The Philosophy of Physics
Lecture Nine

Alternative Interpretations of Quantum Mechanics

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Alternative Interpretations of Quantum Mechanics

The Copenhagen Interpretation

- If a particle has a determinate position, then it lacks a determinate momentum

  (There are other examples of complementary properties, but this is the classic)

- It is impossible to predict with certainty what momentum the particle would have if you were to measure it

- All we can predict is the *probability* of it having various different momenta; these probabilities are recorded in a **wavefunction**

- If we do measure the particle's momentum, the wavefunction *collapses*, and the particle comes to have a determinate momentum (but not a determiante position)

The Measurement Problem

- According to Copenhagen, measurements are a very special kind of interaction
  - The wavefunction of an unmeasured system evolves in accordance with the deterministic Schrödinger Equation
  - The wavefunction of a measured system collapses in accordance with the stochastic Born Postulate

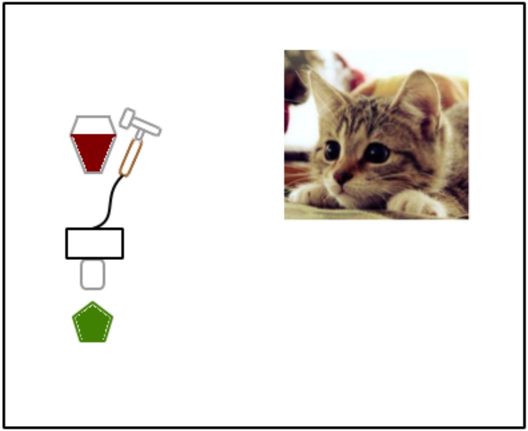
- But what makes an interaction a "measurement", rather than just another physical interaction?

- And why would a "measurement" have such radical effects?
  - Measuring devices are just ordinary things, ultimately made up of particles that are governed by the Schrödinger Equation
  - Why should an interaction with such a device then over-rule that equation?

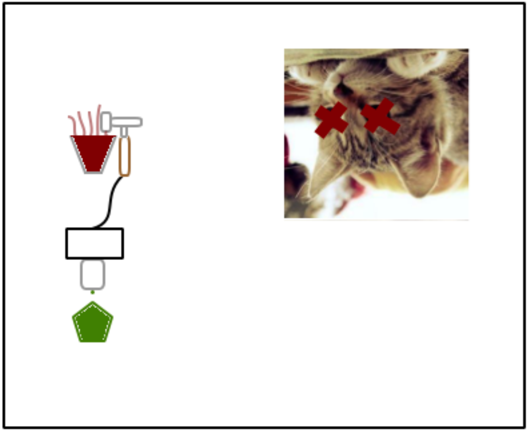
Schrödinger's Cat

One can even set up quite ridiculous cases. A cat is penned up in a steel chamber along with the following diabolic device (which must be secured against direct interference by the cat); in a Geiger counter there is a tiny bit of radioactive substance, so small, that perhaps in the course of one hour one of the atoms decays, but also, with equal probability, perhaps none; if it happens, the counter tube discharges and through a relay releases a hammer which shatters a small flask of hydrocyanic acid. If one has left this entire system to itself for one hour, one would say that the cat still lives if meanwhile no atom has decayed. The first atomic decay would have poisoned it.

Schrödinger's Cat



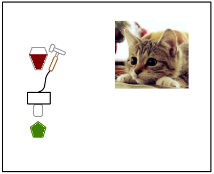
Schrödinger's Cat

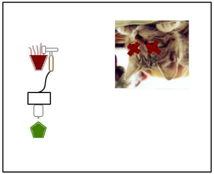


Schrödinger's Cat

> *The [wavefunction] of the entire system would express this by having in it the living and the dead cat (pardon the expression) mixed or smeared out in equal parts.*
>
> *(Schrödinger 1935 pp. 156–7)*

Schrödinger's Cat





- Until we measure the whole system of the box, it is in a superposition of two states:
  - No atom decayed, and the cat is alive
  - An atom decayed, and the cat is dead
- On the Copenhagen interpretation, that means that until we open the box and see, there is no fact of the matter as to whether the cat is alive or dead!

Avoiding the Measurement Problem

- In this lecture, we will look at two attempts to avoid the Measurement Problem

(1) The GRW Theory, which dissociates wavefunction collapse from measurement

(2) The Many Worlds Theory, which denies that wavefunctions ever collapse

Alternative Interpretations of Quantum Mechanics

The GRW Theory

- In 1986, Ghirardi, Rimini and Weber proposed a new version of quantum mechanics, now called the **GRW Theory**
- The GRW Theory is a lot like standard QM
  - GRW accepts **objective wavefunction collapse**
  - GRW accepts that unless there is a collapse, wavefunctions evolve in accordance with the deterministic **Schrödinger Equation**
  - GRW accepts that when there is a collapse, wavefunctions evolve in accordance with the stochastic **Born Rule**
- The big difference between GRW and standard QM is about what makes wavefunctions collapse

Spontaneous Collapse

- According to standard QM, **measurements** make wavefunctions collapse
- According to GRW, wavefunctions collapse **spontaneously**
- Every particle has a set probability of collapsing in a given period of time
- An individual electron has a 1 in 10^{15} chance of collapsing in a second; so on average, individual electrons collapse after 10^{8} years

What Happens after a Collapse?

- In standard QM, when we measure property X of a particle, the particle's wavefunction collapses, and it comes to be in an eigenstate of X (if it wasn't already in one)

  (This is actually a bit mysterious. How does the particle know that we were measuring property X?)

- GRW detaches collapse from measurement, and so can't tell the same story about what happens after a collapse

- Instead, in GRW, collapses (or *hits*) only ever make a wavefunction contract around a given point
  - Roughly, as a wavefunction evolves in accordance with the Schrödinger Equation, quantum particles become "smeared out" across space
  - When a wavefunction collapses, particles become localized in a small region

What Happens after a Collapse?

- Before the collapse, the electron's wavefunction is spread out in space

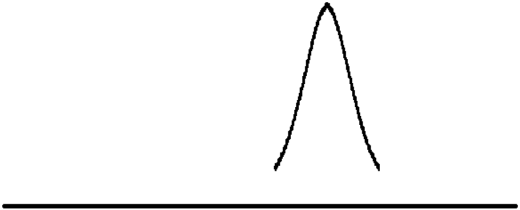
What Happens after a Collapse?

- After the collapse, the electron's wavefunction contracts around a given point

What Happens after a Collapse?

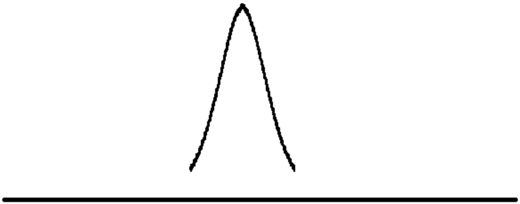
- It is impossible to predict with certainty which point the wavefunction will contract around

What Happens after a Collapse?



- It is impossible to predict with certainty which point the wavefunction will contract around

What Happens after a Collapse?



- But the probability of it contracting around a given point is proportional to the square of the amplitude of the pre-collapse wave at that point (à la the Born Rule)

Two Related Questions

(1) If wavefunctions collapse so rarely, what substantial difference can collapses make to the evolution of the universe?

(2) If wavefunction collapse has nothing to do with measurement, then why don't we ever observe electrons smeared out?

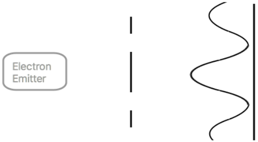
Entanglement to the Rescue!

- A macro object is made of *lots* of quantum particles, and it is overwhelmingly likely that some of those particles will spontaneously collapse in a given second
  - A human body contains approximately 10^{28} electrons, and on average 10^{13} of those electrons will spontaneously collapse every second
- Moreover, the particles which make up an individual macro object will be **entangled** with many of the other particles making up that macro object
- When a particle spontaneously collapses, it makes all the particles it is entangled with collapse too
- So on average, the vast majority of the particles which make up a macro object will collapse every second

Measurement and Collapse

- Measuring devices are macro objects
- When we measure the location of a particle, we entangle the particle with the particles that make up the measuring device
- It is overwhelmingly likely that one of the particles in the measuring device will collapse at any given moment, which will make the particle we are measuring collapse
- That is why we don't observe "smeared out" particles!

Measurement and Collapse



- As the electron goes from the emitter to the slits, it becomes "smeared out"
- It then passes through those slits as a wave
- When it comes into contact with the screen, it becomes entangled with the particles in the screen
- One of the particles in this screen will collapse very shortly after this entanglement
- At this point, the electron will collapse, and its position will be recorded as a localized dot on the screen

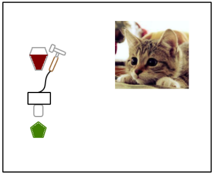
Measurement and Collapse

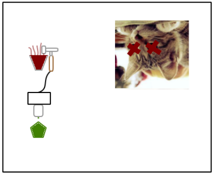
- **QUESTION:** What if we are measuring a property *other* than position? Why don't we ever measure a superposition of momenta?

- **CONJECTURE:** All measuring devices record properties in position
  - For example, in the position of a needle, or in different points in a screen lighting up
  - This seems plausible: physics is ultimately the science of motion

- **ANSWER:** We don't measure superpositions of momenta because the components of the measuring device collapse into determinate positions

Schrödinger's Cat





- The cat is not determinately alive or dead until a collapse happens
- But there are so many entangled particles in a cat that it is overwhelmingly likely that the cat will quickly collapse into a living or dead state
- This will happen whether we observe the cat or not!

Alternative Interpretations of Quantum Mechanics

The Problem of Local Beables

- The GRW Theory is a theory about the wavefunction of a system, which does not exist in physical space
- So how does GRW relate to things which **do** exist in space?
- John Stewart Bell called this the **Problem of Local Beables**
  - A *beable* of a theory is just something in the ontology of that theory
  - A *local* beable is something in the ontology which is localized in space
  - The *problem* of local beables is the problem of positing plausible local beables for a given quantum theory
- **WARNING: not everyone thinks we need to posit local beables**

The Flash Ontology

- Every collapse is centred on a spatial point, and are in that sense localized to that point
- Bell's proposal was to posit collapse events as the local beables of GRW
- According to this **flash ontology**, all that exists are momentary collapse events, or *flashes*

The Flash Ontology

The GRW jumps (which are part of the wavefunction, not something else) are well localized in ordinary space. Indeed, each is centred on a particular space-time point ($\mathbf{x}$,t). So we can propose these events as the basis of the 'local beables' of the theory. These are the mathematical counterparts in the theory to real events at definite places and times in the real world [...] A piece of matter then is a galaxy of such events.

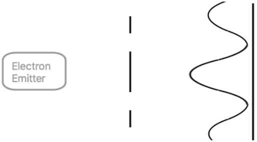
(Bell, 2004, 'Are there quantum jumps?', pp. 204–5)

A Sparse Ontology

- Recall that collapses happen rarely, so there are very few physical flashes
- Most of the Universe is empty space, including areas which supposedly contain matter
  - We ordinarily think of your body as containing 10^{28} electrons, but really it is a fireworks display of 10^{13} electron flashes per second
- **QUESTION:** Why haven't we ever noticed that the Universe is so empty?
- **ANSWER:** When we look at a macro object, we become entangled with that macro object; flashes in the macro object collapse our wavefunction, and so make the object seem solid

The Double Slit Experiment

- Earlier I said that the electron becomes "smeared out", passes through the double slits as a wave, then becomes entangled with particles in the screen, and collapses



- **But really, there is no electron!**
- The wavefunction evolves from a state we call 'electron emitted' to 'electron in superposition of locations' to 'electron detected', but these are just our labels for stages in an abstract evolution
- In the real world there are just flashes, and in all likelihood, there will be no 'electron flash' during the 'journey of the electron'

Alternative Interpretations of Quantum Mechanics

Many Worlds

- In 1957, Everett proposed a new version of QM, now known as the **many worlds** theory
  - Many Worlds rejects the whole idea of wavefunction collapse
  - Wavefunctions *always* evolve in accordance with the deterministic **Schrödinger Equation**

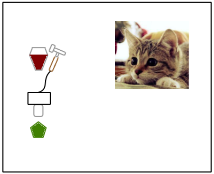
- According to Many Worlds, when a wavefunction is a susperposition of two states, **then both of those states exist!**

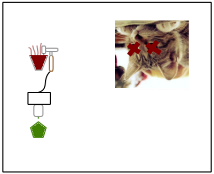
- When an electron is in a superposition of passing through two different slits, there are really **two** electrons in **two** different worlds: in one the electron passes through one slit, in the other it passes through the other

Decoherence

- According to Everett's original version of Many Worlds, the world "branches" whenever the wavefunction enters a superposition of multiple states
- It turns out that that leads to *lots* of branches!
- In modern versions, the world branches only when the wavefunction enters a superposition of multiple *decoherent* states
  - Two states *decohere* when they will no longer interfere with each other ever again
- For ease, we will set this complication to one side — superpositions of macro systems very quickly decohere

Schrödinger's Cat





- The wavefunction always stays in a superposition of *Alive cat* and *Dead cat*
- So there are two worlds, with two cats: one survives, the other dies

Schrödinger's Cat

- If you look in the box, then the wavefunction enters into a superposition of *Alive cat, Happy you* and *Dead Cat, Sad you*
- So there are two yous: one happy, the other sad!
- That is why we don't observe superpositions: we end up in a superposition of observations!

Many Worlds versus Possible Worlds

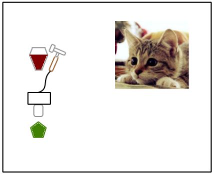
- David Lewis argued for a plurality of possible worlds, all as real as our own, but it is important not to confuse Lewis' theory with Many Worlds
- Lewis' worlds could be governed by *any physical laws*, whereas the Many Worlds are all governed by Schrödinger's Equation
- Lewis' worlds are all completely separate, but the Many Worlds are connected
  - If there is only one world with an electron passing through the top slit in the double slit experiment, then we will not get a wave interference pattern on the screen
  - But if there are two worlds, one with an electron passing through the top slit and the other with the electron passing through the bottom, then we get a wave interference pattern

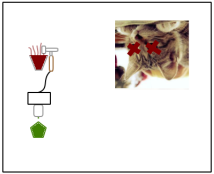
Alternative Interpretations of Quantum Mechanics

The Born Rule

- Some of the most important objections to Many Worlds have to do with **probabilities**
- Although Many Worlds rejects wavefunction collapse, it still accepts that the Born Rule tells you how *probable* the possible outcomes of a given measurement are
- But it is difficult to explain what this talk of “probability” could possibly mean

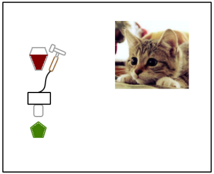
Schrödinger's Cat

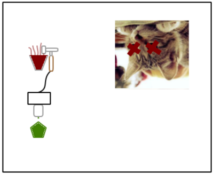




- Born's Rule tells us that if we look at the cat, there is a 0.5 chance it will be dead, and a 0.5 chance it will be alive
- But on Many Worlds, there does not seem to be any chance involved in what will happen
- The world will (with certainty) split into two, with one alive cat and one dead cat

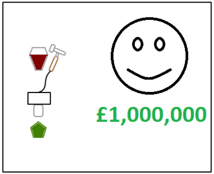
Schrödinger's Cat

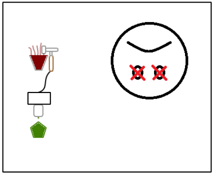




- **SUGGESTION:** There are two worlds, one with an alive cat and one with a dead cat. So there is a 0.5 chance you will end up in a world with an alive cat, and a 0.5 chance you will end up in a world with a dead cat
- **PROBLEM:** You will also split: there will certainly be a you in the world with an alive cat, and a you in the world with a dead cat

Quantum Suicide





- **OFFER:** Enter Schrödinger's Box; if you survive I'll give you £1,000,000
- If Many Worlds is false, you should think carefully about the bet: a 0.5 chance of being rich, but a 0.5 chance of dying
- If Many Worlds is true, you should take the deal: the world will split, one version of you will die, but another version of you will be rich

Many Worlds and Decision Theory

- Probability plays a massive role in **decision theory**, which tells you how to make rational decisions
  - Should I do X or Y?
  - Consider how good or bad each possible outcome of X is, and weight it by its probability, then add those results up. That is the **expected utility** of X
  - Now calculate the expected utility of Y, and do whichever has the greatest expected utility
- Some Many Worlders try to defend their theory by proving that (given plausible assumptions), you ought to follow standard decision theory even if their theory is true
  - See David Wallace's *The Emergent Universe*, 2012 OUP
- **QUESTION:** Is this the right approach?

With Thanks to Mary Leng

I would like to thank Mary Leng, who let me borrow extensively from her slides in preparation for these lectures