The "Hidden Variables" Interpretation of Quantum Mechanics

The Einstein-Podolsky-Rosen Paradox Revisited

In this class we have learned that in order to understand the behavior of particles on a very small scale we must take the behavior of particles to be determined by a quantum mechanical wave. It is totally unclear just what this wave is a wave <u>in</u>, but simply knowing such things as the wavelength and the strength of the wave are enough to determine the position and velocity behavior (though not the actual position or velocity values) of a particle. All this is perhaps not too hard to buy, as we are already used to treating such things as sound as waves. In the case of quantum waves, however, we went on to discover that in the act of observing a quantum wave (by observing that wave's particle) we changed the behavior of that quantum wave in an unpredictable way--the collapse of the quantum wave. Further, what we observed (position vs. velocity) determined what kind of wave the quantum wave collapsed into. Thus somehow our choice of what we are looking for in a particle necessarily determines the actual quantum wave of that particle.

This is **not** how an element of reality is commonly believed to behave. Usually, something is thought to be real if it is there whether you are looking at it or not. In particular, something "really out there" is there with all it's properties no matter how you are looking at it. Yet in quantum mechanics, it seems (if you want to take the quantum wave as an element of reality) that the quantum wave becomes one thing if you try to measure position and another thing entirely if you try to measure a velocity! But if you try to deny the reality of quantum waves then you will have a <u>very</u> hard time understanding the various experiments detecting the quantum wave (everything from atomic spectra to the interference experiments). This is the essence of our problem.

This problem was explicitly brought out in the paper of Einstein, Podolsky, and Rosen called "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?", published in 1935. This is the paper that outlined what has become known as the Einstein-Podolsky- Rosen (EPR) paradox which was described in a simple form in last week's notes. In this paper the authors gave a criterion for whether of not an object is an element of reality:

"If, without in any way disturbing a system, we can predict with certainty (i.e. with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity."

This criterion fits well with the above intuition about how reality is supposed to behave with respect to observation. The basic idea here is 'if I can repeatedly observe it without interacting with it then it must be there'. Then the problem becomes how to observe something without interacting with it.

Einstein, Podolsky, and Rosen concocted an example that did just that. Imagine two particles bound together and motionless relative to the observer. Now imagine that the two particles fly apart in opposite directions (this actually happens in the world). 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). As 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 can predict with certainty the velocity of the other particle. Since they fly exactly apart, by measuring the position of one particle I can predict with certainty the position of the other particle. Thus without interacting with the second particle I can predict both it's velocity and it's position (though not in the same experiment as when I measure one quantity (say a velocity) on the first particle I impart some new motion on it thus destroying it's relationship with the other particle). So, according to the Einstein-Podolsky-Rosen criterion for reality, the velocity and position of the second particle are elements of physical reality. So far, so good. The quantum description of this second particle, however, is totally incapable of giving both an actual position and an actual velocity to the second particle as this description is in terms of the quantum wave. Thus quantum mechanics is unable to completely describe the reality of the second particle's state. Thus quantum mechanics must be incomplete.

This paper and the EPR paradox raised quite a furor. As Leon Rosenfeld (an early champion of the Copenhagen Interpretation) later said, "This onslaught came down upon us as a bolt from the blue...". The physics of the EPR paradox is completely sound. When the dust settled, there were basically two responses:

The Quantum Mechanics Camp: Quantum Mechanics is Complete. The criterion for physical reality being somehow independent of observation is an inappropriate denial of the revolution in our picture of reality brought to us by Quantum Mechanics. Somehow in some way our observing the first particle determined the reality at the second particle (in exactly the same way that our observation determined the reality of the first particle). This happens instantaneously even though we may wait until the particles are light years apart before we perform any measurements (though luckily it has been shown that one cannot send messages that way so that relativity theory is safe).

The Reality Camp: (This evolved into the Hidden Variables interpretation) While there is something very right about quantum mechanics, it is still incomplete. There must be some more complete, presumably deterministic, 'hidden' physics underlying quantum mechanics, just as the physics of moving atoms underlies our theories of heat and temperature. The quantum wave is somehow an average over these unknown 'hidden' physical realities that are really there. We are now stuck with the quantum wave only because we don't know what is really going on.

As we spent the last class in the quantum mechanics camp, the rest of these notes will be an examination of the history of hidden variables.

The claim of the hidden variables interpretation is this: Reality is really made of some hidden physics that we really don't know about. Quantum mechanics is our best current knowledge of this hidden realm but this knowledge is incomplete. Once we discover and fully understand how this currently hidden reality works, we will have the ability to completely predict the behavior of particles.

There is one thing that hidden variable theories must do, and that is completely contain all the tested predictions of quantum mechanics, because quantum mechanics is so successful.

The Fall and Rise and Fall of Hidden Variable Theories

The idea that quantum mechanics is actually some average over some as yet unknown physics is as old as the wave function itself. This idea is a natural reaction to the lack of certainty that comes with the introduction of the quantum wave. This idea was supposedly disposed of, however, by John Von Neumann in 1932 (Von Neumann, by the way, gave us the mathematical description of the quantum measurement process). He 'proved' that a deterministic underlying physical theory must necessarily disagree with quantum mechanics, independently of the details of the underlying theory. As quantum mechanics was being completely vindicated by experiment this apparently settled the matter.

Then David Bohm came along in 1952 and actually constructed an explicit example of an underlying deterministic theory which completely mimicked quantum mechanics in it's predictions. Bohm was not claiming that this underlying theory described any reality, rather he was just showing that it could be done and that somehow Von Neumann's proof to the contrary had a hole in it. Then John Bell finally, in 1964 (published in 1966), showed where Von Neumann, in his non-existence of hidden variables proof, made an overly restrictive assumption. Thus it seemed that the possibility of hidden variables was back and perhaps we didn't have to believe in the quantum wave after all.

Later in 1964 Bell went on to examine the EPR paradox in the light of hidden variable theories. He discovered that if hidden variable theories are to completely mimic the predictions of quantum mechanics in the case of the EPR paradox then these hidden variable theories must be "non-local" in the sense that what happens here may instantaneously effect what is happening light years away. Unlike in the pure quantum case, this is a physical force of some kind, so this is in complete contradiction with relativity theory, and so is even less palatable to a physicist than going over to the quantum mechanics camp.

If one **insisted** on local hidden variable theories, that is theories that behaved according to relativity theory, then Bell showed that these types of hidden variable theories <u>must</u> make predictions different from quantum mechanics in EPR type experiments. The specific different predictions that these local hidden variable theories make is expressed in what has become known as 'Bell's Inequality' (sometimes mislabeled Bell's Theorem). They simply say that you should get different numbers in certain experiments than would be predicted by quantum mechanics.

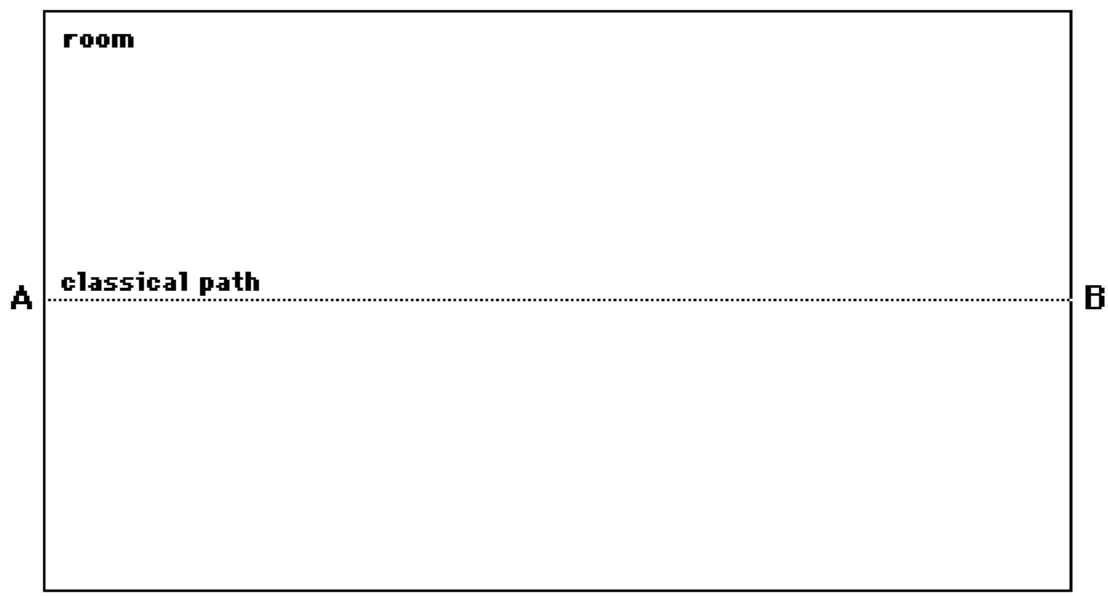
Starting in 1969, several experimenters (John Clauser, Michael Horne, Abner Shimony, Richard Holt, Stuart Freedman, Edward Fry, Randall Thompson, M. Lamehi-Rachti, W. Mittig and Alain Aspect, to name a few) proposed and carried out several actual experiments testing the Bell inequalities with both photons and protons. In all cases (except one which caused some excitement before it was chalked up to experimental error) quantum mechanics clearly gave the correct results in opposition to local hidden variable theories.

So where we now stand is this: It seems clear from experiment that local (which is to say well behaved) hidden variable theories are excluded from being possible descriptions of nature. It is still possible to imagine that there is an underlying deterministic theory of which quantum mechanics is an approximation, but this underlying theory must violate special relativity (which is probably the most solidly tested theory in physics). As this seems rather unreasonable to most working physicists, the consensus is that quantum mechanics with it's quantum mechanical wave is the underlying reality.

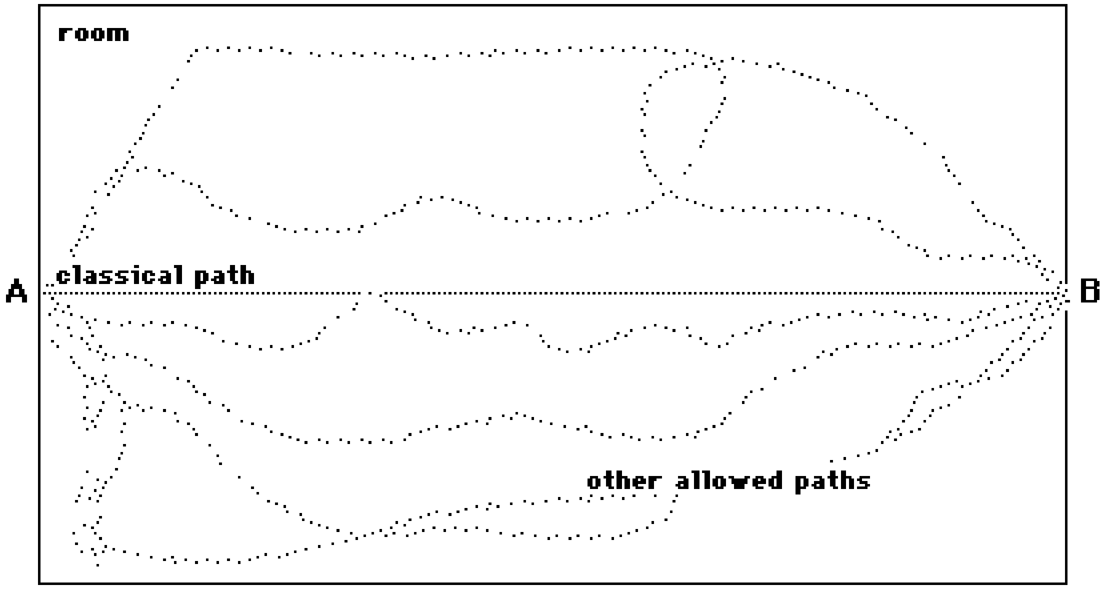
Another approach to the wave function: The Feynman Path Integral

There is a new approach to quantum mechanics due to Richard Feynman that is rapidly taking over in research in quantum field theory. Here I want to give a brief and simple description of this approach.

Feynman starts by saying that there is no wave function, rather what is strange about the world and gives rise to the wave aspects of nature is that motion is not what you think it is. Consider an electron moving from one end of the room to another, saying that it started at some particular place and ended at another place. Label the starting point A and the ending point B. Classically, in the absence of any forces, the electron would travel in a straight line, the straight line from A to B:



Feynman says "no, actually the electron traveled along every conceivable path starting at A and ending at B at the same time." That is, the electron did not travel in any sense along any particular path, but rather was somehow everywhere at once (even though it is still a particle):



Then Feynman says that there is associated with this particle a quantity called an amplitude which is given by adding up all the particle paths (whatever that means) with each term in the sum of particle paths multiplied by a weight function (a mathematical term). Thus each term in the sum looks like

(weight function) times (path)

And the amplitude of the particle looks like

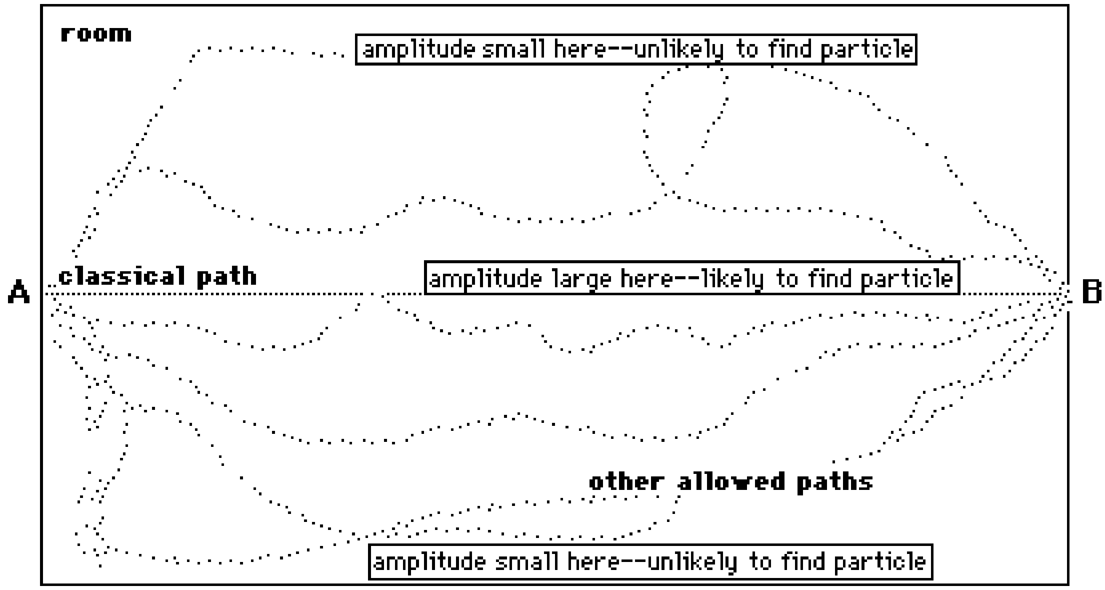
amplitude = sum of [(weight function) times (path)] added up over all paths

This amplitude is called the Feynman path integral.

All the physics is contained in the weight function, and it is designed so that the paths that are radically different from the classical straight line will, on the average, cancel each other out in the sum that gives the amplitude. This cancellation becomes less and less likely for paths closer and closer to the classical straight line path.

Then Feynman discovered that this amplitude with this special weight function behaves exactly like the wave function of orthodox quantum mechanics. In this way Feynman derived the wave function of quantum mechanics by taking a radically different view of motion.

The significance of this amplitude is that when we look to find the electron at a particular point, the probability that we will find the electron at that point is given by the magnitude of the amplitude. Thus in the above example where the electron is moving from point A to point B, the amplitude along the classical straight line is very large so it is likely that we will find the particle traveling along the classical straight line. Far from the classical path, the amplitude is small (though not zero) due to the average cancellation, so it is unlikely that we will see the particle there (though there is some chance):



While all this is very pretty and somewhat compelling as an understanding of how quantum phenomena arise, it should be kept in mind that the construction of the weight function is very artificial and ad hoc (though not any more so than orthodox quantum theory). It would be very nice to motivate this weight function as then we would have some understanding of why quantum mechanics is true. Currently, the closest we are to this is the observation that the Feynman path integral arises naturally when asking questions about random processes in general mathematics (the field of stochastic calculus). Perhaps this implies that at some level the universe is truly random. This is a very new area of research.