Quantum mechanics: the measurement problem and quantum non-locality

Christian Wüthrich

http://www.wuthrich.net/

Introduction to Philosophy of Physics

The puzzle of measurement

Feynman, R. P., 'Simulating physics with computers', *International Journal of Theoretical Physics* 21 (1982): 467-88.

Feynman (1982, 471)

> *[We] always have had (secret, secret, close the doors!) we always have had a great deal of difficulty in understanding the world view that quantum mechanics represents. At least I do, because I'm an old enough man that I haven't got to the point that this stuff is obvious to me. Okay, I still get nervous with it... you know how it always is, every new idea, it takes a generation or two until it becomes obvious that there is no real problem. It has not yet become obvious to me that there's no real problem. I cannot define the real problem, therefore I suspect there's no real problem, but I'm not sure there's no real problem.*

The problem with the standard view of QM

In a nutshell

Principle C asserts that the dynamics of any quantum system is described by the Schrödinger equation, which is a linear and deterministic equation. Principle E asserts that whenever a measurement is made upon a quantum system, its state collapses into an eigenstate of the measured observable. This collapse is non-linear and indeterministic. As stated, the two Principles are thus incompatible. They could be made compatible if we gave a precise and complete dynamical prescription for all quantum systems in all circumstance, e.g., by giving necessary and sufficient conditions for what is a 'measurement' and what the precise collapse dynamics is.

Schrödinger's cat

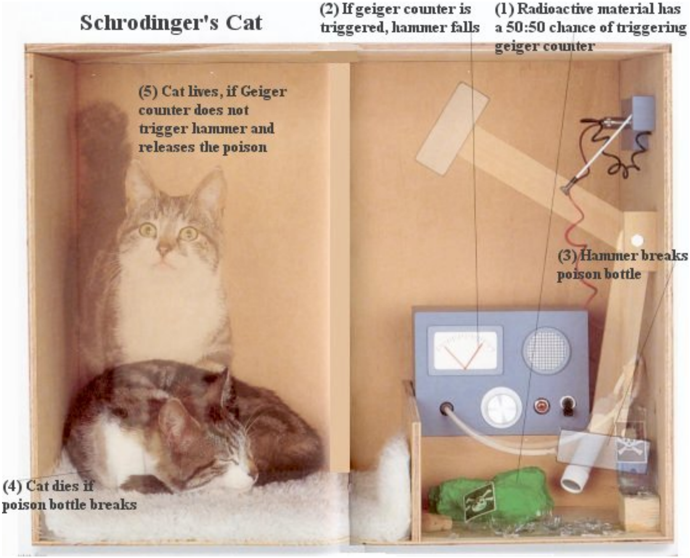
Schrödinger, E., 'Die gegenwärtige Situation in der Quantenmechanik' ('The present situation in quantum mechanics'), *Naturwissenschaften* 23 (1935): 807-812; 823-828; 844-849.

Schrödinger (1935)

> *One can even set up quite ridiculous cases. A cat is penned up in a steel chamber, along with the following 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 the 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 an hour, one would say that the cat still lives if meanwhile no atom has decayed. The psi-function of the entire system would express this by having in it the living and dead cat (pardon the expression) mixed or smeared out in equal parts.*

Schrödinger (1935)

> *It is typical of these cases that an indeterminacy originally restricted to the atomic domain becomes transformed into macroscopic indeterminacy, which can then be resolved by direct observation. That prevents us from so naively accepting as valid a 'blurred model' for representing reality. In itself it would not embody anything unclear or contradictory. There is a difference between a shaky or out-of-focus photograph and a snapshot of clouds and fog banks.*


Schrodinger's Cat
(2) If geiger counter is triggered, hammer falls
(1) Radioactive material has a 50:50 chance of triggering geiger counter
(5) Cat lives, if Geiger counter does not trigger hammer and releases the poison
(3) Hammer breaks poison bottle
(4) Cat dies if poison bottle breaks

📄 Jeff Barrett (1999). *The Quantum Mechanics of Minds and Worlds*. OUP. §2.5, pp. 43f.

- After exactly one hour, the cat is in the superposition state

$$\frac{1}{\sqrt{2}}|\text{alive}\rangle + \frac{1}{\sqrt{2}}|\text{dead}\rangle, \tag{1}$$

  but to have a macroscopic object like a cat in a superposition state like this seems bizarre...
- So, we could insist on definite measurement outcomes (and linear dynamics), but that would mean that the quantum state (the wave function) of the cat is not complete (there is a fact of the matter whether the cat is dead or alive).
- Copenhagen orthodoxy: Our act of observation collapses the superposition to one of its terms, making the cat definitely dead or alive.
- It is somehow our lifting of the lid of the box that causes the collapse.

Maudlin's version of the measurement problem

Tim Maudlin. Three measurement problems. *Topoi* 14 (1995): 7-15.

Theorem (Measurement Problem (MP))

"The following three claims are mutually inconsistent.

1.A *"The wave-function of a system is complete, i.e. the wave-function specifies (directly or indirectly) all of the physical properties of a system.*

1.B *"The wave-function always evolves in accord with a linear dynamical equation (e.g. the Schrödinger equation).*

1.C *"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)." (7)*

'Proof.' Essentially along the lines of Albert's chapter 4, e.g. if 1.A is true, and thus the wave function must specify every physical fact about the measuring device, and 1.B is true, then 1.C must be false, etc. ☐

Taxonomize the solutions to MP

1. Hidden-variables theories deny 1.A, since they postulate more reality than is represented in $|\psi\rangle$
    - Examples: Bohmian mechanics, modal interpretations such as van Fraassen's (1991)
2. Collapse theories abandon 1.B, since they assert that dynamics is, at least sometimes, non-linear
    - Examples: Copenhagen, Spontaneous Localization theory of Ghirardi, Rimini, Weber (1986) (GRW); Continuous Spontaneous Localization theory of Perle (1990)
3. Multiverse theories reject 1.C, since they maintain that measuring devices indicate both (or all) outcomes
    - Examples: many-world theories, Everett's Relative State interpretation (1957)

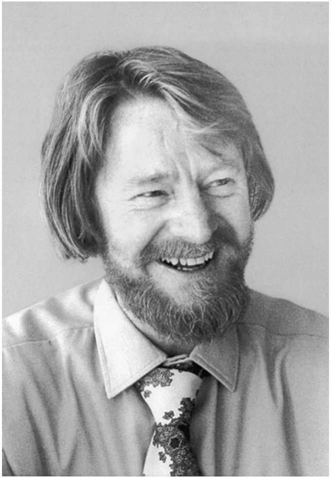
New physics

- A solution to MP must thus by necessity either be a hidden-variables theory, a collapse theory, or a multiverse theory (or some combination thereof).

⇒ each option involves the postulation of new physics, according to Maudlin:

1. Hidden-variables theories must specify what additional variables there are and what dynamical laws govern them.
2. Collapse theories must provide the non-linear dynamical equations and specify when exactly they apply (something the Copenhagen interpretation did not do).
3. Multiverse theories must explain why it seems as if there are definite outcomes; in other words, they must answer why Schrödinger's cat seems either definitely alive or definitely dead.

John Stewart Bell (1928-1990)



- studied physics at Queen's University Belfast, PhD U Birmingham, CERN
- 'On the Einstein-Podolsky-Rosen paradox' (1964): derivation of Bell's inequality
- Bell's theorem: this inequality, derived from basic assumptions about locality and separability, conflicts with the predictions of QM

Bell's relevance

N. David Mermin, 'Is the moon there when nobody looks? Reality and the quantum theory', *Physics Today*, April 1985, 38-47.

- By the mid-60s, almost all physicists just moved on and worked with QM, but didn't reflect its foundations.

⇒ many of them didn't notice, and still fail to appreciate the relevance of Bell's theorem

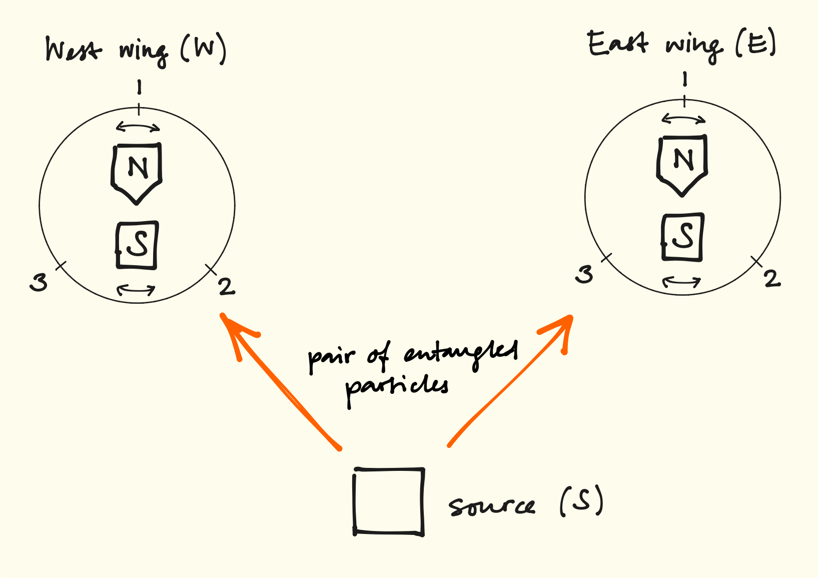
- But not all: "Bell's theorem is the most profound discovery of science" (Henry Stapp)
- A bit more nuanced (but only a bit): "Anybody who's not bothered by Bell's theorem has to have rocks in his head" ("a distinguished Princeton physicist")
- Mermin's classification of physicists:
    - Type 1 bothered by EPR and Bell's theorem, type 2 (the majority) not bothered
    - Type 2a explain why not, but either miss the point entirely or make assertions that are demonstrably false
    - Type 2b refuse to explain why they are not bothered

A simple version of the EPR-Bohm thought experiment

N. David Mermin, 'Is the moon there when nobody looks? Reality and the quantum theory', *Physics Today*, April 1985, 38-47.

- based on Mermin (1985)
- Three pieces: two detectors (W and E), and a source (S)
- Each detector has a switch with three settings (1, 2, 3), and responds to an event by flashing a red (R) or green light (G).
- There are no connections or signals between the pieces other than the two particles sent from S to W and E (this can be tested by sliding walls, etc).
- The switch of each detector is independently and randomly set to one of its settings, and a button is pushed at S to initiate the process of creating a pair of entangled particles and sending them to the opposite wings.
- Many runs of the experiments are made, and lots of data of form (11GG, 23GR, etc) is collected.

A simple version of the EPR-Bohm thought experiment



A simple version of the EPR-Bohm thought experiment

The data has two features:

1. For those runs when settings were the same in W and E, we find that the light always flashed in same colour. (PERFECT CORRELATION)
2. For all runs regardless of the settings in W and E, the pattern of flashing is completely random. In particular, half of the time the same colour flashes, half of the time a different one does. (NO CORRELATION)

Challenge:

Find an account which explains both of these features.

How can this data be explained?

- The perfect correlation cries out for explanation.
- Traditional possibilities: (i) the events are really parts of one larger event, or (ii) W causes E or vice versa, or (iii) they have common cause
- If the detectors could communicate, this would be easy. But they don't. And can't.
- Neither can the detectors have been preprogrammed always to flash the same colour, since they also need to account for data point 2, and their settings are random and independent.

Born offers an explanation (in a letter of May 1948 to Einstein):

> *[O]bjects far apart in space which have a common origin need not be independent... Dirac has based his whole book on this.*

Mermin: could we have a common cause explanation?

That is, a "local hidden variable" explanation?

- A common cause explanation: both particles are imparted the same ordered triple of labels as they leave the source (three bits of information, e.g. RRG, GRG, etc; 2^3 possibilities), each telling the detector which colour to flash, depending on its setting.
- These instructions must cover each of the possible detector settings because there is no communication between the source and the detectors other than the particles.
- This also means that instructions must be carried in every run, since one can never know at the source whether the settings are the same:

⇒ This can easily account for data 1.

- But despite the naturalness of this type of explanation (arguably the only natural explanation), it cannot be true: it's inconsistent with data 2!
- Note that "we are about to show that 'something one cannot know anything about'—the third entry in an instruction set—cannot exist." (Mermin 1985, 43) (one can never learn more than two of the entries in the instruction sets imparted on the particles)
- Here's the argument for the inconsistency with data 2. Consider a possible instruction set, e.g. RRG.

⇒ The detectors will flash the same colour for settings 11, 22, 33, 12, 21, and different colours for settings 13, 31, 23, 32 (3^2 settings).

- Since the settings are random and independent, each of the nine possibilities are equally probable.

⇒ The instruction set RRG will result in the same colour flashing in 5/9 of the time.

- Evidently, the same holds for instruction sets RGR, GRR, GGR, GRG, and RGG (because the argument uses only the fact that one colour appears twice, and the other once).
- Two more instruction sets are left: RRR and GGG, but these both result in the same colours flashing all the time (with probability 1). But this gives us the famous:

Theorem (Bell's theorem (baby version))

If instruction sets exist, the same colours will flash in at least 5/9 of all the runs, regardless of how the instruction sets are distributed among the runs.

- This is (the baby version of) Bell's inequality: the probability that the same colours flash is larger or equal to 5/9.
- It's now obvious that data 2 cannot be accounted for: data 2 violates Bell's inequality!

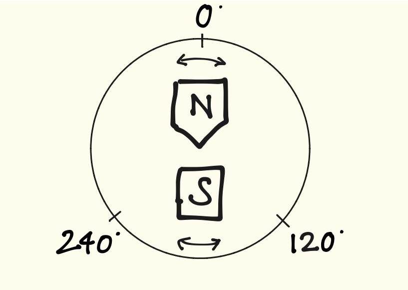
Thus, there cannot be a common cause explanation.

The standard QM explanation

- Let the source produce a pair of spin-1/2 particles in a so-called 'singlet state':

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle). \tag{2}$$

- Each detector contains a Stern-Gerlach magnet, oriented along three directions perpendicular to the line of flight, each separated by 120°:



- The light on detector W flashes R if the particle is deflected north (spin ↑) and G if deflected south (spin ↓); detector E uses opposite colour conventions.
- This allows us to account for the data:
- Data 1 is accounted for by the structure of the singlet state, which ensures that the measurements along the same axis yield opposite spin and thus the same colour.
- To get data 2, we need the concept of an expectation value. This requires a bit more math than we do here (but not much more), so go and read it up in the article by Mermin if you are interested!

Comments

- The simplified thought experiment captures the relevant features of the EPR-Bohm experiment.
- The Baby Bell theorem shows why there cannot be a common cause, contra Einstein, Podolsky, and Rosen (1935, 'EPR') who argued that QM was incomplete (because it didn't contain such a common cause).
- Bell was the one who added the runs with different settings in order to extract from QM the prediction about data 2.
- It was exactly data 2 that showed that a common cause story is incompatible with the predictions of QM.
- Alain Aspect, Paris 1982; Nicolas Gisin, Geneva 1997: detectors are 10 km apart, settings chosen after photons left source

⇒ experimental falsification of common cause theory

Bell's assessment of his result

J.S. Bell, 'Bertlmann's socks and the nature of reality', in *Speakable and Unspeakable in QM*, 139-158.

Bell sees at least four different positions that one might:

1. QM is wrong in sufficiently critical situations. But that's unconvincing in the light of empirical evidence.
2. The detector settings are not independent variables. But this would imply strange conspiracies between spatially distant apparatuses, or our free will is conspiratorially entangled with them or both.
3. Causal influences can go faster than light, perhaps by reintroducing an aether. But this would create formidable challenges...
4. Perhaps there is no reality beyond some 'classical' 'macroscopic' level.

Bell's assessment of his result

There are actually more options:

5. The measurement events in the two wings are not separate, i.e., they are like different aspects of the same event.
6. There is backward causation such that the settings in either or both of the wings (which can be set after the particles departed the source) causally influence the common cause at the source event.

Note:

One of these options must be true.

Additional considerations on nonlocality

David Z Albert (1992). *Quantum Mechanics and Experience*. Harvard University Press, Ch. 3.

- EPR thought that the nonlocal character of measurements on non-separable states is a merely disposable artifact of the particular formalism of standard QM.
- The upshot of Bell's theorem is that this is demonstrably wrong:

Albert (1992, 70)

> *What Bell has given us is a proof that there is as a matter of fact a genuine nonlocality in the actual workings of nature, however we attempt to describe it, period. That nonlocality is... necessarily... a feature of every possible manner of calculating... which produces the same statistical predictions as quantum mechanics does; and those predictions are now experimentally known to be correct.*

Important

This result in independent of quantum mechanics—it is nature itself that is non-local.

Three final comments

Tim Maudlin, *Quantum Non-Locality and Relativity*, Ch. 1.

Three results concerning the 'quantum connection':

1. It is unattenuated: in contrast to classical (instantaneous) action, the quantum connection is unaffected by distance.
2. It is discriminating: while gravitational forces affect similarly situated objects in the same way, the quantum connection is a private arrangement between entangled particles.
3. It is instantaneous: while Newton's theory of gravity has gravity propagate instantaneously, it need not do so, and GR certainly involves no instantaneous gravitational action; but the quantum connection appears to act essentially instantaneously.