Title: Interpretation of Quantum Theory: Lecture 7

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Abstract:

The Measurement Problem

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Before the measurement, state is:

$$\left(\alpha|\uparrow\rangle + \beta|\downarrow\rangle\right) \otimes |\text{"no result measured"}\rangle$$

After the measurement, state seems to be:

$$\alpha|\uparrow\rangle \otimes |\text{"measured}\uparrow\text{"}\rangle + \beta|\downarrow\rangle \otimes |\text{"measured}\downarrow\text{"}\rangle$$

...but is really one of

$$|\uparrow\rangle \otimes |\text{"measured}\uparrow\text{"}\rangle \quad (\text{Pr. } |\alpha|^2)$$

or

$$|\downarrow\rangle \otimes |\text{"measured}\downarrow\text{"}\rangle \quad (\text{Pr. } |\beta|^2)$$

Status of the quantum state

(2)

Quantum theory seems to be about the unitary evolution of some "quantum state"

… but what is it?

"States" in physics usually are one of two things:

1) some hopefully-complete description of the actual physical system
   (e.g. electric & magnetic field
   point on configuration space in classical physics)

2) some partial, probabilistic, *in-principle-unnecessary* description of the actual physical system
   (e.g. the probability distributions used in statistical mechanics)

③

Which one is the quantum state?

… both.

Before measurement, it's normally treated as a **physical** state: something that can interfere with itself, be manipulated in experiments, prepared in one way or another, etc.

After measurement, it's normally treated as a **probabilistic state**: we might *say* that the system is in state

$$\sum_i \lambda_i |\psi_i\rangle \otimes |\text{"measure } i\text{"}\rangle$$

but what we *mean* is that the system is in *physical* state

$$|\psi_1\rangle \otimes |\text{"measure 1"}\rangle$$

or

$$|\psi_2\rangle \otimes |\text{"measure 2"}\rangle$$

or…

Possible resolutions of the problem

1. Regard the state as always physical, and change the theory

Why change it?

Because if a state like

$$\alpha|\text{"measure}\uparrow\text{"}\rangle + \beta|\text{"measure}\downarrow\text{"}\rangle$$

is physical, that seems to say that measurements we make don't have definite outcomes…
and they do. (ask an experimentalist!)

So we could

- Change the dynamics so as to be non-linear (e.g. GRWP collapse theory)
- Add "hidden variables" to say which term in the wave-function "corresponds to our actual measurements" (e.g. de Broglie-Bohm theory)

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2. Regard the state as always probabilistic… and rewrite the theory to say what it's a probabilistic description *of*.

e.g. maybe there are hidden variables and they are probabilistically described by the wave-function, but in principle we could throw away the wave-function and just use the hidden variables.

1 & 2 are *research programmes* – no completed theory that realizes either of them.
Committed to *redoing* much of fundamental physics

(not necessarily a criticism!)

What if we don't want to redo fundamental physics?

… then we need a theory in which

a) the wavefunction description of reality is complete (or "as complete as possible" anyway)
b) it evolves unitarily at all times.

We could then try resolution

3. The wavefunction is a probabilistic state but there is *no* physical state underlying it*

e.g (some versions of) Copenhagen interpretation
    ensemble interpretations (Ballentine)
    (some versions of) information-theoretic interpretations (Fuchs)

* does this make sense? Exercise for the reader!
If you don't think it does, you're left with…

4. The Everett interpretation

- The quantum state is a *physical state* (no probabilistic / ensemble / ignorance interpretation of it; it's as real as the electric field)
- The quantum state is a complete description of reality (no extra hidden variables)
- The quantum state always evolves unitarily (no collapse)

Complete description!

… from the point of view of physical postulates, the Everett interpretation just says "take QM completely literally".

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How can this make sense?

- Theory (apparently) predicts *indefinite outcomes of experiments*
- We don't see indefinite outcomes!

Central insight:

A state like

$$\alpha\,|\text{"measure}\uparrow\text{"}\rangle + \beta\,|\text{"measure}\downarrow\text{"}\rangle$$

is correctly understood as describing two "worlds"

- isolated, or nearly isolated, chunks of reality
- each approximately classical
- in one we get one result, in one the other

hence "many-worlds interpretation"

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Problems

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1. *why* does it make sense to regard a quantum state as describing multiple worlds?

2. does it even make sense to imagine *ourselves* splitting into multiple copies when measurement occurs?

3. What about *probability?*

Structure of lectures

Today: 1, 2
Thursday: 3

Also Thursday: nonlocality in the Everett interpretation.

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The validity of "World" talk

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|\text{"I see spin up"}\rangle + |\text{"I see spin down"}\rangle\right)$$

- Why are $|\text{"I see spin up"}\rangle$ and $|\text{"I see spin down"}\rangle$ the worlds?
- Why not $\alpha|\text{"I see spin up"}\rangle + \beta|\text{"I see spin down"}\rangle$

  and $\beta^*|\text{"I see spin up"}\rangle - \alpha^*|\text{"I see spin down"}\rangle$

... indefinite even within a world

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The decoherence basis

We want a basis to pick out the worlds, such that each world is macroscopically definite.

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the basis preferred by *decoherence*

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Why not add a new physical postulate to QM:

“the quantum state, decomposed in the decoherence basis, describes an ensemble of worlds”

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NO!

- Decoherence is *vague*: it only *approximately* picks out a preferred basis,, and we don't want essential approximateness in our physical laws

- Decoherence is (or might be) *ambiguous*: no-one has succeeded in finding a *microscopically-stateable* set of rules to pick out the decoherence basis

- It misses the point: the advantage of the Everett interpretation is that it is an *interpretation*, not a recipe for new physics.

Instead what we need is an *argument* as to why, without any new physical postulate, it's *already* true that a decohered state is correctly described as an ensemble of worlds

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How to study tiger hunting patterns

Strategy 1: solve the 10^{35} or so simultaneous differential equations that govern the dynamics of the atoms and electrons in the tiger's hunting grounds
… insane

Strategy 2: identify certain patterns within that swirl of molecules as cells etc, and use the language of cell biology, accepting a (small) reduction in theoretical accuracy
… still ludicrously hard

Strategy 3: identify certain patterns within the cell description as tigers, deer etc, and shift to the language of zoology & evolutionary adaptationism
… the norm

3 depends on **2** and **2** depends on **1**, but we cannot abandon **3** and just use **1** or **2** without (a) losing all explanatory power, and (b) taking forever.

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Classical patterns in the quantum state

Applying this to quantum mechanics:

Macroscopic objects like cats, apparatus needles, people etc. are patterns instantiated, ultimately, in the positions and momentums of approximately-localised quantum-mechanical particles

… i.e. in expectation values of POVM operators $\hat{O}(p,q)$ that correspond to (fuzzy) measurements of position and momentum.

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Schrodinger Cat expt

The device

Begins in state $|\text{"initial"}\rangle$

At 12 noon, if we input a spin-$\frac{1}{2}$ particle the device executes

$$|\uparrow\rangle \otimes |\text{"initial"}\rangle \longrightarrow |\uparrow\rangle \otimes |\text{"cyanide released"}\rangle$$

$$|\downarrow\rangle \otimes |\text{"initial"}\rangle \longrightarrow |\downarrow\rangle \otimes |\text{"cat treat released"}\rangle$$

Therefore if we put the device in the box with an unfortunate cat:

- If we input $|\uparrow\rangle$, it evolves into a dead cat
- If we input $|\downarrow\rangle$, it evolves into a live cat
- If we input $\frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle)$ it "evolves into a weird superposition"

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So...

- If we input $|\uparrow\rangle$, there is a certain pattern Cat_1 instantiated in the expectation values of $|\psi\rangle$
- If we input $|\downarrow\rangle$ there is a different such pattern Cat_2
- If we input $\frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle)$ then both patterns are instantiated, each evolving with no interference from the other

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