Chapter 24: A Brief Introduction to Quantum Theory

Special and General Relativity fundamentally undermined Newtonian intuitions about space and time, but it fundamentally preserved the <u>deterministic</u> character of Newtonian physics.

Quantum mechanics, which is the study of how the world behaves at the micro level poses fundamental challenges, not only to determinism, but also realism, i.e., the view that the state of the world is independent of our perception of it.

• Brian Greene's <u>Elegant Universe</u> (Chapter 5, The Quantum Café) dials this in nicely.

Before proceeding, your author usefully distinguishes three aspects of quantum theory.

- The quantum facts, i.e., the outcome of the experiments.
- Quantum theory, i.e., the mathematics of quantum theory.

 Interpretations of quantum theory; i.e., the metaphysical views compatible with quantum facts and the theory.

Chapter 25: Some Quantum Facts

This chapter deals with the attempt to understand the behavior of microphysical entities. The fundamental question is whether microphysical entities are particles or waves. This distinction is <u>conceptual</u>. Nothing, it seems, can be <u>both</u> a particle and a wave, since particles and waves have incompatible characteristics. Specifically:

- A wave is a process that is spread out over space and time.
- A particle is an <u>object</u> that can be assigned a precise position and velocity.

Prior to the results of quantum mechanics, the smart money was on particles, since this would preserve the idea that little things are just little version of big things. Specifically, although we knew little things are more easily disturbed and harder to measure, the general expectation prior to the 1930's was that we would learn that little things behaved deterministically.

But this expectation was spectacularly undermined by experiment. This chapter does a good job of relating the

results of these experiments. It is also very nicely laid out in full in :

• The Feynman Double Slit

As well as this excerpt from the movie:

What the Bleep Do We Know?

Chapter 25: The Mathematics of Quantum Theory

The actual mathematics of quantum theory is well beyond our scope, but it's important to get a grasp on some general points.

The most important point to understand is that a certain kind of mathematics is required to properly model the results of the double-slit experiments. The basic fact to remember is that whether or not an electron is properly represented as a particle or a wave depends on when and where we do our measurements.

In the two slit experiments without the use of detectors, the electrons behave like waves until the very end (hence the interference pattern). But when we position the detectors behind the slitted screens, the electrons behave like particles, going through either one slit or the other, and producing particle like behavior when they hit the photographic paper.

This means that <u>prior to measurement</u>, we require a mathematical representation of an electron that represents both its wave nature, <u>and</u> the capacity of this wave to resolve itself into a particle with a certain position and velocity (the term for this phenomenon is "collapsing the wave packet").

So, in the two-slit experiment, going through one slit will be represented by one subset of the modeling equations, and going through the other slit will be represented by the other subset. Up until the point that the electron has actually been detected, all of these equations represent the behavior of the electron. The equations allow us only to attach a certain probability between (0 and 1) to the wave packet collapsing in any particular way.

The important point is that the equations do not provide us with any basis whatsoever for saying that, prior to measurement, the electron has a particular position and velocity. This is what is so weird.

If we revisit the equations of Newtonian mechanics, like the second law

• F=ma

Or the conservation of momentum

• $m_1v_1 = m_2v_2$

we realize that these equations, interpreted as applying to particles, permit us to infer that <u>whether or not</u> a particle is measured, it has a definite physical property. We can say, using these equations, <u>at any point</u> in the trajectory of a classical particle, what these properties will be. In quantum mechanics we can not do that.

Einstein's dissatisfaction with quantum mechanics stemmed from remaining strongly connected to these classical intuitions. We can express this discontent as follows:

Lots of macroscopic phenomena in the world <u>appear</u> to be non deterministic. For example, if I take a big handful of BB's and toss them into the air in an empty room, there is no way that any physicist will be able to predict anything but the most <u>general</u> characteristics of the distribution of the BB's. Of any particular BB, we will in only be able to associate a certain probability with it showing up in a certain part of the room. But this is <u>not</u> because the only appropriate mathematics for representing the behavior of the BB's is wave mechanics. It's because the physical interactions are so incredibly complex and sensitive, that we could never have the computing power to make accurate calculations.

So, if we can not predict the path and ultimate resting place of a particular BB, this is because there are certain variable controlling its motion that are simply hidden from us. This is what we call a "hidden variable" argument. Einstein and others with similar intuitions thought that the same must be true of electrons and other particles. But the mathematics of quantum mechanics does not bear this out, and no one has ever been able to demonstrate the existence of a hidden variable.

The Interpretation of Quantum Theory

Richard Feynman summarizes the results of the single and double slit experiments as follows:

"If you have an apparatus which is capable of telling which hole the electron goes through ... then you can say that it either goes through one hole or the other. It does; it is always going through one hole or the other - when you look. But when you have no apparatus to determine through which hole the thing goes, then you cannot say it goes through one hole or the other ... to conclude that it goes through one hole or the other when you are not looking is to produce an error in prediction. That is the logical tightrope on which we have to walk if we wish to interpret Nature."

As we've said several times above, the weirdness of quantum theory consists in the fact that the way an electron (or other subatomic entity) behaves depends on whether or not it is being measured. Moreover, this weirdness is not generally thought to be explainable in terms of hidden variables as discussed above.

Erwin Schrödinger, dramatized this weirdness by demonstrating that it had what he believed to be absurd implications for the macro world as well in the well known experiment <u>Schrödinger's Cat</u> thought experiment.

Einstein himself co-developed a thought experiment that we now call the EPR paradox (for its three authors Einstein, Podolsky, and Rosen) which was intended to demonstrate the absurdity of quantum theory in even more undeniable way. But this experiment backfired spectacularly as we will see in the next chapter.

The Standard Interpretation of Quantum Theory

The Standard Interpretation, which is also called the Copenhagen Interpretation, claims that electrons have no specific properties prior to measurement. This interpretation is <u>realistic</u> in the sense that it interprets the wave function that describes the elementary particle as being a literally accurate description. Since, according to this wave function, the particle prior to measurement is in no particular state, but rather a superposition of states, each of which represent a certain <u>probability</u> that the electron will be found only in one place or another, it follows that the electron does not have any definite properties like location or velocity prior to actually being measured.

As your author notes, this is very much as if we were to acknowledge the reality that there are coins in your pocket, but deny that there is any <u>particular</u> <u>number</u> of coins or any particular <u>type of coin</u> prior to actually pulling them out and looking. This does not sound like any traditional form of realism at all. In fact, it is strikingly idealistic insofar as it asserts that reality is ultimately constituted by an act of observation.

Variations on the Standard Interpretation

Variations on the standard interpretation are distinguished by (a) how liberally we define the act of measurement and (b) what constitutes a quantum object.

1. According to the <u>mildest</u> version of the standard interpretation:

- Measurements are made by physical devices and do not require any kind of interaction with a human or animal perceptual system.
- Quantum objects are restricted to the microphysical world.

This is the least bizarre interpretation, but it is not unproblematic. Detectors, after all, are just physical objects, and it is not clear why causal interaction with something we call a detector is any different than causal interaction with any other kind of object.

2. According to the <u>moderate</u> version of the standard interpretation:

• Measurements are made only by sentient beings.

• Quantum objects are (still) restricted to the microphysical world.

This form of the standard interpretation invokes consciousness, but does not require the consciousness of human beings. For example, Schrödinger's cat's perceptual system may be able to do the measurements necessary to insure its own death.

Of course, according to this version there is something special about consciousness that causes the collapse of the wave packet, and this remains an entirely mysterious process.

3. According to the <u>radical</u> version of the standard interpretation:

- Measurements are made only by human beings.
- Everything is a quantum object.

This version assumes the further burden of explaining what is special about human consciousness. However, the idea that all objects are quantum objects is based on the fact that macro objects are simply concatenations of elementary particles.

All versions of the Standard Interpretation are deeply, philosophically dissatisfying. No model is offered for how or why measurement should have the effect that it does, and the stronger versions seem to be dualistic, i.e., treating mental processes as involving special causal powers.

Hidden variable interpretations

As we already noted, hidden variable interpretations insist on the kind of realism that says reality is determinate. From this point of view it simply makes no sense to say that elementary particles actually lack any definite properties. Rather, it must be that the mathematics is incomplete. Einstein expected that quantum mechanics would ultimately be replaced by a fully determinate characterization of the behavior of elementary particles.

There have been some hidden variable theories, notably David Bohm's theory, which your author discusses briefly. Bohm's modification of the mathematics of quantum theory is as predictive as the standard mathematics, and admits of a determinate interpretation. Unfortunately, it turns out to require superluminal signals; i.e., faster than light information transfer, which is impossible according to relativity.

The Many Worlds Interpretation

The Many Worlds Interpretation is similar to the hidden variable theories in that it does not attach any metaphysical significance at all to the act of measurement. However, it is like the Standard Interpretation in that it accepts the superposition of states in the wave function as descriptive of reality.

What is different about Many Worlds is that it does not interpret the alternative states of the wave function as states which may or may not happen. Rather, it interprets them as describing events all of which <u>do in fact</u> happen.

Of course, this does not really make any sense from a traditional point of view. It can not be, for example, that the particle passes through <u>both</u> the first slit <u>and</u> the second slit. It can not be that Schrödinger's cat both lives and dies. Claims like these run afoul of the basic law of non-contradiction.

Resolving this apparent contradiction requires quite a leap of the imagination. According to Many Worlds, every event actually happens, but in a different world. So, if you are the physicist doing the slit experiment with detectors, the reason you measure the particle going through slit A, is because you are in the world in which A actually happens. However, according to MW, there is another world in which a "counterpart" of you detects the particle going through slit B.

It is an understatement to say that the Many Worlds interpretation is a bit problematic. However it is worth noting that it is actually <u>the most popular</u> interpretation among physicists today.

It is also worth noting that MW bears a very strong resemblance to Possible Worlds semantics, which is taken very seriously in metaphysics. The basic idea of Possible Worlds is that a sentence like

• It is possible that my head will explode as a result of studying philosophy.

actually means that <u>there is a possible world</u> in which my head explodes as a result of studying philosophy. Moreover, according to the strongest interpretation of possible worlds semantics, these worlds are just as real as the world we actually inhabit.

Of course, all of this is easily dismissed as a lot of philosophers and physicists going off the deep endand perhaps this will ultimately be shown by some well-grounded Einsteinian determinist- but its important to understand that both the Many Worlds interpretation of quantum mechanics, and the Possible Worlds account of the nature of possibility represent some of humanity's best efforts to date to deal with very difficult questions about two of the most perplexing concepts: probability and possibility.

It is also worth noting that these theories may be relevant to deeper questions about the origin of the universe and the nature of free will.

Free Will

According to classical physics, the sense that humans are (within limits) free to do as they please is an illusion. We have this illusion because we are not capable of predicting our own future actions. And this is due to the logical impossibility of any mechanism at all, including the human brain, of having a complete internal model of itself. (Analogously, you could never make a picture of everything, because the picture is part of everything and the picture couldn't have a picture of itself.)

The Copenhagen interpretation asserts that the universe is fundamentally indeterministic, and some philosophers have thought that this may be the key to understanding human freedom as something more than an illusion. However, this may be a bit of a stretch. The synaptic firings in our brain that provide the mechanism of human decision making are very little more affected by quantum indeterminacy than bowling balls. It seems very unlikely that quantum indeterminacy could underwrite the freedom we associate with ordinary human decision making.

Part of the appeal of the Many Worlds interpretation is that it is fully deterministic. So, on the face of it,

MW does not appear to be compatible with a classical account of free will. However, it supplies us with an interesting way of accounting for the fact that we believe that the alternate pathways we observe in ordinary human decision making really do exist. They really <u>do</u> exist, according to MW. On the other hand, MW can not help you with the intuition that you are to be congratulated for making the right choices, and blamed for making the wrong ones. Because on MW, all those outcomes, good and bad, actually do happen, somewhere.

The Origin of the Universe

One of the enduring questions of philosophy and science is

• "Why does anything exist at all?"

This question resonates. It sounds meaningful, though it's not clear how it could ever be answered. The problem is that for whatever entity we might invoke to explain the origin of the universe (we could just agree to call that entity God), the question arises again: Why does God exist? However, there is another related question which may have an answer:

• "Why does the universe have the particular properties it has?"

It seems like this question could have an answer. To say that it doesn't have an answer is to say that it is really just a miraculous coincidence that of all the different kinds of universes that we can imagine existing, the vast majority of which would not contain anything resembling human life, the one that does contain human life just turned out to be the one that exists.

The idea that there are multiple worlds provides an alternative framework for answering this question: If <u>all possible universes exist</u>, then of course this one would have to exist, too. On this view, there is no further question about why we ended up in this particular universe. We were going to be in one of them all along, and this is it.

Chapter 28: EPR, Bell's Theorem, Aspect's Experiments, and the Locality Assumption

As we've noted several times, Einstein was deeply dissatisfied with the indeterminacy of quantum mechanics, and he developed a thought experiment to demonstrate that it is committed to an absurdity.

The absurdity consists in a violation of what is called the "locality assumption." You'll recall that one of the things that made Newton's law of gravitation is that it permitted instantaneous action at a distance. According to Newton, if the sun disappeared at one moment, the earth would, at that very moment spin out of orbit. According to Einstein, on the other hand, the effect of gravity would be felt about 8.3 minutes later. This is because gravity is propagated as a wave through the fabric of space-time at about the speed of light.

Newton's theory violated the locality assumption, whereas the general theory of relativity preserved it. Roughly speaking, the locality assumption says that spatiotemporally distant objects can not directly and/or instantaneously affect each other. They can only affect each other through a process (such as a wave or moving particle which takes time) and which brings the objects and/or their effects into the same locality. In a seminal paper Einstein, Podolsky, and Rosen argued that quantum mechanics is incomplete on the basis that it violates the locality assumption.

The argument is very simple. It depends on one extra quantum fact, which is that it is possible to generate two quantum particles that both have the same property, though we do not know what that property is. The EPR paradox is described using various particles (electrons, photons, etc.) and various properties (spin, polarity, etc.)

Your book uses photons and the property of polarity. So, we can generate two photons at a certain source, which are correlated in the sense that they have the same polarity, though we do not know what that is until it is actually measured.

Let's says that polarity comes in two flavors: Up and Down, and that there is a 50/50 chance of either one occurring. Recall that, according to quantum mechanics, prior to measurement the photon is neither Up nor Down, but is simply described by a wave function (call it UpDown) in which Up and Down are represented as having equal probabilities. Now suppose that the photons move away from each other at the speed of light.

Detector A

The thought experiment doesn't require any particular distance, but let's suppose they go to detectors a billion or so miles away, and that detector B is slightly further away than detector A. Suppose that detector A measures the photon as being Up. Recall that according to quantum mechanics, prior to being measured, the photon was neither Up nor Down, but Updown. Recall also that the photons were generated under conditions that their spins would be correlated. This means that a moment later, when the second photon reaches detector B it will also be Up.

That's all you need to know. The paradox is that, according to quantum mechanics, the measurement at detector A, not only collapsed the wave packet of the photon it was measuring, but it instantaneously collapsed the wave packet of the other photon over 2 billion miles away. This violates the locality assumption. Einstein argued that there is simply no way that that one photon could "know" what was happening to the other. Notice that on a hidden variable theory there is no problem here. Hidden variable theories assume that the photons have a particular polarity the entire time, one which we discover (not create) by the act of measurement.

This supposedly paradoxical property has become known as "entanglement".

Bell's Theorem

It's important to understand that the EPR paradox is entirely metaphysical; meaning that it has no testable consequences. We can perform the experiment that Einstein imagines, but all we would ever confirm is that the elementary particles are always correlated as expected. We have no way of testing whether our measurement of the first particle collapsed the wave packet of the second particle, because that is a claim about what happens to the second particle <u>prior</u> to actually measuring it. Bell's contribution was to actually identify a measurable prediction that followed directly from the mathematics of quantum mechanics which, if confirmed, would demonstrate that nature actually does violate the locality principle.

Your author provides a first pass at understanding the nature of Bell's theorem, and we will not try to go any deeper than that. What Bell exploits is the fact that we can set up detectors to measure 3 different properties of elementary particles, as well as the fact that these properties are correlated in statistical ways.

To understand this your author asks you to conceive of the detectors as a couple of coke machines with different settings. These coke machines aren't normal. Pushing the button will only deliver the specified soda with a certain probability. (Note that this is actually true of every real coke machine, but the probability of you pushing a button and getting the soda you want is pretty high.)

The experimental setup on p. 288 looks like this (duh):



The button in the middle actually triggers an impulse, which sends signals to both machines. It may as well be a photon signal, to preserve the analogy with EPR. There are still two different outputs: U-sodas and D-sodas, which each occur 50% of the time. The added complication is the three different machine settings, L, M, and R. The M setting corresponds to the assumptions of EPR, namely that although we don't know whether we are going to get U or D, we always know that if both machines are set on M, then the machines will register the same output.

Hence, for a long series of soda purchases where both machines are set to M we get a distribution like this

A@M: DUDUDUUUUUDUDUUUUUUUUUUUUUUUUUUUUUUU

B@M: DUDUDUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU

Note that this is only one of many possible outputs that produces a roughly 50% distribution.

The L and R settings on the machine produce slightly different results. When one machine is put in the M setting and the other is put in the L setting you do not get perfect correspondence, but rather about 75% correspondence, meaning that about 25% of the time you will get a U-soda from one and a Dsoda from the other.

Similarly, when one machine is left in the M setting and the other is put in the R setting, you <u>also</u> will get a 25% difference as above.

Now we ask a simple and easily answered question.

 On the basis of the above data, <u>and</u> on the assumption that the machines do not know or care what setting the other is in, what happens when one machine is in the L setting and the other machine is in the R setting?

The answer, statistically, is very straightforward. Since both states, over the long run, deviate from perfect correspondence by 25% you will get a 50% deviation when the dial of one is set to L and the other is set to R.

You will note, of course, that this 50% difference is based on the assumption that one coke machines doesn't know or care what the other is dispensing, and hence does not adjust to the corresponding output in any way. What happens is just a function of the state that each machine is in.

None of this is that interesting, really. What is interesting is that when we reconceive the coke machines as photon detectors, with U and D interpreted with respect to polarity as in the EPR paradox, and L, M, and R being interpreted as different settings on the detectors- this part of your author's analogy is admittedly sketchy- the 50% expectation corresponds to a testable prediction in quantum theory. However, what is not just interesting, but shocking, is that quantum theory itself does <u>not</u> predict the 50% disparity. This is what Bell discovered. In fact, the mathematics of quantum theory predicts a 75% disparity in a roughly analogous experiment.

What this means is that, in fact, quantum theory does predict a testable EPR type result. Just as Einstein claimed, quantum theory really does predict that the behavior of specific particles will be entangled; it specifically predicts a correlation between the properties of the quantum entities even though the locality assumption blocks any causal explanation for this.

At this point, Bell's theorem supports Einstein's claim that quantum theory violates the locality assumption, and therefore must be incomplete. But Bell's theorem is different than EPR in that it permits testable predictions. In the 1980's Alain Aspect performed the requisite tests, which actually confirmed the predictions of quantum theory.

Hence, the current state of quantum theory is that entanglement is a real phenomenon. This book ends in a discussion of just how quantum theory violates the locality assumption, and whether it is possible to employ entanglement in such a way as to transfer information instantaneously to remote regions of space.

Your author provides a compelling reason for thinking that this is not possible. Basically it is that while we are theoretically capable of insuring that what happens in what region of space will automatically happen in another remote region of space, entanglement itself does not allow us to influence just what that thing will be. With respect to the above example, we can insure a correlation between the polarity of photons in our region and photons in a remote reason, but we can not influence control over the probability that the polarity will be U or D at any given time, which is what we would need to send any actual information.

However, this is not obviously correct. In recent years scientists have actually articulated a mechanism by which the phenomenon of entanglement may be employed informationally, to vastly increase the speed of computers. This is known as <u>quantum computing</u>. While generally acknowledged as a theoretical possibility, research into quantum computing is very recent, and at this point we do not know whether it is physically possible.

Here is a very interesting <u>recent interview with David</u> <u>Deutsch</u> who first defined the quantum computer, and who also accepts the many worlds interpretation of quantum mechanics.