The measurement paradox

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

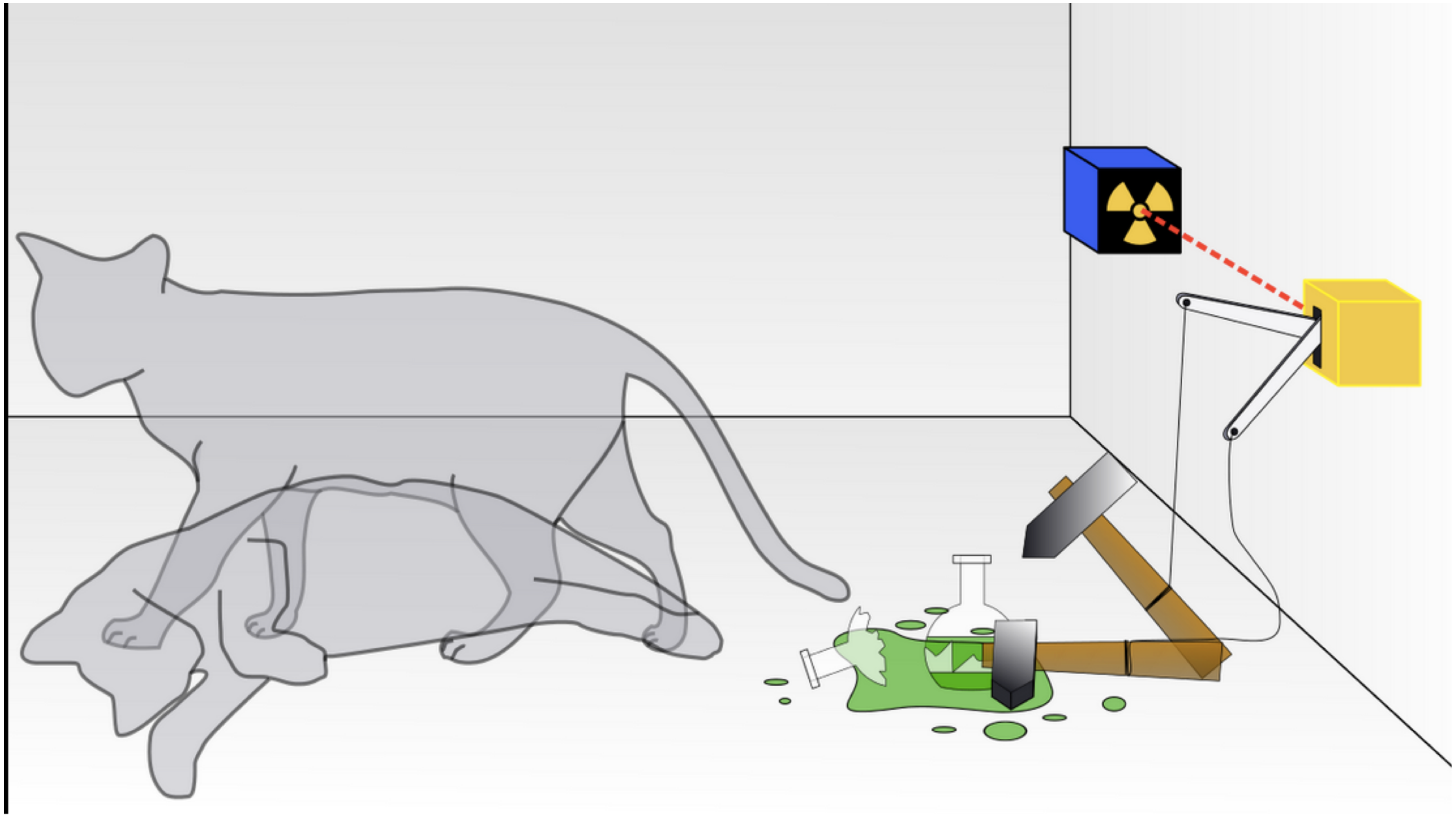
There are a variety of ideas about how to deal with it- none really satisfactory.

419: Outline with topic paragraphs due today on COMPASS

"Collapse of the wavefunction"

- What happens in a measurement?
- During a measurement they electrons acquire positions and momentum. Their wavefunction changes.
- It is not the disturbance which causes the collapse, but the transfer of information to the outside world.
- According to the Copenhagen interpretation there are 2 steps
  - An unmeasured wavefunction advances deterministically.
  - A measurement forces nature to choose between classical possibilities. It does so randomly. Afterwards there is a new wavefunction.
- The collapse happens faster than the speed of light, even backwards in time. How can that be?
- Observations are consistent with relativity but "reality" is not.

Schrödinger's Cat parable (1935)



A quantum description of measurement

- The macroscopic set-up creates a situation describable by Ψ (the quantum system) and ϕ (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.“

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

- 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 $\left(\varphi_1^{final}\ and\ \ \varphi_2^{final}\right)$
 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>.
- The "projection postulate" turns out to follow naturally: obeying the wave eq, represents a situation in which, if the apparatus measures ψ= $\frac{\psi_1^{final}\varphi_1^{final}}{\sqrt{2}}$ 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?</u>

The Output State

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

  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?

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, …)
- 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)

Non-local hidden variables?

- Is there any NON-LOCAL HV theory that reproduces the results of QM?
- The answer is apparently yes, (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.
- 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.

- 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?

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

- The narrowing of the wave-packet violates energy conservation (COE). 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 classical, 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).
- 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.

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.

Why Preferred Basis?

- 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 is a fundamental decoherence process to cosmological horizons: 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.

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.”
- "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.”
- But what triggers a branching? That is not in the theory.
- How can an event here, trigger a branching of the Universe?
- For physics to be the same forward and backward in time evolution, worlds must coalesce.

The problem with Many Worlds

Ballentine, *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 many times, the total measure of the wave-function in worlds which experience different probabilities from the standard QM results vanishes.
- However, 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."
- 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.

Many Worlds and Bare Quantum

The MW idea at least clarifies what the bare linear equations predict.

- 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.