Return to measurement
A closer look at various resolutions

NOTE: the quiz will not cover "measurement"

How to go from a deterministic theory with superimposed possibilities to a random single experience is known as the 'measurement problem'.

There are a variety of ideas about how to deal with it- none really satisfactory.

A quantum description of measurement

- The macroscopic set-up creates a situation describable by Ψ (which describes the quantum system) and φ(which describes the macroscopic apparatus). Initially, these are independent, so if Ψ has two possible values, Ψ_1 and Ψ_2, the overall wavefunction of the whole thing would be $\frac{1}{\sqrt{2}}\left(\psi_1^{initial} + \psi_2^{initial}\right)\left(\varphi^{initial}\right)$
- Ψ changes in time, as described by the Schrödinger equation.
- When the micro-system (say a single particle) encounters a measurement apparatus, the wave functions describing the particle and the apparatus become "entangled", i.e. they are no longer independent. Either Ψ goes into state 1, and all the needles, etc. represented by φ go to read "1", or each goes to "2."

$$\frac{1}{\sqrt{2}}\left(\psi_1^{initial} + \psi_2^{initial}\right)\left(\varphi^{initial}\right) \rightarrow \frac{1}{\sqrt{2}}\left(\psi_1^{final}\varphi_1^{final} + \psi_2^{final}\varphi_2^{final}\right)$$

- So far, we have just described how the wave-function obeys the equation.
- Interference between possibilities (1) and (2) now disappears, because there are zillions of particles in different positions in $\left(\varphi_1^{final} \; and \quad \varphi_2^{final}\right)$ and there is no chance whatever that the waves representing these two possibilities will overlap.

Loss of Interference

- Here's the key point: if you have just one particle, going through two slits, the two paths show interference only if they get to the same place. The (x,y,z,t) coordinates must all be the same. The wave function representing MANY particles is a function of ALL their coordinates, so if there are two lumps of this wave function evolving in time, they show interference only if ALL the coordinates of ALL the particles can get to the same places by each path, at the same time. This simply never happens once many particles are involved in a complicated system.
- Thus we now have two distinct possibilities, represented by : $\frac{\psi_1^{final}\varphi_1^{final}}{\sqrt{2}}$ *and* $\frac{\psi_2^{final}\varphi_2^{final}}{\sqrt{2}}$
- We now have gotten rid of the interference, while postulating <u>nothing different from the linear wave equation</u>, and without worrying about "duality" or any such philosophy.
- The "projection postulate" turns out to follow naturally: obeying the wave eq, represents a situation in which, if the apparatus measures $\psi = \frac{\psi_1^{final}\varphi_1^{final}}{\sqrt{2}}$ again, it will get the same result. That is, no piece of the wavefunction represents a solution with the successive measurements of the same thing giving opposite results.
- <u>So why is there any philosophical problem about QM, other than the usual shedding old ideas?</u>

The Output State

- At this point the solution to the equation gives $\frac{\psi_1^{final}\varphi_1^{final}}{\sqrt{2}} + \frac{\psi_2^{final}\varphi_2^{final}}{\sqrt{2}}$

  Both distinct possibilities are still there, even though they don't interfere!
- Why should you be troubled that both possibilities remain?
- Schrödinger's cat:
  - Say that the micro-variable is a quantum spin, and the measurement apparatus is set up to kill a cat if the spin is up, and give it some food and water if the spin is down. This is not a science-fiction idea, but a relatively trivial thing to set up in an ordinary lab.
  - The result of the solution of the linear wave equation is that the cat is both alive and dead, in a superposition. This does not mean "in a coma" or "almost dead" but BOTH fully alive and purring or thoroughly dead and decomposing.
  - Furthermore, once you look, your wave function becomes entangled with those of the cat, etc. The solution of the linear wave equation now describes a superposition of a you who has seen the dead cat and a you who has seen the live cat!
- Which is real?
- If the linear wave equation by itself describes the world of our experience- it must describe many such worlds!

Ideas to deal with the measurement problem

- (folk version of Copenhagen) Ψ collapses, don't ask how
- (formal Copenhagen) Ψ wasn't ever real, so don't worry about how it collapses. It was just a calculating tool
- "macro-realism": Ψ does too collapse, but that involves deviations from the linear wave equation. (Pearle, …)
- mentalism: Ψ does too collapse, due to "consciousness", which lies outside the realm of physics. (Wigner, …)
- "hidden variables" were always around to determine the outcome of the experiments, so Ψ doesn't have to collapse. (Einstein, DeBroglie, Bohm …)
- (Many Worlds). There's nothing but the linear wave equation, you just have to understand what it implies. Ψ doesn't collapse, all those different branches occur but have no reason (until you understand the wave equation) to be aware of each others existence. (Everitt, …)
  - (Many Thoughts) There are non-linear criteria for what constitutes a thought. Under special circumstances that may lead to $|\Psi|^2$ probabilities. (Hanson, Mallah)
- (quantum logic). Classical Boolean logic is empirically disproved (as a description of our world) by QM, just as Euclidean geometry was shown by G.R. not to describe our world. (Putnam but he no longer holds that view)

Return to Copenhagen

- Here's what Bohr had to say about the EPR proposal, in which it seemed that various properties of particles could be shown to have definite values (i.e. "elements of physical reality", by measuring pairs of correlated particles. Counting ALL those properties (S_{1x}, S_{1y}, S_{2x}, S_{2y},…which couldn't all be measured at once) led to violations of the uncertainty relation, and hence of QM.
  - "*The apparent contradiction in fact discloses only an essential inadequacy of the customary viewpoint of natural philosophy for a rational account of physical phenomena….The interaction between object and measuring agencies entails-because of the impossibility of controlling the reaction of the object on the measuring instruments…the necessity of a final revision of the classical ideal of causality and a radical revision of our attitude towards the problem of physical reality. The criterion of reality proposed contains an essential ambiguity… regarding the expression 'without in any way disturbing the system' The principal point is that such measurements demand mutually exclusive arrangements*."
  - However, this interpretation leaves open the question of *how* our old ideas need to be revised. Is it local causality, reality, or induction that goes? Although only "causality" and "reality" are mentioned, the point seems to be that *induction* fails. Again, how does the particle emitter know what measurement situations will be made for the emitted particles? Or vice-versa?

Hidden Variables (some history)

- The initially most appealing solution is some sort of hidden variable theory. That is, nature is ultimately like the classical picture, with each event following directly from local causes. The history of this idea as a response to QM is interesting:
  - Einstein, Schrödinger, DeBroglie thought it would work.
  - Bohr, Heisenberg, etc. assumed that it couldn't work.
  - We've seen that Bohr won the debate with Einstein as to whether there was some way around the uncertainty principle.
- Von Neumann had a purported proof that NO hidden variable theory could reproduce the results of QM. The proof was accepted for decades, until Bohm came up with a counter-example. Bohm showed that Von Neumann had snuck in a hidden assumption: that the measured property must depend only on the micro-system, and not also on the measurement apparatus.
- Bohm constructed an HV theory which could explicitly reproduce the results of QM for a single local variable, e.g. spin.
- But John Bell followed up on the original Einstein ideas for ways to show the incompleteness of QM by showing that for spatially extended systems, no LOCAL HV theory can reproduce the results of QM.
- And experiments agreed with QM, violating the predictions of all local realist theories.

Non-local hidden variables?

- Rather than reproduce the twists and turns in this development (remember Copernicus/Newton/Einstein) we ask:
- Is there any NON-LOCAL HV theory that reproduces the results of QM?
- The answer is apparently yes, thanks again to Bohm.
- Bohm's *local* theory works approximately as follows:
  - There is some actual value to the position of any particle. There is also an actual wave, guiding those particles. (shades of DeBroglie)
  - The wave obeys the usual linear equation of QM.
  - There is an equation describing how the actual set of positions changes in time, under the influence of the wave.
  - For some reason, not entirely clear, it is not given to us to know the actual positions of everything, but rather we only know some probabilities, with the probability of some set of coordinates proportional to $|\psi|^2$ for those values.
- It follows directly from Bohm's equation describing the motion of the coordinates that the probability density remains proportional to $|\psi|^2$ forever, if it starts that way. A swarm of dots distributed in coordinate space according to the probability rule would follow streamlines in the probability flow.
  - Crude observation allows us to measure macro-variables, so that we can always eliminate the possibility that the actual coordinates are in one of the remote branches of the solution of the wave equation.

Bohm's limits

Bohm's interpretation seems to reproduce all the measured properties of QM. Any objections?

- You can't have separate coordinate dots for each particle (local). You need a single multi-dimensional coordinate to stand for every single particle!
- Does saying that a true set of coordinates exists make a testable claim? Is it like saying "there is a special reference frame in which the ether is at rest, but we can never find it"? If the assertion that one set of coordinates is "real" does have some meaning, what are the experimental implications?
- The underlying theory requires a unique reference frame. Only the statistical averages for large-scale variables (on the assumption that the "equilibrium" distribution has been reached) show Lorentz invariance.
- It restores dualism: the wave function and the real particle coordinates are very different entities. The particles don't even have any influence on the wave-function. Why do ordinary position coordinates play a special role for the particles, but not for the wave?
- The probability densities are fixed by the actually occurring "branches" of the wave function, the other branches are irrelevant. Why can we observe well enough to say which distinct macroscopic branch of the wave function contains the actual particle coordinates, but not well enough to have *any* effect on the probabilities *within* a branch? In other words, how does Bohm maintain the sharp distinction between the measured and unmeasured properties, i.e. between the parts of the wave function within which the coordinate probabilities precisely obey the "equilibrium" $|\psi|^2$ law, and those for which no probabilities are needed at all?

Mentalism

Proposed by von Neumann and advocated by Wigner, among others, especially pop-journalists. There is something special about consciousness. It lies beyond the laws of physics as usually understood. E.g. Mermin: "Physical reality is narrower than what is real to the conscious mind."

- Human observation collapses the wave function, so a superposition is never observed.
- This is a bit hard to argue with since (shades of Berkeley) we don't have much access to a world devoid of consciousness.
- However, there are some serious difficulties:
- The whole proposal requires putting people at the center of the existence of the universe. How does that square with everything else we know, e.g. evolution? The world we see shows overwhelming evidence of having once been free of consciousness. Were the laws of physics entirely different then? Who (bacterium, amoeba, monkey, Wigner,…) was finally conscious enough to collapse the wave function and make positions, etc of particles exist? Just how did Wigner get there before anything had positions?
- There is NO evidence that consciousness plays some role distinct from any other phenomena involving macroscopic masses and times.

Mentalism (cont.)

- Mermin's form (not exactly collapse):
  - "The problem of consciousness is an even harder problem than the problem of interpreting quantum mechanics… consciousness is beyond the scope of physical science, at least as we understand it today… Physical reality is narrower than what is real to the conscious mind. Quantum mechanics offers an insufficient basis for a theory of everything if everything is to include consciousness… The notion of *now*- the present moment- is immediately evident for consciousness… Physics has nothing to do with such notions. … This *particularity* of consciousness- its ability to go beyond time differences….has a similar flavor to its ability to go beyond its own correlations with a subsystem, … to an awareness of a particular subsystem property."
- The question is not whether we understand consciousness but rather whether consciousness violates general physical laws
- Is being aware exclusively of one part of the whole state going "beyond" physical reality? Or is it consciousness that is "narrower" than reality?
- I won't follow up mentalism further, because I can't pretend to take it seriously. However, that does NOT mean that we can't later seriously consider how, if the wave function represents many qualitatively distinct outcomes, the nature of the outcome we see is determined by the pre-selection for its consistency with consciousness.

Explicit Collapse non-linear theories

- The logic: All large-scale observations give only one result. The linear wave equation, which works beautifully on a small scale, generally gives multiple distinct results on a large scale. The obvious way to fix things is to find non-linear terms in the true wave equation, which induce the wave to collapse according to the probability rules, given enough mass/time/particles involved in the process.
- *This approach is not a mere reinterpretation of QM*. It's a proposal to change it, so that both the large scale and small-scale events are described by a unified mathematical form.
- Main attempts:
  - Ghirardi, Rimini, and Weber (GRW): Some sort of random "hits" collapse ψ, forcing it to be nearly localized in space. There's a constant rain of these "hits", but it's so light that a hit is very unlikely unless many particles are involved. Nevertheless, there's a significant range between the largest scale on which interference is found and the smallest (the size of our brains) on which a single collapsed world is allegedly known to be found, so there's enough room to adjust the GRW hit rate parameter.
  - P. Pearle: There's a *continuous* random term needed in the wave equation to make ψ grow or shrink exponentially in different places. In effect, this term is non-linear because its probability density depends on the prior value of ψ.

Problems with the non-linear collapse suggestions

- The narrowing of the wave-packet violates energy conservation. Of course, we don't know that C.O.E. is exactly right, so this problem merely constrains the collapse process to be slow enough (and spread-out enough) to not violate C.O.E. too much.
- The particular fields, etc., employed seem to come from nowhere. To some extent, the theories are just invoking a random-looking hidden variable. These random variables look like <u>classical</u>, not quantum, fields, so the theory is dualistic.
- There is no prior theory to explain why ψ is forced to collapse into nearly *localized* states, as opposed to any other sort of state (e.g. dead cat +live cat). Some connection with the unfinished business of quantum gravity?
- A state which is localized in one reference frame is not localized in others. Making Lorentz-invariant collapse processes gives infinite energy production unless special ad-hoc constraints are added
- The "hits" or random field which cause the collapse must have some built-in non-locality, to avoid having correlated pairs collapse to inconsistent packets.

In favor of non-linear collapse

- At least there are some predictions. Specifically, there must be a wave-function collapse even when the linear wave equation predicts no loss of coherence. This effect is in principle measurable.
- There are many constraints on the parameters, which must be consistent with macroscopic observation, observed energy conservation, particle decay rate., …As a result, some forms of the theories are already eliminated. (E.g. ones in which the collapse rate depends linearly on the number of particles involved, regardless of their masses.)
- There is at least a hope that some parameters describing the scale of the collapse could tie-in with something from the (as yet unknown) quantum theory of gravity.
- If the theory is fully developed, (big if) it would remove the whole fuzz about "interpretation" of QM, although it would not make the QM picture of the world seem similar to experience at our scale.