# Lecture 12: Thurs Feb 23

Last time we discussed a few interpretations of quantum mechanics and today we cover a few more. The first of these isn't so much an interpretation, but rather a proposal for a new physical theory.

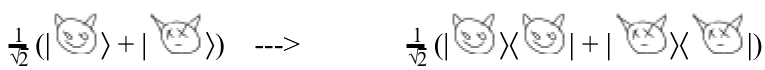
**Dynamic Collapse**

Says that maybe quantum mechanics isn't a complete theory. It does a good job of describing microscopic systems, but maybe we're not looking at all of the rules that govern reality.

The idea is that there exist some physics rules that we haven't discovered which say that qubits evolve over unitary transformations, but that the bigger the system is, the more likely it will collapse. Thus, we can view this collapse as being a physical process that turns pure states into mixed states.

$\sum_i \alpha_i |i\rangle$ ~> $|i\rangle$ with probability $|\langle\Psi|i\rangle|^2 = |\alpha|^2$

So in the Schrödinger's Cat example, Dynamic Collapse would say that it doesn't matter how isolated the box is. There exists some physical law that says that a system that big would eventually evolve into a mixed state.



So if you measured in the alive/dead basis, you should be able to distinguish between these two states.

Theoretically you could implement a measurement in any basis of a multi-qubit system. What this means for our cat, is that there should exist a unitary transformation to get the "cat system" into a basis where we can measure any of it's qubits and get 0 if the cat is alive and 1 if the cat is dead.

Professor Aaronson is currently doing research into what other problems you'd have a solution for if you solve this problem (are able to measure in an arbitrary basis). There's already a theorem which says that if you can distinguish between this and that state, then you must have the technological ability to rotate between them.

> Which means implementing the Schrödinger's Cat experiment in real life need not involve animal cruelty: if you were able to distinguish between the alive state and dead state, you should be able to rotate the dead cat back into the alive state!

The idea of these Dynamic Collapse theories is that even if you had the technology to distinguish between the two states, a system as big as a cat wouldn't maintain itself in a pure state for a significant amount of time.

The trouble with this is that it's not *really* interpreting quantum mechanics, it's just proposing new laws of physics. Physicists have a high bar for such proposals, and the burden of proof is on you to explain exactly how big a system needs to get to collapse. Fundamentally, there should be implications which we're able to measure the effects of.

The point is that if you propose a Dynamic Collapse theory, the burden is on you to clarify how it works mathematically. Some suggestions include:

- Collapse happens when some number of atoms get involved
    - which is contradictory to our understanding of atoms, which relies on reductionism
- Collapse happen after a certain mass is reached

One famous proposal is the…

**Ghirardi-Rimini-Weber Theory (GRW)**

which says that each atom has some small probability of collapsing at any point, and that if one atom collapses, the entire system collapses. Thus, the bigger the system, the more likely it collapses.

Just like measuring one qubit of $\frac{1}{\sqrt{2}}(|00...0\rangle + |11...1\rangle)$ will resolve all of the qubits to 0 or 1.

another proposal is the…

**Penrose Interpretation**

which says that superpositions collapse when enough mass gets involved.

Why mass? mass here ▼ or ▼ mass there

Say we have the superposition of $|*\ \ \rangle + |\ \ *\rangle$. General relativity tells us that mass curves space-time. Specifically, we know that space-time can be bent like a mattress. That means a mass in one location would make spacetime curve differently than having it somewhere else.

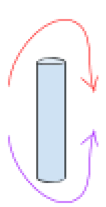
The thing is, no one really knows how to combine general relativity and quantum mechanics, it's one of the biggest open problems in physics. What the Penrose Interpretation is suggesting is that this could be the place where we do so.

The trouble with these theories is that they need to keep adjusting their answers to questions like "How much mass is enough to collapse it?" based on experimental evidence, which keeps producing examples of bigger and bigger states in superposition.

Early on, we discussed the significance of the Double Slit Experiment as performed with photons. People eventually tested it with protons, then molecules, and in 1999 Zeilinger performed it with Buckyballs: molecules large enough to be seen with the naked eye.

To go even further...

**Superconducting Qubits**



If you take a coil, about 10mm across, and cool it to almost absolute zero, you'll see a current that's in superposition of electrons rotating clockwise or counterclockwise about it.

This constitutes a superposition of billions of particles!

We'll come back to these in time, as they're an important technology for quantum computers.

Penrose has a specific prediction for the scale at which collapse happens, which may be testable in our lifetime, but with GRW, the prediction retreats every time superposition is shown to be possible at a news scale.

A popular position among people who want nature to be simulatable in a classical computer (and thus don't want quantum computers to work) says that:

A frog can be in a superposition of two states. However, a complex quantum computer wouldn't work because systems lose superposition after *sufficient complexity*.

This position is interesting because it could be falsified by building a quantum computer, and reaching falsifiable theories is what moves these discussions from philosophy to science.

<u>What happens if we keep doing experiments and quantum mechanics keeps perfectly describing everything we see?</u>

i.e. we want to not add any new physical laws, but we insist on being realists (saying that there exists a real state of the world without believing that unitary transformations and measurement are separate).

This gets you to…

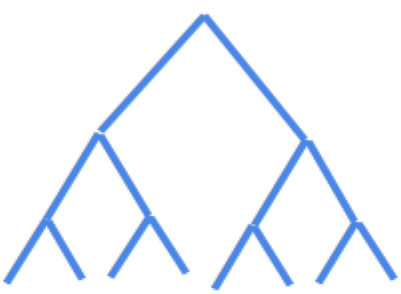
**Everett's Many Worlds Interpretation (1957)**

Says that the entire universe is a single state, and that the entire history of the universe is the vector $|\Psi\rangle$ that represents reality going through unitary evolution.

You can think of measurement as a special case of entanglement. It's just your brain becoming entangled with the system that you're measuring. A cNOT gate is applied from the system you're observing onto you.

$$\frac{|0\rangle + |1\rangle}{\sqrt{2}} |\text{You}\rangle \quad -> \quad \frac{|0\rangle|You_0\rangle + |1\rangle|You_1\rangle}{\sqrt{2}}$$

Essentially you've now branched into one of the two possibilities.



The universe branches every time that a macroscopically detectable effect occurs. If we were to write down the state of the Earth a month from now, you'd have P(Austin is sunny) + P(Austin is rainy), etc.

We perceive only one branch, but there exist countless other branches where one month later every possible thing that could happen happens.

Some versions of this interpretation chose words carefully to avoid sounding like there exist several physical worlds, but they all imply it. When Everett came up with this as a grad student at Princeton, his advisor told him to remove references about the physical existence of several worlds, because it wouldn't chime with the physics establishment at the time, so he published without it.

Eventually Everett left physics for nuclear work. The only lecture he gave on the topic was at UT decades later when people were finally coming around to the idea. Deutsch, the biggest current advocate of the Many Worlds Interpretation, was there.

One important point to consider is interference between branches.

We don't expect different branches to interfere with one another, because what has happened, happened, and can't be changed. $|0\rangle|You_0\rangle$ shouldn't affect $|1\rangle|You_1\rangle$

This shouldn't need to be a problem. To get the current world, you apply unitary transformations representing every branching between the beginning of time and now. Interference would only happen if two states are reached by applying different unitary transformations. Quantum mechanics says that this is less likely to happen than an egg unscrambling itself (it's thermodynamically disfavored).

But if we take this seriously, keeping in mind:

- Branches never collapse
- The universe is finitely large

Then eventually branches are going to start colliding with one another.
Many Worlds says that this will happen in the timescale of $10^{100}$ years.

We've said that measurement is the one irreversible part of quantum mechanics, but Many Worlds says it's not. In principle we could apply $U^{-1}$ to get a measurement to unhappen, though like unscrambling an egg, thermodynamics isn't going to make it easy.

The next question we may ask is:
"Where to probabilities come from?"

It's not enough to say that sometimes we see 0 and sometimes we see 1. Quantum mechanics gives very specific probabilities that each will occur, but if the world is just branching once for each observation, then how can we justify these probabilities correlating to anything meaningful?

Everett circumvents this by saying that if the universe split several times, then the probability is connected with the percentage of times it would go to either branch, but many people in the past 50 years don't buy this argument, and have looked for other explanations.