Title: PSI 2018/2019 - Foundations of Quantum Mechanics - Lecture 15

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Abstract:

Quantum Foundations Lecture 15

PSI Review Class: 25th January 2019

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10) Interpretations of Quantum Theory

1) A Map of the Madness
2) de Broglie-Bohm Theory
3) Spontaneous Collapse Theories
4) Everett/Many Worlds
5) Copenhagenish Interpretations

10.5) Copenhagenish Interpretations

- **There Is No Copenhagen Interpretation**
- Copenhagen Interpretation is supposed to refer to the views of some of the founders of quantum theory, e.g. Bohr, Heisenberg, Pauli, …
  - If you read their views, they are all slightly different and contradictory.
- Bohr's views are most closely associated with the word "Copenhagen"
  - but Bohr is notoriously difficult to read and has been interpreted in very different ways in the intervening years.
  - Some issues, e.g. Bell's theorem, contextuality, ψ-ontology, were not even fully formulated in Bohr's lifetime. You won't find a clear statement on any of them in Bohr's writing.
- Historical note: Don Howard (Philosophy of Science, 71:669-682 (2004)) argues that the idea of a unified "Copenhagen Interpretation" was invented by Heisenberg in the mid 1950's. Before that people spoke of ideas in the "Copenhagen spirit", but the idea of a complete and conclusive interpretation was not mentioned.

Copenhagenish Interpretations

- In the intervening years, many scholars have developed more fully worked out interpretations in the Copenhagen spirit – Copenhagenish Interpretations.
- Examples:

Objective	Perspectival
Copenhagen (Bohr)	Qbism, i.e. Quantum Bayesianism mk 2 (Fuchs, Schack)
Quantum Bayesianism mk 1 (Caves, Fuchs, Schack)	Relational Quantum Mechanics (Rovelli)
Quantum Pragmatism (Healy)	
Information Interpretation (Bub, Pitowsky)	

  - Objective: There is an objective fact of the matter about what an observer observes.
  - Perspectival: What is true depends on where you are sitting.
- I am more interested in analyzing coherent sets of ideas than in history, so I try to formulate what is common to all Copenhagenish interpretations, without claiming to accurately represent Bohr.

Frauchiger-Renner Theorem

- Frauchiger and Renner (arXiv:1604.07422 (2016)) have proved a theorem that makes life very difficult for objective Copenhagenish interpretations.
- Version I will present attributed to L. Masanes (https://scirate.com/arxiv/1604.07422#653).
- My analysis also influenced by M. Pusey (https://youtu.be/_9Rs61l8MyY).
- This is remarkable!
  - Copenhagenish interpretations are usually immune to no-go theorems.
  - We usually start by saying, “assume physical systems have properties λ”, which Copenhagenists deny.
  - So it’s extremely unusual to be able to place constraints on these interpretations.

Principles of Copenhagenish Interpretations

- Copenhagenish interpretations are what happens when:
  - You are deeply skeptical that the quantum formalism is a direct representation of reality.
  - You want the ordinary classical reality that we see around us to be straightforwardly true.
  - You nonetheless want to view quantum theory as a complete fundamental theory of physics.

- There are 4 common principles of Copenhagenish interpretations:

1. Observers Observe (No solipsism)
2. Universaility
3. Anti-ψ-ontology
4. Completeness

Observers Observe

- I know from my experience that I am the type of entity that experiences definite outcomes when I make a quantum measurement.
- I posit that there are other similar entities in the universe (e.g. students) and I don't doubt that they have the same experience.

- This does not mean that consciousness, human observers, etc. is *necessary* in order for a definite outcome to occur, e.g. we could accept a decoherence account of when definite outcomes occur, only that a human observation is *sufficient* for a definite outcome to occur.
- Objective version: When you make a measurement and observe the result then these are objective facts.
- Perspectival version: When you make a measurement and observe the result then these are facts *for you*. There is no fact of the matter for me unless I repeat the measurement myself or interact with you.

Universaility

- Quantum theory is a fundamental physical theory.
- Anything in the universe (if not everything at once) can in principle be described by quantum theory.
- There are no fundamentally “classical” or “non quantum” systems in the universe.

- $\Rightarrow$ In principle, I can arrange a situation in which I would describe the state of a student as a superposition of macroscopically distinct states.

- Copenhagenism is not operationalism: there is no undefined primitive of *measurement* that is put in by hand. In this regard it is similar to Everett.

A problem?

- You might have thought that the measurement problem immediately rules out observers observe + universaility.
  - Universaility implies:

$$\alpha|\uparrow\rangle|M_\uparrow\rangle + \beta|\downarrow\rangle|M_\downarrow\rangle$$

  - Observers observe implies:

either $|\uparrow\rangle$ or $|\downarrow\rangle$

- But this assumes we believe that quantum states are objective ontic states, or assumes something like the eigenvalue-eigenstate link.

Anti-ψ-ontology

- Quantum states are not ontic, i.e. not intrinsic properties of an individual quantum system.
  - Instead they represent:
    - our knowledge
    - our information
    - our beliefs
    - what we can say
    - advice
  - about the quantum system, depending which Copenhagenish view we are considering.
- Therefore, two different descriptions of a measurement need not be contradictory, e.g. they could represent the descriptions of two different observers who have access to different information.
- Note: I would be happy to call this ψ-epistemic, but some Copenhagenists dislike that label.

Completeness

- Further, there is no deeper description to be had, i.e. no ontic states assigned to systems we are describing quantum mechanically. This is either because:
  1. Quantum systems have properties but they are ineffable: it is literally impossible to talk about them. The moon is there when nobody is looking, but it is fundamentally *impossible* to describe its properties in language, pictures, mathematics, computer code, or anything else.
  2. Quantum systems have no properties. The moon is not there when nobody is looking.
- Option 1 is necessary for an objective Copenhagenish interpretation.
- Option 2 can be made perspectival, i.e. *for me* the moon has no properties when *I* am not looking at it. It may have properties for other observers.
- In either case quantum states represent knowledge/information/beliefs/what we can say/advice about the outcomes of future measurements we might make, not about some underlying reality.

The Heisenberg Cut

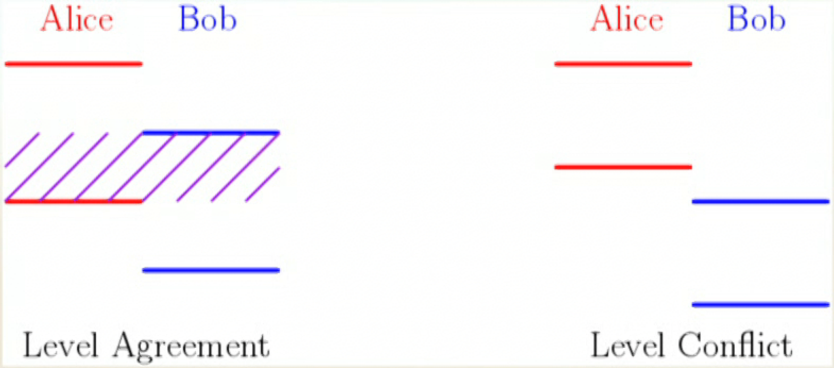
- The four principles: observers observe, universality, anti ψ-ontology, and completeness are in a certain amount of tension.
- If universality is true, I can describe another observer making a measurement as
$$\alpha|\uparrow\rangle|\text{you } \uparrow\rangle + \beta|\downarrow\rangle|\text{you } \downarrow\rangle$$
- But if completeness is true then I cannot ascribe you any properties when I describe you as a quantum system in this way.
- In particular, if I want to account for *my own* observations, then that is ascribing a property *to me* so I cannot include myself in my quantum descriptions.
- Therefore, I necessarily have to split the world into two parts:
  - The part I am going to describe quantum mechanically.
  - The part I am going to exclude from that description so that I can ascribe it properties (the "classical" part).
- The split between these two parts is called the Heisenbeg cut.

The Shifty Split

- If universality is true, then there cannot be a fundamental place where I have to put the Heisenberg cut. It is moveable.
  - This was called the shifty split by John Bell.
- In Bohr's view, the location of the cut should be decided pragmatically:
  - There will be a lowest level I can place the split: If I coherently interfere degrees of freedom I put in the "classical" part I will get the predictions wrong.
  - There is also a highest level: I must always put the split before myself in order to account for my own observations.
- Today, we might use decoherence theory to decide where the lowest level is.
- There will be a range of possible levels of description between the highest and lowest levels. The fact that different quantum states are assigned at different levels does not matter because we are anti-ψ-ontologists. So long as the levels agree on the predictions for the experiments *actually performed*, everything is fine.

Level Agreement

- Each observer has a different range of levels between their highest and lowest.
- You might have thought that, for any two observers, it is always possible to find a range of levels that they can agree upon:



- The Wigner's friend experiment shows that level conflicts can happen.

Wigner's Friend

- The Wigner's friend experiment is just like Schrödinger's cat, except that Wigner puts his friend inside a box to make a measurement instead of a cat.
  - The difference is that the friend is unambiguously an observer.
  - We can place a large enough environment inside the box, or whatever you think is necessary for an observation to occur inside.
- After the measurement, but before he opens the box, Wigner can place the cut above his friend and use the state:

$$\alpha|\uparrow\rangle|\text{friend}\uparrow\rangle + \beta|\downarrow\rangle|\text{friend}\downarrow\rangle$$

- The friend's highest level is below herself, so she necessarily uses:

$$|\uparrow\rangle \quad \text{or} \quad |\downarrow\rangle$$

- Friend: Come on Wigner, put your cut lower so we can reach level agreement!
- Wigner: Sorry, I am contemplating doing an interference experiment on you, so this is my lowest possible level.
- There is a level conflict.

Long-Run Level Agreement

- Level conflicts happen (admittedly in rather impractical experiments).
- However, you might have thought that in the long run, after the whole experiment is over, level agreement will always be possible.
- Reason: As soon as the friend tells Wigner her measurement outcome, they will both be able to place the cut below the friend, and both be able to agree upon:

$$|\uparrow\rangle \quad \text{or} \quad |\downarrow\rangle$$

- But this doesn't always happen. If Wigner actually does a coherent experiment on his friend then disagreement persists.
- I call this the Wigner's Enemy experiment, because it involves Wigner erasing his friend's memory, which is a pretty nasty thing to do.
  - Friends don't recohere friends.

Wigner's Enemy

- Let's cheat a bit and assume that the friend's "ready" state is $|\text{friend} \uparrow\rangle$, so we can treat her as a qubit.
- Let's give a specific unitary interaction for the measurement:

$$|\uparrow\rangle|\text{friend} \uparrow\rangle \rightarrow |\uparrow\rangle|\text{friend} \uparrow\rangle \qquad |\uparrow\rangle|\text{friend} \downarrow\rangle \rightarrow |\uparrow\rangle|\text{friend} \downarrow\rangle$$

$$|\downarrow\rangle|\text{friend} \uparrow\rangle \rightarrow |\downarrow\rangle|\text{friend} \downarrow\rangle \qquad |\downarrow\rangle|\text{friend} \downarrow\rangle \rightarrow |\downarrow\rangle|\text{friend} \uparrow\rangle$$

- This unitary is its own inverse, so Wigner can undo the measurement and recohere his friend by applying the unitary a second time.
- According to Wigner, undoing the measurement yields:

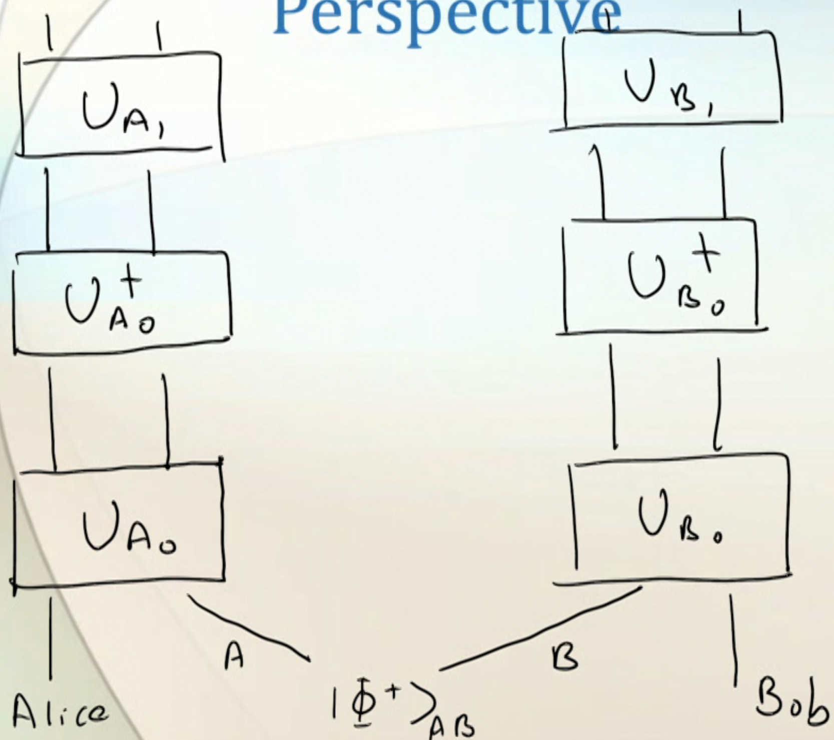
$$(\alpha|\uparrow\rangle + \beta|\downarrow\rangle)|\text{friend} \uparrow\rangle$$

- According to the friend, before the undoing, she was either in state:

$$|\uparrow\rangle|\text{friend} \uparrow\rangle \text{ or } |\downarrow\rangle|\text{friend} \downarrow\rangle$$

- Consider the case $|\uparrow\rangle|\text{friend} \uparrow\rangle$. Then, the undoing leaves her state unchanged.
- After the undoing, both agree that friend is uncorrelated with the system, so there is no level conflict, but they disagree on the state of the spin.

Frauchiger-Renner: Wigner's Perspective



- According to the objective version of observers observe, there is a fact of the matter about what the outcome of A_0, A_1, B_0 and B_1 is on every run of the experiment. Denote these outcomes a_0, a_1, b_0 and b_1.

- If we repeat this experiment multiple times, then relative frequencies exist, so a joint probability distribution

$$P(a_0, a_1, b_0, b_1)$$

exists.

Fine's Theorem

- Theorem: The existence of a locally causal model for a Bell experiment is equivalent to the existence of a joint probability distribution over all the observables, the marginals of which give the correct operational predictions. A. Fine, Phys. Rev. Lett. 48:291 (1982).
- We only need the converse part here:
- Proof:

Simply let $\lambda = (a_0, a_1, b_0, b_1)$ and $\Pr(\lambda) = P(a_0, a_1, b_0, b_1)$.

Let $\Pr(a|x,\lambda) = \delta_{a,a_x}$ and $\Pr(b|y,\lambda) = \delta_{b,b_y}$.

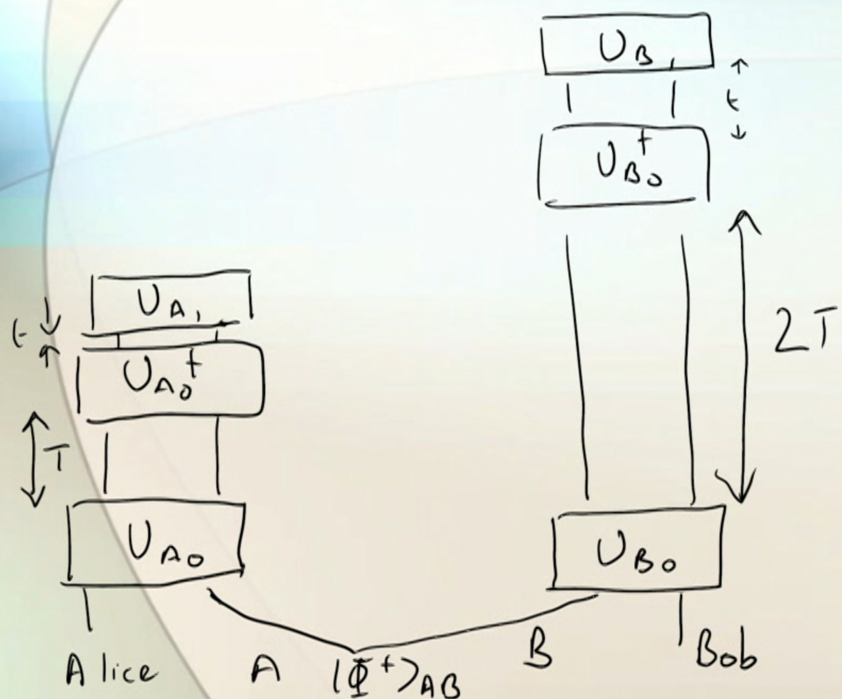
Then,

$$\Pr(a,b|x,y) = \sum_{\lambda} \Pr(a|x,\lambda)\Pr(b|y,\lambda)\Pr(\lambda) = P(a_x, b_y)$$

Which Probabilities have to be Quantum?

- Since there is a local model, the outcomes in the FR experiment have to satisfy Bell inequalities, but we know that the quantum predictions do not.
- Conclusion: At least one of the marginals $P(a_0, b_0), P(a_1, b_0), P(a_0, b_1), P(a_1, b_1)$ must fail to agree with the quantum predictions.
- Which marginals absolutely *have* to obey the quantum predictions?
  - Depends on how Wigner performs the experiment.
  - If a pair of outcomes persists for a very long time, such that Alice and Bob can discuss them, write Nature papers about them, etc. then their marginals have to obey the quantum predictions, otherwise quantum theory would be falsified.
  - If a pair of outcomes does not persist for long enough for Alice and Bob to discuss them then their marginal does not strictly have to obey quantum theory.

Frauchiger-Renner Variant 1

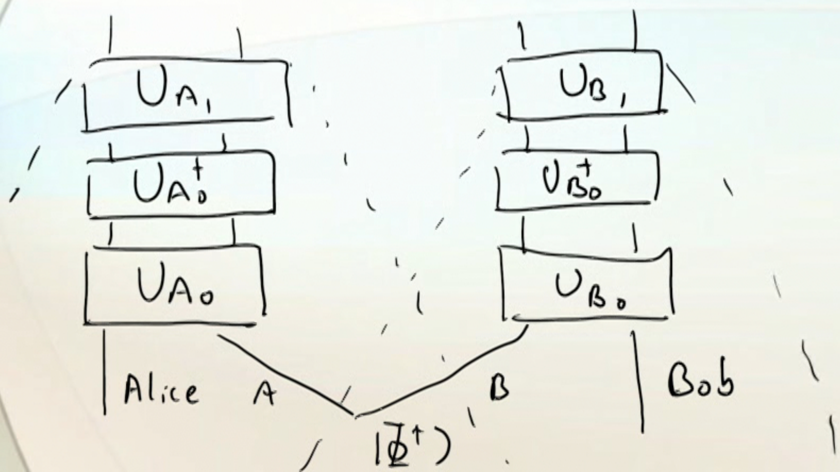


- Let $T = 10$ years, $t = 0.5$ ns.
- Then $P(a_0, b_0), P(a_1, b_0)$ and $P(a_1, b_1)$ have to be quantum.
- But not $P(a_0, b_1)$

A Loophole

- We can't get a contradiction, because there is always at least one marginal that doesn't have to be quantum.
- Note, however, that there is nothing in the formalism of quantum theory that would explain why we get different non-quantum marginals in these two experiments.
- We would have to imagine some mechanism that communicates to Alice's system whether or not Bob's second measurement has happened yet and vice versa.
- In a hidden variable model, we may be prepared to posit such a mechanism, but Copenhagenish quantum theory is just supposed to be raw quantum mechanics, interpreted anti-realistically.
- Since Copenhagenists only have the quantum formalism to rely on, it is reasonable that sequences of observations that are described the same way in the quantum formalism ought to make the same predictions.
- $\Rightarrow$ The same marginals have to be quantum in both experiments, so all of them do, and we get a contradiction.

Spacelike Variant



- We can even perform the experiment in such a way that all four pairs of observations:

$$(A_0, B_0), (A_1, B_0), (A_0, B_1), (A_1, B_1)$$

are spacelike separated, so for every pair, there is a frame in which they coexist.

- Strictly speaking, only $P(a_1, b_1)$ has to be quantum in this case, as for all the others there is not enough time for Alice and Bob to compare results before the erasure.
- But there seems no good reason for arbitrarily choosing a non-quantum marginal in this case.
- Just performing the experiment a bit faster should not affect what is quantum, and this is a faster version of both variants.

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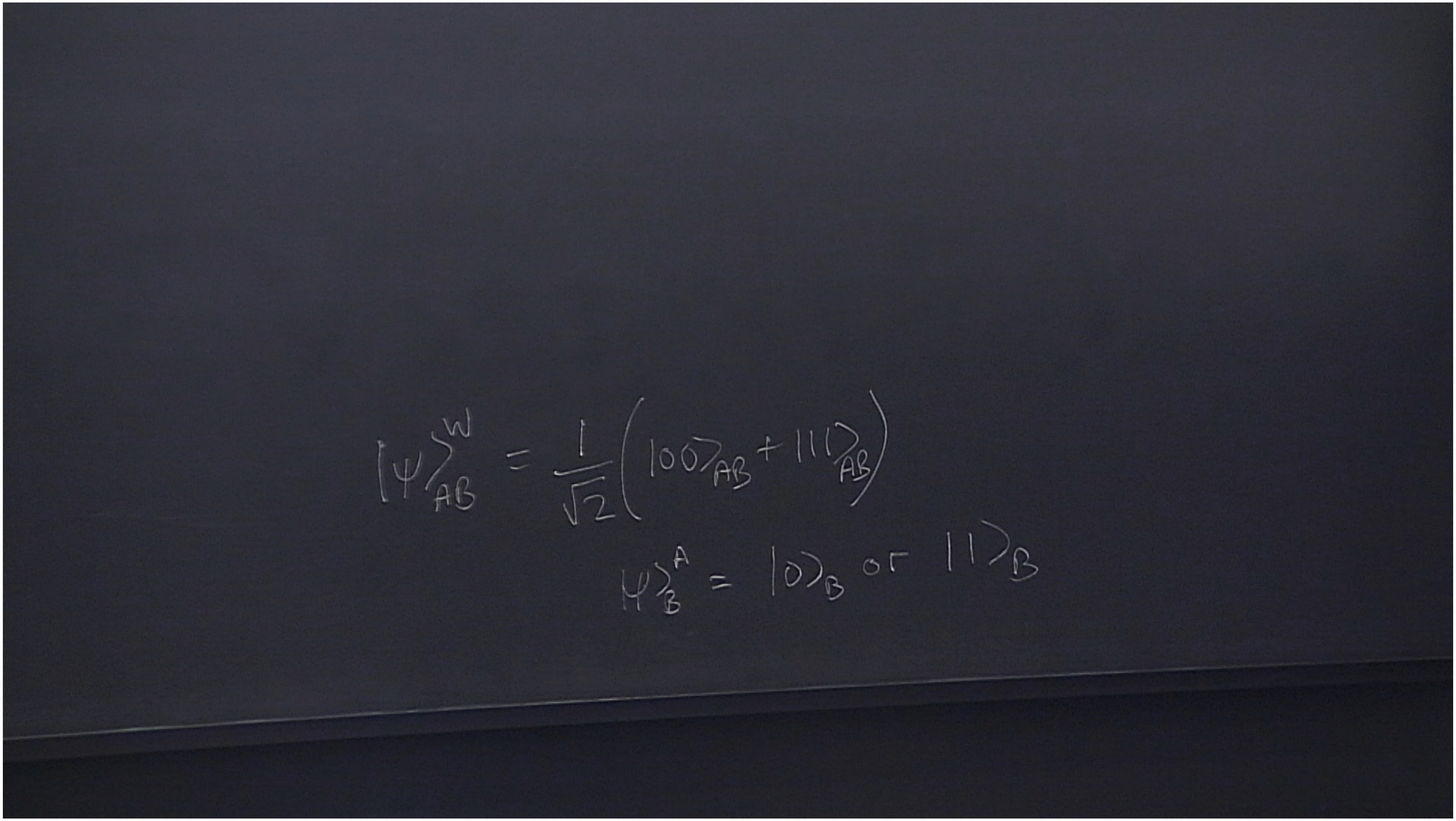
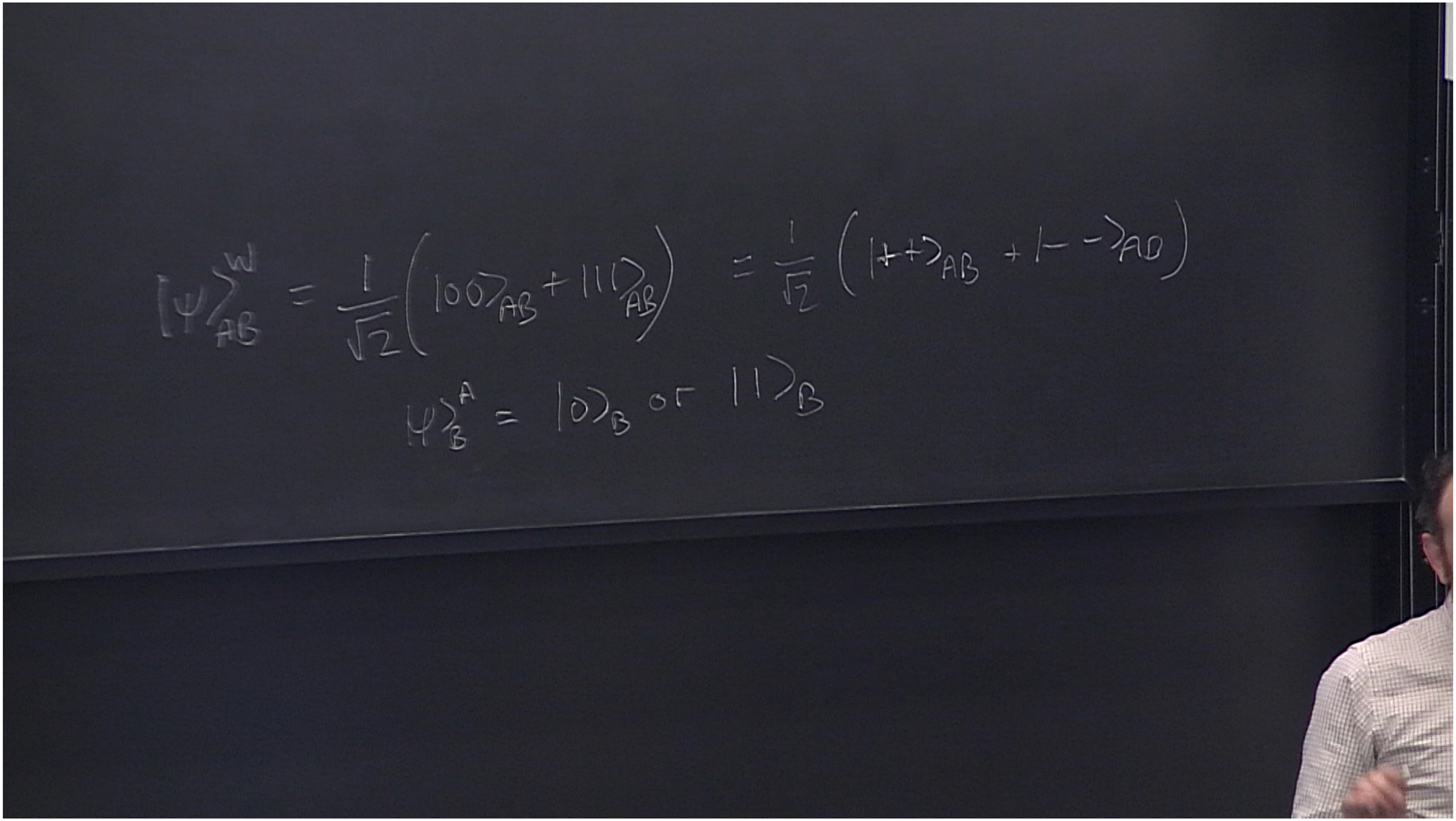
Perspectival Interpretations: QBism

- For a Copenhagenist, the obvious thing to give up is the objectivity of outcomes.
- If Alice's outcomes only exist for Alice and Bob's outcomes only exist for Bob and neither exist for Wigner, then there is no global (Wigner) perspective on which all outcomes can be said to exist, and hence no joint probability distribution.
- QBism is an interpretation of this type. It is the combination of:
  - Pure subjective Bayesianism: All probabilities are subjective Bayesian, so quantum states always represent the degrees of belief of a decision-making agent. Different agents have different states. There is never a requirement for two agents to assign the same state (even with no level conflict).
  - Perspectival Copenhagenism: An agent's quantum state describes beliefs about their own personal reality. If another agent's observation is not reflected in that state then it does not exist for them.

Perspectival Interpretations: Relational

- Rovelli's Relational Quantum Mechanics (should be called Perspectival Quantum Mechanics):
  - Physical systems only have properties from the perspective of other systems, but these perspectival properties are objective.
  - E.g. The measurement has an outcome from the perspective of (the physical system called) the friend, but not from the perspective of (the physical system called) Wigner.
  - These properties are determined by the eigenvalue-eigenstate link, but only applied perspectivally. There is no conflict in the measurement problem because the two descriptions are from the perspective of different physical systems.
  - Rovelli thinks there is nothing special about measurements. I can equally talk about the properties of a single electron from the perspective of another electron.
  - I think this runs into a basis problem like Everett, but we can solve it by only assigning properties from the perspective of systems that are decohered.


$|\psi\rangle^{W}_{AB} = \frac{1}{\sqrt{2}}\left(|00\rangle_{AB} + |11\rangle_{AB}\right)$
$|\psi\rangle^{A}_{B} = |0\rangle_{B}$ or $|1\rangle_{B}$


$|\psi\rangle^W_{AB} = \frac{1}{\sqrt{2}}\left(|00\rangle_{AB} + |11\rangle_{AB}\right) = \frac{1}{\sqrt{2}}\left(|++\rangle_{AB} + |--\rangle_{AB}\right)$
$|\psi\rangle^A_B = |0\rangle_B$ or $|1\rangle_B$

Summary

- Unless we are willing to permit contortions about which marginals are allowed to be non-quantum, Frauchiger-Renner rules out objective Copenhagenish interpretations, i.e. most of them except QBism and Relational QM.
- It is remarkable that we can constrain Copenhagenish interpretations at all.
- The perspectival move will not appeal to many Copenhagenists, as Copenhagen is usually thought to be built on level-headed empiricism, i.e. the things we see in the lab do straightforwardly happen.
- It is this straightforward empirical attitude that drives many to Copenhagen instead of Everett, which says that there is a long path from the ontology to understanding what we see in the lab as an emergent phenomenon.
- FR may drive you towards realism, but we have plenty of results, e.g. Bell, that make realism problematic too.
- We should probably investigate more exotic types of ontology that might get around all of these no-go results.

Course Summary

- I hope to have convinced you that there is an interplay between mathematical foundations, conceptual foundations, interpretations and the way we go about doing calculations in quantum theory. These things are better done together.
- There are many ways of providing an ontology that save the phenomena in quantum theory. What we should focus on now is which one is correct, i.e. leads to progress in physics.
- If you decide to pursue quantum foundations, I hope you will contribute to this.
- However, if you don't, I hope you will occasionally pause in your physics calculations to ask:
    - What would a ψ-epistemicist think is happening here?
    - What do the various interpretations say is really happening here?
    - Does this suggest a new approach to the foundations of quantum theory?
- By doing so, you may end up doing your physics in a different way from others in your field, and see new avenues that others would miss.