IPP-QM-4: The measurement problem

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MT25

The course

1. Basic quantum formalism
2. Density operators and entanglement
3. Decoherence
4. The measurement problem
5. Dynamical collapse theories
6. Bohmian mechanics
7. Everettian structure
8. Everettian probability
9. EPR and Bell's theorem
10. The Bell-CHSH inequalities and possible responses
11. Contextuality
12. The PBR theorem
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14. QBism
15. Pragmatism and relational quantum mechanics
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Quantum ‘interpretation’

The measurement problem

Initial responses to the measurement problem

Contemporary presentations of the measurement problem

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- What does this really mean?

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- In this sense, ‘interpretation’ is broader than just correlating a physical theory with the world, for it also involves *changing* the formalism of the theory.
- It’s good to be aware of this, but we’ll follow the canon in using ‘interpretation’ in this broader sense.

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- Let's see how this pans out in more detail...

Measurement basics

- What is a measurement?

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- An interaction between object system and measuring apparatus such that the apparatus is left in some definite state telling us something about the system measured.

Initial propositions

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Together, these imply that one can (and should) describe the measuring apparatus quantum mechanically. So going forward:

1. assign states ('pointer states') to apparatus,
2. describe the behaviour of apparatus according to quantum rules,
3. insist that measurement be accurate and repeatable.

Quantitative presentation of measurement problem

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- If a subsystem begins in an eigenstate $|a_i\rangle$ of the observable $\hat{A}$ to be measured, then post-measurement the pointer state $|r_j\rangle$ of the apparatus will be correlated to that value of the observable:

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(NB: We should really have $f(|a_i\rangle)$ on the RHS here, since measurements generally disturb the state—i.e., the projection postulate is false.)

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- So how to deal with these (decohered—see previous lecture) macroscopic superpositions?
- We need to get from a superposition 'and' to disjunction 'either/order'—*but how??*

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Initial responses: collapse/consciousness?

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Both of these responses are by now widely acknowledged to be very bad...

(John Stewart Bell FRS, 1928–90)

Bell's 'Against 'Measurement" (1989)

Here are some words which, however legitimate and necessary in application, have no place in a formulation *with any pretension to physical precision:* system*,* apparatus*,* environment*,* microscopic*,* macroscopic*,* reversible*,* irreversible*,* observable*,* information*,* measurement*.*

The concepts 'system', 'apparatus', 'environment', immediately imply an artificial division of the world, and an intention to neglect, or take only schematic account of, the interaction across the split. The notions of 'microscopic' and 'macroscopic' defy precise definition. So also do the notions of 'reversible' and 'irreversible'. Einstein said that it is theory which decides what is 'observable'. I think he was right—'observation' is a complicated and theory-laden business. Then that notion should not appear in the formulation *of fundamental theory.* Information? Whose *information? Information about* what*?*

On this list of bad words from good books, the worst of all is 'measurement'. (Bell 1989, p. 215)

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> *What exactly qualifies some physical system to play the role of 'measurer'? Was the wavefunction of the world waiting to jump for thousands of millions of years until a single-celled living creature appeared? Or did it have to wait a little longer, for some better qualified system...with a Ph.D.? If the theory is to apply to anything but highly idealised laboratory operations, are we not obliged to admit that more or less 'measurement-like processes are going on more or less all the time, more or less everywhere? Do we not have jumping then all the time?* (Bell 1989, p. 216)

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This hardly sounds promising, but let's consider these views in a bit more detail in any case.

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Difficult to make sense of this view...

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- We can ascribe determinate properties to quantum mechanical systems.
- But only in the context of a given experimental scenario.
- Given different contexts, we ascribe different (classical) properties, but not at the same time.
  (e.g. position/momentum, or colour/hardness are 'complementary' observables).

More on Bohr

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- But in QM, the post-measurement joint state of the object-plus-apparatus is *entangled*.
- Only in such cases can we ascribe classical quantities to systems: one is permitted to speak of e.g. an electron’s having a definite momentum only in a specified experimental context.

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- His point is that, since the object and the apparatus form an entangled pair, they cannot be understood separately.
- Bohr did not assert that one describes "classically" all of and only that which stands on the instrument side of the cut. Instead, Bohr asserted that one describes "classically" those degrees of freedom of both instrument and object that are coupled in the measurement.

Modern prospects for Bohr-type views

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> *Bohr insisted that the formalism can only be interpreted by specification of a (classically defined) context of measurement. But there are now plenty of examples of causal spacetime explanations for the phenomena that Bohr considered (as given in all the major realist schools today, whether pilot-wave theory, GRW theory, or the Everett interpretation); and we have in decoherence theory technology for obtaining approximately classical descriptions from quantum ones that evade Bohr's strictures entirely.* (Saunders 2005, pp. 24-25)

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(Note the suppressed premise: only one outcome occurs.)

Maudlin's trilemma, version 1 (problem of outcomes)

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1. The wavefunction of a system is *complete*, i.e. the wavefunction specifies (directly or indirectly) all of the physical properties of a system.
2. The wavefunction always evolves in accordance with a linear dynamical equation (e.g. the Schrödinger equation).
3. Measurements of, e.g., the spin of an electron always (or at least usually) have determinate outcomes, i.e., at the end of the measurement the measuring device is either in a state which indicates spin up (and not down) or spin down (and not up).

Maudlin's trilemma, version 2 (problem of statistics)

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2. The wavefunction always evolves in accordance with a linear dynamical equation (e.g. the Schrödinger equation).
3. Measurements situations which are described by identical wavefunctions sometimes have different outcomes, and the probability of each possible outcome is given (at least approximately) by Born's rule.

Notes on Maudlin

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- Maudlin also has a third version of the measurement problem which he calls the ‘problem of effect’, but this is very different so I won’t consider it further here.
- Muller (2023) contends that Maudlin’s presentation can be sharpened, and that in fact there are *six* measurement problems of quantum mechanics. I won’t go into this further but I recommend his article to you.

Wallace on the measurement problem

Rather than seeing the measurement problem as a clash between two different kinds of dynamical process (i.e., dynamical evolution and collapse), Wallace (2012) says that we should see it as a clash between two different ways of thinking about the quantum state of some subsystem after decoherence. These are:

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1. As a physical superposition state (i.e., an *improper* mixture.)
2. As a genuine probabilistic mixture of states (i.e., a *proper* mixture.).

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- Let's try now to be a bit more systematic about possible responses to the problem.
- We'll begin by distinguishing *anti-realist* from *realist* responses to the problem.

Scientific realism and anti-realism

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Anti-realism is the denial of scientific realism. (Note: van Fraassen himself is a scientific anti-realist!)

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- **Metaphysical realism:** There is a mind-independent world which has mind-independent properties.
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Anti-realist approaches deny one or more of these.

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  - (More judicious) "a proposition has meaning if sense-experience would be sufficient to decide its truth" (Heath, 1960)

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- **Operationalism**
  - Physical quantities are defined by the means by which they are measured.
  - "Time is what is measured by clocks" Never said by Einstein. "Temperature is what is measured by thermometers" (Schroeder, 1999).
  - Bridgeman is the figurehead (see excellent SEP article by Chang).

Versions of scientific anti-realism

- **Constructive empiricism**
  - "*Science aims to give us theories which are empirically adequate; and acceptance of a theory involves as belief only that it is empirically adequate.*" (van Fraassen 1980, p. 12, emphasis in original)
  - Note: constructive empiricists are still committed to the literal interpretation of scientific theories (even if one is ultimately agnostic about the non-observational parts of the theory in question).

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Question: Which of Psillos' three realist sub-commitments do each of these anti-realist approaches deny, and why?

Classifying approaches to quantum mechanics

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- For now, I want to turn to approaches to the measurement problem which are *obviously* realist in nature.

Realist approaches to the measurement problem

- **Collapse**
  - Orthodoxy: Dirac/von Neumann.
  - Consciousness: Wigner/von Neumann.
  - Change the equations: ‘dynamical collapse theories’ (GRW, CSL, etc.)

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  - Hidden variable theories (e.g. Bohmian mechanics)
  - Everett

Next time: dynamical collapse theories!

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