Quantum mechanics (QM) is very odd. It presents both an immensely practical and a deeply troubling conception of the physical world. As such, its uses stretch from optimizing nanoelectronics to examining the very nature of reality. In this article we will see how QM forces us into a dramatic rethinking of one of the most fundamental tenets of modern science, locality.

I. LOCALITY ACCORDING TO SPECIAL RELATIVITY

Locality is the idea that things can only be affected by their immediate surroundings. By the early 20th century special relativity had shown that nothing, including information, could travel faster than light. This suggested a more concrete meaning for “immediate surroundings”: Systems could only affect one another if the space-time gap between them was time-like. Or, in plain English, two events can only have a cause and effect relationship if light could have travelled from the location of the first event to that of the second in the time between their respective occurrences.

Imagine the sun has just now blown up. The sun blowing up is an event which happens, like every other event, at some point in space and time. The picture below is a space-time diagram. Obviously it’s not a very accurate space-time diagram since it’s not four dimensional; never mind, we’ll make do. Any event whose location and time are known can be represented by a point on such a diagram. As always we have freedom to choose our coordinate system however we like. Let’s make the explosion of the sun the event which takes place at the origin, the vertex of the cones.

Now let’s consider another event: An observer on Earth looking up at the sky. The observer is a certain distance and a certain direction from the sun. In reality we would, of
course, need three dimensions to characterize his spatial location relative to the sun but let’s pretend we can do it with two. Then the observer’s space-time position at the instant of the sun’s explosion lies somewhere on the “hyper surface of the present” (hyper because it’s three dimensional and, thus, isn’t really a surface at all). As time marches on, the space-time position of the observation event simply travels up the time axis, with its space coordinates remaining more or less the same (neglecting Earth’s motion). Eventually, the space-time point which represents the observation event will fall within what is labelled the “future light cone”. It is at this point that our unsuspecting observer’s sky will suddenly take on a particularly ominous hue. The events within the future light cone may have been caused by the explosion of the sun while the events within the past light cone may have been the causes of that explosion. Anything outside of those regions can have no causal relationship to whatever happened at the origin, in this case, the sun blowing up. The former events, which lie within the two cones, are called time like while the latter are called space like. Hopefully now my original definition of locality makes more sense. To restate it:

**Locality is the idea that two events can only be causally related if**
their space-time separation is time like (i.e. they lie within each other's light cones).

By the way, the light cones can be thought of as follows: light propagates outward from the event at the origin at a fixed speed in every direction. Thus, at the initial moment obviously the light hasn’t had time to get anywhere. After some time the light will have travelled all the way to the outer surface of some sphere (represented as a circle in our two dimensional representation of space). These circles (really spheres) are all stacked on top of each other for each moment of time, resulting in the cones that you see in the diagram.

Thus, the future light cone tells us how far light will have travelled from the origin in a given time. Anything outside of this cone couldn’t possibly be caused by whatever happened at the origin; this is because there is no way for the information produced by the event at the origin to have reached it without having travelled faster than light, which is impossible. Similarly, the past light cone encloses all of the events which could have been the causes of the event which took place at the origin. The longer ago a causal event took place, the larger the space it can effect at the present moment.

Now that we’ve introduced locality, let’s figure out what quantum mechanics has to say about it. The focus of this discussion will, eventually, be on a 1935 thought experiment imagined by, who else, Einstein as well as two other physicists named Podolski and Rosen. This thought experiment lead to the deduction of what is now called the EPR paradox.

In order to understand the EPR paradox we will consider a simple example based on the quantum mechanical idea of spin angular momentum (or just spin). It would be prudent, then, to first introduce and try to wrap our heads around some of the weird properties of quantum spin.

II. QUANTUM SPIN

Spin, in the classical sense, is nothing new: The Earth spins, tops spin, etc. In the quantum world, however, we can’t think of spin in the same way. This is because, in QM, the particles which we are discussing are often fundamental building blocks of matter (e.g. electrons); fundamental in the sense that they are point particles, indivisible and with no insides. When something spins, in the classical sense, it rotates about some point within itself. A point particle, though, has nothing within itself about which to rotate!
So if the point particles don’t actually spin, why give them a property with that name? Well, although the actual motion of the particles is certainly not one we would recognize as classical spinning, there are subtle similarities between the classical and quantum notions of spin. When a charged, macroscopic ball spins it creates a magnetic field. Specifically, it becomes a magnetic dipole with a North and a South pole. This is because of Maxwell’s Equations which state, among other things, that movement of electrical charge (i.e. current) creates a magnetic field. Charged quantum particles, like the electron shown below, create magnetic fields just as if they were macroscopic balls of charge spinning in the classical sense. Thus, we at least have some kind of justification for calling spin, spin.

![Electron as a magnetic dipole](image)

The next weird thing about spin in QM is perhaps not very surprising: it is quantized. We will be thinking mostly about electrons throughout so we’ll use them as our example here. Electrons have a certain value of spin, call it a. We can set up an experiment to measure the component of the spin in a certain direction. Our classical intuition leads us to expect that our measurement might return values in a continuous range from -a (spin...
pointing anti-parallel to axis of measurement) to +a (parallel). In other words, we expect to get all kinds of results: -a/4, -a/8, +7a/32, whatever. In fact, though, what we find is that only two values are ever measured: -a and +a. Nothing in between. That is what I meant by spin being quantized: When measured, it can only take on one of two values instead of any value in the continuous range from -a to a, as we would expect classically. Bizarre? Yes. But it’s what puts the quantum in quantum mechanics.

Now that we have some idea what spin is, we can begin to develop and understand the EPR paradox and the thought experiment that spawned it.

III. THE EPR-BOHM EXPERIMENT

Consider a particle sitting around doing nothing. A pion, say. Our pion then suddenly decays to an electron and a positron (i.e. anti-electron) in a pretty typical event. The pion has no intrinsic spin angular momentum (this is a property of pions) and, let’s say, no other angular momentum. Armed with the knowledge that total angular momentum must be conserved in the decay, we deduce that the net angular momentum of the electron and the positron must also add to zero. Now, let’s set up some detectors, one to detect the spin of the electron and one for the spin of the positron. We’ll suppose that the two detectors measure spin along the same axis, which we call the z-axis.

Say the measurement of the electron returns the value +a. We then immediately know, even without a direct measurement, that the spin of the positron must be -a so that the total adds to zero. That’s, essentially, the EPR paradox. Seems a bit anticlimactic, doesn’t it? Well, it’s not. In order to understand why, we need to take a closer look at what makes QM so weird in the first place. There are several ways to interpret the mathematical formalism of quantum mechanics. The two that we care about here are the realist and orthodox (AKA Copenhagen) interpretations. To introduce the two, we’ll reconsider the experiment we just thought up.

What Quantum Mechanics Tells Us

Quantum mechanics is all about probabilities. It can always answer questions like ”What is the probability that the measurement of this electron’s spin will yield result x?” but cannot
always answer questions like "What is the spin of this electron?" In other words, instead of concrete, black and white predictions, QM often can only provide us with probabilistic answers.

So, for example, in the EPR-Bohm experiment we talked about earlier (the one with the decaying pion) quantum mechanics cannot tell us what the spin of the electron or the positron is until one of them is measured by the detector. We only know that the total spin must be zero. The two obvious possibilities are that either the positron is spin up and the electron is spin down or the other way around, with the electron being spin up and the positron spin down. QM tells us that the system is actually in some combination (i.e. superposition) of those two states. What that means physically, don’t ask me [7].

Realists have issues with this probabilistic gobbledygook (Einstein’s complaint that "God does not play dice” characterizes their position pretty well) while followers of the Orthodox interpretation take quantum mechanics at face value. Let’s try to understand both of these positions in more detail by attempting to advocate each.

The Realist Position

What kind of nonsense is this? If a physicist can’t make 100% accurate, completely dependable predictions of the results of measurements, then his physics isn’t right! If quantum mechanics can’t give us concrete answers instead of some kind of probabilistic garbage, then it must be missing something! There must be some kind of hidden variables that haven’t been taken into account.

Here’s what happens in the EPR-Bohm experiment: After the pion decays the electron and the positron both get a spin in some well defined direction. If we knew all the hidden variables then we would know, without any measurement, exactly which of the two particles has spin up and which has spin down. The fact that QM can’t tell us that kind of thing just proves that it is an incomplete theory.

A complete theory would give us knowledge of all the variables hidden from us by QM and, thus, allow us to predict the results of the two measurements with total certainty. That’s physics!
The Orthodox Position

Quantum mechanics has never made any wrong predictions before and has proven useful in tons of different arenas. Let’s just trust it at face value, bizarre as it might seem.

When the pion decays the electron and the positron go into a kind of state of indecision. This state is the result of adding (actually subtracting, but that’s irrelevant) the two obvious states we mentioned earlier:

(Superposed State) = (Electron Up, Positron Down State) + (Electron Down, Positron Up State)

When the measurement is carried out on the system, it has to choose between one of these two obvious states. In this case, either has a 50-50 chance of being chosen. Once the measurement has been made we know the state the system is in and the realists among us can rest easy. So, for example, if we measure it to be in the (Electron Up, Positron Down State) we can then safely say that the electron has a spin pointing up and the positron has one pointing down. We could not say this before the measurement, though. In other words, we have to accept the proposition that the measurement itself affects the system in a dramatic way.

The Realist’s Response: The EPR Paradox

Suppose the detectors are one light year away from one another. Also, let’s say that the electron detector is significantly closer to the decaying pion’s initial location than the positron detector. Then it’s safe to assume that the electron will reach its detector in less time than the positron. Now imagine the electron’s detector returns the result that the electron was spin up. If we know the electron is spin up then the positron must, at that very same instant, be spin down in order to conserve angular momentum.

So, according to an orthodox interpretation the fact that the electron was measured as spin up somehow travels across one light year of space instantaneously and causes the positron to become spin down. This violates locality and requires faster than light transfer of information!
IV. SUMMARY

That’s the EPR paradox: If we believe the orthodox interpretation of QM then locality is violated, as demonstrated in our simple thought experiment. This implies that, in order to preserve locality we need to put our stock in the realist interpretation, which claims that quantum mechanics is an incomplete theory and there are some kind of hidden variables lying around somewhere that no one knows about.

In other words, because of the EPR paradox either locality or QM is wrong. Both can’t be right.

Experiments like the one we discussed above have convincingly shown (see Bell’s Theorem) that QM is a correct theory and that locality is, in fact, violated. The concepts we discussed in the previous three posts lie at the heart of tremendously exciting recent experiments in quantum teleportation and computation which may be the basis for all kinds of revolutionary new technologies.

[1] Krane, K. (1996). Modern Physics, John Wiley and Sons, Inc.
[2] Griffiths, D. (2005). Introduction to Quantum Mechanics, Pearson Education International
[3] Einstein, A., Podolski, B., Rosen, N., (1935). Physical Review, 47 777-780.
[4] Wikimedia Image
[5] National High Magnetic Fields Laboratory Webpage
[6] A Stern-Gerlach detector which uses inhomogeneous magnetic fields to isolate different spins can be used for this purpose
[7] This is the origin of the difficulty posed by the famous problem of Schrödinger’s cat which, being dependent on a quantum mechanical event for survival, apparently exists in a superposition of alive and dead until observed