Tues Feb 28

Everett's Many Worlds Interpretation (Continued)
Everett's Many Worlds Interpretation raises many questions.
Today we'll tackle two of the most important:

1) Where do the (Born) probabilities come from?

In practice we see probabilistic results to experiments. It's the reason that we know that quantum mechanics works in the first place. So people tend to be hesitant about the Everett Interpretation because it's not abundantly clear why these probabilities would arise.

Many Worlders say that there exists a "splitting of the worlds" in such a way that amplitudes of ⅗ and ⅘ would correspond to 9/25th "volume of worldness" going one way, and the other 16/25th going the other.

Some philosophers don't really buy this because if worlds are equal, why wouldn't they just occur with even probabilities? Why bother with amplitudes at all? Many Worlders say that probabilities are just "baked into" how quantum mechanics works. They justify this by arguing that we already agree that density matrixes bake the Born Rule in (since the main diagonal represents Born Rule probabilities).

There's all sorts of other technical arguments that come into play, which boil down to "if nature is going to pick probabilities, they might as well be these," lest we get faster-than light communication, cloning, etc.

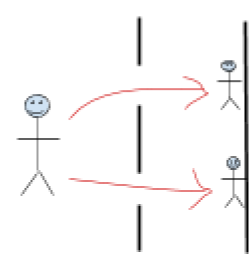
There's also been plenty of discussion surrounding the meta-question…

"If there's no experiment that could differentiate the Copenhagen Interpretation from Many Worlds, why bother arguing about it?"

Many Worlders say that the opponents of Galileo and Copernicus could also claim the same about Copernican vs Ptolemaic versions of observations of the planets, since Copernican heliocentrism made no difference to the predictions of celestial movement.

Today we might say that the Copernican view is better because you could fly outside of the solar system and see the planets rotating around the sun; it's only our parochial situation of living on Earth that motivated geocentrism. On that note, it may be harder to think up a physically possible analog for the Many Worlds interpretation, since we can't really get outside of the universe to the see the branching.

There is one neat way you could differentiate the two, though...



Last time we talked about increasing the scope of the Double Slit Experiment. Bringing that thread to its logical conclusion, what if we could run the experiment with a person?

It would then be necessary to say that observers can branch, and that a person is a quantum system. That means it would no longer be enough to use the Copenhagen interpretation.

If you talk to modern Copenhagenists about this they'll take a quasi-solipsistic view, saying that if this experiment were run, "the person being behaving quantumly doesn't count as an observer, only I, the experimenter do."

Another place to consider the differences of interpretations is their relationships with special relativity.

Both the Copenhagen Interpretation and Dynamic Collapse appear to be in some tension with special relativity.

If Alice and Bob share a Bell Pair, and Alice measures her qubit in some basis, Bob's qubit instantaneously collapses to that basis. Sure, Bob won't immediately know the result of Alice's measurement, and thus describes his state as I/2, but that's still a problem.

Simultaneousness for far away things isn't well defined in special relativity, so people argue that Alice's measurement immediately causing a change in Bob's qubit conflicts with it.

You can see this more clearly by taking a frame of reference where Bob's change happens first. How can we say that Alice's measurement caused it?

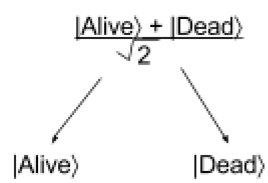
The Many Worlds Interpretation doesn't have to deal with this snag because it doesn't assert that collapse actually happens in the first place. It's ok to view Bob's change as happening first because Alice's measurement didn't cause it, it was just a branching of the universe.

The second question we want to tackle is the **Prefered Basis Problem**. It says:

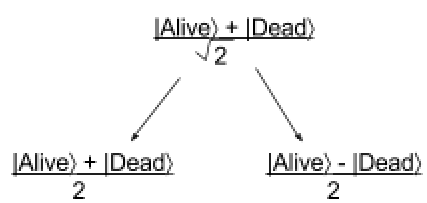
"Let's say I buy into the argument that the universe keeps branching, well then…"

2) <u>In what basis is this branching occurring?</u>

With a Schrodinger's cat, you can say that the world branches into either the alive state or the dead state.



But it could equally have branched into



instead.

There's a whole field of physics that tries to answer questions like these, called...

Decoherence Theory

which says that there are certain bases that tend to be robust to interactions with the environment, but that most aren't.

So for the example above, decoherence theory would say that an alive cat doesn't easily decohere if you poke it, but that a cat in the ½ (|Alive⟩ + |Dead⟩) state does, because the laws of physics pick out certain bases as being special.

From the point of view of decoherence theory we say that an event has definitely happened only if there exist several records of it scattered all over the place (where it's not possible to collect them all).

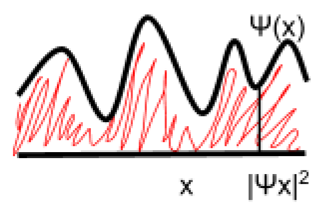
This is perhaps best compared to putting an embarrassing picture on Facebook. If only a few friends share it, you can still take it down. On the other hand, if the picture goes viral, then the cat is out of the bag, and deleting all copies becomes an intractable problem.

This is as far as we'll cover Many Worlds/Decoherence.
To pick up the broader conversation about interpretations of quantum mechanics…

You may think that all the options we've seen so far are bizarre and incomprehensible (Einstein certainly did), and wonder if we could come up with a theory that avoids all of the craziness. This leads us to…
Hidden Variable Theories
which try to supplement quantum state vectors with some sort of hidden ingredients. The idea is to have $\alpha|0\rangle + \beta|1\rangle$ represent a calculation to make a prediction on what the universe *has already* set the qubit to be: either $|0\rangle$ or $|1\rangle$.

The first of these is...
Bohmian Mechanics
which was proposed by Bohm in the 50s.

Normal quantum mechanics says that a particle has some probability of being found at several locations as an amplitude wave. But we now want to also say that there exists a real place where the particle is. Bohm tries to explain how if a particle follows the wave function, that it may continue to do so even if it only truly exists in one place.



There are many rules that could satisfy this property, so there's no experimental way to know which is correct.

Given a quantum state represented as an amplitude vector, when we multiply by a unitary transformation, we want to be able to say "this is the state we are *really in* after the unitary" with probabilities represented as:

$$\begin{pmatrix}\beta_1\\ : \\ \beta_n\end{pmatrix} = \begin{pmatrix}U_{11} & & \\ & \dots & \\ & & U_{nn}\end{pmatrix}\begin{pmatrix}\alpha_1\\ : \\ \alpha_n\end{pmatrix}$$

There are many, many such matrixes. For example you could put $\begin{pmatrix}\beta_1\\ \beta_n\end{pmatrix}$ in every column, which would say that you're always jumping randomly over time in such a way that preserves the Born Rule. You could have been in a different galaxy a planck time ago.

The big selling point of Bohmian Mechanics is that there's only one random decision that has to be made. "God needs to use a RNG to place the hidden variables" at the beginning of time, but afterwards we're just following the Born Rule.

Bohm and others noticed lots of weird consequences of Bohmian Mechanics. It looks nice with just one particle, but problems start to arise when you look at a second. Bohmian Mechanics says that you need to give a definite position for both particles, but people noticed that you can only get that with faster-than-light influence in hidden variables (since Alice's local transformation moves Bob's qubit).

This wouldn't be useful for faster-than-light communication or the like, since hidden variables are explicitly defined as unmeasurable.

When Bohm proposed this, he was super eager for Einstein to accept the interpretation, but Einstein didn't really go for it, because of the sort of things listed above.
What Einstein really wanted (in modern terms), is a…
Local Hidden Variable Theory
where hidden variables can be localized to specific points in space and time.
The idea is that when entanglement is created, the qubits flip a coin and decide, "if anyone asks, let's both be 0," coming up with such answers for all questions that could be asked (infinite bases and whatnot), and that each qubit carries a copy around independently.

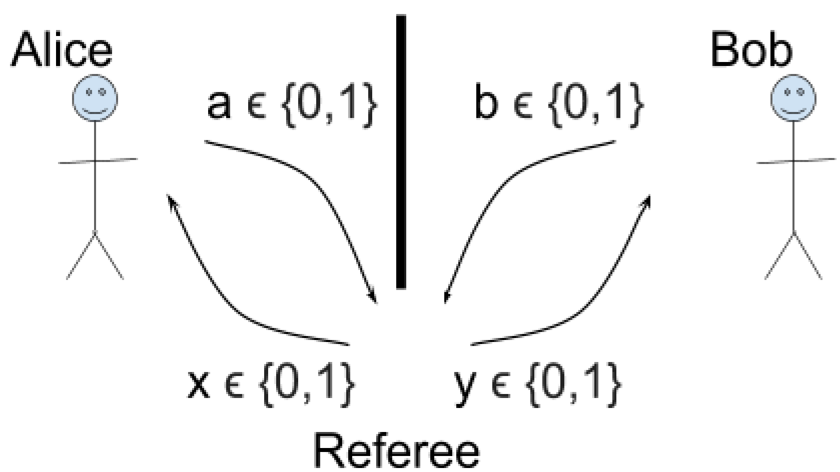
This is <u>not</u> Bohmian Mechanics: in 1963 John Bell actually wrote a paper that points out the non-locality of Bohmian Mechanics. Bell says that it would be interesting to show that all hidden variable theories must be non-local, and in fact the paper has a footnote that says that since publication, a proof of this has been found.

This proof is the…
Bell Inequality / Bell Theorem
which has changed people's understanding of quantum mechanics perhaps more than anything since the field's inception. It came as a result of Bell philosophizing about the question "Is there an experiment that could follow the rules of quantum mechanics, but would violate the possibility of local hidden variables?"

Bell came up with such an experiment. We'll describe it differently from how Bell did—more computer science-y—as a game between Alice and Bob, where the win probability can be improved through shared entanglement. It's called…

The CHSH Game
named after four people who in 1999 wrote a paper saying "this is what Bell was trying to say." The game doesn't involve quantum mechanics, but quantum mechanics can help us win.

It's a bit of a precursor to quantum computing in that it's one of the first instances of looking to see what basic information processing tasks quantum mechanics can help us solve better.



The idea is that Alice and Bob are placed in separate rooms, and are each given a challenge bit (x and y, respectively) by a referee. Then Alice sends back bit a, and Bob bit b.

They win the game iff $a + b = xy \pmod 2$

So if either x or y is 0: a, b should be the same bit

If $x = y = 1$: a, b should be different bits

Alice and Bob are allowed to agree on a strategy in advance.

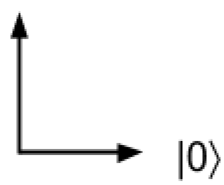
The classical strategy to maximize winning probability is sending the referee $a = b = 0$. They win 75% of the time, losing only if both x and y are 1.

To prove that this is optimal, you'd want to show that introducing randomness isn't going to help. Basically you'd write $a(x) + b(y) = xy \pmod 2$ such that a is a function on x (and b on y), and prove that this is going optimal when they're constant functions.

The Bell Inequality is just the statement that the maximum classical win probability for this is 75%.

Bell noticed an additional fact though. If Alice and Bob had a pre-shared Bell Pair, there's a better strategy. In fact, the maximum win probability for a quantum strategy is $\cos^2(\pi/8) \sim 85\%$.

The strategy involves Alice and Bob measuring their entangled qubit based on whether x and y are 0 or 1.

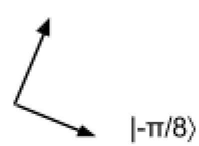
If $x = 0$, Alice measure in 

and if $x = 1$, Alice measures in 

She sets a to 0 if she measures $|0\rangle$ or $|+\rangle$

and 1 if she measures $|1\rangle$ or $|-\rangle$

If y = 0, Bob measures in the X basis rotated by $\pi/8$ clockwise. 

and if y = 0 rotated by $-\pi/8$. 

He sets b to 0 if he measures $|\pi/8\rangle$ or $|-\pi/8\rangle$

1 if otherwise

This strategy has the amazing property of making Alice and Bob win with probability $\cos^2(\pi/8)$ for all possible values of x and y.