impossible in applied science without measurement. The idea of the leading role of measurement in physics has been established in scientific thought since the days of Galileo. The whole history of natural science and philosophy witnesses to the mounting significance of mensuration in the development of human culture and scientific understanding. The thinkers of antiquity, and Leonardo da Vinci, Descartes, Newton, Leibniz, Lomonosov, Kant, Hegel, Gauss, Helmholtz, Mendeleev, Einstein, and Bohr made a profound analysis of fundamental aspects of the problems arising, developing the theory of mensuration and its logical foundation. Light was thrown on the methodological and epistemological foundations of this theory from the standpoint of dialectical materialism in the work of the classics of Marxism-Leninism. This was first done by Karl Marx in *Capital* on the material of political economy, and in other works; the whole course of Marx's ideas about measurement, as Engels noted, had a direct bearing on mensuration in science.[1]

So one cannot agree with those authors who—in this case either knowingly or unwittingly ignoring the history of science and philosophy—do not see any broad theoretical problems in the idea of measurement. Measurement cannot be reduced to the simple procedure of 'look and see', recording the readings of a measuring device. In this respect Lebesgue is certainly right when, speaking about the measurement of geometric quantities, he draws attention to the fact that though 'a geometrical measurement begins physically..., it is only achieved metaphysically'.[2]

This statement is valid not simply to the measurement of geometric quantities: 'metaphysics', or rather theoretical thinking, cannot be banished from the measurement either of geometrical or of any other quantities. Indeed, it is impossible, in particular, in measurement, to avoid the concept of infinity (with which, for example, the concept of absolutely accurate measurement is conjugate), and infinity cannot be studied in a visualised, empirical manner.

Let us note in addition that no physical theory that reflects objective reality can ignore the need to link its mathematical apparatus up with the readings of the experimental devices. How is the passage made in physics from mathematical abstractions to the 'observed' in experiment, and from the observed experimental data to the equations of theory? Analysis of this question leads to most important philosophical problems specially connected with the development of modern, non-classical physics, which usually deals with objects and phenomena not directly perceivable, understanding of which does not fit into the schemes of classical theories.[3] On the other hand, problems of determining physical principles on the basis of measuring observable properties, and the transition from the principles of the theory to the measured properties, had already been posed by classical physics.

Mensuration thus unites the formulas (the mathematical part) of theory with the 'visualisation' (the 'visualisable' part). Problems of the accuracy of one theory or another cannot be solved independently of measurement. Mensuration also belongs, of course, to the crossroads, so to say, of the ideas of discontinuity and continuity in the cognition of nature. This list alone is sufficient (analysis of the related problems is also our concern) to conclude that the philosophical status of mensuration is still very, very far from crude obviousness.

What, then, is mensuration? If we bear its definition in mind we can justifiably say that it is a cognitive process in which information is obtained through experiment on the numerical value of a measured quantity. This definition, like definitions of this kind in general, is necessary for everyday use.[4] On the other hand, it is necessary, in order to get a quite complete scientific understanding of mensuration, to analyse its manifold real forms in their interconnection. The act of measurement itself usually implies the following elements as constituents of mensuration: (1) the object of measurement, i.e. the measured quantity; (2) the unit of measurement, i.e. the quantity with which the measured quantity is compared; (3) the observer, i.e. the subject making the measurement, and also the measuring instruments; (4) the methods by means of which the measurement is made and (5) the result of the measurement of the quantity. Some of these elements, which can be distinguished relatively clearly when we are dealing with an individual completed measurement made by an observer, may drop out when the measurement procedure is continuous and is included in the general system of operation of an automatic device. The observer may then not be directly involved in the measurement, since the information produced by the devices recording the measurement results is processed directly by the automatic device itself, which uses it to generate commands for its own working units.

Do the possibility and fact of automatic measurement mean that mensuration itself, in some cases at least, is ceasing to be a cognitive process? One meets such statements in the literature.[5] One cannot, however, agree with them. Any automatic device, no matter how 'perfect' it seems, is essentially an artificially constructed organ of labour or organ of man's cognition, and it would be only a physical system outside its relation to and peculiar connection with man (which connection expands his field of activity, including cognition). This circumstance also answers the question posed.

Let us note, finally, that any accurate measurement is impossible outside application of the laws governing the measured quantities, and is based on definite theoretical premises.

These remarks outline the context of the exposition that follows. It does not in the least claim to be a complete analysis of the problems of measurement.

2

The Concept of Measurement. Direct Measurement

If one says that physics (in the broadest sense of the term) is a science about the general laws of variation and transformation of realities in inanimate nature or, more definitely, about the laws of variation and transformation of fields and matter, one always implies that the properties of physical realities cannot be separated from their quantitative determinations, i.e. (which is the same thing) that a physical quantity is a kind of synonym of a certain property of a physical reality, and that the regular connections between these properties are expressed as relations between physical quantities (the equations of physics).

The objects of physics are studied in experiment and in the final analysis should be perceived either directly by the sense organs or in a mediated way, through the readings of the instruments. A necessary premise of the cognition of nature in physics is therefore that, in taking both the quantitative and the qualitative character of physical quantities into account, it finds the correspondence between the empirical data and the quantitative determinations (numbers). The establishing of this correspondence is sometimes called measurement.[6]

There are objections to this definition of measurement: it is said to be, at least, incomplete.[7] And indeed, in our view, it contains too much and at the same time too little for an understanding of measurement. Is it possible, for example, to call determination of the moment of an event measurement? Or does mineralogists' determination of the hardness of a body by the Mohs scale of hardness in which the hardness of a certain ten minerals is taken as the standard of hardness (the hardness of talc is 1, of gypsum 2, etc., up to diamond, whose hardness is taken as 10) represent measurement? In other words, can one call the instant of an event or, say, hardness quantities, if it is assumed that a quantity is what can be measured?

We have arrived, consequently, at the following questions: what is measurement, and what is a physical quantity?

Measurement differs from so-called arithmetisation, and from what, in our view, should be called quantitative ranking; as will be shown below, they are the conditions of existence of mensuration, although they may also make sense (exist) without it.

The *arithmetisation* of a certain class of properties of things is the establishing of rules by which it is possible to determine from the property of a class a number (or certain set of numbers) corresponding to it, and from a certain number (or set of numbers) to determine the property corresponding to it. If, for instance, one ascribes a pair of numbers to each point on a plane, according to a certain rule (each pair of numbers corresponding to one point and one point only on the plane), one thereby arithmetises the plane (since each point on it possesses the property of having a certain position on it).

Arithmetisation considered by itself is a totally arbitrary process (in the example above the plane can be arithmetised by means of the Cartesian system of coordinates, the system of polar coordinates, or other coordinate systems, and all these methods are equivalent), but in everyday life and scientific research it is governed by quantitative *ranking*, and through that by measurement, which constitutes its starting points and its peculiar 'cellule'.

If the properties of a certain class are such that it is possible to employ the concepts 'bigger' or 'smaller', they are called intensities (or intensive quantities). If this class is arithmetised in such a way that a higher intensity corresponds to a bigger number, the arithmetisation is *quantitative ranking*. A liquid B, for instance, is denser than another liquid A if the latter floats on the former, but not conversely (symbolically $B > A$ or $A < B$). Other examples of intensities, in addition to density, are temperature, the colour of a monochromatic beam (if a certain additional definition is introduced), hardness, and viscosity.

A set of different intensities A, B, C, D, etc., can be ranked in a sequence of intensities $A < B < C < D$, and so on, in which A precedes B, B precedes C, and so on. If the differences between two successive intensities in this sequence are equal (symbolically $B > A = C > B = D > C$), the intensities are called extensities (or extensive quantities), and the sequence itself becomes a sequence of extensities.

The arithmetisation of a class of extensities (e.g. a class of lengths, volumes, electrical resistances, masses, etc.) is *measurement*. The employment of a unit of measurement established arbitrarily is typical of mensuration. When the lengths of things are being measured, for instance, we count how many times a certain rod, selected as the unit of length, can be laid along each of them in a certain way. The situation is analogous to the measuring of, say, the volumes of vessels by means of a measuring vessel, or the masses of bodies by weighing. Such examples are endless, but it is essential to note that such-and-such a type of quantity is measured by means of a method that is specific for it; the qualitative aspect of the physical quantity finds expression, in particular, in that.

So, in mensuration, we determine the relation of a (measured) quantity to another homogeneous quantity (which is taken as the unit of measurement); this relation is expressed by a number (which is called the numerical value of the measured quantity).

A few words are called for on a fuller and logically closed definition of an extensive quantity, without which mensuration cannot be comprehended. It can be given axiomatically, and there is more than one system of appropriate axioms. Nagel cites Hoelder's system of axioms characterising the concept of an extensive quantity.[8] This point is also clearly made in Kolmogorov's article on quantity in the *Great Soviet Encyclopedia*,[9] which formulates axioms of division, continuity, etc., in addition to the axioms of order and combination. The axiomatic method employed to study the concept of quantity makes it possible to establish all the necessary fundamental characteristics of this concept more fully.[10] If the concept of an extensive quantity is generalised so that the class of these quantities includes negative ones and zero, in addition to positive quantities, then, when an arbitrary positive quantity is selected as the unit of measurement, all the others can be expressed in the form of $Q = q\,[Q]$ (the basic equation of measurement), where Q is the measured quantity, $[Q]$ is the unit of measurement, q is a real number, and $q\,[Q]$ is the result of the measurement.

Extensive quantities are more fundamental in physics than any other kind of quantity. They make it possible to get a quantitative expression of intensive quantities on the basis of established regularities: the value of temperature, for example (as the level of the thermal state), is determined by measuring the temperature interval between the zero value and the determined one. On the other hand, the very definition of an extensive quantity contains an indication towards 'bigger and smaller'. Extensive and intensive quantities are thus two aspects of one and the same concept.

Let us return to measurement. From the methodological standpoint, or rather from the angle of the general methods of obtaining the results of measurement, the division of measurements into direct and indirect ones is of very great interest. In direct measurement, the result is obtained from the act of measuring the quantity itself independently of measuring other quantities. In indirect measurement the result is obtained in terms of direct measurements of quantities that are connected with the measured one by a certain mathematically expressed dependence. In this section we shall discuss only direct measurement.

Measurement in science, unlike measurement in everyday life, is above all *accurate* measurement. There is a well-developed classification of 'accuracies', including the 'highest accuracies' in the theory and practice of measurements.[11] The concept 'metrological accuracy' is essential for our theme, for this reason: metrological accuracy is the highest accuracy that can be attained in the measurement of a given quantity in certain established units.[12] Allowing for the fact that measurement results are no more accurate than the standards are,* one can say that measurements made with metrological accuracy are those that are reducible to standards.

We now have to consider on the logical plane: how did measurement with metrological accuracy arise, or how did that form of measurement which we are entitled to call its standard form arise?

The standard form of measurement developed from simpler ones. The initial form is the random or individual form of measurement, whose specific feature is that a certain kind of quantity, characterising one thing, is measured by means of any other single thing characterised by the same kind of quantity.

Thing $A = b$ things B (the equals sign means 'equal with respect to such-and-such a property').[13]

* In metrology by 'the accuracy of a measure or measuring device' is meant the degree of certainty of a result obtained by means of the given measure of device. See M. F. Malikov, *Osnovy metrologii* (Fundamentals of Metrology), Part 1, Committee for Weights and Measures, Moscow, 1949, p 308.

This form already reveals the special features of measurement as a cognitive process providing information about the measured quantity. The measured property of object *A* is expressed qualitatively through the capacity of another object *B* to be comparable with respect to this property; its quantitative expression is that *B* appears as a numerically determined property of *A*. The property of an object (in its quantitative determination) does not exist simply in its expression by means of another object, but independently of any such expression, i.e. it is not the result of measurement that determines the quantity but the quantity itself that determines the result. On the other hand, within the limits of the relation between object *A* and object *B* in terms of a common property, *B* is not expressed in any way, i.e. it functions simply as a measure.

Furthermore, a feature of mensuration is that the individual becomes the representative of its own opposite, the general, in measurement. We would stress yet again that here the individual represents the general only within the limits of the relation of the things in terms of this general: a definite quantity of iron represents only heaviness with respect to a sugar-loaf whose weight is being measured by it; iron fulfils this role, however, only within the context of the weight relation (into which it enters with sugar), and sugar enters this relation only because both iron and sugar possess weight.[14] Finally, it must be considered a specific feature of measurement that a thing functions in it as a property.

The individual form of measurement is only met in the early historical stages of the development of production and human culture. In Babylonia, for example, there were three separate, unconnected groups of measures of length, which had arisen independently of one another: one based on the 'cubit' (a finger's breadth [digit], span, and cubit), which measured short intervals; one based on the *gar* (approximately equal to six metres); and a third group—the 'mile' and 'hour's walk'—measures for long distances.[15]

The individual form of measurement is quite unsatisfactory for the tasks of measurement. In it a thing expresses the properties of only one object; all other objects possessing the same property are not involved in the expression. At the same time the individual form of measurement passes by itself as it were to *developed* or *expanded* form. By the first form the property of an object A is only measured in one thing B, regardless of what this thing is (a span, cubit or *arshin*, or metre if the matter in hand is, say, the length of object A). To the extent that one and the same thing enters the relation with respect to one and the same property sometimes with one and sometimes with another thing, various individual expressions of measurement result. The individual expression of measurement thus turns into a number of various individual expressions, and we obtain the *developed*, or complete form of measurement:

$$\begin{aligned}\text{Object } A &= b \text{ objects } B\\ &= c \text{ objects } C\\ &= \ldots\ldots\end{aligned}$$

Leaving aside analysis of the developed form of measurement,* let us simply point out its drawbacks:

(1) the series of expressions is not finished; (2) they are not connected with each other; (3) if the properties of all the objects that constitute a given series are measured in this form, a vast set of series is obtained, extraneous to one another.

Each of the equations involved in the complete form of measurement (and, therefore, the whole series) can be reversed.** In this case we obtain the *universal* form of measurement

$$\text{Object } B = \frac{1}{b} \text{ of object } A$$

$$\text{Object } C = \frac{1}{c} \text{ of object } A$$

$$\ldots\ldots\ldots\ldots\ldots\ldots$$

In this form the properties (of one and the same kind) of things are measured by one and the same thing singled out from the aggregate of these things; for example, the lengths of solids are measured by the metre and so represent their lengths through their relation to the metre. In this case the

* Note, in particular, that a developed form of measurement existed, for example, in France historically before introduction of the metric system.

** Its practical realisation took place (when we appeal to history) when, for instance, the meridian of Paris was measured in feet in a quest for a 'natural' unit of length, and conversely when the length of the metre was made more precise and expressed in terms of the length of a meridian of the earth.

metre, in realising length, differs from itself as an individual element and from all other solid bodies as individual elements, and thereby expresses what it has in common with other bodies, i.e. expresses length. In their equating with the metre the solids possessing length prove to be not only qualitatively equal, i.e. lengths in general, but at the same time quantitatively comparable magnitudes of length.

Reasoning abstractly it can be said that every thing in a set of things characterised by the same property can be the universal measure of this property. Historical practice and science, however, necessarily choose one definite object as the universal measure which is therefore singled out from a set of things (it is not necessarily a natural thing but can be made artificially).

As a universal measure a thing has only one specific property with respect to other things from which it has been singled out, namely, to be their universal measure. When the singling out proves to be the final lot of one definite thing, it begins to function as a standard. In general, we call the standard of a quantity that object whose physical properties coincide with the 'property' of expressing this quantity or, in short, a standard is an objectivised (embodied) universal measure. That is how the standard metre, represented by a platinum-iridium bar with a certain cross-section, got the privileged position of the standard of length.

With the transition from the individual form of mensuration to the developed one, and from the developed form to the universal, essential changes take place from the angle of the accuracy of measurements. In the transition from the universal form to the standard, on the contrary, progress consists solely in the 'property' to be a universal measure now finally merging, by virtue of circumstances we shall discuss in the next section, with the physical properties of the standard as a definite body.

3

Standards and Units

In this section, as in the preceding one, we shall frequently speak, for clarity's sake, of the measurement of lengths, but all our reasoning also relates *mutatis mutandis* to the measurement of other quantities.

One can assume that things that possess length cannot be compared with one another, and therefore be measured, without a standard. In actual fact, however, if the lengths of objects are commensurable, they possess this property independently of whether or not there is a standard of length. It is by virtue of this commensurability that they convert such an object as the standard metre into a measure of length common for them all.

A measure that has completed its cycle of development returns in the form of a standard of measurement to the form in which it existed in the individual form of measurement, but this is not just a return to the initial form but rather a new step forward (the 'negation of negation'). On the other hand, the metre as the standard of length expresses its length only in the developed form of measurement, i.e. the metre has no standard of length.

This idea, or rather its essence, can be formulated in another way: the very concept of a standard as a universal measure requires the existence only of one standard. In metrology this requirement is met through a hierarchy of measures of the measured property, the foundation of which is formed by the so-called primary standard.*

What then is the necessary condition for a thing to function as a standard? For this purpose, it must satisfy a certain set of conditions. The *first condition* is that a thing representing a common property of a set of compared objects should have the 'property' of representing purely quantitative differences. And this property implies uniformity, qualitative identity between copies of the standard. It is realised in metrology by the requirement, for instance, that working metres be made of the same material, that measurements by them be made in identical conditions, that the working metres themselves be made and kept in exactly the same conditions. Working metres, however, are not identical as things: they are affected by differences in macroscopic structure, and by the fact that their conditions of use and production are not absolutely iden-

* Standards are divided into the following groups according to their metrological purpose: (a) fundamental standards (including prototypes); (b) master standards; (c) standard copies; (d) reference standards; (e) standards of comparison; (f) working standards. The *fundamental* standards are primary, the working ones tertiary, the remainder are secondary (see M. F. Malikov. *Op. cit.*, pp 318-325).

tical. Analysis of facts and considerations of this kind confirms that measurements reducible to standards in essence signify measurements by ideal average standards.

A *second condition* of converting a thing into a standard follows from a standard's having to represent purely quantitative differences: namely, that only that thing can be a standard that can be divided into any number of parts and combined with itself without losing its qualitative definiteness. Working measures or gauges are produced in such a way that this requirement is met as far as possible: measure sets, measure shops, gauges. But what does the arbitrary divisibility of a thing mean, or its arbitrary combinability with itself, the more so that a real finite object does not possess these properties to an absolute degree? Points like that will be considered in the sections that follow; let us note here that measurements that can be reduced to standards are ideal standards from the angle of the second condition of measurement.

The whole content of the first section actually amounted to this, that the property of compared objects is not created in measurement but simply expressed, i.e. that measurement by itself does not in principle alter the objects compared. But since measurement is *experimental* comparison, in which the compared objects may form physical relations and physical situations may arise that are 'bizarre' from the angle of classical physics, possibilities of this kind must necessarily be analysed so as to construct a theory of mensuration in modern physics. Our further exposition is devoted to the relevant issues. At the same time, since a standard represents an objectivised universal measure, i.e. serves for measurement, it should not change either in the process of measurement or outside it, so long as it remains a standard. Its immutability means that the property materialised by a standard is preserved unaltered in the thing that serves as a standard, and that all changes experienced by this thing due to certain conditions (temperature, various fields, etc.) can be allowed for. This is the *third condition* for an object to function as a universal measure.

No real object serving as a standard, of course, has the property of immutability in the absolute, but it is chosen or produced in such a way that it has a certain minimum of constancy that is much higher than the constancy of the things measured by it. Measurements that can be reduced to standards are undoubtedly ideal standards from the angle of the third condition of measurement.

A standard can thus perform its job in essence as a standard that is ideal in three respects: (1) the quantity is measured essentially by an ideal average standard; (2) the thing is arbitrarily divisible and arbitrarily combinable with itself only in the abstraction, while remaining qualitatively the same thing, and the standard measures only when it is such an ideal object; (3) immutability is an axiomatic property of a standard, and only an ideal thing can be absolutely constant.*

When things are measured, it becomes necessary to relate them to a standard as a materialised unit of measurement. The latter is then expanded into a scale through division into equal parts or through combining with itself. Every object that serves as a standard has such scale even before being converted into a standard, since the thing, according to the second condition of its functioning as a standard, can be divided into any number of parts and combined with itself. Because, for instance, the lengths of things are related to each other as similar quantities measured by the metre, the latter is turned from a measure of length into a scale.

The measure of a quantity and scale are two different functions of the standard. The standard of length is a measure of length as the materialised common property of things compared for length; it is a scale as a definite thing. As a measure of length, the standard of length provides the material for expressing lengths, in order to convert the lengths of things into a mentally imagined number of metres; as a scale, the standard of length measures this number of metres. The measure of length measures things as possessing length; a scale, on the contrary, measures various imagined numbers of metres by a given metre (which is then the unit). The definition of the unit of measure, and of its subdivisions and multiples, is a purely arbitrary matter; at the same time it must be generally accepted and be obligatory within the limits of mensuration practice.

Measurement of the lengths of things thus has a dual, inseparably interconnected significance: (1) to measure the

* It does not follow by any means from this that an *ideal* standard underlies measurement. On the contrary, the existence and role of an ideal standard in measurement are determined in general by real standards.

length of any thing means to express its length in terms of a specific thing that has length (this specific thing being called a standard); (2) to measure the length of any thing means to compare the magnitude of this length (expressed in the standard) with the magnitude of the length of the standard adopted as the unit. This applies *mutatis mutandis* to direct measurements of other quantities.

Let us now consider the views of certain other authors on the standard and unit.

Wallot stressed that units should be absolutely constant and readily comparable with the measured quantities, and defined the unit (for direct measurement) by means of a 'primary measure' (*Urmasse*).[16] According to him this 'primary measure' was, for instance, the line-standard metre; he did not, however, answer such questions as what the 'primary measure' was, or why such-and-such measure was primary, and so on.

The neo-Kantian Sigwart said that if it was impossible to find an absolute scale of value it followed in the final analysis that we were faced, following the direct empirical path in mensuration, with the impossibility of attaining objective results.[17] Sigwart obviously could not manage the dialectics of direct measurement. Because the things that figure as standards are variable (since they are real objects), he doubted the possibility of obtaining objective data about a measured quantity in experiment.

The neo-positivist Reichenbach denied measurement any objective meaning whatsoever. He distinguished statements about facts from so-called real definitions, by which he meant conventions, purely arbitrary agreements about physical objects. The definition of the metre through its prototype kept in Sèvres was, in his opinion, a real definition. He thus reduced the functions of a standard to that of a scale, and since the establishment of a unit of measurement is an arbitrary agreement, he concluded from that erroneously that the defining of the measure of any physical quantity is, in principle, conventional.[18]

In conclusion let us consider the limitations of direct measurement.

1. Any thing that is measured must, on the plane of direct measurement, be measured by as many standards as it has properties in common with other objects; or, to put it differently, there must be as many standards independent of one

another, from the aspect of direct measurement, as there are kinds of quantities in nature, regardless of whether they are connected by regularities.

(i) It is impossible to have as many standards as there are different properties, the more so that new physical phenomena are being discovered that have to be covered by the theory. (ii) It is wrong in all circumstances to abstract the regular connections between physical phenomena, but direct measurement does not allow for precisely that point.

Thus, the problem arises of measuring quantities of many kinds by a limited number of standards. Direct measurement neither does nor can solve it.

2. The thing measured is not internally connected with the standard, in direct measurement, i.e. the measured quantity and the unit of measurement are external to each other. That is the reason why, in experimental conditions of measuring, the result of the measurement, in certain circumstances, reflects not so much the measured quantity as variations in the thing serving as the standard. This limitation can only be overcome if the measured quantity is internally connected with the unit of measurement (and that is beyond the limits of direct measurement).

3. Direct measurement cannot determine the value of quantities characterising, say, celestial bodies and phenomena, or the values of quantities characterising physical bodies not directly perceptible by the sense organs (atoms, electrons), and, in general, the values of quantities not amenable to direct experimental comparison.

In Section 5 it will be shown that the limitations of direct measurement are overcome by indirect measurement.

4

Sensory Perception and Abstract Thought in Mensuration

Things observed, that are comparable in some common property, may produce an impression of identity or difference in respect to this property on our senses. Quantitatively such identity and difference can be called equality or inequality of the things as regards this property. For example, if a colour studied in a colorimeter proves to be perceptibly identical to a mixture of certain known colours, it is said it and the colour of the mixture coincide. Our sense organs themselves provide only scanty information about measured quantities expressible by the 'equal' or 'not equal', the more so that their structure puts definite limits on our ability to see, hear, smell, and in general sense (and even within these limits this ability does not provide accurate information about our environment).*

A problem arises of how to go beyond the limits imposed by sense perception and to obtain accurate knowledge about the measured quantities.

Measuring the length of a field by pacing it, determination of the area of a forest by eye, and determination of the volume of a body by feel give satisfactory information (for certain practical purposes), in spite of their 'inaccuracy' (in this case the term 'sensory measurement' would be legitimate); it was not fortuitous that, in the historically first forms of measurement, when there was not yet science and developed technique, the role of a unit was played by parts of the human body (which is expressed by the terms 'cubit', 'foot').

For accurate knowledge such measurements are quite inadequate, of course; and with the development of industry and growth of trade and a private economy more accurate data about quantities were needed. This was solved by the historical development of practice and science, which gave society experimental devices and measuring instruments.

The first experimental devices (the measuring rod, dividers, and scales), as a matter of fact, simply made more precise what man already knew from simple observation.

The development of the experimental science and technique in fact also disclosed the imperfection of the sense organs, a fact that stimulated some physicists (including Helmholtz) to doubt the possibility of any exhaustive cognition of the world around us. In reality, however, the fact that we can demonstrate the imperfection of our sense organs and that this proof is based on perceptions coming from these imperfect senses, indicates that human cognition is not only

* Perception takes place in certain conditions: there are upper and lower thresholds of sensation; there is the Weber-Fechner law; and the observer's psychophysical state has to be taken into account. These and similar circumstances have to be allowed for by the measurement technique and by the general theory of mensuration.

able to surpass the limits imposed by the special structure of the human organs of perception but actually does so in its study of nature.

Perception is also inevitably involved in accurate measurement by means of instruments. Nobody, for instance, will determine the base line for geodesic measurements by eye; at the same time, however, it is only the eye that detects the coincidence of a hairline and the reference object; or, to take another example, one cannot mark the coincidence of a column of mercury and a division of the scale with one's eyes closed.

Perception is thus a necessary component of any accurate measurement, and this implies the coincidence, say, of a needle, a spot of light or the top of a column of mercury with a scale division, or the matching of colours. An instrument reading perceived by the senses underlies a judgment about the result of the measurement, with a more or less long chain of inferences between the reading and the result. For instance, a researcher, observing the displacement of an ammeter needle, records a variation of current; a string of bubbles is perceived visually in a cloud chamber, but the conclusion concerns the trajectory of an alpha-particle.

Perception is not usually independent in mensuration; its true role in cognition of a quantity can only be understood from the standpoint of the measurement process as a whole, when thought, processing the material of observations into concepts, recreates in the researcher's mind a quantity that actually exists outside it. If everything occurred differently, it would have been impossible to extract the result of the measurement of a quantity from an instrument reading about the quantity measured.

Perception is thus only the starting point in the study of quantities. Even direct measurement cannot be reduced to 'pure' empirical observation of certain phenomena but is a complex cognitive process in which abstract thought plays an essential role. In measurements of quantities reducible to standards the fundamental significance of theoretical thought for determining the result of the measurement is quite clear. Let us take an example first in order to characterise the role of thought in measurements. In this example, we would note, it is not at all a matter of the method, which is typical of the measurement of length, although it stresses a certain aspect of mensuration, but rather of a kind of mental experiment.

It is required to compare the lengths of intervals A and B with each other, adopting the length of B as the unit of measurement. B is laid along A the maximum possible number of times (without division). It may happen that it fits precisely q times (a whole number) into A. Then the relation between the lengths of A and B will be $A = Bq$.

It usually happens, however, that an interval R remains over, whose length is smaller than that of B; in symbolic form we have $A = Bq + R$. The same operation can be performed with intervals B and R, R and R_1, R_1 and R_2, and so on, and we obtain a series of equations:

$$\begin{aligned} A &= Bq + R, \\ B &= Rq_1 + R_1, \\ R &= R_1 q_2 + R_2, \\ &\cdots\cdots\cdots \\ R_{n-2} &= R_{n-1} q_n + R_n, \end{aligned}$$

where $q, q_1, q_2, \ldots q_n$ are integers, and $R, R_1, R_2, \ldots, R_n$ are decreasing lengths of the corresponding remainders.

In practice, there will be always n for which $R_n = 0$; then R_{n-1} will be the common measure of the lengths of two intervals (commensurate intervals the ratio of whose lengths is expressed by a finite continued fraction). But there may also be incommensurate intervals (as is proved in geometry), i.e. which have no common measure of their lengths.

In the last case the ratio A/B can be expanded into an infinite continued fraction:

$$\frac{A}{B} = q + \cfrac{1}{q_1 + \frac{1}{q_2} + \cdots + \frac{1}{q_n} + \cdots}$$

It can be demonstrated that this infinite continued fraction is a finite irrational number, and A/B can be computed with an arbitrary degree of accuracy by means of rational numbers.

This well-known Euclidean algorithm interests us in many respects. (1) It can be shown directly sensually that the lengths of intervals are commensurate and only commensurate, which is due to the existence of a threshold of sensitivity in our sensory organs. When they are equipped with the appropriate devices, this only increases the number of steps in the measurement; from the aspect of perception, however, the proposition above is still valid. The numerical result of measurement is therefore always directly represented by a rational number. (2) It can be shown, in terms of geometrical theory, that there are both *incommensurate* and *commensurate* ratios of quantities. Hence, (3) the perceptible result of the comparison of quantities (without the appropriate theoretical correction) is not yet an accurate result. Generally speaking, exact ratios between (uniform) quantities cannot be established by their directly perceptible comparison: such a comparison yields only the preliminary material for determining the exact ratio of quantities. (4) Accuracy of measurement is intimately related to the concept of infinity, and the incommensurate ratios only witness to this in their own way.

Geometrical measurements are not the only ones that need thought. Theoretical thought is an element of the measurement of any physical quantity. In the next section we shall consider the role that physical laws (the *ratios* of quantities) play in obtaining exact measurement results. Discovery of a law necessarily implies mental activity. As we shall see later, the finding of exact expressions for the results of measuring quantities, the simple form of which is the A/B considered above, coincides with the discovery of laws of nature.

Physics is thus not satisfied with individual empirical measurements; it uses them to move towards exact knowledge, generalising the empirical material and ridding it of haphazard elements.

Since physics became established as a science (Galileo, Kepler, Newton), its systematising factor and the most important source of its concepts (together with experience) has been mathematics; conversely, mathematics has grown from physics. Mathematical ideas shape the notions and principles of physics, and in modern physics they play a tremendous heuristic role on their own. But in relation to physics mathematical abstractions acquire physical flesh, so to say, only through measurement; on the other hand, experimental observations are only raised to the level of theoretical generalisation through measurement.

From this it will be clear that the concept of the connection of mathematical abstractions (which figure in physical equations) with experimental observations, or the 'measurement recipes' (as Mandelstam put it[19]), are extremely important for interpreting physical concepts. Each period in the development of physics and mathematics has made its contribution to analysis of this concept. Any logically formed physical theory of broad scope has its own mathematical apparatus or formalism (e.g. classical formalism has numbers and vectors, the formalism of quantum mechanics—linear operators) which corresponds to its own specific rules of the relation between its mathematical abstractions and experimental observations.

On that plane a physical concept is a kind of synthetic result of perception and abstract cognition, the physical concept itself being interpreted according to the specific features of the formalism of a certain physical theory. In this interpretation, the point of view of Niels Bohr is of fundamental significance. He never tired of explaining that it would have been impossible to describe real experiments without employing concepts of classical physics that represent a generalisation of everyday experience.

According to him, the question of the physical meaning of the abstractions of classical mechanics (which expresses most clearly the epistemological and methodological features of classical physics) did not lead to any special difficulties in it (the values of the variables of its mathematical apparatus are numerical values of physical quantities mathematically expressed by these variables). In non-classical theories matters have become more complicated. In quantum mechanics, for instance, solution of the problem of how to express the physical meaning of the concepts of its formalism, considering observation data described in classical concepts, has proved far from trifling. It is not the purpose of this chapter to analyse this solution; matters relating to it were discussed in Chapter III, but we would like to make a comment relevant to the theme of this section.

In quantum formalism the eigenvalues of its operators correspond to the numerical values of physical quantities that are represented mathematically by operators. The specific nature of quantum operators and relations between them reflects the specific nature of quantum quantities.* In order

* The uncertainty relation for position and momentum, for example, is derived from the commutation relation $\hat{P}_x\hat{X} - \hat{X}\hat{P}_x = \frac{\hbar}{i}$ (where $\hat{P}_x$ and $\hat{X}$ are the momentum and position operators, $\hbar$ is Planck's constant divided by 2π, and $i = \sqrt{-1}$).

to infer the position of an electron, say, from the observed distribution of specks on a photographic plate, a system of definite principles and concepts that are 'odd' from the standpoint of classical physics (e.g., 'relativity with respect to the means of observation', 'probability, as the numerical measure of the potentially possible', 'the difference between the potentially possible and the realised') is required.*

On this basis appropriate conclusions about the physical quantities relating to micro-particles not directly perceivable are drawn from the observation data. If, for instance, the isolated concepts of a particle's velocity and position employed in classical theory reflect the fact that the latter studies the motion of macroscopic bodies, in quantum mechanics the situation is quite different. The electrons in the atom do not behave either as particles or as waves but possess particle and wave properties simultaneously: it is then already impossible to speak of an electron's isolated position and velocity; it is necessary to employ new concepts that are remote from the usual classical ones and yet connected with them.

The roles of perception and abstract thought in a physical theory are thus equally important in their own way, and this comes out quite definitely in the measurement of physical quantities.

In summing up, we would like to stress that both sensory perception and abstract thought have a place in mensuration, or rather the dialectical unity of the two.

5

Laws of Nature and Measurement. Indirect Measurement

In practice the process of indirect measurement is clear: quantities connected with the measured one through a certain mathematically expressed dependence (relation) are measured directly, and the value of the measured quantity is determined from the dependence. But what is the funda-

* The considerable theoretical significance of 'new primary concepts' in quantum mechanics was noted by Fock, who gave a rough list of them (V. A. Fock. Comments on Bohr's Paper About His Discussions with Einstein. *Uspekhi fizicheskikh nauk*, 1958, ***66***, 4: 599-600.

mental basis of this form of measurement? That is to say, of the measurement which, as noted above, removes the limitation of direct measurement and makes possible progress of scientific cognition? In particular, what is the unit in indirect measurement? Analysis of these questions is the theme of this section.

Let us note to start with that metrological direct measurement is indirect measurement in its *formal content*. Indeed, metrologically accurate measurement of a quantity is a measurement that can be reduced to ideal standards and instruments and to ideal conditions; and such reduction implies the use of dependences that relate the measured quantity to certain other quantities. In order to get a true result in metrological weighing, for instance, it is necessary to introduce corrections for the loss of weight in air, to exclude the effect of inequalities in the arms and the errors in the weights, let alone observing the scales' state of sensitivity and determination of the zero point from the oscillation of balance arm.

As regards its *actual content*, however, metrological direct measurement is direct measurement, because it is not the external circumstances in which the result is obtained that is essential but the method, the form of obtaining it.

Metrological direct measurement is thus *ideal* direct measurement. It is the starting point of accurate indirect measurement.

Indirect measurement is not only such according to its formal content, but also to its actual content. The heart of the matter in *ideal* direct measurement is reduction to ideal standards, instruments, and conditions; mathematical dependences are only used to introduce 'corrections' into the results, while the measurement itself can be done in principle without using them. In indirect measurement, however, the corresponding reduction to ideal standards is only a preliminary condition for obtaining the result. The very idea of 'corrections' (in the sense of ideal direct measurement) is totally alien to indirect measurement, and determination of the measured quantity without resorting to dependences does not make sense in principle in indirect measurement.*

* The historical precondition for the establishment of indirect measurement in science was discovery of the internal unity and transformations of various physical bodies and processes. In this respect the years between 1819 and 1850 were typical (the work of Oersted; the

Let us pass to the problem of the unit in indirect measurements.

The equations of physics express dependences (relations) between quantities characterising not only individual, concrete systems and processes but also classes of systems and motions. Although the second dependences are the most essential, we shall begin our analysis with the first since they represent the elementary form of the relations that physics is dealing with.

Assume that it is possible to say, on the basis of the appropriate experiments, that at a pressure of one atmosphere and a temperature of 20°C, a cubic centimetre of mercury weighs 13.6 grammes, two cubic centimetres 27.2 g, three cubic centimetres 40.8 g. We obtain a dependence between the volume of mercury and its weight that is expressed by the equation

$$P_1 = 13.6V_1, \tag{1}$$

where P_1 is the result of measuring the weight of the mercury (in grammes), and V_1 is the result of measuring the volume of mercury in cubic centimetres.

If the weight and the volume of mercury were measured, respectively, in any other units differing from the gramme and cubic centimetre, it could be demonstrated that the structure of all the corresponding equations would not differ from that of equation (1). In the symbolic form we have

$$P = kV, \tag{2}$$

where P is the weight of the mercury, V is its volume expressed in units which are not quantitatively specified, and k is a proportionality factor that depends on the choice of the units of weight and volume.

Equation (2) can also be written as follows:

$$P[P] = kV[V], \tag{3}$$

where $[P]$ and $[V]$ are the units of measurement of weight and volume, respectively. Since k is the result of dividing

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discovery of thermal electricity; the work of Ampère; the discovery of electromagnetic induction and of the law of the conservation of energy). On this basis the so-called absolute system of Gaussian and Weberian units emerged, which became the cornerstone of the theory of indirect measurement.

P by V, we can denote it by

$$k = \frac{P\,[P]}{V\,[V]}.$$

Let us divide the numerical value of P by the numerical value of V and introduce a symbol $[P/V]$; then

$$k = \left(\frac{P}{V}\right)\left[\frac{P}{V}\right]. \tag{4}$$

Equation (4) can be interpreted as follows: the proportionality factor k is a certain quantity whose numerical value is $\left(\frac{P}{V}\right)$, and the measurement unit is $\left[\frac{P}{V}\right]$.

In general (as is illustrated by our example), the value of the proportionality factor is always associated with the unit of measurement, which differs from the units of quantities that are measured directly in its mediated nature; it depends on the units of other quantities (which figure in the equation), and is characterised by a structure with respect to those units. The proportionality factor accordingly functions as the embodiment of the dependence (relation) between the quantities.

In a single equation the proportionality factor is a derivative of the other (primary) quantities. The importance of the concepts of the proportionality factor, dependent and independent units, and a derivative comes out quite clearly when we pass from single equations to systems of equations and to a system of systems of equations, i.e. to a physical theory.

The modern physical theories are usually logically closed systems of principles and basic concepts in accordance with the axiomatic method of their construction.* From this position the concepts of basic and derivative quantities are legitimate since the first are defined (indirectly) in terms of the theory's system of principles (in classical mechanics, for instance, in terms of Newton's axioms of motion; in thermodynamics in terms of its two principles), while the second are derived when the axioms are employed in concrete situa-

* Some theories (e.g. classical or quantum mechanics) are logically closed systems; others (e.g. the theory of elementary particles) are only being logically constructed. Matters of the connection between logically closed and open theories, and of the trends in modern physics toward a logically whole system of theories are not discussed in this chapter.

tions from the sphere of phenomena that is covered (or should be covered) by the given theory (and its system of axioms).

From this the concepts of *basic* and *derivative* units emerge, as units of measurement of the corresponding basic and derivative quantities, respectively, that characterise a certain sphere of phenomena, and also the concept of a *system of units* that includes the basic units (as the basis of the system) and the derivative units. The metric system was a system of units for measuring geometrical quantities; but the first developed expression of a system of units for measuring physical quantities was the Gaussian and Weberian system of absolute units mentioned above.

How do things stand with basic quantities and, correspondingly, with the basic units, in non-classical theories? The approach to solving the problems arising is ultimately determined by the fact that (1) classical mechanics is the limiting case of relativistic mechanics (when $c \to \infty$, where c is the velocity of light) and the limiting case of quantum mechanics (when $h \to 0$, where h is Planck's constant); and (2) non-classical theories cannot avoid using classical concepts in measurement, which are relativised in appropriate fashion.*

Thus, the sphere of both the theory of relativity and quantum mechanics includes classical basic quantities, but as approximate quantities (with respect to classical ones), with an accuracy determined by c and h as fundamental quantities of the theory of relativity and quantum mechanics, respectively. As for the basic units of measurement in these theories, we shall consider them below in connection with analysis of so-called dimensionless quantities.

But let us return to basic and derivative units.

By making use of axioms and the more complex dependences consistently obtained from them (which determine the equations) we can link the basic and derivate units by similar dependences, the proportionality factors being taken as unity. Dimensional theory is concerned with problems of this kind.[20] Its fundamental concepts include dimensionality, which shows how the derivative unit is linked with the basic ones. In classical mechanics (with its basic quantities of length l, mass m and time t and the basic units $[L]$, $[M]$,

* We use term 'relativised classical concepts' (in the broad sense of the term 'relativised') to denote the analogues of the classical concepts in non-classical theories that are governed by the principles of these theories.

$[T]$ corresponding to these quantities), for example, the dimensional formula for all units of derivative quantities has the form of an exponential monomial $L^l M^m T^t$.

This form of dimensional formula is determined by the following condition, as dimensional theory demonstrates: the ratio of two numerical values of any derivative quantity is invariant in relation to the choice of dimensions for the basic units. The use of dimensional analysis is based on this invariance principle: the validity of physical equations can be checked by the dimensional formula and, in the appropriate conditions, the law governing one physical phenomenon or another determined. In this respect this invariance principle has the same heuristic value for establishing the laws of phenomena as other, deeper principles of invariance.

A dimensional formula can serve as the definition of a derivative quantity in a logically closed classical theory. This method of defining a quantity or, on a broader scale, of defining a quantity by specifying the method of measuring it, is common in classical physics. Bridgman unjustifiably turned it into a certain philosophical principle (the operational method of definition) that supposedly embraced the whole of physics, but as Born correctly noted, this method of definition is limited to classical physics.[21]

Now let us consider how many basic units there should be in a system of units and what their nature should be. The answer, it would seem, follows from the exposition above: the number and nature of the basic units are determined by the number and the nature of the basic quantities, i.e. by the system of units that forms the foundation of a theory. There are many systems, however, differing both in the number and nature of their basic units.[22] In general, there is a common point of view in the literature that the number of basic units is arbitrary and can be increased or decreased.[23] On the other hand, there is also the view that it would be more useful to discard systems of units (it is supported, for instance, by the physicist Robert Pohl).

In order to get an understanding of all this, let us first consider some examples. As we have already mentioned, there are three basic quantities in classical mechanics in accordance with Newton's axioms of motion: length l, mass m, and time t, with the units $[L]$, $[M]$, and $[T]$, respectively. When Newton's axioms are extended (or generalised) to include (weak) gravitational fields, and certain observation data are taken into account,* we obtain Newton's gravitational theory, with the law of universal gravitation in which a dimensional constant γ appears that does not come into the equations of mechanics (it is called the universal gravitational constant, and its value is determined experimentally).**

Thus, in Newton's theory of gravitation, the basic quantities known from classical mechanics are supplemented by the universal gravitational constant.

The gravitational constant γ makes it possible to 'rid' the LMT system of units of the basic unit $[M]$. To this end, we take $[\gamma]$ as unity, in other words, use the equation $[\gamma] = [L^3M^{-1}T^{-2}]$. Hence we obtain $[M] = [L^3T^{-2}]$, i.e. the formula of dimensionality of the mass unit in the unit system LT.

This unit system is natural in the problems in which the gravitational force is taken into account. Besides, in this case it is not that the basic unit $[M]$ is 'removed' from the unit system LMT, but this system is transformed into the system of units $\gamma\ LT$ in which $[\gamma]$ is considered as a dimensionless unit.

Another example. When the axioms of motion of classical mechanics are extended to include electromagnetic phenomena (taking into account such data as the results of the Michelson-Morley experiment, etc.), we get the equations of the special theory of relativity, containing the universal constant c—the velocity of light *in vacuo.* It makes it possible to get rid of the basic unit of time. For that, the constant c is regarded as a dimensionless unit, and after a certain argument the conclusion is reached that the time during which light travels a unit of length *in vacuo* should be taken as the unit of time. In several branches of physics and astronomy dealing with phenomena in which the velocity of light *in vacuo* is essential this unit of time (with the dimension $[L]$) is more natural than the second, the definition of which is based on the Earth's rotation around its axis. In this example it can also be shown that it is not so

* Extensive observations of the planets' motion were generalised by Kepler in the form of the laws known by his name (1609-1619).

** There is a qualitative difference between gravitation and all other forces since the gravitational acceleration of a body is independent of its mass.

much that one basic dimensional unit is 'removed' from the system of units as that another dimensionless unit is 'substituted' for it.

As a last example in our argument let us consider the International System of Units (denoted as *SI*), adopted in 1960 by the International Committee of Weights and Measures. There are six basic units forming its foundation: length (metre), mass (kilogram), time (second), electric current (ampere), thermodynamic temperature (Kelvin), luminous intensity (candela). By establishing uniformity in the units of measurement, it covers all spheres of pure and applied science, linking measurements of mechanical, electrical, thermal, and other quantities, and taking their specificity into account. From the angle of their practical application it is very convenient. On the other hand, for certain areas of measurement, and for theoretical analysis if one has in mind their special features, other systems of units prove to be convenient (as was briefly mentioned above).

Thus, by generalising the material cited and other material like it we reach the following conclusions: (1) the number and nature of basic (dimensional) units is adequate, generally speaking, to the number and nature of the basic quantities, but in certain theoretical and practical conditions such correspondence is not necessary; systems of units are possible only on the basis of the laws appertaining to certain spheres of phenomena, and the connection between them reflects on the logical plane (or should reflect) the connection between the spheres of natural phenomena belonging to them; (2) the basic units of a system may include both dimensional and dimensionless units; the number of dimensional and dimensionless basic units equals the number of basic quantities in a given theory (excluding universal constants); (3) the different systems of units (in the sense of the number and nature of the basic units) correspond to different classes of dimensional and dimensionless quantities,* with the possibility of quantities' changing their dimensions or non-dimensionality in passing from one system to another; (4) there is no predominant system of (di-

* Quantities whose numerical values depend on the dimensions of the basic units are called dimensional. Quantities whose numerical values do not depend on the dimensions of the basic units are called dimensionless or non-dimensional; non-dimensionality is one of the simplest forms of invariance.

mensional) units; all *possible* systems of (dimensional) units are equivalent in measurement but that does not mean that choice of the system for *actual* use is independent of the conditions of the mensuration.

In the context of these conclusions let us consider the so-called natural system of units. The father of the idea of this system, Max Planck, was interested, above all, in getting rid of the special features of those concrete bodies and phenomena that form the basis of the modern system of measurement units and measures, i.e. in eliminating the arbitrary and random elements that are to some extent inevitable in the modern system of measurement. Planck continued the work of the authors of the metric system in the conditions of twentieth century science. His natural units are based on four universal constants: the velocity of light *in vacuo*, the gravitational constant, the quantum of action, and Boltzmann's constant; these should, in his opinion, be preserved for all times and all extraterrestrial and extrahuman cultures, as long as the laws of nature determining these universal constants remained invariable.

In Planck's single natural system of units the randomness that is inevitable when physical realities are taken as standards of measurement is reduced almost to nothing. The role of standards in this system is fulfilled by the universal laws of nature. These laws become ideal standards in the fullest sense of the term, while the concept of dimensionality itself disappears, which is the great significance in principle of Planck's natural system for the problematics of mensuration. But the system itself is inconvenient to use either for molecular or atomic phenomena (let alone macroscopic ones), because of the smallness of the units for length, time and mass.

The main drawback of Planck's system in principle is that the introduction of such a *unified* system of natural units opens no perspectives for physical theories: in quantum mechanics, for instance, the construction of units on the basis of gravitational constant, the velocity of light and Boltzmann's constant is unnatural since they play no important role in the phenomena studied by it.

In this case the natural unit systems for individual physical theories that have appeared since Planck's system are more promising. The point is that the laws of nature are not invariant with respect to the change of scale of certain domains of physical phenomena, and the universal constants now known are on the boundaries of these domains; for example, the laws of classical mechanics are applicable in a domain in which velocities are small compared with the velocity of light *in vacuo*, and effects are large in comparison with Planck's constant. This corresponds to the fact that, in (non-relativistic) quantum mechanics, classical electrodynamics, and quantum electrodynamics, say, there are their own natural systems of units. For quantum mechanics, for instance, the basic units are Planck's constant h, electron charge e (or rather its square), and electron mass m_0; the length scale here, in particular, is Bohr's atomic radius $r_B = \frac{\hbar^2}{m_0 e^2}$, while the velocity scale is the atomic unit of velocity $\frac{e^2}{\hbar}$; $\left(\hbar = \frac{h}{2\pi}\right)$. Use of these systems has its theoretical and practical advantages, which have been discussed in the physical literature.[24]

Is the perspective of 'dimensionless physics' broader in any sense? It is still difficult to answer. As yet relativistic quantum mechanics (in which h and c play an important role) does not exist as a logically closed theory. There are no logical bridges between Einstein's gravitational theory and quantum theory. Synthetic theories of this kind are knocking on the doors of contemporary physics. Their creation would possibly mean the discovery of universal constants as yet unknown, and appearance of new basic concepts and principles that might include qualitatively new notions about the most profound properties of space and time.

Questions like this are on the boundary of modern physical knowledge, and only assumptions of one kind or another are possible at present. At the same time there is no doubt that the explanation of 'universal non-dimensionals' embodying the most fundamental foundations of modern physics is not to be found in its known theories but at a deeper level.

To conclude this section, let us return to the questions of measurement that are met in present-day physical literature.

It was noted above that the concept of measurement implies acceptance of the idea that measurement does not alter the properties of the object measured, that there are sufficiently constant bodies (solids) and sufficiently constant processes to serve as the appropriate standards. All these features are inconceivable if one ignores classical physics and (a) its understanding of moving matter as an aggregate of moving particles, and space and time as receptacles of changing bodies of various degrees of complexity, and (b) its methods of cognising nature. Classical physics did not so much find the basis for and explain the properties of the hardness of bodies, and the stability of atoms, and interpret the properties of motion, space, and time in a definite way, as simply accepted them as experimental data.

Non-classical physical theories have already found the basis for such an understanding and explanation of the existence of properties and relations postulated by classical theories. Quantum theory, for instance, on the basis of knowledge of the properties of electromagnetic interactions has demonstrated the stability of the atom as an electromagnetic system, i.e. the stability of atoms has been explained by laws of nature. Atomic dimensions and energies have been determined and explained on this basis, and the quantum-mechanical description of atomic properties led in turn to understanding of a host of characteristics of matter, and of the constants on which so much empirical data had been collected in classical physics.[25]

All this was expressed by G. Chew in his comments on Wick's paper *The Extension of Measurement*[26] presented at the jubilee meeting devoted to the 400th anniversary of the birth of Galileo, in the following way: 'if there were no electromagnetic interactions but only short-range interactions, it seems unlikely that matter would assume the required sort of configuration.'[27] According to Chew, if the interaction between the measuring instrument and the object were nuclear rather than electromagnetic, it would not be at all obvious that the measurement would retain its meaning, because 'the measurement notion depends on the possibility that when one system is looking at another system it does not completely change its nature'.[28]

Many other physicists spoke in the discussion on Wick's paper. Without going into its details, let us refer to the comments of Wheeler and Feynman.

In Wheeler's opinion, when measurements are made there is the fact that the observer is spatially separated from the object looked at, 'but in the case of a closed universe, we have no platform on which to stand to look at the universe—there is no place on the outside to poke it from',[29] i.e. we have no observation point from which the universe could be considered as an external object. He, therefore, put a number of questions; he asked whether or not it meant that 'the whole character of physics is different when we look at the universe as a whole than when we look at a part of it...'.[30]

Feynman raised objections to Chew's remarks: 'I do not see any sense whatever in discussing how measurements might look if there were no electromagnetic interactions. On the other hand, it is perfectly clear that when we learn more about strong interactions we may find that our concepts of physics, of philosophical bases of physics, just as many times before, have been changed, may be changed in such a way that ideas of measurement are in fact altered.'[31]

It would seem that Feynman was much closer to the truth than Chew. His argument about measurement followed the line of development of scientific cognition: from absence of knowledge to its existence, and from shallow knowledge to deeper knowledge. All physical knowledge about nature and its laws is found, in the final analysis, from experimental material and the readings of measuring instruments, which (data) are described in the language of classical concepts. This was shown with extreme clarity by Bohr when he studied measurement in quantum mechanics. A physical theory, however, that reflects the phenomena of nature and their regular connections is not a set of instrument readings or a set of some sort of formal equations, but, as already established, a combination of these parts in some higher synthesis, which, as a matter of fact, is the only one that can be called *a physical theory*. Every fundamental (closed) theory, in particular, has its own rules linking its formalism and instrument readings: quantum mechanics enunciated this most convincingly for the first time in history. It is necessary, of course, to find not only the formalism (without which there is no *theory* in physics) but also the rules of its connection with the experimental data (without which there can be no *physical* theory), and such a successful search is the constructing of a physical theory.

Problems of this kind are resolved by the development of physics as a science; the problematics of measurement are a part of them. In this respect modern physics provides excellent material.

The same considerations apply to the problems of measurement posed by Wheeler. The progress of modern astrophysics, which studies stars, galaxies, and the Universe in general in their change and development, and not from a static point of view, as was the case before the 1940s, can be taken to provide concrete answers to these questions. We have in mind the new element in the understanding of measurement, which is inseparable from solution of problems and study of phenomena that have been still unexplained in the conditions of the twentieth century revolution in astronomy (the discovery of quasars, pulsars, etc.), rather than general formulations of 'answers'.

Modern astrophysics is closely related to the modern theory of elementary particles, and not just because it has been recognised that nuclear reactions are the source of stellar energy. These two leading spheres of modern physical science are also connected methodologically. The problem of the formation of a quantum of electric charge, of the spectrum of masses and charges of the elementary particles now known, and why they, and not other particles exist, questions that even now lack theoretical interpretation, fall within the competence of both disciplines. And does the idea that the existence of each elementary particle cannot be independent of the existence of each and all of the other elementary particles, which figures in the modern theory of strong interactions, have nothing to do with Wheeler's questions?

All these issues relate to the problem of measurement in various modern physical theories. Our job, however, was not to analyse it (in any sense thoroughly), or not even to analyse the formulation of the problem but to stress the fact that the problem of measurement becomes meaningful only when it is considered as an inalienable part of theory (in accordance with the concreteness of the theory and its coverage of reality). As a theory arises and is built, acquiring a certain shape, the problem of measurement becomes deeper and more meaningful in it.

This has been concretely established by quantum mechanics in its own sphere, and in this respect it can serve as a sort of prototype for other fundamental theories of non-classical physics, including those being developed. The next two sections of this chapter will be devoted to the problem of measurement in quantum mechanics.

6

The Concept of Measurement in Quantum Mechanics

In this section we shall consider only what is most typical on the plane of the problem raised.

The classical interpretation of measurement is both the starting point (the recording of macroscopic parameters) and the finish (the experimental checking of physical statements) of the description of experimental data in the theory of relativity and in quantum theory, but the measurement data are comprehended in these theories in their own way, in accordance with what distinguishes non-classical theories qualitatively from classical physics. In what follows we shall be concerned with the influence of quantum ideas, which express the spirit of modern physics most clearly, on understanding of the essence of measurement; we shall not discuss relativistic ideas here.

The idea that the effect of measurement (the measuring instrument) on the object measured cannot be reduced to zero is most characteristic for a quantum interpretation of measurement. This idea constitutes the main content of the uncertainty relation (principle), which is frequently formulated as follows: the greater the accuracy in determining a particle's position the smaller is the accuracy in determining its momentum, and conversely. There is also another interpretation: namely, that measurement puts the object into a new state, some of the influence exerted by the instrument on it remaining in principle indeterminable.

A number of philosophical questions thus arise if we have in mind that measurement provides information about a quantity. It can be assumed, for instance, that the operation of obtaining information about an object alters the object itself in a way that is indeterminable in principle; such an assertion, however, sounds more than strange from the standpoint of science. Some, it is true, consider that an object has less reality from the quantum-mechanical aspect than the measuring instrument, or that it exists only in coordination with the instrument. We analysed these notions in Chapter II and shall not dwell on them here.

It can also be assumed that the act of obtaining information about an object cancels out the previous information about it, and that this is stated in quantum mechanics in the language of the wave function; the latter as it were represents a record of information about the object's state, and measurement simply means the observer's revision of the information about the object.

Such a seemingly reasonable interpretation of the uncertainty relation is also unacceptable for science: according to it, a physical equation containing the universal constant h describes only the observer's knowledge about material realities, rather than the realities themselves. The term 'information' can, of course, be given the meaning it has in information theory. There is nothing, in general, against that, but it would be wrong to think that it solves the problem of measurement in quantum mechanics, the more so since Planck's constant h (which underlies the uncertainties of measurement in quantum mechanics) and Boltzmann's constant k (which plays a fundamental role in its own way in information theory) cannot be reduced to one another. Or rather, the fact that measurement yields information about a quantity does not mean at all that the theory of measurement should be a special case of information theory, just as the analogy between the processes of translation and radiation does not mean at all that the theory of radiation is a special case of the theory of coding.[32]

So, what is measurement in quantum mechanics? Let us note first that quantum mechanics deals with the measurement of quantities characterising the *motion* (*behaviour*) of electrons and in general of micro-objects. Only in some cases can their *motion* be regarded roughly as the *motion* of 'classical' particles or *propagation* of 'classical' waves; in no experiment, however, do micro-objects behave exactly like the particles and waves that classical physics is concerned with. To take an extreme case, micro-objects behave as particles in some conditions of observation, and in others as waves. It is the job of quantum mechanics to study the laws and properties of this motion. Questions about the various types of charge, rest masses, and other parameters characterising the electron and other elementary particles do not come within its province.*

* Quantum electrodynamics and quantum field theory (the theory of elementary particles) have their problems related in one way or another to measurement, but we shall not go into them.

Issues relating to measurement once posed and solved in classical theory have been continued and generalised in a way in the problem of measurement in quantum mechanics. They are, primarily, points about the frame of reference and relativity and absoluteness (invariance). In classical mechanics physical systems in which the law of inertia holds and the concept of relativity in relation to an inertial reference frame is introduced become the frames of reference.* In Einstein's relativistic mechanics the concepts of the frame of reference and relativity were developed further.

The concepts of frame of reference and relativity in quantum mechanics are being broadly and essentially developed today in physics. In this theory, atomic phenomena cannot be separated, in their description, from the conditions in which they are observed. The means of observation (the measuring instruments) become frames of reference in it and accordingly the concept of relativity in respect to the means of observation is introduced, which is alien to classical physics (and to Einstein's theory).**

Let us consider the quantum-mechanical concept of measurement in greater detail, taking the example of electron diffraction. Let an electron beam pass through a crystal and the electrons hitting the screen cause scintillations that in the aggregate produce a diffraction pattern. This pattern reflects the statistics of electron behaviour. From the distribution of diffraction maxima it is possible to determine the electron's wavelength and therefore its momentum before passing through the crystal, i.e. to determine the quantities that describe electron motion when it is in the state of de Broglie's plane wave. The presence of scintillations indicates that the electron, having passed through the crystal, is in the state of a narrow wave packet, i.e. has a definite position and an indefinite momentum.

* In classical mechanics frames of reference are connected with Galileo's transformation; in it, accordingly, *relative* quantities (e.g. momentum), whose numerical values change in passing from one frame of reference to another, figure, and also *absolute* (invariant) quantities, whose numerical values do not change in such a transition (they include, for example, the duration of an event).

** This concept was first introduced implicitly by Bohr, who made a deep analysis of the essence of measurement in quantum mechanics. In its explicit form it was formulated by Fock, who developed Bohr's ideas and refined them. (See V. A. Fock. *Kvantovaya fizika i stroyenie materii* (Quantum Physics and the Structure of Matter) Leningrad University Publishers, 1965.)

In this example the electron gun creates conditions in which the electron exists in the state of a plane wave; the crystal engenders conditions in which the electron exists in the state of a wave packet; in that sense one can call the electron gun and the crystal state-preparing devices, or preparatory devices.

This example illustrates, in particular, that the state of an object is something objectively real that exists independently of whether the property of the object is recorded or not (in our example, whether or not the electrons hit the screen). In other words, the phenomena reflected by quantum mechanics do not depend on any observation of them; as Bohr remarked, 'the decisive point is that in neither case does the appropriate widening of our conceptual framework [the point in question is the concept of complementarity as compared to classical concepts.—*M.O.*] imply any appeal to the observing subject, which would hinder unambiguous communication of experience'.[33]

* * *

Schrödinger's paradox about the cat that was discussed in the physical literature of the 1930s is of interest in connection with these questions. The interpretation of the wave function as the record of the observer's information about the possible results of the experiments relating to microscopic phenomena served as the condition of the paradox's appearance. Schrödinger talked about a cat that was in a chamber together with the following device, namely a Geiger counter containing such a small amount of radioactive substance that not more than one atom decayed per hour. The counter registered a decay and operated a little hammer that broke an ampoule of prussic acid.

The observer had to consider, from the standpoint of the above interpretation of the wave function (and this is where the paradox lies) that the chamber accommodated in equal degree both a living and a dead cat. This allegedly followed from the superposition of quantum states $\psi = c_1\psi_1 + c_2\psi_2$, where ψ describes the state of the whole system, ψ_1 is the state of the living cat (the counter is at rest), ψ_2 is the state of the dead cat (the counter triggered).

What then is the solution of the paradox? In the view of consistent positivists, the paradox arises because the commonsense point of view is ascribed to quantum mechanics by which its laws and concepts have objective meaning; in reality, however, the positivists argue, the laws of quantum mechanics connect initial conditions accessible to observation with the results observed. And it is meaningless to go further. The absurdity of the statement about the cat that it is half dead and half alive, in fact demonstrates that the situation is seemingly just that—senseless.

According to the seemingly contrary view of Kovalchuk and Lomsadze there is a paradox only 'if the quantum-theoretical state, in this case that of the cat, is interpreted not as the observer's information about the cat's objective characteristics but as its certain objective characteristics'. From the angle of this interpretation, the ψ-function of the whole system means that 'objectively the cat is either alive or dead', but 'the observer does not know as yet whether it is alive or dead'.[34] Without going into the authors' considerations, let us simply note that such an interpretation contradicts quantum mechanics since in this case the authors mistakenly identify the 'uncertainty' and 'lack of knowledge'. In general, the view that 'the state of a micro-particle should be understood not as an objective characteristic of this particle but as the observer's information about its objective characteristics' means essentially that the classical concept of a particle is absolute and cannot be replaced by any other.

We shall not cite other similar interpretations that allegedly make it possible to avoid Schrödinger's paradox. It seems to us that all of them, and the paradox itself, rest, as Heisenberg aptly said, 'on careless formulations in the early quantum-theoretical literature' that rightly needed correction.[35]

The paradox of the cat arose because in the relevant argument the cat, in a quite illegitimate manner, was likened to a micro-particle with properties that are odd from the classical point of view (the concept of quantum state was applied to the cat), because the behaviour of a microparticle was described in concepts of classical theory without being revised on the basis of quantum-mechanical laws. Schrödinger's paradox, regardless of its author's intentions, indicates, *in its own way*, that classical and quantum concepts are not identical, that so as to describe the motion of micro-objects, classical concepts are replaced by more general and meaningful ones in which they constitute the limiting case. To put it bluntly, quantum mechanics is by no means the best method to solve whether the cat is alive or dead.

Schrödinger's paradox and others like it have again become fashionable of late in the literature on philosophical aspects of quantum physics, in which one observes 'a turning of the tide', as the philosopher Max Bunge put it. In this case Bunge had in mind the trend against positivist and similar views in physics which is now supported by well-known West European and American scientists and philosophers.[36]

For our part, we would note that there is also a strong antidialectical tendency in this 'turning of the tide', the clearly expressed desire to return to 'good old' classical ideas and schemes that we have already touched on in Chapter II.[37] We cited Heisenberg's statement above, when he raised objections to contemporary opponents of complementarity principle and noted that their critical remarks can be justly applied to careless (*nachlässige*) formulations of the old (and not of the current) quantum-mechanical literature.[38] We should like to add that it is because the terminology and reasoning in the complementarity principle have now been made more precise, and the logical formulations further developed (compared with the literature of the thirties and forties), that the famous paradoxes, which are being discussed again by present-day opponents of the complementarity principle, were long ago resolved.

Something similar can be seen in the present-day Marxist literature on the philosophical aspects of physics. Recent publications of Blokhintsev's on the fundamental issues of quantum mechanics have in essence gravitated towards the trend in the modern philosophical and physical thought that Bunge referred to so figuratively.[39] In this connection, let us consider his ideas very briefly.

Blokhintsev presents his point of view as if the philosophical problems of quantum mechanics, discussed since this theory was created, are now considered on the same level as in the forties, and as if study of them has allegedly made no advance as regards the depth and the consistency of the analysis (in particular, his publications make no mention of the fact that through the combined efforts of physicists and Marxist philosophers certain results have been achieved in this direction during the past two decades). He even ignores (let alone analyses) the present-day interpretation of the wave function and other very important concepts of quantum mechanics developed from the angle of a refined and further developed idea of complementarity (the wave function as a reflection of potential possibilities of the interaction between the measuring instrument and the micro-object; the concept of relativity with respect to the means of observation). Blokhintsev, avoiding all this, puts forward another interpretation of quantum mechanics than the conception of complementarity.

In Einstein's discussion with Niels Bohr, Bohr, of course, was right, although his argument cannot be considered consistently materialist philosophically. In Blokhintsev's view 'it is important that this discussion gave grounds for interpreting the wave function as the observer's "notebook"'.[40]

Is this statement of Blokhintsev's correct? If Bohr was right as a physicist in his argument with Einstein (because it became clear that the state of an object may change even when there is no explicit interference by any measuring instrument), the task was to comprehend this fact logically and epistemologically, without positivist 'additions' about the decisive role of the observer, or about the wave function providing *information* on the possible results of the *experiment* (instead of an objective description). It was just this that was resolved as a result of refining and critically reworking and developing Bohr's ideas. Blokhintsev, as we have already noted, followed a different path, and suggested a (in his opinion) more progressive theory for understanding measurement in quantum mechanics.[41] It is the right of any scientist to do that, but Blokhintsev's opponents also have the right to ask him why he bypassed the present-day development of the conception of complementarity, which had in fact freed it of just those philosophical shortcomings which Blokhintsev wants to eliminate from quantum mechanics from the standpoint of the conception of complementarity.

If we summarise Blokhintsev's view on the questions posed here, it boils down, in his own words, to the following. Quantum mechanics studies microsystems μ in a certain macroscopic situation $\mathfrak{M}$. This situation can be broken down into two parts: one dictates the conditions of the microsystem's motion (determines its state); the other is macroscopically unstable, and a micro-particle can produce a macroscopic phenomenon in it. Repetition (i.e. reproduction) of identical sets $\mathfrak{M} + \mu$ forms a *quantum ensemble*.[42]

We refrain from presenting the other considerations and details of his theory, and would simply make two comments.

(1) In Blokhintsev's theory these 'interactions' that include the 'interaction of the microsystem and the measuring instrument' are *force* ones; in general, he does not even mention the non-force interaction. We would be justified to say that, in fact, according to him, quantum-physical concepts are not specific in character. Even though he recognises the unity of the particle and wave properties of the micro-objects, he accepts it simply as a pure, empirical fact that actually proves to be outside the sphere of the mathematical and logical apparatus of quantum mechanics. In other words, Blokhintsev does not, in essence, accept quantum-physical concepts (e.g. relativity with respect to the means of observation) that represent a step forward in cognition of the motion of matter, compared with classical physical concepts, and consequently also leaves out the dialectical transition from the latter concepts to quantum-physical ones.

(2) The measured micro-object, of course, affects the measuring instrument; without that we would know nothing about it (without the necessary cascade process in a cloud chamber, it would be impossible to observe the track of a particle moving in it). But does quantum mechanics *study* this action of the micro-object on the measuring instrument? If one sticks consistently to this point of view, classical mechanics studies not the motion of, say, a bullet but the holes made by it in a target, and so on. Blokhintsev's corresponding statements, it seems to us, rather resemble the assertions that neither particle nor wave are absolute concepts, and that in quantum mechanics one cannot do without concepts unknown to classical theory, but in his statements the distinguishing quantum features and the very quantum content disappear.

* * *

Let us return to the problem of the measuring instrument. It is quite essential to remember that it is necessary, in order to learn about the properties of a micro-object, to use a measuring instrument that combines a device preparing the state of the micro-object and a recording device providing data allowing us to form an opinion about the micro-object's properties. From this angle the measuring instrument is both a preparing device and a recording device united in a single whole. Measurement includes both preparation of a state and recording in the sense above.

The recording device cannot fail, in accordance with its function, to be a classical object (system), i.e. a real object (system) such that use of it for measurement implies the existence of conditions making it possible to neglect the quantum properties. It follows from this that the preparing device also cannot fail to be a classical object (system). Therefore, from the quantum-mechanical standpoint, there cannot be a single device that puts the object into the state, say, of a plane wave and at the same time of a wave packet. There can be only two mutually exclusive types of device for preparing the appropriate states of the object (or realising the conditions for complementary phenomena: the complementarity principle). This is determined by the dual corpuscular-wave nature of the micro-objects.

Now let us pass to some conclusions about measurement in quantum mechanics.

Measurement does not create physical properties in either classical or quantum theory. It serves cognitive and practical purposes and provides information about the objects being studied in accordance with the principles of the respective theory. The electron, before passing through a crystal lattice, is in a state with a certain momentum (and an uncertain position)*; after passing through the crystal it proves to be in a state characterised by a certain position (and uncertain momentum). Measurement alters the state of the micro-object; the wave function that characterises its state describes potential possibilities, which are converted into reality in certain conditions realised by the instrument, and this transition occurs in measurement.

The change of an object's state under the effect of measurement thus does not result from a force (physical) effect on the object, like a gravitational or electromagnetic effect. The basis of the effect of measurement on the state of a micro-object, and the non-force character of this effect,** consist

* The 'uncertain' quantity has only a distribution of probabilities.

** On the non-force interaction or effect see V. A. Fock. Comments on Albert Einstein's Creative Autobiography. *Uspekhi fizicheskikh nauk*, 1956, *59*, 1: 116. The non-force effect is closely associated with directly in the particle-wave nature of the micro-object. There is no uncontrollable interaction between the micro-object and the instrument that can be considered the basis of a change in the micro-object's state.

The change of quantum state under the impact of measurement resembles the change of a body's mechanical state in classical theory when the transition is made from one frame of reference to another moving in respect to the first. The mechanical state, however, is unrelated to the measuring instruments, whereas it is meaningless to consider quantum state as unrelated to the measuring instruments. Let us recall once more that Bohr was against the use in quantum mechanics of statements like 'disturbance of phenomena by observation' or 'creation of physical attributes of objects by measurements' and noted that the term 'measurement' should be 'used in its plain meaning of standardized comparison'.[43] The effect of measurement on the state of the object is a non-force one, as we said above, and the preparing device is wholly responsible for this effect. As for the recording device, it provides information on the state of the object before recording and does not, as one should expect, provide any information about the object's state after the recording.

The uncertainty relation reveals the specific in the understanding of quantum state. According to it the quantum state is one in which a certain value of momentum and position does not exist simultaneously, or, in symbolic form, $\Delta X \Delta p_x \geqslant \geqslant h/2\pi$, where ΔX is the uncertainty in the value of position, and Δp_x is the uncertainty of the value of momentum. This relation can be also expressed as follows: the greater the uncertainty in position, the smaller is the uncertainty in momentum (the limiting case being de Broglie's plane wave), and the smaller the uncertainty in position, the greater is the uncertainty in momentum (the limiting case being an infinitely narrow wave packet). It is because, we repeat, a micro-object is not a particle in the classical sense and

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the concept of the 'potentially possible'. This connection is obvious in quantum mechanics. The situation with other non-force effects is similar not only in quantum mechanics but also in science in general. Take an example from everyday life. When a woman bears a child, her father's state inevitably changes: he becomes a grandfather. (There is no direct 'force effect' here. And of course, when a daughter marries, her father is a potentially possible grandfather.)

has inseparable corpuscular-wave properties that its position and momentum do not both have a certain value at the same time.

The mathematical form of the uncertainty relation is included in the mathematical apparatus of quantum mechanics, which expresses the relations and dependences between the relative (in the above sense) quantities in the language of linear operators. The uncertainty relation, in the form in which it was given above, can be derived from a certain, more general operator expression.

In the literature the term 'inaccuracy' is frequently used alongside the term 'uncertainty' or 'indeterminacy' in discussions of the 'uncertainty relation': for example, 'the more *accurately* the position of the electron is determined, the more...'. Fock noted that use of the term 'inaccuracy' is insufficient and sometimes incorrect.[44] Indeed, in its literal sense, 'inaccuracy', when applied to the uncertainty relation, served the idea of uncontrollability in principle, which turned the uncertainty relation into an agnostic enigma. This can be traced, for instance, in Brillouin, who justifies the uncertainty relation (and one cannot agree with this) by 'experimental errors' and the fundamental inaccuracy of measurement.[45] The 'uncertainties' belong to the sphere of stochastic and statistical concepts, and they are usually employed in quantum theory with a meaning deeper than in, say, thermodynamics. The term 'uncertainty' should therefore undoubtedly be preferred to 'inaccuracy' when it is a matter of quantum effects.

The uncertainty relation is associated in its own way with the problem of the absolute accuracy of measurement which was developed even in classical physics. Let us consider it in winding up.

A single measurement, like a single fact, is of little significance by itself in science. Even the establishing of the very simple relation $a = kb$ between two quantities a and b calls for their repeated measurement. On the other hand, the laws of nature are laws only when they can be checked at any time, in any place, and by any observer; and for that, again, repeated measurements are necessary. Measurement thus has meaning for science only when repeated a large number of times, i.e. when its result appears as a certain set.

The results in the set of repeated measurements of a quantity do not usually coincide empirically. The question arises which of them depicts the quantity most reliably, i.e. the problem of the accuracy of the measurement arises. High accuracy implies that the result of the measurement is independent of the effect of the individual special features of the observer, the measuring instrument, the method of measurement (the problem of so-called systematic errors), and the effect of the chance factors (from the point of view of measurement) that accompany the measurement process (the problem of so-called random errors). In order to exclude the random errors that are inevitable in observations and experiments, the law of large numbers of the theory of probability is employed, which is based on the principle of the unity of the necessary and the random.

The problem of accuracy presents special interest when measurement is considered in its, so to say, pure form unobscured by the effect of circumstances foreign to the measurement itself. Measurements of a certain length, for instance, first by a carpenter's rule, then by a standardised yardstick, then by an eyepiece micrometer, then by an interferometer lead to results of increasing accuracy. One can ask whether an absolutely accurate value of the measured quantity exists. The question cannot be answered without the principle of the unity of the discontinuity and continuity of moving matter, which is associated with the dialectic approach that has not been reached by classical theories.

In Max Born's view it is physically meaningless in general to speak of the absolutely accurate value of a quantity expressed by a real number, since it contradicts the principle of observability. The statement 'coordinate $x = \pi$ cm', for example, should be excluded from the usage of physics, because, by cutting off the infinite decimal fraction expressing π at the 20th or 25th digit, we get two numbers that cannot be distinguished either from each other or from π itself.[46]

Indeed, π is meaningless as the numerical value of a certain length when the length of an interval and the circumference are directly compared. If, however, one starts with certain geometrical laws, there is nothing nonsensical in the statement that 'the circumference of a circle whose diameter is one centimetre equals π centimetres'. The concept of absolute accuracy of measurement cannot be separated from cognition of the infinite, and the latter cannot be reduced to infinite repetition of one and the same thing.

It is meaningless, for example, infinitely to increase the accuracy of the measurement of quantities characterising the motion of a bullet, because at a certain stage a qualitative change of the quantity occurs, and it acquires an already different physical meaning: this is clearly demonstrated by the uncertainty relation. The concept of absolutely accurate measurement is a meaningless one if it is employed without allowing for the concrete content of the quantity measured. When this content is taken into account, however, absolutely accurate measurement becomes a quite legitimate concept; it is the continuous refining of the value of a quantity with the development of science and technique.

That this definition of absolute accuracy of measurement opens up a broad philosophical perspective can be seen very clearly in the problem of improving the accuracy of the measurement of length. As Ising demonstrated, the Brownian motion of the parts of instruments sets a limit to increase of the accuracy of measurement. For instance, the length of a measuring rod fluctuates owing to the thermal motion of its atoms, and for that reason direct measurement of length by it results inevitably in an error of an order of magnitude corresponding to the distance between atoms. This limit, however, is not the absolute limit of accuracy, although there exists a contrary point of view.[47] This is quite definitely demonstrated, let us say, by the fact that the definition of the metre as the standard of length by the international platinum-iridium prototype, operative before 1960, was replaced by a new definition based on the properties of luminous radiation. According to the latter definition, the metre is the length equal to 1,650,763.73 times the wavelength *in vacuo* of the orange radiation of krypton-86.[48]

There is equipment to reproduce the metre in luminous wavelengths, and problems of a possible further improvement of the accuracy of the standard method for reproducing the metre in wavelengths of spectral lines are being studied, taking into account such outstanding results of the advances of modern physics as atomic beams *in vacuo*, lasers, and the Mössbauer effect. It is worth noting that the transition to the 'light metre' is a fundamental step in the sense that now not a body possessing certain properties functions as the standard here, but the laws of nature, in this case quantum laws. In fact, the wavelength of the radiation of an atom is taken here for exact definition of the unit of length, and the fact that this length is a constant follows from quantum considerations. The idea that the laws of nature can serve as a kind of ideal standard seems quite obvious when one remembers that there are laws (as, for instance, in the atomic world) that lead to characteristic dimensions and strictly defined sets. The discovery of such laws brings joy to the admirers of precision in the cognition of nature.

The question of absolute accuracy of measurement acquires a special interest from the angle of the above considerations the further we descend into the structural levels of matter. According to Brillouin, it is absolutely impossible to measure distances that are much less than 10^{-15} centimetre, simply because there is no yardstick available for such small orders of magnitudes. Let us assume, he argues, that we would like to measure a length of the order of 10^{-50} cm. The wavelength appropriate for the purpose, that could serve as a standard, would possess such a quantum of energy that it would be 'capable of blowing to pieces the laboratory and the whole earth'.[49] These considerations, he concluded, were 'sufficient to prove the absolute impossibility of measuring 10^{-50} cm'.[50] There is an error in his conclusion similar to that noted above. In quantum mechanics, for instance, the uncertainty relation establishes limits of applicability of the classical model of an object's behaviour, or the classical method of description, which ignores the fact that the object has wave properties, in addition to corpuscular ones, that are inseparable from the latter, rather than a fundamental limit to the accuracy of measurement.

Brillouin's imaginary measurement of lengths of the order of 10^{-50} cm gives roughly the same picture. Are we justified in applying to the world of interacting high energy elementary particles that are transformed into one another spatial and temporal conceptions (and also those connected with them) of a nature corresponding to the macroscopic and atomic scale? It is enough to pose the question this way to see the illegitimacy of Brillouin's argument from the standpoint of the logic of modern physics' development.

In the theory of elementary particles being developed there are serious grounds for assuming that the question of the details of particles' behaviour at very close distances is meaningless. Instead of the 'customary' Hamiltonian formalism, the formalism of the scattering matrix has come to the fore and also various forms and versions of non-local quantum field theory with the new universal constant of the dimension of length, so-called elementary length. A revision of the idea of metric space-time that seemed eternal in physics is accordingly not excluded in the realm of the ultra-small. It is quite possible that the concepts 'further away' and 'closer', 'earlier' and 'later' will lose their 'macroscopic' meaning in the high energy physics. In short, we can now think of the birth of a very modern physics in which fundamental physical concepts and principles already established are perhaps only approximate.

The last word in clarifying these issues, which are extremely important for high energy physics, and are formulated in a particularly hypothetical form, belongs to experiment, of course, but there is no doubt that (objectively employed) all-round, universal flexibility of concepts will have the greatest significance in their solution,[51] and not some proclaimed principle or other of the limited nature of cognition. In fact, Brillouin's imaginary experiment, which in some respects closely resembles Heisenberg's famous one with the X-ray microscope, says as much. In its own way, it leads one to accept the (now commonplace) idea that the development of physics is not limited by the boundaries of its classical concepts and principles.

Thus, the unceasing cognition of ever deeper and deeper laws of nature is the source and basis of absolutely accurate measurement in the sense discussed above.

7

On the Interaction of the Atomic Objects and Measuring Instruments

Since the time of Galileo, the identifying of the concepd 'observation' and 'measurement' in physics has provet in a certain respect justified, because physics became (and will forever remain) a quantitative or, as it is said, an exact science. Something similar happened in quantum mechanics in which, from Bohr's day, the interaction of a 'classical object', called in a certain connection an instrument, with a 'quantum object' (e.g. the electron) is spoken of as measurement. It is noted that this interaction occurs independently, and without the participation, of an observer. In Landau and Lifshitz' excellent course of theoretical physics one can find precisely such a statement, and there are as many as you like in the literature on quantum mechanics.[52]

Such identifying of 'interaction' and 'measurement' in quantum mechanics (frequently discussed in the works of Bohr, Heisenberg, and the other founders of this physical theory) also has its definite content and meaning from the philosophical (logical and epistemological) aspect. This is also often mentioned in current literature on quantum theory. Their analysis, which is the task of this chapter, should certainly present interest in more than a 'quantum-mechanical' respect.

Let us discuss the interaction itself of the measuring instrument and the measured object to begin with. Any measurement, and not just in quantum mechanics, always implies the possibility of a reciprocal change of the state of the instrument and of the object. (1) Without a change of the instrument's state nothing would be known about the measured object; (2) the very process of measurement can affect its result. This possibility is realised in certain conditions, since both the measuring instrument and the measured object are *physical* realities (*physical* objects) and there is *force* effect between them (with transfer of momentum, energy, or both, from the one physical object to the other).

Are we dealing with that kind of interaction in quantum mechanics?

When it is a matter of measurement in classical physics, the very essence of the measurements necessitates existence of the concept of a force effect in the theory of the appropriate measurements. The interaction of the instrument and the object, which is practically inseparable from the measurement itself, affects its result; in classical theory, however, this influence can be abstracted in the final analysis, and ignored, since the force interaction of the measuring instrument with the object measured can be arbitrarily small in principle (which is reflected in the theory of the processes being studied). If we want to measure accurately the temperature of the water in a container by a thermometer, for instance, we must allow for the change in the water's temperature as a result of immersing the thermometer in it. But, on the basis of the theory of heat exchange, we can draw a conclusion about the water's temperature before the thermometer was immersed in it from the thermometer readings, i.e. 'get rid' of its distorting effect on the water's temperature.

The situation with measurement in quantum mechanics would seem to be exactly the same. Let us assume that an electron flux (from an electron gun) passes through a crystal, and that the electrons hitting a screen produce scintillations that form a diffraction pattern. De Broglie's wavelength and, consequently, the electron's momentum before passing through the crystal, are determined from this pattern, i.e the data of the diffraction experiment, plus quantum theory, allow us to infer the electron's state before the crystal that altered it was used.

And yet, while the formal structure of measurement is the same in classical theory and in quantum mechanics, their essential content is profoundly different. It was not fortuitous that there was such an intense polemic around the problem of measurement in quantum mechanics. The point is that quantum mechanics is a radically new theory, as regards its foundations, compared with classical theories, including relativistic physics; it contains the concept of the wave function* (in our second example it is expressed by de Broglie's wave), specific to its theoretical content, and since measurement is impossible without applying the theory of the phenomena being studied to the instrument readings, the difference between the content of 'quantum' and 'classical' measurement becomes clear from that.

We would emphasise once more that any measurement, since it is based on experiment, is inconceivable without a force action (effect) of the measuring instrument (device) on the object measured; the problem in measuring an object is in fact to get rid of the outside influences, external to the measured object itself (and its inherent quantitative characteristics), that distort the measurement result. In that one cannot do without the theory of the respective phenomena, and

* The laws of classical mechanics (and consequently the laws of those theories that employ its fundamental concepts in one way or another) are used to study the motion of systems (objects) when the dimensions of the region in which the phenomena occur are large compared with de Broglie's wavelength. This is equivalent to a requirement that the quantities of the dimension of the effect for a process should be larger than Planck's constant h (i.e. than the universal constant specific to quantum phenomena).

some or other of its principles: in this case they are intended, so to say, to clear the result of measuring a quantity of everything that is not proper to the measured quantity itself (in the context of the theory of the relevant phenomena), i.e. to obtain thereby an adequate expression (in certain measures) of the quantity itself (the parameter of the object measured).

As already noted, it was always possible in principle, in classical theory, to 'exclude' (eliminate) the relevant effect of the measurement or observation, which meant exclusion of the measuring instrument and, therefore, in the end, of the observer, since the instrument is a kind of extension of the observer, his artificial organ of cognition. In this case the sting is not that the physicist can make the instrument, but that the object serving as an instrument is linked, as it were, by the physicist to his sense organs thus, so to say, 'extending' his brain.

It seems to us that this 'classical path' of understanding of measurement was actually also followed by quantum mechanics in the first stages of its construction as a *physical* theory. Such a 'classical' beginning of the understanding of measurement in quantum mechanics was inevitable not just historically. As we shall see later, however, the development of this understanding proved to be quite unique, resembling, at first glance, the development of the problematics of measurement in classical physics but characterised, in fact, by a content unknown to classical physics.

The famous imaginary experiment with an X-ray microscope conceived by Heisenberg so as to illustrate the physical meaning of the uncertainty relation, brings out the essence of the initial understanding of measurement in quantum mechanics which we arbitrarily called 'classical' above. From the standpoint of this experiment, the electron cannot be observed (its position cannot be determined) if there is no interaction between it and a photon (i.e. if it is not illuminated by light of a certain wavelength λ)*; the momentum $p = \hbar/\lambda$ transferred by the photon, however, introduces an uncertainty $\Delta p_x \sim \hbar/\lambda$ into the electron's initial momentum; as a result, increase in the accuracy of measurement of the electron's position leads to a loss of accuracy

* The error Δx in the determination of the electron's position will be of the order of a wavelength λ, i.e. $\Delta x \sim \lambda$.

in the measurement of momentum $\Delta x \Delta p_x \sim \hbar$; in other words, the photon-electron interaction makes simultaneous accurate determination of the electron's position and momentum impossible.

Reasoning of this kind also contains the source of the idea of an uncontrollable (indeterminable) interaction between the measuring instrument and the micro-object; at one time this idea was regarded as the core of the conception of complementarity, and the dialectics of the atomic processes were revealed and at the same time obscured in it. We shall not dwell on the principle of uncontrollability (indeterminacy) (it has been extensively discussed in the physical and philosophical literature), but we would like once more to stress here that the conception of complementarity, in the sense of the accuracy and perfection of the terminology and reasoning (and consequently of the further development of the theory's logic), is now very far removed from the formulations that can be found in the relatively early work on quantum mechanics. To this end, let us consider some of Bohr's ideas.

He spoke, in 1935, of 'the impossibility, in the field of quantum theory, of accurately controlling the reaction of the object on the measuring instruments, i.e., the transfer of momentum in case of position measurements, and the displacement in case of moment of measurements'.[53]

And how did the uncontrollable interaction arise? We learn this from Bohr's following considerations: 'The *finite interaction between object and measuring agencies* conditioned by the very existence of the quantum of action entails—because of the impossibility of controlling the reaction of the object on the measuring instruments if these are to serve their purpose—the necessity of a final renunciation of the classical ideal of causality and a radical revision of our attitude towards the problem of physical reality'.[54]

Thus, from this angle the interaction between the measuring instrument and the measured micro-object can be classified as a *force* effect *that is, however, uncontrollable*. The fact that classical physics does without an uncontrollable (force) effect can be explained by quantum of action's being very tiny so that we are justified, when considering the interactions between macroscopic objects, in abstracting ourselves from its existence. On the other hand, when atomic phenomena are discussed, it is in principle impossible to neglect the existence of the quantum of action (because of the smallness of the phenomena), so that it is necessary to assume that the effect in transfer of momentum or energy cannot be smaller than the value of the quantum of action and, consequently, that effect of the measuring instrument on the object cannot be reduced to nothing in measurement; these are considerations that cannot be by-passed from the standpoint of the idea of uncontrollability in principle.

Discovery of the quantum of action thus seemingly leads inevitably to acceptance of the idea of uncontrollability in principle, and the quantum-mechanical probabilities, and the impossibility of separating the behaviour of an atomic object from its relation with the measuring instrument (in the study of phenomena) are seemingly necessarily linked internally with the uncontrollability principle. We shall now try to clarify whether this is true or whether the heart of the matter does not consist in the 'force effect' between the atomic object and the measuring instrument.

* * *

Bohr's discussions with Einstein on the problems of the theory of knowledge in atomic physics can help us deal with the question posed. Bohr, as we know, could not convince Einstein of the fruitfulness of his interpretation of quantum mechanics when they argued about the resolving of the paradoxes posed by Einstein, although he always managed to demonstrate the inconsistency of these paradoxes and, therefore, that Einstein was wrong. A half-joking remark by Ehrenfest, who was a close friend of the two great physicists, has come down to us: 'I'm ashamed of you, Einstein. You put yourself here just in the same position as your opponents in their futile attempts to refute your relativity theory.'[55]

It seems to us that there is a deep meaning in all this. At that time in the arguments on quantum mechanics the term 'uncontrollability in principle' was pushed to the fore with Bohr, in the meaning that was discussed above. The term 'complementarity', which also appears in his publications of that period, was not yet clearly separated from 'uncontrollability in principle' (as happened in his later works). The argument, properly speaking, was concerned with the content of the concept of the measuring instrument's interaction with the micro-object and, as we shall show later, that helped solve the problem.

Einstein, in rejecting Bohr's conception, denied the uncontrollability principle in the form in which it existed at that time in the development of quantum mechanics. Bohr, in defending his conception, advanced as its basis the complementarity principle, which was not then, however, clearly defined (it was the dispute in fact that promoted its definition) and got lost, as it were, in the idea of uncontrollability. It would be quite instructive to trace in detail the logic of the remarkable dispute between Bohr and Einstein on the philosophical positions of quantum mechanics. It is probable that it would then be found that Einstein was to some extent justified in disagreeing with the idea of the uncontrollable interaction, while Bohr, in defending his interpretation of quantum mechanics, also, in essence, did not support 'uncontrollability in principle', although he used the term. We shall make only some general brief comments to clarify this point.

The essence of Bohr-Einstein discussion on the philosophical problems in quantum physics (which took place in 1935) consists in the following. If a system composed, say, of two electrons (which at some time were in a physical interaction*) is characterised by means of the wave function, the effect associated with measuring the first electron alters the state of the second one even when it is very far removed from the first. Einstein saw a paradox in these statements, which accord with the content of quantum mechanics, since they are incompatible with the principle of short-range interaction which implies the existence of independent realities in two parts of space distant from each other. In his view, the answer to the paradox was to recognise that modern quantum mechanics gave an incomplete, indirect description of reality, which would later be replaced by a complete, direct one. The last comment was directed against the understanding of quantum mechanics that did not essentially distinguish between the states of micro-objects (characterised by wave functions) and possible information about them, i.e. which converted micro-objects' states into something very far from objective reality.

* In this case 'physical' is a synonym of 'force'. Force effects are by no means identical in their physical nature. The interactions of electric charges, for example, differ from the gravitational effect in classical physics, and both of them differ in nature from the interaction of an electron and a photon in quantum physics.

Such was Einstein's paradox to which he returned in other publications.[56,57] One cannot, however, agree with the solution he suggested; or rather, there is no paradox here, as Bohr demonstrated, although his argument does not appear satisfactory from the standpoint of the revised terminology and reasoning of his last works.

Einstein was certainly right when he recognised the momentum and spatial characteristics of an atomic object, i.e. its quantum state, as objective, in other words, as existing independently of the instrument readings perceived by man; he was wrong, however, when he identified these characteristics in essence with classical concepts. An atomic object's momentum and spatial characteristics do not appertain to the object as such but to it in certain conditions that are recorded by instruments of various kinds; the quantum state has something to do with the potential possibilities of an interaction between the object and the measuring instrument (which may be either, say, a cloud chamber or a diffraction device). The underlying philosophical reason for this state of affairs is that an atomic object does not behave either as a classical particle or as a classical wave but as a material system that unites the properties of particles and waves (fields) in a unique manner. The interaction of two such atomic objects considered by Einstein differs qualitatively from all interactions between particles or fields known in classical physics, and this is reflected by quantum mechanics.

Fock regards the interaction between two atomic objects with a common wave function (the case analysed in Einstein's paper) as a special interaction which he calls a non-force one. He believes that Einstein was wrong when he renounced all interactions except the force ones.[58] In reality, as he suggests, there are many different kinds of interaction both in science and in everyday life which are non-force ones.

It is worth adding to what has been said about non-force interactions that the specific feature of the non-force interaction that figured in Einstein's paradox was that it was not an interaction of particles in the sense of classical physics but of the micro-objects simultaneously possessing both corpuscular and wave properties.

The understanding of the interaction between the measuring instrument and the measured atomic object as uncontrollable interference with a phenomenon, an understanding which was considered to form the basis of quantum mechanics, created an erroneous impression both of the content of this theory itself and of the new element that it contributed to philosophy. The idea of uncontrollability in principle is a distorted, exaggerated expression of the need to reflect in the logic of concepts something unexpected introduced into science by the development of atomic physics. The quest for these concepts or, in Bohr's words, the perfecting of the terminology and argument, and the development of the formulation of the approach to the cognition of atomic phenomena that he described by the concept of complementarity, all this is discussed in his famous book *Atomic Physics and Human Knowledge*, the deep philosophical content of which, in our view, is still far from being assimilated.

One can clearly trace in this book how Bohr (who never attributed decisive significance to formal schemes in logical analysis), surmounting the contradictions, came, not directly, but by a zigzag path, to a materialist and dialectical interpretation of quantum mecanics in order to become convinced in and steadily follow an already definite, clear philosophical road. Whereas, in his first articles (during the thirties and forties), when discussing the problems of quantum mechanics, he spoke not so much of the objective character of the quantum description as of the observer and ascribed to the idea of uncontrollability in the sense mentioned above the main role in establishing order in the apparent chaos into which physics had been plunged by the quantum theory, he changed his point of view, as is well known, in his last publications. The turning point in this respect was his paper Discussion with Einstein on Epistemological Problems in Atomic Physics (1949).[59] One can clearly see in it the struggle between concepts that in time would leave the pages of his works and concepts that were in better accord with quantum mechanics and its mathematical apparatus that was established and checked experimentally. Let us cite, in this connection, what seems to us the most lucid passage in this paper.

In stressing the idea that no matter how far phenomena might go beyond the context of a classical physical explanation, the experimental data should be described by means of classical concepts, Bohr concluded that a sharp line could not be drawn between '*the behaviour of atomic objects and the* *interaction with the measuring instruments which serve to define the conditions under which the phenomena appear*'. Furthermore, he formulated an idea about complementarity that quantum effects were responsible for the impossibility of comprehending the 'evidence obtained under different experimental conditions ... within a single picture'; rather the evidence 'must be regarded as *complementary* in the sense that only the totality of the phenomena exhausts the possible information about the objects'.[60]

When one puts together everything that Bohr said in his discussions with Einstein, and bears in mind the interaction between the measuring instrument and the micro-object, one has to note that this interaction is not a *physical* or *force* interaction. Fock in pointing out the unsatisfactory character of Bohr's term 'uncontrollable interaction' said: 'As a matter of fact, it is a matter here not of an interaction in the proper sense of the term but of the logical connection between the quantum and classical methods of description at the junction between that part of the system which is described in quantum-mechanical terms (the object) and that part which is described in classical terms (the measuring instrument).'[61]

Ideas of this kind led to the now well-known propositions that the classical conception about the motion (behaviour) of a particle is limited (this is expressed by the uncertainty relation), that there is relativity with respect to the means of observation characteristic of quantum mechanics, and that atomic objects are described through physical concepts that are more precise and general than those of classical theory.

In this book it is neither possible nor necessary to set out the logical aspects of these considerations in greater detail, but we would like once more to emphasise that Bohr never tired of developing and logically perfecting the approaches to the cognition of atomic phenomena which he had defined through the concept of 'complementarity'. Correct application of this concept, according to him, implied recognising that the interaction between atomic objects and the measuring instruments constituted an inseparable part of the quantum phenomenon, and not recognition of observation as 'interference with a phenomenon'.

The following scheme summarises what has been said in this section about the interaction of the measuring instrument and the object measured.

Classical Theory. The *force* interaction and *controllability*. Einstein saw the ideal for the quantum theory as well in an understanding of measurement of this kind.

Quantum Theory. a) *Force* interaction and *uncontrollability* (complementarity). This understanding of measurement in quantum mechanics was developed by Heisenberg and Bohr in the thirties and forties.

b) *Non-force* interaction in the sense of a logical interrelation and *uncontrollability* (complementarity). This understanding of measurement in quantum mechanics was held by Bohr in 1949.

c) *Complementarity* and *relativity* with respect to the means of observation. The concepts of controllability and uncontrollability have no meaning. This is the contemporary understanding of measurement in quantum mechanics.

It must be remembered that points (a), (b), and (c), when regarded on the historical plane, were not, so to speak, rigid.

* * *

In conclusion, let us make a few comments on the role of the instrument in the theory of knowledge in relation to atomic physics, without which the content of the above may not appear concrete.

We shall not consider the instrument here specially as the most important means for cognising physical phenomena; scientists are quite familiar with this question in practice; as for its theoretical aspect, that has been thoroughly analysed in the existing literature on physics, and it is not our business to go into the details of it. We would like simply to note that the natural shortcomings and limitations of the sense organs that supply us with information on the external world are surmounted in the cognition of nature, as we well know, by combining them with the activity of thought; the material expression of this is precisely that man makes and uses instruments.

The progress of pure and applied science has led to the creation of a system of instruments, or experimental devices, unified into a single, organic whole that can be called a developed experimental set-up.

Every developed experimental set-up usually includes four elements: (1) a recording device that fixes the phenomena in the instrument by which the objects being studied are judged; (2) apparatus that makes it possible for phenomena not directly perceivable by a given sense capacity to be comprehended in a mediated way, through other phenomena that are directly perceivable by this sense capacity; (3) apparatus that expands the limits of perception of a given sense capacity; (4) an experimental device that supplies the energy to bring the recording instrument into the state in which it can perform its functions. The elements of a developed experimental set-up can be combined with one another, and the last three elements exist just so that the recording apparatus can best perform its task, i.e. fix the appropriate phenomena in the instrument.

The experimentation implies, besides use of an instrument by which a phenomenon or object is studied (it figures above as an element of a developed experimental set-up; it can be called an instrument in the proper sense of the term), the realisation of certain conditions without connection with which the existence of the phenomena being studied cannot be discovered. These conditions are either sought in nature (natural conditions: in this case experimentation passes into observation) or created by the experimenter by means of the appropriate experimental set-up. Examples of such set-ups are provided by the physics equipment and instruments of all kinds that either reproduce the appropriate set of phenomena or create conditions in the absence of which it is impossible to know anything, in a certain respect, about the phenomena being studied (e.g. vacuum equipment to study the properties of a gas in a strongly rarefied state; prisms to study light; diffraction devices and the cathode-ray tube to study electron behaviour). It can be called *initial-state preparation apparatus** and it also constitutes an element of a developed experimental set-up.

To do its job the initial-state preparation apparatus is joined to the set-up proper and forms a united whole with it during the research.

These two types of experimental apparatus cannot, however, be identified either physically or logically, although one can find cases in the literature where it is done. Fock has stressed the need to distinguish between them (in the terms

* The term 'initial-state preparation apparatus' is justified from the standpoint of the measurement problem in quantum mechanics. It is also used when discussing measurement problems in classical mechanics. (See Willis E. Lamb, Jr. An Operational Interpretation of Non-relativistic Quantum Mechanics. *Physics Today*, 1969, *22*, 4: 23.)

of the experiment) when it is a matter of measurement in quantum mechanics.[62]

In classical theory the preparation apparatus provides the conditions in which the phenomenon being studied is least distorted by disturbing effects as yet unknown to the researcher. In quantum mechanics this apparatus creates conditions outside which, and independently of which, there can be no phenomena for cognising the corpuscular and wave aspects of an atomic object's behaviour. Thus, we repeat, a part of the apparatus is included in the phenomenon, while the instrument proper is something external in relation to the phenomenon it serves to cognise.

At the same time, the difference between the preparation apparatus (which belongs, in a certain respect, to the system observed) and the instrument proper (which in a certain respect cannot be separated from ourselves) should not be exaggerated; it is relative, not absolute. Bohr well understood that a sharp line cannot be drawn between the cognised object and the cognising subject, the system observed and the equipment used to observe it (he analysed many aspects of this question in nearly every one of his publications). One illustration that he gave himself is striking. If a blind man holds his stick firmly in his hand 'it can serve as a sort of prolongation of the latter to explore the surroundings by touch'. On the other hand, if it is held loosely, 'it becomes itself an object whose presence is revealed to the hand by the sense of touch, and it loses thereby its function of instrument of observation'.[63]

Let us return to Heisenberg's experiment with the X-ray microscope. The observer learns the electron's position with an accuracy that is the greater the shorter is the light wavelength, i.e. light (with its wave properties) serves as a means of cognising the electron's behaviour; the quantum properties of this same light (which represents a flux of photons), however, make it a sort of inseparable part of the electron's cognised behaviour. In the end, the electron's position and momentum prove to be complementary concepts.

Still, the relative difference between the preparation apparatus and the instrument as a means of observation considered above, or, if the matter is considered more broadly, between the cognised object and the cognising subject, or, even more broadly, between matter and mind, is not a relative and only a relative difference. It was the understanding of this difference as exclusively relative that lay at the philosophical foundation of the interpretation of quantum mechanics in which uncontrollability in principle, the idea that a wave function is a record of the observer's information, was lauded to the skies by positivism and other idealist trends in contemporary philosophy.

When we analyse philosophical concepts and statements appertaining to the problem of the interaction between the measuring instrument and the atomic object, we cannot avoid the basic philosophical question of the relation between matter and mind. In *Materialism and Empirio-criticism* Lenin developed Engels' formulation of this question and stressed the absolute nature of the opposition between matter and mind within the context of the basic question of philosophy, namely, what should be taken as primary, and what as secondary. 'Beyond these bounds,' he wrote, 'the relative character of this antithesis is indubitable.'[64] This relativity which has been 'blown up' by positivists and subjective idealists in a one-sided way, was not seen by representatives of metaphysical anti-dialectical materialism.

Lenin's ideas provide the necessary basis for successful quests for a solution of philosophical problems concerned with the relation between the cognising subject and the cognised object.

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X

AXIOMATICS AND THE SEARCH FOR PRINCIPLES AND FUNDAMENTAL CONCEPTS IN PHYSICS

1

The Axiomatic Approach to Physical Research

Nature is one in its diversity and is matter in motion This idea of dialectical materialism has become a common view of modern physics that is reflected in its methodology and logic as well as in its content. The two principles of the development and the unity of nature are also linked by modern physics in its explanation of and search for new phenomena and laws; one of the main tasks of this chapter is to demonstrate this.

Strictly speaking, the definite general view of nature (the world-outlook problem) held by physics at one period or another of its historical development has always been internally connected with the logic of research characteristic of it at the same period (the methodological problem). That was the situation before classical physics, when physical knowledge based on the everyday observation and lacking (with certain exceptions*) systematic methods of research, corresponded wholly with the very general and indefinite views of the philosophers of the period and their sometimes (if one thinks of ancient philosophy) inspired natural-philosophic guesses. That was also how it was in classical physics when the method of research proclaimed by Newton, and later called the method of principles, which was a sort of modification of Euclid's axiomatics, had a certain correspodence with the atomistic approach to nature (which was held by Newton himself).

The unity of nature is reflected in the unity of cognition.

* We have in mind Archimedes' statics.

This unity found its original form in axiomatics; geometrical knowledge was the first part of the knowledge of its time to become a science, in being constructed axiomatically by Euclid. Euclid's geometry is a logical system of geometrical concepts where statements follow from one another so precisely and consistently that from the point of view of the thinking mind none of them raises any doubt.

At the same time, Euclid's geometry was not created by reason out of itself and was by no means an *a priori* construction. The word 'geometry' ('land measuring') itself witnesses that it developed out of practical needs, namely, from the requirements of measuring plots of land (in the states of antiquity) and from astronomical observations (in ancient Egypt and Babylon), as a generalisation of the corresponding observed data. Before Euclid, the mathematicians of the day were occupied in solving many mathematical problems of everyday life, the connection between which they did not always grasp, and with the properties of individual geometrical figures (the triangle, circle, etc.); they knew individual theorems but they could not deduce them from a single logical principle. This empirical approach to geometry (and in general to mathematics) was historically inevitable in its first stage of development. After Euclid (it has long been a commonplace) such an approach was no longer necessary.

Does this circumstance mean that geometry (and, therefore, its development) has not drawn anything from experiment since Euclidean times? To answer that, let us compare the axiomatic construction in geometry (at least its general features) with the axiomatic approach (or axiomatic method of research in the broad sense of the term) in physics, which has been established in this science since Newton, and analysis of which is one of the main tasks of this chapter.

The complete or closed system of one physical theory or another (classical mechanics was the first to take this path) consists of basic concepts and principles (called axioms in geometrical language) which link these concepts through certain relations, and of corollaries that are deduced from the axioms by logical deduction. It is these corollaries that should correspond to the experimental data (be checked in experiment). A physical theory cannot be *physical* without this, or rather experiment and only experiment is the criterion of truth of physical theories, i.e. only experiment finally certifies that a theory reflects objective reality and, therefore, certifies that the mathematical apparatus (formalism) of the theory is appropriate.

The axiomatic approach in physics thus enables its theories to master the truth through logical thinking. Modern physics distinguishes six closed systems of concepts, connected by axioms each of which describes a certain sphere of phenomena of nature. The *first* system is Newtonian or classical mechanics, which includes statics and dynamics. The *second* system formulated for the purposes of the theory of heat is connected with (but by no means is 'reduced' to) classical mechanics through the statistical approach. The *third* system was deduced from the study of electricity and magnetism (and given shape by Maxwell). The *fourth* system is the (special) theory of relativity, a kind of combination of classical mechanics and Maxwell's electromagnetic theory that was given final form in the work of Einstein and Minkowski. The *fifth* system embraces primarily quantum mechanics, and through it the theory of atomic spectra and chemistry. Finally, the *sixth* closed system of concepts is the general theory of relativity, which was given this name by its author, Einstein, and has not yet found its final form as a *physical* theory (it mainly consists of a developed mathematical apparatus). In addition, the possibility of the existence of a *seventh* closed system of concepts must be mentioned which may have to be formulated in connection with the construction of a modern theory of elementary particles, and which would link quantum mechanics and the theory of relativity in a deep synthesis.

Each system of concepts in physics has a corresponding mathematical apparatus (formalism) inherent to it, which describes a definite domain of physical phenomena, evidence about which is provided by experiment; the limits of the applicability of a system's concepts are also established by experiment (as regards their correspondence to nature). We shall discuss the relation between these axiomatic systems in the sections that follow.

The experiment, of course, has no direct connection with the closed systems of geometry, but the needs of the experimental sciences (i. e. all the sciences about nature) frequently present mathematics with certain tasks (the physical sciences usually do it through their formalisms), which the latter either fulfills, or will later. In this sense (in a mediated way) the mathematical disciplines are also connected with experiment. Even in the direct sense, although not altogether conventionally, geometry may be an experimental science. One can read this in Newton's works*, and in Einstein it is formulated even more definitely. 'If ...,' he wrote, 'one regards Euclidean geometry as the science of the possible mutual relations of practically rigid bodies in space, that is to say, treats it as a physical science, without abstracting from its original empirical content, the logical homogeneity of geometry and theoretical physics becomes complete'.[1]

The whole strength of mathematics is that it not only can but has to abstract from 'its original empirical content' if it wants to obtain new scientific results. In certain conditions, however, especially when the matters of the relation between mathematics and objective reality, or the objective meaning of its concepts and theses are being studied, it returns to its 'empirical content', which provides new stimuli for its development. This was the case, for example, when the differential and integral calculuses were formulated, or when Gauss failed to confirm the ideas of non-Euclidean geometry through measurements; and it was done in its own way, and at a higher level of development of mathematics and physics, by Einstein's theory of gravitation.

Thus, it follows even from this preliminary sketch of the axiomatic and empirical approaches to geometry and physics, that these approaches do not contradict each other and do not totally exclude one another. Such a counterposing was quite frequent, nevertheless, in the rising science and philosophy of the ancient world, and in the Middle Ages; according to the thinkers of Ancient Greece, experiments were an improper occupation, while the medieval schoolmen who, of course, respected only the authority of Holy Scripture, succeeded only in developing formal logic. From the time of Renaissance, which corresponds to the starting point of the modern science (in the broad sense of

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* In Newton's words, 'geometry is founded in mechanical practice and is nothing but the part of universal mechanics which accurately proposes and demonstrates the art of measuring'. *Sir Isaac Newton's Mathematical Principles of Natural Philosophy and His System of the World* (CUP, Cambridge, 1934), p XVII.

the term) and the new philosophy, counterposing of the axiomatic and empirical forms of approach as the absolute opposites slowly but consistently disappeared from basic research and the struggle of ideological trends. These opposites became relative, while the axiomatic and empirical approaches proved to be aspects of a single general method of research in modern science, though even now one runs across relics of the old counterposing of these approaches in the relevant literature.

* * *

Let us consider certain features of the axiomatic method of research more closely.

This method has changed and been enriched with new possibilities of explaining and predicting the phenomena studied since Euclid's times. Whereas it could be spoken of in its initial, as one might say Euclidean, form as '*informal*' or '*material axiomatics*'[2] (as Kleene puts it), now, since Hilbert's famous work and studies in mathematical logic, axiomatics appears as both 'formal' and 'formalised'. These two notions differ from the first in the concepts and their relations appearing in them in their pure form, as it were, free of empirical content, and in formalised axiomatics the language of symbols (formalism) is employed instead of verbal language, while in the material axiomatics deduction is not in fact isolated from empiricism and visualisation.

This also applies *mutatis mutandis* to axiomatic constructions in physics. In the axioms or principles (sometimes called fundamental laws) of Newton's mechanics it is a matter of inertial mass and force, acceleration, space and time, and the relations between these concepts. They (i. e. the relations and concepts) are the original ones in the context of Newton's mechanics and by themselves are idealised expressions of experimental facts. First expounded in Newton's *Principia*, they can serve as a model of informal axiomatics in classical physics.

The development of the axiomatic method in physics for the most part repeats its development in geometry. In modern physics, with its very complex and ramified mathematical apparatus, one has every right to speak of the existence of formal, and especially of formalised, axiomatics (which in a certain sense is the pinnacle of development of the axiomatic method). This has become absolutely clear since the establishment and construction of the theories of non-classical physics. A rigorous, and to some degree exhaustive, analysis of the related questions would take us far beyond the framework of this chapter; we shall try to give just a general idea of what the issue is.

Consider the equation

$$F = \frac{d(mv)}{dt}.$$

It expresses Newton's second law, which implies that the mass of a body is constant. This equation, however, can be also considered in the context of the special theory of relativity; in this case m denotes

$$m = \frac{m_0}{\sqrt{1 - v^2/c^2}},$$

where m_0 is the mass of a motionless body, ('the rest mass'), v is the body's velocity, and c is the velocity of light. This equation thus expresses the law of relativistic mechanics which implies that the mass of a body changes with its velocity. It may also express the law of motion in quantum mechanics; it is well known that in quantum mechanics, and in classical mechanics, quantities are connected (as we know) by the same equations, but in quantum mechanics they contain operators, i. e. concepts of a different mathematical nature than those of classical mechanics.

The reader may rightly ask what the basis for such 'substitutions' in the equations is (i. e. for replacing numbers by operators, and m by a more complex expression), and what is in general their logical meaning. To answer this means to talk about the very content of classical, relativistic, and quantum mechanics, the transition from the special theory and its concepts to the deeper, more general theory, whose concepts are more meaningful than those of the special theory, i. e. from the angle of the above, it is equivalent to speaking about the understanding of mass in relativistic mechanics and of the way this understanding was reached, and of the fact that, in quantum mechanics, operators mathematically depict physical cases that are never met by classical theory, to talking about the very logic of the rise of the special theory of relativity and quantum mechanics.

We would like, thereby, to emphasise that the formal and formalised axiomatic constructions of a physical science embrace the development of its content, promoting deeper and deeper comprehension of nature. It must be noted here that the interpretation of its formalisms has special significance in physics compared with the analogous problem in mathematics; we shall discuss this below.

In what way is the axiomatic method essential for physics? In its logical and methodological aspects, the significance of this method in physics (both in the form of material axiomatics and in its higher forms, the formal and formalised) is not simply great but, as we shall try to show, cannot be overestimated. When it is compared with other methods of research, one cannot but agree with Hilbert who said about the axiomatic method in mathematics, that 'notwithstanding the great pedagogical and heuristic value of the genetic method, the axiomatic method is preferable for the final representation and full logical substantiation of the content of our knowledge'.[3]

It seems to us, we repeat, that what Hilbert said about the axiomatic method in mathematics applies as well to physical axiomatics. In this case, of course, as always, one must not succumb to the extreme view and exaggerate Hilbert's profound thought.

Let us begin with the *genetic* method mentioned by Hilbert. We shall touch on its content, but in a way rather different from Hilbert's.[4] We wish to speak of the role of the genetic method in cognition and at the same time, unlike Hilbert, to stress that it is, in its own manner, 'included' in the axiomatic one.

How is the concept of number introduced? Assuming the existence of zero and starting from the statement that when a number is increased by one the next number emerges, we obtain a natural series of numbers and develop the laws of counting with them. If a natural number a is considered and one is added to it b times, we obtain a number $a + b$ and thereby define (introduce) the operation of *addition* of natural numbers (and with it a result called the sum).

Let us now add a numbers b times; we thus define (introduce) the operation of *multiplication* of natural numbers and will call the result of the operation the product of a and b, denoting it by ab. In a similar manner, omitting the corresponding argument, we define the operation of *raising to a power*.

Consider the so-called inverse operations of addition, multiplication, and raising to a power. Assume that we have numbers a and b; how can one find the number x that satisfies the equations $a + x = b, ax = b, x^a = b$? If $a + x = b$, then x is determined by substraction; $x = b - a$ (the result of which is called the difference). The operations of *division*, *extracting the root*, and *computing the logarithm* (the last two operations are inverse in relation to raising to a power) are introduced in a similar manner.

With these definitions as the basis, it is possible to construct the axiomatics of natural numbers. The relevant axioms can be grouped: a) axioms of conjunction; b) computational axioms; c) axioms of order; d) axioms of continuity. We shall not dwell on their analysis (Hilbert's book has everything necessary about this, the difference between his presentation and ours being, however, that in his work these axioms function as those of a *real number*; this point will be clarified below).

We have come to the main point of our argument. As follows from the practice of looking for solutions of equations in which these numbers appear (they were interpreted as natural numbers, but from the standpoint of arithmetical axiomatics they are usually considered as the *positive integral parts of a rational number*; it seems to us that this is only correct when they are approached retrospectively), the inverse operations (subtraction, division, root extraction) cannot be performed in every case. We shall not cite the relevant facts; they are well known now to any schoolchild, but will assume that the inverse operations are realised *in all cases.* As a matter of fact, this assumption came true in arithmetic during its historical development, and in the end as a kind of logical résumé of this development, whole numbers of integers and *fractions*, positive and *negative* numbers, rational and *irrational* numbers entered it.

This kind of dividing of a natural number into these two opposite elements, and the relation between them led to the concept of relative number, of number as a ratio, and of a real number; the last consequently developed from the simple concept of a natural number through successive generalisations. The concept of a real number is being developed further in modern arithmetic, but what we have said is sufficient for our purposes.

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To go deeper in points considered above would mean to sink ourselves completely in the content of scientific disciplines appertaining to mathematics that were created to analyse them. We are interested only in what follows.

In assuming that inverse operations are realisable in all cases, for instance, if one has subtraction in mind, that it is possible to subtract a bigger number from a smaller one (i.e. to solve the equation $a - b = x$ where $b > a$), we thereby already go beyond the context of the theory of natural numbers. Assumptions of this kind imply looking for and introducing (defining) new concepts of number, broader and more meaningful in their totality than the concept of a natural number. To do that axioms formulated during introduction of natural numbers are employed, which are regarded as embracing new numbers which make it possible to give appropriate definitions of the latter. One can demonstrate in an example of subtraction that as a result of applying axioms we can obtain, say, $(14-6)-10 = (10-2)-10$ or $4-6 = 0-2$.

Similarly one can define (introduce) the numbers $0-1$ or -1, $0-2$ or -2 (which we have done), $0-3$ or -3, $0-4$ or -4, $0-5$ or -5, etc. By comparing negative numbers with natural numbers, we can easily see the opposition between them; therefore, if the natural numbers are denoted as *positive* integers, the new numbers should be called *negative* integers.

Introducing natural numbers we *deduced* the axioms applying to them; now these axioms *define* a new class of numbers which appear as positive and negative integers (i.e. as relative numbers). The formal aspect of the axioms themselves remains the same, but their content becomes richer: it is already impossible to define the addition of negative numbers, and the addition of negative and positive numbers as a consecutive increase of a number a by one b times, although all forms of addition unknown to the theory of natural numbers (as well as the addition of natural numbers) are covered by the system of axioms formulated as the axiomatics of natural numbers. Only now the symbols in the axiom equations signify new numbers found through these axioms, rather than natural numbers.

Fractions and integers, irrational and rational numbers are introduced in a similar manner. From this angle a series of natural numbers is a set of positive integers and rational numbers that oppose negative integers, fractions and irrational numbers that do not belong in this series.

Feynman called application of the axiomatic method to determine new, broader classes of numbers (in our example, natural numbers → relative numbers → numbers as ratios → real numbers), an application in which the heuristic function of axiomatics, so to say, becomes explicit, an 'abstraction and generalisation'.[5] This method was, as a matter of fact, used by Marx in his *Mathematical Manuscripts*, when he developed the dialectics of the transition from algebra to differential calculus.[6] A dialectical analysis of certain aspects of questions arising can be found in the work of I. A. Akchurin et al (1968).[7]

In this application of axiomatic method it is stressed in fact that axiomatics by no means excludes acceptance of the variability of basic concepts and logically closed theories; on the contrary, it implies the necessity for new basic concepts and principles to arise. Everything that makes the axiomatic method so valuable for the logical shaping and the full logical substantiation of scientific theories gets its true (and not in the formal-logical sense) completion and expression adequate to reality through this kind of application of axiomatics.

Bourbaki expressed this beautifully about mathematics: 'The unity which it [the axiomatic method—*Ed.*] gives to mathematics is not the armor of formal logic, the unity of a lifeless skeleton; it is the nutritive fluid of an organism at the height of its development, the supple and fertile research instrument to which all the great mathematical thinkers since Gauss have contributed, all those who, in the words of Lejeune-Dirichlet, have always labored to "substitute *ideas* for *calculations*".'[8]

The situation in physics is much the same. The principle of relativity, for instance, which is a consequence of the principles of Newton's mechanics, i.e. the principle of relativity in Galileo's form of it, did not hold in the case of the propagation of light. The phenomenon was governed by the principles of electromagnetic theory. It thus became a matter of expanding the sphere of applicability of mechanical principles by including electromagnetic phenomena in it. This meant, however, that the principles of Newton's mechanics should form a single integral system with the principles of electromagnetic theory. Their combining led to the birth of new concepts that were broader and more meaningful than those of classical mechanics. The concepts of space and time were the first to undergo change; the concepts of absolute space and absolute time disappeared; they were replaced by the concepts of relative space and relative time, which proved to be aspects of a single four-dimensional space-time continuum. Galileo's transformation (which connects inertial reference frames in Newtonian mechanics and implies absolute space and time) was accordingly replaced by the Lorentz transformation (which connects inertial reference frames and implies relative space and time). The principle of relativity had already appeared in its generalised Einsteinian form, and relativistic mechanics emerged.

Our second example is provided by quantum mechanics. In this theory (which is discussed here with its logically closed form in mind) there is a basic postulate: namely that for each physical quantity (dynamic variable) in classical mechanics there is a certain linear operator in quantum mechanics which acts on the wave function; it is assumed that the relations between these linear operators are the same as between the corresponding quantities in classical mechanics.

In quantum mechanics a postulate that connects an operator with the value of a quantity characterising the reading of the measuring instrument (by means of which knowledge of the micro-object is obtained) also has a basic role.

Our two examples represent a kind of logical summary of the state of affairs that had developed in the theory of relativity and quantum mechanics when these theories were constructed. Like any summary, it does not depict the whole diversity of the logical and actual situations that had built up when these theories were being created, does not reproduce the details of the combination of thought and experiment which brought the principles of these leading theories of modern physics into being. In order to avoid possible misunderstandings in clarifying the method discussed here by which the new concepts were found (by means of axiomatics) we must draw special attention to the fact that axioms, having been deduced in the defining of such-and-such fundamental concepts become in turn the basis for deducing new, broader, more meaningful fundamental concepts than the initial ones. The equations expressing the axioms now contain symbols without real meaning; and the essence of the matter is how to find these real meanings, i.e. to find new concepts (and that means to construct a new theory). This is done, as we know, by the methods of mathematical hypothesis, fundamental observability, and other theoretical techniques of modern physics.

When one takes such circumstances into account, it becomes clear that although (we shall take a well-known example) the structure of the axioms of relative numbers or real numbers is identical with the structure of natural number, it is impossible still to learn just from this isomorphy, how, say, one should add or multiply negative numbers. Similarly, the fact that the structure of the principles in classical, relativistic, and quantum mechanics is the same does not by itself guarantee knowledge of the main laws of relativistic and quantum mechanics (when the laws of classical mechanics are known). It is useful to recall Engels' remark here on the law of the negation of the negation. Knowledge of the fact that this law of dialectics covers the development of grain and the calculus of infinitesimals, he said, 'does not enable me either to grow barley successfully or to differentiate and integrate[9]'. As we have seen, the situation with axiomatics is similar. That, however, does not diminish the fruitful methodological role of the laws of dialectics, or of axiomatics, in any way; it is worth stressing once more that this methodological role is not the dogmatic finger of the Almighty even when this deity appears disguised as a scientist.

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The problems of axiomatics considered above necessarily include the problem of interpretation. We shall discuss it here in concluding this section. M

The concept 'interpretation', as it originated in mathematics and was adopted in modern logic, does not coincide with the normal usage of the concept (or of 'comment'). Interpretation brings out the meaning of the symbols and formulas in scientific theories in which the axiomatic method plays a leading role (in the deductive sciences which, according to Einstein, include physics as a fundamental science). Interpretation rests not on a visualisation but on certain logical foundations which we shall not analyse here. It establishes a system of objects that form a domain of values of the symbols used in a theory, and its job as a logical operation consists precisely in determining the objects in which the symbols and formulas of the theoretical system can be realised.

The following difference in the meaning of the concept of interpretation in mathematics and physics, which individual authors sometimes find it difficult to see, is of great significance. The logical operation of interpretation can play a decisive role in mathematics in certain conditions in clarifying matters that are very important for mathematical knowledge (for instance, the problem there used to be of the consistency of non-Euclidean geometry). But for all that, the main point is not the connection of the symbols (terms) and formulas (relations) of its theories with the objectively real world. Mathematics is not liberated in principle from this connection, of course, regardless of attempts of idealistically-minded authors to do so (about which we have spoken above). There is no immanent necessity, however, in mathematics itself for the values of the symbols of its theories, and through them also the symbols, to be connected with the data of observation and experiment. This fundamental feature of mathematical theories is expressed quite clearly and definitely in the systems of formal axiomatics. In Hilbert's *Grundlagen der Geometrie* (Foundations of Geometry) for example, 'points', 'staight lines' and 'planes' denote those things (objects) and their relations in respect of which only one assumption is made, namely, that they satisfy the axioms; in Hilbert's geometry one abstracts oneself from the visualised points and straight lines of Euclid's meaningful geometry (which represent idealisations of the normal solids, and the relations between them).

What is the situation in physics in this respect? In both physics and mathematics the formalisms of their theories can be given more than one interpretation. For instance, the axioms formulated by Hilbert can be interpreted in a way in which they are given in Euclid's *Elements*, and also in such objects of theoretical arithmetic as real numbers (analytic interpretation). And in physics, if we take, for example, the expression

$$E=\frac{p^2}{(2m)}+V_{\text{pot}},$$

it can be interpreted as a formula of total energy in classical mechanics, and also as the Schrödinger equation if one has in mind the operator form of this expression; it then becomes

$$\left(E-\frac{p^2}{2m}-V\right)\psi=0,$$

where

$$E=-\frac{\hbar}{i}\frac{\partial}{\partial t}, \quad p_x=\frac{\hbar}{i}\frac{\partial}{\partial_x}, \text{ etc}$$

Notwithstanding this, however, the symbols of formalisms in physics are necessarily connected with the readings of instruments and with observational and experimental data, i.e. the symbols in physical theories must be connected through interpretation with the objectively real world. Mathematics, as we have seen, operates differently. Without so-called empirical, or natural interpretation a physical theory is not a *physical* theory, in the same way as without formalism a physical theory is not a physical *theory*.

From this standpoint, if every scientific theory* in general is built up from logical (or, in certain special conditions, mathematical) apparatus (formalism) corresponding to it and its interpretation, a *physical* theory consists of a formalism (mathematical part) and an empirical interpretation (the visualised part). This does not, of course, mean that such-and-such a physical theory (or rather, its formalism) cannot be interpreted through the objects of another physical theory; it means only that no physical theory, if, we repeat, it is to be called a *physical* theory, can do without empirical interpretation. The transition from the data of observation or experiment to the formalism of theory, and from the formalism of theory to the data of observation or experiment (it is only as a result of such a transition that a real theory can be formed) is a very complex process, a leap that can only be analysed by dialectical logic.

With construction of the theories of modern physics, the view became common that the laws of classical mechanics,

* We would remind the reader once again that this concerns deductive theories.

say, were not absolute universal laws of nature and were limited to a certain realm of physical phenomena or (in a rather modified and more general form) that it was impossible to regard the laws of the macroworld as valid in the microworld. This understanding of the laws of physics was consistently introduced in relation to the mathematical apparatus of the theories (in the developed formalism of the special theory of relativity four-dimensional vectors were employed, in quantum mechanics linear operators). But with respect to the rules of the relation of the concepts of the formalism (i.e. mathematical abstractions) to the experimental data (without which these concepts have no real physical meaning) such understanding of physical laws is not accepted by all authors, or rather they do not allow sufficiently for the fact that the rules of the connection between the formal concepts and the experimental data (or the receipts for the transition from mathematical quantities to physical ones) do not necessarily coincide in classical and non-classical theories. It is worth recalling here the interpretations given to the mathematical apparatus of the special theory of relativity and quantum mechanics by the opponents of Einstein's and Bohr's conceptions.

One can consider the rules of connection of the concepts of a theory's mathematical apparatus with the experimental data, or the concrete receipts that govern the connection of the mathematical quantities in the formalism with the physical ones, as expressions (definitions) of the corresponding physical concepts. This means, from this standpoint, that the construction of a new fundamental theory implies the exclusion of certain old fundamental concepts (which are retained in the old theory) and the introduction of new ones. The exclusion of the old fundamental physical concepts in the cause of creating a new theory is far from simple. So far the idea is still maintained in one form or another in the scientific literature that it is necessary and sufficient to be satisfied with the fundamental concepts of classical physics (space, time, motion, particle) in any physical theory. The receipts of the transition here from mathematical quantities to physical ones in the new theory do not so much make it possible to embrace the new objective reality at which the old theory came to a stop, as serve simply as a means of computation. Questions relating to this have been considered throughout our book.

Translation of the language of formalism into the language of experiment, and vice versa, in one physical theory or another or the reflection of objective reality by a theory, or, in short, the physicist's conversation with nature is a process of a kind in which one cannot take a step without dialectics.

2

Certain Aspects and Functions of the Axiomatic Method

Knowledge acquires its most developed and perfected form, as we know, in science (its model being physics), which ensures adequate cognition of nature. Systems and structural approaches are inherent in science as the highest form of knowledge, unlike other forms. Their presence means that a set of concepts considered outside the theoretical construction is not yet science.

From this point of view, the axiomatic method plays a most important role in science since it was developed historically as a method of theoretical construction of science and, therefore, as the method determining its architecture. The axiomatic method helps cognise the most general laws operating in the sphere of phenomena covered by any one science; axioms arise, or principles of an (axiomatically) created scientific system, which unite the set of interconnected phenomena under study into a single structure.

In an axiomatically constructed theory its statements are deduced from axioms. It would seem to follow from this that the axiomatic method, which ensures exactness of the concepts employed, and certainty, consistency, and conclusiveness in the argument, excludes the idea of flexibility of concepts, recognition of the variability of scientific propositions, and a transition from certain scientific theories to other, deeper ones. Hence the conclusion can easily be reached that this method simply serves in science for the full logical substantiation and final shaping of the content of scientific cognition, and that, by its nature, it is alien to dialectical thinking.

This assertion, however, is undoubtedly an extreme one. Introducing order into the language of scientific or theoretical concepts is an essential task of the axiomatic method, but it cannot be reduced simply to such putting into order. As we showed with examples in the preceding section, the axiomatic method allows one to find the new elements in physics not only in the sense that concepts or statements that exist potentially in a given theory are brought out and made explicit in the course of deduction, but also in the deeper sense that the method makes it possible to find new principles and fundamental concepts that are used as the logical foundation of a new theory. We find the same thing also in mathematics, to understand the essence of which is the major goal of the axiomatic method. According to Bourbaki, 'where the superficial observer sees only two, or several, quite distinct theories, lending one another "unexpected support"... through the intervention of a mathematician of genius, the axiomatic method teaches us to look for deep-lying reasons for such a discovery, to find the common ideas of these theories, buried under the accumulation of details properly belonging to each of them, to bring these ideas forward and to put them in their proper light'.[10]

Bourbaki's point of view on the axiomatic method in mathematics reflects the content and spirit of modern mathematics. It seems to us that the axiomatics in modern physics is similar to that about which Bourbaki writes; we shall try to demonstrate in what follows that that is the position.

How do physicists themselves deal with the question of axiomatics in their science? We shall briefly discuss the views of Einstein and Feynman.

Einstein believed it is possible, through the use of purely mathematical constructions, to find those concepts and regular connections between them that provide the key to understanding the phenomena of nature. The corresponding mathematical concepts could be prompted by experiment but they could not in any case be deduced from it. Einstein dwelt more than once on the point that experiment remains the sole criterion of the suitability of the mathematical constructions of physics. 'But,' he emphasised, 'the creative principle resides in mathematics. In a certain sense, therefore, I hold it true that pure thought can grasp reality, as the ancients dreamed.'[11]

Feynman, it would seem, disagrees with Einstein. So long as physics is not complete and we are trying to discover new laws, he says, 'we must always keep all the alternative ways of looking at a thing in our heads, so physicists do Babylonian mathematics, and pay little attention to the precise reasoning from fixed axioms'.[12]

According to Feynman, this situation will change when physicists know all the laws of nature, i. e. when physics becomes complete, and he believes that quite probable.[13]

Let us consider Einstein's and Feynman's statements in greater detail.

Both of them stress the explanatory and predictive functions of the axiomatic method as most important for any theory, but which do not lead beyond the context of this theory. While Einstein accepts this without reservation, Feynman acknowledges their greatest significance for theory in principle, i. e. for the time when physics has cognised all the laws of nature, which is quite probable (on the other hand, physics in the incomplete state it is in today needs a Babylonian, i. e. empirical, method when much is known but it is not completely realised that this known can be deduced from a set of axioms).

Thus, both Einstein and Feynman deny the function to the axiomatic method that we would call heuristic, i. e. the function of searching for a new fundamental theory (and, therefore, new axioms) that was discussed in general at the beginning of this section; in Einstein's statements this can be seen directly, but in Feynman's understanding the function of the search for new fundamental propositions belongs to the Babylonian method.

These considerations of theirs about the axiomatic method need, however, to be understood *cum grano salis*. Both of them draw attention to the fact that one cannot be content just with employing mathematics in physics. Mathematics, Feynman says, prepares the abstract reasoning that the physicist can use if he has 'a set of axioms about the real world'; but the physicist should not forget about the meaning to all his phrases, and 'it is necessary at the end to translate' the conclusions into the language of nature. 'Only in that way can (the physicist) find out whether the consequences are true. This is a problem which is not a problem of mathematics at all.'[14]

But the physicists' reasoning, he continues, is frequently useful to mathematicians; one science helps another. Without dwelling on this, let us look at Feynman's final thought: 'To those who do not know mathematics it is difficult to get across a real feeling as to the beauty, the deepest beauty, of nature.'[15]

Einstein said approximately the same thing, but unlike Feynman he put forward an additional idea that is quite essential on the plane of our problems.

Einstein more than once developed the idea that 'the axiomatic basis of theoretical physics cannot be extracted from experience but must be freely invented'.[16] That, however, does not mean at all that he adhered to Plato's philosophy or defended the *a priori* approach or questioned the possibility of finding the right way to understand nature. Einstein's statements have to be considered as a whole so as to judge his philosophical and methodological ideas in physics properly. He maintained that 'experience is the alpha and omega of all our knowledge of reality',[17] and that 'there is ... a right way, and that we are capable of finding it'.[18] He took his stand on the *many-sided nature* of cognition; this dialectical feature of his epistemological views was discussed in the first chapters of this book.'[19] Here we would like to draw the reader's attention simply to the following point.

One has to agree with Einstein when he stated, with the formal logic in mind, that the axioms of physics cannot be deduced logically from the empirical data. The axioms of physical theories, he noted, could not be reached by the 'logical path' but only by that of 'intuition based on penetration into the essence of experience'.[20] The term 'intuition', it seems to us, should be replaced by 'fantasy'; the most rigorous science cannot do without fantasy, as Lenin aptly said in his *Philosophical Notebooks*.[21] And that is not far from the idea that scientific creative work and dialectics are always in harmony. In Section 3 of this chapter we shall consider matters related to this more fully.

* * *

Einstein considered that there were shortcomings to some extent in Newton's views on the principles of mechanics, which consisted in the fundamental concepts and principles of his system, in the belief of the author of the *Principia*, being deduced logically from experience. The same idea about the basic laws and fundamental concepts of physics permeated the views of most scientists of the eighteenth and nineteenth centuries.

According to Einstein, as we have seen, such an understanding is erroneous; it was only the general theory of relativity that brought clear recognition of its erroneousness. The general theory of relativity, he said, 'showed that one could take account of a wider range of empirical facts, and that, too, in a more satisfactory and complete manner, on a foundation quite different from the Newtonian.'[22]

We do not think that the views of Newton and the scientists about whom Einstein spoke, do deserve such a characterisation. The axioms of classical mechanics were, in fact, deduced from the data of experience, but that does not mean at all that they were logically deduced (i. e. by means borrowed from formal logic). The principles both of classical mechanics and of other classical theories are generalised facts of experience, and the corresponding generalisations are made at the level of experimental data. As regards generalisation, it is not simply an operation in formal logic. 'The approach of the (human) mind to a particular thing,' Lenin wrote, 'the taking of a copy (a concept) of it *is not* a simple, immediate act, a dead mirroring, but one which is complex, split into two, zig-zag-like, which *includes in it* the possibility of the flight of fantasy from life.... For even in the simplest generalisation, in the most elementary general idea ("table" in general), *there is* a certain bit of *fantasy*."[23] In the principles of classical theories this is expressed through their content's possessing elements that cannot be deduced by the logical means of the given system.

The fundamental laws of many of the theories of classical physics were discovered in a similar manner (by the method of principles). Maxwell's electromagnetic theory was an exception since its principles were obtained by the method of mathematical hypothesis. This theoretical method has become widely used in non-classical physics; it visibly demonstrates the correctness of Einstein's idea that the fundamental laws and concepts of physics are free creations of the human mind. This method has great significance in finding from nature the principles of quantum mechanics and quantum electrodynamics. The method of fundamental observability had the same importance in obtaining the principles of quantum mechanics and of the special and general theory of relativity. Let us consider the general theory of relativity in the light of Einstein's remark above about it.

In Einstein's view the fact that one can point to two, essentially different theoretical foundations (classical theory and the general theory of relativity) that explain the appropriate set of experiments reveals the speculative nature of the principles that underlie the theory. But is the example of the general theory of relativity convincing in this respect?

Newton's theory of gravitation and Einstein's gravitational theory were in fact built and constructed as a generalisation of the same data of experience. The predictive function of Einstein's theory, however, as became clear, proved to be broader than the corresponding function of Newton's theory: the general theory of relativity predicted and explained phenomena which were obstacles to Newton's theory of gravitation (the motion of Mercury's perihelion; the deflection of light in the Sun's gravitational field). In addition, both theories also differ in certain respects, which precludes their comparison on one and the same logical plane, proposed by Einstein. The general theory of relativity could not have been created in Newton's time; furthermore, this theory itself would not have been constructed if there had not been the special theory of relativity, and the latter would also have not been formulated if classical mechanics had not existed.

In other words, Einstein's example is too abstract, although it can be used to illustrate his idea of the speculative nature of the basic principles of a theory in the sense above. If this example is translated to the plane of reality, it speaks not simply of principles being just *suggested* by the experiment (as was assumed by Einstein) but of the formation of the principles of a theory being dependent on circumstances appertaining to the level of development of physics and science as a whole, including philosophy, and also on the state of spiritual and material culture. This is the basis of the answer to the question why a theoretical system is almost unambiguously determined by the sphere of observations, although there is no logical way from the observations to the theory's fundamental principles and concepts.

Does all this mean that the principles of classical theory are generalised facts of experience, and the principles of non-classical theories something else? Let us note for the present (it will be discussed in greater detail in Section 3) that the principles of non-classical theories are also generalised facts of experience. Unlike classical theories, however, in which the generalisations are made at the level of experimental data, in non-classical theories the generalisation is made at the level of theory: the point is that, for example, classical mechanics was necessary for the special theory of relativity and quantum mechanics, as the basis for the description of experiments. With this is associated that function of the axiomatic method in physics whose existence could not be even suggested in eighteenth and nineteenth century science, and which took shape as non-classical theories developed. We shall now pass to questions relating to this.

We have several times pointed above to two functions of the axiomatic method. One of them, the ordering function (which unites the explanatory and predictive functions) expresses the tendency of a theory (as a certain system) toward logical completeness, and in this sense to the completion of its development as a certain theoretical system. The other function, the heuristic one (in which the axiomatic method finds ways of resolving the paradoxes that have arisen during the development of a theory), expresses the theory's tendency to go beyond the context of its system that makes it precisely such-and-such a theory and not another one. Below, to the end of this section, we shall discuss the axiomatic method from the aspect of its ordering function (the heuristic function being considered in Section 3).

The axiomatic method arose in physics, as we know, together with classical mechanics. Like Newton's mechanics, it is in some respect a product of Newton's Rules of Reasoning in Philosophy that he included in the third book of the *Principia*. These Rules have something in common with Descartes' Règles pour la direction de l'esprit. In the literature one more often meets a stressing of their differences, determined by the personal philosophical positions of Descartes and Newton (for example, Newton's sharply negative attitude to Descartes' theory of vortices is well known) than any mention of their similarity. In our view it is essential, in order to understand the philosophical essence of classical science when it was being built, to pay attention rather to the common element in Descartes' Règles and

Newton's Rules. It constitutes a part, as it were, of the 'spirit of the times' that also put its stamp on the content and laws of development of the science of the time, thereby promoting its very comprehension. Let us compare the two sets of rules in this connection.

Descartes:

1. Only that should be regarded as true which appears before the mind in such clear and lucid form that it does not provoke any doubt.
2. The difficulties that one encounters should be divided into parts so that they may be overcome.
3. It is necessary to start with the simplest objects and to ascend gradually to the cognition of the complex, assuming the presence of order even where the objects of thinking are not given in their natural connection.
4. It is necessary to compile the lists and surveys of the objects under study as fully as possible.

Newton:

1. 'We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearance.'
2. 'The same natural effects we must, as far as possible, assign the same causes.'
3. 'The qualities of bodies, which admit neither intensification nor remission of degrees, and which are found to belong to all bodies within the reach of our experiments, are to be esteemed the universal qualities of all bodies.'
4. 'In experimental philosophy we are to look upon propositions inferred by general induction from phenomena as accurately or very nearly true, notwithstanding any contrary hypotheses that may be imagined, till such time as other phenomena occur, by which they may either be made more accurate, or liable to exceptions.'[24]

Newton's Rules served as the foundation that produced the axiomatic method in physics as an experimental science. Descartes' Règles do not mention experiment at all; his position implied that the initial assumptions (axioms) of physics should be treated only as hypotheses, while clarity and obviousness were regarded as the criteria of truth.

There is thus a sharp difference in the interpretation of axioms and truth in physics in Newton and Descartes. One should remember, however, the hypothetical element in the content of the principles of Newton's mechanics (discussed above). According to Descartes and Newton, moreover, cognition developed from the simple to the complex and, if one allows for the fact that, as follows from Descartes' Règles, clarity is a kind of synonym of simplicity, and that Newton stressed, in his explanations of his Rules, that nature is simple and did not affect 'the pomp of superfluous causes', one can see that there is much in common between the two sets of rules in spite of certain serious differences.

There is nothing surprising in that. Descartes, a great philosopher and the founder of analytical geometry, occupied himself with mechanics, optics, astronomy and acoustics from his youth, and made outstanding discoveries in them. And he saw in mathematics a general method for studying the physical world. His ideas had a great influence on the development of classical physics and have, to some extent, affected the development of physics to the present time. Huyghens' wave theory of light, the analytical mechanics associated with the names of Euler, Lagrange, and Hamilton, Maxwell's electromagnetic theory, the field theory, modern quantum mechanics—all these disciplines, in one form or another, and to some extent or another, emerged and became established under the influence of Descartes' ideas. His methodological rules are a kind of spiritual ancestor of the method of mathematical hypothesis in modern physics, and of the modern view on the role of the mathematical apparatus in physical theory if one has in mind simply the mathematical form of the 'hypothetical' physics against which Newton fought. Let us, however, return to our theme.

One can see from the content of Descartes' Règles and Newton's Rules that a constructed physical theory should satisfy the principles of completeness, independence, and consistency in so far as it remains a finished system. This idea was expressed explicitly much later, when the logical foundations of modern mathematical knowledge were laid.

Let us touch on certain features of Newton's methodology compared with Descartes'.

Newton's fourth rule says that the statements drawn from phenomena by means of induction are trustworthy so long as they are not disproved by new phenomena. This rule directly points to the fact that 'experience is the alpha and the omega of all our knowledge of reality'; it would seem to be at a total variance with Descartes' methodology. The words quoted, however, are Einstein's[25] who did not diverge at all from Descartes in saying: 'But the creative principle resides in mathematics.'[26] We are consequently convinced once more that the opposition between Newton's and Descartes' Rules is not absolute, that the 'empirical' and 'mathematical' approaches in physics, when understood correctly, are not opposed to each other but complement one another, and form an inseparable unity.

Finally, let us make the last comment on the 'empirical' and 'mathematical' methods in physics, whose founders were Newton and Descartes respectively. Classical theories arose and developed, for the most part, in such a way (we mentioned this in connection with a different point in Section 1) that determining the formulas for measuring quantities in them (the definition of physical quantities) preceded the search for equations (i.e. the propositions and, finally, the axioms) of the theory, while the content of the physical concepts itself appeared to be independent of the axioms. Newton's definitions of relative space, relative time, and relative motion* were formulated independently of the axioms of mechanics; and these concepts figure in his axioms. In addition, he introduced definitions of absolute space, absolute time and absolute motion, but these concepts play the role in his theory rather of a certain purely philosophical supplement and not of physical concepts.** Newton's axiomatic method can be described as close to informal axiomatics.

Modern physical theories, on the other hand, arose by another axiomatic path that is close to formal axiomatics. When a theory is created in modern physics, its mathematical apparatus is first found, the physical meaning (content) of its concepts being still (totally or partially) unknown; their content is only revealed later as they become defined.

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* Newton wrote of the concept of 'relative time', for instance: '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 (Sir Isaac Newton. *Op. cit*, p. 61).

** Newton's 'relative time' and 'relative space', let us recall, do not coincide with the 'relative time' and 'relative space' of Einstein's theory of relativity.

Generally speaking, when an axiomatic theory is constructed, its fundamental concepts do not exist independently of the axioms; being governed by the latter, they can be defined through them. This circumstance was indicated, as a matter of fact, by formal axiomatics. To take an example from classical theory, Newton's first axiom can serve as an (implicit) definition of the inertial reference frame, one of the fundamental concepts of classical mechanics.[27]

Such are certain features of the axiomatic method in physics, when we consider its ordering function.

* * *

In conclusion, let us consider briefly the principles that must be satisfied by the axioms of a logically complete (axiomatised) physical theory.

The axioms underlying the theory of a certain sphere of natural phenomena are elements of a system that has a certain structure. This means that they are connected through relations, which include the independence of axioms and their consistency and completeness. Such an aggregate of axioms is called the set of axioms.

The independence of axioms expresses the fact that each axiom in a set is exactly a fundamental statement in a given theory; that is why it belongs to the set only of the fundamental propositions of a theory, in which no statement can be deduced from any other. If it is affirmed, for instance, that the exposition of a theory should begin with the simplest relations between its objects, it is the independence of the axioms in the content of the axiomatic method that expresses this statement.

The consistency of axioms means that no axiom of the set can contradict any other. When there is such a contradiction, it is impossible to interpret the theory constructed on the axioms; as regards empirical interpretation this amounts to experiment not confirming the theory. The consistency of a system of axioms is thus a *necessary* requirement of their truth. By itself, however, the requirement is not sufficient to resolve the problem of the truth of a theory based on a consistent system of axioms. Here experiment, experience, and practice, of course, come to the fore. On the other hand, consistency of axioms is the necessary and sufficient condition for unity of the propositions of a physical theory, if the latter is a deductive one. One has to take into account, however, that an axiomatised theory reflects adequately the sphere of phenomena corresponding to it, if one abstracts the connections between this sphere as a whole and others, and abstracts the transitions of the phenomena of this sphere to those of a broader sphere.

For the purposes of our book, the principle of the completeness of the axiomatic system of a given theory can be expressed as follows: as regards the system of axioms, this requirement consists in the system's being adequate for the theory of a certain sphere of phenomena to cover all the phenomena of that sphere (i.e. to explain all the known, and to predict all the unknown, phenomena of this sphere), linking them in a single chain of deductive reasoning.

We shall not discuss the criteria of the completeness of an axiomatic system; in physics, however, when it is a matter of the completeness of such-and-such a theory, experience frequently plays the decisive role. The paradoxes at the junction of classical mechanics and classical electrodynamics, for instance, combined with the negative result of the Michelson-Morley experiment, led to the conclusion that neither the axiomatic system of classical mechanics nor that of classical electrodynamics was a complete system if each was assumed to cover phenomena appertaining to the electrodynamics of moving bodies. Einstein solved this problem, as we know, when he created his theory of relativity which has now become an engineering discipline.

It is necessary to emphasise that only the totality of the requirements of independence, consistency, and completeness of the system of axioms forming the logical foundation of a theory ensures the deductive integrity of the latter, unity of its concepts and of the varied relations between them.

As for the guarantee of a theory's fullest reflection of its sphere of phenomena (i.e. of the phenomena plus their essence, laws, etc.), the requirement of completeness is the most significant one in its axiomatic construction. The other two requirements (of independence and consistency) simply support completeness; without this 'support', however, completeness would be unable to do its job.

The objects of a given axiomatic system, connected through certain relations, are its initial fundamental concepts defined implicitly by axioms (which provide an accurate, complete description of the relations between the system's objects). The theory of such related objects is considered built when it is possible to deduce logical corollaries from the system of axioms (according to certain rules), abstracting all other assumptions (statements) with respect to the objects concerned. How is this axiomatic ideal realised in a physical theory (or in physics as a whole)? Analysis of the matters relating to that goes beyond the frame of this Section.

3

On the Axiomatics of Contemporary Physical Theories

Let us first consider the meaning of the expression 'physically exact concept.' Above we stressed, in one connection or another, that a physical concept in any physical theory is neither an instrument reading nor a mathematical abstraction; in a physical concept that reflects the objectively real, the two are fused together as it were. Exact physical concepts are exact for the reason that they correspond to the objectively real (in the final analysis, this correspondence is established by experiment).

So-called abstract physical concepts cannot be counterposed to so-called visualisable physical concepts on the planes of their relation to the objectively real, or of their accuracy. Both the former and the latter reflect the objectively real and, if they correspond to it, they are exact concepts. No physical concept exists without a connection with experimental data, but abstract concepts are connected with such data by a more complex logical chain of reasoning (implying knowledge of the laws of nature) than visualisable concepts.

Both types of concept thus make use of the concepts of everyday language in their definitions, but the degree of this use cannot be compared; in the definitions of the visualisable concepts it is relatively easy to find the roots of their origin in experiment, but abstract concepts are connected with the experimental data in a mediated, and frequently very complicated, way. In the axiomatic construction of a theory its concepts and the relations between them are defined quite exhaustively.

At the same time, exact concepts can rightly be called exact only within the limits of a certain closed system; in that sense they are relatively exact or approximate concepts if there is no single closed system.

The concepts of a theory thus contain both an element of abstract thinking and an element of imagination. This applies to both the classical and non-classical theories of physics. In a classical theory, however, its concepts are a direct generalisation of the experimental data (the corresponding concepts of everyday language being raised in it, so to say, to the first degree of abstraction); in quantum theory, on the other hand, its concepts are not such a direct generalisation of the experimental data; the data are generalised in it in a mediated way, through the use of classical concepts.

From this standpoint classical concepts are not at all *a priori* with respect to quantum theory, in the sense that quantum theory employs only classical concepts (with the corresponding limitations). Quantum mechanics employs its own basic concepts and principles; accordingly, its concepts that differ qualitatively from classical ones, do not differ from them in any way in the sense of their certainty, clarity, and exactness. The same has to be said of the concepts of other constructed non-classical theories.

The tendency to establish exact concepts in science that arose from axiomatics does not by itself ensure adequate cognition of nature. Nature is inexhaustible as a whole and in any of its parts. Science and its theories and concepts that reflect nature consequently have to change and develop, reflecting it more deeply and completely; the old concepts (and theories) cease to be exact as regards the new sphere of 'finer' phenomena of nature, new exact concepts and theories being developed that correspond to the new sphere. Thus, when physics masters a new area of natural phenomena, the limits of applicability of its old concepts and theories are determined on the one hand, and on the other hand new concepts and theories are developed. These two processes, which appertain to concepts and theories, are, as a matter of fact, a single process of the development of science. Initially the inadequacy of the old concepts in regard to the new sphere of phenomena is established empirically, and difficulties and paradoxes arise in the existing theory (this is, so to say, the new theory's period of uterine development). Later the development of scientific cognition leads to precise determination of the applicability of the old concepts and theories, but this means, at the same time, the formulation of new concepts and their system: the new theory begins its existence.

That was how things stood with the theory of relativity and quantum mechanics, which now represent closed systems of concepts (axiomatised theories). Such is the situation with the modern theory of elementary particles, in which the presence of difficulties and paradoxes speaks of a need for fundamentally new concepts, and system of 'crazy ideas'.

As a result, the conclusion is inevitable that science neither can nor does manage in its development just with exact concepts. In certain conditions, when a new theory is being born, i.e. when it is a theory only 'in itself' and has no developed system of concepts, science uses, and cannot avoid using, imprecise concepts without which it is impossible in practice to construct a rigorous, consistent, complete theory.

The tendency in the development of science that leads to the establishment of exact concepts in it is thus interwoven with, and merges with, an opposite tendency whose specific feature is to employ imprecise concepts in science. Imprecise concepts are inevitable with every advance of science. They disappear when a certain cycle of its development is completed, so as to emerge again at a new stage of its development.

* * *

There is not simply something in common between the question of the physically exact concept and that of the process of formation of this concept itself, but, as we see, an inseparable connection between them. This point was not considered, as a matter of fact, in eighteenth and nineteenth century physics and in essence could not be. It then seemed that the sole system of axioms had been found that covered existing physics and should embrace all future physics; the physical equations and related concepts corresponding to it seemed absolutely exact and not restricted by any limits in this exactness. This system of axioms was embodied in the system of principles of mechanics formulated in Newton's *Principia*, which could only be modified but whose basis remained the same; the theoretical development of physics was regarded as consistent application of Newton's mechanics to broader and broader spheres of natural phenomena, discovered in experiment.

Since the theory of relativity, and especially quantum mechanics, became established, this understanding of axiomatics in physics, of course, has radically altered; with the new understanding of fundamental principles the question arose of the formation of a physical concept as a certain logical process.

In Section 1 we mentioned six 'closed systems' of appropriately ordered concepts, definitions, and axioms in physics, each of which describes a certain sphere of natural phenomena, and all of them are connected to some extent with one another. These 'closed systems' undoubtedly reflect the existence of discontinuities or leaps in nature and correspond to the fact that the forms of motion of matter are connected through transitions and differ qualitatively from one another.

In accordance with this understanding of physical axiomatics the equations of physics, and the quantities figuring in them, are never absolutely exact; or rather they are absolutely *exact only within their applicability*, and beyond it the question no longer arises. A more general and deeper theory (for instance, the theory of relativity or quantum mechanics) determines the field of applicability at certain points of the special and simpler theory from which it developed (in our example of classical mechanics, it is the limiting case with the tendency of the velocity of light to approach infinity and Planck's constant—zero); in this case the more special and simpler theory is an approximation of a theory that is deeper and more general, while the corresponding quantities of the simple theory become approximate ones (for example, absolute simultaneity is an approximate quantity, i.e. a quantity such as preserves its meaning only within certain limits established by the theory of relativity).

We must stress that *approximate* quantities are no 'worse' (or 'better') than *exact* ones (which relate to a more general theory) in the sense of their being adequate to objective reality in the same way as the laws of Newton's mechanics are valid within their sphere of applicability, and cannot be 'improved', whereas the laws of mechanics of the theory of relativity are valid in a broader sphere of phenomena than that reflected by classical mechanics, without discarding Newton's laws. The more general theory, moreover, employs *approximate* quantities in the appropriate conditions without which its quantities would have no physical meaning (suffice it to note that the practical procedures of measurement in the theory of relativity and quantum mechanics implied use of *approximate* quantities that were, in the first place, quantities of classical physics).

Thus, the approximate nature (i.e. the limits of significance) of a quantity in such-and-such a theory is determined by the more general, deeper theory; the quantity then sheds the illegitimate universalism that is inevitable until a certain time.

The approximate nature of a quantity in a certain theory is discovered through the more general, deeper theory developing from it with its new underlying principles and basic (fundamental) concepts. But the process of physical cognition can also go in the opposite direction, when a theory is transformed into a more particular one with the formation of concepts that did not exist in the original theory. Fock, who brought out the fundamental significance of approximate methods in theoretical physics, reviewed this process of physical cognition (which is inseparably connected with so-called approximate methods in physics).[28]

We shall not go into details of the philosophical problems associated with the analysis of approximate methods in physics, except to make the following comment. Modern physics rejects the metaphysical prejudice that the cognitive value of a special theory is less than that of a more general theory; a special theory covers a narrower sphere of phenomena—in that sense alone does the general theory provide more complete and therefore more adequate knowledge of objective reality; but in their own spheres of applicability these theories are equivalent as regards coverage of their corresponding spheres of phenomena; from the standpoint of cognition it is all the same whether we move in one direction along a genetic series of axiomatic systems or in the opposite direction. For modern physics the absolute is by no means, therefore, 'better' (or 'worse') than the relative as regards cognition; the same holds for the relation between the exact and the approximate. To illustrate this, let us assume that in certain phenomena in which atomic objects are involved the wave nature of matter is not essential (particles moving in a cloud chamber); then, in these conditions, we would be justified in abstracting from the uncertainty relation, which limits the concept of a particle; classical physics and its concept of the trajectory of a particle, i.e. concepts that are impossible in quantum mechanics, come to the fore.

When one reasons abstractly and takes into account the view now widely held, one can say that every physical theory and every physical concept are in principle approximate.

Why do we make the stipulation: 'takes into account the view...' etc? The point is that physicists have now become so accustomed to the idea of the variability, relativity, uncertainty, it would seem, of everything, that acceptance of the relativity of the fundamental statements of science does not cause much perplexity. What appeared to be heresy in eighteenth and nineteenth century science, when its theoretical foundation rested on Newton's indisputable mechanics, is regarded in twentieth century science as almost hackneyed, in view of the idea of the variability of fundamental physical propositions. On the other hand, the idea that physics can arrive at something constant and final in the sense of its principles now appears strange, although it was considered quite normal in the days of classical physics. Meanwhile the idea that physics can be 'completed' in the sense of construction of its principles is now being voiced by individual scientists[29]; because of that our stipulation above was necessary.

Furthermore, by employing the expression 'when one reasons abstractly', etc., we thereby stress the fact that a physical theory (physical concept) contains a number of elements of physical neglect about which nothing is known at a given stage of development of physics but it is assumed that something will be known in the future. In the examples above certain physical theories (certain physical quantities) figured as *really* approximate theories (quantities), and not just approximate in principle, and their approximate nature was demonstrated. Here, on the other hand, we mean theory in general and the fact that it contains neglected elements in principle.

This idea is based on semi-empirical/semi-general considerations; since the rise of non-classical physics, fundamental physical theories have been replaced by more general, deeper ones, and physics is now apparently on the eve of a new, similar change, in connection with the difficulties of constructing a theory of elementary particles and formulating a new cosmological theory; so it was and is now, and so it will be in future.

Let us return again to real theories. In order to demonstrate that such-and-such a theory is approximate, we have to prove that it does not cover certain phenomena that are covered by a more general theory. The methodology of this question is, in fact, the methodology of the quest for and construction of a new theory, and here (the point concerns fundamental theories), non-classical physics has its own theoretical methods (unknown to the old physics), which achieve their end. These methods (the principle of observability, mathematical hypothesis, etc.) have the following inextricably connected premises in common: (1) by cognising something unknown, i.e. by going beyond the limits of the cognised, we extend established concepts, principles, and theory to this something; (2) this extension does not exclude but implies, on the contrary, that one may have to alter (revise) some of the theory's established basic concepts and principles qualitatively and, therefore, in the final result, to construct new basic concepts and principles, i.e. a new theory. These two premises, in spite of their opposite nature, are essentially one, but depending on the conditions, which also include the cognised something, one or other of them comes to the fore.

As regards the first, it can be thought that it would not be justified to extend principles and concepts that reflect the circle of known phenomena to the unknown things, for it would be wrong to extend the concepts of trajectory and particle to atomic phenomena—that could be demonstrated after long discussions and various theoretical misadventures when, as it seemed, one had to proceed directly from the appropriate thesis, and the truth would be found more quickly!

The point, however, is that a new theory cannot be constructed, as it is, in general, impossible to cognise, of nothing and, therefore, one cannot, in cognising the unknown, do without established knowledge. An established theory (or one or other of its bits), when applied to unknown phenomena so as to cognise them, functions in respect to them only as a hypothesis, with all the propositions and conclusions following from that fact. Without hypothesis discoveries in science are impossible, of course, and a hypothesis, understandably, in order to fulfil its task, must satisfy certain requirements.

A hypothesis is internally connected with fantasy, but fantasy cannot be unrestrained and unchecked in science. Which theoretical structure can be more ideal in this respect than an established scientific theory, verified by experiment, which operates as a hypothesis!

It is therefore logically justified that physicists, after a really unexpected discovery, do not immediately put forward staggering ideas and theories in order, so to say, to catch the unexpected phenomenon in the net of cognition, but study the discovered phenomenon very thoroughly, with, it would seem, unnecessary sluggishness, by means of the *old* theories and *established* principles. The discovery of radium did not immediately destroy the notion of the atom's invariance; the Michelson-Morley experiment was analysed many times on the basis of the theories of classical physics; the same must be said of the phenomena with discovery of which quantum theory began its development.

When we extend everything we already know to unknown phenomena, or to new spheres of natural processes, moreover, it is only thus that we open the way to scientific progress. What kind of science would it be, if it enabled cognitive problems to be solved (and solved them) only from the sphere of the known! The boundary between the two premises of physical cognition discussed above passes exactly through this point.

As for the second of these premises, the most essential thing relating to it, in our view, has been analysed to one degree or another in Marxist literature on the methodology of modern physics, and we refer the reader to it.[30]

All these problems gravitate to the idea of the dialectical unity of absolute and relative truths. For physicists who do not consciously accept dialectical materialism, this idea is frequently a stumbling block. A vivid example of this, on the plane of the issues discussed above, are the statements of Richard Feynman, a distinguished physicist who unconsciously, as we have often seen, applies the principles of dialectics to resolve the problems of his science.

According to him, 'there is always the possibility of proving any definite theory wrong; but ... we can never prove it right.... Newton ... guessed the law of gravitation, calculated all kinds of consequences for the (Solar) system and so on, compared them with experiment—and it took several hundred years before the slight error of the motion of Mercury was observed. During all that time the theory had not been proved wrong and *could be taken temporarily to be right. But it could never be proved right, because tomorrow's experiment might succeed in proving wrong what you thought was right.... However, it is rather remarkable how we can have some ideas which will last so long*' (my italics—*M.O.*).[31]

One finds such passages quite often in Feynman's book. From the standpoint of the unity of the exact and the approximate previously discussed, it is not very difficult to disprove Feynman's seemingly factual considerations: the deviation of Mercury from the motion predicted by Newton's theory can be explained by Einstein's theory of gravitation, which is correct in a broader sphere of application than Newton's; the latter, on the other hand, is a limiting case of Einstein's gravitational theory. In his argument Feynman touched on statement that experiment is the criterion of a theory's truth, but he, it must be assumed, is not familiar with the dialectical idea of the *relative* nature of this criterion.[32] In Feynman's opinion, it would seem, a physical theory, if it is correct (true), should be universal and final; in his view physical science is moving in essence to the latter; at least, we find the following concluding lines in his book: 'Ultimately, if it turns out that all is known, or it gets very dull, the vigorous philosophy and the careful attention to all these things that I have been talking about will gradually disappear.'[33]

* * *

It is held, and rightly so, that the presence of a system of axioms in a theory is an indication of its logical completeness (closed state), but in the history of knowledge and science the logical completeness of a theory has usually been regarded as a synonym of sorts of its universality and invariance. This was justified historically, we may say, by 2000 years' reign (to the middle of the nineteenth century) of Euclid's geometry as the sole geometrical system, or the 200 years supremacy (to the twentieth century) of Newton's mechanics as the final, indisputable theoretical system of physics. We have tried to show the illusory nature of this notion when axiomatic ideas are considered on the logical plane. The logical completeness of a theory does not preclude its development but, on the contrary, implies it; we propose to examine this idea more definitely in the concluding part of this section.

The first blow against the ideal of the classical understanding of axiomatic construction in physics was struck by Maxwell's electromagnetic theory. In fact, however, the essence of this understanding of axiomatics did not change; during the heyday of the electromagnetic picture of the world many physicists replaced the bodies of mechanics and Newton's axioms by an electromagnetic field and Maxwell's equations (and Newton's mechanics itself seemed refuted, with no relation to the foundations of the Universe). At that time the point of view of dialectical materialism on this issue was expressed by Lenin. When the electromagnetic picture of the world was being built up he pointed out the inconsistency of the opinion that materialism asserted 'a "mechanical", and not an electromagnetic, or some other, immeasurably more complex, picture of the world of *moving matter*'.[34] And, as the development of physics since Maxwell's electromagnetic theory has demonstrated, Lenin was right.

The final blow to the classical understanding of axiomatics in physics was dealt by the theory of relativity, and especially by the development of quantum mechanics when it took on its contemporary shape.

It became clear (this fact was mentioned above in connection with other matters), that Newtonian mechanics had limits to the realm of phenomena that it was expected to explain and predict, i.e. limits to its applicability, and that electromagnetic phenomena on moving bodies, and also atomic phenomena, could not be described and explained by the concepts and principles of Newtonian mechanics. Experimental studies of the relevant phenomena, plus analysis of the theoretical situations arising in classical physics, led on the one hand to the theory of relativity, and on the other hand to quantum mechanics. Now, of course, the physicist has become accustomed to the idea that no closed physical theory is absolute, that there are limits of its applicability, and that, in this sense, it is approximate. But how is one to find the limit of applicability of a theory? And what is this limit? Let us begin with the second question. There are phenomena that cannot be described in the language of the concepts of a certain theory or, if they can be so described, cannot be explained by it; such a theory leaves out the sphere of these phenomena, i.e. the sphere of applicability of such-and-such a theory; this is that realm of phenomena that is, or can be, explained by it. In other words, another theory, already different in principle, operates (i.e. describes, explains, and therefore predicts) beyond the limits of applicability of such-and-such a theory.

We shall not analyse the matter of a theory's limit of applicability in detail. One aspect, however, deserves attention. The expression 'the limit of a theory's development' is frequently used and, apparently, quite logically. What does it mean? And how is it related to the expression 'the limit of a theory's applicability' just discussed?

This question only seems artificial. The point is that ordinarily it is said to be meaningless to speak of the development of an axiomatic system. Indeed, all the theorems of an axiomatic system can be interpreted as being implicitly contained in its axioms and rules of inference. Only the activity of a mathematician (or a corresponding device) can make any theorem contained in it explicit (and there is an infinite number of such theorems of various degrees of ordering in an axiomatic system). At the same time everyone knows that it is by no means easy to infer (or deduce) theorems from axioms; and the obtaining of, say, a geometrical (or mechanical) fact and statement from the corresponding system of axioms is, as always with cognition, the solution of a problem of searching for an unknown from known data! Engels said that even formal logic was a method for finding new results.

The deductive method (which includes the axiomatic method proper), like any method employing formal and dialectical logic, cannot do without imagination or fantasy. It is worth recalling once more that, according to Lenin, even the most elementary generalisation contains an element of fantasy.[35] The role of imagination increases greatly, of course, when it is a matter of the ever broader and deeper generalisations with which science is concerned and without which it ceases to be science;* it is a gratifying task to study this role.

Thus, in so far as the deductive method or, considering its higher form, the axiomatic method, leads from the known to the unknown and increases scientific knowledge, an axiomatic system should be regarded as a theoretical one that can and does develop in certain conditions. The development of an axiomatised theory is the obtaining of new, previously unknown facts and propositions within the limits of its applicability. As follows from its definition, this development of a theory occurs, so to say, within itself. The theory does not go beyond its limits in this development but remains the same from the standpoint of its principles (system of axioms).

Let us turn to the question of how to find the limit of applicability or limit of development of an axiomatised theory.

The answer, of course, cannot be reduced to demonstrating that one constructed theory contains another constructed theory, with the first determining the limits of applicability of the second in a way inherent to it and showing that the latter is its limiting case. It is not a method of solving the problem; rather it implies the existence of such a solution. Can the limits of applicability of a theory, or the boundaries of the realm of phenomena explained by it, be found empirically?

It depends on the circumstances. The result of Michelson-Morley experiments or the so-called ultraviolet catastrophe became in fact the limits of the applicability of classical theories: from these two 'little clouds' in the clear sky of classical physics there developed the theory of relativity and quantum mechanics. However, the motion of Mercury's perihelion which had been known for quite some time and was not covered by Newton's theory of gravitation, had not by any means become the limiting point of the theory's applicability. Einstein's theory of gravitation, which

* The use of cybernetic machines to solve the problems involved (a machine has been able, for instance, to 'discover' a theorem unknown to mathematicians) only confirms this idea. Any 'intelligent' machine is a kind of extension of the human brain; it does not 'think' or 'create' by itself, but in combination with a person it greatly increases the latter's power of cognition; and there is almost no limit to this increase. The point has been discussed many times in the literature.

determined the limits of applicability of Newton's, was not found along the methodological path on which the theory of relativity and quantum mechanics arose. The decisive role in the creation of Einstein's theory of gravitation was played by the principle of equivalence, which implies the identity of inertia and gravitation, i.e. an experimental fact played an essential role, namely that the acceleration of all bodies falling *in vacuo* is the same; this fact was known to Newton who did not include it in the theoretical content of his theory of gravitation but accepted it simply empirically.

It happens sometimes that an established theory does not explain certain known experimental facts; scientists become accustomed to that; but, as it turns out, their theoretical interpretation or explanation (justification) goes beyond the limits of the established theory, and sometimes only a person of genius can see this circumstance. That is how it was with the general theory of relativity, or Einstein's theory of gravitation, which rested on the same experimental material (the same experimental base) as Newton's theory at the time it was formulated, but added a set of new ideas to it that were alien to classical conceptions. The logical aspect of the rise of a theory in this way will be discussed below.

So, how can one find the limits of the applicability of an axiomatised theory and of its principles and concepts, i.e. determine the realm of phenomena beyond which it is no longer valid and a new theory is required?

A logically constructed theory or axiomatised theoretical system that functions correctly within the context of its applicability should be consistent and complete. Gödel has shown that the consistency and completeness of a system itself cannot be proved by its theoretical means. It is usually accepted without proof (it was tacitly implied during the historical development of Euclidean geometry and Newtonian mechanics) that such-and-such a theory is consistent and complete if the specifically opposite is not required, in the same way as it is accepted without proof that a theory is universal if there are no facts contradicting it (as was noted above). The consistency and completeness of any theoretical system means that none of the statements which it contains implicitly and explicitly can be in contradiction with it and all should be explained by it, i.e. that all of them are finally explained in it on the basis of its axioms and fundamental concepts.

It follows from this that, if a phenomenon which is (say) to be explained within the context of a given theory not only cannot be explained but, on the contrary, contradictions (paradoxes) arise that cannot be resolved by this theory when explanation is attempted, we would be justified in considering their presence as an indication that the theory is nearing its limit.

It is possible of course that after due reflection stimulated by the contradiction individual statements and concepts of the theory may be revised, and the contradiction resolved in terms of the given theory; in that case the contradiction and the way it is resolved serve only to improve the theory logically in terms of its principles. The same holds *mutatis mutandis* for the question of a theory's completeness. At one time Einstein, Rosen, and Podolsky formulated propositions from which it seemingly followed that quantum mechanics in Bohr's probabilistic interpretation was incomplete. It became clear, however (as Bohr showed), that Einstein was wrong: the initial proposition of his paradox in relation to the problems of quantum mechanics was ambiguous.[36] We are not interested in such cases: they appertain to the problem of logically perfecting a given theory in relation to its axiomatics, and not to that of the limits of its applicability.

Let us now turn to the paradoxes that develop in a theory and are not resolved by its means; they are indications that the theory is nearing its limit, as was noted above. But that means (and we draw attention to it) that the necessity is arising to look for a new theory whose principles and fundamental concepts differ from those of the first, for a theory such as would resolve said paradoxes (or rather, in which they would not exist). The main task of all our further exposition is to analyse the corresponding problems.

First of all we would stress that the logical path (and expression) of the historical movement from classical to modern physics was the birth of said paradoxes in a (classical) theory and their resolution. To some extent this feature was also characteristic of Maxwell's electromagnetic theory, the closest precursor of non-classical theories. Maxwell, who unified all the experimental data on electricity and magnetism found by Faraday, and expressed them in the language of mathematical concepts, saw a contradiction of sorts between the resulting equations. In order to correct the situation, he added an expression to the equation without any experimental justification (it appeared later), and the theory of electromagnetism was born. Maxwell's method of mathematical hypothesis also proved to be extremely fruitful in further research,* it has frequently brought whole theories to physics.

Einstein's theory of relativity can serve as another example. It was created at the junction of classical mechanics and classical electrodynamics, as a result of resolving a paradox, a contradiction between Galileo's principle of relativity and the principle of the velocity of light *in vacuo* being independent of the motion of the radiating source when these principles were considered together. Podgoretsky and Smorodinsky have called such 'junction' paradoxes 'encounter contradictions'.[37] The paradox above and its resolution are an excellent model of dialectical contradiction in relation to major problems of modern physics, on which one can find relevant studies in Marxist philosophical literature[38]. A most important role in resolving this paradox, i.e. in formulating the theory of relativity, was played by the method of fundamental observability.

Quantum mechanics also developed in a certain sense as a result of resolving an 'encounter contradiction', in this case, that of classical *corpuscular* mechanics (again Newton's mechanics) and classical *wave* theory. The role of the wave theory, however, was played here not by the corresponding theory of *matter* but by the theory of electromagnetism; the 'encounter' was therefore by no means as 'simple' as with the (special) theory of relativity. Quantum mechanics developed as a result of resolving not only an 'encounter contradiction' but also a number of other contradictions, some of which will be considered below. Here it is essential to point out that a rising new theory is, in the language of modern logic, a metatheory of sorts in relation to the original ones (this also applies to the theory of relativity).

The problem that could be called that of the stability of the structure of ordinary bodies, molecules, corpuscles (particles) or of the atoms that, from the standpoint of Newtonian mechanics, underlie matter and the motion of

* Maxwell himself thought that he was being guided by a mechanical model of the ether; in certain circumstances, however, illusions often represent something real.

which determines, in the end, all universal changes, was of the greatest significance for understanding how quantum mechanics arose. Newton 'found a way out' by postulating the *infinite hardness* (*of divine origin*) of the primary atoms, etc.[39] The same problem arose in all its direct visualability, so to say, when it became clear that the 'primary' atom was a system consisting of electrically charged particles (a positive nucleus and negative electrons), and the problem of its stability had to be solved from the standpoint of classical electromagnetic theory. 'Rutherford's atom', as we know, was unstable, but the problem was solved by a (then young) Danish physicist Niels Bohr who constructed an atomic model, applying Planck's *hypothesis* of quanta to 'Rutherford's atom'. 'Bohr's atom' proved to be really stable, which was explained in terms of the laws of nature, i.e. the ancient atom finally acquired stability, and not because somebody tried to convince himself and others of this in his own name or that of God, but because it was necessitated by the quantum laws of the motion of matter. From there, too, development of the main stem of the quantum theory sprang, whose content absorbed the idea of the unity of corpuscular and wave properties of micro-objects and led in 1924-1926 to the creation of quantum mechanics.

Nevertheless, when one thinks deeply about how the problem of the stability of the structure of the atomic particles of matter was solved, the idea that it could have been done differently and not as it was even seems strange. For in fact, the properties and motion of macro-objects can only be explained by the laws of motion and properties of the micro-objects composing them when the latter are not ascribed the properties and motion of macro-objects, if one does not want to fall into *regresus ad infinitum*. That is what was done by quantum mechanics, which brilliantly demonstrated that the laws governing micro-objects are quite different from those governing macro-objects. But then the hardness of macro-bodies, the constancy of standards of length and time, i.e. the physical characteristics of macro-objects without which measurements and, therefore, physical cognition, are impossible, must get their substantiation in quantum mechanics, as the mechanics of objects at atomic level.

On the other hand, man (if we may be allowed to express it so) is a macroscopic being; he learns about the microworld only when the micro-objects act on macro-objects that he links to his sense organs; these macro-objects (they become measuring instruments for him) enable man to learn about the microworld in a mediated way. Thus man, when cognising the micro-objects, cannot help but use classical concepts, since only in terms of them can he describe the readings of instruments, i.e. since as he measures he cannot do without using classical theories.

Such is the relationship between quantum and classical mechanics, to put it briefly; it leads us to an understanding of the relationship between the basic principles of the theory of physics which, it seems to us, is typical of twentieth century physics.

Note first that the mechanics of the atomic world (quantum mechanics) not only cannot be reduced to the mechanics of macro-bodies (classical mechanics) (the theory of electromagnetism also cannot be reduced to classical mechanics, and does not absorb the latter), but the relationship between them contains something more. Quantum mechanics, as was stated above, is the basis, in a certain sense, of classical mechanics; it justifies some of its fundamental concepts that reflect the properties of macro-objects, i.e. it deals with these concepts in the same way as classical mechanics, in which the derivative concepts are justified by axioms.

It must also be added to this that the fundamental concepts, in their connections that form the basic equations of classical mechanics, were developed from notions taken from everyday experience (hardness, inertia, force) and the relations between them. That lends the axioms of mechanics the necessary physical meaning without which these equations would be converted into purely formal ones, and it would be impossible to call them physical. As for the main fundamental concepts and their connections, expressed by the basic equations of non-classical theories, the mathematical abstractions corresponding to these equations are connected with nature (i.e. have, so to say, become physicised) in each theory according to the rules inherent in it, using the concepts of classical physics.

From the standpoint of what has been said, a theory's axiomatic system contains basic concepts and their connections that are not logically justified in this system but are postulated on the basis of certain considerations, which are taken into account when the system is being constructed. In this respect the theory is called *incomplete* (and open), but this incompleteness is different in principle from, say, that of quantum mechanics which Einstein had in mind in his discussion with Bohr mentioned earlier. The fundamental concepts and connections that form the axiomatic system of a theory can be substantiated by a deeper, broader theory than it, with new axiomatics, etc. On the logical plane the status of the 'substantiation' of fundamental concepts and their connections in the axiomatics of a theory is similar to that of an axiomatic system's consistency and completeness, which, as Gödel demonstrated, cannot be justified by the means of this system. Or, in more general form, the basic statements of a theoretical system cannot be obtained *by its logical means*, but they can be found by the logical means of a broader, deeper theory[40]. Using the same logical terminology one can say that quantum mechanics is a kind of metatheory of classical mechanics.

Let us return to the example of Einstein's theory of gravitation discussed above. Newton's theory, and classical mechanics did not 'brood' over the proportionality or (with the appropriate choice of units) equality of the gravitational and the inertial mass of a body; it was just stated by classical mechanics. To find the justification of the equality between the gravitational and inertial masses of a body, or better justification of the statement that 'the gravitational and inertia masses of a body are equal' would have meant to go beyond the limits of Newton's gravitational theory and to construct one that would be a novel metatheory with respect to it. This was what Einstein did when he created a new theory of gravitation, or, as he called it, the general theory of relativity. We shall speak about this in Einstein's own words, with citations from his works, limiting ourselves just to comments.

Having spoken about the proposition that 'the *gravitational* mass of a body is equal to its *inertial* mass', Einstein said further that it 'had hitherto been recorded in mechanics, but it had not been *interpreted*' (in this case we employ the expression: classical mechanics did not *substantiate*, did not find grounds). And he concluded: 'A satisfactory interpretation can be obtained only if we recognise the following fact: *The same* quality of a body manifests itself according to circumstances as "inertia" or as "weight" (lit. "heaviness").[41] By having formulated this idea he thus gave grounds for the equality of the gravitational and inertial mass, empirically stated in classical theory, and laid the basis for his theory of gravitation.

The following excerpt (which we give without comment) from his paper *What Is the Theory of Relativity?* can serve to illustrate his basic 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 forbids it'.[42]

If one draws together everything that has been said about a theory and its metatheory, the following conclusion suggests itself. The paradoxes arising in a theory that *cannot be resolved by its logical means* are an indication that the theory has reached its limits of applicability, and that its axiomatics (axiomatic construction) is its highest logical completion possible from the standpoint of its actual content and axiomatic form. Such paradoxes differ fundamentally from those that develop in a theory and *are resolved by its logical means*, i.e. from those that provide evidence of the theory's logical imperfection (incorrectness in the reasoning or inaccuracy in the premises). The existence of paradoxes that are not resolvable by a theory's logical means indicates the need to search for more general, deeper theories in terms of which they are resolved (the resolving usually coincides with the construction of the general theory being sought). The existence of this kind of paradox thus means, in fact, that the physical cognition of objects does not stay long at the level of such-and-such a theory but develops further, embracing new aspects of material reality, without discarding the knowledge already achieved by it; the existence of this type of paradox also means that the theory that contains paradoxes but does not resolve them in its own terms, potentially contains a theory that is more general and deeper than it. From this position every axiomatised theory necessarily contains knowledge that cannot be substantiated in its terms; otherwise cognition would become frozen at a certain point, and the knowledge gained would be converted into a metaphysical absolute.

The development of a theory of contemporary physics is ensured by a genetic series of theoretical systems representing axiomatic structures that are either closed or under logical construction and connected through certain relationships, the more general theoretical system in the genetic series of such structures growing out of the more special one. The single axiomatic system of the whole of physics, in the spirit of the mechanistic ideals of the eighteenth and nineteenth centuries, was buried by the development of physics. This system also proved to be logically impossible, as Gödel's theorems have shown; the logical development of a theory and of physical science as a whole is expressed by a genetic hierarchy of axiomatic systems combining a tendency to stability with one toward variability, which are inherent in individual axiomatic systems and in their aggregate.

A single axiomatic system (structure) in the spirit of classical physics has been put an end to, but in the realm of ideas, more than in any other, the dead clings to the living. A single axiomatic system is being reborn in modern physics, too, though in a form seemingly far removed from its 'classical' model. In our day we can find the following conception about physical science in the literature: physics is constructed in principle as a rigorous, consistent, axiomatic system covering all its branches, in which the historically earlier theory (and its axiomatics) is the limiting special case of the historically later one (which proves to be broader than the first). In due course the same happens to the last theory, and so on. Feynman paints approximately such a picture in the axiomatics of modern physics. The following question then arises, however: does this 'and so on' continue to infinity? We shall not go into its details and shall try to answer it.

It is asked whether there really is an indisputable single axiomatics embracing all physics that allows for its present and possible future development.

The question is answered in essence by the material above on the relationship of a 'theory' and a 'metatheory' in physics. All that remains here is to stress certain aspects of the problem.

When a theory is generalised, i.e. when we pass from the special to the general theory, the former by no means disappears completely in the latter, and the latter does not at all become the sole true theoretical system in physics, as would be the case if there were a single axiomatics in physical science. In reality, the special theory is preserved in the general one in a modified form (this also holds in respect of certain of its concepts); it remains in the general theory as an approximate one, and its concepts are also preserved as approximate. From this angle we can also speak of absolute simultaneity in Einstein's theory of relativity. A theory is not discarded when it passes into a more general theory, but remains as relative truth, i.e. absolute truth within certain limits; this is the very 'best' for a theory from the standpoint of its relation to objective reality, since it is being found how far it is true.

All this is associated with answering the following questions (some of them considered above). Why is it necessary to use Euclidean geometry in seeking the 'non-Euclidean nature' of a certain spatial form? Why do we learn about the properties of the space-time continuum from separate measurements of space and time? Why are the concepts of classical mechanics employed to describe the experiments that constitute the experimental basis of quantum mechanics?

We are convinced that dialectical contradiction, the source of every development of life, also operates in axiomatics.

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[38] For more details see M. E. Omelyanovsky. On Dialectical Contradictoriness in Physics. *Voprosy filosofii*, 1970, No. 11.

[39] Sir Isaac Newton. *Mathematical Principles of Natural Philosophy. Optics* (Encyclopaedia Britannica, Chicago, 1952), p 541.

[40] Kurt von Gödel. Über formal unentscheidbare Sätze der Principia Mathematica und verwandter Systemei. *Monatshefte für Mathematik und Physik*, 1931, *38*: 173-198. On this point there is excellent material in V. A. Fock's article cited above (*Uspekhi fizicheskikh nauk*, 1936, *16*, 8). It reviews the historical development of theoretical physics to some extent reversing the course of this development.

[41] Albert Einstein. *Relativity. The Special and General Theory* (Hartsdale House, New York, 1947), p 77.

[42] Albert Einstein. *Ideas and Opinions*, p 231.

IN LIEU OF A CONCLUSION

The philosophical question of how objective knowledge is achieved, and from what it follows that physical statements are not purely subjective constructions and that nature exists independently of experience and of the theory that has grown from it long occupied an important place in classical physics.

From the standpoint of classical science the answer to this problem did not appear very complex. For eighteenth and nineteenth century scientists it seemed obvious to accept the objective reality of the external world, reflected in physical theories. It was customary to explain observed phenomena in terms of a mechanical model. The concepts in which the measurable properties of physical bodies and their motions then known were expressed were not very far removed in level of abstractness from those developed in everyday experience. Materialism and mechanistic views prevailed in classical physics and were shared by its representatives, though frequently not philosophically consciously.

As physics moved from the macroscopic objects perceived in everyday experience deeper into spheres of phenomena cognition of which called for non-classical theories and their abstractions, unknown to classical physics, in addition to very sophisticated experimental equipment, the problem of the objective and the subjective became more and more complex in physics. In modern physics this problem took on a form that differs essentially from that in which it appeared in the physics developed under the aegis of Newton and Maxwell. From the end of the nineteenth century, paradoxical situations began to arise in which the observed data did not fit into theoretical schemes and conceptions existing at that time. The theory of relativity and quantum mechanics emerged and developed, and became established as non-classical theories, i.e. as theories with a mathematical apparatus (formalism) unknown to classical physics, and basic concepts and principles quite different to classical ones.

The physics of our day develops through the transition of some fundamental theories into others that are deeper and more general and differ qualitatively from the initial ones. This kind of development is inextricably bound up with the disappearance of certain basic concepts essential to the initial theory, and the formation of new basic ones (without which the new system of knowledge cannot be regarded as a theory). The disappearance of the former and appearance of the latter is a single process in which the former (if they figure in it as a kind of absolute concept, or invariant) are relativised in a way and become aspects of new absolute concepts, or invariants, in a deeper theory. Instead of the classical concepts of absolute length and absolute duration, for example, in the theory of relativity, corresponding relativistic concepts representing aspects of the most important invariant of the theory of relativity became established, i. e. the interval, which 'combines' length and duration in a special manner.

When fundamental physical theories are characterised epistemologically by increasing degree of generality, i. e. classical mechanics and electrodynamics—the theory of relativity and quantum mechanics—quantum field theory (the theory of elementary particles), one is justified in saying that the relativisation of the old absolute (invariant) concepts and introduction of new absolute (invariant) ones in the course of the generalising of a theory and its transition into a new one signify a progressive movement from 'subjectivism' to objective knowledge, and ever deeper, more complete cognition of the objectively real in which the one-sidedness and subjective constructions of individual physical theories internally connected with it become blurred as it were. On the other hand, the theories, by preserving their content that corresponds to objective reality, become more and more integrated in this progressing motion.

In our view this is the philosophical significance of the idea of invariance as regards the relation between the objective and the subjective in modern physics. Thus, the theory of relativity and quantum mechanics have concretely demonstrated that certain of the fundamental concepts of classical mechanics, and this science as a whole, are approximate (although these concepts are absolute within the limits of their applicability). The uncertainty relation, for example, which established the limits of applicability of the classical particle concept, took into account, let us say, that electrons possess wave properties in addition to corpuscular ones; beyond these limits the classical concept of a particle has no objective meaning.

In modern physics Lenin's ideas of the relationship between matter and consciousness, and between the objective and the subjective, play a most important role. Matter and consciousness, the objective and the subjective preserve their absolute oppositeness only within the limits of the basic question of philosophy.[1]

Lenin thus linked a materialist solution of the basic question of philosophy inseparably with the dialectics of cognition, with how knowledge is formed from ignorance, how it becomes deeper and deeper, and more complete, reflecting the external world that exists independently of man. In physical science, especially in non-classical physics, this finds very clear, marked expression.

Positivism (regardless of whether it is a matter of Mach's views or of neopositivism) for which, as we know, the existence of a physical world independent of experience was, at best, a pseudo-problem, by-passed the problematics of the origin and source of physical knowledge, and at the same time, the problematics of its development. Mach criticised Newton's theory of space and time from an idealist standpoint adhering to the purest philosophical relativism on this issue, and rejected Einstein's theory of relativity. Later positivists, including such eminent philosophers as Carnap and Reichenbach, accepted the theory of relativity and quantum mechanics, but for them physical theories were only a logical means of systematising the observed. Thus, Reichenbach ignored the real dialectical unity of the particle and wave properties of matter, which was unknown to classical physics and which is considered in Bohr's conception of complementarity developed by Fock and others. By introducing certain assupmtions about 'particle' and 'wave', which (in his own words) are 'neither true nor false', he put forward a theory of equivalent descriptions in his philosophical argument on quantum mechanics. According to this theory, in certain conditions the corpuscular and wave interpretations 'both are admissible, and they say the same thing, merely using different languages'.[2]

As for the objective and the subjective in modern physics, it is important to bear in mind that Einstein, Bohr, Born, and its other architects held the same anti-positivist position as regards cognition in physics, in spite of the difference of their philosophical views. Einstein, for example, always stressed that in their theories physicists are dealing with nature, which exists independently of the mind cognising it. While doing justice to classical physics and holding Newton in high esteem, he considered the theory of relativity a new step in the development of knowledge in physics, expressing the idea, moreover, that the modern theory of relativity (i.e. theory of gravitation) should only be regarded as a certain limiting case of a more profound theory (not yet created). These considerations of the founder of the theory of relativity speak for themselves. One can find similar statements on this point in the works of Bohr, Born, and other great physicists of our time, who have opposed positivism and subjectivism in science.

* * *

Spokesmen of the 'philosophy of science' and scientists of the non-socialist world have become distinctly suspicious of positivism of late. Without going into the reasons for it, let us note that mounting attention is being paid in modern bourgeois philosophy to the development of scientific cognition; the study of this development is gradually becoming the basis for comprehending the structure of science, its theories that have taken shape, and the logical problems of established science. Unlike positivism, the subject-matter of which was the logic of already existing knowledge, the most recent trends in the bourgeois philosophy of science aim at identifying the forms and methods that make it possible to bring out the developing content of scientific knowledge. In short, if the logic of the scientific revolutions, above all in physics, i.e. the logic of the transition from one fundamental theory to another, deeper one, was outside the purview of positivists, philosophical problems of this kind of revolution are being brought to the fore in the post-positivist approach. Karl Popper has made the first steps in this direction. His ideas, however, including his principle of 'falsifiability', strictly speaking, only formulated the relevant questions (leaving aside his latest publications). For him, study of the development patterns of scientific knowledge and the study of its logical structure were different, though mutually related, problems.

Imre Lakatos, taking Popper's ideas as his starting point, concludes that the logic of science can only be the theory of its development. He scrupulously analyses the matters involved in the fact that every empirical disproof of a theory ('falsifiability' in Popper's terminology) poses a problem of refining and progressively altering a theory. Lakatos tries to clarify the rational reference points in the development of knowledge during a scientific revolution.

Thomas Kuhn analyses the problem of revolutions in science differently than Popper and Lakatos. In his view there is a period in science of the predominance of established principles that guarantee its 'normal' functioning, and a period of crisis when new 'paradigms', i.e. sets of new principles and new scientific methods and approaches are taking shape. Unlike Lakatos, Kuhn suggests that the change of paradigms cannot be explained rationally or logically, and tries to justify his position.

We shall not discuss the views of Popper, Lakatos, and Kuhn, and of other Western philosophers close to them, about the development of scientific knowledge, but simply note that these philosophers have not solved the problems of development of scientific knowledge in its most essential features. Popper, for instance, in his argument about the contradiction between the theoretical and the empirical, did not find ways of resolving it. Kuhn denied regularities in the transition between 'paradigms'. The methodology of Lakatos' 'research programmes' (in his interpretation they play the role of Kuhn's paradigms) in fact lacks constructiveness.

From the Marxist standpoint the negative aspects of all these and other views of Western opponents of positivism on the development of science are quite understandable;

they ignore materialist dialectics, above all the dialectics of the connection between the objective and the subjective, when they analyse the development of scientific knowledge. The understanding of cognition as the reflection of nature in human thought, an understanding that must not be regarded without motion, or free of contradictions, but in an eternal process of movement and of the rise and resolution of contradictions, is that which opens up a philosophical perspective for dealing with matters concerning scientific revolutions and the development of science.[3] Modern bourgeois philosophers do not see this.

The enormous significance of the dialectics of the objective and the subjective in the philosophical problematics of physical knowledge stands out clearly in dealing with the problem of the relationship between the abstract-logical and visualisable, or mathematical apparatus (formalism) of a theory and the data observed in experiment described in terms of our everyday language, a problem which is essential to contemporary physics. This is also the problem of a mental picture of the concepts and theories of contemporary physics. The line of materialism on this issue implies acceptance of the dialectical unity of sensory cognition and abstract thinking that reflects objective reality. The combination in a single whole of the mathematical formalism of a physical theory and of experimental data expressed in the concepts of classical physics corresponds to the line of dialectical materialism. Born was wrong when he said that, according to dialectical materialism, it would be sufficient to limit oneself to 'the objective world of formulas with no relation to perception (Anschauung)'.[4]

As for a mental picture, Einstein had an idea of considerable philosophical significance for physics. Its essence is that the abstract-logical in a physical theory by itself does not yet say anything about the objectively real; only in connection with the mental picture does the abstract-logical (mathematical) reflect the objectively real and become an object of verification by experiment.[5] This profoundly dialectical idea renounces from the very beginning the conventionalist, positivist scheme for dealing with the problem.

Bohr's idea which we have already mentioned is of great importance in this regard: 'However far the phenomena transcend the scope of classical physical explanation, the account of all evidence must be expressed in classical terms.'[6] When one ponders over this idea of Bohr's, its materialist nature comes out quite definitely. Quantum mechanics, for instance, like other non-classical theories, grew out of experiment and was confirmed by it, which means, however, that it cannot help using classical, visualisable concepts since its validity is checked by experimental means that are macroscopic objects, and the readings of the means or instruments from which conclusions are drawn about atomic objects and phenomena are perceived by a person. Nature, with which science is concerned, is matter in motion, and matter cannot be cognised if it does not act on the human sense organs (either directly or indirectly, through the instruments). What would man know about the atomic world existing independently of his consciousness if it did not make itself felt through macro-phenomena perceived by him that are connected in a regular way with micro-phenomena?

Various fundamental physical theories (the theory of relativity, say, or quantum mechanics) make use of experimental data described in the language of classical concepts, and the theories themselves (let us note) differ in their content. One may ask in what form the experimental data described by classical concepts are included into the non-classical theory. The problem lies not in the description of the data (that problem is solved) but in their comprehension in terms of certain concepts connected with certain physical statements covered by a certain fundamental theory.

On this score physicists are not unanimous. Many of them do not bother about the question just stated, assuming that it is sufficient to use the observed data and the theory's mathematical apparatus to find observable data not yet known, i.e. that there are no new basic physical concepts in non-classical theory. This semi-unconscious point of view, incidentally, is not very far, in fact, from positivism, according to which a physical theory is only a logical means of systematising the observed.

In the case of the theory of relativity, according to Heisenberg, the new situation with concepts can best be described in mathematical language. Physicists, he says, could either try to adjust their language to the mathematical formalism of the new theory (which happens in the theory of relativity) or make do with the language of classical concepts, knowing that it has only limited applicability (as happens in quantum theory).'[7] Heisenberg consequently does not even pose the question of the new basic physical concepts in a new fundamental theory, i.e. concepts such that their content is determined by the basic physical laws of the new fundamental theory, and interprets the change in the basic classical concepts in such a way as to obscure this change itself.

The change in the fundamental concepts when a new theory is born from an old fundamental one does not mean adaptation of the old fundamental concepts to the new mathematical formalism or their restriction to a certain sphere of applicability, but signifies the rise of new fundamental concepts differing qualitatively from the old ones and the building at the same time of a new fundamental physical theory. The theory of relativity, for instance, was born at the junction of classical mechanics and classical electrodynamics, as a result of resolving the contradiction between Galileo's principle of relativity and the principle that the velocity of light *in vacuo* is independent of the motion of the source. The new axiomatics and the new basic concepts that formed the conceptual basis of Einstein's theory of relativity were also a result of this. From this angle the concepts of relative space, time, and simultaneity in Einstein's theory are not the classical concepts adjusted to the mathematical formalism of the theory, but fundamentally new physical concepts reflecting real space and time in their deep, internal interconnection (the practice of physical observation and experiment witnesses to the validity of this).

Questions on this plane have been very thoroughly considered by scientists who are conscious adherents of dialectical materialism and by Marxist philosophers.[8] As for Popper, Lakatos, and Kuhn, who should not by-pass the dialectics of the development of basic physical concepts, it would seem, in their studies of 'scientific revolutions', they actually left this dialectics out of their purview—they do not even use the term 'change of a classical concept'. In Kuhn's view, the transition from, say, the physics of Newton and Maxwell to the special and general theory of relativity has no rational explanation, whereas these problems have been solved in the research of Soviet scientists in terms of dialectical materialism and its theory of knowledge and logic (which was discussed, in particular, above).[9]

Let us now consider more concrete aspects of these problems. The concept of relativity figures quite often in physics. Abstracting from it in classical mechanics and Einstein's theory, let us analyse it in quantum mechanics, which we consider the pinnacle of its development in physics. The point at issue is relativity with respect to the means of observation; this concept is found implicitly in Bohr's work; explicitly, as a relevant principle, it was formulated by Fock.[10]

This principle requires objects and phenomena on an atomic scale to be described in terms of the concept of relativity with respect to the means of observation. Assume an electron beam to pass through a crystal lattice by which one can observe the diffraction pattern produced by electrons. With respect to this means of observation, the wave aspect of electron motion is manifested, i.e. the concept of the wave properties of the electron has no meaning outside this relation. Suppose the positions of electrons hitting a photographic plate to be determined as certain dark points in the emulsion; with respect to this means of observation the particle aspect of electron motion manifests itself, i.e. outside this relation the concept of the electron's corpuscular properties is meaningless. Thus, the idea of relativity with respect to the means of observation makes the particle-wave nature of electrons literally visible.

If one remembers that the means of observation or instruments are a kind of extension of the human sense organs and at the same time (as we have seen from study of atomic objects) that they belong, on a certain plane, to the observed physical system, it follows that no sharp line can be drawn between the objective and the subjective in experimental research, and that there is no absolute difference between the cognised object and the cognising subject, the observed system and the measuring instrument. The difference between the objective and the subjective during an experiment (observation, measurement) is not absolute, not extreme, but relative, fluid in a way.

The question of the relation between the objective and the subjective in physical cognition should thus not be separated from that of relativity with respect to the means of observation. In classical physics this problem was not so much solved as posed; no bridge had been built so to say to connect the objective and the subjective in the experimental research.

Such a bridge began to be built in Einstein's theory, but the problem of the relationship between the objective and the subjective in physical knowledge has been resolved most fully in quantum mechanics and its concept of 'relativity with respect to the means of observation'. It was Bohr who stressed that one must not draw a sharp line in experiment between the observed system and the experimental set-up. He analysed many aspects of this problem and emphasised the idea that description of the effect of the measuring instrument is a *sine qua non* in quantum physics for the determination of the phenomenon itself. On this plane his own illustration from everyday experience, already referred to above, is of interest. 'When the stick is held loosely,' he said, 'we feel it as an external object; when it is held firmly, the sense of an alien body is lost and the sensation of content is localised directly at the point where the stick is in contact with the body being investigated.'[11]

At the same time, this difference between the objective and the subjective in experiment, between the cognised object and the cognising subject, is not purely and simply a relative one; it contains an element of the absolute. The source of the experience is objectively real. An understanding of this difference as purely relative became the philosophical basis of the interpretation of quantum mechanics in which the idea of uncontrollability in principle, the idea that the wave function is just a record of the observer's information, and so on, were lauded by modern positivism and other contemporary idealist trends. These ideas tried to delete the dialectics of physical cognition; in the long run they all suggest that in physics there are no new basic concepts in the new fundamental theory apart from the basic concepts of classical physics, and that there cannot be.

* * *

The problems discussed above have something in common with what we shall call here the question of the activity of human consciousness; it has acquired a new philosophical nuance in modern physics.

According to Lakatos, there is an important difference between (in his own words) the 'passivist' and 'activist' theories of knowledge. From the standpoint of the first 'true knowledge is Nature's imprint on a perfectly inert mind: mental activity can only result in bias and distortion. The most influential passivist school is classical empiricism'.[12] From the standpoint of the second, he says, 'we cannot read the book of Nature without mental activity, without interpreting it in the light of our expectations or theories'.[13]

Similar expressions can also be found in Heisenberg, though with certain differences relating to what, according to him, modern physics contributes to knowledge. Heisenberg believed that man describes and explains not nature itself but nature as it appears to him because of his way of posing questions and methods of research. Heisenberg highly esteemed the statement of the German physicist and philosopher Carl Weiszäcker that 'Nature is earlier than man, but man is earlier than natural science'. 'The first half of that statement,' we read in Heisenberg's works, 'justifies classical physics and its ideal of total objectivity. The second half explains why we cannot rid ourselves of the paradoxes of quantum theory and the need to employ classical concepts.'[14]

The authors of these statements, it must be assumed, either did not know or ignored the theory of knowledge of dialectical materialism. The person cognising nature does not by any means treat it passively in doing so. As we know, the kernel of the theory of knowledge of dialectical materialism was already contained in Marx's 'Theses on Feuerbach'. Man has been dealing millions upon millions of times in his historical practice with objects and phenomena of macroscopic dimensions, and with their movement and changes, which occur at relatively low speeds (compared with the velocity of light). Classical physics, the first expression of which was Newton's physics, was based on this practice, which also confirmed its validity.

But 'the criterion of practice', as Lenin wrote, 'can never, in the nature of things, either confirm or refute any human idea *completely*.'[15] The relativity of this criterion (as regards the development of physics) is expressed in the fact that the practice of physical observations, experiments, and discoveries (about which classical physics did not and could not know) became the basis of, and confirmation of the validity of, the theory of relativity and quantum theory. Physical knowledge has now become incomparably more complete and rich than the physical knowledge of the eighteenth and nineteenth centuries. Convincing evidence of this is the scientific and technical revolution of our time.

It is wrong to assert that only classical physics describes nature as objectively real in its pure form and that the rise of quantum physics has confirmed the view that science describes nature affected by our methods of research. For the classical picture of nature does not reflect it fully and is much too coarse and idealised; this was demonstrated in their own way by the theory of relativity and quantum mechanics, which describe and explain nature more completely than classical theories. But then it is wrong to state that classical physics describes and explains nature without taking into account ourselves.

When the point is considered more broadly, we have every right to say that the reflection of nature in the observations and abstractions of such-and-such theory idealises, simplifies, and coarsens the reflected object in one way or another. At the same time the progress of knowledge and the development of theory and science as a whole are overcoming these idealisations and simplifications, which are inevitable in individual cognitive acts, in each individual theory, and in its statements and concepts. The development of physics from classical to relativistic physics and quantum theory reflects nature more fully and deeply, without exhausting it. This progress of physical knowledge, which cannot be imagined without ever newer changes of nature by the person cognising it does not, by any means, resemble a one-sided increase in the role of the subjective in science to the detriment of its objective content.

The objective and the subjective thus cannot be opposed and separated from each other in the course of knowing nature, although Heisenberg, for instance, interprets the difference between them in classical physics as purely absolute, and in quantum physics as purely relative. The one-sidedness of the objective and the subjective is being overcome by the continuous development of scientific theories and science as a whole, which are more and more completely reflecting the material world. 'Nature is *both* concrete *and* abstract, *both* phenomenon *and* essence, *both* moment *and* relation. Human concepts are subjective in their abstractness, separateness, but objective as a whole, in the process, in the sum total, in the tendency, in the source.'[16] These ideas of Lenin are expressed with surprising clarity in the development of physics—from classical theories to contemporary ones.

The theory of knowledge of dialectical materialism, which Lenin raised to the higher level corresponding to twentieth century science, makes it possible to eliminate idealist speculation from around modern physics and to map out proper ways of tackling its philosophical problems. Western scientists' disregard of materialist dialectics when analysing these problems proves to be contrary to the science they represent and makes them supporters and adherents of reactionary philosophy and religion. In this sense Heisenberg's last publications are typical: they contain statements that if it is difficult to find a place for religion in the system of concepts of classical science (according to him, it followed the materialist path), the situation is quite different in modern physics. This happened, he said, in connection with 'an emancipation of our thinking, namely that we have learned from the development of physics in recent decades how problematic the concepts 'objective' and 'subjective' are.'[17] He also stated that 'it is difficult for Soviet philosophy to come to terms with the theory of relativity and quantum theory'.[18]

There is no need here for a polemic against Heisenberg on these issues. The development of Marxist-Leninist philosophy and modern physics has adequately refuted him and other voluntary or involuntary opponents of dialectical materialism. The philosophy of dialectical materialism is the only true philosophy of modern physics and of all contemporary science. This has been demonstrated concretely by the development of science in the twentieth century.

Today the struggle between two major philosophical trends, two major parties in philosophy, materialism and idealism, has become particularly bitter in the philosophical problematics of modern physics and science as a whole. *Modern* materialism, in other words, *dialectical* materialism, gains ever new victories in twentieth century science. Science's ideological source of strength in the USSR and other socialist countries consists in its having valued and assimilated the very great and valuable tradition of its great teachers, Marx, Engels, and Lenin: to be party-committed in philosophy from beginning to end, to support the line of materialism consistently and fully against all types of idealist obscurantism and reactionary ideology.

The General Secretary of the CPSU Central Committee, L. I. Brezhnev, in his vivid, profound speech at the ceremonial session in the Kremlin Palace of Congresses on 7 October 1975, devoted to the 250th anniversary of the USSR Academy of Sciences, said remarkably about the Party commitment of Soviet science: 'I would like to dwell especially on one most important question, the Party commitment of our science. Whatever discipline the Soviet scientists work in, they are always characterised by a typical feature: their high communist consciousness and their Soviet patriotism. The Soviet scientist (if, certainly, it is a truly Soviet scientist) bases his whole scientific activity on the scientific ideology of Marxism-Leninism, is an active champion of communism, fights any reactionary and obscurantist forces. Our scientists subject all their practical activity to the task of realisation of the noble communist ideals.'[19]

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[3] See V. I. Lenin. *Collected Works*, Vol. 38, p 195.

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[8] See, for example, the books in the series *Dialekticheskii materializm i sovremennoe estestvoznanie* (Dialectical Materialism and Modern Science) (Nauka Publishers, Moscow, 1962-73). They have a rich bibliography.

[9] See also M. E. Omelyanovsky. Experimental Observation, Theory, and Dialectics in Physics. *Voprosy filosofii*, 1976, 10.

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[19] L. I. Brezhnev, *Leninskim kursom* (Following Lenin's Course) (Vol. 5, Politizdat, Moscow, 1976), p 364.

Professor Omelyanovsky's book presents an integral analysis of the main problems of materialist dialectics in modern physics with special attention to those problems or aspects that have come to the fore in recent philosophical and methodological studies. It considers the methodological function of materialist dialectics in modern physics and basic research, traces the philosophical evolution of the Copenhagen school, and analyses such very important epistemological matters as the problems of reality, contradiction, determinism, visualisation, observability, and measurement. Much space is devoted to discussion of elementarity in quantum physics, and there is a special chapter on axiomatics and its connection with the quest for basic concepts and principles in physics.

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