Interpretation of QM

- The Measurement Problem
  - Thought Experiment: Schrödinger's Cat
    - A cat is trapped in a box with a vial of poison
      - + The vial will open if a nucleus decays. There is a probability 1/2 that this happens in 1hr (or whatever time you want)
      - + After that hour, the state of cat + nucleus is

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|\text{alive}\rangle|N\rangle + (\text{phase})|\text{dead}\rangle|N_1 N_2 \cdots\rangle\right)$$

→ + What on earth does that mean?

- Copenhagen/Orthodox calculation: when you open the box, the wavefunction collapses to one "eigenstate" or the other
  - + Something about conscious observation does this (Wigner, Wheeler)
  - + Or maybe we just need to define measurement better.
  - + But why aren't we (the observers) quantum too?
  - + Often we take this position but "Shut up + calculate" (Feynman)
- Many-Worlds (Everett)
  - + The state is really

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|\text{alive}\rangle|N\rangle + |\text{dead}\rangle|N_1 N_2 \cdots\rangle\right) \times |\text{observer}\rangle|\text{rest of universe}\rangle$$

before and

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|\text{alive}\rangle|N\rangle|\text{see alive}\rangle + |\text{dead}\rangle|N_1 N_2 \cdots\rangle|\text{see dead}\rangle\right) \times |\text{rest of universe}\rangle$$

after observation. But evolution follows Schrödinger's Equation

  - + As information spreads, the universe's wavefunction branches every time. And with every quantum event
  - + Everything possible happens in some branch of the wavefunction

- Decoherent (or Consistent) Histories
  + Maybe most sophisticated. Under somewhat active research
  + Simply put, macroscopic (or "big") systems are made of very many particles bound to each other. If you try to put a cat (+ by extension the air it ~~touches~~/breathes, etc) in a superposition, the extremely complicated N-particle Schrödinger eqn forces the wavefunction into an eigenstate very quickly.
- → What's Right? Who really knows?

- The EPR paradox + Bell's Inequality
  - Einstein, Podolsky, + Rosen Thought Experiment
    - A is 3 lyr from earth, B is 4 lyr from earth in opposite direction
      + On earth, C produces a π^0 at rest, which decays to $e^\pm$ pair
      + e^- goes to A, who measures S_z. e^+ goes to B (later), who measures S_z.
    - The result?
      + Initial spin state is $\frac{1}{\sqrt{2}}\left(|\uparrow\rangle_-|\downarrow\rangle_+ - |\downarrow\rangle_-|\uparrow\rangle_+\right)$ $(s=0)$ b/c π^0 has $s=0$
      + If A measures $|\uparrow\rangle_-$, then B must measure $|\downarrow\rangle_+$, + vice-versa
      + <u>But</u> the measurements are spacelike separated. Information?
    - EPR says the info cannot go faster than c (<u>local</u>)
      + Therefore, there must be a "hidden variable" that contains it from start
      + Note: this contradicts usual QM that the state is undetermined until measurement.
  - Bell's Proposal (J.S. Bell, 1964)
    - New Experiment
      + Same as EPR but A + B measure spins $\vec{a}\cdot\vec{S}$, $\vec{b}\cdot\vec{S}$ ie, their polarizers are at an angle.

+ Consider the product of measurements

$$\frac{4}{\hbar^2}(\vec{a}\cdot\vec{S}|_A)(\vec{b}\cdot\vec{S}|_B) \quad \text{For } \vec{a}=\vec{b}, \text{ this is always } -1.$$

In general

$$P(\vec{a},\vec{b}) = \frac{4}{\hbar^2}\langle \vec{a}\cdot\vec{S}|_A \ \vec{b}\cdot\vec{S}|_B \rangle = -\vec{a}\cdot\vec{b} \text{ in usual QM. (see 14th}$$

- What about local hidden-variable theories? λ = hidden variable
  + There is a function $A(\vec{a},\lambda)$ $(=\pm 1)$ that secretly knows whether you measure spin $\pm$ for the electron and one $B(\vec{b},\lambda)$ for positron
  + For angular momentum conservation, $B(\vec{a},\lambda) = -A(\vec{a},\lambda)$
  + We see $P(\vec{a},\vec{b}) = \int d\lambda\, \rho(\lambda)\, A(\vec{a},\lambda) B(\vec{b},\lambda)$ for prob. density $\rho(\lambda)$

    So

$$P(\vec{a},\vec{b}) - P(\vec{a},\vec{c}) = -\int d\lambda\, \rho(\lambda)\, A(\vec{a},\lambda)\left[A(\vec{b},\lambda) - A(\vec{c},\lambda)\right]$$

  + Note $A(\vec{b},\lambda)^2 = 1$ and $|A(\vec{a},\lambda)A(\vec{b},\lambda)| \le 1$

$$|P(\vec{a},\vec{b}) - P(\vec{a},\vec{c})| \le \int d\lambda\, \rho(\lambda)\, |A(\vec{a},\lambda)A(\vec{b},\lambda)|\,(1 - A(\vec{b},\lambda)A(\vec{c},\lambda))$$

$$\le 1 + P(\vec{b},\vec{c})$$

- The point: The QM result violates the inequality for 

  + Experiments give the QM result
  + QM is <u>nonlocal</u>. Wave function collapse is instantaneous.
  + But you can't send messages, since you can't control if the e^- at A is ↑ or ↓. All that you have is a correlation if A + B later compare results.
  + Perhaps it is better to say that QM is local (or <u>causal</u> b/c it obeys relativity) but that it is not "real" in the sense that quantities like spin do not have a definite value "until measured" (whatever that means).