Schrodinger’s Cat and Wigner’s Friends

According to the Copenhagen interpretation, the state vector for 2-particle quantum state does not disentangle as particles separate in space-time. Instead of changing into two separate vectors, one associated with each particle, the state vector remains entangled and, when a measurement is made, the state collapses instantaneously no matter how large the separation distance.

EPR's view of physical reality says that if two particles are isolated from each other, then they are no longer described by single state vector when a measurement is made.

The reality they are referring to is called **local reality** and the ability of particles to separate into 2 locally real independent physical entities is called **Einstein separability.**

In the EPR experiment, the Copenhagen interpretation denies that the 2 particles are Einstein separable and thus denies they are locally real until a measurement is made on one or other, at which point both become localized and real(the so-called collapse process).

Entangled States and Schrodinger's Cat

Schrodinger proposed a most famous QM paradox.

In our earlier discussions, the notion of the collapse of a state vector was presented without reference to the point in the measurement process at which the collapse occurs.

One might assume that collapse occurs at the moment a microscopic quantum system interacts with macroscopic measuring device.

Is this assumption justified?

A macroscopic measuring device is composed of microscopic entities - molecules, atoms, protons, neutrons and electrons. Interactions takes place on microscopic level, which should use quantum mechanics for their description.

Suppose a microscopic quantum system described by state vector $|\psi\rangle$ interacts with measuring instrument(any device which responds to an interaction with a quantum system producing macroscopic results like pointers or dials) with two measurement eigenstates $|\psi_+\rangle$ and $|\psi_-\rangle$.

These eigenstates combine with macroscopic device to reveal one of 2 possible outcomes of a measurement, deflection of pointer to left (+ result) or right (- result).

Recognizing that the instrument itself consists of quantum particles, we describe the state of instrument before measurement by a state vector $|\phi_0\rangle$, corresponding to central pointer position.

The total state of the **quantum system+measuring instrument** before the measurement is made described by state vector $|\phi_0\rangle$, given by:

$$|\Phi_0\rangle = |\psi\rangle|\phi_0\rangle = \frac{1}{\sqrt{2}}\left(|\psi_+\rangle + |\psi_-\rangle\right)|\phi_0\rangle = \frac{1}{\sqrt{2}}\left(|\psi_+\rangle|\phi_0\rangle + |\psi_-\rangle|\phi_0\rangle\right)$$

where $|\psi\rangle$ has been expressed in terms of its measurement eigenstates (we assume that they form an orthonormal basis as usual) and where

$$\langle\psi_-|\psi\rangle = \langle\psi_+|\psi\rangle = \frac{1}{\sqrt{2}}$$

i.e., both final pointer results are equally probable.

Here is a description of what happens if we treat the macroscopic measuring instrument as quantum object.

First, how does $|\Phi_0\rangle$ evolve in time during act of measurement?

From earlier discussions, we know the application of a time evolution operator $\hat{U}$ allows us to calculate the state vector at later time, which we denote by $|\Phi\rangle$, as

$$|\Phi\rangle = \hat{U}|\Phi_0\rangle$$

or

$$|\Phi\rangle = \frac{1}{\sqrt{2}}\left(\hat{U}|\psi_+\rangle|\phi_0\rangle + \hat{U}|\psi_-\rangle|\phi_0\rangle\right)$$

What is effect of $\hat{U}$ on these states?

If the instrument interacts with a quantum system which is already present in one of measurement eigenstates ($|\psi_+\rangle$ say), then the total system (quantum system+instrument) must evolve into product quantum state $|\psi_+\rangle|\phi_+\rangle$, which is equivalent to saying that the interaction will always produce + result (the pointer always moves to the left), i.e., the state $|\phi_+\rangle$ corresponds the pointer pointing left.

In this case, the effect of $\hat{U}$ on the initial product quantum state $|\psi_+\rangle|\phi_0\rangle$ must be to yield the result $|\psi_+\rangle|\phi_+\rangle$, i.e.,

$$\hat{U}|\psi_+\rangle|\phi_0\rangle = |\psi_+\rangle|\phi_+\rangle$$

or, in other words, if the quantum system is in a state(with probability = 1) corresponding to a definite pointer position, then the measuring device state must evolve into a state where the pointer is pointing to the proper place. This is what happens in the laboratory.

Similarly, we must have

$$\hat{U}|\psi_-\rangle|\phi_0\rangle = |\psi_-\rangle|\phi_-\rangle$$

Using these special case results, we then have for the evolution of any arbitrary state the result

$$|\Phi\rangle = \frac{1}{\sqrt{2}}\left(|\psi_+\rangle|\phi_+\rangle + |\psi_-\rangle|\phi_-\rangle\right)$$

where the measuring device states $|\phi_+\rangle$ and $|\phi_-\rangle$ correspond to the pointer ending up at + or - , respectively.

This result suggests that the measuring instrument evolves into superposition state in which pointer has equal probability to point either to the left or right, but **not into a definite pointer state.**

Thus, neither quantum system nor pointer has a definite value.

This state will remain a superposition(pointer does not point) **unless we allow for collapse** so that the pointer can point (take on a definitie value)!

If this were the final state of the system, then the pointer should never settle down and point somewhere! It has even been suggested that it would have to "flutter" back and forth between the two macroscopically different pointer positions.

Collapsing the state vector of system + measuring-device seems to require a further measurement.

But then whole argument can be repeated ad infinitum and we keep getting larger and larger superpositions.

Are we therefore locked into an endless chain of measuring processes?

At what point does chain stop or at what point does the state vector collapse so we see the pointer actually pointing?

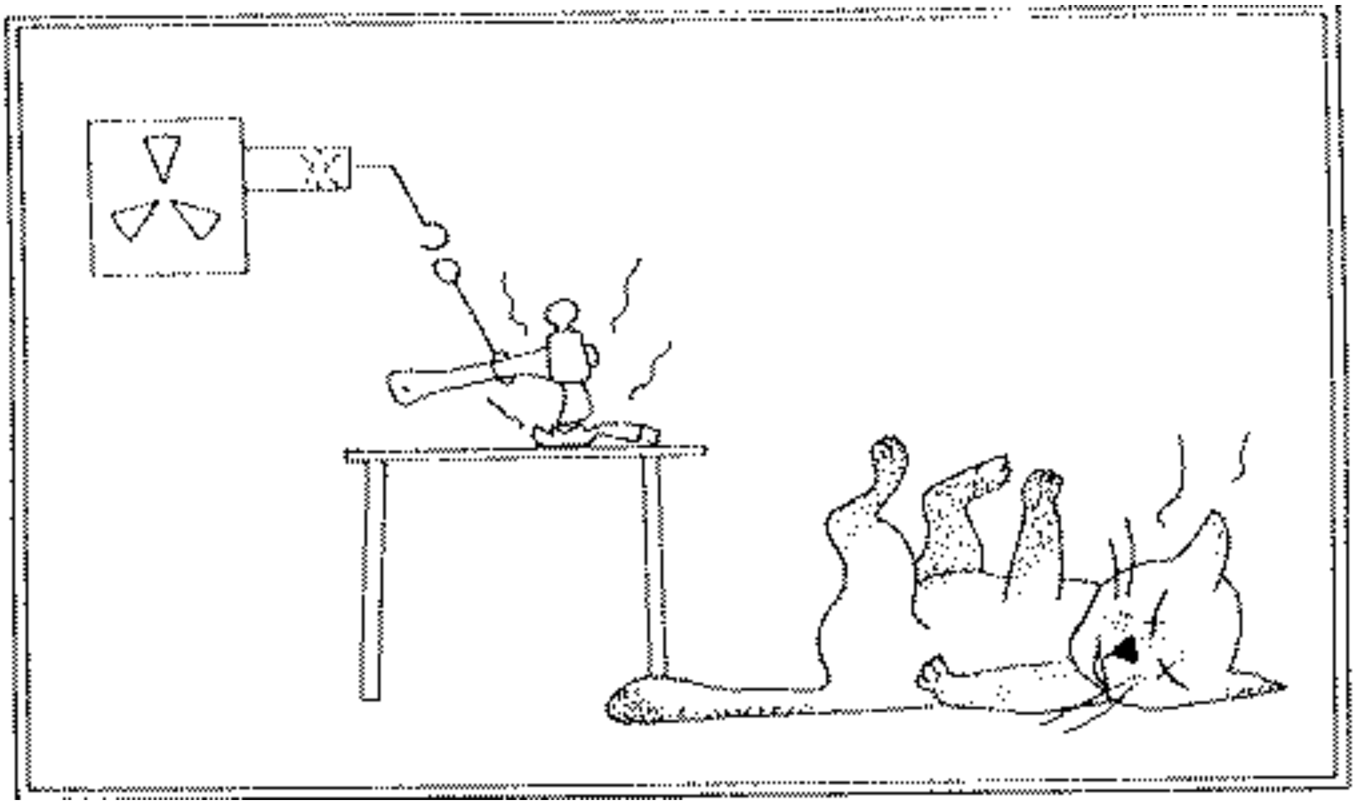
This problem is created by our inability to obtain collapse of state vector using a continuous, deterministic equation of motion from which the time evolution operator is derived.

Schrodinger called state vector $|\Phi\rangle$ given above **entangled** because, once generated, it impossible to separate into constituent parts except by invoking some kind of nondeterministic collapse - some discontinuous process - some non-unitary time evolution.

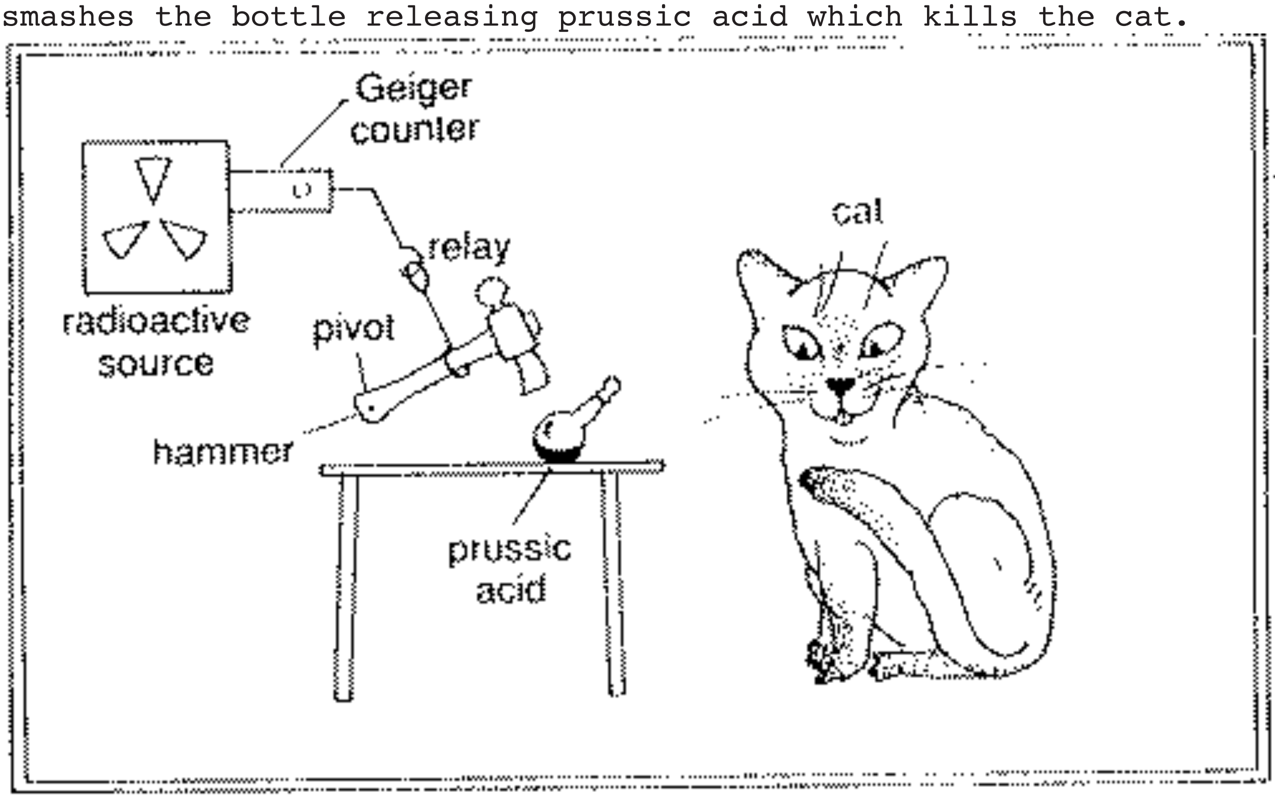
Such a collapse is not accounted for in equations of orthodox quantum theory ... we had to add it as a fifth postulate.

The paradox of Schrodinger’s cat is designed to show up this apparent absurdity by shifting focus from microscopic world of sub-atomic particles to the macroscopic world of cats and human observers.

The essential ingredients are shown in the figures below.



A cat is placed in steel chamber together with radioactive source, a detector, a hammer mounted on pivot and bottle of prussic acid. The chamber is closed. From the amount of radioactive material in the source and the known time for its decay(half-life), it is expected that within one hour the probability is 1/2 that one atom has disintegrated (decayed). If an atom does disintegrate, then the detector is triggered sending a signal to release the hammer that smashes the bottle releasing prussic acid which kills the cat.



Prior to actually measuring a disintegration, the state vector of the radioactive atom must be expressed as linear superposition of measurement eigenstates, corresponding to the physical states of undecayed atom and decayed atom.

However, as seen above, treating the measuring instrument as quantum object and using the equations of quantum mechanics leads to a superposition of two possible outcomes of measurement.

But what about cat?

These arguments seem to suggest should express the state vector of (system + cat) as linear superposition of products of state vectors describing disintegrated atom and dead cat and of state vectors describing intact atom and live cat, i.e.,

$$|\Phi\rangle = \frac{1}{\sqrt{2}}\left(|\text{no decay}\rangle|\text{live cat}\rangle + |\text{decay}\rangle|\text{dead cat}\rangle\right)$$

where the state vector of the dead cat is shorthand for the state corresponding to triggered detector, released hammer, smashed bottle, released prussic acid and dead cat.

Prior to the measurement, the physical state of cat is therefore "**blurred**" - neither alive nor dead but some peculiar combination of **both alive and dead** states. We can perform a measurement on the (system+cat) by opening the chamber and determining its physical state.

Do we suppose at that point (system+cat) collapses and we record the observation that cat is alive or dead as appropriate?

What happens?

The only result that QM predicts is that if we set up N (N large) similar systems, then when we open the N boxes after 1 hour we will find 1/2 the cats alive and 1/2 the cats dead.

That is what actually happens experimentally.

Millions of measurements and probability always wins!

Although obviously intended to be somewhat tongue-in-cheek, Schrodinger's paradox nevertheless brings our attention to important difficulty we must confront.

The Copenhagen interpretation says elements of empirical reality are defined by the nature of experimental apparatus we construct to perform measurements on a quantum system. It insists we resist temptation to ask what physical state a particle (or a cat) was actually in prior to measurement as this question is without any meaning within this interpretation of QM.

This positivist interpretation sits uncomfortably with some scientists, particularly those with a special fondness for cats.

Some have accepted the EPR argument that quantum theory is incomplete. They have set about searching for an alternative theory, one that allows us to attach physical significance to properties of particles without need to specify the nature of measuring instrument, that allow us to define independent reality and that reintroduces strict causality.

Even though searching for such a theory might be engaging in meaningless metaphysical speculation, they believe that it is a search that has to be undertaken.

These are the **hidden variables** people! They have not succeeded with this approach and as we now know the Bell/EPR arguments say that this is a futile search.

Wigner's friend

Now we investigate the influence of **consciousness(the human brain)** on quantum mechanics.

In the early 1960s, physicist Eugene Wigner addressed this problem using an argument based on a measurement made through the agency of a second observer. This argument is known as **paradox of Wigner's friend.**

Wigner reasoned as follows:

Suppose a measuring device is constructed which produces a flash of light every time a quantum particle is detected to be in particular eigenstate $|\psi_+\rangle$. The corresponding state of the measuring device (the one giving the flash of light) is $|\phi_+\rangle$. The particle can be detected in one other eigenstate, $|\psi_-\rangle$, for which corresponding state of measuring device (no flash of light) is $|\phi_-\rangle$.

Initially, the quantum particle in a superposition state

$$|\psi\rangle = c_+|\psi_+\rangle + c_+|\psi_-\rangle$$

The combination (particle in state $|\psi_+\rangle$, light flashes) given by product $|\psi_+\rangle|\phi_+\rangle$. Similarly the combination (particle in state $|\psi_-\rangle$, no flash) given by product $|\psi_-\rangle|\phi_-\rangle$.

If we treat the combined system - (particle+measuring device) - as single quantum system, then we must express the state vector of this combined system as

$$|\Phi\rangle = c_+|\psi_+\rangle|\phi_+\rangle + c_-|\psi_-\rangle|\phi_-\rangle$$

as earlier.

Thus, Wigner can discover the outcome of next quantum measurement by waiting to see if the light flashes.

However, he chooses not to do so.

Instead, he steps out of laboratory and asks a friend to observe the result.

A few moments later, Wigner returns and asks his friend if she saw a light flash.

How should Wigner analyze situation before his friend speaks?

If he considers his friend to be part of larger measuring **device** with states $|\phi'_+\rangle$ and $|\phi'_-\rangle$, then total system of (particle + measuring device + friend)

is represented by the superposition state

$$|\Phi'\rangle = c_+|\psi_+\rangle|\phi'_+\rangle + c_-|\psi_-\rangle|\phi'_-\rangle$$

Wigner can therefore anticipate there will be probability $|c_+|^2$ that his friend will answer **Yes** and probability $|c_-|^2$ she will answer **No.**

If his friend answers **Yes**, then as far as Wigner is concerned the state vector $|\Phi'\rangle$ collapses at that moment and probability that the alternative result was obtained is zero. Wigner therefore infers that particle was detected in eigenstate $|\psi_+\rangle$ and that the light flashed.

Wigner probes his friend a little further. He asks:

What did you **feel** about flash before I asked you?

To which friend replies: I told you already, I did[did not] see the flash.

Wigner concludes (not unreasonably) that his friend had made up her mind about measurement before she was asked about it.

Wigner wrote that state vector $|\Phi'\rangle$=.... involving a superposition of $|\phi'_+\rangle$ and $|\phi'_-\rangle$ appears absurd at this point because it implies that his friend was in state of suspended animation before she answered his question.

And yet we know that if replace Wigner's friend with simple physical system such as a single atom, capable of absorbing light from flash, then the mathematically correct description is in terms of the superposition $|\Phi'\rangle$, and not either of collapsed states $|\psi_+\rangle|\phi'_+\rangle$ or $|\psi_-\rangle|\phi'_-\rangle$.

It follows, according to Wigner, that a being with consciousness must have a different role in quantum mechanics than an inanimate measuring device like an atom.

Of course, there nothing in principle to prevent Wigner from assuming this friend was indeed in state of suspended animation before answering the question. However, to deny existence of the consciousness of his friend to this extent is surely an unnatural attitude.

This is **solipsism** - a view that all information delivered to your conscious mind by your senses is a figment of your imagination, i.e. **nothing exists but your consciousness.**

Wigner was, therefore, led to argue that state vector collapses when it interacts with first conscious mind it encounters.

Are cats conscious beings?

If they are,then Schrodinger’s cat might be spared the discomfort of being both alive and dead: its fate has already been decided by own consciousness before a human observer lifts lid of box.

Conscious observers, therefore, appear to violate physical laws which govern the behavior of inanimate objects.

Wigner calls up a second argument in support of his view.

Nowhere in physical world is it possible physically to act on an object without some kind of reaction.

Should consciousness be any different?

Although small, the action of a conscious mind in collapsing the state vector must produce an immediate reaction -- the knowledge of the state of system is irreversibly generated in the mind of observer.

This reaction may lead to other physical effects, such as the writing of the result in a laboratory notebook or publication of research paper.

In this hypothesis, an influence of matter over mind is balanced by an influence of mind over matter.