The measurement problem

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146 Philosophy of Physics: Quantum Mechanics

The puzzle of measurement

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

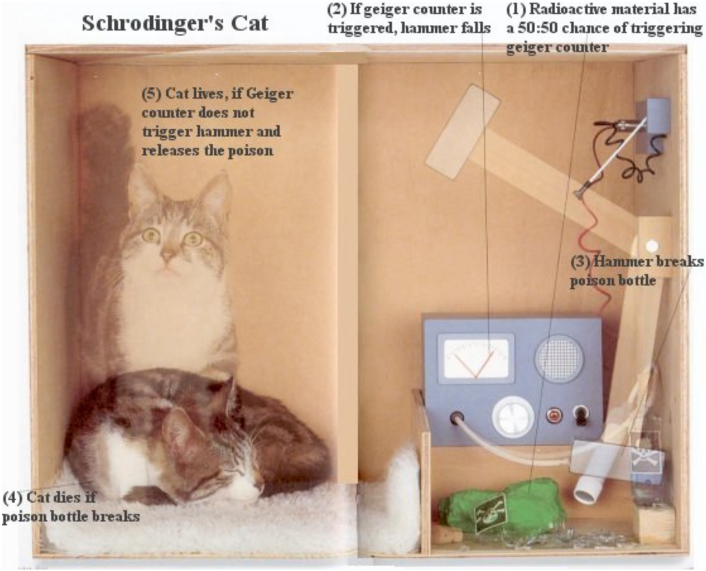
"[We] always have had (secret, secret, close the doors!) we always have had a great deal of difficulty in understanding the world view that quantum mechanics represents. At least I do, because I'm an old enough man that I haven't got to the point that this stuff is obvious to me. Okay, I still get nervous 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." (471)

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.

"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.

"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

Barrett, J., *The Quantum Mechanics of Minds and Worlds*, Sec. 2.5, particularly 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.
- OK, but it gets weirder...

Eugene Wigner (1902-1995) and his friend

- Hungarian physicist and mathematician, fled to the US
- Nobel 1963 "for his contributions to the theory of the atomic nucleus and the elementary particles, particularly through the discovery and application of fundamental symmetry principles"
- What causes the collapse of the wave function?
- Answer: the consciousness of the observer

$\Rightarrow$ Wigner's 'idealism'

- Illustration: the paradox of Wigner's friend

Wigner's friend

Barrett, J., *The Quantum Mechanics of Minds and Worlds*, Sec. 2.6. (great source for this material).

- Suppose you put one of Wigner's friends in the box with the cat. Measurement: ask the friend whether the cat is alive or dead.
- If we consider your friend as part of the experimental setup, quantum mechanics predicts that before you ask Wigner's friend whether the cat is dead or alive, he is in a superposition of definitely believing the cat is dead and definitely believing that the cat is alive.

$\Rightarrow$ absurd consequence of Bohr's view

- Wigner's solution: there is a natural division between what constitutes a measurement and what does not—the presence of a conscious observer, and of course the friend is conscious.

- Not popular because it raises many conundrums: does the cat have consciousness?
- More seriously, Wigner's view requires a division of the world into two realms, one occupied by conscious beings who are not subject to the laws of physics but who can somehow miraculously disrupt the ordinary deterministic evolution of the physical systems, and the other by the physical systems themselves, which evolve deterministically until a conscious being takes a look at what's going on.
- Problem: Copenhagen requires such a division between system and classical world of observation reports...

Albert's formulation of the measurement problem

Albert, Ch. 4.

- Suppose that everything evolves according to Schrödinger eq.
- Suppose we have hardness measuring device: device with dial with three settings ('ready', 'hard', 'soft').
- Set the device such that it reads 'ready' and then feed e^- into it, and they get there hardnesses measured. These measurements are recorded by final position of dial ('hard' or 'soft').
- Assumptions entail that it must act such that:

$$\begin{aligned} |\text{ready}\rangle_m |\text{hard}\rangle_e &\longrightarrow |\text{`hard'}\rangle_m |\text{hard}\rangle_e \\ |\text{ready}\rangle_m |\text{soft}\rangle_e &\longrightarrow |\text{`soft'}\rangle_m |\text{soft}\rangle_e \end{aligned} \quad (2)$$

  where the subscripts *m* and *e* designate the states of the measuring device and the electron, respectively.

⇒ from (1) and (2) and the linearity of the Schrödinger eq, it follows that a black state evolves, with certainty, into

$$\frac{1}{\sqrt{2}}|\text{`hard'}\rangle_m|\text{hard}\rangle_e + \frac{1}{\sqrt{2}}|\text{`soft'}\rangle_m|\text{soft}\rangle_e \tag{3}$$

- (Verify for yourself that this is the case.)
- But if we assume that measurements have definite outcomes, then by the postulate of collapse (Postulate E), and by Born's rule (Postulate D) for the probabilities, we get

$$\begin{array}{lll} \textit{either} & |\text{`hard'}\rangle_m|\text{hard}\rangle_e & \text{(with probability 0.5)} \\ \textit{or} & |\text{`soft'}\rangle_m|\text{soft}\rangle_e & \text{(with probability 0.5)} \end{array} \tag{4}$$

- But this is measurably different from (3)!
- (4) has definite outcomes but violates the Schrödinger eq, while (3) is a state in which there is no matter of fact about where the pointer is pointing...

A "somewhat sharper" formulation

- Introducing Martha who is a competent observer, i.e. the Schrödinger eq entails that Martha (= physical system, whose state is indicated by subscript *o*) behaves like this:

$$|\text{ready}\rangle_o|\text{ready}\rangle_m \longrightarrow |\text{`ready'}\rangle_o|\text{ready}\rangle_m$$
$$|\text{ready}\rangle_o|\text{`hard'}\rangle_m \longrightarrow |\text{`hard'}\rangle_o|\text{`hard'}\rangle_m$$
$$|\text{ready}\rangle_o|\text{`soft'}\rangle_m \longrightarrow |\text{`soft'}\rangle_o|\text{`soft'}\rangle_m$$

  where $|\text{ready}\rangle_o$ is the physical state of Martha when she is alert and intent on reading off the pointer setting, $|\text{`xyz'}\rangle_o$ is her physical state in which she believes that the pointer is pointing to 'xyz'.

- From the competence of the observer, and the linearity of Schrödinger's eq, it follows that when Martha has read off the pointer reading for state (3), the overall state will be, with certainty,

$$\frac{1}{\sqrt{2}}|\text{`hard'}\rangle_o|\text{`hard'}\rangle_m|\text{hard}\rangle_e + \frac{1}{\sqrt{2}}|\text{`soft'}\rangle_o|\text{`soft'}\rangle_m|\text{soft}\rangle_e \qquad (5)$$

- But again, the requirement for definite measurement outcomes (essentially Postulates D and E), entails that when Martha is done, then

$$\begin{array}{lll} \textit{either} & |\text{`hard'}\rangle_o|\text{`hard'}\rangle_m|\text{hard}\rangle_e & \text{(with probability 0.5)} \\ \textit{or} & |\text{`soft'}\rangle_o|\text{`soft'}\rangle_m|\text{soft}\rangle_e & \text{(with probability 0.5)} \end{array} \qquad (6)$$

- But again: (5) and (6) are empirically different, only (6) is empirically correct; (5) is "unspeakably strange": "it's a state in which there is no matter of fact about whether or not Martha thinks the pointer is pointing in any particular direction." (79)
- And (5) is really strange: "This is a state wherein... it isn't right to say that Martha believes that the pointer is pointing to 'hard,' and it isn't right to say that Martha believes that the pointer is pointing to 'soft,' and it isn't right to say that she has both of those beliefs (whatever that might mean), and it isn't right to say that she has neither of those beliefs." (79fn)

$\Rightarrow$ The Postulate of Dynamics (Postulate C) and the Postulate of Collapse (Postulate E) are in flat contradiction.

Maudlin's first problem: the problem of outcomes

Maudlin, *Topoi* **14** (1995): 7-15.

Theorem (Measurement Problem 1 (MP1))

"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 MP1

1. Hidden-variable theories deny 1.A, since they postulate more reality than is represented in $|\psi\rangle$
   - Examples: Bohm's theory, modal interpretations such as van Fraassen's (1991)
   - less tendentious: additional variables (AV) theories
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)
   - less tendentious: non-linear theories
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)
   - logically possible: 'nulliverse' theory

New physics

- A solution to MP1 must thus by necessity either be a AV theory, a non-linear theory, or a multiverse theory (or some combination thereof).

⇒ each option involves the postulation of new physics:

1. AV theories must specify what additional variables there are and what dynamical laws govern them
2. Non-linear theories must provide the non-linear dynamical equations and specify under 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

Maudlin's second problem: the problem of statistics

- Strictly speaking are the three claims in MP1 not logically inconsistent:
- We could say that any superposition state the detector outcome 'UP'.
- A bit less crude: the detector outcome is determined by term with largest coefficient (in all cases), 50-50 superposition states are of measure zero
- But any such brute force solution of MP1 seems to run afoul a new problem...

Theorem (Measurement Problem 2 (MP2))

"Formally, the following three claims are mutually inconsistent:

2.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.*

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

2.C *"Measurement situations which are described by identical initial wave-functions sometimes have different outcomes, and the probability of each possible outcome is given (at least approximately) by Born's rule." (11)*

'Proof.' If the wave-function always evolves deterministically (2.A), then two systems with identical initial wave functions will have identical final wave functions. Since wave functions are complete (2.A), this identity would be total. Particularly, they cannot contain detectors indicating different outcomes, contra 2.C. □

1. An AV theory solves MP2 by denying 2.A: systems with identical wave functions may still be physically different, and thus lend themselves to different outcomes
    - But the additional variables would have to be manifest, i.e. having an observable effect on the pointer of the measurement device.
2. Non-linear theories solve the problem by assuming an indeterministic evolution (by denying 2.B).
    - In the standard interpretation and in GRW theory, collapses are postulated to be irreducibly stochastic.
3. But multiverse theories face a difficulty: they cannot make sense of Born's rule and thus cannot reproduce actual quantum-mechanical measurements.

The difficulty of multiverse theories with probabilities

- How can a multiverse theory mark a difference between a 50-50 superposition and a 75-25 superposition?
- Maudlin: they can't, and that's the deep reason why they fail.
- Problem: in 75-25 case, it can't mean that the two worlds corresponding to the different outcomes are unequally likely, since they both exist.
- Typical answer: somehow, those branches in which the observed long-time frequencies of very long (infinite?) sequences of measurements match those predicted by Born rule get assigned a probability that approaches 1.
- Maudlin: this constitutes a petitio principii (i.e. it begs the question): every one of the branches equally likely to occur (with probability 1)

"There is, in the Many Worlds picture, simply nothing for the numbers generated by Born's rule to be probabilities of, and this problem is not ameliorated if those numbers approach 1 or 0. The denial of 2.C... cannot be reconciled with the quantum theory as it is used to make predictions. Without also employing either additional variables or a non-linear, stochastic evolution of the wave-function, the multiverse (or nulliverse) views cannot solve our problems, and if they do invoke either of these, then the postulation of the many worlds is sheer extravagance." (12)

Concentrating on the first two option, we thus find that

> *"[a]s J. S. Bell succinctly put it, 'either the wave-function, as given by the Schrödinger equation, is not everything, or it is not right'... Putting together the two problems, we can say that whatever new physics we invent to solve the measurement problem, it must be so constructed that (a) measurements typically have outcomes and (b) probabilities are assigned to those outcomes which at least approximate the probabilities derived by use of Born's rule. These conditions supply the standard by which one can evaluate new theories." (12)*

Maudlin's third problem: the problem of effect

- Some interpretations, such as van Fraassen's modal interpretation and Richard Healey's interpretation, manage to solve MP1 and MP2, but not MP3:

Theorem (Measurement Problem 3 (MP3))

The result of a measurement therefore has predictive power for the future: after the first measurement is completed we are in a position to know more about the outcome of the second than we could before the first measurement was made. Any theory which seeks to replicate the empirical content of the traditional theory should have this feature. Let us call this the problem of effect, to indicate the effect of the first measurement on the particle (or at least our knowledge of the particle).

- Bohm's theory and GRW, and perhaps others, can also solve this problem and thus survive the test...