432018 PHILOSOPHY OF PHYSICS (Spring 2002)

Lecture 5: The 'measurement problem' and 'collapse theories' of QM

Preliminary reading: Sklar, pp. 179-91.

1 Introducing the measurement problem — Schrödinger's cat

We introduce the measurement problem by considering 'Schrödinger's cat'. In this thought experiment, a live cat is put in a box with a radioactive source that has a 50-50 chance of emitting a radioactive particle. If it does emit such a particle, then a phial of poison is broken and the cat perishes. If it doesn't, the cat lives. The situation is set up so that we cannot observe the state of the cat — i.e. whether it is alive or dead — unless we open the box. Thus, we don't *know* whether the cat is alive or dead until the box is opened.

If this situation is thought of in a classical manner, we want to say that, at all times, the cat is either dead or alive depending on whether the radioactive source emitted a particle or not. In this case, we open the box merely so that we can come to know what has passed since the box was closed — i.e. the probabilities are *epistemic*. Further, if we observe that the cat is dead, it has been dead since the time when the poison was released.

However, Schrödinger was concerned with what would happen if we treated this situation in a quantum manner. Prior to the opening of the box, the cat is supposedly in a *superposition* of states. One state corresponds to the cat being alive and the other to the cat being dead. Since the probability of the radioactive source emitting a particle is 50-50, the probability of finding the cat alive or dead on opening the box is 50-50.[1] Now, prior to opening the box and hence making the observation, since the cat is in a superposition of the alive or dead states, we can't really say what the state of the cat *is*. That is, since it is in a superposition of the alive and dead states, it is neither alive nor dead and it can't be both alive and dead (since that would be contradictory). Also, it is certainly not 'half dead' nor 'half alive' — whatever we are to take these terms to mean. However, on opening the box — i.e. on making an observation — the superposition supposedly *collapses* onto one of the two states it contains. That is, it collapses into the alive state and we find a cat that is alive or it collapses into the dead state and we find a cat which is dead. Indeed, by a similar argument, we can't say that the radioactive source emitted a particle, or that it didn't, until we open the box. That is, prior to the box being opened, the source is also in a superposition of states, namely the states where it has and hasn't emitted a particle.

Now, the measurement problem runs as follows: Nothing appears to happen until we open the box. That is, prior to opening the box, the source has neither emitted a particle nor has it not emitted a particle, and consequently, the cat is neither dead nor alive. But, on opening the box, the superposition of these states collapses and either the source has not emitted a particle and the cat is alive or the source has emitted a particle and the cat is dead. Thus, according to this everything must happen instantaneously at the moment of observation even though the source had a 50-50 chance of emitting a particle and killing the cat at any time during the cat's captivity in the box. Isn't this absurd?

2 Formalising the measurement problem

More formally, the measurement problem arises from an apparent inconsistency in the postulates which form the basis of the quantum mechanical formalism. Consider the following argument:

A. The state of a system *always* evolves in accordance with the Schrödinger equation and, in particular, this evolution is continuous. [Postulate 3, i.e. the cat should stay in a superposition.]

[1] And, as such, the probabilities here don't appear to be epistemic since they determine the probability of a certain outcome as opposed to, say, how our knowledge changes.

B. On measurement, systems with states given by a superposition of the appropriate eigenstates, can give different outcomes depending on which of these eigenstates the system 'collapses' (i.e. changes discontinuously) into. (Note that, using Postulate 4, the different outcomes occur with probabilities that can be calculated using Born's rule.) [Postulate 5, i.e. when we open the box we find that the cat is alive or dead.]

But, if the state of the system *always* evolves according to the Schrödinger equation — i.e. continuously and deterministically — how can it discontinuously and probabilistically collapse into an eigenstate on measurement? Especially since, in QM, measurement seems to be a form of interaction[2] and, as such, measurements should be accounted for by Postulate 3.

Further reading: Responses to the measurement problem can be found in:

- A. Fine, *Measurement and Quantum Silence* in S. French and H. Kamminga (eds.), *Correspondence, Invariance and Heuristics* (Kluwer, 1993), pp. 279-94.
- A. Fine, *Insolubility of the Quantum Measurement Problem* in Physical Review D, **2** (1970), pp. 2783-7.
- H. Brown, *The insolubility Proof of the Quantum Measurement Problem* in Foundations of Physics, **16** (1986), pp. 857-70.

3 Solutions to the measurement problem — a taxonomy

The formalism of QM, despite the threat of inconsistency alluded to above, does seem to be adequate. After all, the formalism allows us to make good predictions about the outcomes of many different experiments. As such, the formalism is taken to be, by and large, correct. Indeed, as we shall now see, the problems only really manifest themselves when we try to *interpret* the formalism. And further, your 'choice' of interpretation tends to rely on what you think the measurement problem tells us about the quantum world.

Basically, the 'solutions' to the measurement problem fall into two groups, namely:

- **Collapse theories**: These are theories that accept the collapse postulate and then try to explain what is so special about measurement, i.e. why it is not governed by the Schrödinger equation. (For example: von Neumann and Wigner, the Copenhagen interpretation, GRW.)
- **No-collapse theories**: These are theories that deny the collapse postulate and then try to provide an alternative way of connecting QM with experience. But, these alternatives force us to re-evaluate other claims that we may make about measurement and, in particular, two popular options have been:
  - **The way of illusion**: These deny that we experience determinate outcomes, i.e. the superpositions don't *really* collapse, and as such there must be some explanation as to why it *appears* that they do. (For example: the bare theory, many worlds, many minds.)
  - **The way of incompleteness**: These deny that the states we use to represent quantum systems are *complete* descriptions of the system, and as such, there must be 'something else' that we have failed to take into account. (For example: Bohm, the modal interpretation.)

In the next few lectures, we shall examine the plausibility of each of these alternatives by looking at some of the interpretations they have given rise to.

4 Collapse Theories

We start with collapse theories since they are closest to our current understanding of the formalism. In particular, we look at von Neumann's reasons for thinking that collapse is necessary; Wigner's attempt at a deeper explanation of why collapse occurs and how collapse figures in Bohr's Copenhagen interpretation.

[2] After all, it seems to affect the state of the system!

4.1 Von Neumann and Wigner

When we considered the formalism of QM, we adopted von Neumann's version of the theory and this was based on his view of what was happening. We shall start with this and then turn to Wigner's attempt to flesh out von Neumann's idea.

Von Neumann

Von Neumann suggested that we should just 'bite the bullet' and accept that the dynamics given by the Schrödinger equation is wrong about what happens during a measurement, even though it is right about everything else. Consequently, we have two types of dynamical evolution in QM as given in Postulates 3 and 5, i.e.

I. When *no measurement* is being made, the states of all physical systems evolve in accordance with Schrödinger's equation, i.e. their evolution is continuous and causal.

II. When *there is a measurement*, the states of the measured systems evolve in accordance with the collapse postulate, not in accordance with Schrödinger's equation, i.e. the evolution is discontinuous and non-causal.

But, there is a **problem**:

- What is a *measurement*? If we can't answer this question, we can't make the distinction between (I) and (II) given above since what determines whether one or the other applies is whether or not a measurement is being carried out!

In particular, the word 'measurement' doesn't have any precise meaning in ordinary language and von Neumann didn't make any attempt to specify a meaning for it either.

Wigner's suggestion

Wigner tried to flesh out von Neumann's idea by suggesting that there were two fundamentally different types of physical system:

i. *Purely physical* systems — i.e. systems which do not contain observers — that always evolve in accordance with the Schrödinger equation. (At least, as long as they remain isolated from observers.)

ii. *Conscious* systems — i.e. systems which *do* contain observers — that evolve in accordance with the collapse postulate.

To *motivate* his suggestion, consider what happens when we have a type (ii) system, i.e. when we have a system which contains an observer:

- Suppose that the system in question is an electron, e, and we have some apparatus, a, for measuring its spin in the x-direction. We shall label the corresponding spin-up and spin-down states of the electron by $|\uparrow_x\rangle_e$ and $|\downarrow_x\rangle_e$, and the corresponding final states of the apparatus as $|\uparrow_x\rangle_a$ and $|\downarrow_x\rangle_a$ depending on whether the result it gives is 'the electron is spin-up in the x-direction' or 'the electron is spin-down in the x-direction' respectively.

- If we can discover that *after* the interaction between the electron (i.e. the physical system) and the measuring apparatus, the apparatus was in a state $|\uparrow_x\rangle_a$, then it would be known that the final state of the electron is $|\uparrow_x\rangle_e$.

- But, how do we discover that the apparatus is in the state $|\uparrow\rangle_a$? By using another apparatus to measure the state of the first apparatus. That is, we use another apparatus, a', to measure the state of the first apparatus.[3]

[3]That is, if we can discover that *after* the interaction between the first and second apparatus, the second apparatus was in the state $|\uparrow_x\rangle_{a'}$, then it would be known that the final state of the first apparatus is $|\uparrow_x\rangle_a$, and indeed, that the final state of the electron is $|\uparrow_x\rangle_e$. This second apparatus is sometimes called 'Wigner's friend', and the apparent need for it (and other such apparatus) is sometimes referred to as 'The paradox of Wigner's friend'.

- But, this leads to an infinite regress since then we need to know the state of the *second* apparatus which, in turn, requires a *third* apparatus etc.

So, simply put, Wigner's point is that: If we are ever to know the outcome of a measurement, then this regress has to stop somewhere. That is,

- A measurement must be a finite operation, completed by an *act* of observation. (For example: seeing a flash.)
- The process leading to the result of the measurement can't involve a type (i) system since it has to be completed by an act which is discontinuous and non-causal. That is, observation must be an act that involves a type (ii) system.

This may prompt us to ask two questions: *How* and *why* does this act occur? To which, Wigner gives two answers:

- The act occurs as a result of the collapse of the superposition. Why? Because:

  > Immediately *after* the measurement of the electron's x-component of spin, the observation gives the result 'spin-up in the x-direction', the state of the apparatus is $|\uparrow_x\rangle_a$ and the state of the system is $|\uparrow_x\rangle_e$. Such determinate outcomes can occur *via* the collapse postulate, i.e. the superposition state (predicted by the Schrödinger equation) is 'projected' into the eigenstate corresponding to the result obtained in the measurement. (That is, due to the measurement, the type (I) dynamics ceases to apply and the type (II) dynamics takes over. Note that, after the measurement, the type (I) dynamics takes over again.)

- The act of observation occurs due to the *mind* of the conscious observer. Why? Because:

  > Given that QM applies to all purely physical systems (whether macro or micro — see later), the collapse cannot occur due to an interaction with a purely physical system.[4] Thus, the collapse must occur *via* an interaction with a non-physical system, i.e. the *mind* of a conscious observer.

But, there are **problems**:

- This assumes that *mind-body dualism* is true and this is a very problematic philosophical position.[5]
- This is pretty much the position we wanted to avoid when we used Schrödinger's cat to motivate the measurement problem.

Further Reading: J. Brown, *Von Neumann and the Anti-Realist* in Erkenntnis, **23** (1985), pp. 149-59.

4.2 Bohr's Copenhagen interpretation

We have already met Bohr's Copenhagen interpretation and in this section, we see how Bohr attempted to solve the measurement problem.

Bohr starts by introducing a distinction between two sorts of physical system:

I. *Macroscopic* systems. These systems evolve in accordance with the collapse postulate.

II. *Purely microscopic* systems, i.e. systems which don't contain macroscopic subsystems. These systems always evolve in accordance with the Schrödinger equation (as long as they remain isolated from macroscopic systems).

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[4]Indeed, if this was not the case, we would have to be able to account for the special nature of measurement (since collapse *only* occurs in measurement). In particular, if purely physical systems were involved, we couldn't explain why collapse *only* occurs during measurement (since purely physical systems are everywhere).

[5]In particular, dualists usually claim that the mind has no spatial location. So, how can something with no spatial location *interact* with a physical system? And, *where* does the collapse occur? *In* the mind?

The basic idea is the following: *macroscopic* objects have to be described in *classical* terms, and we can only determine the properties of *microscopic* objects in virtue of their relationship to a macroscopic object. Consequently, Bohr claims that *collapse* occurs when microscopic objects are 'observed' using a macroscopic object.

But, there are **problems**:

- As we have seen, Bohr's Copenhagen interpretation and the 'philosophy' that underlies it is complex and usually unclear.
- More importantly though, there is nothing in the formalism of QM that justifies the macro-micro distinction.

Further reading: C. Hooker, *The Nature of Quantum Mechanical Reality* in R. G. Colodny (ed.), *Paradigms and Paradoxes* (University of Pittsburg Press, 1972).

4.3 The GRW theory (for interest only)

There is also a collapse theory, proposed by Ghirardi, Rimini and Weber (GRW), which doesn't evoke mental efficacy or vague distinctions. In this theory, collapse occurs *via* a new kind of physical interaction. In particular, if we have a system that is in a state which is given by a superposition of the eigenstates of some operator, this interaction will cause the state of the system to collapse, in a discontinuous and probabilistic manner, into one of these eigenstates. Indeed, the probability (per unit time) of any given system undergoing collapse *via* this interaction is proportional to the number of particles in the system, and so a macroscopic (i.e. 'large') system is unlikely to be found in a superposition whereas a microscopic (i.e. 'small') system is.[6]

To see how this works in the case of the experiment considered above, we recall that the electron is to have its x-component of spin measured, and so prior to the measurement the electron (i.e. 'e') is in a superposition of the eigenstates $|\uparrow_x\rangle_e$ and $|\downarrow_x\rangle_e$, i.e.

$$\frac{1}{\sqrt{2}}\Big[|\uparrow_x\rangle_e + |\downarrow_x\rangle_e\Big].$$

Also, the apparatus (i.e. 'a') that we are using to measure the electron's x-component of spin has final states given by $|\uparrow_x\rangle_a$ and $|\downarrow_x\rangle_a$. So, prior to the outcome of the measurement, the combined 'electron plus apparatus' system is in the superposition

$$\frac{1}{\sqrt{2}}\Big[|\uparrow_x\rangle_a|\uparrow_x\rangle_e + |\downarrow_x\rangle_a|\downarrow_x\rangle_e\Big].$$

But, the apparatus contains a large number of particles, many of which are in the pointer (say) that indicates the outcome of the measurement. As such, the GRW interaction will quickly cause this superposition to collapse[7] so that the apparatus is in one of its two possible final states. That is, the superposition above will collapse into either the $|\uparrow_x\rangle_a|\uparrow_x\rangle_e$ state or the $|\downarrow_x\rangle_a|\downarrow_x\rangle_e$ state giving us the desired determinate outcome.

There are, of course, **problems** with this theory. But, since we have only sketched the ideas involved we can't really address them here. Anyone who is interested in finding out more about the GRW theory and the problems associated with it can take a look at the reading given below.

Further reading: Accounts of the GRW theory can be found in:

- G. C. Ghirardi, A. Rimini and T. Weber, *Unified dynamics for microscopic and macroscopic systems* in Physical Review D, **34** (1986), p. 470-9.

[6]Although this seems to be utilising Bohr's vague macro-micro distinction, this is not actually the case. All the GRW theory maintains is that the *probability* of a system undergoing collapse in a given period of time, i.e. of being affected by such an interaction, is proportional to the number of particles it contains. That is, here, talk of macro and micro is just to give us a feel for the kind of systems that could persist in a superposition for an extended period of time.

[7]That is, there is a high probability (per unit time) that the apparatus will find itself in a determinate final state due to the interaction.

- D. Z. Albert, *Quantum Mechanics and Experience* (Harvard University Press, 1994), pp. 92-111.
- J. S. Bell, *Are there quantum jumps?* in J. S. Bell, *Speakable and unspeakable in quantum mechanics* (CUP, 1993), Ch. 22 (pp. 201-12).

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