Lecture Notes on Parallel Universes

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1 Introduction

Parallel universes are a staple of science fiction. The earliest example I've found is the 1934 short story "Sidewise in Time" by Murray Leinster [1]. Parallel universes were introduced as a serious physics theory in 1957 by Hugh Everett III [2]. Other versions of parallel universes appear in more recent physics theory. Author Brian Greene described nine versions of parallel universes in his 2011 book, *The Hidden Reality* [3].

These ideas did not come from physicists looking for other universes to explore; they popped out of math that was useful for something else. Most of them began with quantum physics in one way or another. Quantum physics deals with the basic structure of the universe, including atoms and photons of light. Parallel universes are generally assumed to have no possibility of communication with our universe, so they remain speculative. Science fiction writers, of course, always find some exception to this rule. Physicists continue to explore possibilities to observe or even experiment with parallel universes.

The original idea of parallel universes is the most popular one in the physics community. This lecture will focus on the Many Worlds of Hugh Everett.

2 History

Everett never actually used the term "parallel universe". He wrote about "relative states" and "branches" of the quantum wave function for his Ph.D. thesis at Princeton. His goal was to clarify the foundations of quantum mechanics, as a step toward developing a theory of quantum gravity. Everybody else understood those branches to be parallel universes, since we can't imagine anything else they might be.

Everett's work was not well received at the time. He went to work on military research, and died in 1982 at the age of 51. However, Bryce DeWitt at The University of Texas at Austin started popularizing Everett's approach in the 1970's. This became known as the Many Worlds Interpretation of quantum mechanics.

3 Schrodinger's Cat

Schrodinger's cat is the best-known example of what Everett was working on. Schrodinger wrote his cat story as part of a 1935 paper about the challenges of understanding what the math of quantum mechanics actually means. A translation is available in the collection of papers by Wheeler and Zurek [5]:

> '"One can even set up quite ridiculous cases. A cat is penned up in a steel chamber, along with the following diabolical device (which must be secured against direct interference by the cat): in a Geiger counter there is a tiny bit of radioactive substance, so small, that perhaps in the course of one hour one of the atoms decays, but also, with equal probability, perhaps none; if it happens, the counter tube discharges and through a relay releases a hammer which shatters a small flask of hydrocyanic acid. If one has left this entire system to itself for an hour, one would say that the cat still lives if meanwhile no atom has decayed. The first atomic decay would have poisoned it. The ψ-function of the entire system would express this by having in it the living and the dead cat (pardon the expression) mixed or smeared out in equal parts."

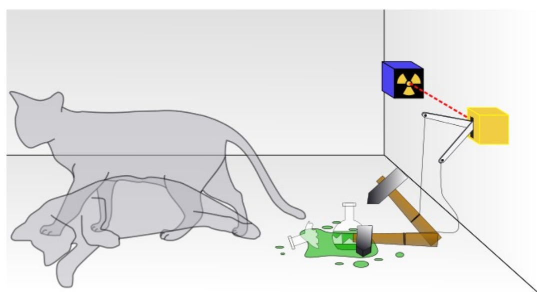

Figure 1: Schrodinger's Cat

The ψ-function tells us mathematically everything we know about the system. It includes probabilities for different things, such as live cat and dead cat. This is different from classical mechanics, where we just calculate a trajectory from the forces and initial conditions. For example, suppose we shoot an arrow from a bow. The forces acting on the arrow in flight are gravity, which pulls the arrow toward the ground, and air resistance, which slows the arrow down. If we know the speed and direction of the arrow when it leaves the bow, we can calculate where it goes. Probabilities come into the calculations only when we don't have all the information we need about the initial conditions, or when the calculations are too complicated, as in statistical mechanics of gas molecules.

4 Why So Weird?

Scientists discovered the structure of the atom in the early 20th Century, and tried to understand it in terms of classical physics. Figure 2 shows a picture. This is not very close to reality; calculations from classical electrodynamics show that if the electrons orbited the nucleus as planets orbit the sun, the atom would emit electromagnetic radiation, the atom would lose energy, and the electrons would spiral into the nucleus within less than a second. For stable atoms, as we find in reality, classical physics does not work.

Similar problems arose in the study of light. Max Planck was studying the efficiency of street lights in 1900 when he found that he could match the experimental results by assuming light came in discreet packages, "quanta", of energy. Today we say light travels as a wave, but interacts as a particle. Soon after, in 1905, Albert Einstein used the quantum idea to explain the photoelectric effect in terms of light particles, called photons, interacting with electrons. This was the work he won the Nobel Prize for.

Louis de Broglie is credited with the idea, from his 1924 Ph.D. thesis, that electrons can have the same properties as light: both can act as either waves or particles. In 1926, Erwin Schrodinger published his wave equation, now known as the Schrodinger Equation. This equation can be solved exactly for the hydrogen atom. In fact there are many different solutions for the hydrogen atom, with different values of energy and angular momentum for the electron. These solutions are interpreted as different possible states of the atom. Each state is effectively a standing wave.

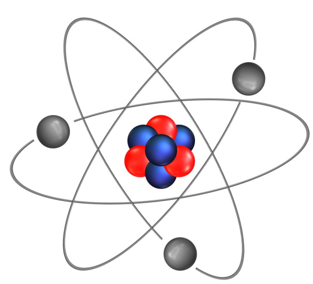

Figure 2: Classical Picture of an Atom

Moving from the hydrogen atoms to more complicated atoms and molecules, quantum mechanics has developed into a highly successful theory of the basic structure of matter. Further development of the theory covers subatomic particles and electromagnetic waves. Some of the results are surprising. Quantum physics is often considered weird, but we use it because it works. All of modern chemistry and electronics is based on quantum concepts and calculations.

5 The Quantum Measurement Problem

Classical physics works for everyday life and for most large objects in the universe; quantum mechanics works for the building blocks of all these objects. For the last 100 years, physicists and philosophers have pondered how the transition from quantum to classical occurs.

Sometimes we can derive the results of classical physics from quantum physics applied to a large number of particles; for example, if an object has a mass much greater than the mass of an electron, then its wavelength is so small that we can never see the wave properties. However, it's easy to find experiments where this doesn't work. Schrodinger's cat is a prime example.

The wave function of quantum mechanics is a bit different from ordinary functions such as sine or exponential. The wave function, ψ, contains all the information about a system. For a complicated system such as a cat, or a Geiger counter or flask of poison, we can't solve the Schrodinger equation to get all the detail. However, we can still do calculations using ψ, just assuming it exists. This is not so different from classical physics: we can calculate how much water flows through a fire hose without knowing the trajectory of each water molecule.

For the nucleus that may radioactively decay in the Schrodinger's cat story, we can write ψ as

$$\psi = \frac{1}{\sqrt{2}}\,|\text{decay} > + \frac{1}{\sqrt{2}}\,|\text{no decay} > \tag{1}$$

Then when we make a measurement to see whether the nucleus has decayed, we get either it did decay or it did not decay, each with probability of $\frac{1}{2}$. That's how it works in these simple calculations: the probability of a result is the square of its coefficient. By using different types or amounts of radioactive material, or running the experiment for different times, we can make the probabilities anything from zero to one. They just have to add up to one.

Of course the calculations are much more complicated for semiconductor design and chemical bond calculations, but Everett was concerned about the basics. For Schrodinger's cat, the wave function for the entire experiment would be:

$$\psi = \frac{1}{\sqrt{2}}\,|\text{decay, Geiger counter click, flask broken, cat dead} > + \tag{2}$$

$$\tfrac{1}{\sqrt{2}}\,|\text{no decay, no Geiger counter click, flask intact, live cat} >$$

and there is a probability of $\frac{1}{2}$ for each outcome.

The founders of quantum mechanics all agreed this is how the math works, but most of them were not completely happy with it. It appears to tell us the cat is alive and dead at the same time, until we open the box and look; then it instantaneously jumps to one state or another. Further, many experiments over the last 100 years show us we can't predict which quantum state is going to show up in a measurement; the result of any particular experiment is random. It is only by repeating the experiment many times that we see the statistical results.

The ψ wave function does not *always* contain probabilities. If we used a pair of dice in the box instead of a radioactive material, then in principle we could calculate exactly how the dice will turn up if we know the precise details of how we tossed the dice. Also in roulette wheels and other games of chance, the result appears random just because we don't have precise data on the conditions of how fast the wheel spins, how much friction it has, etc. But classical mechanics is deterministic: with perfectly precise data on initial conditions and forces, we can theoretically calculate any trajectory. Quantum mechanics is different: even with the best possible information on initial conditions and forces, there is still an element of probability.

Einstein complained that quantum theory means God is playing dice with the universe. He said the theory is not complete; there must be something else that will let us calculate experimental results without using probabilities. Bell's theorem tells us Einstein missed the boat here. In a sense, God does play dice with the universe.

Schrodinger wrote his cat paper to show something was wrong, because we don't think a cat (or any macroscopic entity) can be in a superposition of states. However, atoms can be in a superposition with probabilities for one experimental result or another, and all macroscopic entities are made up of microscopic ones. The cat story is one way to amplify the quantum effect.

The usual "solution" to the quantum measurement problem is the assumption that whenever a microscopic system (such as an atom) in a superposition of states interacts with a macroscopic entity in its environment, the wave function "collapses" to one or the other possibility. This is not entirely satisfactory, because we like to know the mechanism for processes in physics. Also, the wave function can be spread out over an arbitrarily large distance, as in the Bell's theorem experiments. Aspect and colleagues, for example, used high-speed electronics to change the path of an entangled photon while it was in flight. Thus it could not communicate to its entangled partner what kind of polarization measurement it encountered, without sending that communication faster than light [6]. In principle, we could send the two photons a few light years apart and then collapse the entire wave function by measuring either one of them. This appears to violate special relativity.

6 Everett's Answer

Everett had a different idea. He said whenever an experiment can give two different results, the wave function splits into two branches. I don't know exactly what Everett considered those two branches to be, but the rest of the physics world interprets them as parallel universes. And similarly if there are more than two possibilities in the wave function, it splits into the appropriate number of branches.

Everett showed mathematically that his "relative state" theory produces the correct statistical results. If I do the Schrodinger's cat experiment multiple times, then I will split into multiple "branches", and on the average, each branch of me will find a live cat half the time and a dead cat the other half. See Figure 3.

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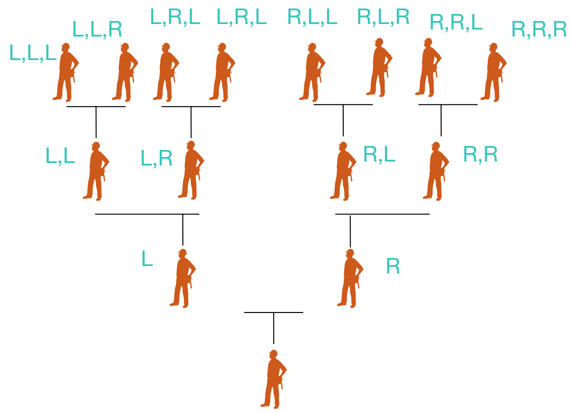

Figure 3: Observer Bob splits into many copies as he measures the spin of an electron to be left or right. He does the experiment multiple times with identical electrons in the same superposition of states, with 50% probability for each outcome.

Now I have never observed any other branches of myself, or any splitting process. So those other branches must go into some type of parallel universes that have no interaction with our universe. And there must be an enormous number of such extra universes, because quantum processes happen everywhere, all the time, regardless of whether we are paying attention to them. Every chemical reaction, and every nuclear reaction in every star, involves quantum probabilities.

Many Worlds is truly a mind-boggling expansion of our perception of what reality may include. It tells us everything that can possibly happen, given the laws of physics, does happen somewhere. Assuming that our brains are made of atoms and obey the laws of physics just like any other chemical system, then every decision we could possibly make, we do make in some universe somewhere. Neil deGrasse Tyson commented, humans used to think there was just one planet, then one solar system, then one galaxy, then one universe. Why not an unlimited number of each?

I'm not surprised that the physics community was slow to accepts Everett's Many

Worlds. I am surprised at how popular it has become. As in collapse of the wave function, the mechanism is missing. And splitting the universe into multiple copies seems a lot harder than collapsing the wave function at a distance, even if it's a distance of light years.

7 Alternatives

There are several alternative interpretations of quantum mechanics, dealing with the measurement problem. Each one has its advantages and disadvantages.

7.1 GRW Spontaneous Collapse

Author Tim Maudlin [7] described the relatively recent work of GianCarlo Ghirardi, Alberto Rimini, and Tulio Weber, published in 1986 and known as GRW theory. It says the wave function for any particle collapses spontaneously about once every 10^{15} seconds, and whatever particles are entangled with it collapse with it. Macroscopic objects have around 10^{23} particles, so at any instant, the wave function for one of them collapses and the entire object takes a definite state.

Here we need to consider what an isolated system is. In classical mechanics, everything is connected to everything else, at least through gravity. The gravitational field never falls to zero, so to list *all* the forces acting on a particle, we have to include all the mass in the universe. Of course we ignore almost all that mass, because it's so far away that the force is too small to measure.

Also in quantum mechanics, everything is connected to everything else. Theoretically, there is a wave function for the entire universe. However, we can separate out a single electron in a particular hydrogen atoms and calculate an excellent approximation to the wave function. For molecules, we use the approximation of individual chemical bonds, even though all the electrons and nuclei in the entire molecule belong in the wave function for the molecule. For larger chemical systems, such as cats and humans, again there is theoretically a wave function for the entire system, but it's a good approximation to consider molecules separately.

When we talk about "entangled particles", we usually mean particles for which it is an excellent approximation to say they are separate from the rest of the universe, but they are connected to each other so strongly that there can be no useful approximation of separate wave functions for them. It takes a lot of effort to separate individual atoms or electrons from the rest of the universe, and even more effort to isolate entangled pairs of particles. That's what makes quantum computing so difficult. But it's easy to find large numbers of atoms entangled with each other: just look at any solid object.

In the Schrodinger's cat story, everything in the box is connected in a theoretical wave function. All the atoms are entangled with each other. So when any one of them undergoes a spontaneous collapse, they all collapse together.

GRW theory has the advantage that a macroscopic object is never observed in a superposition of states. We have to make the special effort to isolate a particle in order to observe a wave function that includes probabilities. The disadvantage of GRW theory is that it still doesn't have a mechanism for individual collapses.

Spontaneous collapse ideas have not yet become popular, but I think they have the most potential.

7.2 Bohm and de Broglie Pilot Waves

Sometimes the same problem can be solved by very different math methods. For example, we use Newton's second law $F = ma$ to solve many problems in classical mechanics. Another approach is given by Lagrange's equations, which are more complicated. They are mathematically equivalent. Lagrange's equations were developed because they are easier to solve for certain types of classical problems. As a bonus, the Lagrangian functions are used extensively in General Relativity and Quantum Field Theory.

In the 1950's, David Bohm developed a formulation of quantum mechanics with pilot waves, using ideas introduced by Louis de Broglie. The pilot wave method of doing quantum calculations is more complicated, but gives the same result as standard quantum mechanics. So far it has not led to any further results, so I confess I have not spent the time to understand it in any detail.

7.3 Shut Up and Calculate

The standard view of quantum mechanics is the Copenhagen interpretation, developed by Niels Bohr and other pioneers in the first half of the 20th Century. David Mermin gave an amusing summary of this as "Shut up and calculate" [8]. That is, shut up about the philosophical aspects of quantum theory; the calculations give us the right answers to so many problems in chemistry, materials science, and particle physics. The problem of how the wave function collapses is left for future inspiration.

8 Conclusions: How Many Worlds?

Everett's solution to the quantum measurement problem is not my personal favorite. I think future inspiration is the most likely answer. However, I have the greatest admiration for what Everett did to expand our minds. Several other theories now include parallel universes, and one of them, inflation theory, offers what I consider a reasonable mechanism for their formation.

Many people consider quantum mechanics to have spiritual significance. In the most general sense of what spiritual means, I agree completely. Classical physics painted a picture of a universe highly restricted by deterministic laws of motion. By contrast, quantum physics includes vastly more territory to explore.

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