Puzzling Aspects of Quantum Mechanics, Part I: The Measurement Problem

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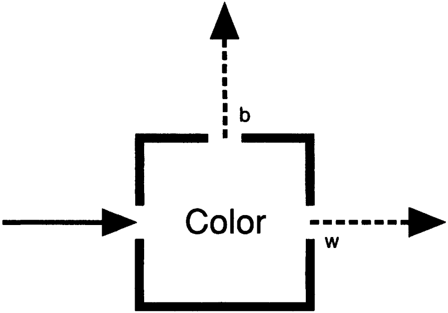
Outline of lecture

1. Quantum superposition: the curious physics of electrons
2. An introduction to the measurement problem: Schrödinger's cat and Wigner's friend
3. The measurement problem in full regalia and how it entails the need for new physics

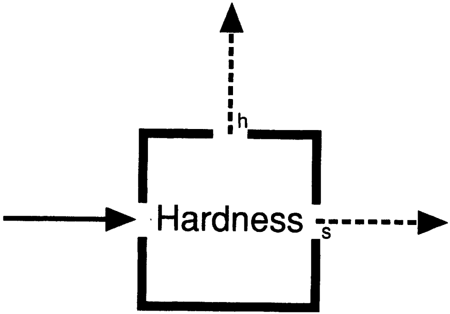
Quantum superposition: Setting things up

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

- electrons with two properties: “color” (black, white), “hardness” (soft, hard)
- color box: measuring device with three apertures such that incoming e^- are sorted according to their color



- hardness box: similar device sorting e^- into hard and soft ones



- measurements repeatable: if after measurement, e^- is fed into same type of box w/out tampering, then same measurement outcome will be observed

- Q: Are properties related, i.e. are there correlations bw values of hardness and color of e^-?

$\Rightarrow$ combine boxes to measure correlations

- precisely half of e^- coming out of one aperture of first box come out of each aperture of second box

$\Rightarrow$ no correlations, color (hardness) of e^- entails nothing about its hardness (color)

Three-box experiments

- suppose we have three boxes alined for subsequent measurement, s.t. the first and third box are of same type as one another, but of different type from second box
- no tampering with e^- bw boxes
- e^- going into third box is presumably known to have a particular pair of color and hardness properties (e.g. white and soft)

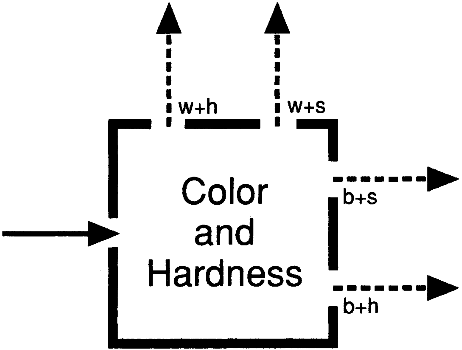
$\Rightarrow$ it seems as if we can predict the outcome of the third measurement

- It turns out that we can't: precisely half of the e^- will come out of each aperture of third box.
- Apparently, presence of middle box itself constitutes some sort of tampering: middle box seems responsible for changing half of e^- since we know that two identical boxes in sequence show a different behaviour.

- Can boxes be built less crudely, can intermediate measurements be refined such as to avoid this? No, every device that qualifies as e.g. hardness box will randomize color.
- What is it that determines precisely which e^- have their properties changed by second box and which don't? Let's look for correlations bw measurable properties of incoming e^- and their final measurement outcome. But there is absolutely no such correlation... $\Rightarrow$ this Q has no answer

Color-and-hardness boxes

- boxes w/ five apertures, incl. one for each pair of measurement outcomes



- box like that would have to consist of a color box and a hardness box

$\Rightarrow$ Problem: the second device will randomize e^- wrt to first measurement

- Albert: "So the task of putting ourselves in a position to say 'the color of this electron is now such-and-such and the hardness of this electron is now such-and-such' seems to be fundamentally beyond our means." (7)

$\Rightarrow$ example of uncertainty principle, since measurements of one of the two incompatible properties disrupts the measurement of the other

Werner Heisenberg (1901-1976): uncertainty

Principle (Uncertainty Principle)

The uncertainty in a simultaneous measurement of momentum and position is always greater than a fixed amount, approximately equal to Planck's constant:

$$\Delta x \cdot \Delta p \geq h.$$

- $\Rightarrow$ to measure both x and p accurately at the same time is impossible
- $\Rightarrow$ one cannot be pinpointed exactly, unless we are willing to be quite uncertain about the other

Stern-Gerlach experiment

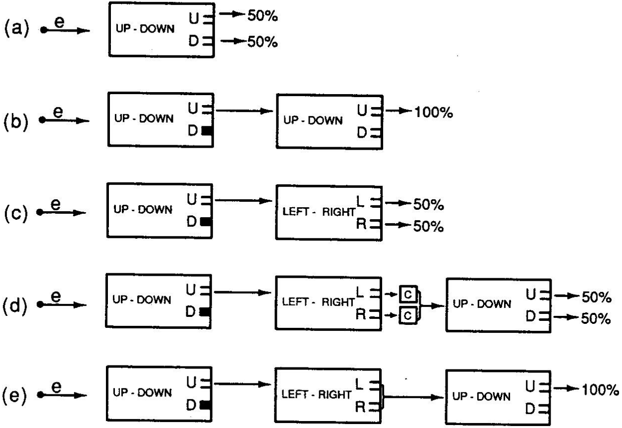
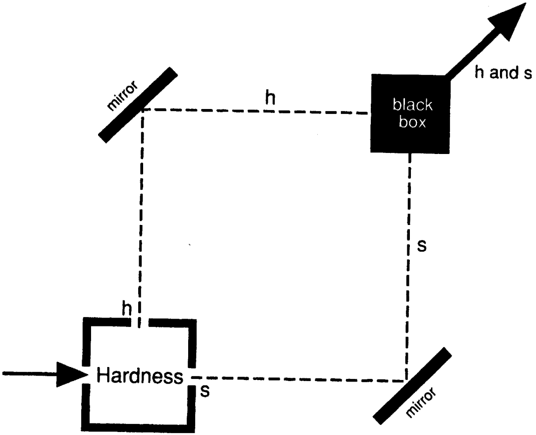


Figure: Stern-Gerlach experiment with “mixture” (d) and “superposition” (e) (Sklar, Fig. 4.4)

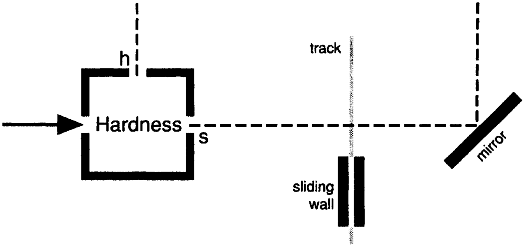
Two-path experiments

- Consider a more complicated device as in the following figure:



- Suppose that white e^- is fed into device and measure its hardness at *h and s*. Expectation: we find half hard and half soft e^-. And this is what we find.
- Suppose that hard e^- is fed into device and then measure its color at *h and s*. Expectation: find half of e^- to be white and half black. And this is what we find.
- Suppose we feed white e^- into device and measure their color at *h and s*. Expectation: half should be found to be white, half black. But this is not at all what we find: all e^- are found to be white!

- Add a sliding wall as in the following figure:



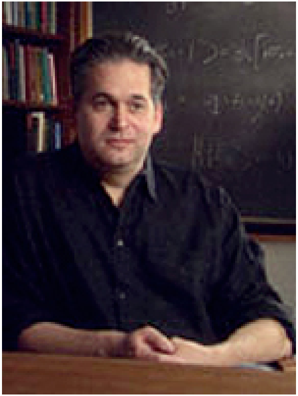
- What happens if we slide wall in?
- Expectation: overall output goes does down 50%; given that all e^- were just found to be white, they should still be so, right?
- But they are not: only half of the e^- are now white, the other half black.

Considering routes of electrons: superposition

Which route does an electron take when wall is out?

- Can it have taken *h*? Apparently not, since these e^- are known to randomize color.
- Can it have taken *s*? No, same reason.
- Can it somehow have taken *both* routes? Apparently not, since whenever we stop experiment and look to see where the e^- is, we find it either on *h* or on *s*.
- Can it have taken *neither* route? No, since if we wall up both routes, nothing goes through.

In David Albert's words:



"Electrons passing through this apparatus... do not take route *h* and do not take route *s* and do not take both of those routes and do not take neither of those routes; and the trouble is that those four possibilities are simply all of the logical possibilities that we have any notion to entertain... The name of that new mode (which is just a name for something we don't understand) is superposition." (11)

Electrons in superposition states

We can write these superposition states as follows (for later reference):

$$
\begin{aligned}
|\text{black}\rangle &= \frac{1}{\sqrt{2}}|\text{hard}\rangle + \frac{1}{\sqrt{2}}|\text{soft}\rangle,\\
|\text{white}\rangle &= \frac{1}{\sqrt{2}}|\text{hard}\rangle - \frac{1}{\sqrt{2}}|\text{soft}\rangle,\\
|\text{hard}\rangle &= \frac{1}{\sqrt{2}}|\text{black}\rangle + \frac{1}{\sqrt{2}}|\text{white}\rangle,\\
|\text{soft}\rangle &= \frac{1}{\sqrt{2}}|\text{black}\rangle - \frac{1}{\sqrt{2}}|\text{white}\rangle.
\end{aligned}
$$

The puzzle of measurement

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

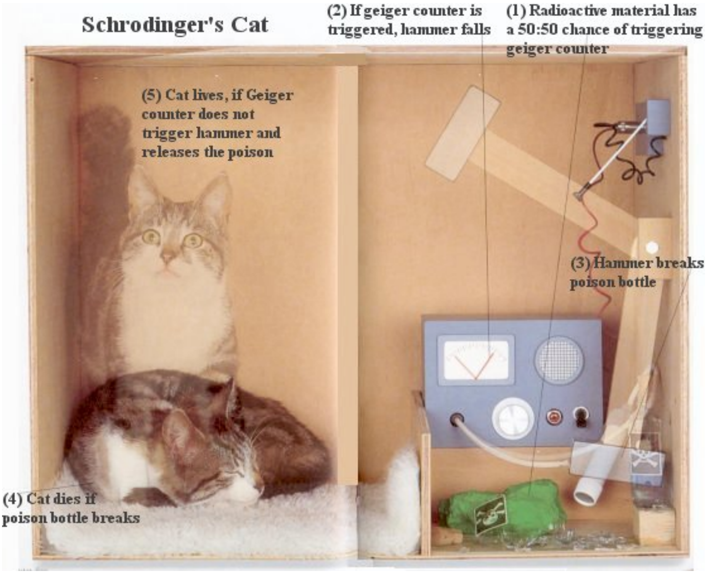
> *"[We] always have had (secret, secret, close the doors!) we always have had a great deal of difficulty in understanding the world view that quantum mechanics represents. At least I do, because I'm an old enough man that I haven't got to the point that this stuff is obvious to me. Okay, I still get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

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

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

  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 fct) 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 fct?
- Answer: the consciousness of the observer

$\Rightarrow$ Wigner's "idealism"

- Illustration: the paradox of Wigner's friend

Wigner's friend

- 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 bc 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 bw system and classical world of observation reports...

Finally: The measurement problem

Albert, Ch. 4.

- Suppose that everything evolves according to the Schrödinger equation.

Principle (Schrödinger evolution)

Given the state of any physical system at any "initial" time, and given the forces and constraints to which the system is subject, the Schrödinger equation gives a prescription whereby the state of that system at any other time is uniquely determined. This dynamics of the state vector is thus deterministic.

- The dynamical laws are linear: if any state $|A\rangle$ at t_1 is evolved into another state $|A'\rangle$ at t_2 and any $|B\rangle$ at t_1 is evolved into $|B'\rangle$ at t_2, then $\alpha|A\rangle + \beta|B\rangle$ at t_1 is evolved into $\alpha|A'\rangle + \beta|B'\rangle$.

- Suppose we have hardness measuring device: device with dial with three settings (“ready”, “hard”, “soft”).
- Set the device s.t. it reads “ready” and then feed e^- into it, and get their hardnesses measured. These measurements are recorded by final position of dial (“hard” or “soft”).
- Assumptions entail that measuring device must act such that:

$$|\text{ready}\rangle_m |\text{hard}\rangle_e \longrightarrow |\text{“hard”}\rangle_m |\text{hard}\rangle_e \quad (1)$$

$$|\text{ready}\rangle_m |\text{soft}\rangle_e \longrightarrow |\text{“soft”}\rangle_m |\text{soft}\rangle_e \quad (2)$$

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

$\Rightarrow$ 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, and by Born's Rule for the probabilities, we get

$$\begin{array}{lll} \textit{either} & |\text{“hard”}\rangle_m|\text{hard}\rangle_e & \text{(w/ prob 0.5)} \\ \textit{or} & |\text{“soft”}\rangle_m|\text{soft}\rangle_e & \text{(w/ prob 0.5)} \end{array} \tag{4}$$

- 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...

Instrumentalism and realism

Potential solution to the measurement problem: instrumentalism

Definition (Instrumentalism)

"Instrumentalism can be formulated as the thesis that scientific theories—the theories of the so-called 'pure' sciences—are nothing but computational rules (or inference rules); of the same character, fundamentally, as the computation rules of the so-called 'applied' sciences." (Karl Popper, Conjectures and Refutations: The Growth of Scientific Knowledge*, Routledge, 2003)*

- Problem: this precludes scientific realism—but we might like to say that QM tells us something true about the world...
- Specifically, if the Copenhagen interpretation just tells us that there is a "collapse", a "reduction of the wave packet", we want to know where, when, and how exactly this physical process occurs.

Maudlin's formulation 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.

- 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.*
- B *"The wave-function always evolves in accord with a linear dynamical equation (e.g. the Schrödinger equation).*
- 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 A is true, and thus the wave function must specify every physical fact about the measuring device, and B is true, then C must be false, etc. □

Taxonomize the solutions to MP

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

New physics

- A solution to MP must thus by necessity either be a AV thy, a non-linear thy, or a multiverse thy (or some combination thereof)—if we're realists.

$\Rightarrow$ each option involves the postulation of new physics:

1. AV thys must specify what additional vars there are and what dynamical laws govern them
2. Non-linear thys must provide the non-linear dynamical eqs and specify under when exactly they apply (something the Copenhagen interpretation did not do)
3. Multiverse thys 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

Concentrating on the first two options, 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)*