On The Mysterious Aspects of Quantum Mechanics

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There are many aspects of quantum mechanics that are very different than the classical world. This paper looks at some of the most important ideas and experiments in quantum mechanics that exhibit these strange aspects. Surprisingly the vast majority of these mysterious aspects can be explained by a single postulate which we call "The Wholeness Postulate." This simply says that "The outcome of an experiment depends on the ***whole*** setup of the experiment." This seemingly obvious statement will have ramifications throughout all of the foundations of quantum mechanics. By looking at what we mean by "whole" we will see the important role that space, time and free-will play in quantum mechanics.

One of the greatest developments in all of physics is quantum mechanics. With the exception of gravity, all other physical phenomena are described by this theory. The interactions from inside of an atom, to the workings inside the sun follow the laws of quantum mechanics. These laws show us that the world is extremely mysterious and defies our attempts to make sense of it. In this article, we will discuss some of the highlights of quantum mechanics and see what they say about our universe. The weirdness we shall describe cannot be brushed away. As strange as the results sound they are a part of science.

Although there are many different, strange, and counterintuitive parts of quantum mechanics, we shall show that most of the bizarre aspects can be understood as consequences of the following simple intuitive idea:

The Wholeness Postulate

The outcome of an experiment depends on the ***whole*** setup of the experiment.

This makes sense. After all, one should expect that different experiments should yield different outcomes. What was unexpected was how much of the whole experiment was needed as opposed to just parts of it. The word "whole" is emphasized because, as we shall see, most of the strange

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aspects of quantum mechanics can be understood as simple consequences of what we mean by that word. We shall return to this postulate over and over again.

Let us begin our tour of several aspects of quantum mechanics.

Superposition. The first experiment is called the double-slit experiment. Richard Feynman, in discussing this experiment, waxed lyrical:

> We choose to examine a phenomenon which is impossible, absolutely impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the only mystery. We cannot make the mystery go away by "explaining" how it works. We will just tell you how it works.[2]

The experiment was first performed by Thomas Young in the beginning of the nineteenth century. Imagine shinning a light onto a barrier with two small slits that are very close to each other. If you close one of the slits and shine a light at the wall, the light will pass through the single open slit and radiate out to the screen behind the slit. The light will be intense directly across from the open slit and will be less intense farther away from the slit.

If the second slit is opened, something very interesting happens. The light passes through both slits with an alternating pattern where some regions have intense light and some regions have less light. We call such a pattern an *interference pattern*. The reason for this strange light pattern is that light is acting like a wave with crests and troughs. When the crests of the light wave from one slit meet the crests of the other light wave, they combine and the light is intense. In contrast, when the crests meet the troughs, the waves cancel each other out and there is less light.

Now for the most amazing aspect of this experiment and probably the most mind-blowing result in all of science. Physicists have a way of performing this experiment by releasing one piece of light or *photon* at a time. After releasing a photon, it passes the barrier, hits the screen and makes a little light. They perform this experiment millions of times and see the pattern that the photons make on the screen. The remarkable aspect is that an interference pattern is still found. That is, many of the individual photons will land in the area where there was a high intensity, and few will land in areas where there is low intensity. How can this be? When we have many photons, we can say that the photons are interfering with each other like waves in a pond. But when each photon is released one at a time, what can a single photon interfere with to make such a pattern? The answer is that the single photon interferes with *itself*. The individual photon does not pass through one slit or the other slit. Rather, the photon passes through *both* slits simultaneously and when the single photon emerges through both slits, it interferes with itself.

How can one object pass through both slits simultaneously? That is the major mystery of quantum mechanics. Usually an object has a *position*, that is, a single place where the object is

[2] From Feynman (1963), volume III, Page 1-1.

found. But here, an object can be found in more than one position. The phenomenon of being in more than one place at one time is called *superposition*.

Whenever I open my eyes, I see objects in exactly one place, not in many places. It seems as though we live in a world with position not superposition. This computer screen I am looking at is only in one place. And yet, there is superposition. We might not see it, but we see the consequences of superposition. After all, we do not see wind either, but we see the trees bend.

Researchers are not in total agreement as to why we do not see things in superposition. All that is known is that when the system is *measured*, we no longer see a superposition. We say the system *collapses* from a superposition of many positions to one particular position. The *measurement problem* asks why this collapse occurs and is one of the major discussion points in the philosophy of quantum mechanics.

This concept of superposition is the main idea in quantum mechanics. It will be our central concern throughout the rest of this article. Position of an object is not the only property that is subject to such craziness. Many other properties in the quantum world like energy, momentum, spin, and velocity, also have many values simultaneously and then collapse to one value when measured. For all these different properties of quantum systems, superposition will be the norm until the system is measured.

The Wholeness Postulate is easily seen for the double slit experiment. The outcome of the experiment (whether or not there will be interference) depends on the setup of the whole experiment, i.e., whether or not both slits are open. This instance of the Wholeness Postulate is not so strange.

Randomness. Objects are in a superposition until they are measured, and when they are measured they collapse to a single position. The obvious question is to which of the possible positions does a measured superposition collapse? Physicists tell us that it is random. There is no deterministic law that states exactly to which position each object will collapse. The laws that tell us how the particle will collapse are probabilistic laws. That is, the laws say that there is a probability that it will collapse this way and a probability that it will collapse that way.

At this point, you might be skeptical about this lack of determinism. After all, all the other laws of physics are deterministic. There must be something that physicists are missing that would explain the seeming randomness of it all. You would not be alone with such skepticism. Albert Einstein, one of the forefathers of quantum mechanics, also did not believe it. He expressed his skepticism with the rather colorful phrase “God does not play dice with the universe.” Einstein did not believe that the fundamental laws of physics are random. Supposedly, Niels Bohr responded “Don’t tell God what to do.” The universe works the way it does and it does not have to satisfy our wishes. Most contemporary physicists assure us that Einstein was wrong and the universe at its very core is not deterministic and hence random.

There are those who have taken up Einstein's challenge and are looking for laws of quantum mechanics that are deterministic. They believe the laws are governed by *hidden variables*. That is, there are extra variables in the system that cannot be seen but when they are taken into account, the laws of quantum mechanics are deterministic. This is similar to a chaotic system in the classical world. Consider the lottery machines that work by mixing up balls in a giant jar. Such machines are used because there is no way to predict which balls they will choose. Nevertheless, despite the machine being unpredictable, the laws describing what goes on in the machine are totally deterministic. Every ball bounces around following fixed deterministic laws but there are too many individual parts of the system for there to be predictability. The exact position of every ball and every air molecule are the hidden variables in this system. Some physicists posit that quantum mechanics also has variables that cannot be seen. Such hidden variables are a possibility, and if they are true then all of the laws of the universe are deterministic.

How are we to look at the randomness in quantum mechanics with respect to the Wholeness Postulate? If we are going to accept that quantum mechanics is deterministic and that there really exist hidden variables, then the Wholeness Postulate says that you have to take into account the hidden variables to totally determine the outcome of an experiment. While that might not be feasible, it remains true. In contrast, if one believes that quantum mechanics is random and there are no hidden variables, then, at a deep fundamental level, there really are no rules about outcomes of experiments. Or to say the least, the outcome of an experiment does not depend on anything. They are random.

Heisenberg's Uncertainty Principle. Watch a car speeding down a highway. It is easy to determine both the color of the car and the speed of the car as it is moving. One can effortlessly figure out a person's weight and height simultaneously. Similarly, one can determine the exact position and momentum of a flying baseball. The point is that it is not hard to determine two different properties of an object. This obvious fact is true for the world we live in but simply fails in the quantum world. There are situations in the subatomic world where two properties cannot be determined at the same time. This is the essence of Heisenberg's uncertainty principle. For example, it is impossible to know both the position and the momentum of a moving subatomic particle.

In detail, given two such properties, X and Y, we will get one pair of answers if we measure X first and then measure Y, and other answers if we measure Y first and then measure X. For example, first measuring the momentum and then the position of a subatomic particle will yield different answers than first measuring the position and then the momentum of that particle. This leads to the obvious question: what exactly are the momentum and the position of the object? Why are we getting two different answers here? Aren't there objective values of these properties that are independent of our observations?

Researchers going back to Niels Bohr take this one step further. They proclaim that it is wrong to say that humans learn the properties when they measure them. Rather, they say that the very act of measurement causes the properties to become well defined. Before any measurements, the properties are in a superposition. When X is measured, the X property collapses to a single value while the Y value remains in a superposition. If the Y property is then measured, then it too collapses. The point is that if the measurements were done in a different order then the values could collapse into different values.

With respect to the Wholeness Postulate, we see that the outcome of the experiment depends on the whole experiment within time. That is, the outcome of the measurement Y depends on whether measurement X was done first in time or not. We cannot take each measurement by itself. All the measurements and the order in which they were performed must be taken into account.

Notice that there is a radical new element that comes into play here. The outcome of the measurement Y depends on whether or not the person doing the experiment decided to perform measurement X first. The experimenter is not separate from the experiment. Rather, the experimenter has become part of the experiment and influences the outcomes of the experiment. The person who does the experiment influences the world that he or she is investigating. This is a revolutionary idea. No longer is there a closed system and an experimenter examining that closed system. Now the human experimenter is also part of the system. This can be seen in terms of the Wholeness Postulate: the experimenter is part of the *whole* experiment.

The Kochen Specker Theorem. You might say that all this talk of superposition is nonsense and that when a subatomic object is measured there is a determination of a property that was there before we measured it. The measurement did not cause the property to come into existence; it was always in existence. Alas, this seemingly sane and bold stance is wrong and we shall prove it.

We need some preliminary notions. One of the central ideas of quantum mechanics is the notion of *spin.* Certain subatomic particles have spin. Given a direction, a particle can either spin positively or negatively or not spin at all. As with most properties of quantum mechanics, before a particle with spin is measured the particle will be in a superposition of both positive spin and negative spin.

There is a form of the Heisenberg uncertainty principle for spin. It says that there are certain directions such that if you measure the spin in one direction and then measure the spin in another direction you are going to get different answers than if you measure them in the other order. In general, if the two directions are orthogonal to each other, then we can measure spin in both directions in any order and get the same outcomes. As long as they are orthogonal, Heisenberg's uncertainty principle will not play a role. If, however, the angles are not orthogonal to each other, then we will not be able to measure those two directions simultaneously.

In 1967, Simon Kochen and Ernst Specker described an experiment to show that objects do not have properties until they are measured. They worked with a certain subatomic particle called a "spin 1 particle" that has the following property: if you choose any three orthogonal directions for measuring spin, two of the directions will have spin and the third direction will not have spin. Since these three directions are going to be orthogonal, Heisenberg's uncertainty will not play a role. However, there are many different triplets of orthogonal directions (see Figure 1). For any choice of a triple that you make, two of them will have spin and a third will not.

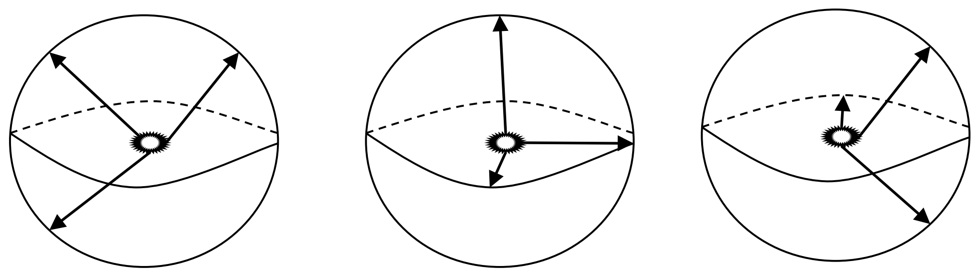

Figure 1 A spin 1 particle with three different triplets of orthogonal directions.

Suppose you did not believe Niels Bohr and you felt that objects have properties even before they were measured. Then you would believe that whether or not the particle had spin in any direction was a fact that was true even before measurement. In other words, before any measurement in any direction takes place, there is spin or there is no spin. And when we measure it, we determine what already existed before.

Unfortunately you would be wrong! It is simply impossible to attribute spin or lack of spin before measurements to *all* the possible directions. If you think of a subatomic particle as a sphere then each point on the sphere corresponds to a direction from the center of the sphere to that point. Saying that the directions have or do not have spin is like assigning 1's or 0's to the points of the sphere. We have the following conditions on assigning the 1's and 0's:

1. If a particle is spinning in one direction then it must also be spinning in the opposite (antipodal) direction. So if a 1 is assigned to a point on the sphere, then a 1 must be assigned to the opposite point because it is the same direction. Similarly, if a 0 is assigned to one point, it must be assigned to its opposite point.
2. Also, for any three orthogonal directions chosen, two of them will be spinning and one will not. That is, two points will get a 1 and one point will get a 0.

There is simply not enough room for the particle to be assigned such properties. This is a mathematical fact!

It would take us too far afield to provide a rigorous proof of this fact. It suffices to provide an intuition of why it is true. Consider for a moment that the North Pole direction does not have any spin. We can depict this as a “0” at the North Pole of the spheres in Figure 2(a). From the first proviso the South Pole direction also lacks spin. Now look at the directions orthogonal to the North-South direction. These directions are along the equator of the sphere. By proviso 2, all of those directions must have spin. We depict the spins as a thick line around the equator. In part (b), we further imagine that the direction slightly to the east of the North Pole also does not have spin. This is depicted by another 0. By proviso 1, the direction slightly to the west of the South Pole also does not have spin. The directions orthogonal to this are slightly off the equator and must have spin. Those directions are also depicted as a thick black line. Yet a third direction off the North Pole is depicted in (c). We go urther in (d). In (d), half of the sphere has thick dark lines and there are two thin lines of directions from the poles to the equators that do not have any spin. We are not done. If you believe that every direction has or does not have spin, you should be able to continue this process and assign to every point either a 0 or a think black point. It should be obvious that such an assignment cannot be made. There simply is not enough room! There is too much black line for every point of 0. There is no way we can give every point of the sphere a determination of whether or not there is spin.

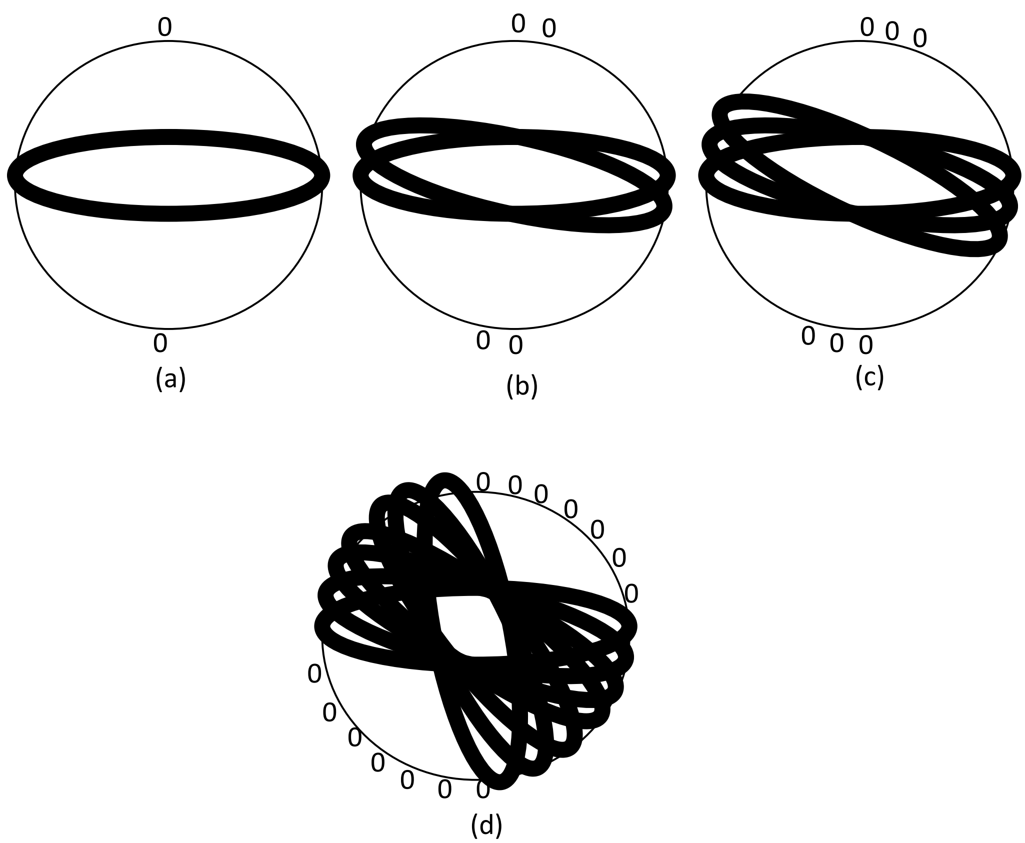

Figure 2 The intuition of the Kochen Specker Theorem

What we have shown is that one cannot take it as fact that every direction has or does not have a spin before measurement. Only after choosing three orthogonal directions and performing an experiment can we determine if there is spin. Before the measurement, there is a superposition of spinning and non-spinning in all directions.

We have just proved that objects cannot have certain well-defined properties until we measure them. We showed geometrically that there is not enough room for there to be such properties Albert Einstein (who died before Kochen and Specker described their experiment, but was nevertheless told of Bohr's ideas that objects don't have properties until they are measured), ridiculed this by asking whether one was really to believe "that the moon exists only when I look at it." But again, the vast majority of contemporary physicists would tell Einstein that, as crazy as it sounds, the moon is only there when it is measured.

From the perspective of the Wholeness Postulate, the Kochen-Specker theorem tells us that we cannot look at one measurement of an experiment at a time. We have to look at all the measurements to determine the outcome of an experiment. Whether or not there is spin in the X direction depends if you measuring X with Y and Z or measuring X with Y' and Z'. You might get a different outcome with different triplets. This aspect of quantum mechanics is called *contextuality*. The outcome of a measurement in the experiment depends on the context of the whole experiment. While with Heisenberg's unertinty principle we were concerned with the order of which measurements are made, here we are concerned with which other measurements are made.

Schrödinger's Cat. One might try to be flippant about all these problems. After all, what does the "real" world have to do with all this quantum stuff? We have never seen a subatomic particle in one position, let alone in a superposition. How does this idea of superposition in the subatomic world affect the larger world? One of the founding fathers of quantum theory, Erwin Schrödinger, described an interesting experiment which has come to be known as *Schrödinger's cat*. Imagine a sealed box with a piece of radioactive material in it. This material is subject to the laws of quantum mechanics and is in a superposition of "ready to decay" and "not ready to decay." Place a Geiger counter which can detect any decay into the box with the radioactive material. Connect the Geiger counter to a hammer that will break a vial of poisonous gas when the Geiger counter beeps. Now place a living cat inside the box and close the box.

As with all quantum mechanical processes, we cannot determine whether or not the radioactive material will actually decay. Hence, there is no method of determining whether or not the Geiger counter will beep. If the radioactive material decays, the Geiger counter will beep, the poison will be released and the cat will die. On the other hand, if the radioactive material does not decay, then the cat will be alive. Since there is a 50-50 chance for the decay to occur in the time given, there is a 50-50 chance that the cat is dead. That is, before we open the box, the cat will be in a superposition of both being alive and dead. It is only after the box is opened and a measurement is made that one of these possibilities really happens. The experiment has successfully transformed the weirdness of the subatomic world into the everyday world of cats and human beings.

This fits in nicely with the Wholeness Postulate. In order to determine the outcome of a macroscopic experiment, we must take into account the microscopic world. The two realms cannot be separated.

Eugene Wigner took Schrödinger's cat experiment one step further to get to the heart of quantum mechanics. This experiment has become known as *Wigner's friend.* Imagine Wigner setting up the experiment and placing a live cat in the box. He then closes the box and walks out of the room. Rather than Wigner opening the box, he has a friend open the box. Before opening the box we have that the radioactive material is in a superposition; the poison is in a superposition and the cat is in a superposition. Question: when the friend opens the box, is he also in a superposition of seeing the cat alive and seeing him dead? No human being has ever reported being in a superposition. Does the superposition only collapse when Wigner learns of the result or earlier when the friend learns the result? The obvious answer is that the friend is not in a superposition. Rather, the whole system collapses when the friend looks at it. The one thing that the friend has that no other physical object has is consciousness. Wigner uses this to show that a superposition collapses when any conscious being observes it. Why should this be? Wigner takes this as proof that the only thing in the world that can collapse a superposition to a position is human consciousness. Human beings only observe positions, not superposition, so it must be something about consciousness. What is it about consciousness that brings about this collapse of a superposition to a position?

The Wholeness Postulate says that we have to take into account a conscious observer. If there will not be a conscious observer to the experiment than the outcome will stay in a superposition. There is an experiment which shows this more clearly. Consider the double slit experiment. If both slits are open, then there will be an interference pattern of the light. Imagine putting a high-powered camera at each slot to see which slot each photon passed through. If there is a conscious observer looking to see which slit the photon passed, the observer will report seeing the photon passing one slit or another slit. *But not both.* No one has ever reported seeing a superposition. There will not be an interference pattern. If there is no observer, then the photon will go into a superposition and there will be an interference pattern. Let's take this little experiment further. Assume the camera is hooked up to an observer who is across the universe and sometimes is looking at both slits and sometimes not. In that case, whether or not there will be an interference pattern depends on whether or not there is a conscious observer across the universe. And somehow the photon here, must know this information before it gets to the slit. The Wholeness Postulate demands a lot of information to determine the outcome of an experiment.

Entanglement. Another counterintuitive aspect of quantum mechanics is *entanglement*. This concept shows that the whole special universe is more inter-connected than previously believed.

We first need to learn more about spin. There are important physical laws called *conservation laws* which state that certain quantities in a system stay the same. Quantum mechanics states that there is a conservation of spin law. This means that throughout an experiment the amount of spin of all the subatomic particles must remain the same. When a particle does not have any spin and decays into two particles that do have spin, these two particles will each be spinning both positively and negatively in a superposition. Since there is a conservation of spin law, if one particle was measured to have positive spin then, in order to maintain the no-spin status of the whole system, the other particle must have negative spin.

When two such particles, A and B, are separated does A spin positively and B spin negatively or vice versa? The answer is that each of the two particles is in a superposition of spinning both ways. Only when one of the particles is measured does it collapse into a particular spin direction. And here is the amazing part: the instant one of the particles collapses one way, the other must collapse the exact opposite way. This is true even if the two particles are light-years apart. That is, in order for the universe to maintain conservation of spin, measuring one particle's spin will collapse the other particle's spin across the universe. Although these two particles are far away, they are entangled with each other.

In 1935, Einstein, Podolsky, and Rosen wrote one of the first papers about entanglement which came to be known as "EPR." The goal of the paper was to show that there is something missing in the world of quantum mechanics. Einstein imagined two particles with spin flying apart from a no-spin particle source.[3] Let us envision that the particles are sent across the universe to Ann and Bob who are going to measure different properties of the particles. Ann measures the spin of her particle at a particular direction. If she finds that her particle is spinning positively, she automatically knows that Bob's particle must be spinning negatively in that direction. On the other hand, if Ann finds her particle is spinning negatively, she knows that Bob's particle is spinning positively.

There is something seriously wrong here. In all of previously known physics, objects affect other objects that are close by. One object has to be near or local to another object in order to affect it. This property of physics is called *locality*. However entanglement shows that by Ann measuring her particle, Bob's particle far, far away instantly collapses its superposition of spins. How can Ann measuring her particle affect another particle across the universe? Rather than being local, entanglement shows that quantum mechanics is *non-local*.[4]

[3] This is actually slightly different from the original EPR experiment. In that experiment they measured position and momentum. We are discussing David Bohm's variation of the experiment in which spin is the phenomenon examined.

[4] Gravity also has a feeling of non-locality to it. However, there are two major differences between gravity and entanglement. For one, gravity works at the speed of light. In contrast, entanglement is instantaneous. A second major difference is that the gravity force fades as the two objects get further apart. In contrast, the entanglement phenomenon remains as powerful and as instantaneous, regardless if the two objects are five feet apart or five million light years apart. This makes entanglement much stranger than gravity.

Researchers like to compare quantum entanglement to a similar thought experiment. Imagine someone taking a dollar bill and ripping it in half. He places the two halves in two different sealed boxes without telling which half went into which box. One box is given to Ann and the other is sent to Bob on Alpha Centauri a mere 2.565×10^{13} miles away. Once the box is with Bob, Ann opens her box. If she sees the left side of the dollar she immediately knows that Bob has the right side of the dollar. On the other hand, if Ann has the right side of the dollar, she knows that Bob has the left side of the dollar. So Ann gained information about something millions of miles away and gained this information instantaneously. There seems nothing mysterious about this. One can say that the properties of the half dollar bill traveled with it from earth to Alpha Centauri. Can we say the same with the particles?

Einstein, Podolsky, and Rosen concluded that there are two possibilities in the case of the spinning particles. Either (a) there is some mysterious, non-local interaction that explains how Bob's particle is affected by Ann measuring her particle. If this was true, our naïve notion of space where distant objects and measurements are independent of each other is wrong. Or (b) something similar to what is going on with the dollar bill is happening with the particles. In other words, the particles are not in a superposition. When they split up at the source they have fixed values of spin. That is, the particles have their spin values when they leave their source, and when Ann measures her particle she finds out what her particle's spin values are and instantly knows what Bob's values as well.

EPR discounted possibility (a) since they could not imagine that physics can work in such a strange manner. Rather, they preferred to accept possibility (b) as the correct view. In that case, we must ask what is missing in quantum mechanics. Why could quantum mechanics not tell what spin it is in prior to measuring it? Einstein postulated that there must be hidden variables which stay with the particles from the time they leave their sources until the time they hit their measuring devices. These hidden variables are like the split dollar bill. They ensure that properties of the particles have a fixed value. Until physicists learn more about such hidden variables, Einstein and his coauthors insisted that quantum mechanics is incomplete and waiting to be finished.

That's the way the physics world remained for almost 30 years until John Bell showed that, in fact, option (b) is wrong and only option (a) is possible. In 1964, Bell published a paper, "On the Einstein-Podolsky-Rosen Paradox," which famously showed that no regular hidden variables can explain away the mysteries of quantum entanglement. This result---which came to be known as *Bell's theorem* --- demonstrated that superposition is a fact of the universe[5] and that our notion of space needs to be adjusted.

[5] We saw this already with the double-slit experiment and more emphatically with the Kochen-Specker experiment. Although the Kochen-Specker result is cleaner and does not require two particles to prove that superposition is a fact, Bell's theorem was three years earlier than the Kochen-Specker theorem. Furthermore, Bell's results were

The intuition behind Bell's theorem is that if we assume that there are hidden variables and that these hidden variables describe the properties of particles, they must satisfy some regular logical truths. In particular, if we allow Ann and Bob to each measure the spin of their particles in three different specified directions, then these spin properties must satisfy certain logical truths. Bell describes what these logical properties are and then shows that they are not satisfied by the quantum mechanics of spin. He concludes that the particles did not have these properties while traveling from the source to the observers. They are in a superposition before measurement.

There is still a way to believe in hidden variables and the fact that particles have spin properties even before they are measured. Rather than say that the hidden variables keep track of three different spin values (for the three possible measurements that Ann can perform) say that the hidden variables keep track of the nine different measurements that Ann and Bob can possibly ask. That is, Ann can perform three measurements and Bob can perform three measurements which means that there are a total of nine different measurements that can be performed on the two particles. If you assume that there are such hidden variables, then in fact the logical problems above go away. However, we remain with one very perplexing problem: how does Ann's particle know what measurements Bob will perform? After all, Bob could be across the universe. Such a theory is called a *non-local hidden variables theory*. The very fact that such hidden variables need to take into account information that is very far away causes most physicists to disregard this possibility.

Regardless of the existence or non-existence of non-local hidden variables, one thing remains certain: the notion of space where measurements do not affect distant objects is wrong. As we saw above, EPR set up a dilemma. Either (a) the universe we live in is non-local or (b) quantum mechanics is incomplete and contains non-local hidden variables. Either way, there are non-local effects.

Once again, our defender of the sane, rational view of the world, Albert Einstein, found it difficult to accept that distant points of our universe were so intimately connected. He derided entanglement as "spooky action at a distance." But once again, we must point out that many contemporary experiments show that Einstein was mistaken. The universe is a lot weirder than even he imagined.

In essence, entanglement and Bell's theorem is the ultimate expression of the Wholeness Postulate. It says that the outcomes of experiments depend on the whole experiment including Ann's and Bob's measurements. In other words, we cannot just look at what Bob will measure or what Ann will measure. Rather we have to consider what each one will measure and from where their particles came. If the particles came from a single system with no spin, then the outcomes will take that into account. The two particles can be traveling for millions of years before they are measured. They can also be across the universe when measured. This means that the

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shown to be true experimentally which made a huge impact on the physics world. In contrast, the Kochen-Specker theorem has been largely ignored by experimentalists until recently.

Wholeness Postulate demands us to potentially take into account non-local phenomena. We need to consider all of space and time to determine the outcome of an experiment.

Quantum Eraser Experiments. We now know enough to describe some cutting-edge research called "quantum eraser experiments." These experiments take the famous double-slit experiment and go much farther.

What if there was a way of "seeing" which slit the photon passed? Perhaps we can "tag" the photons when they pass through the slit so that we can later tell which tag it has and hence which slit it passed. In that case, there will not be a superposition and there will not be an interference pattern of the photons. In fact, we can do this: photons can be tagged by placing polarization filters next to each of the two slits. Polarization filters block light coming in certain directions. They can be oriented in different directions and block light in those directions.

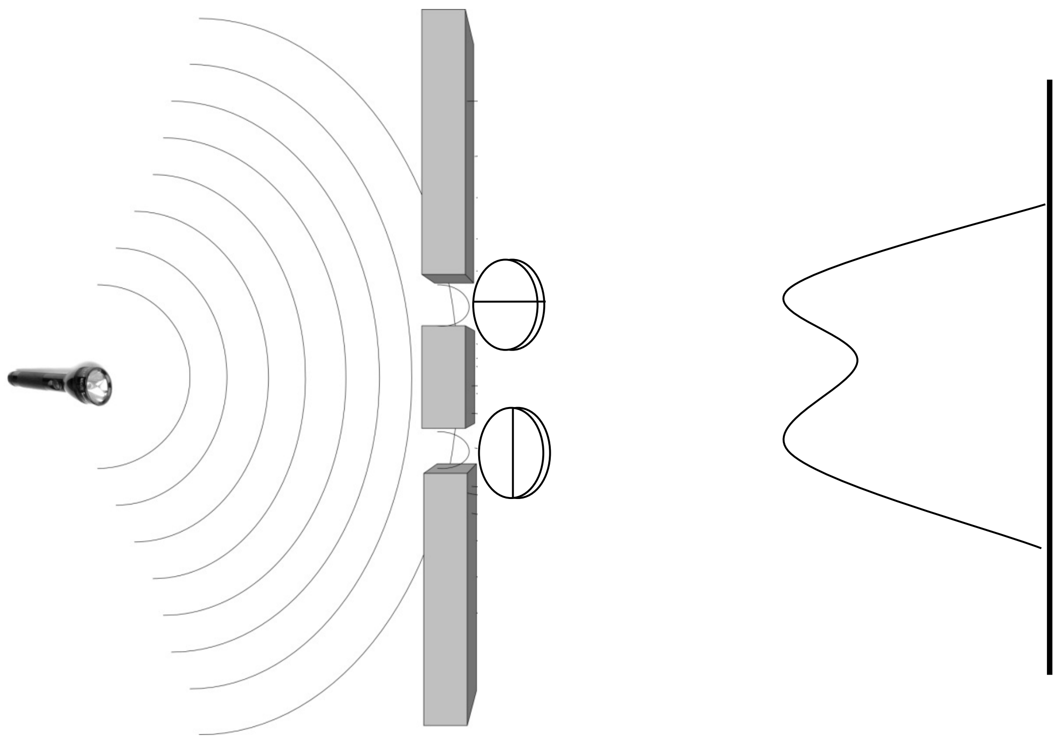

Figure 3 The double slit experiment with polarization markers

Set up the double slit experiment with polarization filters and in Figure 3. Notice that one filter is set horizontally and the other is set vertically. This will insure that the photons that pass through different slits are tagged differently and we can tell which slit the photon passed. Sure enough, when such an experiment is carried out, since there is information available that would tell us which slit the photon passed through, there will *not* be an interference pattern. The screen on the right will show light without interference.

There is an obvious question: when the photon leaves its source, does it go into a superposition or a position? We saw that if both slits are open and there is no way to tag the photons then they go into a superstition. If, however, there is a way of tagging the photons, they do not go into a superposition and there is no interference. When the photons leave their source, how do they "know" if there is going to be a tagging device on the other side of the slits? After all, the filters can be far away from the source of the photons. And yet, somehow the photons "know" what to do. In terms of the Wholeness Postulate, this makes sense: the outcome of the experiment depends on whether there are tagging devices in the experiment.

We are not done yet. A large polarization filter can be placed between the other polarization filters and the screen as in Figure 4. This polarization filter is set in the diagonal direction.

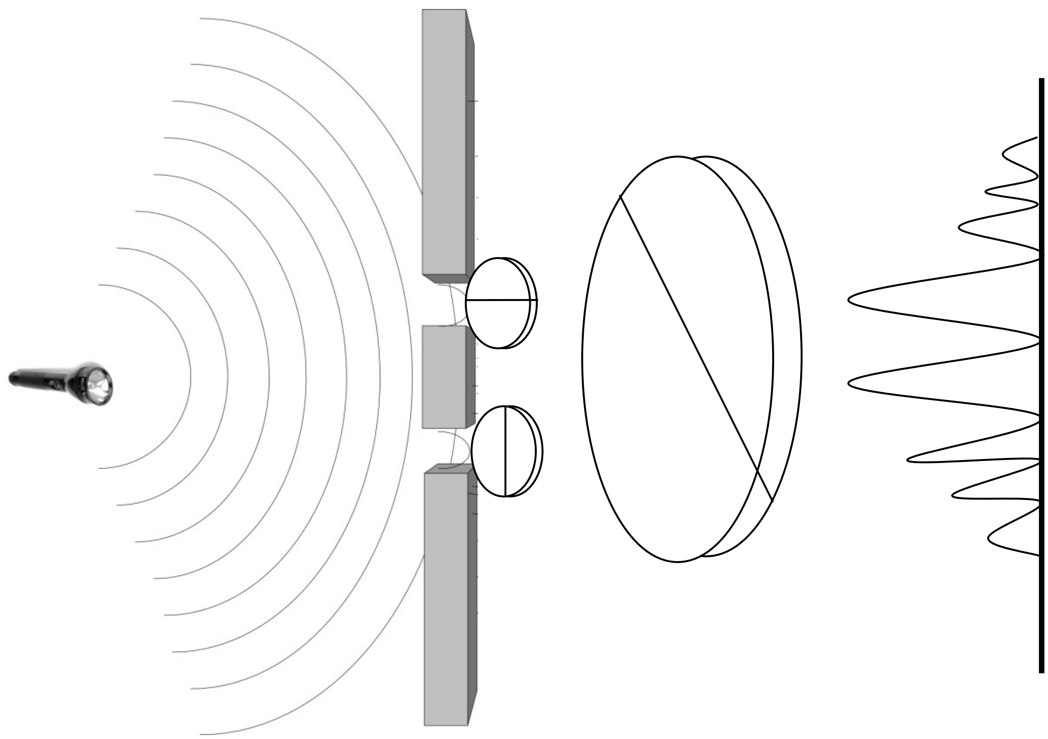

Figure 4 Double slit experiment with a quantum eraser

Let us see what happens as the photon makes its journey. If the photon goes through the top slit, it will pass the horizontal filter and come out horizontal. It will then have to go through the diagonal filter, and if it comes out, the photon will come out diagonal. Similarly, if the photon goes through the bottom slit, it will also go through the vertical filter and if it passes the diagonal filter will again come out diagonal. Either way, the diagonal filter "erases" the tagging information of which slit the photon passed. Without that information or our ability to get that information, the photon reverts to its superposition status and will interfere with itself.

Amazingly enough, this is exactly what happens when the experiments are carried out: there is an interference pattern.

Already we have an extremely interesting scenario here. When the photon approaches the slits, it has to determine if it should go through one or both slits. This depends on whether or not there will be a diagonal polarization filter on the right side of the slits. Somehow the photon "knows" what it will find on the other side of the slit. If the filter is not there, it will go through one of the slits and if it is there, it will go through both slits. How does the photon know what will be on the other side of the barrier? This again conforms to the Wholeness Postulate. Here we see that the outcome depends on the setup of the *entire* experiment including whether there is an eraser filter on the right side of the barrier.

Physicists take this experiment one step further with something called a *delayed choice quantum erasure*. Imagine that the diagonal polarization filter is far away from the slits and it is on rollers so that it can be moved away from the screen quickly.[6] To recap: if we leave the eraser in place we will get an interference pattern and if we take the eraser away there will be no interference. However the experiment can be set up so that the eraser can be left in place or pulled away after the photon has passed the slits in the barrier. The diagonal polarization filter can be in place and we can let the photon go. Because the filter is in place, we know that the photon is going to go into a superposition and go through both slits. Once it is passed the slits, we can then pull the diagonal filter away and then the photons will be in a position and not form an interference pattern. In contrast, if the diagonal polarization filter is not in place, then the photon will be in a position and go through one of the slits. Once the single photon is passed the single slit, we can push the filter back in place. Then the photon somehow goes back into a superposition and gives interference.

There are two crazy ways of looking at this: (a) After the photons pass the slits, by moving the diagonal polarization filter the experimenter is changing what the photons did in the past before they got to the slits. Or (b) somehow before the photons come to the slits, they "know" if the observer will pull away the filter or not. In short, either (a) the experimenter changes the past or (b) the photon "knows" the future. Both options are mindboggling.

It is hard to understand what it means to change the past. Such a concept violates our notions of cause and effect and all of science. In contrast, option (b), where the photon acts as if it "knows" the future, fits in well with our Wholeness Postulate. The outcome depends on the *whole* experiment including what the experimenter *will do* while the experiment is in progress. Here *whole* emphasizes that the experiment takes place in time and the outcome depends on the experiment from its start until its very end. The outcome takes into account whether or not the

[6] We are really simplifying the actual experiment here. The real experiment has to do with turning on and off the diagonal filter and is done with entangled particles. For simplicity sake we are describing the spirit of the experiment.

experimenter is going to pull away the diagonal filter. As Yogi Berra says, “it ain’t over till it’s over.”

How can the photon “know” what the experimenter will do? What about the experimenter’s free will? [7],[8] Doesn’t the experimenter have free will to decide on whether he wants to pull the eraser away or not?[9] Let us be careful in our language. A photon does not have consciousness or “know” anything. What we mean is that whatever physical law that is controlling the actions of the photon must take into account all the actions of the experimenter. The reason why this is amazing is that the laws that govern the action of the photon must take into account the *future* actions of the experimenter even though such actions do not exist yet. That is, those laws controlling the action of the photon must take into account the laws controlling the actions of the experimenter. If we are going to assert that the experimenter has free will and there is nothing controlling the actions of the experimenter, then there is nothing controlling the actions of the particle either. In other words,

human beings have free-will ➔ particles have free-will.

Do particles really have free will? Can we believe such a thing? They do not seem to show any free-will action. There is another way of seeing this: what if the particle does not have free-will and its actions are totally determined by laws? Well, then a human being also has no free will. That is, the contrapositive:

particles do not have free will ➔ human beings do not have free-will.

From the scientific perspective this is not strange at all. After all, human beings are made out of particles. Abiding by the usual dictum of reductionism, the scientist would have to say that particles following habitual laws of physics implies that humans must follow habitual laws of

[7] A person has free will if his actions are not predetermined by what happened in the past. In other words, the person acts for no other reason than this is what he wants. (Whatever “he” can possibly mean. Human beings are full of conflicting ideas and desires. Which is the real “he”? The one who wants the cake or the one who wants to lose weight?) This is not a simple idea. After all, if I help an old lady cross the street because my mother used to tell me that I should want to do such a thing, am I performing a free-will action or is it previous programming by my mother? What if my mother had not told me to do such actions? Another question: If someone puts a gun to my head and tells me to perform a bad deed, and I do perform the deed, am I exercising free will or is he forcing me to do it? After all, I do not need to perform the deed. Random acts are “not predetermined by what happened in the past. At what point does a free-will act become an act of randomness? None of these questions have easy answers.

[8] In 2006, John H. Conway and Simon B. Kochen published what they called “The Free Will Theorem.” This theorem is based on an experiment that is a combination of the EPR and Kochen-Specker experiments. Whereas the Kochen-Specker experiment concerns one particle, the Conway-Kochen result depends on two spin-1-particles that are entangled. Two different observers are making measurements on the two particles. The result that they claim is that if a human being has free will, then so do the particles. There is a bit of a controversy whether or not this result was actually proven. Regardless, we believe we have duplicated their result from the delayed choice quantum erasure experiment.

[9] It is not clear how an experimenter’s free will is impeded by the fact that a photon has knowledge of what free will choice the experimenter will make. Even if the experimenter had knowledge of what he himself will choose, does that mean he did not have free will to choose? Free will is about control of actions not about knowledge of actions.

physics. If he believes that particles have no free will, then he is forced to believe that humans, made out of particles, also have no free will.[10]

Regardless of your beliefs about free will[11], experiments have shown that the Wholeness Postulate must take into account the future and the free-will actions of the experimenter.

Complex numbers. Quantum mechanics uses the mathematics of complex numbers. This seems shocking because the measurements that we make are real numbers. Since we measure properties with real numbers we expect the laws of physics to be stated with real numbers. They are not! Rather, complex numbers are used in a most fundamental way. It would be very hard to perform any calculations in quantum mechanics without complex numbers. What does the Wholeness Postulate have to say about complex numbers? Perhaps nothing. Or perhaps there is a connection. Complex numbers have to do with a quantum phenomenon known as phase. The Wholeness Postulate might be saying even though phase cannot physically be measured, we have to take it into account phase in order to predict the outcome of an experiment. The most famous experiment that takes phase into account is the Aharonov–Bohm effect.

Discreteness. And finally, the last strange aspect of quantum mechanics that we shall discuss, was actually the first one discovered by scientists. In the first few years of the twentieth century, Max Planck found that certain types of energy had only discrete values. Whereas you can turn your thermostats to any value between 72.4 and 72.5, quantum mechanical systems had energy being released in certain units and could not have energy between these units. As time went on, the forefathers of quantum theory realized that it was not only energy that had this discreteness but many other properties of quantum mechanics also had this characteristic. They found that particles had discrete spinning states, space was discrete, and time also discrete. Electrons jump from shell to shell but do not pass the intermediate distance. I do not see how this strange aspect of quantum mechanics fits into the Wholeness Postulate. Perhaps it does not. The universe is a strange place and not all the strangeness has to fall out of one postulate.

Concluding Thoughts. The Wholeness Postulate is not a shocking idea. One would expect that the outcome of an experiment should depend on the whole experiment. What is shocking is how much information of an experiment has to be taken into account. We have shown that we must take into account all the parts of the experiment, the order in which measurements are made, and the context of those measurements. We have shown that we have to take into account measurements that were made across time and on the other side of the universe. We also must

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[10] There is one possibility that we did not mention. Maybe particles do have free will and the experimenter's decision on whether or not to pull away the diagonal polarization filter is somehow determined by the particle's decision to go into a superposition or not. That is, the particle controls the human observer. This, of course, is ludicrous. Nevertheless, it is worth mentioning an important experiment by Benjamin Libet. He found that certain parts of the back of the brain were excited seconds *before* humans became aware of making certain decisions. In other words, there is a place in the back of our brains that are controlling us and telling us what to want and what to do. For more, see part III of the excellent Nørretranders (1998). Recently neurologists have taken Libet's experiments much further.

[11] "We must believe in free will, we have no choice." Isaac Bashevis Singer.

keep track of the experimenter, his consciousness, his free will and his future actions. Where does this stop. We are pretty sure that the outcome of an experiment does not take account of the experimenter's socks or whether they match or not. His socks do not seem important for an experiment, but his mental state and his future actions do. Why?

If we are to take the Wholeness Postulate to its extreme, we have to take all of space and time into account to determine the outcome of an experiment.[12] If you feel that the universe is totally deterministic, then you can figure out the outcome of any experiment from looking at the whole of space-time. One usually thinks of an experiment as bracketing some phenomena and trying to hold outside influences in check while seeing how certain phenomena behave. The Wholeness Postulate says that this is hard to find what is "outside" of an experiment.

[12] There is a school of thought that deals with the measurement problem by using the multiverse. Without getting into the details, this school believes that whenever a measurement is made the universe splits into many different universes with each possible outcome belonging to one universe. While I have no way of disproving the multiverse, there is also no way of proving it. If one followed the multiverse theory, the Wholeness Postulate says that you have to take into account the entire multiverse in order to determine the outcome of a measurement. I am grateful to John Connor for pointing this out to me.