Title: Foundations and Interpretation of Quantum Theory - Lecture 4

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Abstract: <span>After a review of the axiomatic formulation of quantum theory, the generalized operational structure of the theory will be introduced (including POVM measurements, sequential measurements, and CP maps). There will be an introduction to the orthodox (sometimes called Copenhagen) interpretation of quantum mechanics and the historical problems/issues/debates regarding that interpretation, in particular, the measurement problem and the EPR paradox, and a discussion of contemporary views on these topics. The majority of the course lectures will consist of guest lectures from international experts covering the various approaches to the interpretation of quantum theory (in particular, many-worlds, de Broglie-Bohm, consistent/decoherent histories, and statistical/epistemic interpretations, as time permits) and fundamental properties and tests of quantum theory (such as entanglement and experimental tests of Bell inequalities, contextuality, macroscopic quantum phenomena, and the problem of quantum gravity, as time permits).</span>

1. Some Challenges to Interpreting Quantum Theory
   - The indeterminism and uncertainty of quantum predictions.
   - Coherent superposition and the wave-particle duality.
   - The special role of measurement.
2. The Copenhagen Interpretation
   - What is the Copenhagen Interpretation?
   - Criticism of the Copenhagen Interpretation
3. Literal Realism of the Orthodox Interpretation
   - The Literal Realism of von Neumann and Dirac
   - Literal Realism and Measurement
4. Criticism of the Orthodox Interpretation
   - Literal Realism and Schrodinger's cat
   - The Measurement Problem
   - Einstein's Perspective
   - Orthodox Interpretation and Non-locality

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# What are some of the challenges to interpreting quantum theory?

Let's start by considering some of the historical issues that have motivated much heated debate about interpretation.

- **The indeterminism and uncertainty of quantum predictions.**
  - Indeterminism of outcomes
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# The Orthodox Interpretation and Literal Realism

- The orthodox interpretation is usually understood to go further and suggest that the pure quantum state *is* the fundamental ontology.
- This idea, that **the objective reality of the world is literally just the quantum wavefunction itself**, is what I call **literal realism**.
- This is psychologically a very natural interpretation for physicists admiring their own theory... After all, why wouldn't one presume such a status for the **central mathematical object** in the **most fundamental theory of nature**?

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# The projection postulate is necessary

> "This discontinuous transition from the wavefunction into one of [the eigenstates of the observable] is certainly not of the type described by the time dependent Schrödinger equation. This latter always results in a continuous change of [the wavefunction], in which the final result is uniquely determined and is dependent on [the wavefunction]."

von Neumann (1932/1955)

- But now that we understand *open system quantum mechanics* better, is it be possible for the state after measurement to be somehow determined by the quantum state associated with some *additional degrees of freedom* of the environment, and hence the projection postulate could be deduced from a unitary transformation on some larger Hilbert space?

# The projection postulate is necessary

- If we demand *faithful measurements*, which just means that the measurement apparatus works properly, then for any $|\chi\rangle$,

$$U|\mathrm{up}\rangle \otimes |\mathrm{ready}\rangle \otimes |\chi\rangle = |\mathrm{up}\rangle \otimes |\mathrm{left}\rangle \otimes |\chi'\rangle$$
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where $|\chi'\rangle$ and $|\chi''\rangle$ are allowed to be independent of $|\chi\rangle$.

- Now if we prepare a *coherent superposition* over atomic trajectories, then by linearity it follows that (for any $\chi$) we must have:

$$U(\alpha|\mathrm{up}\rangle + \beta|\mathrm{down}\rangle) \otimes |\mathrm{ready}\rangle \otimes |\chi\rangle = \alpha|\mathrm{up}\rangle \otimes |\mathrm{left}\rangle \otimes |\chi'\rangle + \beta|\mathrm{down}\rangle \otimes |\mathrm{right}\rangle \otimes |\chi''\rangle.$$

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# The projection postulate is necessary

- The main point is that linearity of unitary evolution makes it impossible for any other quantum degrees of freedom to (non-linearly) drive the state of the apparatus to a state consistent with only one of the possible outcomes.
- Hence the projection postulate (which serves this role of singling out either the 'left' or 'right' state) can not be modeled by any unitary transformation acting on (any choice of) quantum systems.

# von Neumann struggles to make sense of measurement

**von Neumann felt the resulting situation was "unexplained":**

> "We have then answered the question as to what happens in the measurement of [an observable]. To be sure, the "how" remains unexplained for the present."

von Neumann (1932/1955)

- von Neumann goes through a long analysis to show that, within his interpretation, the application of the projection postulate can be applied in a consistent way either to the system directly or to the system + apparatus.
- He insists that ultimately the postulate must be applied whenever an "interaction" takes place between the "measuring portion" and the "measured portion" of the world.

# von Neumann struggles to make sense of measurement

"That is, we must always divide the world into two parts, the one being the observed system, the other the observer. In the former, we can follow up all physical processes (in principle at least) arbitrarily precisely. In the later, this is meaningless. The boundary between the two is arbitrary to a very large extent. ...That this boundary can be pushed arbitrarily deeply into the interior of the body of the actual observer is the content of the principle of the psycho-physical parallelism - but this does not change the fact that in each method of description the boundary must be put somewhere, if the method is not to proceed vacuously, i.e., if a comparison with experiment is to be possible. Indeed experience only makes statements of this type: an observer has make a certain (subjective) observation; and never any like this: a physical quantity has a certain value. [*continued on next slide*]

# von Neumann struggles to make sense of measurement

> Now quantum mechanics describes the events which occur in the observed portions of the world, so long as they do not interact with the observing portion, with the aid of the process 2 [Schrodinger evolution], but as soon as such an interaction occurs, i.e., a measurement, it requires the application of the process 1 [projection postulate]. The dual form is therefore justified."

von Neumann (1932/1955)

- This arbitrary boundary between the 'measurer' and the 'measuree' is sometimes called the "von Neumann cut." Clearly von Neumann took great pains to justify this boundary and its arbitrariness.

# von Neumann struggles to make sense of measurement

> "First, it is inherently entirely correct that the measurement of the related process of the subjective perception is a new entity relative to the physical environment and is not reducible to the latter. Indeed, subjective perception leads us into the intellectual inner life of the individual, which is extra-observational by its every nature (since it must be take for granted by any conceivable observation or experiment). Nevertheless, it is a fundamental requirement of the scientific viewpoint - the so-called principle of the psycho-physical parallelism (!) - that it must be possible so to describe the extra-physical process of the subjective perception as if it were in reality in the physical world - i.e., to assign to its parts equivalent physical processes in the objective environment, in ordinary space. "

von Neumann (1955)

**For Dirac, a consequence of literal realism is that the projection postulate must represent a physical process, an actual 'jump':**

"When we measure a real dynamical variable, the disturbance involved in the act of measurement causes a jump in the state of the dynamical system. From physical continuity, if we make second measurement of the same dynamical variable immediately after the first, the result of the second measurement must be the same as that of the first. Thus after the first measurement has been made, there is no indeterminacy in the result of the second. Hence, after the first measurement has been made, the system is in an eigenstate of the dynamical variable, the eigenvalue it belongs to being equal to the result of the first measurement. This conclusion must still hold if the second measurement is not actually made. In this way we see that a measurement always causes the system to jump into an eigenstate of the dynamical variable that is being measured, the eigenvalue this eigenstate belongs to being equal to the result of the measurement."

Dirac (1958)

**Literal realism (but not quantum theory itself) implies the absence of causality:**

> "The question of causality could be put to a true test only in the atom, in the elementary processes themselves, and here everything in the present state of our knowledge militates against it. The only formal theory existing at the present time which orders and summarizes our experiences in this area in a *half-way satisfactory manner*, i.e., quantum mechanics, is in compelling *logical contradiction with causality*. Of course it would be an exaggeration to maintain that causality has thereby been done away with: quantum mechanics has, in its present form, several serious lacunae, and it may even be that it is false, although this latter possibility is highly unlikely, in the face of its startling capacity in the qualitative explanation of general problems, and in the quantitative calculation of special ones."

von Neumann (1932/1955)

# Literal realism implies the absence of causality

> "This concept of quantum mechanics, which accepts its statistical expression as the actual form of the laws of nature, and which abandons the principle of causality, is the so-called statistical interpretation."

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- Note that von Neumann is oddly using the label "statistical interpretation" to refer to his "literal realist" view that quantum states specify the "complete ontology".
- However, nowadays the label "statistical interpretation" refers to the exact opposite point of view, in particular that of Einstein and Ballentine, which posits that quantum states do not give a complete description of the properties of individual systems.
- In any case the key point here is that it is the **unnecessary interpretational assumption of completeness** that implies the loss of causality.

# Literal Realism and Schrodinger's cat

Schrodinger's cat paradox is an expression of the *under-determined reality* resulting from *literal realism*:

> "A cat is penned up in a steel chamber, along with the following diabolical device (which must be secured against direct interference by the cat): in a Geiger counter there is a tiny amount of radioactive substance, so small, that perhaps in the course of one hour one of the atoms decays, but also, with equal probability, perhaps none; if it happens, the counter tube discharges and through a relay releases a hammer which shatters a small flask of hydrocyanic acid. If one has left this entire system to itself for an hour, one would say that the cat still lives if mean while no atom has decayed. The first atomic decay would have poisoned it. The $\psi$-function of the entire system would express this by having in it the living and the dead cat (pardon the expression) mixed or smeared out in equal parts."

Schrodinger (1935)

# Literal Realism and Schrodinger's cat

- Many commentators take Schrodinger's argument as a literal claim about the *ambiguous ontology* that results from coherent superposition.
- As such they fail to appreciate that Schrodinger's cat argument was a *reduction ad absurdum* intended to ridicule the literal realism of the orthodox interpretation and the anti-realism of the Copenhagen interpretation.
- Consider how Schrodinger introduced the above passage:

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- Consider how Schrodinger introduced the above passage:

> "One can even set up quite ridiculous cases. A cat is penned up in a steel chamber, along with the following diabolical device ..."

- Unfortunately this opening sentence is usually left out when Schrodinger is quoted!

According to von Neumann and Dirac, the question of whether the cat is finally either alive or dead (as opposed to a coherent superposition) depends on when the "dynamical process" for collapse is supposed to have taken place.

- Is the cat's status in an undefined state until it is observed? Or is the cat's own observation enough to collapse the wavefunction?

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> "What exactly qualifies some physical systems to play the role of *measurer*? Was the wavefunction of the world waiting to jump for thousands of millions of years until a single-celled living creature appeared? Or did it have to wait a little longer, for some better qualified system ... with a PhD?"

# The Measurement Problem

All of the above considerations are different aspects of what is now called "the measurement problem".

- The measurement problem is usually identified as the failure of the *unitary evolution* to account for the *unique outcomes* that are observed in practice.
- As we've seen, the projection postulate is designed to solve this problem, but it is creates new problems for the orthodox interpretation:
  - it implies that the fundamental ontology is governed by two different dynamical laws.
  - the question of when a measurement takes place (and which dynamical law should apply) is left unspecified.

# Decoherence and the Measurement Problem

There is a common contemporary view that decoherence somehow solves the measurement problem.

- As we saw previously, by assuming the presence of an environment, which we then trace over, the apparatus pointer is left in the state

$$\rho = |\alpha|^2 |\text{left}\rangle\langle\text{left}| + |\beta|^2 |\text{right}\rangle\langle\text{left}|$$

  which is a weighted mixture of the two possible outcomes.
- Note that we obtain the same mixed state by ignoring the existence of the environment and simply tracing over the atomic system that is being measured.
- So it is clear that decoherence explains why interference effects will not be observed in the pointer, but while some may have considered this to be a problem in need of explanation, it is not the measurement problem.

# Decoherence and the Measurement Problem

- In either case, as von Neumann realized as far back as 1932, the mixed state gives an **inadequate** account of the experimental situation, which is that the pointer must be described by either the pure state $|\mathrm{left}\rangle$ or the pure state $|\mathrm{right}\rangle$ .
- Hence, within the orthodox view, decoherence buys us nothing, and the projection postulate, with all of its assorted interpretation ambiguities, is still necessary.

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# Decoherence and the Measurement Problem

Within the context of modern interpretations, such as many worlds and consistent histories, decoherence provides a crucial ingredient for the self-consistency of those interpretations. It is worth bearing mind that:

- No matter what kind of environment you assume and then trace over, the quantum state of the system + apparatus + environment is still going to be a pure state.
- So the composite system is still in a coherent superposition and will have to confront the same interpretational issues confronted by the original subsystem when it was imagined to be a pure state (without decoherence).
- In other words, to some extent considering the environment explicitly and then ignoring it (by tracing it out), is just sweeping the problem (of coherent superposition) under the rug.

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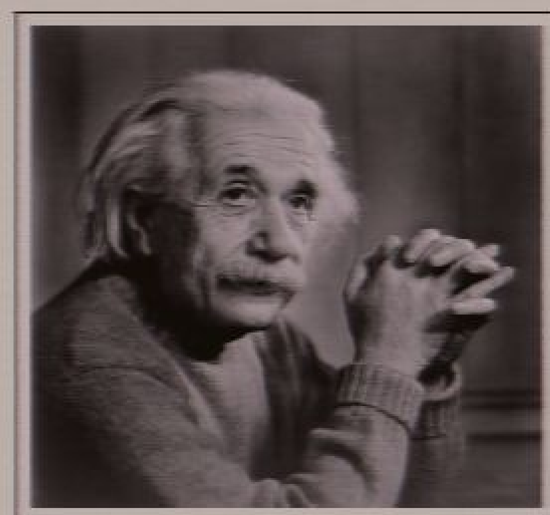
- So then, for whom is the measurement problem not a problem?

# Einstein's Perspective

Einstein believed that quantum theory gave an incomplete description of reality. He advocated this view at least as early as 1927 and maintained it throughout his life.

> "The attempt to conceive the quantum-theoretical description as the complete description of the individual systems leads to unnatural theoretical interpretations, which become immediately unnecessary if one accepts the interpretation that the description refers to ensembles of systems and not to individual systems."



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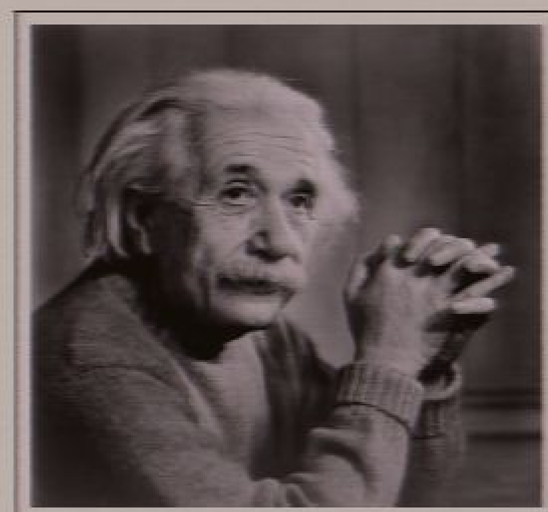

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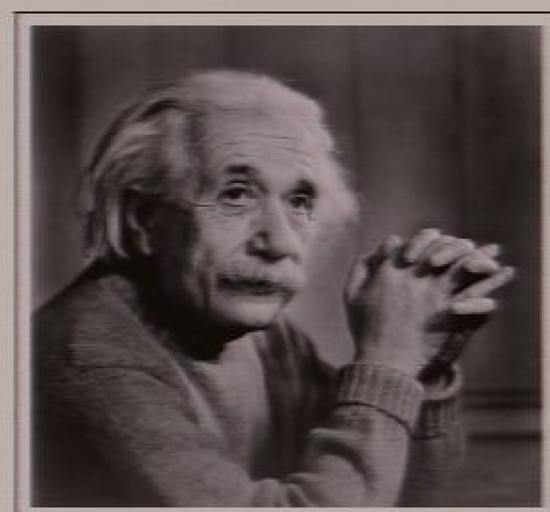

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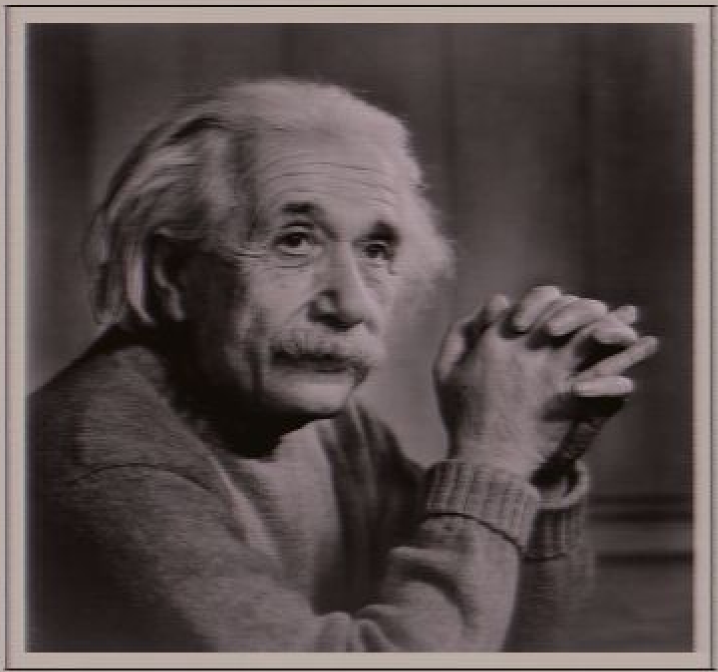

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# Einstein's "reductio ad absurdum" argument

"The system is a substance in chemically unstable equilibrium, perhaps a charge of gunpowder that, by means of intrinsic forces, can spontaneously combust, and where the average life span of the whole setup is a year. In principle this can quite easily be represented quantum-mechanically. In the beginning the psi-function characterizes a reasonably well-defined macroscopic state. But, according to your equation (!), after the course of a year this is no longer the case. Rather, the psi-function then describes a sort of blend of not-yet and already-exploded systems. Through no art of interpretation can this psi-function be turned into an adequate description of a real state of affairs; in reality there is just no intermediary between exploded and not-exploded."

Einstein 1935 (letter to Schrodinger)

"They somehow believe that the quantum theory provides a description of reality, and even a *complete* description; this interpretation is, however, refuted most elegantly by your system of radioactive atom + Geiger counter + amplifier + charge of gun powder (!) + cat in a box, in which the $\psi$-function of the system contains the cat both alive and blown to bits. Is the state of the cat to be created only when a physicist investigates the situation at some definite time? Nobody really doubts that the presence or absence of the cat is something independent of the act of observation. But then the description by means of the $\psi$-function is certainly incomplete, and there must be a more complete description. If one wants to consider the quantum theory as final (in principle), then one must believe that a more complete description would be useless because there would be no laws for it. If that were so then physics could one claim the interest of shopkeepers and engineers, the whole thing would be a wretched bungle."

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# The Ideal of the Detached Observer

For Einstein a key point was that there should be a notion of reality that is independent of observation:

> "Now from my conversations with Einstein I have seen that he takes exception to the assumption, essential to quantum mechanics, that the state of a system is defined only by specification of an experimental arrangement. Einstein wants to know nothing of this. ... Einstein has the philosophical prejudice that (for macroscopic bodies) a state (termed 'real') can be defined 'objectively' under any circumstances, that is, without specification of the experimental arrangement used to examine the system (of the macro-bodies), or to which the system is being 'subjected'. It seems to me that the discussion with Einstein can be reduced to this hypothesis of his, which I have called the idea (or the 'ideal') of the 'detached observer.' "

W. Pauli (letter, 1954)

# Bohr didn't get it

Earlier we've opened the door to a favorable, "operational" reading of Bohr.

- We stressed that Bohr's view could be read as a strictly operational view if we replaced the awkward idea of "classical devices" with the modern notion of "input/ouput information".

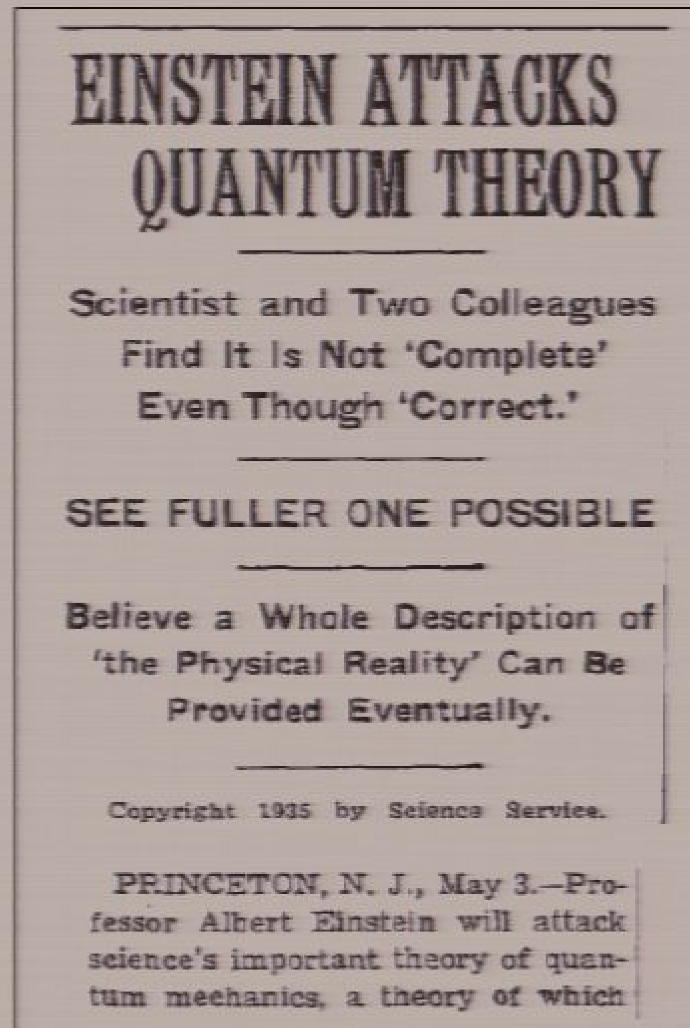
But this may be too favorable. Bohr was not just an operationalist, but a staunch anti-realist (like Fuchs!).

- Bohr steadfastly refused to acknowledge even the logical possibility of Einstein's perspective being valid. For example, as late as 1949 he insisted that the more complete analysis Einstein seeks "is *in principle* excluded."

# Orthodox Interpretation and Non-locality

The most interesting criticism of the orthodox view was devised by Einstein, Podolsky, and Rosen in the celebrated "EPR paper" (1935).

- The goal of the paper was to show that the completeness assumption and a notion of locality were incompatible assumptions.
- For EPR, locality obviously held, and hence the assumption of completeness should be abandoned.



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Scientist and Two Colleagues Find It Is Not 'Complete' Even Though 'Correct.'

SEE FULLER ONE POSSIBLE

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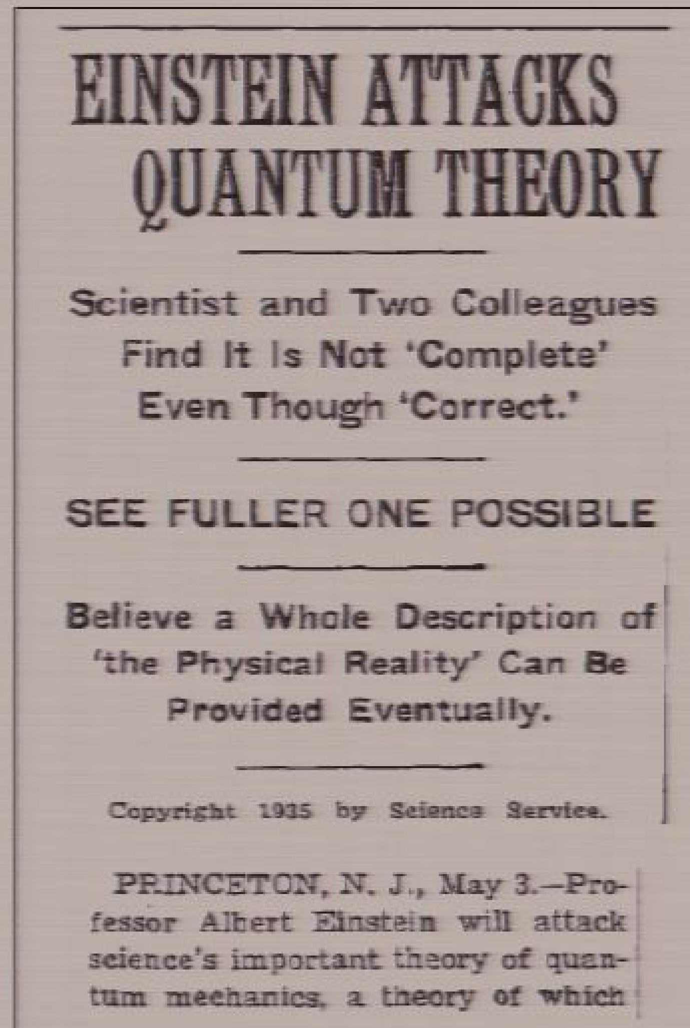

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# The EPR Argument against Completeness

For EPR, a necessary condition for the completeness of a theory is:

(i) "Every element of physical reality must have a counterpart in the physical theory."

For EPR, a sufficient condition for the physical reality of a quantity is:

(ii) "If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity."

# The EPR Argument against Completeness

EPR considered a system of two particles initially produced in a joint eigenstate of their relative position and total linear momentum.
We will consider a simpler system involving a two spin-1/2 particles (proposed by Bohm (1951)) which illustrates the same features (now known as EPRB).

- Consider two particles prepared in the singlet-state,

$$\psi = \frac{1}{\sqrt{2}}\left(|+\rangle_1 \otimes |-\rangle_2 \; - \; |-\rangle_1 \otimes |+\rangle_2\right).$$

- This state has zero total angular momentum, so the spin of the first particle (system $S_1$) is anti-correlated with the spin of the second particle (system $S_2$).

# The EPR Argument against Completeness

- Assume that after the state preparation the particles are separated spatially in such a way that *the two particles can no longer interact*.
- Observe that if measurement of particle 1, along, say, the $z$-axis, yields $+\hbar/2$ then measurement of particle 2 (along the same $z$-axis) must yield $-\hbar/2$, and vice versa. Similarly, if we measure instead $S_x$ for particle 1, then we can predict with certainty the outcome of an $S_x$ measurement for particle 2.
- Hence we can predict with certainty the outcomes of measurements of either $S_x$ or $S_z$ of the second particle "without in any way disturbing the second system" - note the assumption of locality is invoked to guarantee that there can be no such disturbance.

# The EPR Argument against Completeness

- In accordance with the EPR criterion of reality (ii), there must therefore be elements of reality corresponding to both $S_x$ and $S_z$ for the second particle.

- Because quantum mechanical states do not assign definite properties simultaneously for these non-commuting observables (following the eigenvalue-eigenstate link) EPR deduced that the quantum-mechanical description of physical reality given by wave functions must not be complete.

# The EPR Argument against Completeness

The EPR argument presumes (implicitly) a notion of *separability*, i.e., that separately existing elements of reality may be attributed to each system, and a notion of *independence*, i.e., that it is possible to arrange that the elements of reality of one system can not be influenced by the elements of reality of another system.

- The assumption of independence can seemingly be well motivated by the 'locality' guaranteed by special relativity. Einstein later characterized this 'locality' assumption as follows (1949):

"The real factual situation of the system $S_2$ is independent of what is done with the system $S_1$, which is spatially separated from the former."

# The EPR Argument against Completeness

**The Copenhagen perspective:**
While Bohr accepts the idea of separability, from Bohr's Copenhagen perspective the EPR argument does not go through because Bohr explicitly rejects assigning any meaningful reality to atomic objects in the context of unperformed measurements, which EPR must do when they "*counter-factually*" deduce consequences about the results of alternative measurements that can not be performed with the given experimental arrangement.

# The EPR Argument against Completeness

**Bohr's Response in 1935:**

"The finite interaction between object and measuring agencies conditioned by the very existence of the quantum of action entails - because of the impossibility of controlling the reaction of the object on the measuring instruments if these are to serve their purpose - the necessity of a final renunciation of the classical ideal of causality and a radical revision of our attitude towards the problem of physical reality ... [While there is] no question of a mechanical disturbance of the system under investigation ... there is essentially the question of an influence on the very conditions which define the possible types of predictions regarding the future behavior of the system."

Bohr "Quantum Mechanics and Physical Reality" (1935)

# The EPR Argument against Completeness

**Bohr's Response much later:**

"Recapitulating, the impossibility of subdividing the individual quantum effects and separating a behavior of the objects from their interaction with the measuring instruments serving to define the conditions under which the phenomena appear implies and ambiguity in assigning conventional attributes to atomic objects which calls for a reconsideration of our attitude towards the problem of physical explanation . . ."

Bohr (1948)

# The EPR Argument against Completeness

While the dispute between Bohr's anti-realism and EPR's sufficient criterion for reality is subtle, it is much easier to see that the 'literal realism' of the orthodox view automatically implies non-locality.

- If the collapse of the wave function is a physical process (as it is on the assumption that the wave function is complete), then the collapse must be an instantaneous change of physical properties throughout space.
- Even for a single particle with a wavefunction extended through space, the wavefunction must change non-locally upon measurement which localizes the particle.
- The non-locality of this transformation, understood as a *physical transformation* in the orthodox view, is even more explicit when we consider measurements on spatially separated particles that were initially prepared in an entangled state.

# The EPR Argument against Completeness

In Bohm's analysis of the EPR argument in his 1951 textbook on quantum theory (pp. 622-623) he somehow concluded that any more complete interpretation of the quantum mechanics was actually impossible:

"We can now use some of the results of the analysis of the paradox of [EPR] to help prove that quantum theory is inconsistent with the assumption of hidden causal variables . . . [Arguing from the apparent conflict with the uncertainty principle] . . . We conclude that no theory of mechanically determined hidden variables can lead to all of the results of the quantum theory."

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# Bad news for Einstein

In Einstein's view the gedanken experiments with entangled particles display a conflict between the two assertions:

- (1) the description given by the wavefunction is complete.
- (2) the real states (i.e. ontic states) of spatially separate objects are independent of each other.

As we will see, John Bell later showed that any more complete theory, ie hidden variable interpretation, which reproduces the predictions of quantum mechanics must in fact be non-local (the real states of spatially separated objects are not independent of each other).

- As a result one is forced to reject the notion of locality (2) whether one accepts or rejects the assumption of completeness (1)!

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# Summary of the Orthodox Interpretation and its Problems

The interpretational assumption that the quantum state specifies the *complete ontology* implies:

- a theory with two fundamentally incompatible dynamical laws.
- an uncertain distinction of when which of these dynamical laws is actually occurring.
- an awkward ambiguity as to whether sufficiently isolated macroscopic objects have a definite state of existence.
- the apparent necessity of an observer to induce definite properties for the observed system.
- a theory that has fundamental randomness.

Amazingly, all of these problems do not actually follow from the empirical (scientific) content of the quantum theory, but from the interpretational assumptions imposed upon it by the founders of the theory!

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"There exists, however, a simple psychological reason for that fact that this most nearly obvious [ensemble] interpretation is being shunned. For if the statistical quantum theory does not pretend to describe the individual system (and its development in time) completely, it appears unavoidable to look elsewhere for a complete description of the individual system . . . Assuming the success of efforts to accomplish a complete physical description, the statistical quantum theory would, within the framework of future physics, take an approximately analogous position to the statistical mechanics with the framework of classical mechanics. I am rather firmly convinced that the development of theoretical physics will be of that type; but the path will be lengthy and difficult."

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