Quantum mechanics & superposition

Let’s turn now to the second physical theory we’ll be discussing, quantum mechanics.

We’ll be focusing on just one aspect of this theory, which is the concept of **superposition.**

Albert (in the reading from *Quantum Mechanics and Experience* linked from the course web page) explains this concept using two sorts of properties of electrons, and I’ll follow his development of the example.

He calls the two properties color and hardness, and these properties have three important characteristics:

1. They are **“on/off” properties** in the sense that there are exactly two hardnesses - hard and soft - and exactly two colors - black and white - and every electron has exactly one hardness and one color.

2. They are **independent**, in the sense that there is no correlation between the color of an electron and its hardness.

3. The properties are **measurable**, in the sense that we can test for (e.g.) the color of an electron and get the same result each time.

So far, so good. The oddities begin when we try to figure out **both** the color and hardness of an electron.

Suppose that we have a bunch of electrons, and measure the color of all of them. We then isolate the white ones. Now suppose we take this bunch of white electrons and measure their hardness. As expected, since color and hardness are independent in the above sense, we find that ½ of the white electrons are soft electrons and ½ are hard electrons. Now suppose we isolate the soft electrons from this bunch; it then seems that we will have a collection of electrons which all have color white and all have hardness of soft.

But we don’t. If we re-measure the color of the electrons in the isolated bunch - all of which were previously measured to be white - we find that they are ½ white and ½ black.

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But we don't. If we re-measure the color of the electrons in the isolated bunch - all of which were previously measured to be white - we find that they are ½ white and ½ black.

It seems that something about measuring the hardness of the electrons changes their color. This is by itself not terribly surprising. The surprising thing is that the effect, and even the percentages, remain the same no matter how hardness is measured. (The exact opposite effects result from measuring color rather than hardness.)

The weirdness of this sort of effect is brought out nicely by the sort of experiment that Albert describes on pp. 8-11.

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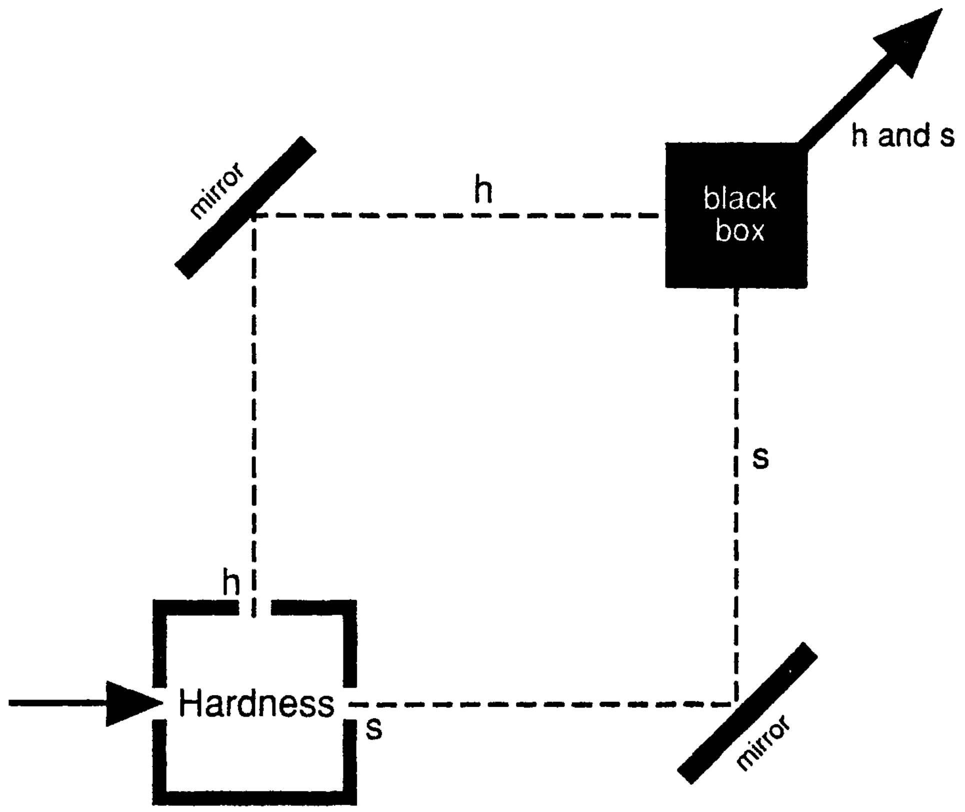
This experiment is a sort of path through which electrons can be fed. They enter at lower left through a box which measures their hardness; if they are measured as soft, they are sent through the slit on the right side of the box, and if they are measured as hard, they are sent through the slit at the top side of the box. Both the "h" path and the "s" path terminate in the black box, through which all electrons exit on path "h and s."



Consider now what will emerge from the black box in the following cases:

A stream of soft electrons are sent into the box.

A stream of hard electrons are sent into the box.

A stream of white electrons are sent into the box.

A stream of white electrons are sent into the box, with the "s" route blocked so that only the electrons which can take the "h" route exit from the box by route "h and s."

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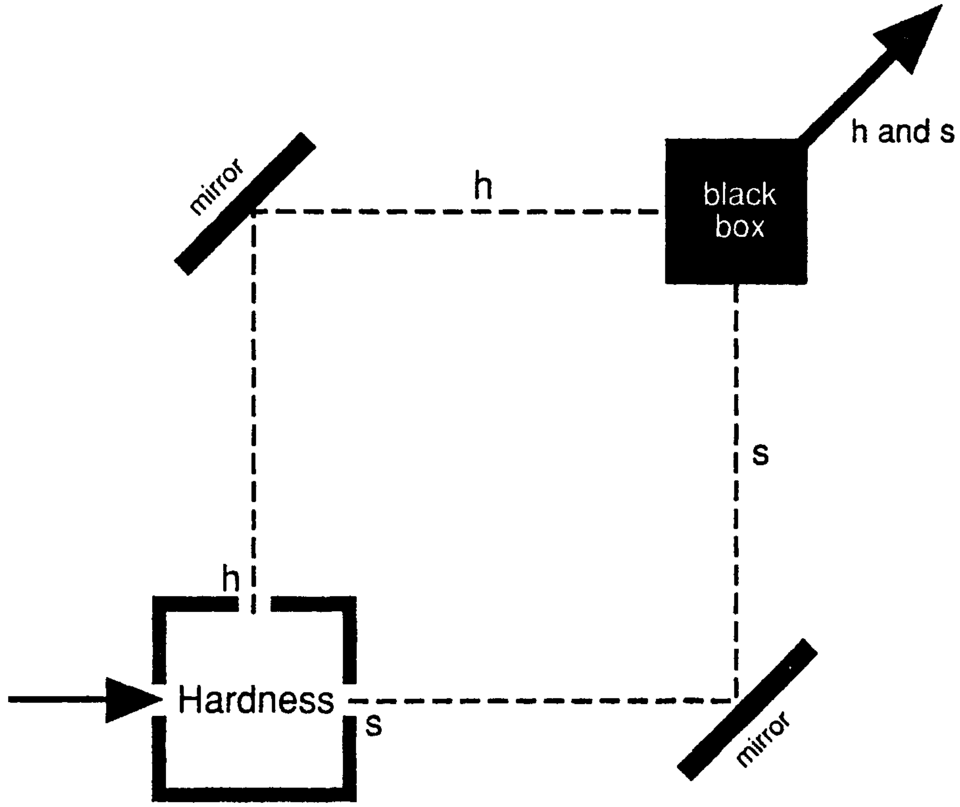

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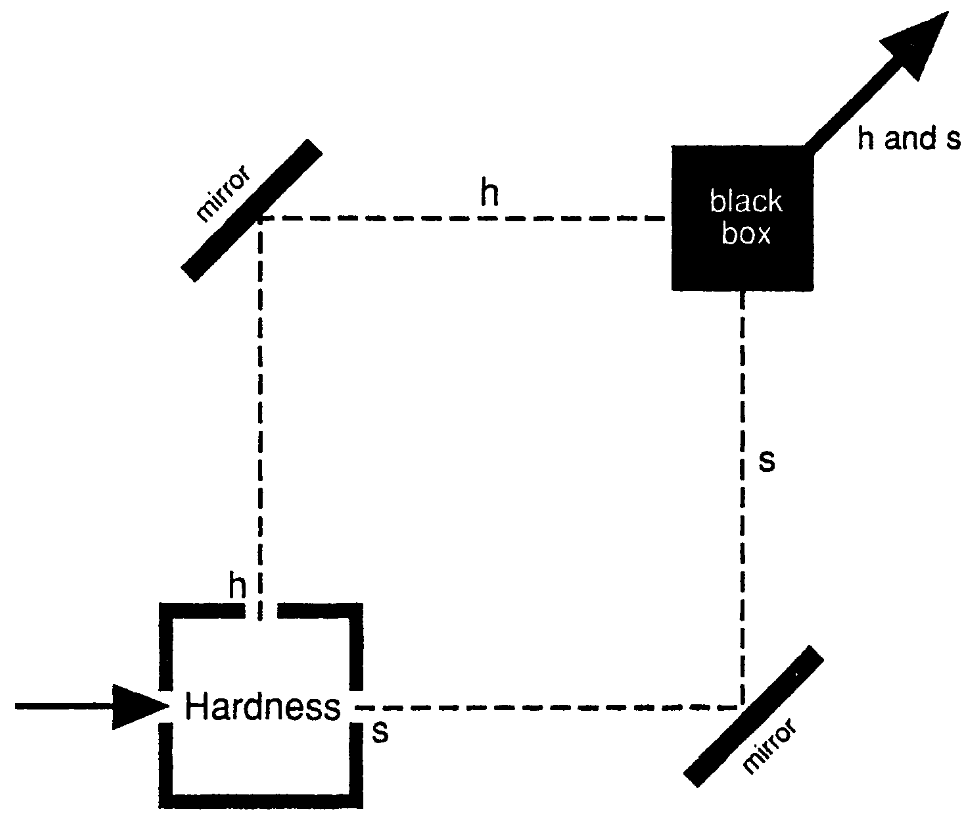
Given the results in the fourth case, focus now on the third case, in which white electrons are fed into the box, and white electrons emerge along route "h and s." Consider this question: how did those white electrons travel from the entrance to the exit?

A natural first thought is that since half of a collection of measured white electrons will be soft and half hard, ½ of the electrons traveled along route "h" and the other ½ traveled along route "s". Why does this seem not to fit the fourth case described above?

A second idea is that each electron in some sense takes both routes; perhaps, for example, they split in half, with one half following the "h" route and one half following the "s" route until they rejoin at the black box. However, if we look at the paths to see what's going on during the experiment, we never find divided electrons, or electrons somehow "spread out" between "h" and "s." Every electron is always on one or the other path, but not both.



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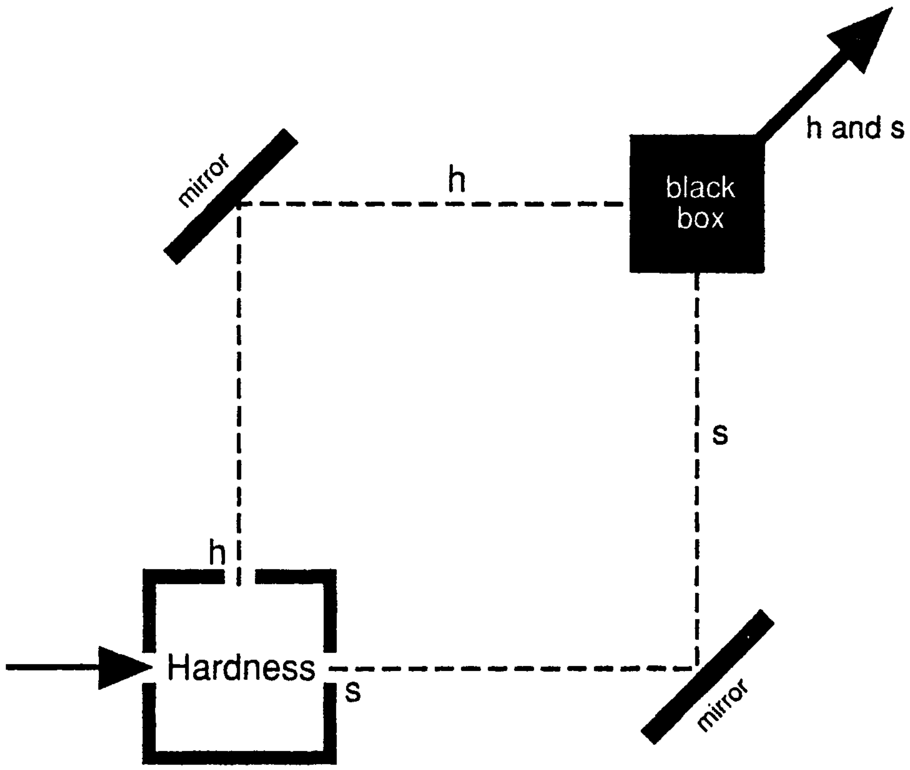
Or maybe they took some third route. But what could this third route be? And why do we always find them on “h” or “s” when we check up on them?

This is thus some very puzzling experimental data. It can also be put in the form of an explicit paradox.

1. If a series of white electrons is sent through the box, all of them will still be white when they emerge along route ‘h and s’.
2. If a series of electrons moves from the entrance of the box to line ‘h and s’, one of the following must be true: (i) they all go along route ‘h’ or (ii) they all go along route ‘s’ or (iii) some go along route ‘h’ and the rest along route ‘s’ or (iv) some go by way of another route.
3. If we block both routes, no electrons arrive at the destination.
4. Option (iv) is false. (3)
5. If we block the ‘s’ route, the electrons which emerge are 1/2 white and 1/2 black.
6. If a series of electrons go through the box through the ‘h’ route, they will emerge 1/2 white and 1/2 black. (4,5)
7. Option (i) is false. (1,6)
8. If we block the ‘h’ route, the electrons which emerge are 1/2 white and 1/2 black.
9. If a series of electrons go through the box through the ‘s’ route, they will emerge 1/2 white and 1/2 black. (4,8)
10. Option (ii) is false. (1,9)
11. If a series of electrons are passed through the box, some of which go along the ‘s’ route and some of which go along the ‘h’ route, the electrons which emerge will be 1/2 white and 1/2 black. (6,9)
12. Option (iii) is false. (1,11)

C. No electrons move from the entrance of the box to line ‘h and s’. (2,4,7,10,12)



The conclusion of the argument is plainly false. Hence, if the argument is valid, it must have a false premise.

The only independent premises of the argument are 1, 2, 3, 5, and 8.

However, 1, 3, 5, and 8 are all experimentally verified, and hence are presumably not plausibly reject-able.

So it seems that we must either say that the argument is not valid, or reject premise 2.

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The only step in the argument whose validity is seriously open to question seems to be the move from (6) and (9) to (11).

Can one reject this, by saying that although the all electrons traveling on route ’s' yields 1/2 white and 1/2 black electrons, and all electrons traveling on route ‘h’ yields 1/2 white and 1/2 black electrons, some electrons being on each path yields all white electrons? Why would this be odd?

Let’s consider instead the possibility that we might reject premise (2).

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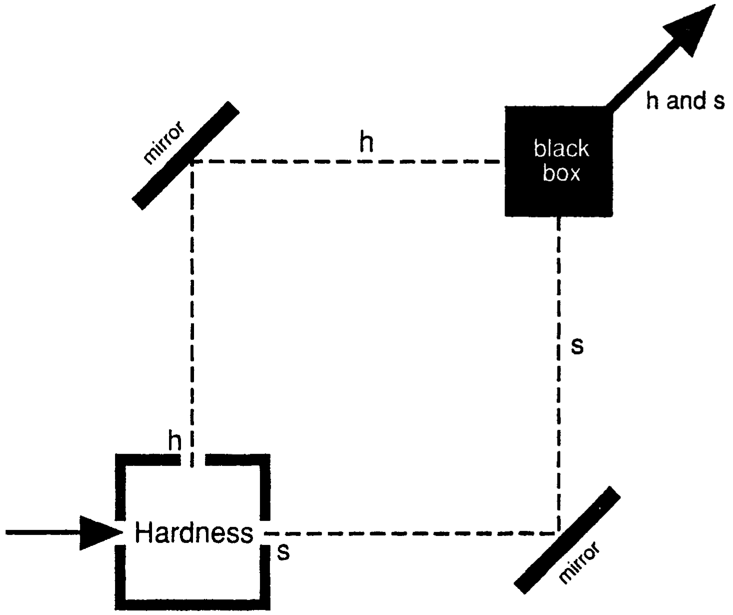

Let's consider instead the possibility that we might reject premise (2).

If premise 2 is false, then the electrons get from the entrance to the exit without following "h", without following "s", without doing some of each, and without following some other path.

If this is right, then there is some sense in which the electron is neither on one path or the other, and is not on both and is not on neither. This is part of what is meant by saying that the electron is in a state of **superposition** of being on route "h" and route "s."

It is not easy to describe this state without contradicting oneself. Suppose that we are describing the path of one of the white electrons, E, on its route from the entrance to the box to route 'h and s.' One is tempted to endorse all of the following claims:

> E is not on route 'h'.
> E is not on route 's'.
> E is on route 'h' or E is on route 's'.

But these claims are jointly contradictory. It can never be the case that 'P or Q' is true along with 'not P' and 'not Q'!

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This looks like a paradox. For it looks like quantum mechanics implies that one of these three claims must be true, even though the claims are contradictory.

One response to this paradox is to say that these three claims are not, in the end, contradictory, because quantum mechanics is such a radical theory that it forces us to revise our view of logic itself. On one way of developing this view, disjunctions — sentences of the form ‘P or Q’ — can be true even if neither of their component sentences is true.

Fortunately, we are not quite forced into this radical view. For we can safely — and consistently with quantum mechanics — deny the third sentence in our list. We can do this by distinguishing between the following two claims:

E is on route ‘h’ or E is on route ’s’.
E is on the union of route ‘h’ and route ’s’.

Compare (to borrow an example from Tim Maudlin) the following two sentences:

The Rocky Mountains are in the United States or the Rocky Mountains are in Canada.
The Rocky Mountains are in the union of the United States and Canada.

E is not on route ‘h’.
E is not on route ’s’.
E is on route ‘h’ or E is on route ’s’.

E is on route ‘h’ or E is on route ’s’.
E is on the union of route ‘h’ and route ’s’.

The Rocky Mountains are in the United States or the Rocky Mountains are in Canada.
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In the example of the Rocky Mountains, we can clearly accept the second sentence but not the first. This suggests that we might be able to do the same in the case of our electron. But then in that case we avoid contradiction, because there is no contradiction between the following three claims (presuming, as before, that ‘on’ means ‘exclusively on’:

E is not on route ‘h’.
E is not on route ’s’.
E is on the union of route ‘h’ and route ’s’.

Still, there remains a puzzle. It is easy to understand how the Rocky Mountains could be in the union of the United States and Canada without being exclusively in either; there are **parts** of the Rocky Mountains which are exclusively in each.

But it isn’t as though part of E is on one route, and another part on the other route. So E’s superposition with respect to the two routes, even if not contradictory, remains extremely difficult to understand. It is simply not clear what it means to say things like “‘E is not just on ’s’ and not just on ‘h’, and has no parts which are just on ’s’ or just on ‘h’ — but, all the same, E is entirely on the space composed of ’s’ and ‘h.’” But this is exactly what we seem to be forced to say. This appears to be a case in which the right response to a paradox is simply to accept a conclusion which, at first sight, looks absurd.

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One might say: 'Well, this just shows that things get very weird when we get to the level of very small things, like electrons. But we can accept that things are a bit odd at this fundamental level without changing anything about our views about the medium-sized objects with which we are acquainted in everyday life.'

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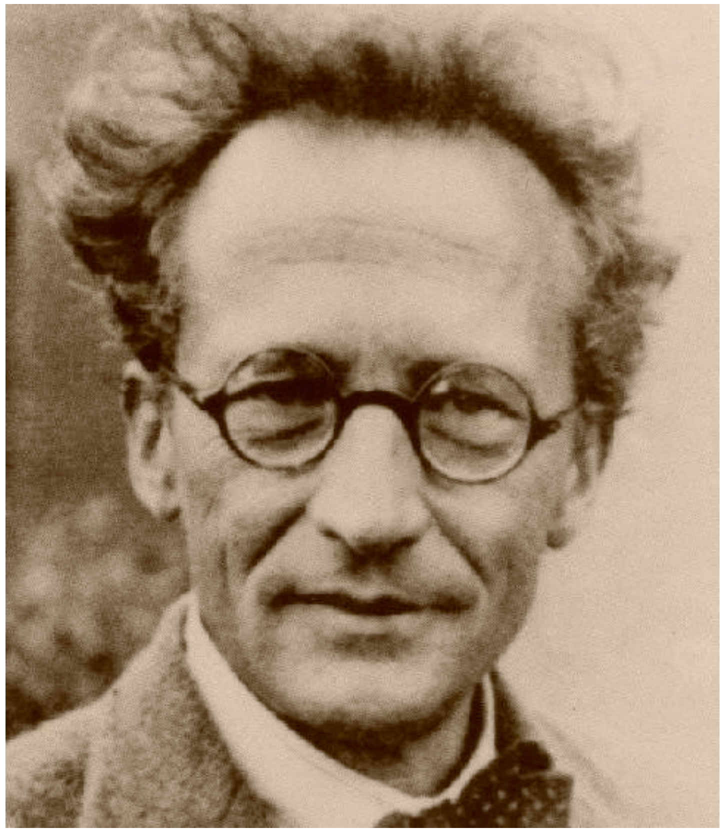
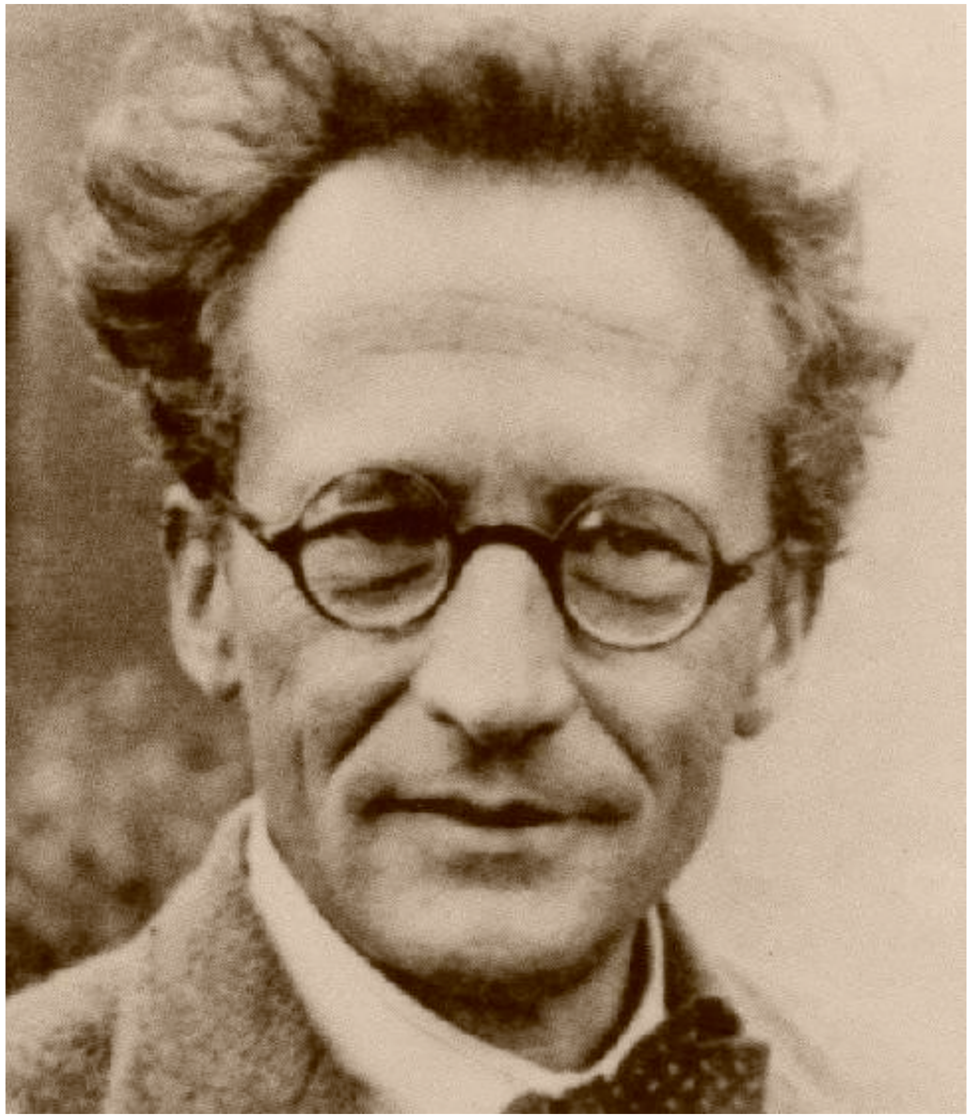
“One can even set up quite ridiculous cases. A cat is penned up in a steel chamber, along with the following device (which must be secured against direct interference by the cat): in a Geiger counter there is a tiny bit of radioactive substance, *so* small, that *perhaps* in the course of the hour one 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, ‘The present situation in quantum mechanics’, §5)



One might equally well imagine that the flask of hydrocyanic acid is linked to the ‘h’ path in the example we discussed earlier, so that the flask is shattered if a given electron passes along this path.

If we reject premise (2) of our earlier argument, and say that the electron was in a state of superposition with respect to the paths — not determinately on path ‘h’, but not determinately not there either — it looks like we will have to say that the cat was, similarly, in a state of superposition, not with respect to its location, but with respect to its being alive.



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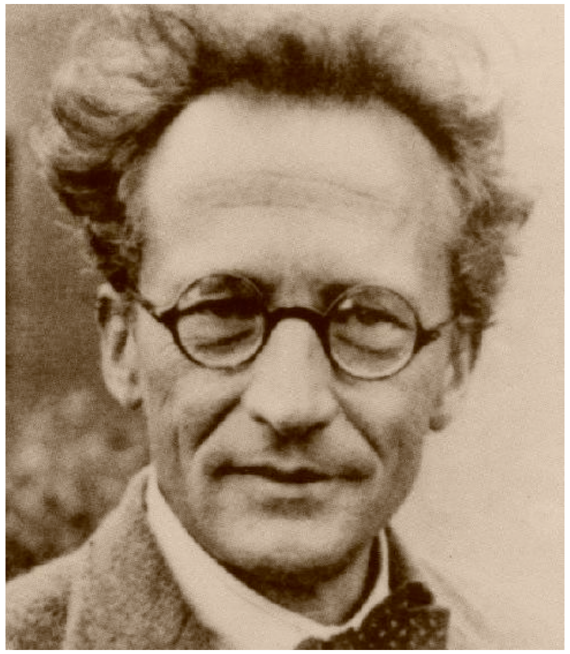
Most of us have a strong inclination to say that this is impossible. A cat can't be in a superposition with respect to dying of cyanide poisoning.

But if this is impossible, then we get a puzzle. For we already have strong evidence for saying that electrons are sometimes in states of superposition; and there seems to be no in principle obstacle to creating a connection, like the one Schrödinger imagined, between microscopic things like electrons and macroscopic things like cats.

The puzzle of Schrödinger's cat is related to a more basic puzzle: how come, when we check up on an electron, we never see it doing anything weird? When we check on its location, it is always on route 'h' or route 's' — never 'smeared' between the two in a state of superposition, whatever that might mean.

There is a standard way of describing what happens when we check up on the location of the electron: one says that states of superposition **collapse** upon measurement. One might also say that, in the case of Schrödinger's cat, we have collapse, so that the cat is either determinately poisoned or not poisoned.

One might wonder: how does the electron know it is being watched? Many early proponents of quantum mechanics held the view that quantum collapse had something special to do with consciousness, and that quantum collapse was somehow to be explained by conscious observation.



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But if we are convinced that there must be collapse in the case of the cat — or any similarly macroscopic on/off property — then it seems unlikely that consciousness is present in all the cases where collapse of the wave function occurs. (And it is unclear, even if it were present, how consciousness could explain collapse.)

The problem of saying just what interactions with particles causes quantum collapse remains unsolved. In a way, this makes superposition doubly puzzling: it is puzzling, not just what it is, but why it goes away.