Quantum Measurements are Noncontextual

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Abstract
Quantum measurements are noncontextual, with outcomes independent of which other commuting observables are measured at the same time, when consistently analyzed using principles of Hilbert space quantum mechanics rather than classical hidden variables.

John Bell in Sec. 5 of [1] while discussing hidden variables in quantum mechanics raised the question of whether quantum theory is "contextual." In particular, does the outcome of a measurement of an observable $A$ on a system $S$ depend on whether $A$ is measured along with an observable $B$ that commutes with $A$, or along with a different observable $C$ that also commutes with $A$ but does not commute with $B$? (In what follows we make no distinction between an observable $A$ and the operator $A = A^\dagger$ that represents it on the Hilbert space $H_S$ of the system in question.) Everyone agrees that if two observables commute they can be measured simultaneously, so there is no difficulty imagining $A$ and $B$ measured simultaneously on a single system using a single apparatus. Similarly one can imagine $A$ and $C$ measured simultaneously by a single apparatus, but since $B$ and $C$ do not commute, the two apparatuses just mentioned must be different. Suppose the first apparatus yields some value of $A$. Would the second have yielded the same result? A theory which answers "Yes" is said to be noncontextual; one which answers "No" is contextual, i.e., the measurement outcome depends on the context, on what else is being measured at the same time. Note that the issue being addressed here is that of individual measurement outcomes, not the probability of an outcome in a situation where measurements may be repeated a large number of times.

It will be argued below that quantum theory is noncontextual: the measured value of $A$ does not depend on which other observable, necessarily one commuting with $A$, is measured simultaneously with it, assuming the measurement is carried out with properly designed apparatus. The basic point is that the outcome of such a measurement can be interpreted as revealing a property that the measured system—we refer to it as a particle—had before the measurement took place. By a quantum property we mean (following von Neumann, see Sec. III.5 of [2]) something represented by a subspace of the appropriate quantum Hilbert space, equivalently the projector onto this subspace, rather than by some additional hidden variable that is not part of the Hilbert space. The techniques needed for this analysis have been available for well over a decade [3-4], but seem to have been ignored in a substantial collection of papers—the number is large, and what follows is far from an exhaustive list—published relatively recently in this [5-14] and in other journals [15-28]. (Some older discussions of the contextuality problem in [29] and in Ch. 7 of [30] are in certain respects clearer than Bell’s original work. The philosopher’s perspective is well represented in [31] and [32].) These papers leave the reader with the misleading (in our opinion) impression that quantum mechanics is contextual because it fails to satisfy certain inequalities derived on the basis of classical hidden variable theories. We believe that, on the contrary, the real issue is that quantum mechanics is not classical mechanics, and when analyzed using conceptual tools consistent with its mathematical (Hilbert space) structure quantum mechanics is noncontextual, using this term in the sense originally employed by Bell.

Textbook quantum theory cannot address Bell’s question for reasons Bell himself pointed out in one of his last publications [33]: it employs “measurement” as a sort of fundamental principle or axiom, a black box which cannot be opened or further analyzed. This is the great “measurement problem” of quantum foundations, which in fact is two problems. The first is that the unitary time development produced by
Schrödinger’s equation when applied to the apparatus as well as the system being measured can lead to a superposition of outputs—pointer positions in the quaint but picturesque language of quantum foundations—which is hard to interpret. Disposing of this “Schrödinger cat,” or, speaking metaphorically, stopping the pointer from wiggling, constitutes the first measurement problem. But when this has been solved the second measurement problem remains: inferring from the macroscopic pointer position some microscopic state of affairs that existed before, not after, the measurement took place. Such inferences are frequently carried out by experimental physicists: think of a neutrino coming from the sun, or a gamma ray emerging from a nucleus and gobbled up by a detector. The widespread idea that a quantum measurement only tells one something about what exists after the measurement is complete arises from an inadequate treatment in textbooks, in which a measurement is often confused with the preparation of a system in a particular quantum state. The two are not unrelated, but they are in fact distinct; see [34] for further discussions of this point.

The consistent or decoherent histories approach, hereafter referred to as “histories,” seems at present the only interpretation of quantum mechanics employing the quantum Hilbert space without using additional hidden variables that gives satisfactory answers to both measurement problems. It is the basis of the analysis that follows. There are by now numerous expositions of the basic histories approach; in order of decreasing length we recommend the following: [4, 35–37]. There have been numerous criticisms; for an analysis of, and response to the major ones the reader is referred to [34] and other work cited there. Its proponents do not regard the histories approach as antithetical to standard quantum mechanics as found in textbooks. It predicts exactly the same probabilities for measurement outcomes, but in addition it allows measurements themselves to be analyzed in fully quantum mechanical terms, and in particular the outcomes of measurements to be related to the microscopic properties the apparatus was designed to measure. The following discussion should for the most part be accessible to readers familiar only with the standard (textbook) approach, though at certain points reference is made to published results in order to shorten a longer discussion. A more detailed but also more abstract and less physical approach to the issue of contextuality will be found in [38].

Rather than discussing abstract principles, let us consider a specific example in which $\mathcal{H}_S$ is three dimensional (think of the spin of a spin-one particle, though angular momentum does not enter the following discussion), with an orthonormal basis $|1\rangle$, $|2\rangle$, $|3\rangle$, and three different observables defined as follows using dyads:

$$ A = |1\rangle\langle 1| - |2\rangle\langle 2| - |3\rangle\langle 3|, \quad B = \frac{1}{2} |1\rangle\langle 1| + |2\rangle\langle 2| - |3\rangle\langle 3|, \quad C = 2 |1\rangle\langle 1| + |2\rangle\langle 2| + |3\rangle\langle 3|. \quad (1) $$

It is obvious that $[A, B] = 0$, and straightforward to show that $[A, C] = 0$ and $[B, C] \neq 0$.

![Figure 1: Apparatus to measure $A$ along with $B$ ($U = U_B$), or with $C$ ($U = U_C$).](image)

An apparatus for measuring these observables is shown schematically in Fig. 1. The incoming particle first passes through a device $V$ (one can think of an electric field gradient acting on a particle with an electric quadrupole moment) which splits the path in two: the upper path, followed by a particle in the state $|1\rangle$, leads to the detector $D_1$. The lower (straight) path, followed by a particle whose state is any linear combination of $|2\rangle$ and $|3\rangle$, passes through a nondestructive detector $M_1$ that measures the particle’s passage without disturbing its internal state, and then through another device $U$ that carries out a unitary transformation $U_B$ equal to the identity $I$ (i.e., the device does nothing) if $B$ is to be measured, or

$$ U_C = (1/\sqrt{2}) \{ |2\rangle\langle 2| + |3\rangle\langle 3| - |3\rangle\langle 2| - |2\rangle\langle 3| \}. \quad (2) $$

if $C$ is to be measured. Following this yet another device $W$ (e.g., think of a Stern-Gerlach magnet) splits the trajectory into one moving upwards if the particle state is in state $|2\rangle$, or downwards if it is in state $|3\rangle$; these terminate in detectors $D_2$ and $D_3$. 

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A particle initially in the eigenstate $|1\rangle$ of $A$ with eigenvalue $+1$ will be detected by $D_1$, whereas any eigenstate with eigenvalue $-1$, some linear combination of $|2\rangle$ and $|3\rangle$, will be detected by $M_1$ and then travel on. Thus a measurement of $A$ precedes the particle’s passing through the box $U$, and the outcome will not be affected by whether the unitary is $U_B$ or $U_C$. Which of these is present could, in principle, be decided at the very last moment, after the particle (if on this path) has passed through $M_1$. A measurement of $B$ is carried out by setting $U = I$, so that initial eigenstates with eigenvalues of $1/2$, $1$, and $-1$ will be detected by detectors $1$, $2$, and $3$, respectively. Alternatively, $C$ can be measured by setting $U = U_C$, $2$; eigenvalues of $2$, $1$, and $-1$ correspond to detection by detectors $1$, $2$, and $3$, respectively.

But suppose the incoming particle has been prepared in a state $|\psi_0\rangle$ which is not an eigenstate of the operators which will later be measured. How can one avoid Schrödinger’s cat, if the detectors themselves are quantum devices, as assumed by most physicists nowadays? The cleanest way to resolve this (first) measurement problem is to employ Born’s idea $[39]$ that a quantum wave function evolving unitarily in time is not to be regarded as physical reality, but instead interpreted using probabilities—the wave function is a “pre-probability” in the notation of Ch. 9 of $[4]$. The modern approach is to set up a suitable framework, a collection of quantum histories in which the ordinary macroscopic outcome results for the detectors are represented by appropriate (“quasi-classical”) projectors on the full quantum Hilbert space of particle-plus-measuring apparatus. For details, see $[4]$, in particular Chs. 17 and 18.

It is, of course, clear given the construction shown in Fig. 1 that if the change from an $A$-plus-$B$ apparatus to an $A$-plus-$C$ apparatus is made after the particle has passed the position of detectors $D_1$ and $M_1$, this cannot affect the $A$ measurement outcome, at least if the future does not influence the past, so in this sense it seems clear that this measurement is noncontextual.$^1$ However, this might leave open the possibility that in some other measurement setup the measurement of $C$ instead of $B$ would affect the $A$ measurement outcome. In order to dispose of this concern we need to address the second measurement problem and show that the outcome of the $A$ measurement reflects a property possessed by the particle before the measurement took place, and this is true (for a properly constructed apparatus) whatever state $|\psi_0\rangle$ the particle is initially prepared in.

Let $t_1$ be a time just before the particle reaches the measuring device, e.g., before it enters the $V$ box in Fig. 1 and assume that its unitary time evolution (it is traveling in a field-free region) from $t_0$, when initially prepared, to $t_1$ is trivial: $|\psi_1\rangle = |\psi_0\rangle$. At time $t_1$ introduce a projective decomposition of the identity on $\mathcal{H}_S$,

$$I = |1\rangle\langle 1| + \left(|2\rangle\langle 2| + |3\rangle\langle 3|\right) = P_1 + P_2$$

and consider a family of four histories at times $0 < t_1 < t_2$,

$$|\Psi_0\rangle \odot \{P_1, P_2\} \odot \{D_1, M_1\}.$$  

Here $|\Psi_0\rangle = |\Psi_0\rangle\langle \Psi_0|$ is the projector corresponding to a state $|\Psi_0\rangle$ at $t_0$ which is a tensor product of an initial apparatus state with the particle state $|\psi_0\rangle$. $P_1$ and $P_2$ are projectors on the particle properties defined in $[3]$, understood to be tensored with the identity operator on the apparatus Hilbert space; and at a time $t_2$, after the measurement is complete, $D_1$ and $M_1$ are projectors corresponding to the two macroscopic outcomes. Here $\odot$ is a tensor product symbol, but for present purposes it can simply be regarded as separating events at different times. The first of the four histories, $|\Psi_0\rangle \odot P_1 \odot D_1$, has the physical interpretation that the particle was in state $|1\rangle$ at time $t_1$, and at time $t_2$ detector $D_1$ has registered its arrival. The other three possibilities, with $P_2$ replacing $P_1$ or $M_1$ replacing $D_1$, are interpreted in a similar way.

A relatively straightforward probabilistic analysis—for details, see the examples in $[35]$ or Chs. 17 and 18 of $[4]$—of this family of histories yields, in the case of a properly constructed measurement apparatus, conditional probabilities

$$Pr(P_1 | D_1) = 1; \quad Pr(P_2 | M_1) = 1.$$

In words, if at time $t_2$ detector $D_1$ has detected the particle, then one is certain (probability 1) that at time $t_1$ the particle had the property $P_1$, i.e., the value of $A$ was $+1$, whereas if the particle’s passage was

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1. A referee raised the issue of whether the future not influencing the past could be part of a “classical intuition” inconsistent with quantum mechanics. There is no evidence to suggest that histories quantum mechanics violates the second law of thermodynamics, though the subject needs further investigation; see Sec. 8.4.3 of $[34]$. Even in classical statistical mechanics there is no really satisfactory derivation of the second law from microscopic dynamics, so no precise proof that the future does not influence the past.

2. The preparation apparatus could also be included, but this adds nothing but a slight complication to the following discussion.
indicated by $M_1$ then it is certain that at time $t_1$ it had the property $P_2$ and the value of $A$ was $-1$. One can regard $\alpha$ as constituting an essential feature of what one means by a competently designed and built apparatus for measuring $A$, whether or not it takes the form shown schematically in Fig. 1 the macroscopic outcome must be able to reveal the prior microscopic state.

By contrast, the assumption made implicitly in textbooks is that in place of $P_1$ and $P_2$ one should at time $t_1$ use the projective decomposition

$$I = |\psi_1\rangle\langle\psi_1| + (I - |\psi_1\rangle\langle\psi_1|) = Q_1 + Q_2,$$

(6)

where $Q_1$ corresponds to unitary time development of the particle state and $Q_2$ to its negation. There is nothing wrong with this choice. However, in general $Q_1$ and $Q_2$ will not commute with the projectors $P_1$ and $P_2$ needed to discuss the microscopic properties the apparatus was designed to measure. There is no way of consistently combining noncommuting projectors in a meaningful quantum description; pretending that this is possible leads to paradoxes. The choice between $\{Q_1, Q_2\}$ and $\{P_1, P_2\}$ at the intermediate time depends on whether one wishes to relate the properties of the particle at this time to its earlier preparation or to the outcome of a later measurement. This does not at all imply that the property at the time $t_1$ depends in any causal sense on which future measurement the particle might undergo; for more on this topic see Sec. 14.4 of [4] (where, the reader should be warned, the term ‘contextual’ is used in a sense different from that employed by Bell and used in the present Letter). For additional discussion of the issue of incompatible frameworks and why they cannot be combined (the single framework rule) see [34], and for specific examples see Sec. 4.6 of [1], and [33].

The preceding discussion for a particle with three states is easily generalized to the case of an arbitrary (finite) number of states. To see this, let $\{P_\alpha\}$ be the projective decomposition which diagonalizes $A$ in the sense that the eigenvalues in

$$A = \sum_\alpha a_\alpha P_\alpha$$

(7)

are distinct: $a_\alpha \neq a_\alpha'$, when $\alpha \neq \alpha'$. Then it is straightforward to show that if $A$ commutes with $B$, every $P_\alpha$ in (7) also commutes with $B$. That is, if a basis is chosen such that the matrix of $A$ is diagonal with identical eigenvalues placed in separate blocks, the corresponding matrix of $B$ is block diagonal, and each of its blocks can be separately diagonalized by a change of basis that leaves the $A$ matrix unchanged. The same comment applies to any other observable $C$ that commutes with $A$, whether or not it commutes with $B$, though of course the bases used to diagonalize $B$ and to diagonalize $C$ must be different if $[B, C] \neq 0$.

A measuring apparatus similar to that in Fig. 1 can be constructed by first separating the incoming particle trajectory into different paths corresponding to the different $P_\alpha$ (thus different $a_\alpha$ values) in (7), and then using nondestructive measurement devices (like $M_1$ in Fig. 1) to detect which path the particle is moving along without affecting its internal state. Following this, on each path install an appropriate unitary, which will in general be different depending on whether one wishes to measure $B$ or $C$, and after each unitary a device to produce a further separation of paths directed into the final detectors. Since the $A$ measurement can be made in advance of either $B$ or $C$, it is evident that this apparatus design provides a noncontextual measurement. A histories analysis analogous to that given in (3) to (5) then shows that this result is completely general and applies to any apparatus properly designed and constructed to accurately measure $A$ together with (or without) any other observable that commutes with $A$. The measurement is noncontextual, for the outcome reveals a property the particle possessed before the measurement began.

It is this link between a measurement outcome and a property of the measured system before the measurement took place that demonstrates that in quantum theory the measurement process is noncontextual. So why is it that one so often hears the contrary? A number of reasons come to mind. First, measurements are inadequately treated in textbooks; one admires authors (e.g., [40,41]) who are brave enough to concord publicly with Bell [33]: here is a problem they have not been able to resolve. But of course without some, at least implicit, theory of quantum measurements one cannot even begin to discuss contextuality. Second, in attempting to fill this serious gap in standard (textbook) quantum mechanics it has been assumed by Bell and many others that microscopic properties might be represented not by Hilbert subspaces, but by hidden variables which are in certain essential respects classical. This is obvious in the best-known hidden variable

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3A referee has asked what happens if at a later time $Q_1$ and $Q_2$ are measured rather than $P_1$ and $P_2$. If the $Q_j$ and $P_j$ do not commute this cannot be done in a single experimental run. One can ask the counterfactual question of what would have happened if the $Q_j$ had been measured instead of the $P_j$. Quantum counterfactuals are discussed in detail in Ch. 19 of [4] and applied to Hardy’s paradox in Ch. 25. Again, there is no indication that the future influences the past.
approach, the de Broglie-Bohm pilot wave \[42, 43\], where the particle is assumed to have a well-defined position at all times. The hidden variables approach seems almost inevitably to lead to the conclusion that quantum mechanics is infested with nonlocal influences, and the choice of a measurement at some spacelike separated point can influence what is going on here, a “contextual” influence. If one uses the histories approach based on a proper Hilbert space analysis with no hidden variables such nonlocality disappears; see the discussion in \[44\], and in a more pedagogical form in \[35\], and with it any notion that violations of Bell inequalities support the idea of quantum contextuality.

Third, the Bell-Kochen-Specker (BKS) result, see e.g. \[29\], is often invoked as grounds for contextuality. For details of the analysis showing that BKS does not imply contextuality we refer the reader to Ch. 22 in \[1\], to the discussion in Sec. 5 of \[38\] referring to the concept of “realism” as presented in \[32\], and to earlier work in \[15\]. To put the matter briefly, BKS is perfectly fine as a mathematical theorem. However, the collections of Hilbert-space projectors used to construct a BKS paradox do not commute with each other, and hence cannot all be used together in a single consistent quantum description of a physical state of affairs; in histories terminology the single framework rule is violated. What BKS is telling us is not that quantum measurements are contextual, but that the textbook treatment of measurements is inadequate for understanding the quantum world.

In summary, decades of research have shown that trying to understand quantum mechanics using hidden variables always leads sooner or later to serious conceptual problems such as a peculiar action-at-a-distance inconsistent with special relativity. Or to measurement contextuality, which, were it true, would seriously undermine confidence in experimental results. By contrast, a consistent Hilbert space approach, with quantum properties represented by Hilbert subspaces, is internally consistent, paradox free (so far as we know at present), and applies without exception to systems of arbitrary size and complexity. Students are taught that they cannot always write \( XY = YX \) in quantum physics, even in cases where this is perfectly fine in classical physics; one must pay attention to whether operators commute. They need to learn the corresponding rules for reasoning consistently about quantum properties, and not simply be told “Shut up and calculate; quantum mechanics only predicts outcomes of measurements.” They don’t believe it, and they shouldn’t.

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