Introduction- Quantum physics is currently one of the most fascinating, yet developing areas of physics; every now and then we get fascinated by the discovery of some or the other magic of particles, so, it is of utmost importance that we take a look at our not-so-distant future from the eyes of this subject. The latest development in the field of quantum computing has revolutionized the speed of a computer. To understand this, we have to take a look at some basic concepts of quantum mechanics.

Now, to start off, the main idea of quantum mechanics is to explain the behavior of particles. Quantum means the fixed amount of something. Here, the particles are seemingly known to exhibit the properties of both waves and physical particles.To understand why, we need to look at the double-slit-experiment. It was quite an interesting experiment, where we shoot electrons(or photons) through 2 slits, and the resulting pattern seen on a screen behind those slits was a pattern that represents waves - dark and light intersections. So it's like the electron, after passing through the slit, acts as a wave and interferes with other similar wave-like electrons, until it collapses at a point. But is that really what happens? If that's the case, which slit did the electrons really go through? To truly understand it, scientists tried different cases. They looked at all the different possible options:
All went through slit 1
All went through slit 2
Some went through either 1 or 2
All went through both 1 and 2
They went through neither

Slit 2 was covered, and the same experiment was repeated. But, as we expected, it resulted in most of the electrons collecting right behind slit 1. So option 1 is wrong. We did the same thing, but this time, we covered slit 1. Again, most of the electrons were collected right behind slit 2. So, option 2 is wrong. If option 3 was the case, we know the pattern we get when they go via only slit 1 or only via slit 2, so we would expect a pattern of case 1 and case 2 combined. But that does not happen, so option 3 is wrong. What if each electron was going through both slits? If that was the case, if we got the screen fully towards the slit, we would expect the interference pattern to occur, but it doesn't. Also, if we shot just 1 electron, then we would expect 2 on the screen in each slit, so option 4 is wrong too. What if they went through neither? It's possible. We repeated the experiment by closing both slits, and we didn't get the interference pattern. In fact, we got nothing on the screen. What if these particles were being sneaky? What if a electron went through 1 slit, then came back through the other slit and something like that happened? We kept a barrier that would detect if the particles even came back, but none of it was detected. Here, we have listed out all of these options, yet neither one is right! This brings us to our answer for this phenomenon. It means that these particles have an extremely complicated interaction, to a point where even we can't comprehend it. We call it the Quantum Superposition of particles. It is kind of tough to explain what we mean by this, but it is rather easier to explain what it is not - it is none of the options listed above! Quantum Superposition refers to the idea that particles can exist in multiple states at once until observed. It makes sense, as we have seen. We can say that the electrons are in a state of quantum superposition of going through slit 1 and slit 2. It is a new thing on its own that cannot be explained via any prior knowledge or existing language. But, you can use math to describe exactly what quantum superposition is. This is why math is known as “the language of quantum mechanics”. So, what we interpret from the math is that electrons can also be thought of as a probability wave that passes through both slits, and then intersects and collapses at a point on the screen. But this is not the only interpretation. What do we mean by a probability wave? Well, it’s not a wave in the real sense, but its mathematical description is very similar to that of a wave equation.

Now, another very important question that we have to ponder on is: why doesn’t quantum superposition happen on a macroscopic scale? Well, to understand, let’s go back to the experiment. Remember: This was done in a dark environment to avoid any light interference. They then thought, what if a light source was kept in between the 2 slits? They could be detected as a flash to us after bouncing off. They repeated this experiment with the light source, and what happened was that they noticed flashes! Indeed some were going through slit 1 and some were going through slit 2! But the resulting pattern was not an interference. The areas directly behind either slit only had gathered electrons. So, this tells us that quantum superposition only takes place when there is no observer of the particles. This phenomenon of superposition is true for any quantum property. For example, the spin. When you measure spin of an electron, it is either going to be up or down, but when un-observed, we can’t really say what it is, and it would be in a quantum superposition of being up and down. Schrodinger’s cat is a thought experiment similar to this, and often has the wrong interpretation. The cat is said to be in a quantum superposition of being dead and alive. It doesn't make sense at first, but then again, this doesn’t necessarily apply for macroscopic objects like cats, due to the number of interactions happening. Linking this phenomenon to chemistry, covalent bonds have electrons that are said to be in quantum superposition. The electron is not said to orbit the nucleus, as we don’t know its specific motion. It is said to be in quantum superposition with all the different places it can all be in. This explains the reason we look at shells in terms of orbitals and not orbits anymore. This is the reason we exist- the bonds of water, DNA etc are all covalent, and highly reliant on superposition.

There has always been the question of what travels the quickest. People generally assume that it is light, but that is just 1 medium of exchange of information. As part of Einstein’s thought experiment, intuitively speaking, information can also travel instantaneously, regardless of the distance between the 2 events, an event at 1 point of the universe could immediately affect the other. This seems to imply faster than light speeds of communication, but in modern day, we can prove this spooky action. All particles have a property known as spin, or in other words, angular momentum. It can either be measured to spin up or spin down. But if we were to measure the spin horizontally, it has a 50% chance of being spin up and 50% chance of being spin down. After this measurement, the particle maintains this spin, so technically, measuring the spin actually changes the spin of the particles. So, when 2 particles are created spontaneously just from energy, they will exhibit properties that in turn conserve the energy used in creating them. So 1 such property is its spin, since the total angular momentum of the universe must stay constant. So if 1 particle is measured to have spin up, then the other must have spin down, measured in the same direction. You might be wondering that the particles must be created with a pre-defined, well-known spin, but that won't work, since if 2 such particles are being measured horizontally, there is a 50/50 chance that they will measure spin up or spin down, causing a 50% chance of both particles having the same spin. This is because when we measure it, we are forcing it to take a direction in our axis. The spin of electrons can either be +½ or -½ due to the pauli exclusion principle, and how they behave under spins. Now, a fun fact to note is that the spin of these particles are in quantum superposition. So, the particles do not have a pre-defined spin! Hence, the chance is 50/50. Since these particles are in superposition and their spin is linked to one another, they are said to be entangled. You may get confused and wonder won't the spin be pre-defined and only in superposition since we didn't measure it? Well, that is not what we are trying to explain here. If 1 particle makes a choice, it 100% influences the choice of the other. Einstein on his own wasn't convinced of this. He sought an alternate explanation, talking about how all this time the particles contained hidden information about which spin they would have if measured in any direction, and we didn't know this information until we measured them. Since this information was with the particles since they were created, no faster-than-light exchange of information was supposed to happen. To truly confirm these theories, John Bell came along to test this idea. There are 2 spin detectors and a pair of entangled particles, one for particle A and one for particle B, that detect spin in either 3 directions, independent of each other. Now, we have to calculate the number of times, as a percentage, the spins were the same or different, by repeating this procedure over and over again. All we need to find is the % of times the 2 detectors give different results. For example, let's look at a case where they know the plans. In order for them to have different measures, one could have up spin for all, or down for all. All other plans could be similar. So we would expect the results to be different 100% of the time. According to more calculations conducted based on the worst case scenario or plans, the percentage should be greater 5 out of 9 times. What were the results? They are different only 50% of the time. So they definitely don't contain hidden information. Now for the case of quantum entanglement mechanics, if A is up in the 1st direction, B will be spin down if also measured in the 1st direction. This would happen randomly ⅓ of the time. But if in the other 2 directions, there is always a ¾ chance of it being spin up, since this would happen at an angle of 60 degrees, and according to the probability that depends on cos^2(theta/2). These directions will be selected ⅔ of the time and particle A will be ⅓ of the time in this case. So particle B will give spin ⅔ * ¾ of the time, resulting in the probability of ½ or 50%. And this is what we expected. Yet, there is still debate on how to interpret these results. Some see it with the same point of view, while others believe that these entangled particles can signal each other faster than light to update their hidden information when one is measured. At the end, this cannot take place faster than light, since the results found in either detector are pretty much random. But, only when they selected the same direction, they got opposite spins. This indeed is not fully explainable with the help of classical physics, yet this can be easily used in our lives as we will see later.

Now, there is a crucial principle, that is known as the Heisinberg's uncertainty principle. It revolves around the idea that if we know the exact position or location of a particle, we can't simultaneously know anything about its motion, and vice versa. So the uncertainty of finding the location is inversely proportional to the uncertainty of finding the motion. This also applies to particles like electrons. But, this analogy with particles is misleading. Think about it. If we have a picture of a tennis ball, and we just move 1 frame forward, we can know its velocity and its location at the same time! Let's revisit the concept of wave-particle duality. Well, doesn't that talk about how electrons for example are both waves and particles at the same time? No. Well, if you think about an animal that flies like a bird, and has a face of a tiger, do we tell that the animal is both a tiger and a bird? No. It's a different animal that just shares some common properties of both. Similarly, an electron has properties similar to that of the traditional particles, for example, they come in lumps like grains of sand. But electrons aren't particles, since they do certain things that normal particles don't do. An example of this is the way they behave in the double slit experiment. So, electrons are not normal particles. But the pattern is an interference pattern, usually gotten via waves. So they also have a property of interference. But, this is not just true for electrons. As a matter of fact, this is similarly true for all standard quantum particles, like protons and neutrons too! So the physics for them is pretty much the same. This is why we call them "quantum objects". So now that we know that this principle applies to quantum objects, how do we deal with the momentum or position of these objects? So let's take a look at momentum. Back in the 1900s, we understood that light is an electromagnetic wave. But in the future, experiments like the photoelectric effect and the black body radiation were a bunch of phenomena that were unexplainable with the definition of light as a wave. Then they realized the quantum physics behind light, and how it was made of photons. Their energy had to be given by the famous equation $E=hv$, where e is energy, h is planck constant, and v is the frequency of light. Guess what? v is also defined as c/λ. If we bring c to the other side, we get that the momentum of an electromagnetic wave is given as E/c. This means that the momentum of these light particles should be Planck's constant divided by the wavelength. So then they realized how all particles could have such properties, and ended up proving the same. This equation works for all these particles. So this is how we think of momentum for all quantum objects. Now, what about position? When this was discovered, they asked, "since electrons have a wavelength, don't they also have a wave equation? Where is it?". And that's where schrodinger came in with the wave equation, also known as the schrodinger equation. It takes into account most properties of these quantum objects. Now, if we were to solve the wave equation, and we were to get a wave, what does that even represent? It's not the result of electrons moving up and down. It is the electron. So what could the peaks and valleys of the wave function mean? We realized that if we take the square of the peaks and valleys, we get the probability of finding the quantum object in space in that particular location. This concept is known as probability density. There is no specific reason to square this value, but it gives us a clearer insight into calculating probability. Usually, we refer to finding them by shining light on them, or using a detector. To reiterate, this well relates back to quantum superposition. It's not like we don't have the tools to measure their position, rather, their position is inherently probabilistic. They don't have a position until you measure them. So, now we know how to think of their momentum and their position via the wave-like nature of these quantum objects. Now let's look at how we can re-create the uncertainty principle. If an electron has a specific value for momentum, they should have a specific value for the wavelength, lambda. So the best way to imagine this is a wave with a specific wavelength. This must extend till infinity, since the one value for the wavelength must be equal for the whole wave. So there will be no uncertainty in the value of momentum. But, for finding its position (amplitude squared), the amplitude is the same everywhere! So the probability of knowing its position is infinite. Since we can find it anywhere in the universe! Now, if we want to narrow down the probability of finding this electron, some places must have a lower amplitude. Now, to do that, we must add different waves with different frequencies, since some values might increase or decrease the amplitude of the combined waves. Now, in the new resulting wave, some places must have a high amplitude and some will have a lower amplitude. So now, since we had to add 2 different waves with 2 different wavelengths, this object has 2 different values for momentum. In other words, there is a 50/50 chance it is either. The position and momentum of such quantum objects are in a fourier transform. We can always further narrow it down. This is due to the fact that these approach infinity, and if we get to a point where we only have 1 amplitude, we would need infinitely many waves to create such a pattern. This is one of the major principles that the realm of the quantum world works on. This is relevant as, although theoretically, it prevents electrons from colliding into the nucleus.

Quantum tunneling is a phenomenon in which particles can pass through barriers they seemingly cannot pass through. This is again the result of these quantum objects acting as both particles and waves. So, based on Heisenberg's uncertainty principle, if we know its momentum, we know nothing about its position, and so there is an extremely small chance that the particle can exist on the other side of the barrier. Let’s see at an intuitive level why this phenomenon takes place. So, let’s take a look at an example. If we were to climb a hill and get to the other side, we could either climb up and then descend, or we could make some kind of hole, or tunnel that would allow us to go through. Now, in the quantum realm, let's think of this hill as an energy barrier. Here, we have a particle on one side of the barrier. So this quantum object has properties of both particles and waves. Now, its wave function would be defined as the probability of finding the particle anywhere in a volume spanned by that wave. So like we saw, we are more likely to find it where the wave peaks, and where the wave troughs, we are less likely to find it. But it still can show up over there! So that wave doesn’t know or care about that mountain. So we can ask, does some of that wave show up on the other side of the mountain? If it does, then there is a probability that the particle can simply appear on the other side of the barrier. And just to remind you, these particles are complex in nature. The thing is that, although it appears after the barrier, if the barrier is thick enough yet thin enough for the wave function to re-appear, it can definitely reduce the amplitude at the other side. Don’t forget. It decreases exponentially inside the barrier, but it still has a chance of existing there. This is another consequence of the wave-particle-nature of these quantum objects.

You might be wondering, How is all of this even relevant to quantum computing?
Well, to understand this, we need to look at how a modern computer works.

So, a normal computer works via electricity, and makes use of the fascinating properties of semiconductors, in this case, silicon. They are “semi” conductors since they can either conduct or not conduct electricity. This is the result of electrons being able to jump from their valence bands to their conducting bands, and switch from time to time. Once again, it relies on quantum tunneling. Computers themselves are electrical circuits. We will come back to this in a moment. Unlike humans, computers can only process information on a base 2 system, known as binary. So these bits store either 1 binary value 0 or 1, on or off, true or false, etc based on high or low voltage. We chose 0 and 1 since these are the most easily understandable values corresponding to binary. In this circuit, the most important component is the switch. A transistor, typically a metal oxide semiconductor field effect transistor, consists of 3 components - source, drain, and gate. These are currently not relevant to us. There are 2 types of transistors. The N-channel type, which makes a circuit when high voltage is applied to a gate, like a push to make, and the P channel, which breaks the circuit when a high voltage is applied to the gate, like a push to break. So transistors act like switches, but rather than a person pushing on them, a voltage applied is used for them to function. In modern computers, they are used in pairs (CMOS), and the gates for both are always connected together. So they receive the same signal. For example, if we apply a voltage of 1, the N-channel opens a route between the high voltage and the output, while the P-channel closes the route to ground. We can always rearrange them to make them seem useful, but we will come back to how these form the base of modern processors. Vast number of CMOS pairs like these allow a computer to think, since when a voltage is applied, they can govern the pathway for the charge, making them influence binary decisions. Silicon is a semiconductor with 4 valence electrons which is mixed with other elements. Now for example Gallium has 3, making it more positive than silicon, making it P type. Arsenic on the other hand has 5 valence electrons, making it more N-type. Typically, for every 1 in a million particles of silicon, particles like these are implanted via chemical diffusion or by firing them out of a particle accelerator. These are known as dopants. Transistors are made by sandwiching one of the dopants between 2 others. For example, the N channel doesn’t itself conduct electricity, but when an electric field is applied, a conducting channel forms (FET). These can be thought to be the electric fields attracting the electrons from the 2 N-doped regions to the P-doped region, which has a deficit. Near the semiconductor stack, we have a conducting electrical terminal. When high voltage, an electrical field forms, and the transistor conducts. But to stop a short-circuit, we need to add an insulating layer in between. The contact is metal, the insulator is silicon oxide, and we have the doped semiconductor, hence mosfet. For computers, we need millions of these CMOS pairs, and they must be small and close together in order for the electrical signals to travel between them quickly. Making a processor depends on a solid block of p-doped silicon called a die. Transistors are then created on top of it by lithography. It consists of 2 main techniques-deposition and etching. A photoresist is deposited on top of the die, and light is shined through a mask exposing predetermined areas of the photoresist. They must be the same size or larger than the wavelength of light used hence very short wavelength UV light is used for lithography. Then etching is used to target the gaps. Then the photoresist is etched away. So all the N-type transistors of a die can be added simultaneously. Then silicon oxide is deposited and etched and finally so is the metal, to leave metal channels on top of the die. These form the tracks, and act like wires at the same time. The billions of transistors are connected by this method. Now, a semiconductor can either allow current to pass through or not. So it translates these binary values into an on or off system, and these are grouped in such a way that they collectively help in the functioning of the computer. Logic gates are then used in order to transfer information with the help of particles, based on inputs. The number of binary bits used to encode a number refers to the number of electrical tracks used. A digital clock is used to synchronize all computer parts and operations, and bytes store 8 bits each.

So these are some of the basic and important ideas that govern modern computer systems. Now let's take a look at how quantum computers make use of all the properties of quantum mechanics discussed in order to speed up and maximize their efficiency at transferring data.

Until this point, we had been using normal particles that obey the laws of classical physics to operate. Now we will look at how a bridge between quantum particles and computer science was made, leading to developments in the field of quantum computing. Until now, we had been making computers faster by adding more processors or memory. The fundamental particles associated with this are the binary bits that usually exist as either 0 or 1. But now, we have seen the development of quantum bits, also known as qubits. These simultaneously exist as waves and particles. These also exist in a quantum superposition between 0 and 1 simultaneously. Not just that-these bits tend to be entangled too! So when one qubit gets information, it directly affects another. These coordinate instantaneously with one another. These qubits being entangled with one another leads to them being able to work in concert, even while they are in an indeterminate state. So instead of doing each calculation with each bit one at a time, a quantum computer can do exponentially more calculations simultaneously. Here, the particle isn't even traveling. It is just the information. This makes it rapid, and much quicker. These use tunneling also to be simultaneously present literally everywhere. This concept might seem too far-fetched, but nonetheless, it is very accurate. It fundamentally shapes the probabilistic nature of quantum systems, impacting everything from quantum computing to how entangled states are measured in teleportation. Now, let's take a detailed look at quantum computers, and different problems with their constituent parts. To understand how quantum bits were used, researchers tried using the outermost electron of a phosphorus atom as a qubit. This atom is embedded in a silicon crystal right next to a tiny transistor. Just to recap, there are extremely few of these atoms, typically about 1 atom in a million of silicon, in order for silicon to switch states between insulating and conducting effectively. The p doped block (gallium) contains an absence of electrons, which carries charge as other electrons take its place. And the n doped block (phosphorus) consists of free electrons, which can again move around carrying charge. The electron has a dipole moment called spin. It has 2 orientations as we saw, up or down (similar to 1 and 0). Now to differentiate which one the electron is in, we need to make use of a strong magnetic field. So for this, we use a superconducting magnet. Basically a large solenoid of the wire that sits inside liquid helium. So now the electron will align with its spin pointing down, since it is its lowest energy state. It would definitely hence take energy to put it back to its spin up state. But not much would be required. At room temperature, it would be bouncing between both up and down spin rapidly. So, we need to cool down the whole apparatus to just above absolute zero, so that we know that the electron will only be spin down. If we want to put information into the qubit, we can put the electron in a spin up state by hitting it with a pulse of microwaves of a very specific frequency, which depends on the magnetic field that electron is present in. So it responds to a particular frequency by going into the spin up state. But we can stop at any point. If we stop our pulse at some specific point, we have created a quantum superposition between the up and down state. And here, there will also be a specific phase between the 2 superpositions. Now, to read this information on the qubit, there is a transistor embedded right next to the atom; if it has spin up when measured, it can jump into the transistor, which has electrons with specific energy levels arranged in that specific manner, and this is due to the fact that the electron has more energy than all the others. The phosphorus atom is left with an extra positive charge, resulting in a positive voltage applied to the gate. So then we get to see a pulse of current that indicates the state that the electrons were in. If there was no current, it was a spin down event for the electron. The researchers now resorted to using the nucleus of the phosphorus atom as a qubit. Although even the nucleus has spin, it is 2000 times weaker than the spin of an electron. Similar conditions are needed to activate these. Although the states are being measured here, these help scientists and researchers to find out about several of their applications, hence modifying certain conditions.

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