Interpretations of Quantum Theory

Mike@PhysicsCafe.org

June 9, 2023

Outline

1. Review the basic postulates of quantum theory.
2. What is unsatisfactory? Why do we need to “interpret” it?
3. There are many interpretations ...
4. GRW
5. Pilot Wave
6. Everett
7. Others

The Postulates

1. The state of a system is represented by a vector in Hilbert space.
2. Quantum states or spaces are combined using the tensor product.
3. A quantum state changes based on a unitary operator.
4. The measurement postulate.

What are the problems?

1. Indeterminism
2. Non-Locality
3. The "ontological status" of the wave function
4. The Measurement Problem

- Indeterminism and Non-Locality might (or might not) bother you, but they don't really introduce any logical inconsistencies in the theory. But without *some* kind of interpretation, it's not clear whether QT even has these attributes.
- The status of the wave function (or quantum state).
  This is not exactly a "problem" in its own right, but it is a question, and different interpretations have different answers.
- The *measurement problem* really is a problem ...

Some of the many interpretations

- GRW (Ghirardi-Rimini-Weber)
  (1) Random. (2) Non-local. (3) Wave function is real.
  (4) Describes the details of the wave function collapse happens.

- Pilot Wave (de Broglie-Bohm, or Bohmian Mechanics)
  (1) Deterministic. (2) Non-local. (3) Wave function is real.
  (4) The wave function influences the position of the particles.

- Everett (Relative State, Many Worlds)
  (1) Deterministic. (2) Local. (3) Wave function status not clear?
  (4) There are no measurements. Simply delete that postulate.

- Transactional Interpretation (quantum version of Wheeler-Feynman absorber theory)

- Huw Price (true time symmetry at the microscopic level)

GRW (Ghirardi-Rimini-Weber)

- The wave function of every individual particle has a very small probability of collapsing per unit of time. (Maybe something on the order of 10^{-16}/second?)
- In any macroscopic measurement there will be so many particles entangled that collapse will be essentially instantaneous. (Maybe something like 10^{21} atoms in a drop of water?)
- This actually qualifies as a *competing theory* rather than a strict interpretation, since it would ultimately provide different results than the standard theory.
- The probability of an individual particle's collapse needs to be updated as we're able to do better experiments (unless of course we actually see a collapse happening.)
- Pros: True wave function collapse provides a potential arrow of time!
- Cons: Probability needs to be "reverse engineered" from experimental results.
- *There are other issues with the original GRW proposal that I haven't touched on, and a more detailed discussion needs to start with more recent variations on the collapse model.*

Pilot Wave

- The name “pilot wave” comes from the idea that the wave function is a real physical entity that exerts an influence on particle motions.

- This idea was originally proposed in the 1920s by Louis de Broglie, and reformulated in the 1950s by David Bohm. Hence it is also know as the *de Broglie-Bohm interpretation*. It’s also sometimes called *Bohmian Mechanics.*

- In this theory, there are real particles and they have real trajectories. (In other words, they really do have both positions *and* velocities.)

- Recall that the wave function $|\psi\rangle$ is a complex function, $\psi(\vec{x}, t)$, where $\vec{x}$ is position and t is time. It can be rewritten in exponential form as Re^{iS}, where R and S are both real functions, and S is the angle or phase in complex space.

- We replace Newton’s 2nd law $a = -\vec{\nabla}U/m$ with the formula $v = -\vec{\nabla}S/m$. In other words the *velocity* of a particle is equal to the gradient of the phase of the wave function (divided by the particle’s mass).

Pilot Wave

- The fact that velocity (rather than acceleration) responds to the influence of the wave function makes this rather like Aristotle's "law of motion." This kind of law does not play well with relativistic physics.
- So this interpretation appears to require either a privileged frame of reference, or something equivalent.

- Pros: Reproduces the predictions of QM with real particles, positions, velocities and trajectories, and is fully deterministic.
- Cons: Appears to contradict relativistic physics. This is typically construed as direct action at a distance by the wave function.

- *It's not obvious from this basic description how the pilot wave works with particle spin experiments. So I've got some work to do before I can relate this to our previous discussions.*

Everett

- Introduced by Hugh Everett III in his 1957 PhD dissertation "The Theory of the Universal Wave Function." Also know as the *Relative State interpretation* or *Many Worlds*.

- In a nutshell, we delete the measurement postulate. The wave function simply evolves based on Schrödinger's equation.

- On the following slides I'll delve into how this is supposed to play out, and where the terms "relative state" and "many worlds" come from.

- Pros: Deterministic, (Arguably) there isn't any non-locality.
- Cons: (1) It's just too weird. (2) Concerns about probabilities. (3) Basis ambiguity.

Textbook Interpretation

- First let's look at a typical textbook description of an experiment. *This is sometimes called the "Copenhagen Interpretation." I don't believe there is such a thing as the Copenhagen Interpretation, but that's a discussion for another time.*

- **Mike measures a quantum coin**

  Before the measurement:

  $$|\text{Coin}\rangle \otimes |\text{Mike}\rangle = \left(\tfrac{1}{\sqrt{2}} |\text{H}\rangle + \tfrac{1}{\sqrt{2}} |\text{T}\rangle \right) \otimes |\text{Will it be heads or tails?}\rangle$$

  After the measurement there are two possibilities:

  (1) $|\text{Coin}\rangle \otimes |\text{Mike}\rangle = |\text{H}\rangle \otimes |\text{I see heads}\rangle$

  (2) $|\text{Coin}\rangle \otimes |\text{Mike}\rangle = |\text{T}\rangle \otimes |\text{I see tails}\rangle$

  Only one of these two events happens and we can't predict which one.

Everett

- Here's how the same experiment works out in the Everett interpretation.
- **Mike measures a quantum coin**

  Before the measurement:

  $$|\text{Coin}\rangle \otimes |\text{Mike}\rangle = \left(\tfrac{1}{\sqrt{2}} |\text{H}\rangle + \tfrac{1}{\sqrt{2}} |\text{T}\rangle \right) \otimes |\text{Will it be heads or tails?}\rangle$$

  After the measurement:

  $$|\text{The joint state}\rangle = \tfrac{1}{\sqrt{2}} \left(\, |\text{H}\rangle \otimes |\text{I see heads}\rangle \, \right) + \tfrac{1}{\sqrt{2}} \left(\, |\text{T}\rangle \otimes |\text{I see tails}\rangle \, \right)$$

- I am now entangled with the coin. You can't write the coin's state and my state separately, only the joint state. In the part of the superposition where the coins is heads, I'm seeing heads. In the part where it's tails, I'm seeing tails. The way my state works out relative to the coin's state inspired the title "relative state formulation" by which Everett's interpretation is sometimes known.
- The term "many worlds" comes from the idea that there is a "world" where I have a coin that's heads up and another world where it's tails.
- *I have a lot more work to do in order to see how something like GHZ or Hardy works out in Everett.*