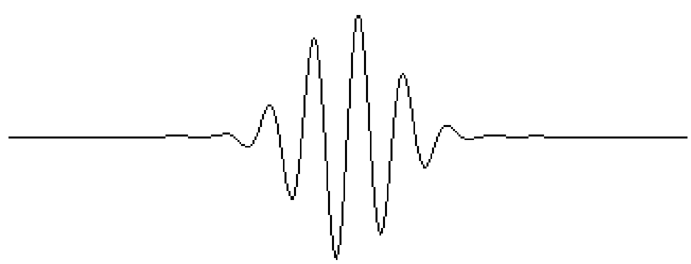
Collapsing Cats and Other Quantum Paradoxes

Last week, we examined the process of measurement in Quantum Mechanics. The theory of measurement in quantum mechanics says that the measurement process is a very special examination of the quantum wave. The basic intuition is that a measurement of a particular quantity is associated with a particular type of quantum wave. A velocity measurement is associated with a sine wave. A position measurement is associated with a spike wave. Measurement of other quantities is associated with other waves (not so easily visualized). If we perform a velocity measurement on a particle whose quantum wave is a sine wave, we will get a clear and unambiguous answer: the velocity of the particle will be given in terms of the wavelength of that sine wave. Similarly, if we perform a position measurement on a particle whose quantum wave is a spike, we will get a clear unambiguous answer: The particle will be at the position of the spike. In this way the meaning of measurement in quantum mechanics is not a problem.

Things get interesting, however, when we try to perform a position measurement on a sine wave or a velocity measurement on a spike or any measurement on a general quantum wave (which may be neither a spike nor a sine wave). We do, of course, get an answer to our observation. Quantum mechanics does not, however, predict what that answer will be. Instead, quantum mechanics tells you all of the possible answers, giving the relative likelihood of each answer. More specifically, quantum mechanics gives the following outline of the process of measurement:

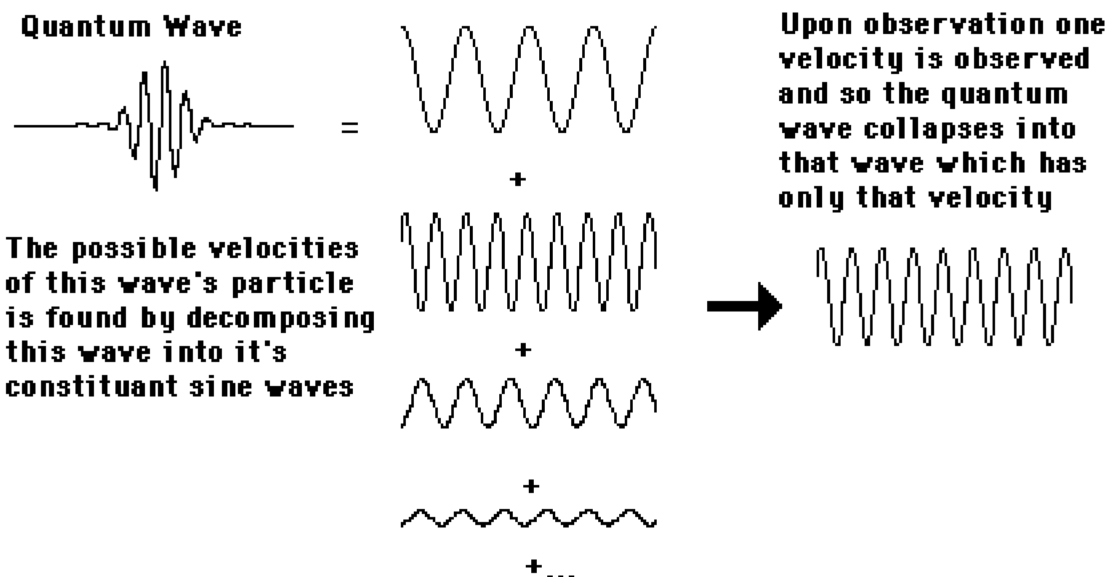
For a general quantum wave, which may look (for example) like this,



here is the process by which some quantity is measured, using the example quantities of velocity and position.

To measure	**a velocity**	**a position**
1) Find the kind of wave associated with this quantity	sine wave	spike
2) Decompose the quantum wave into a sum of this kind of wave	sum of sine waves	sum of spikes
3) When you perform the measurement, you find a single value and so your quantum wave suddenly collapsed to the type of wave associated to the quantity you measured	single sine wave	single spike

This is summarized in the following diagram for the case of a velocity measurement:



When I measure a quantity, I effectively choose a wave determined by both the quantity I chose to measure and how the original quantum wave is made up of these chosen waves. After measurement, the quantum wave becomes the quantum wave that is associated with the particular value of the observed quantity that I found.

It should be mentioned that the mathematical formalism of quantum mechanics only describes steps 1) and 2) in the above process (or those steps before the big black arrow in the diagram). Step 3), the choice of **one** of the waves (that wave corresponding to the value found), is forced on us by the observation that if we measure a quantity on the same particle many times over we will get the same result. The mathematics of quantum mechanics does not (at first glance) indicate how this choice of one of the waves out of the sum of waves takes place, nor does it indicate how this chosen wave becomes the particle's quantum wave.

What does the mathematics say about the process of measurement? If we describe a device measuring the velocity of a particle in terms of the mathematics of quantum mechanics (basically this is done by describing the device itself in terms of a quantum wave), we find that the device's wave is decomposed along with the particle wave. No choice of a particular observed value ever takes place. For example, if we were to measure the velocity of a particle with the quantum wave of the above diagram, the quantum wave of the device would split with one component for every component of the particle's quantum wave in terms of sine waves. This is **not** what we experience when we use a device to measure a velocity. Therefore the idea of the collapse of the quantum wave is imposed on the mathematics of quantum mechanics.

How can this be justified? Clearly there is a problem and the idea of the collapse of the quantum wave solves this problem. But we need more justification than this, since we find that the mathematics of quantum mechanics works everywhere else.

There are really two questions here: Why does the wave function collapse, and what does this collapse (in particular our amount of control over the collapse) say about the quantum description of reality?

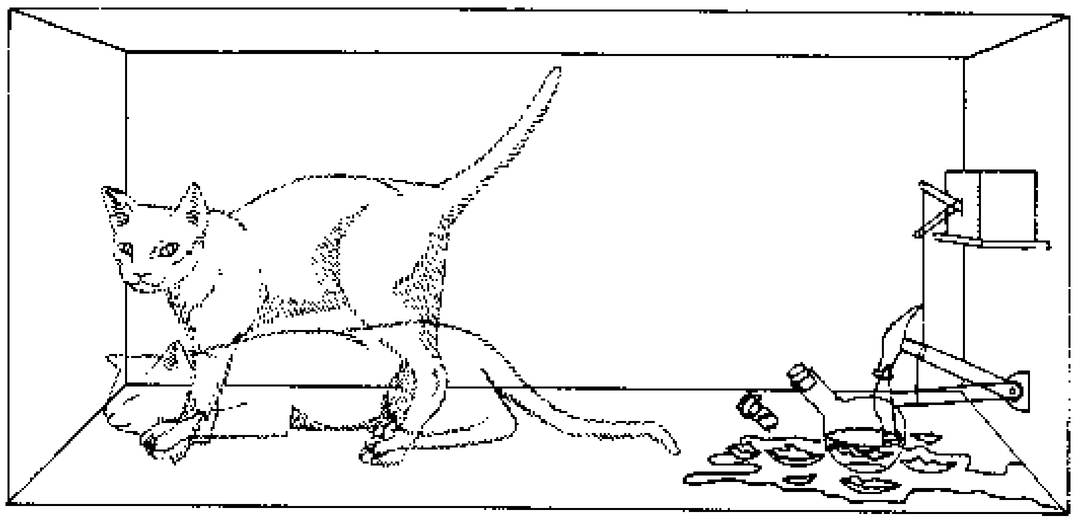
One answer that is often given is that perhaps quantum mechanics only applies to microscopic systems. Then when we measure a quantity (like velocity) we must ultimately use some macroscopic device (like a needle on a gauge). Then if quantum mechanics only applies to microscopic systems it is a mistake to describe the macroscopic device in terms of a quantum wave. Then the quantum wave magically collapses somewhere between the microscopic and macroscopic world.

Many people have a lot of trouble with this answer since it presents a rather artificial distinction between microscopic and macroscopic worlds. Further, it sheds no light whatsoever on the mystery of the collapse of the wave function. Erwin Schrodinger (inventor of the wave formulation of quantum mechanics) came up with the following rather striking example to bring the point home.

The Schrodinger Cat Paradox

(Schrodinger never actually did this!)

Imagine putting a cat in a box with the following "diabolical" device: A measurement is made on the velocity of a particle. I know from the particle's quantum wave that there is exactly a 50% probability that the particle is moving faster than a certain amount, and exactly a 50% probability that the particle is moving slower than the same amount (Schrodinger actually used the time of radioactive decay in his thought experiment). Connected to the device is a hammer that will be released only if the particle is measured to be going faster than that certain amount. Under the hammer is a glass flask of hydrocyanic acid. **If** the particle is observed to be going faster than a certain amount then the hammer will fall on the flask and the cat will die. **If** the particle is observed to be going slower than the same amount the hammer will not be released and the cat will live.



Now put the cat in the box, close the lid, and press the button telling the diabolical device to perform one measurement. Now open the lid and look inside.

The mathematics of quantum mechanics tells us that the particle's measured velocity satisfies both cases (faster and slower than the critical amount) at the same time and the measuring device split into two states, one with the hammer up and one with the hammer down. Both states are equally real according to the mathematics of quantum mechanics. Since the state of the hammer determined the state of the cat, the cat is equally alive and dead according to the mathematics of quantum mechanics. Yet when we open the box and look in we find the cat either entirely alive or entirely dead, **not** both!

It is instructive to examine the various interpretations of the quantum wave in terms of this example. For today, I will consider only those interpretations that in some way admit that the wave function is a fundamental aspect of reality.

The **Copenhagen Interpretation** would say that the question "is the cat dead or alive?" only has meaning after we looked in the box to observe whether the cat was in fact dead or alive. This point of view is mute on the role played by the quantum wave in the world, only talking about the quantum wave in relation to a particular observation. It is also mute on whether the cat counts as an observer. What this interpretation does say is that if you repeated this experiment with many cats half would die and half would live.

The **Consciousness Interpretation** would say that by looking the observer caused the collapse of the quantum wave into one of the observed states with the cat being either dead of alive. Before the observer looked, the cat was neither alive nor dead but was in some kind of limbo state, waiting for an observer to look. Though the act of looking by the observer causes the collapse into one state or the other, the observer has no control over what state the system actually collapsed into. Note that in this example it is assumed that cats are not conscious (I know better).

The **Many Worlds Interpretation** would say that we should take the mathematics of quantum mechanics at face value and admit that the cat really is in both states of being alive and dead. Further, the observer is also in both states of seeing the cat as alive and seeing the cat as dead. Then one finds via some calculations with the mathematics of quantum mechanics that the state in which the observer sees the cat alive cannot **ever** communicate with the state in which the observer sees the cat dead. Thus each state thinks that it is the only one and that the quantum wave collapsed. In fact the quantum wave never collapses, it just feels that way to observers inside the system. It is also claimed that one also finds that in repeated observations the probabilities of quantum mechanics simply fall out of the mathematics. A more modern version says the probabilities come from considering the interaction of the measurement with its environment.

This summarizes the current state of the art in the understanding of why the quantum wave collapses. There still remains the more subtle question of what that collapse says about the quantum description of reality.

The Einstein-Podolsky-Rosen Paradox

Consider a particle described by some general quantum wave, like in the diagram in the beginning of these notes. Without actually doing a measurement, what can we say about that particle's velocity? We can say that if we actually do a measurement we would find such and such a velocity with such and such likelihood. But can we say that the particle actually has a velocity without doing such a measurement? Similarly, can we say that the particle has a position without actually doing a position measurement? One thing quantum mechanics seems to clearly say is that we cannot exactly measure **both** the position and the velocity of the same particle at the same time. This is because velocity and position measurements use completely different types of waves (sine and spike). Can one then even say that a particle has a position and velocity at the same time?

These questions are brought out more clearly in the Einstein-Podolsky-Rosen paradox, henceforth referred to as the EPR paradox. Imagine two particles bound together and motionless relative to the observer.

••

motionless

Now imagine that the two particles fly apart in opposite directions (this actually happens in the world).

<-- • •-->

flying apart with equal and opposite velocities, total motion still adds up to zero

Now it is a true fact that the total quantity of motion in a closed system is absolutely conserved (this is called the law of conservation of momentum). Because the two particles were motionless when they were bound together, the total quantity of motion of this system is zero. After the particles fly apart, their individual quantities of motion must be equal and opposite so that the total for the whole system still adds up to zero.

In this way, by measuring the velocity of one particle after they fly apart I know the velocity of the other particle. Thus I have measured the velocity of both particles. I only interacted, however, with one of the particles. So it seems that the other particle (which I did not interact with) has collapsed it's quantum wave to the sine wave that corresponds to the velocity that I measuredm even though my measurement did not directly interact with that particle.

Now suppose that I did a position measurement on the first particle instead of a velocity measurement. Then, since I know that the velocity of the second particle is exactly opposite that of the first, I know that the second particle has a position which is the same distance from the starting point as the first particle but in the opposite direction. Therefore I have measured the position of both particles, collapsing the quantum wave of both particles to spike waves, even though I did not interact with the second particle.

Thus, without interacting with the second particle, I can determine either its position or its velocity. Thus, say Einstein, Podolsky, and Rosen, the particle really does have a velocity and a position, since it seems unreasonable to them that our measurement process determined the existence of a quantity for a particle that we did not interact with. The quantum wave of the second particle, however, cannot possibly reflect this knowledge of both position and velocity according to the rules of quantum mechanics. Therefore quantum mechanics cannot be a complete (and by implication fundamental) description of reality.

When Einstein, Podolsky, and Rosen presented this paradox in 1935, they intended it to show that the quantum mechanical description of velocity and position cannot be complete, as there was no quantum wave that could reflect our knowledge of the second particle. It has turned out, however, that the EPR paradox has had further implications, which will be described next week.