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On the Notions of Causality and Complementarity[1]

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THE CAUSAL MODE of description has deep roots in our conscious endeavors to utilize experience for practical adjustment to our environments, and is in this way inherently incorporated in common language. By the guidance which analysis in terms of cause and effect has offered in many fields of human knowledge, the principle of causality has even come to stand as the ideal for scientific explanation.

In physics, causal description, originally adapted to the problems of mechanics, rests on the assumption that the knowledge of the state of a material system at a given time permits the prediction of its state at any subsequent time. Here, however, already the definition of state requires special consideration and it need hardly be recalled that an adequate analysis of mechanical phenomena was possible only after the recognition that, in the account of a state of a system of bodies, not merely their location at a given moment but also their velocities have to be included.

In classical mechanics, the forces between bodies were assumed to depend simply on the instantaneous positions and velocities; but the discovery of the retardation of electromagnetic effects made it necessary to consider force fields as an essential part of a physical system, and to include in the description of the state of the system at a given time the specification of these fields in every point of space. Yet, as is well known, the establishment of the differential equations connecting the rate of variation of electromagnetic intensities in space and time has made possible a description of electromagnetic phenomena in complete analogy to causal analysis in mechanics.

It is true that, from the point of view of relativistic argumentation, such attributes of physical objects as position and velocity of material bodies, and even electric or magnetic field intensities, can no longer be given an absolute content. Still, relativity theory, which has endued classical physics with unprecedented unity and scope, has just through its elucidation of the conditions for the unambiguous use of elementary physical concepts allowed a concise formulation of the principle of causality along most general lines.

However, a wholly new situation in physical science was created through the discovery of the universal quantum of action, which revealed an elementary feature of "individuality" of atomic processes far beyond the old doctrine of the limited divisibility of matter originally introduced as a foundation for a causal explanation of the specific properties of material substances. This novel feature is not only entirely foreign to the classical theories of mechanics and electromagnetism, but is even irreconcilable with the very idea of causality.

In fact, the specification of the state of a physical system evidently cannot determine the choice between different individual processes of transition to other states, and an account of quantum effects must thus basically operate with the notion of the probabilities of occurrence of the different possible transition processes. We have here to do with a situation essentially different in character from the recourse to statistical methods in the practical dealing with complicated systems that are assumed to obey laws of classical mechanics.

The extent to which ordinary physical pictures fail in accounting for atomic phenomena is strikingly illustrated by the well-known dilemma concerning the corpuscular and wave properties of material particles as well as of electromagnetic radiation. It is further important to realize that any determination of Planck's constant rests upon the comparison between aspects of the phenomena which can be described only by means of pictures not combinable on the basis of classical physical theories. These theories indeed represent merely idealizations of asymptotic validity in the limit where the actions involved in any stage of the analysis of the phenomena are large compared with the elementary quantum.

In this situation, we are faced with the necessity of a radical revision of the foundation for description and explanation of physical phenomena. Here, it

[1] The purpose of this article is to give a very brief survey of some epistemological problems raised in atomic physics. It was originally published in *Dialectica*, International Review of the Philosophy of Knowledge, Editions du Griffon, Neuchâtel, Switzerland, Vol. 7/8 (1948), p. 312. A fuller account of the historical development, illustrated by typical examples which have served to clarify the general principles, is included in a chapter of *Albert Einstein: Philosopher-scientist*, being published by The Library of Living Philosophers, Inc., Evanston, Illinois, under the editorship of Paul Arthur Schilpp.

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must above all be recognized that, however far quantum effects transcend the scope of classical physical analysis, the account of the experimental arrangement and the record of the observations must always be expressed in common language supplemented with the terminology of classical physics. This is a simple logical demand, since the word "experiment" can in essence be used only in referring to a situation where we can tell others what we have done and what we have learned.

The very fact that quantum phenomena cannot be analyzed on classical lines thus implies the impossibility of separating a behavior of atomic objects from the interaction of these objects with the measuring instruments which serve to specify the conditions under which the phenomena appear. In particular, the individuality of the typical quantum effects finds proper expression in the circumstance that any attempt at subdividing the phenomena will demand a change in the experimental arrangement, introducing new sources of uncontrollable interaction between objects and measuring instruments.

In this situation, an inherent element of ambiguity is involved in assigning conventional physical attributes to atomic objects. A clear example of such an ambiguity is offered by the dilemma mentioned, as to the properties of electrons or photons, where we are faced with the contrast revealed by the comparison between observations regarding an atomic object, obtained by means of different experimental arrangements. Such empirical evidence exhibits a novel type of relationship, which has no analogue in classical physics and which may conveniently be termed *complementarity* in order to stress that in the contrasting phenomena we have to do with equally essential aspects of all well-defined knowledge about the objects.

An adequate tool for the complementary mode of description is offered by the quantum-mechanical formalism, in which the canonical equations of classical mechanics are retained while the physical variables are replaced by symbolic operators subjected to a non-commutative algebra. In this formalism Planck's constant enters only in the commutation relations

$$qp - pq = \sqrt{-1}\,\frac{h}{2\pi} \qquad (1)$$

between the symbols q and p standing for a pair of conjugate variables, or in the equivalent representation by means of the substitutions of the type

$$p = -\sqrt{-1}\,\frac{h}{2\pi}\frac{\partial}{\partial q} \qquad (2)$$

by which one of each set of conjugate variables is replaced by a differential operator. According to the two alternative procedures, quantum-mechanical calculations may be performed either by representing the variables by matrices with elements referring to the individual transitions between two states of the system or by making use of the so-called wave equation, the solutions of which refer to these states and allow us to derive probabilities for the transitions between them.

The entire formalism is to be considered as a tool for deriving predictions, of definite or statistical character, as regards information obtainable under experimental conditions described in classical terms and specified by means of parameters entering into the algebraic or differential equations of which the matrices or the wave functions, respectively, are solutions. These symbols themselves, as is indicated already by the use of imaginary numbers, are not susceptible to pictorial interpretation; and even derived real functions like densities and currents are only to be regarded as expressing the probabilities for the occurrence of individual events observable under well-defined experimental conditions.

A characteristic feature of the quantum-mechanical description is that the representation of a state of a system can never imply the accurate determination of both members of a pair of conjugate variables q and p. In fact, due to the noncommutability of such variables, as expressed by (1) and (2), there will always be a reciprocal relation

$$\Delta q \cdot \Delta p = \frac{h}{4\pi} \qquad (3)$$

between the latitudes Δq and Δp with which these variables can be fixed. These so-called indeterminacy relations explicitly bear out the limitation of causal analysis, but it is important to recognize that no unambiguous interpretation of such relations can be given in words suited to describe a situation in which physical attributes are objectified in a classical way.

Thus, a sentence like "we cannot know both the momentum and the position of an electron" raises at once questions as to the physical reality of such two attributes, which can be answered only by referring to the mutually exclusive conditions for the unambiguous use of space-time coordination, on the one hand, and dynamical conservation laws, on the other. In fact, any attempt at locating atomic objects in space and time demands an experimental arrangement involving an exchange of momentum and energy, uncontrollable in principle, between the objects and the scales and clocks defining the reference frame. Conversely, no arrangement suitable for the control of momentum and energy balance will admit precise description of the phenomena as a chain of events in space and time.

Strictly speaking, every reference to dynamical concepts implies a classical mechanical analysis of physical evidence which ultimately rests on the recording of space-time coincidences. Thus, also in the descrip-

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tion of atomic phenomena, use of momentum and energy variables for the specification of initial conditions and final observations refers implicitly to such analysis and therefore demands that the experimental arrangements used for the purpose have spatial dimensions and operate with time intervals sufficiently large to permit the neglect of the reciprocal indeterminacy expressed by (3). Under these circumstances it is, of course, to a certain degree a matter of convenience to what extent the classical aspects of the phenomena are included in the proper quantum-mechanical treatment where a distinction in principle is made between measuring instruments, the description of which must always be based on space-time pictures, and objects under investigation, about which observable predictions can in general be derived only by the nonvisualizable formalism.

Incidentally, it may be remarked that the construction and the functioning of all apparatus like diaphragms and shutters, serving to define geometry and timing of the experimental arrangements, or photographic plates used for recording the localization of atomic objects, will depend on properties of materials which are themselves essentially determined by the quantum of action. Still, this circumstance is irrelevant for the study of simple atomic phenomena where, in the specification of the experimental conditions, we may to a very high degree of approximation disregard the molecular constitution of the measuring instruments. If only the instruments are sufficiently heavy compared with the atomic objects under investigation, we can in particular neglect the requirements of relation (3) as regards the control of the localization in space and time of the single pieces of apparatus relative to each other.

In representing a generalization of classical mechanics suited to allow for the existence of the quantum of action, quantum mechanics offers a frame sufficiently wide to account for empirical regularities which cannot be comprised in the classical way of description. Besides the characteristic features of atomic stability, which gave the first impetus to the development of quantum mechanics, we may here refer to the peculiar regularities exhibited by systems composed of identical entities, such as photons or electrons, and determining for radiative equilibrium or essential properties of material substances. As is well known, these regularities are adequately described by the symmetry properties of the wave functions representing the state of the whole systems. Of course, such problems cannot be explored by any experimental arrangement suited for the tracing in space and time of each of the identical entities separately.

It is furthermore instructive to consider the conditions for the determination of positional and dynamical variables in a state of a system with several atomic constituents. In fact, although any pair, q and p, of conjugate space and momentum variables obeys the rule of noncommutative multiplication expressed by (1), and thus can be fixed only with reciprocal latitudes given by (3), the difference $q_1 - q_2$ between the space coordinates referring to two constituents of a system will commute with the sum $p_1 + p_2$ of the corresponding momentum components, as follows directly from the commutability of q_1 with p_2 and of q_2 with p_1. Both $q_1 - q_2$ and $p_1 + p_2$ can, therefore, be accurately fixed in a state of the complex system and we can consequently predict the value of either q_1 or p_1 if either q_2 or p_2 respectively, is determined by direct measurement. Since at the moment of measurement the direct interaction between the objects may have ceased, it might thus appear that both q_1 and p_1 were to be regarded as well-defined physical attributes of the isolated object and that, therefore, as has been argued, the quantum-mechanical representation of a state should not offer an adequate means of a complete description of physical reality. With regard to such an argument, however, it must be stressed that any two arrangements which admit accurate measurements of q_2 and p_2 will be mutually exclusive and that therefore predictions as regards q_1 or p_1 respectively, will pertain to phenomena which basically are of complementary character.

As regards the question of the completeness of the quantum-mechanical mode of description, it must be recognized that we are dealing with a mathematically consistent scheme which is adapted within its scope to every process of measurement and the adequacy of which can be judged only from a comparison of the predicted results with actual observations. In this connection, it is essential to note that, in any well-defined application of quantum mechanics, it is necessary to specify the whole experimental arrangement and that, in particular, the possibility of disposing of the parameters defining the quantum-mechanical problem just corresponds to our freedom of constructing and handling the measuring apparatus, which in turn means the freedom to choose between the different complementary types of phenomena we wish to study.

In order to avoid logical inconsistencies in the account of this unfamiliar situation, great care in all questions of terminology and dialectics is obviously imperative. Thus, phrases often found in the physical literature, like "disturbance of phenomena by observation" or "creation of physical attributes of objects by measurements," represent a use of words like *phenomena* and *observation* as well as *attribute* and *measurement* which is hardly compatible with common usage and practical definition and, therefore, is apt to cause confusion. As a more appropriate way

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of expression, one may strongly advocate limitation of the use of the word *phenomenon* to refer exclusively to observations obtained under specified circumstances, including an account of the whole experiment.

With this terminology, the observational problem in atomic physics is free of any special intricacy, since in actual experiments all evidence pertains to observations obtained under reproducible conditions and is expressed by unambiguous statements referring to the registration of the point at which an atomic particle arrives on a photographic plate or to a corresponding record of some other amplification device. Moreover, the circumstance that all such observations involve processes of essentially irreversible character lends to each phenomenon just that inherent feature of completion which is demanded for its well-defined interpretation within the framework of quantum mechanics.

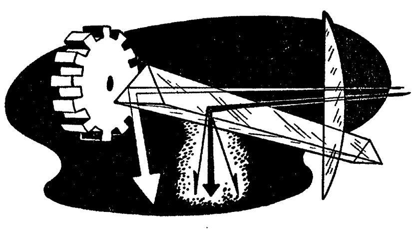
Recapitulating, the impossibility of subdividing the individual quantum effects and of separating a behavior of the objects from their interaction with the measuring instruments serving to define the conditions under which the phenomena appear implies an ambiguity in assigning conventional attributes to atomic objects which calls for a reconsideration of our attitude towards the problem of physical explanation. In this novel situation, even the old question of an ultimate determinacy of natural phenomena has lost its conceptional basis, and it is against this background that the viewpoint of complementarity presents itself as a rational generalization of the very ideal of causality.

The complementary mode of description does indeed not involve any arbitrary renunciation of customary demands of explanation but, on the contrary, aims at an appropriate dialectic expression for the actual conditions of analysis and synthesis in atomic physics. Incidentally, it would seem that the recourse to three-valued logic, sometimes proposed as means for dealing with the paradoxical features of quantum theory, is not suited to give a clearer account of the situation, since all well-defined experimental evidence, even if it cannot be analyzed in terms of classical physics, must be expressed in ordinary language making use of common logic.

The epistemological lesson we have received from the new development in physical science, where the problems enable a comparatively concise formulation of principles, may also suggest lines of approach in other domains of knowledge where the situation is of essentially less accessible character. An example is offered in biology, where mechanistic and vitalistic arguments are used in a typically complementary manner. In sociology, too, such dialectics may often be useful, particularly in problems confronting us in the study and comparison of human cultures, where we have to cope with the element of complacency inherent in every national culture and manifesting itself in prejudices which obviously cannot be appreciated from the standpoint of other nations.

Recognition of complementary relationship is not least required in psychology, where the conditions for analysis and synthesis of experience exhibit striking analogy with the situation in atomic physics. In fact, the use of words like *thoughts* and *sentiments,* equally indispensable to illustrate the diversity of psychical experience, pertain to mutually exclusive situations characterized by a different drawing of the line of separation between subject and object. In particular, the place left for the feeling of volition is afforded by the very circumstance that situations where we experience freedom of will are incompatible with psychological situations where causal analysis is reasonably attempted. In other words, when we use the phrase "I will" we renounce explanatory argumentation.

Altogether, the approach towards the problem of explanation that is embodied in the notion of complementarity suggests itself in our position as conscious beings and recalls forcefully the teaching of ancient thinkers that, in the search for a harmonious attitude towards life, it must never be forgotten that we ourselves are both actors and spectators in the drama of existence. To such an utterance applies, of course, as well as to most of the sentences in this article from the beginning to the end, the recognition that our task can only be to aim at communicating experiences and views to others by means of language, in which the practical use of every word stands in a complementary relation to attempts of its strict definition.



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