More on Quantum Measurement

<u>Next time</u>:

Concluding remarks on QM

And perhaps, start on irreversibility of time

The preferred-basis problem

- Consider a wave-packet travelling freely in space. It initially has some distribution of momentum and position. The wave equation says that the momentum distribution won't change, but as a result the position distribution will keep growing. A freely moving particle-wave would quickly become tremendously spread out.
- (e.g. for a hydrogen atom initially confined to a region of 10^{-4} cm, the initial momentum spread must be at least 10^{-23} gm-cm/s, so the initial velocity spread is a range of about 10 cm/s. In one second, the atom would be smeared over 10 cm !)
- Letting the atom interact with a large apparatus designed to "measure' its location forces the atom to be somewhere much more specific, if the apparatus itself is to be in one place or another. None of this answers the question of why a collection of atoms would ever decide to be in a state with well-defined position to begin with. What is so special about position?
- Traditional approaches to measurement simply assumed that there are pre-existing localized macroscopic objects, without explaining that in terms of a more fundamental theory. A few (non-linear collapse) theories do have localization arising as a process, but only by putting that result into an unconstrained theory. We'll see that in modern approaches, based on the distinction between an observer and its environment.

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)

Many Worlds

- The MW picture (which includes several variants) starts from the astounding success of the QM linear time-dependence eq (e.g. the prediction that the electron gyro-magnetic ratio is 2.00231931439, in agreement with expt.!)
- The general history of physics, in which constructs such as "field" and "potential" have gone from seeming like short-hand for the behavior of familiar things to seeming like the fundamental ingredients of "things" suggests that the entities best described by accurate equations need to be taken the most seriously. That's ψ, the quantum state.
- What happens if the world is described by *nothing but* ψ, and that ψ obeys exactly the linear equation?
- As we saw before, in a "measurement" situation, the result of the linear equation is the superposition of two (or more) states representing entirely different outcomes, with completely negligible interference effects of these “waves” with each other. Why then do we experience only *one* outcome?
- Look at what those two states represent. One represents, e.g., a dead cat, a you who has seen only a dead cat, other people who have seen only a dead cat, etc. The other also represents a perfectly consistent world in which the cat is alive, you and everybody else saw a live cat, etc.
  - assumption- you are represented fully by quantum variables

Why Collapse?

- What makes you insist on saying that the other possibility disappeared, rather than that you lost contact with it? What *evidence* is there that there was a discontinuous break or other anomaly in the evolution of ψ, when the linear wave equation *already* predicts that each separate macroscopic experience would be internally consistent?
- In other words, the linear wave equation predicts (with some help from decoherence arguments) that:
  - Measurement gives macroscopically definite <u>experiences</u>, such as we have.
  - Each possible outcome does occur, so that in any actual chain of experience, one can only give probabilities for outcomes, not certainties.
  - Thus the MW theorists claim that adding anything to the wave-equation is entirely superfluous, that in itself it predicts the world as we experience it. It also predicts many qualitatively similar parallel worlds, which offends intuition.
- The claim is that it is more in keeping with the spirit of physics to make the equations simple and consistent rather than to restrict the picture of the world to a familiar one. The equations have no collapse, so why insert one?

The standard objection to Many Worlds

- “MW is profligate with worlds.”
- But:"At least the worlds are like the observed one, and come out of a working equation. Other theories are profligate with *collapses*, when no such process has been observed or arisen from a usable equation."

Why Preferred Basis?

- Remember the preferred basis problem: why are some quantum states possible to experience, but others aren't? In the pure linear theory of an *isolated system*, all quantum states (including dead cat superposed with live cat) appear symmetrically. What breaks the symmetry?
- There are explanations of why some states are more equal than others. An underlying theme is that some states are not capable of being experienced by anything like a mind, whose existence presupposes that some smallish numbers of local variables can be singled out and followed in a predictable way. *This idea invokes an "outside" system which interacts with any system under study.* Only certain states of the "inside" (more or less the same states that we experience, in which big things actually are somewhere) produce stable correlations with particular outside states. These "pointer" states are the only ones which we can experience.
- There are big questions about how this helps in describing the universe as a whole. There are recent papers attributing a fundamental decoherence process to cosmological horizons. (remember those from General Relativity?) I.e. every physical process influences regions which can never exert an influence back. Each version of our local process creates a different version of things beyond the horizon, and thus can no longer interfere with other local version. They become separate worlds.

The problem with Many Worlds

Ballentine, in Foundations of Physics,1973

- Let's grant that the MW picture somehow predicts macroscopically "collapsed" experiences. In simple cases the probabilities predicted for the different outcomes are easy to read from the theory (As MW theorists claim) but they are in gross disagreement with data (contrary to the MW claim.)
- Here's the problem: take a particle that could go through either of two slits. If there's a detector behind each slit, those give macroscopically distinct results. Each one represents a "world" with a distinct version of "you" in it. The obvious interpretation would be that since one world observed each outcome, the outcomes are equally likely. Now make one of the slits big, the other little. We know that we are more likely to see the result that the particle went through the big slit. How does that come out of the theory?
- The original MW answer is that, if you do the same experiment an infinite number of times, the total measure of the wave-function in worlds which experience different probabilities from the standard QM results vanishes.
- However:
  - We do real experiments a finite number of times.
  - Nothing in the theory suggests any way that the weaker branch of ψ should be experienced in any way differently that the stronger branch.

Probability problem in Many Worlds

- Therefore it seems that the bare MW theory predicts, for such simple cases, that each discrete outcome have the *same* probability, regardless of the measure (integral of $|\psi|^2$) of the piece of the quantum state that gives that outcome.
- Graham:
  - "It is extremely difficult to see what significance measure can have when its implications are completely contradicted by a simple count of the worlds involved, worlds that Everett's own work assures us must be on the same footing."
  - That measure-independent probability would contradict a huge amount of data.
- Perhaps we should not be surprised that a theory which proposes that all dynamical equations in ψ are purely linear does not easily generate an interpretation in which $|\psi|^2$ plays a key role.
- There are a variety of attempts to fix the probability problem. These include postulating "many minds" which somehow are carried along with the quantum state, more minds with bigger pieces of the state.
- Thus, "fixing" the probability predictions is usually done by verbal tricks, ruining the original appeal of the theory, which was to have the physical meaning flow directly from the dynamical equations. We'll see new attempts to fix the problems.

"Proofs" of Born Probabilities

- There are many "proofs" that the Born probabilities (proportional to measure) are the only possible one.
- All take the form of showing that any other probability expression would be pathological.
  - Probabilities of sequences of events wouldn't factorize.
  - The probability that Schroedinger's cat would survive Tuesday's experiment would go up or down on *Wednesday* depending on what sort of quantum fleas lived on live or dead cats.
- Is the argument that other results would be crazy sufficient to show that the underlying theory implies the observed results?
- Does classical equipartition imply finite blackbody radiation because any other result would be crazy?

Many Worlds and Bare Quantum

The MW idea at least clarifies what the bare linear equations predict- a topic that had been oddly avoided by the CI. The MW approach also clarified certain things that were not originally apparent:

- It might be possible to make a mathematically coherent theory which still
  - predicts probabilistic experience
  - is consistent with the linear part of quantum mechanics
  - at the expense only of the gut feeling that there must not be any aspects of the universe completely inaccessible to one experience
- This was the key lesson from the Many Worlds interpretation: dynamical equations like those of QM can lead to multiple branches, each with consistent correlations among all its own variables but with quite different results than other branches. The theory may say that there's a "you" that sees the live cat and a "you" that sees the dead cat, but it also says that these have no influence on each other, and that weird things like encountering someone who saw the opposite result will not occur.
- <u>The macroscopic definiteness of experience is NOT proof of unique outcomes of quantum processes</u>
  - Unless you make the auxiliary assumption, on the basis of no evidence, that "you" , the experiencer, remain unique.

Many, Many Worlds?

Remember that when philosophers try to fix MW to give the right probabilities, they in effect hypothesize that for each of the many possible outcomes of an experiment, there are many worlds (or minds) which share that outcome. Then by adjusting the numbers of such worlds for the different outcomes, one could obtain the correct probabilities for the different outcomes simply by counting how many outcomes there were of each type.

- The problem is that the standard linear theory predicts *no dependence* of the numbers of any outcomes on how much of the wave occurs, i.e. on the measure of that component, but experience shows that the probabilities *do* depend on the measure of the wave components.
- Let's accept that the linear time-dependence equation works very well at a small scale, but that experience (always inherently at a large scale) is not described by it alone. We then follow the non-linear collapse idea by saying that the obvious solution is to find non-linear corrections to the wave equation which become important at some intermediate scale. A choice still remains since such terms could either:
  - give collapse, following the correct probabilities
  - give an additional decoherence process, to fix the many-worlds probabilities. (i.e. many, many worlds) The stronger branches of ψ would have to show more splitting along some unobserved axis, e.g. involving quantum gravity variables, so that there would be more distinct "worlds" with those results.
- <u>If some evidence is found that interference is lost when the linear equation says it should be retained, then EITHER non-linear collapse OR non-linear MMW might turn out to work, since both predict this effect.</u>

How a non-linear many-worlds theory might work

- Let there be some pointer states, macroscopically consistent, which can develop correlations with some particular states of an outside system
  - associated with quantum gravity?
- So far this is not news. But now let the process by which those correlations develop be non-linear, e.g. it happens only when the measure of the state along some pointer reaches a threshold value. Then the pointer state branches off the original state, becoming correlated with some new outside variable. If that's all there is to it, the state will branch into little pieces, which will not branch any more. So you need for the threshold level to keep shrinking.
- Take an experiment which could have produced two distinct outcomes, A and B, with 2/3 of the measure of the state on outcome A.
- Following the algorithm, we generate large numbers of A and B branches. The ratio of A branches to B branches approaches two- the correct quantum probability!

Which non-linear approach is worse?

- Both approaches (probabilistic collapse or pure decoherence) introduce non-linear effects.
- "Many worlds" remains profligate with worlds.
- But non-linear collapse introduces ingredients that are both random and classical, in order to produce unique outcomes.
- Many-many worlds has another big problem:
  - Why is it now? There are enormously more future you's than now you's!

What Should We Count?

Real MW situations are *not* like the toy model with a batch of discrete worlds emerging. The splitting ("decoherence") is continuous. Simple world counting might give wrong results but *there aren't any simple worlds to count* in real situations.

- What should we count to get probabilities?
- Let's count distinct *thoughts*.
- What's a thought?
- A robust computation of a quantum device (e.g. you.)
- What makes a computation robust?
- The "signal" must exceed the "noise".
- What noise? Let's try to figure out from the observed probabilities.
- Postulate: There's a background of quantum noise, unrelated to the coherent world we're experiencing. In standard representations (e.g. as a function of spatial position) this background looks like rapidly varying complex numbers.
- To make a computation robust the coherent part of ψ averaged over some coordinate region must exceed the noise, just as in ordinary image-processing problems. Random noise averages out, with the average going ->0 as $1/(\text{volume})^{1/2}$.
- Therefore to get a robust measure of ψ one must average over a volume proportional to $1/|\psi|^2$.

Why the right state?

- Therefore the number of distinct robust computations would be proportional to measure, $|\psi|^2$!
- But why would there be the right background noise in the quantum state to give this?

- Remember the arguments that any probability other than measure gives weird, unstable results? Could any sort of rational mind function in such a universe?
- If Many Worlds is correct, all sorts of universes with all sorts of combinations of states would exist.
- Only universes with the right sorts of states would be observable from within.
- And none are observable from without!
- So the states with the right noise to give the correct probabilities would be *post-selected* from all the possible states by the requirement that rational beings be arguing about them.
- Our first glimpse of “anthropic” explanations.