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Causality and Complementarity[1]

BY

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ON SEVERAL occasions[2] I have pointed out that the lesson taught us by recent developments in physics regarding the necessity of a constant extension of the frame of concepts appropriate for the classification of new experiences leads us to a general epistemological attitude which might help us to avoid apparent conceptual difficulties in other fields of science as well. Since, however, the opinion has been expressed from various sides that this attitude would appear to involve a mysticism incompatible with the true spirit of science, I am very glad to use the present opportunity of addressing this assembly of scientists working in quite different fields but united in their striving to find a common ground for our knowledge, to come back to this question, and above all to try to clear up the misunderstandings which have arisen.

Before entering into the problems to be discussed, I need recall only briefly how often the development of physics has taught us that a consistent application even of the most elementary concepts indispensable for the description of our daily experience, is based on assumptions initially unnoticed, the explicit consideration of which is, however,

[1] Address delivered before the Second International Congress for the Unity of Science, Copenhagen, June, 1936.

[2] "Atomic Theory and Description of Nature", four essays and an introductory survey; Cambridge, 1934; quoted in the text as A I, A II, A III, A IV, and A E; further, "Light and Life" Nature 131, 421; 457, 1933; and "Can Quantum Mechanical Description of Physical Reality be Considered Complete?" Physical Review LXVIII, 696, 1935; quoted as B and C respectively.

essential if we wish to obtain a classification of more extended domains of experience as clear and as free from arbitrariness as possible. I also hardly need to emphasize how much this development has contributed to the general philosophical clarification of the presuppositions underlying human knowledge. Even though these acquisitions are in many respects of a lasting character, we have nevertheless received only recently an incisive admonition that the analysis of new experiences is liable to disclose again and again the unrecognized presuppositions for an unambiguous use of our most simple concepts, such as space-time description and causal connection.

It was in fact the clarification of the paradoxes connected with the finite velocity of propagation of light and the judgment of events by observers in relative motion which first disclosed the arbitrariness contained even in the concept of simultaneity, and thereby created a freer attitude toward the question of space-time coördination which finds expression in the theory of relativity. As is well known, this has made possible a unified formulation of the phenomena appearing in different frames of reference, and through this brought to light the fundamental equivalence of hitherto separate physical regularities. The recognition of the essential dependence of any physical phenomenon on the system of reference of the observer, which forms the characteristic feature of relativity theory, implies, however—as especially Einstein himself has emphasized—no abandonment whatever of the assumption underlying the ideal of causality, that the behavior of a physical object relative to a given system of coördinates is uniquely determined, quite independently of whether it is observed or not.

However, a still further revision of the problem of observation has since been made necessary by the discovery of the universal quantum of action, which has taught us that the whole mode of description of classical physics, including the theory of relativity, retains its adequacy only as long as all quantities of action entering into the description are large compared to Planck's quantum. When this is not the case, as in the region of atomic physics, there appear new uniformities which cannot be fitted into the frame of the ordinary causal description (A_I). This circumstance, at first sight paradoxical, finds its elucidation in the recognition that in this region it is no longer possible sharply to distinguish between the autonomous behavior of a physical object and its inevitable interaction with other bodies serving as measuring instruments, the direct consideration of which is excluded by the very nature of the concept of observation in itself (A_{II}).

Indeed this circumstance presents us with a situation concerning the analysis and synthesis of experience which is entirely new in physics and forces us to replace the ideal of causality by a more general viewpoint usually termed "complementarity." The apparently incompatible sorts of information about the behavior of the object under examination which we get by different experimental arrangements can clearly not be brought into connection with each other in the usual way, but may, as equally essential for an exhaustive account of all experience, be regarded as "complementary" to each other. In particular, the frustration of every attempt to analyse more closely the "individuality" of single atomic processes, symbolized by the quantum of action, by a subdivision of their course, is explained by the fact that each section in this course definable by a direct observation would demand a measuring arrangement which would be incompatible with the appearance of the uniformities considered. Notwithstanding all differences, a certain analogy between the postulate of relativity and the point of view of complementarity can be seen in this, that according to the former the laws which in consequence of the finite velocity of light appear in different forms depending on the choice of the frame of reference, are equivalent to one another, whereas, according to the latter the results obtained by different measuring arrangements apparently contradictory because of the finite size of the quantum of action, are logically compatible.

In order to give as clear an idea as possible of the new epistomological situation which we meet in atomic physics, we may briefly consider those measurements designed to obtain an account of the space-time course of some physical event. The account consists in the last analysis in the establishment of a series of unambiguous connections between the behavior of the object and the measuring rods and clocks which define the system of reference involved in the space-time description. It is thus only as long as we may completely ignore, in the description of all the important circumstances of the event, all interaction between the object and these measuring instruments, which unavoidably accompanies the establishment of any such connection, that we can speak of an autonomous space-time behavior of the object under observation, independent of the conditions of observation. In case, however—as in the region of quantum phenomena—this interaction plays an essential rôle for the appearance of the phenomena themselves, the situation is completely changed, and we are in particular forced to renounce the combination, characteristic of classical physical description, of the space-time coördination of the event with the general conservation

theorems of dynamics. For the use of rods and clocks to fix the system of reference makes it by definition impossible to take into account the energy of momentum which might be transferred to them in the course of the phenomenon. Conversely, those quantum laws whose formulation rests essentially on the application of the concept of energy or momentum can appear only under circumstances of investigation from which a detailed account of the space-time behavior of the object is excluded.

As is well known, a mode of description suitable to this situation has been found in the so-called quantum mechanics, in which sufficient freedom for the consistent coördination of the new regularities has been achieved by the substitution for the usual kinematical and dynamical quantities of symbols which obey laws of calculation of a novel type. There is also from the point of view an interesting formal analogy between quantum mechanics and the theory of relativity, in that it has been possible in both cases with the help of abstract concepts of arithmetic and geometry respectively, to build up strictly logical formalisms which allow a mastering of the new domains of experience. In connection with the often discussed question whether such formalisms can be regarded as an extension of our power of visualization, it must not be forgotten that the representation of the coördination of space and time in the theory of relativity by a four dimensional manifold, as also the connecting of kinematic and dynamic quantities in quantum mechanics by non-commutative algebra, rest essentially on the old mathematical artifice of the introduction of imaginary quantities; in fact the fundamental constants, the velocity of light and the quantum of action, are introduced into the formalism as factors of the $\sqrt{-1}$, the one in the definition of the fourth coördinate, the other in the commutation laws of canonically conjugate variables.

It is of course not my intention here to go deeper into such special points; I wished only to emphasize that in these fields the logical correlations can only be won by a far-reaching renunciation of the usual demands of visualization. It would in particular not be out of place in this connection to warn against a misunderstanding likely to arise when one tries to express the content of Heisenberg's well known indeterminacy relations—which play as important a rôle in the judgment of the consistency of the essentially statistical mode of description of quantum mechanics as the Lorentz transformation does in solving the paradoxes which appear in the theory of relativity—by such a statement as: "the position and momentum of a particle cannot simulta-

neously be measured with arbitrary accuracy." According to such a formulation it would appear as though we had to do with some arbitrary renunciation of the measurement of either the one or the other of the two well-defined attributes of the object, which would not preclude the possibility of a future theory taking both attributes into account on the lines of the classical physics. From the above considerations it should be clear that the whole situation in atomic physics deprives of all meaning such inherent attributes as the idealizations of classical physics would ascribe to the object. On the contrary, the proper rôle of the indeterminacy relations consists in assuring quantitatively the logical compatibility of apparently contradictory laws which appear when we use two different experimental arrangements, of which only one permits an unambiguous use of the concept of position, while only the other permits the application of the concept of momentum defined as it is, solely by the law of conservation.

We thus see that the impossibility of carrying through a causal representation of quantum phenomena is directly connected with the assumptions underlying the use of the most elementary concepts which come into consideration for the description of experience. In this connection the view has been expressed from various sides that some future more radical departure in our mode of description from the concepts adapted to our daily experience would perhaps make it possible to preserve the ideal of causality also in the field of atomic physics. Such an opinion would, however, seem to be due to a misapprehension of the situation. For the requirement of communicability of the circumstances and results of experiments implies that we can speak of well defined experiences only within the framework of ordinary concepts. In particular it should not be forgotten that the concept of causality underlies the very interpretation of each result of experiment, and that even in the coördination of experience one can never, in the nature of things, have to do with well-defined breaks in the causal chain. The renunciation of the ideal of causality in atomic physics which has been forced on us is founded logically only on our not being any longer in a position to speak of the autonomous behavior of a physical object, due to the unavoidable interaction between the object and the measuring instruments which in principle cannot be taken into account, if these instruments according to their purpose shall allow the unambiguous use of the concepts necessary for the description of experience. In the last resort an artificial word like "complementarity" which does not belong to our daily concepts serves only briefly to remind us of the epistemo-

logical situation here encountered, which at least in physics is of an entirely novel character (A_E).

The repeatedly expressed hopes of avoiding the essentially statistical character of quantum mechanical description by the assumption of some causal mechanism underlying the atomic phenomena and hitherto inaccessible to observation would indeed seem to be as vain as any project of doing justice to the increased profundity of the picture of the world achieved by the general theory of relativity by means of the ordinary conceptions of absolute space and time. Above all such hopes would seem to rest upon an underestimate of the fundamental differences between the laws with which we are concerned in atomic physics and the every day experiences which are comprehended so completely by the ideas of classical physics. Not only is the well known dilemma between the corpuscular and undulatory character of light and matter avoidable only by means of the viewpoint of complementarity, but the peculiar stability properties of atomic structures which are in obvious contrast with the properties of any mechanical model, but which are so intrinsically connected with the existence of the quantum of action, form the very condition for the existence of the objects and measuring instruments, with the behavior of which classical physics is concerned. On closer consideration, the present formulation of quantum mechanics in spite of its great fruitfulness would yet seem to be no more than a first step in the necessary generalization of the classical mode of description, justified only by the possibility of disregarding in its domain of application the atomic structure of the measuring instruments themselves in the interpretation of the results of experiment. For a correlation of still deeper lying laws of nature involving not only the mutual interaction of the so-called elementary constituents of matter but also the stability of their existence, this last assumption can no longer be maintained, as we must be prepared for a more comprehensive generalization of the complementary mode of description which will demand a still more radical renunciation of the usual claims of so-called visualization.

I hope by these remarks to have conveyed the impression that in abandoning the causal description in atomic physics we are not concerned with a hasty assertion of the impossibility of comprehending the wealth of phenomena, but with a serious effort to account for the new type of laws here encountered in conformity with the general lesson of philosophy regarding the necessity of a balance between analysis and synthesis. Just in this connection it appeared to me to be of interest to point out that also in other regions of human knowledge we meet appar-

ent contradictions which might seem to be avoidable only from the point of view of complementarity. I am far from sharing, however, the widespread opinion that the recent development in the field of atomic physics could directly help us in deciding such questions as "mechanism or vitalism" and "free will or causal necessity" in favor of the one or the other alternative. Just the fact that the paradoxes of atomic physics could be solved not by a one sided attitude towards the old problem of "determinism or indeterminism," but only by examining the possibilities of observation and definition, should rather stimulate us to a renewed examination of the position in this respect in the biological and psychological problems at issue.

In the first place, regarding the question of the extent to which we can hope to explain the characteristic features of living organisms with the sole help of the experience acquired from the study of inanimate nature, we must above all keep in mind that even a definition of life itself contains epistemological problems. When we usually refer to a machine as dead, we mean scarcely anything else than that we are able to describe the circumstances essential for its functioning by means of the conceptions of classical physics. Still in view of the insufficiency of the classical mode of description in atomic physics, such a definition of the inanimate would hardly any longer be adequate. Yet the newly recognized possibility of inducing macroscopic effects by individual atomic process, which plays an essential part in the functioning of organisms—in any case for the sensitiveness of sense perceptions (AIV)—has been an incentive to the taking up anew of the question of a possible "explanation" of life. But at the same time the recognition of the fact that we must descend to the domain of atomic phenomena if we wish to bridge the gulf between the living and the inanimate, should bring before our eyes in a forceful way the practical and conceptual difficulties connected with this problem.

So far as we are at all in a position to follow the behavior of atoms in organisms under similar conditions of investigation as in the fundamental experiments of atomic physics, of course we can only meet with the laws disclosed by these experiments which, in spite of their feature of individuality, foreign to classical mechanics, can give us clearly no immediate understanding of the so-called holistic or finalistic characteristics of the activities of life. The only logical possibility of avoiding any contradiction between the formulation of the laws of physics and the concepts suitable for the description of the phenomena of life ought therefore to be sought in the essentially different character of the condi-

tions of investigation concerned. On a previous occasion (B) I have tried to express this situation by saying that every experimental arrangement suitable for following the behavior of the atoms constituting an organism in as exhaustive a way as implied by the possibilities of physical observation and definition would be incompatible with the maintaining of the life of the organism. This would in fact be quite analogous to the circumstance that all observations obtained by experimental arrangements which allow of a space-time account of the behavior of the constituents of atoms and molecules stand in a complementary relation to those obtained under conditions permitting the study of the intrinsic stability of atomic structures so essential for the physical and chemical properties of matter.

To make this view clearer, it was pointed out in the article cited, that the continuous metabolism of organisms inseparably connected with life prevents us even from distinguishing strictly which atoms belong to a living organism, and that we are thus presented with a problem the treatment of which, quite apart from its complication, is beyond the scope of the methods of atomic mechanics. These methods, which govern our entire knowledge of physics and chemistry concern, just as do those of classical mechanics, in fact only systems for which it is possible in principle to specify what are to be regarded as the elementary constituents. This situation suggests that those essential features of living organisms which are brought to light only under circumstances which exclude an exact account of their atomic constituents are laws of a nature which stands in a complementary relationship to those with which we are concerned in physics and chemistry. Thus the existence of life itself would have to be regarded in biology, both as regards the possibilities of observation and of definition, as no more subject to analysis than the existence of the quantum of action in atomic physics.

I have endeavored to make it clear that in such considerations there is no question whatever—as has been sometimes feared by philosophers and biologists—of so-called purely metaphysical speculations or of an arbitrary renunciation of the possibility by continued research, of further increasing our knowledge of the functioning of organisms. Rather, they aim at avoiding futile controversies by an analysis of the presuppositions and of the appropriateness of the conceptual structures involved. Though the viewpoint of complementarity rejects every compromise with any anti-rationalistic vitalism, it ought at the same time to be suited for revealing certain prejudices in so-called mechanism. On the one hand, any violation of physico-chemical laws in organic

life—such as the often mistakenly maintained contradiction between the activities of life and the fundamental theorems of thermo-dynamics —would be excluded from this point of view; on the other hand any insistence on an analogy between the existence of life itself and such laws should be rejected as irrational. As already emphasized in the article mentioned, this situation therefore implies no limitation whatever in the application to biology of the physico-chemical methods of description and investigation; in fact, the appropriate use of such methods—just as even in atomic physics all our experiences must rest upon experimental arrangements classically described—remains our sole and inexhaustible source of information about biological phenomena.

According to its tendency to make room for the phenomena of life within the conceptions suited to the description of material systems, the viewpoint discussed stands far removed from every attempt to exploit in a spiritual sense the failure of causal description in atomic physics. On the contrary, the viewpoint toward fundamental biological questions which we have here discussed, would rather seem suited to put the old problem of psycho-physical parallelism in a new light. The considerations which I have presented on previous occasions (A_{III}, B) on questions of psychology in connection with problems of atomic physics followed indeed two essentially different aims. The one was by means of well-known examples of the difficulties of analysis and synthesis of psychic phenomena connected with introspection to remind ourselves that in this region of knowledge we had already been forced to face a situation presenting in several respects a formal similarity with that with which,to the great disquietude of many physicists and philosophers, we have met in atomic physics. The other aim was to express the hope that the epistemological attitude which had led to the clarification of the much simpler physical problems could prove itself helpful also in the discussion of psychological questions. In fact, the use which we make of words like "thought" and "feeling," or "instinct" and "reason" to describe psychic experiences of different types, shows the existence of characteristic relationships of complementarity conditioned by the peculiarity of introspection. Above all, just the impossibility in introspection of sharply distinguishing between subject and object as is essential to the ideal of causality would seem to provide the natural play for the feeling of free will.

I am afraid that the short indications to which I have been obliged to restrict myself with respect to the last and many other points of this lecture will remind you only too well that in the last resort the direct

use of any word must stand in a complementary relationship to an analysis of its meaning. I hope, however, that I have to some extent succeeded in giving you the impression that my attitude is in no way in conflict with our common endeavors to arrive at as great a unification of knowledge as possible by the combating of prejudices in every field of research.

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