PART VII

REALISM AND QUANTUM MECHANICS

Comments on Kochen's Specification of Measurement Interactions*

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These comments are divided into two parts. My remarks at the meeting were prepared without access to a copy of Professor Kochen's lecture, and so could not constitute a detailed critical evaluation. They appear in Section 1 with only minor revisions. Section 2 was prepared subsequently on the basis of the text of the lecture as delivered; it contains points of criticism and requests for clarification, which are inevitably rather briefly stated.

1. Realism and Quantum Mechanics

Quantum mechanics raises many philosophical issues. I shall focus on one: the issue of realism. The realist holds that the proper form of acceptance of a scientific theory is to believe that it presents a true, or at least partially true, account of the workings of the world. Unless the subject matter of the theory itself involves cognitive agents (as perhaps does that of psychology), the realist holds further that statements of the theory have whatever truth they do possess independently of the observer, whose function is rather the epistemological one of discovering which sentences in the language of the theory are true. Some eminent physicists have expressed themselves in ways which *prima facie* seek to exclude such a realistic interpretation of quantum mechanics. According to Wigner, "...it is not possible to formulate the laws of quantum mechanics in a fully consistent way without reference to the consciousness. All that quantum mechanics purports to provide are probability connections between subsequent impressions...of the consciousness." ([14], p. 172) And Bohr once said "There is no quantum world. There is only an abstract quantum physical description. It is wrong to think that the task of physics is to find out how nature *is*. Physics concerns what we can say about nature." [2]

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Such statements prompt the question: is it possible to formulate the theory of quantum mechanics in such a way that it admits of a realistic interpretation? Some philosophers have apparently assumed that this question may be answered affirmatively, and then treated utterances such as those I have quoted as expressions of a general philosophical view (perhaps positivism or instrumentalism), the adoption of which has persuaded physicists not to adhere to a realistic interpretation of quantum mechanics even when this is presented as an option. Now it is very plausible to suppose that positivism and other philosophical views indeed had some influence on the development of quantum mechanics. But whether or not this is so, the theory, once developed, possesses internal features which make it very difficult to formulate in such a way as even to admit of a realistic interpretation.

A text-book formulation of quantum mechanics typically presents the statistical content of the theory in the form of measurement conditionals: that is, as sentences to the effect that if a system is in a particular quantum state and if a measurement occurs, then there is a certain probability attached to a specified measurement outcome. A realist would like to think that such sentences are true, or at least approximately so, and that what makes them true is the state of the world independent of any observer who may seek to verify this truth. Yet such a measurement conditional explicitly contains the word 'measurement'. And on one natural understanding of the term, a measurement is an act of some observer which, if successful, gives him or her knowledge of some structural feature of a phenomenon. With this understanding, the truth-conditions of a measurement conditional are not observer-independent in the way the realist requires. Indeed, if the statistical predictions of quantum mechanics have this form, and if measurement is so understood, then quantum mechanics makes no nontrivial statistical predictions concerning a world without observers. The realist must face the challenge of reformulating the statistical predictions of quantum mechanics so that these consequences may not be drawn.

A natural attempt is simply to excise talk of measurement from the statistical predictions. Each measurement conditional is replaced by a possessed property conditional. This is a sentence to the effect that if a system is in a given quantum state, then there is a certain probability attached to its possession of a specified property. The term 'measurement' has been omitted from the antecedent of the conditional, and talk of a measurement outcome replaced in its consequent by talk of a possessed property. This attempt is so simple and straightforward as to be naive: and so I shall call this the naive realist approach to the interpretation of quantum mechanics. The naive realist may go on to attribute the appearance in the usual formulation of quantum mechanics of measurement conditionals rather than possessed property conditionals to the influence of nonrealist philosophical views. He rejects these views, and thereby feels entitled to substitute possessed value conditionals for measurement conditionals in his formulation of quantum mechanics.

Unfortunately this kind of realism is too naive. It fails to take account of the physical circumstances which the founders of quantum mechanics sought to understand; and it fails to square with the properties of the mathematical structures they created to achieve this understanding. A conclusive demonstration of the first failure is hard to give, although it is perhaps this failure which has been most influential in convincing physicists of the untenability of a naive realist interpretation of quantum mechanics. In recent years the second failure has been demonstrated in a manner sufficiently convincing as to force the naive realist to become more sophisticated.

Recall that the naive realist formulates the statistical content of quantum mechanics by means of possessed property conditionals. What are these properties? Pertaining to a quantum system are certain measurable quantities (observables) known as dynamical variables. The name rightly suggests that particular values of these quantities (for example, of energy, of each component of momentum or position) are not in general unchanging features of the system. Corresponding to each dynamical variable and each range of values is a property which the system possesses just when the value of the variable lies in that range. On the naive realist account, each such property is always determinately either possessed or not possessed by the system. The possessed property conditionals correlate a description of a system specifying which of these properties it possesses, with the quantum state description, by giving the chance that each property is possessed in each quantum state. Measurement or observation merely reveals what properties a system possesses, and so may provide a test of the statistical predictions of the theory as expressed in possessed property conditionals. To perform such a test one could prepare a large number of systems described by a single quantum state, and then observe what fractions possess certain properties. If these fractions tend to approximate to the probabilities specified by the corresponding possessed property conditional, then the theory is to that extent confirmed.

Now if this account is correct, then two things follow. In order that all the possessed property conditionals be intelligible, it must be the case that every dynamical variable always has a precise value. And in order that each such conditional be true, there must be a way of distributing these values among the members of a large collection of systems in a single quantum state, so that the fraction of these systems with particular values for any set of dynamical variables assigned a joint probability by quantum mechanics, approximates to the joint probability assigned by the corresponding conditional. However, there are convincing arguments to the effect that both these consequences are false [8]. The mathematical work of Gleason [7], and of Professor Kochen himself in collaboration with Professor Specker [10], provides the basis for very powerful arguments to the falsity of the first consequence; and, suitably interpreted, papers of Bell [1] and Wigner [15] on the impossibility of a local hidden variable theory for quantum mechanics may be seen to yield the falsity of the second consequence.

If naive realism fails, what should the realist try next? One approach is quantum logic. For one school of quantum logicians ([2], [12]) views the Gleason and Kochen and Specker proofs as promoting a re-examination of the content of the claim that a quantum system always determinately either does or does not possess all its properties. Perhaps by a modification of the logic of such property ascriptions one can come to see that there is a sense in which this is true in spite of these proofs, and that this sense is just what is required to render the naive realist's possessed property conditionals intelligible? I shall not further consider such approaches, save to remark that the second argument against naive realism must still be faced, that there is room for dispute as to whether the resulting interpretation is really realistic, and that the approach presupposes particular answers to a range of highly controversial questions in the philosophy of logic.

Another approach would be to somehow restrict the set of possessed property conditionals that need interpreting. If this can be done, then the arguments from Gleason's and Kochen and Specker's work may be evaded. For these show that it is not possible for <u>all</u> dynamical variables to have simultaneous precise values: this does not exclude some privileged set of variables from always possessing precise values.[3] One may therefore attempt to interpret directly only those conditionals about possessed values for those variables. Other conditionals are to be given an indirect interpretation: in so far as they are part of the theory at all, this is because they are a result (perhaps approximate) of applying the directly interpreted conditionals to some more complex system of which the original system forms a component part. Such an approach would be similar in many respects to that outlined by Cartwright [4] in which the only real probabilities in quantum mechanics are for energy interchanges.

Beside these and other attempts to improve on naive realism, there is a different kind of approach, which I shall call the <u>interactive</u> <u>realist</u> approach. Instead of trying to excise talk of measurement from the statistical predictions of quantum mechanics, the realist may seek to preserve but neutralize such talk. On one understanding of the term a measurement is a cognitively directed act of some observer . There exists a well-established alternative usage according to which the term 'measurement' applies to just a particular class of physical interactions, any member of which may, but need not, be employed by an observer in his quest for knowledge. Understanding 'measurement' in this second way, the realist construes the statistical content of quantum mechanics as given by <u>interaction</u> <u>conditionals</u>: as sentences to the effect that if a system is in a particular quantum state, and if a measurement-type interaction occurs, then there is a certain probability attached to its subsequent possession of a specified property. I think the approach taken by Professor Kochen in his lecture is of this kind.

The interactive realist does not assume that each dynamical variable always possesses a precise value. Rather, the occurrence of a measurement-type interaction selects certain dynamical variables as those which have precise values. If it is assumed that this selection does not occur <u>before</u> the interaction takes place, then measurement does not in all cases reveal possessed values, but must sometimes give rise to the measured value. While it is not unexpected that measurement should effect a change in the properties of a system, it is at least surprising that measurement should bring into being the very property it reveals. And one may object to such a notion of measurement on semantic grounds. But these are not appropriate in the context: measurements are just a class of physical interactions, and quantum mechanics gives the chance that such an interaction will result in the possession of any one of a certain set of properties. And at least part of the customary epistemic force of the term 'measurement' is preserved in this usage. For measurement-type interactions are pragmatically distinguished from other interactions by the feature that they may be used to gain knowledge at least of the post-interaction properties of a system.

However, such a pragmatic distinction cannot ultimately be satisfactory to the realist. For it rests the truth-conditions of an interaction conditional on an expression ('measurement-type interaction') whose reference has been characterized in terms that are unclear and apparently still observer-dependent. Thus the interactive realist faces the task of giving a purely physical characterization of the class of measurement-type interactions. But even if he can succeed in this task, there is a further problem. If quantum mechanics is only concerned to account for the behavior of systems during an interaction of a special class, does this interpretation not restrict the universality of the theory to an unacceptable extent? So this type of interactive realist approach raises two important questions: What makes an interaction a measurement interaction? Doesn't this unacceptably restrict the universality of the theory? One of the chief merits of Professor Kochen's interpretation is that it gives relatively clear answers to these questions. And one of the most important challenges to the interpretation is to deny the adequacy of these answers.

One may attempt to answer these questions as a follower of Bohr. A measurement interaction is an interaction with a classical system; and since all we can expect of any physical theory is prediction and explanation of the way the world behaves at the classical level, quantum mechanics is as universal as any physical theory can be expected to be. Such answers seem unsatisfactory. The restriction of the goals of a physical theory seems dubious, ill-supported by Bohr's arguments, and ignored in practice by most quantum physicists. But the crucial objection is that we have been given no precise criterion of what counts as a classical system; and it is very hard to see how any such criterion could be given. For example, 'classical' cannot mean 'macroscopic': Bohr explicitly considers the application of quantum mechanics to macroscopic objects, and low-temperature physicists do it every day. And it cannot mean 'obeying the laws of classical mechanics': these conflict with the laws of quantum mechanics itself, so no system is a classical system in this sense.

It seems worthwhile explaining why these questions are so important for the interactive realist approach. For one may think that determination of the class of measurement interactions may safely be left to the experimental physicist, and that the degree of universality consequent upon this determination is not open to criticism from the philosopher. But the questions are not to be dismissed so easily. For without some <u>theoretical</u> restriction, there is nothing to prevent the application of quantum mechanics itself to the object-apparatus interaction associated with a measurement. And notoriously this results in the measurement problem. The application leads to the conclusion that there exist initial object states resulting in a final object-apparatus state which as usually interpreted implies that the apparatus fails to register any result at all (its pointer points nowhere at all)! If there were some characterization of the class of measurement interactions giving a theoretical reason preventing the application of quantum mechanics to the object-apparatus interaction associated with a measurement, then this problem would not arise. But such a theoretical reason would apparently require a modification of the theory of quantum mechanics itself. And the modification would then constitute a kind of restriction on the universality of the unmodified theory which must influence any attempt to interpret the latter.

Professor Kochen's approach seeks to give a theoretical characterization of the class of measurement interactions without any substantial modification of quantum mechanics. A measurement interaction is indeed just a particular type of interaction between quantum systems, and may be described fully and correctly by quantum mechanics. This does not lead to the measurement problem, however, as the interpretation of the quantum state of a composite system is modified. It now becomes quite consistent to suppose that while the object-apparatus state subsequent to their interaction is indeed as quantum mechanics predicts, still the apparatus registers a definite, and correct, result.

An interactive interpretation must give some account of how a measurement interaction affects the properties of a quantum system. And realism imposes constraints on this account. An important question here is: does a measurement interaction change the set of properties a system possesses, but in such a way that both before and after interacting the system determinately either does or does not possess each property? Or does a measurement lead to the <u>realization</u> of some property which was formerly merely potential? That is, does it result in the determinate possession or non-possession of each of a set of properties, although certain of these were formerly neither possessed nor not possessed by the system? Professor Kochen takes the second alternative: an <u>interactive property</u> is a property which a system only possesses or fails to possess consequent upon the occurrence of a suitable interaction. This line appears to raise problems for realism, for in the absence of an appropriate interaction, a sentence ascribing a certain interactive property to a quantum system will be neither true nor false. So the philosophical question arises: is this notion of an interactive property acceptable to the realist?

It seems to me that one difficulty the realist faces here has parallels in fields unconnected with quantum mechanics. Having such-and-such surface tension is a property appropriate to a substance only in the liquid phase. Is it a violation of realism that a solid neither has nor fails to have a surface tension of such-and-such? If not, then why should it constitute a violation of realism that interactive properties, which are appropriate to a quantum system only under certain conditions, should be neither possessed nor not possessed under other conditions?

What is required by the realist is that the conditions of realization for an interactive property be clearly and unambiguously specifiable. I consider in Section 2 the question of whether or not Professor Kochen's interpretation meets this requirement.

Before proceeding with more detailed critical remarks, I conclude this first part by sketching the picture of the quantum domain which emerges from Professor Kochen's interpretation. This picture is rather a strange one. Not just what position a system has, but whether the system has a position at all will depend on its history of interaction with other systems. And similarly for all other properties associated with dynamical variables. Clearly it is necessary for the interpretation to ensure that the interactive history of most macroscopic objects be such that it is at least an extremely good approximation to ascribe some fairly definite position, momentum, energy, etc. to them. But at the microscopic level this cannot be so: an electron may behave in a particle-like way at one time, and a wavelike way at another, and which way it behaves now may depend on some other system with which it interacted in the past, and which may not even now be near the electron. This sounds strange. But quantum mechanics is a strange theory.

2. Measurement Interactions

A realistic interpretation of quantum mechanics must make clear how the world would behave if the theory were true. And it must also outline how it is that we human observers can come to know that the world is one way rather than another. While Professor Kochen has provided some novel[4] suggestions about the ontology of quantum theory, his approach is somewhat procrustean as well as importantly incomplete in this first respect; and it is subject to severe difficulties in the second, epistemological, respect.

We are told that interactive properties are realized at the conclusion of an interaction. But when is an interaction concluded? If, when the interaction terms in the total Hamiltonian are strictly zero, one may wonder whether interactive properties are ever actually realized. But if, when these interaction terms become sufficiently small, then how small, and why pick just this size? Perhaps the most natural reply is to take the first horn of the dilemma and claim that all actual interaction Hamiltonians in fact become zero at some time, even though the approximate model Hamiltonians we employ in calculations may not. The experimental fact is that interactions cease, and if our models do not reflect this fact then they are in this respect inadequate, though adequate for other purposes. An example would be our model Hamiltonian for the Coulomb interaction between two charged particles. For no separation of the two particles does this equal strictly zero, though for large separations it becomes for most purposes negligible. According to what is apparently the most plausible development of his view, Professor Kochen would hold that the actual Coulomb interaction becomes zero at some finite separation, in order that an actual interaction between two charged particles cease, and some set of interactive properties be realized. But then what is the real Coulomb interaction Hamiltonian, and can one justify our use of the approximate model interaction Hamiltonian in calculations of scattering cross-sections?

A more dramatic example in which one may wonder whether an interaction ever literally ceases is provided by Schrödinger's cat. On Kochen's account, when the interaction (between the atomic system and a series of macroscopic systems culminating in the cat) has ceased, the cat is already alive or dead. But if the interaction involves the triggering of a Geiger counter by an atomic decay product, and if the decay product is absorbed in the Geiger counter, then the interaction terms in the decay product-Geiger counter system remain non-zero. And yet we wish to say that the interaction ceases with the cat definitely alive or dead.

Suppose however that the details of when interactions cease can be spelled out in a satisfactory and natural way. A second difficulty for Kochen's approach concerns the specification of the interaction algebras which determine what properties are then realized. The formal result concerning tensor product Hilbert spaces to which Professor Kochen appeals guarantees the existence, but not the uniqueness, of a pair of correlated Boolean σ-algebras of projection operators in the two component spaces. Thus there are circumstances in which the final quantum state of a pair of previously interacting systems does not uniquely determine the resulting σ-algebras of properties realized: one notable state for which this is so occurs in the unmodified Bohm version of the EPR thought-experiment. Now any actual interaction proceeds in accordance with some interaction Hamiltonian, and this may provide additional information, sufficient to uniquely pick out one pair of correlated interaction algebras even in an otherwise degenerate case. It may, but Professor Kochen has given us no reason to think that it does. What is required to complete his ontological picture is the provision of a precise algorithm which, for any interaction, specifies just which interaction algebras of properties are realized at the conclusion of that interaction. This algorithm may appeal to only those features of the interaction which are already represented within the theory, such as the compound state and interaction Hamiltonian. It may not appeal to the uses (e.g., measurement) to which this interaction is put, nor to details of other interactions the system has undergone, or may subsequently undergo.

A third objection is this: there are examples of interactions which result in correlated pairs of systems such that a non-orthogonal decomposition of the mixed statistical state of a component system seems called for on physical grounds (cf., Cartwright, [3]). In such a case, Kochen's approach requires that the properties realized at the conclusion of the interaction correspond to a biorthogonal decomposition, even though physical considerations would apparently favor the realization of properties corresponding to the non-biorthogonal decomposition. Here the approach, though consistent, fails to square with the physics of the situation. But if a non-biorthogonal decomposition is permitted, then the uniqueness problem becomes much more severe, since any state in the image space of the statistical operator of a component system appears with non-zero coefficient in some non-biorthogonal decomposition of the state of the compound system.

One aspect of Professor Kochen's approach which makes it attractive to the realist is the absence from its fundamental account of the world of references to measurement. But if we are to investigate the behavior of the world we must make measurements to determine properties of systems, and quantum mechanics should also enable us to understand how this is possible. Does Professor Kochen's approach provide the basis for a quantum mechanical understanding of measurement processes?

According to Professor Kochen, certain interactive properties may be realized at the conclusion of any interaction between quantum systems. If we are to know which interactive properties a system actually possesses at the conclusion of a particular interaction, it will in general be necessary to perform a measurement on that system. Now a measurement must itself be considered to be an interaction between this system and a further measuring system, capable of inducing the realization of some correlated property in the measuring system. A measurement interaction is therefore an interaction characterized by a particular kind of interaction Hamiltonian, which will correlate the individual state of the measuring system with (the relevant feature of) the individual state of the measured system. Let us investigate the nature of the Hamiltonian required for this purpose.

Suppose the value of dynamical variable A is to be measured on system S by measuring system M. If the initial individual state of S makes true val(A)=a_i, then the measurement interaction must leave M in a distinct individual state corresponding to val(A)=a_i. Suppose then that the initial statistical state of S is φ_i (where $A\varphi_i = a_i\varphi_i$) and that of M is ψ_0. We require that the interaction have the following effect on the combined statistical state

$$\varphi_i \otimes \psi_0 \rightarrow \chi_i \otimes \psi_i = U(\varphi_i \otimes \psi_0)$$

where U is the unitary time evolution operator of the compound system. Here the final individual state of M may be correlated with the initial statistical and hence(?) individual state of S (the general biorthogonal expansion $\Sigma\, a_i(\chi_i \otimes \psi_i)$ would not give this correlation). Since this must hold for an arbitrary initial state φ_i, we have by linearity of the law of time evolution

$$\varphi \otimes \psi_o \rightarrow \Sigma\, c_i(\chi_i \otimes \psi_i) \quad (\text{where } \varphi = \Sigma\, c_i\varphi_i).$$

Now the final superposition must realize some individual state of M out of those uniquely correlated with val(A)=a_i, for varying i. Hence the expansion must be biorthogonal. Thus the requirement on the total Hamiltonian governing a measurement interaction is that it correspond to a time evolution operator U such that

$$U(\Sigma\, c_i\varphi_i \otimes \psi_o) = \Sigma\, c_i(\chi_i \otimes \psi_i)$$

for arbitrary c_i, and with $(\chi_i, \chi_j) = (\psi_i, \psi_j) = \delta_{ij}$.

Now since this U is indeed unitary, such an interaction is indeed dynamically possible. It may now seem that we have given an adequate quantum mechanical account of a measurement interaction. However there are two reasons why this is not so. The first reason has to do with restriction * imposed by Professor Kochen on property changes in interactions.

* is related to the projection postulate, which asserts that the quantum state of a system immediately after a measurement of some observable is given by the normalized projection of the original state vector onto the eigenspace of this observable corresponding to the eigenvalue found in the measurement. In effect, * asserts for individual states just what the projection postulate asserts for statistical states. Presumably it is required so as to recover the benefits of the projection postulate while preserving consistency with the time evolution prescribed by the Schrödinger equation. However, the blessings of the projection postulate are known to be mixed: there are in the literature powerful arguments for the conclusion that the projection postulate is rarely if ever obeyed in any actual measurement [11]. And in the literature on measurement in quantum mechanics, a whole category of measurements is recognized

(Jauch [9], p. 165, calls these measurements of the second kind) which consists of measurements which do not obey the projection postulate. Professor Kochen says of * that it is an intuitively reasonable fundamental assumption of quantum mechanics which has always been verified in actual interactions. However intuitively reasonable it may be, it is hardly uncontroversial to claim that * is a fundamental assumption of quantum mechanics, particularly since it appears to be quite simple to give examples of interactions which violate it. An obvious counterexample is furnished by any scattering experiment in which an incoming particle with definite momentum interacts then separates with definite, but different, momentum. A second counterexample is more to the present point, since it concerns the coherence of Kochen's account of measurement interactions.

Suppose that we require * of the individual states of the system under investigation in a measurement process, and suppose that the initial individual and statistical state of this system is represented by χ_j. Then we have

$$U(\chi_j \otimes \psi_o) = \Sigma\, c_i^j(\chi_i \otimes \psi_i). \quad (\chi_j = \Sigma\, c_i^j \varphi_i)$$

but by *, if the individual state of the system is represented by the vector χ_j, then the final individual state of this system must also be represented by χ_j, and the final apparatus individual state must be represented by ψ_j. But then the interaction results in individual apparatus state ψ_k with probability δ_{jk}, not probability $|c_k^j|^2$, and the interaction fails to meet the requirements of a measurement interaction after all. Similarly, applying * to the apparatus individual state ψ_o, no interaction can ever change that state, provided that the ψ's (including ψ_o) form an orthonormal set. But this means that no interaction can function as a measurement interaction irrespective of the initial individual state of the system under investigation. Thus accepting * seems fatal to the project of explaining how we can use interactions to obtain knowledge of the individual state of a system. But since * is independently implausible, perhaps its abandonment will permit such an explanation after all.

The second reason why the above quantum mechanical account of a measurement interaction is inadequate concerns the relation between the individual and statistical states of a system. The above analysis of a measurement interaction showed how the final apparatus individual state reflected the initial system pure statistical state. But to connect this to the initial system individual state, some further principle is required. An obvious principle to try is this: if the pure statistical state of a system which has an individual state is φ, then the individual state of that system consists of the ultrafilter of all statements assigned unit probability by the application of the quantum statistical algorithm to φ. If this were true, then knowledge of the final apparatus individual state would yield knowledge of the initial individual, as well as statistical, state. Furthermore, the attribution to Kochen of this principle is rendered initially plausible by an examination of the way he introduces the statistical state via *. For this seems to guarantee the truth of the principle. But matters can't be so simple, as becomes clear in Kochen's discussion of his version of the EPR thought-experiment. This discussion will be examined shortly. The important feature for present purposes is that to handle this case Kochen has to deny the above principle linking individual to pure statistical states of a system. But without some such link, the above account of measurement fails to explain how we can obtain knowledge of the individual state of a system; and so the postulation of such individual states remains undesirably metaphysical, and their use to underpin the statistical assertions of quantum mechanics makes it mysterious how we can have reason to believe these assertions are even approximately correct.

This second obstacle to an account of measurement rested on the difficulty of inferring the individual from the statistical state of a system. But in order to complete the account of the epistemology of quantum mechanics, we also require rules for the coherent attribution of statistical states to systems. An obvious problem here concerns the transition from a mixed to a pure statistical state to describe a previously interacting system. Under what circumstances and for what purposes is this transition permissible and what knowledge dictates the attribution of one rather than another pure state to a system or collection of similarly prepared systems?

Professor Kochen's treatment of his version of the EPR thought-experiment is puzzling, and highlights a number of difficulties for his approach. We are invited to consider a variant of Bohm's version of the EPR situation in which the compound system is in a state with zero spin in the z direction, but non-zero total spin (it is a superposition of spin zero and spin one states). The angle ϑ is chosen so that the biorthogonal decomposition of the state Φ in terms of eigenstates of z-component of spin is unique, so that σ_z^1, σ_z^2 are realized at the conclusion of the interaction. Consideration of σ_x^2 measurements reveals the conditional certainties expressed as follows

$$\sigma_x^2 = \tfrac{1}{2} \rightarrow \sigma_d^1 = \tfrac{1}{2}$$

$$\sigma_x^2 = -\tfrac{1}{2} \rightarrow \sigma_e^1 = \tfrac{1}{2}$$

If these are to be accommodated by assigning any state to system 1 after the σ_x^2 measurement, this state must be δ. But before the measurement of σ_x^2, 1 was assigned individual state ζ_+^1 or ζ_-^1. It thus appears that simultaneous with the measurement of σ_x^2, the state of system 1 changes instantaneously and discontinuously from ζ_+^1 or ζ_-^1 to δ, in spite of the fact that 1 and 2 may then be spatially and physically isolated. To avoid this case of apparent instantaneous action at a distance, Kochen says that though the individual state of 1 is *and remains* ζ_+^1 or ζ_-^1, nevertheless its statistical state changes from a mixture of ζ_+^1 and ζ_-^1 to δ. And since a statistical state represents our knowledge, not the world, it may change discontinuously and "at a distance" without any awkward physical or metaphysical consequences.

What are we to make of this account? First note that the assignment of individual state ζ_+^1 and statistical state δ to 1 after the σ_x^2 measurement furnishes the promised counterexample, to the principle ennunciated above linking the individual to the statistical state of a system. This has unpleasant consequences for the interpretation of these states. For how can we find out whether the individual state of 1 is ζ_+^1 or ζ_-^1, or indeed verify that it is either one of these? If we interact 1 with some measuring system, then the resulting individual state of that system must reflect the statistical state δ, not the individual state ζ_+^1. For example, there will be a finite probability ($\cos^2\vartheta$) that the apparatus system will go into the state which, on the above account of measurement, is supposed to indicate that the individual state of 1 is ζ_-^1; and this is so irrespective of whether the individual state of 1 is ζ_+^1 or ζ_-^1! This merely demonstrates the incompatibility between the projected account of measurement and the treatment of the EPR-type case. But the latter treatment has paradoxical features independent of the account of measurement . For we are required to countenance a situation in which we have justified belief in many statistical, and some non-statistical, subjunctive conditional statements about the future behavior of 1, and yet none of this is grounded in present truths about the actual present state of 1. But surely for a realist there must be some present property of 1 in virtue of which we can now know that if a δ-realizing interaction with 1 were to take place, then the δ property would certainly be realized? And yet no such property is represented in the present individual state of 1. Is such a property represented in the present statistical state of 1? Here we face a dilemma. Since the statistical state is supposed to represent only our knowledge, we may take it that the answer must be no. But then we are left with true ungrounded subjunctive conditionals, which seems unacceptable to the realist. On the other hand, if we assume the answer is yes, then the statistical state must after all incorporate ontological aspects. But then the abrupt change in the statistical state of 1 on measuring σ_x^2 must after all be a case of real physical action at a distance.

Such considerations recall a principle Einstein ([6], p. 777) applied to the EPR case. "If, without in any way disturbing a system, we can predict with certainty (that is, with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity." Now Kochen's treatment of the EPR-type case does not violate this criterion, though at first sight it appears to. For it appears that there must be an element of physical reality corresponding to σ_δ^1 (or else σ_ε^1) after the σ_x^2 measurement, since this measurement may be supposed not to affect system 1, and there is probability unity that system 1 have σ_δ^1 (or else σ_ε^1) after that measurement. However since the individual state of 1 after the σ_x^2 measurement does not assign a truth value to σ_δ^1, we seem to have a violation of Einstein's criterion. Actually this is not so. For we can predict with probability unity not that system 1 has σ_δ^1 (say), but only that σ_δ^1 will be realized in a subsequent δ-realizing interaction. But while the letter of Einstein's criterion is not infringed, its spirit certainly is. Kochen's account of his EPR-type thought experiment would not be acceptable to Einstein, or indeed to any realist.

Notes

[1] My research has been supported by the Thyssen Foundation, whose generosity permitted me to accept the invitation to comment on the lecture. I have profited from conversations with Nancy Cartwright, William Demopoulos, Hilary Putnam and Abner Shimony, as well as from the views of participants in a seminar at Cambridge University.

[2] I am unable to locate the origin of this quotation.

[3] Dr. J. Dorling has argued in an unpublished paper that a relatively simple strengthening of the Gleason result does exclude this possibility. I am unable to consider this argument here. (See [5]).

[4] Professor Kochen's interpretation is not unlike several other interpretations in the literature. See in particular van Fraassen [13] and the references therein.

Editor's Note

*Kochen's paper, given at the PSA Meeting and discussed in these comments, was not submitted for publication. Dr. Healey's comments are reasonably self-contained and were thought to be worth publishing even without the paper on which the comments are being made.

References

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