Lectures 3 and 4: Historical Perspectives on Interpretation

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Foundations and Interpretations of Quantum Theory

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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
  - Heisenberg uncertainty principle
  - Robertson inequality
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- **Coherent superposition and the wave-particle duality.**

- **The special role of measurement.**
The indeterminism and uncertainty of quantum predictions

**Indeterminism of outcomes**

- Given a measurement of an observable, $A$, unless the preparation lies within an (possibly degenerate) eigenspace of the observable, the outcome of the measurement (i.e. the observed eigenvalue) is not determined by the theory.
The indeterminism and uncertainty of quantum predictions

Indeterminism of outcomes

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- Which outcome is observed is random: only the probability, ie, relative frequency, of each outcome is prescribed by Born’s rule.
The indeterminism and uncertainty of quantum predictions

**Heisenberg Uncertainty Principle**

The *uncertainty principle* due to Heisenberg (1925) states that it is impossible to measure the position and momentum of a particle to arbitrary precision *simultaneously*. The best one can do is

\[
\delta x \delta p \sim \hbar
\]

where \(\delta x\) denotes the resolution for determining \(x\) for an individual system in a single experimental trial and likewise for \(p\).
The indeterminism and uncertainty of quantum predictions

Heisenberg Uncertainty Principle

- The principle is that, while there is no limitation to how small the resolution can be for determining either $x$ or $p$, there is a limitation on determining both within a single experiment.
- The principle is inferred (!) from the Heisenberg microscope example, which shows that simultaneous measurement of position and momentum for a single particle has limited precision.
- The Heisenberg uncertainty principle is a direct result of Einstein’s realization (!) that electromagnetic energy is quantized,

$$E = n \hbar \nu$$

for $n = \{1, 2, 3 \ldots \}$. Hence, even when using light as a probe, there is an unavoidable disturbance that is inversely proportional to the resolution of the measurement $\lambda = c/\nu$. 
Heisenberg Uncertainty Principle

- The particle nature of light places an inverse proportionality between measurement resolution and system disturbance - this differs from the classical picture where the energy of the light probe is proportional to intensity of the wave and there is no fundamental trade-off.

- The Heisenberg uncertainty principle influenced the idea of complementarity developed by Bohr (which we will discuss later).
The indeterminism and uncertainty of quantum predictions

Robertson Inequality
Heisenberg’s uncertainty principle is often confused with Robertson’s inequality (1929).

- Let
  \[ \Delta \hat{A}^2 = \langle \hat{A}^2 \rangle - \langle \hat{A} \rangle^2 \]
  be the variance over an ensemble of measurement outcomes for the observable \( A \) and likewise for \( B \). Then,
  \[ \Delta \hat{A} \Delta \hat{B} \geq \frac{1}{2} |\langle [\hat{A}, \hat{B}] \rangle|, \]
  where the product of the variances is non-zero if the two observables do not commute.
- In the case of position and momentum, this implies
  \[ \Delta \hat{x} \Delta \hat{p} \geq \frac{\hbar}{2}. \]
The indeterminism and uncertainty of quantum predictions

Robertson Inequality

- Robertson’s result is a rigorous inequality, whereas Heisenberg’s result is a heuristic argument.
- Moreover, conceptually the two are quite distinct: one refers to simultaneous measurements on a single system, whereas the other refers to variances of statistics for ensembles of measurements where only one operator is measured on each individual system.
- Note that different experimental measurement set-ups are required for measuring the non-commuting observables in the Robertson inequality, whereas only one experimental measurement set-up is relevant to the Heisenberg uncertainty principle.
The wave-particle duality of light and matter is another challenging concept.

- Einstein’s 1905 analysis of the photoelectric effect suggested the wave-particle duality for light.
- Experiments with electrons, such as scattering of electrons from a crystal lattice, later suggested a wave-particle duality also for particles.
- Of course, the Schrodinger equation is a wave-equation describing particles, but the paradigmatic illustration of wave-particle duality is the double-slit experiment.
- In the double-slit experiment, if the particle passes the slits in a coherent superposition, then a wave-like interference pattern is observed on the screen (under an ensemble of single-particle experiments).
Coherent superposition and the wave-particle duality

Coherent superposition

- If the coherent superposition is compromised, e.g., by measurement of which slit the particle passes through, or decoherence from the environment, then a sum of classical probability distributions is observed at the screen.

- We will see explicitly later exactly how the standard quantum formalism for analyzing “measurement” and/or environmental decoherence confirms/predicts this experimental fact.
Coherent superposition and the wave-particle duality

Notice the there are two seemingly inconsistent narratives that are offered as “explanation” of the double-slit experiment: the wave view vs “superposed reality” view.

- The wave view is to say that the particle acts like a “wave” until it is observed (recall that upon observation only one localized point on the screen is illuminated after the particle passes through the set-up.)

- The superposed reality explanation is that the particle remains a particle but somehow passes through both slits at the same time, in a “superposed reality”.

- So what *is* the story? Is the particle a wave or is it a particle that is in two places at once? Or is neither story satisfactory?

- We will see later that the deBroglie-Bohm interpretation tells an entirely different story.
The special role of measurement

**Measurement** has an unusual role in quantum theory. Consider the process whereby an intervention produces a definite (though perhaps random) outcome.

- The *usual* quantum description of this process refers to an “observer” or “classical apparatus” that lies outside the theory.

- This special role for measurement is explicit in the case of von Neumann’s projection postulate and Bohr’s insistence that the measurement apparatus must be described “classically”. In either of these approaches the consequence is an awkward dualism at the very foundations of the theory.

- Can quantum theory and its interpretation be formulated without a special role for the observer and without the necessity of distinguishing certain aspects of an experiment as “classical”? 

The Copenhagen interpretation is understood differently by different historical commentators.

- The interpretation is usually attributed to Niels Bohr, and sometimes various elements of Heisenberg’s ideas are included.
- There was no consensus between them. Bohr was critical of Heisenberg’s realist tendencies, for example, in his description of the Heisenberg microscope.
What is the Copenhagen Interpretation?

- The label “Copenhagen Interpretation” was never adopted by either Bohr or Heisenberg. Rather, it is a historical construct.
- Some of the difficulty in understanding the interpretation arises in part due to the fact that Bohr’s ideas are difficult to parse and assimilate into a coherent interpretation.
- So rather than attempt to synthesize a particular “close reading” of Bohr I will let you judge yourselves from a selection of direct quotes.
For Bohr, complementarity is a central principle of interpretation:

“Complementarity: any given application of classical concepts precludes the simultaneous use of other classical concepts which in a different connection are equally necessary for the elucidation of the phenomena.”

Bohr (1934)
The Copenhagen Interpretation

The views of Bohr

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- Huh?
- My guess: Bohr is saying that, when you are measuring, eg, the position of a particle then you can’t talk about its momentum, but he is trying hard to avoid realist language that would suppose that the particle has some definite position and momentum prior to measurement.
The views of Bohr

Objective physical reality must be rejected:

“An independent reality in the ordinary physical sense can neither be ascribed to the phenomena nor to the agencies of observation.”

Bohr (1928)

“. . . a subsequent measurement to a certain degree deprives the information given by a previous measurement of its significance for predicting the future course of the phenomena. Obviously, these facts not only set a limit to the extent of the information obtainable by measurements, but they also set a limit to the meaning which we may attribute to such information.”

Bohr (1934)
Another central concept for Bohr is the necessity of a boundary between quantum and classical.

Bohr holds firm to the fact that although “atomic phenomena” must be described by quantum mechanics, our measuring devices must be described using classical physics:

“The experimental conditions can be varied in many ways but the point is that in each case we must be able to communicate to others what we have done and what we have learned, and that therefore the functioning of the measuring instruments must be described within the framework of classical physical ideas.”

Bohr (1934)
The views of Bohr

But by what criterion can we determine where the boundary lies?
Bohr concedes there is none:

There is “the impossibility of any sharp separation between the behavior of atomic objects and the interaction with the measuring instruments which serve to define the conditions under which the phenomena appear.”

Bohr (1949)
The Copenhagen Interpretation

Bohr’s views became textbook dogma:

“It is in principle impossible . . . to formulate the basic concepts of quantum mechanics without using classical mechanics.”

“By measurement, in quantum mechanics, we understand any process of interaction between quantum and classical objects, occurring apart from and independently of any observer. The importance of the concept of measurement in quantum mechanics was elucidated by N. Bohr... Thus quantum mechanics occupies a very unusual place among physical theories: it contains classical mechanics as a limiting case, yet as the same time requires this limiting case for its own formulation.”

Landau and Lifschitz (Quantum Mechanics, pp. 2-3 of 3rd edition (1977))
The necessity of postulating a classical world for the formulation of Bohr’s interpretation is unsatisfactory: if quantum mechanics is the fundamental theory then the requirement of a ‘classical apparatus’ to interpret the theory is *ad hoc*.
Criticism of the Copenhagen Interpretation

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- Perhaps this objection can be overcome by replacing the notion of ‘classical apparatus’ with the more modern and abstract notion of “information”. Hence the ‘classical apparatus’ that serves to define the ‘conditions of observation’ is then just the *input and output information* that defines the task in question.
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- Perhaps this objection can be overcome by replacing the notion of ‘classical apparatus’ with the more modern and abstract notion of “information”. Hence the ‘classical apparatus’ that serves to define the ‘conditions of observation’ is then just the ‘input and output information’ that defines the task in question.

- By taking this turn have we recovered the modern operationalist view, or perhaps even the ‘quantum Bayesian view’?
Furthermore, the exact quantum-classical boundary is left unspecified, leading to a potential consistency problem in the interpretation.

- Specifically, one would expect to be able to describe any physical system, including a measurement device, using the usual unitary quantum mechanics, but Bohr’s dualistic view of atomic-scale anti-realism and macro-scale realism implies the existence of some yet-to-be-determined and somewhat arbitrary quantum-classical boundary.
Criticism of the Copenhagen Interpretation

Bohr’s flat denial of any “atomic-scale” realism just doesn’t seem to be supported by any convincing argument, but merely asserted as dogma.

- It is well-known that Einstein never accepted Bohr’s anti-realism:

  “To believe this [the absence of an atomic-scale reality] is logically possible without contradiction; but it is so very contrary to my scientific instinct that I cannot forego the search for a more complete description.”

  Einstein (1936)

It is unfortunate that the popular view of the celebrated Einstein-Bohr debates is that Bohr won and that Einstein did not understand quantum mechanics.
Criticism of the Copenhagen Interpretation

Were Bohr’s views informed by quantum mechanics, or were they imposed upon quantum mechanics?

“How closely the idea of complementarity was in accord with Bohr’s older philosophical ideas became apparent through an episode which took place ... on a sailing trip from Copenhagen to Svendborg on the Island Fyn... Bohr was full of the new interpretation of quantum theory, and as the boat took us full sail southward ... there was plenty of time to reflect philosophically on the nature of atomic theory. ... Finally, one of Bohr’s friends remarked drily, ‘But Niels, this is not really new, you said exactly the same ten years ago.’ ”

Heisenberg (1967)
Criticism of the Copenhagen Interpretation

Einstein may have been aware of this:

“The Heisenberg-Bohr tranquilizing philosophy - or religion? - is so delicately contrived that, for time being, it provides a gentle pillow for the true believer from which he cannot very easily be aroused. So let him lie there.”

A. Einstein (letter to Schrodinger, 1928)
The Orthodox Interpretation of von Neumann and Dirac

In spite of Bohr’s significant influence the view of quantum mechanics that formed the basis for textbook dogma is the view developed by von Neumann and Dirac, which we will call the **orthodox interpretation**. This view arises from the following considerations:

- Recall the von Neumann projection postulate for measurement of the (non-degenerate) observable $\hat{A} = \sum_n a_n P_n$, where $P_n = |\psi_n\rangle\langle\psi_n|$.
- The state after an ideal filtering-type measurement, when outcome $a_k$ has been obtained, is given by $\rho_k = \frac{P_k \rho P_k}{\text{Tr}(P_k \rho P_k)}$.
- In other words, we have found the system to have property $a_k$, and furthermore, we can reliably predict that, if a subsequent measurement were performed, then the outcome $a_k$ will again be obtained.
The Orthodox Interpretation of von Neumann and Dirac

- One might be tempted to say that, following such an ideal filtering-type measurement, the system, which is in the eigenstate $\psi_k$, indeed “has” the property $a_k$.

- More generally one might say that whenever the quantum state is known to be some vector $\psi_k$, then any eigenvalue $a_k$ in the spectral decomposition of an observable, for which $\psi_k$ is an eigenstate, is a well-defined objective property of the system, and this holds independently of whether an observation is actually made.

- In more philosophical terminology, we say that under these conditions $a_k$ is an ontic property of the system, or is an element of the ontology. That is, it exists.

- Arthur Fine calls this principle the **eigenvalue-eigenstate link** and credits the principle to Dirac and von Neumann.
“The expression that an observable ‘has a particular value’ for a particular state is permissible in quantum mechanics in the special case when a measurement of the observable is certain to lead to the particular value, so that the state is an eigenstate of the observable. In the general case we cannot speak of an observable having an value for a particular state, but we can speak of its having an average value for the state.”

Dirac (1958)
The Orthodox Interpretation

Because pure quantum states are always eigenvectors of some well-defined observable(s), pure quantum states are the source of these objective properties of the quantum systems.

But the orthodox interpretation goes beyond merely asserting that the quantum state identifies some of the possible objective properties of the system through the eigenvalue-eigenstate link...
“In this method of description, it is evident that everything which can be said about the state of a system must be derived from its wave function.”

von Neumann (1932/1955)

- Note the implicit use of the term “state” to mean “ontic state”, for otherwise the statement is a tautology!
The orthodox interpretation asserts that there are **no other objective properties** of the system except those identified in this way.

As a result, the wave function provides the **complete summary** of the ontic properties of the quantum system through the eigenvalue-eigenstate link.
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.
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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?
This hypothesis that the quantum state is an element of the ontology, and moreover provides the complete ontology, leads to some difficult issues when we consider the measurement process.

- Consider the ideal measurement of an observable $A = \sum_n a_n P_n$, applied to a given preparation $\rho$, that yields the outcome $a_m$.

- The post-measurement state $\rho_m$, conditional upon the outcome $a_m$, is determined by Luder’s rule,

$$\rho \rightarrow \rho_m = \frac{P_m \rho P_m}{\text{Tr}(P_m \rho)}.$$ 

- If the observed eigenvalue is non-degenerate, then $P_m$ is rank-one, and the state $\rho_m = P_m = |\psi_m\rangle\langle\psi_m|$ will be pure - in this special case Luder’s rule reduces to the projection postulate, the “process 1” proposed by von Neumann.
The projection postulate is necessary

The projection postulate can not be deduced from the usual unitary evolution of the Schrödinger equation.

- Conceptually it is clear that unitary evolution takes any given initial state to a fixed final state: this is deterministic.
- In contrast, collapse is fundamentally stochastic: applying the same measurement to the same preparation produces different (apparently random) final states (depending on the outcome).
"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

We can illustrate the general principle of why this is not possible by considering a generic model of measurement, where all systems are treated quantum mechanically and all interactions are described using “process 2”, i.e., unitary evolution:

- Consider an atom described by a pure state which can travel along two distinct paths.
- We arrange that both trajectories pass through a detector in such a way that a macroscopic pointer is moved to the ‘left’ if the atom is along the ‘up’ trajectory and to the ‘right’ if the atom is along the ‘down’ trajectory.
- We want to model the measurement process with a unitary transformation and for complete generality we allow for arbitrary additional degrees of freedom denoted collectively by a state $|\chi\rangle$. 

The projection postulate is necessary

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

$$
U|\text{up}\rangle \otimes |\text{ready}\rangle \otimes |\chi\rangle = |\text{up}\rangle \otimes |\text{left}\rangle \otimes |\chi\rangle'
$$

$$
U|\text{down}\rangle \otimes |\text{ready}\rangle \otimes |\chi\rangle = |\text{down}\rangle \otimes |\text{right}\rangle \otimes |\chi\rangle''
$$

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:

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

$$
+ \beta|\text{down}\rangle \otimes |\text{right}\rangle \otimes |\chi\rangle''.
$$
The projection postulate is necessary

- So when we treat the system, apparatus, and all other relevant degrees of freedom as quantum systems, then the final state (after the measurement interaction) of the composite system must be a coherent superposition of both possible outcomes.

- Note that if we choose to describe the apparatus alone, then the partial trace yields the following final state (after the measurement interaction) for the apparatus:

\[
\rho_{\text{final}} = |\alpha|^2 |\text{left}\rangle \langle \text{left}| + |\beta|^2 |\text{right}\rangle \langle \text{right}|.
\]

which is an incoherent superposition of both outcomes.
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 Neummann 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.”

von Neumann (1932/1955)

- 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.
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 meanwhile 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 Schrödinger’s cat

- Many commentators take Schrödinger’s argument as a literal claim about the *ambiguous ontology* that results from coherent superposition.

- As such they fail to appreciate that Schrödinger’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 Schrödinger introduced the above passage:
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:

  “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 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.
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.
Criticism of the Orthodox Interpretation

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 $|\text{left}\rangle$ or the pure state $|\text{right}\rangle$.

- Hence, within the orthodox view, decoherence buys us nothing, and the projection postulate, with all of its assorted interpretation ambiguities, is still necessary.
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.
The Measurement Problem

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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.”

A. Einstein (1949)
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 Schrödinger)
“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 only claim the interest of shopkeepers and engineers, the whole thing would be a wretched bungle.”

Einstein 1950 (letter to Schrodinger)
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/output 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.”
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.

The EPR Argument against Completeness

The EPR argument is awkwardly convoluted. Einstein later acknowledged dissatisfaction with the way the argument was composed - the paper was written mainly by Podolsky.

The basic dilemma for EPR is:

“...either (1) the quantum-mechanical description of reality given by the wave function is not complete, or (2) when the operators corresponding to two physical quantities do not commute the two quantities cannot have simultaneous reality.”
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,

\[ \psi = \frac{1}{\sqrt{2}} (|+\rangle_1 \otimes |-\rangle_2 - |-\rangle_1 \otimes |+\rangle_2). \]

- 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 $+\frac{\hbar}{2}$ then measurement of particle 2 (along the same z-axis) must yield $-\frac{\hbar}{2}$, 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 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)
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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The EPR Argument against Completeness

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- One year later (1952), Bohm published the first hidden variable interpretation of quantum mechanics: “A Suggested Interpretation of the Quantum Theory in Term of ‘Hidden’ Variables”
- Bohm’s hidden variable theory is explicitly non-local.
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, i.e. 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)!
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!
Did these confusions get sorted out quickly?

Were these issues satisfactorily resolved by the next generation of brilliant physicists?
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**R. Feynman (1965)**

“I think that I can safely say that nobody understands quantum mechanics.”
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So where do we go from here?
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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.”

A. Einstein (1949)