By Katie Day – Sir William Borlase's Grammar School

GOLD STEM CREST

A Brief Outlook into Quantum Computing

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Planning my Project

At the start of this project, I recognised that the topic of Quantum Computing was vast and covered many different aspects of physics, engineering, and maths. I wondered whether to solely focus on the algorithmic side, discussing the range of algorithms found to solve problems faced in the world today and their impacts. Another path I contemplated was to focus on the hardware and how the qubits interact and are manipulated to represent theoretical values.

It was clear that whichever path I took, I would need an extensive understanding of the basics of quantum mechanics and how they relate to quantum computing. I realised that I should study quantum mechanics early in this essay for context. I could then build upon this framework to examine the concepts of algorithms and gates in the quantum computing domain. Likewise, I felt it was important to discuss the future of quantum computing. As we start to understand the limits of classical computing, quantum computing is set to be a crucial tool for many aspects of society. In fact, it is the limits of classic computing which are driving the development and opportunities in the quantum field. Additionally, with Climate Change so topical, I have chosen to explore the environmental impacts of quantum computing compared to today's computing

I created an activity log to record my time spent on this project. It helped me be organised and accountable when undertaking this study. Through using log, a recorded my time, I also used it to plan out precisely what to research to do on which days. The log became a vital productivity tool.

To begin with, I read articles and lectures about the different topics within Quantum Computing, and I divided them into six major parts; 'Limitations of Classical Computing',' Fundamentals of Quantum Physics', 'Quantum Gates', 'Quantum Algorithms',' Uses' and 'Where we are right now. This gave me a good starting point for organising my thoughts and allocating sub-topics. As I read and researched further with each new field, I decided whether I wanted to discuss it in my project. It frequently depended on how much detail I would have to go into, its complexity, and if it were a crucial part in explaining the fundamentals of computing.

I considered several ways of approaching my investigation, for example conducting small scales experiments and creating artefacts. However, I felt that the most appropriate method was a research project. Quantum Computing is heavily theory-based, and an essay style project would be the best fit in explaining and exploring my subject.

The wider purpose of this project broader explores the fundamentals and future adaptations of Quantum Computing in society. As I intend to have a career in computer science, the knowledge of the industry I gain from this study will be very beneficial.

Throughout my Project

When planning and researching, I have tried to use a diverse range of resources to consolidate information and data in order to remain as factual as possible. This would help me stay objective and rule out ambiguity. However, this was challenging due to the limited use of the library due to COVID. Instead, I focused on books I could find online, along with articles and lectures on YouTube, which was especially useful in understanding my topic. My mentors likewise provided me with documents and information about my subject, especially about future development in this field. I created a References section in this project to record the information resources. I used alphabetical order and Harvard referencing to organise my sources. This would make them easier to search through. Graphs and images were each named as a *Figure x* with the link associated in the References section.

Introduction

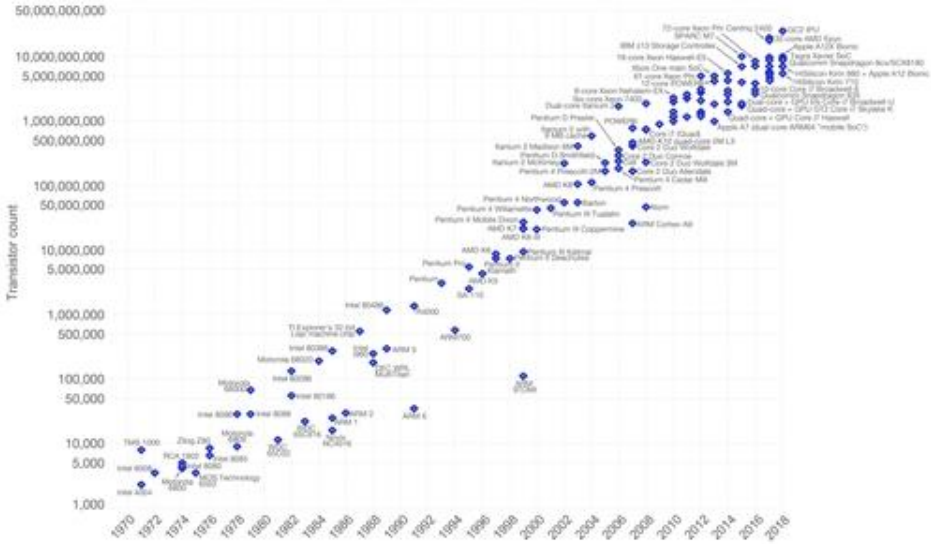
In this project, I will be exploring the fundamentals of Quantum Computing and Quantum Physics, covering why they are needed, the key principles and how the link together. In addition, I examine the countless capabilities this new form of computing has to offer. From modelling atoms to cracking the world's most secure data algorithms – this new revolution will change the way we live.

The Limitations of Classical Computing

A processor is the 'brain' of the computer; it is made up of billions of tiny transistors, which control the flow of electrons – either 0 or 1. These transistors make up Logic Gates, e.g. AND, OR, NOT (the use and meaning of these are discussed subsequently) that perform logical tasks numerically with binary digits. These gates used together forms a circuit. The general rule is that the more transistors available in the processor to use, the more capable a processor is to perform challenging and more complex tasks. When a computer has enough of them (in the billions) it has the capability to perform tasks that a human could never do. The number of transistors available for the processor is normally directly proportional to complexity to the task that can be perform. Over time transistors become smaller and smaller and more can fit into one space. The first modern transistor was made in 1947 and was 14 micrometres in size which is under twice the size of a red blood cell. Today, the processor manufacturer Intel mass-produces transistors to a scale of 14 nanometres which only 14 times bigger than a DNA structure.

However, if a computer's computational capability depends on the amount and size of transistors, is a threshold? Yes, as transistors get smaller, they become closer and closer to the size of the electrons they are trying to control. Additionally, the usual Standard Model we base all our logical and physical conclusions on becomes warped. This is because that when we are trying to manipulate hardware on a molecular level, the Quantum model applies instead – which creates immense challenges.

Trying to apply 'Classical' computing methods in a Quantum model is improbable – as the assumptions and logic in the Standard Model of Physics do not apply. For example, if transistors become small enough – there will be a phenomenon called 'Quantum Tunnelling'. This means that electrons can 'bypass' the transistor – which negates the role of the transistors. Hence there are



limitations in the size transistors can be which places a limit on the mathematical prediction of Moore's Law (that the number of transistors on a processor will double every two years). I doubt back in the 1970s that Gordon E. Moore considered that transistors could ever be this small.

Therefore, if transistors have a size limit, they will need to be extra processers to make increasingly powerful computers. More of them will be required too, and multiple processors can work together to perform the task in 'parallel' – called Parallel or Concurrent processing. However, there will always be a limit on computational power since a classical computer needs to complete every action sequentially. Every outcome, action and consequence has to be accounted for, which increases processor time at an enormous rate. Hence, Quantum Computing is so promising, as it can theoretically complete many tasks all at the same time.

Figure 1 – Transistor count against year

Fundamentals of Quantum Computing

Many different strange phenomena occur on a Quantum scale that makes illogical sense in the Standard Model. Multiple experiments have been proven to be grounded in reality yet do not establish on a Quantum scale. This barrier between the proven Quantum Model and the Standard Model is one of the greatest mysteries in Modern Physics – perplexing the minds of some of the greatest physicians. Most notably, Albert Einstein, who famously called Superposition, 'spooky action at a distance'.

Superposition

One of the most famous experiments in Physics is the Double Slit Experiment, first performed by Thomas Young. Imagine a wall with two slits in it, and then a monochromatic source (same wavelength) of light goes through both slits onto a screen on the other side – we expect to see an 'interference' pattern, where the waves from the two slits interfere with each other. At some points, the waves interfere constructively (when the peak meets the peak), and the waves cancel out (when the waves peak the trough).

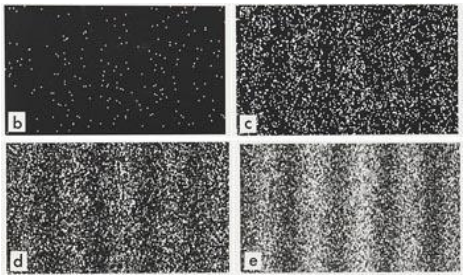


Figure 2

However, what if we did this experiment with electrons? We would assume that electrons would act as particles and only create two single lines roughly the same shape as the slit– not an interference pattern. But surprisingly, we get the same result as with the monochromatic light – how is this possible? We could conclude that the electrons interfere with each other, making them then bounce off each other. Yet, if we did the same experiment again but instead, we sent through the electrons one by one, under the assumption that the electrons would not 'interfere' with each other, we get the same result as before.

Another theory was that the electron splits to go through both slits at once – it would then interfere with itself and then recombines into a single particle. So, we placed a detector by the slits to see which slit the electron passes into – the result is not the 'interference' pattern but a pattern of two strips in the shape of the slits. The electrons are behaving as we assumed previously. If we take the detector away, the result is the interference pattern again.

This means that the electrons 'knew' that they were being measured and decided to change the experiment's outcome. This is a quantum phenomenon called the observer effect/measurement problem.

The experiment showed that electrons could take on two natures – either as a wave or as a particle. This is not just for electrons, as this experiment suggests that any particle can combine both characteristics at the same time. For example, light can act as a wave and a photon that carries bundles of energy. This is called Wave-Particle duality, but can we explain it?

One theory is the Copenhagen Interpretation, where the reason why we see electrons sometimes like particles and other times like waves is that our experiments influence what we see. The results are products of the investigation we do – so something like Wave-Particle duality, which seems conflicting, is the result of ourselves expecting something unreasonable from the Universe. There are other alternative interpretations; however, none have been as popular or robust.

Heisenberg Uncertainty Principle

On a real-life scale, we know definitively where an apple is. Within a few nanometres' uncertainty, an apple's position is minuscule in terms of inaccuracy. However, if we wanted to know the location of an electron – a few nanometres is very significant. Additionally, the principle of an electrising a wave and a particle brings up the question – is an electron in a specified position or in a general area like a wave?

Heisenberg tried to measure the position of electrons by using photons. However, when the photons reach the electrons, the electrons changed velocity and moved to an excited state. Showing that it is impossible to measure the location and the velocity of an electron at the same time. This is known as the observer effect.

This is where the Heisenberg Uncertainty Principle was born. It says that there are bounds to the degree to which both the position and momentum of a particle can even be known. Momentum is proportional to velocity. Since an electron cannot display both the characteristics of a wave and of a particle at the same time it jumps to one position or the other when being observed. This is what happens in the Double Slit Experiment. The more you know about an electron's velocity. The less you know about its position and vice versa. Therefore, the equation in Figure 3 states that it's impossible to measure the momentum p and the position x with the product of them being less than $\frac{h}{4\pi}$

$$\Delta x \Delta p \geq \frac{h}{4\pi}$$

Figure 3

Wave Function

Following on, we cannot know truly where an electron is and what momentum it has. Therefore, we cannot represent the position of an electron on a map such as 'X marks the spot', but instead, we describe the position of an electron as a wave function. The electron can lie anywhere along with this wave. However, there is a probability attached to where the electron is likely to be found. The amplitude of the wave determines the probability; for example, the electron is more likely to be situated where the wave's maximum is compared to being nearer the minimum. It is easier to depict when we square the amplitude to get the probability distribution of the wave. Therefore, the maximum displacement of the wave is where it is most likely the electron is. This probability distribution is seen in the Double Slit Experiment.

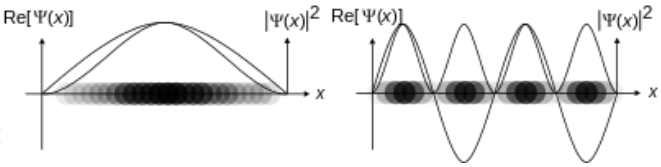


Figure 4

Spins

A spin of an electron is the angular momentum of the electron in a specific direction. Spins can mathematically represent different states. To explain spin further, we will look at the experiment with silver atoms performed by Otto Stern and Walther Gerlach.

A silver atom has 47 electrons, with only one electron being in the outermost orbit by itself. Electrons moving in a circular motion generates a magnetic field. Each electron pair moves in opposite directions which cancel out the combined field. However, a lone electron on the outermost orbit will still generate a magnetic field, making the atom a tiny magnet with a North and South pole.

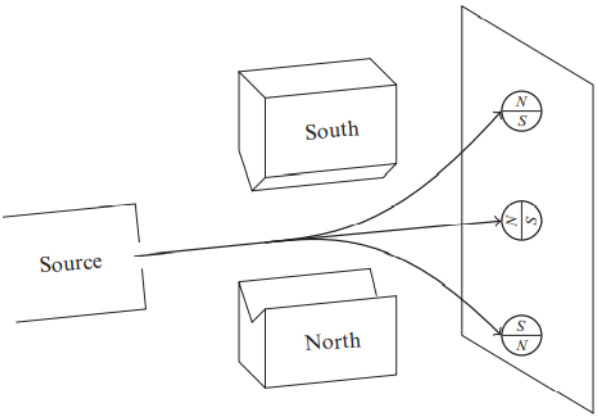


Figure 5

Stern and Gerlach built an experiment to test whether the axes could have any direction or was constrained to one specific direction. They did this by sending a stream of silver atoms through a pair of magnets. If the silver atom deflects downwards, the north magnet wins, and conversely for the south magnet. However, if the atom continues in the same paths, we know that the atom was repelled by both magnets equally.

If we assumed that the atoms could be aligned in any direction, there should be a continuous line from top to bottom. However, this is not what Stern and Gerlach found. Instead, they found only two dots, both at the extreme top and at the extreme bottom showing a maximum deflection. This will only be found in the silver atoms that are only aligned vertically; for example, isotopic spin is used to represent the two states in a 'nucleon', either the proton or the neutron, in Nuclear Physics. This is the same for value in binary. In 2D, the upwards spin could represent the value 1, and the downwards spin could be a 0. However, we called a bit in a Quantum Computer a Qubit (shortened from Quantum bit).

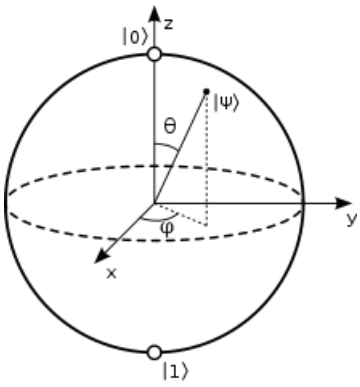


Figure 6

We show the spin of an electron using a vector in a 3D space and we use Paul Dirac's Notation to represent this mathematically. However, for simplicity, we will only be using 2D vectors.

For a spin of an electron, the number of outcomes determines the dimensions of the underlying vector space. For 2-dimensional spin we are in the vector space $\mathbb{R}^2$.

$|v\rangle = \begin{bmatrix} c_1 \\ c_2 \end{bmatrix}$ and ${c_1}^2 + {c^2}_2 = 1$

We represent spin-up as $|\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$ and spin-down as $|\downarrow = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$. Spin-up represents the binary value 0, and spin-down represents the value 1. Any of these qubit states can be represented geometrically on the surface of a unit sphere called the Bloch Sphere. The physicist Felix Bloch additionally defined that a 3D qubit state can be written as:

$$|\psi\rangle = e^{i\gamma}\left(\cos\frac{\theta}{2}|0\rangle + e^{i\phi}\sin\frac{\theta}{2}|1\rangle\right)$$

Figure 7

The angle θ represents the angle around the z-axis (latitude), and angle ϕ describes it around the x-axis (longitude).

To combine multiple qubit states into one whole equation, we use tensor products. $|a\rangle \otimes |b\rangle$ combines the two qubits by multiplying each qubit vector with the other. This is helpful when realising the different outcomes that are possible with each qubit configuration.

Probability of the Spins

Imagine the electron was in a superposition of the two states at right angles from both. When we measure the electron, we see that the electron would jump to either state. But which one? The state of the electron they jump to is entirely random. This is called pseudorandom. However, the probability of the electron jumping to that state depends on the phase difference between the states. Modelling this mathematically, we apply Pauls Dirac's notation further.

Let's model the Superposition between two states. We would show it as $\alpha|\uparrow\rangle + \beta|\downarrow\rangle$, where $|\alpha|^2+|\beta|^2= 1$. Meaning if we measure the electron, there is $\frac{1}{\sqrt{2}}^2$ chance that the electron will either be spin-up or spin-down., which is$\frac{1}{2}$ for both. We would represent the binary number as the Spins. Therefore, this becomes$\frac{1}{\sqrt{2}}|0\rangle\frac{1}{\sqrt{2}}|1\rangle$. Hence, if we know that an electron is in the spin-down state, we would say that $0|\uparrow\rangle + 1\,|\downarrow\rangle$, with when we measure the electron, the probability of the electron being spin-up is $0^2 = 0$ and the probability of spin-down being $1^2 = 1$.

Choosing a Qubit

You can make a qubit out of anything that can possess a spin. However, choosing which particle to use for a qubit is dependent on factors relating to the stability and the logistics of that qubit. DiVincenzo's criteria is a method of finding a suitable and viable qubit.

The first five are necessary for quantum computation:

1. A scalable physical system with well characterized qubit
2. The ability to initialize the state of the qubits to a simple fiducial state
3. Long relevant decoherence times
4. A "universal" set of quantum gates
5. A qubit-specific measurement capability

The remaining two are necessary for quantum communication:

1. The ability to interconvert stationary and flying qubits
2. The ability to faithfully transmit flying qubits between specified locations

(Wikiwand. *DiVincenzo's Criteria.* [Online]. Available from: https://www.wikiwand.com/en/DiVincenzo%27s_criteria)

The two central elements are Coherence Time and Gate Time. The Coherence Time is the lifetime of the qubit for which it will maintain its intended state. Over time, the qubit will interact with its environment (called interference), which will change its spin state, making the qubit useless. Electrons are notorious for interacting with their environment making them hard to transport. Gate Time is the time required for a single gate operation until an error occurs.

This comes onto Qubit Modalities – where the Gate Fidelity is considered. As you can see in Figure 6, we can plot different particles against Gate Fidelity, the number of operations before an error, and the gate's speed. All of this together can show which particles have the best chance of being applicable in a quantum computer setting. The dashed line indicates the error threshold – where the errors become so staggering that adding more error-correcting qubits does not help the accuracy of the gate.

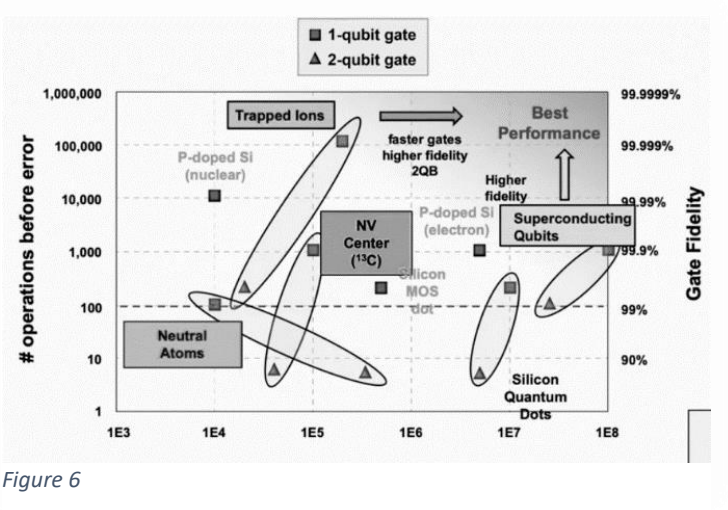


Figure 6

From the graph, the most promising qubits are the Superconducting Qubits and Trapped Ions. Trapped Ions already have a higher fidelity in qubit gates – therefore, they are faster at calculations. Superconducting qubits have a rapid gate speed – but an undertaking is needed to make the errors go down. However, other types of qubits are making promising technological advances. For example, silicon qubits are being investigated as a possible solution to manufacturing qubits at scale in the future.

Manufacturing a Qubit (Superconducting Qubits)

Superconducting qubits is one of the most common ways to manufacture qubits today. Industry giants such as IBM and Google are using this method. This involves decreasing the temperature to near absolute zero of a superconductor material. Once the material is cooled below its critical temperature, there is no electrical resistivity; a benefit of this is that an electrical current can flow through that material indefinitely without a power source.

This phenomenon is due to Cooper Pairs, where an electron interacts with an ion that creates a potential disturbance or phonon; Another electron then becomes attracted to the phonon, and the electrons indirectly interact with each other. This interaction drops the electron into a lower energy state which let the electrons move freely and conduct. Having the ions scatter the electrons instead causes resistance.

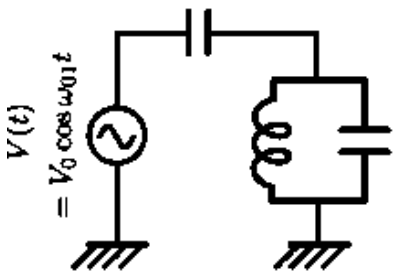


Figure 8 - LC Circuit

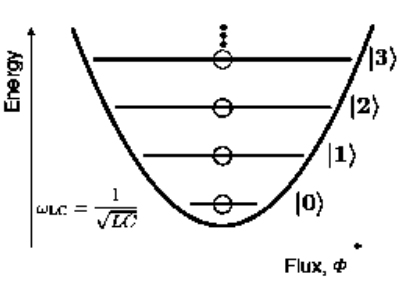


Figure 10 - Harmonic

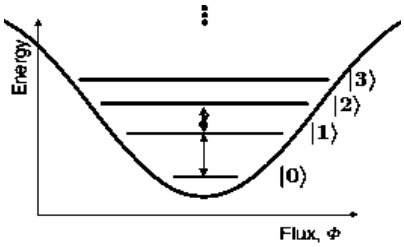


Figure 9 - Anharmonic

A |0⟩ or |1⟩ is represented in the qubit as energy states; spin-down is the lowest energy state, and spin-up is the higher energy state. A' Superconducting circuit' is used to manipulate and retain the qubits state. They are comprised of a capacitator and Josephson junctions. However, to explain the Josephson Junction, it's easier to demonstrate with an LC circuit (Figure 9) consisting of an inductor and a capacitor. The inductor is made from a conductor that is wound into a coil which the current flows through, generating a magnetic field. The capacitator is made up of two conductors separated by an insulator that is used to store energy electrostatically in an electric field. This is results in a positive charge building upon one of the conductors and a negative on the other, which stops the flow of current. The only way for a current to flow is for an alternating voltage to be applied. This is significant because the two components create a 'loop'. The capacitator would store all the charges and stop the flow in the circuit until a voltage is passed through and releases a current. This current comes into the inductor and creates a magnetic field and creates a voltage. This voltage then triggers the capacitor to recharge, and the cycle continues. The oscillation of energy between the two components can manipulate the energy state of the qubit. This is a Harmonic oscillator.

The energy state levels are represented in Figure10 but note how the energy gaps are all uniform. We only need to go up one state and down to mean a |0⟩ or a |1. What happens if we go up on too many? This will increase the number of errors for each qubit if the state of the qubit is invalid. This is why the Josephson Junction is so important.

The junction comprises two Aluminium superconducting electrodes separated by a thin insulator, and it behaves as a non-dissipating and a non-linear inductor, which means that the energy level is spaced in a way that limits the chances that the qubits state is invalid. See Figure 11.

Making a Qubit (Trapped Ions)

Another method of making Qubits is by using Trapped ions; companies like IonQ and Honeywell are pioneering this. What is the benefit of these types of qubits in comparison to Superconducting qubits?

The problem with Superconducting qubits is that they are overly sensitive to noise, so it is more challenging to get a near-identical copy of each. This can lead to qubits prone to errors which is detrimental in the development of large-scale Quantum Computers.

Trapped ions are isolated atoms that have a charge, which can then be individually manipulated and measured. An ion is an atom with an electric charge. The most common used atom is Calcium, which has two electrons on its outer shell

We trap the ions by using an Ion trap. This is where the ions are trapped between four electrodes. The electrodes generate voltages, and create an electric field oscillating at a Radio Frequency, (RF). The reason why the electric field needs to be oscillating is that a static field would not be able to trap the ions in all three dimensions in accordance with Earnshaw's theorem; So instead, it's oscillated in two directions, the switching rate between the directions has to be faster than the time it takes for the ion to escape the trap, so it's done at RF. This creates a 'saddle-shaped' electric field that keeps the ions in place.

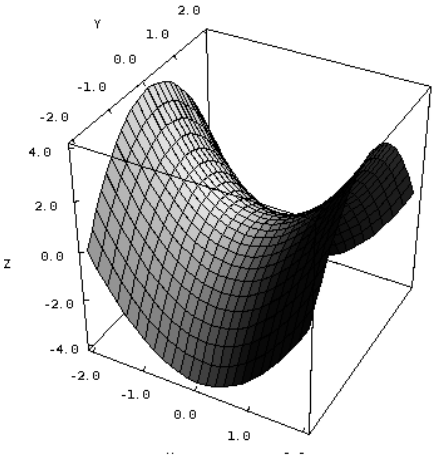


Figure 11 - Saddle Shape Electric Field

Hyperfine and Optical qubits are two ways to create trapped-ion qubits. Both have difficulties in production. The two-ground state hyperfine levels are used for Hyperfine qubits; the ground state and excited state is used in Optical qubits. Hyperfine qubits have an excessive decay time of millions of years, and Optical qubits have a decay time of around a second. However, relative to logic gate operations only taking a couple of milliseconds, both qubits have a long coherence.

Qubits can still move around in this confined space, and we need them to be approximately stationary so that they can be manipulated and measured. To do this, we use Laser Cooling that controls the Kinetic energies of the qubits by emitting single photons that have momentum in the opposite direction the qubit's movement is, which inevitably cancels out the qubit's velocity. We use the Doppler effect to make sure the ion absorbs the photon. This is because ions have resonant properties that the electrons in orbit oscillate at very particular frequencies that only absorb photons of a frequency that are the same as the resonant frequency. This means that the laser needs to be very accurate in which frequencies are being emitted. Hence we use the Doppler Effect, which is where an object is in motion, and the observed frequency is either lower or higher depending on if the motion is towards or away from you. For example, you are by the side of the road, and a car is driving towards you. The car's sound is very high pitched until the vehicle passes, and the sound becomes lower in pitch. The phenomenon area is found with light waves; If the ion is moving towards the laser, the perceived frequency of the laser is higher, and moving away, the perceived laser light is lower. Therefore, if the laser's frequency is tuned slightly below to the frequency required for the ion when the ion is moving towards the laser, the perceived frequency of the photons is closer to the resonant frequency. An ions energy level indicates whether the qubit is in the state $|0\rangle$ or a $|1\rangle$. The ion would be in its ground state. One way to raise the energy level is with the process called optical

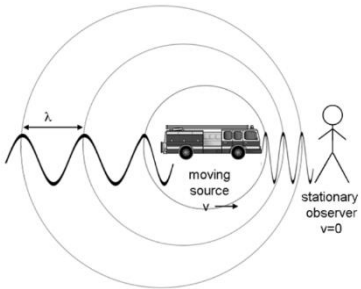


Figure 12

pumping. This method uses a laser where electrons absorb photons; This excites the ions until it decays to one state.

To measure the qubit, a laser with a specific frequency is shone on the electron and the result changes depending on the state. The laser frequency used depends on what is required to excite the ion at that specific state. The outcome will be that the qubit is excited and de-excited continuously when shone on. If the qubit is not in the state we are measuring, the ion will not be excited by the laser. We can tell when the ion is being excited and de-excited, as it emits photons which are captured by a CCD camera.

What is the best qubit?

I have discussed only two of the multiple methods that qubits can be made from, but is there a clear winner? When Google announced Quantum Supremacy with the world's fastest supercomputer for one algorithm, it was made out of superconducting qubits. However, due to the factors discussed earlier, more development is needed for a straightforward superior qubit manufacturing process which can create consistent qubits more effectively within the noise tolerance of the qubits.

Entanglement

Entanglement is the product of two quantum particles interacting with each other, making their quantum states interdependent. Meaning that if one particle was found to have spin-up, the other particle jumps to spin-down. They are always opposite, and the distance between the particles has no effect on the outcome.

To describe this, imagine we sent a pair of gloves to Alice and Bob. One was sent the left-handed glove and the other the right hand. They do not know which hand of glove they will get. Imagine Alice opens the parcels and finds that she has the left-handed glove. She immediately knows that Bob must have the right-handed glove. This is a classical analogy, but the way it works in a quantum system is different.

in the Quantum Model nothing is deterministic due to the Uncertainty principle. When I send a qubit off to Alice and Bob (which are entangled), they are superposed between two states. We cannot know who has which qubit right until Alice opens and measure her qubit. Quantum particles in an entangled state do not have an already pre-determined state, leading to the notion by Bohr that the qubits are only correlated when in an entangled state.

Quantum Entanglement gives us the ability to perform multiple calculations simultaneously. Imagine four qubits entangled with each other. Qubits can store 2^n states compared to the Classical bits only able to store 0 and 1.

Alice and Bob each has qubits superposed in states. Together, this is defined as

$\alpha|a_0\rangle|b_0\rangle + \beta|a_0\rangle|b_1\rangle + \gamma|a_1\rangle|b_0\rangle + \delta|a_1\rangle|b_1\rangle$ Where $|\alpha|^2+|\beta|^2+|\gamma|^2+|\delta|^2 = 1$

An example is:

$\frac{1}{2}|a_0\rangle|b_0\rangle + \frac{1}{2}|a_0\rangle|b_1\rangle + \frac{1}{2}|a_1\rangle|b_0\rangle + \frac{1}{2}|a_1\rangle|b_1\rangle$

From Alice's perspective mathematically, we would write the equation with Alice's common factors being pulled out.

$\frac{1}{\sqrt{2}}|a_0\rangle(\frac{1}{\sqrt{2}}|b_0\rangle + \frac{1}{\sqrt{2}}|b_1\rangle + \frac{1}{\sqrt{2}}|a_1\rangle(\frac{1}{\sqrt{2}}|b_0\rangle + \frac{1}{\sqrt{2}}|b_1\rangle)$

From Bob's perspective

$\frac{1}{\sqrt{2}}|b_0\rangle(\frac{1}{\sqrt{2}}|a_0\rangle + \frac{1}{\sqrt{2}}|a_1\rangle + \frac{1}{\sqrt{2}}|b_1\rangle(\frac{1}{\sqrt{2}}|a_0\rangle + \frac{1}{\sqrt{2}}|a_1\rangle)$

An example of quantum entanglement in real life is with photons. A photon can be split into two 'daughter' photons that have inherited the characteristics of the original photon. This is called Spontaneous Parametric Down Conversion, where photons are beamed into a non-linear crystal and are split into two. The 'daughter' photons inherit characteristics due to the Laws of Conservation of Momentum and Energy.

Quantum Gates

Logic Gates in 'Classical Computing'

Logic gates provide the essential tools to make an algorithm. They are comprised of transistors, resistors, and diodes – these together make up logical conclusions to digital inputs. Examples of Gates are AND, OR, NOT, XOR and others.

Different possible inputs and outputs can be compiled into a truth table. This can show the total number of inputs and outputs possible.

e.g. a AND Gate

Bit 1	Bit 2	Output
0	0	0
1	0	0
0	1	0
1	1	1

e.g. a OR Gate

Bit 1	Bit 2	Output
0	0	0
1	0	1
0	1	1
1	1	1

e.g. a XOR Gate

Bit 1	Bit 2	Output
0	0	0
1	0	1
0	1	1
1	1	0

Added together, these can make logical and mathematical calculations. An example of a simple circuit is the Full Adder, which comprises OR, XOR and AND gates to add numbers together. A and B inputs are the numbers being added together with a CIN which is the Carry bit into the Sum.

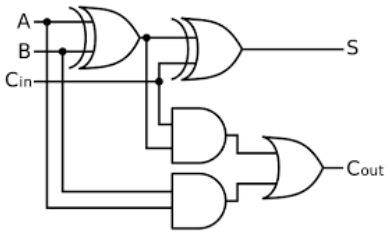


Figure 13

Boolean Algebra

We can represent the Gates using Algebra. The OR gate can be represented as A ∪ B. The AND Gate can be represented as ∩. And the NOT Gate can be represented with ¬ or !, but for simplicity, I will only use ¬. The XOR Gate is represented with ⊕.

A	B	¬A	¬B	¬A ∩ ¬B	¬(¬A ∩ ¬B)
0	0	1	1	1	0
1	0	0	1	0	1
0	1	1	0	0	1
1	1	0	0	0	1

A	B	A ∪ B
0	0	0
1	0	1
0	1	1
1	1	1

Take note that the resulting gates have equivalent outputs. We would call the two gates logically equivalent. This might not seem important, but the ability to use only AND and NOT gates to replicate an OR gate is essential.

Reversible Gates

For a Quantum Circuit to be run, we need to make sure it is reversible. Therefore, having the ability to send qubits through the logic gate to get an outputted value and to be able to send the outputted values through the inverse of that gate to revert to the initial position. Hence you need an equal quantity of inputted qubits as outputted qubits to make sure that no information is lost.

AND GATE

A	B	A ∩ B
0	0	0
1	0	0
0	1	0
1	1	0

If a gate is not reversible, then information is lost. This is seen most in the AND gate, where if the Output is 1, we know that A and B both must be 1. However, if the result is 0, we do not know which bit is a one and even if there is a bit that has the value 1. This lack of information shows that we have lost information.

The study of reversible computation came from the analysis of the Thermodynamics of Computation. This was derived through a curiosity of whether computation can be expressed in thermodynamics, especially when information is lost. John von Neumann speculated that when information is discarded/lost, energy is dissipated as heat. This led to the Landauer limit, which proved and said that there is a minimum possible amount of energy that is lost when discarding one bit of information. What does this mean in the Quantum model?

The most obvious answer is energy efficiency. However, if you input two qubits entangled with each other into a Logic Gate, the gate has only one outputted qubit, which is therefore irreversible. The destroyed information means that the two initially entangled states are no longer entangled.

An example of a Reversible Gate is the CNOT Gate

CNOT GATE

Input		Output	
A	B	A	A ⊕ B
0	0	0	0
1	0	1	1
0	1	0	1
1	1	1	0

INVERSE CNOT GATE

Input		Output	
A	A ⊕ B	A	B
0	0	0	0
1	0	1	1
0	1	0	1
1	1	1	0

Hadamard Gates

Hadamard Gates are used to putting qubits into a superposition. It is represented as $\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix}$ for example, if we say the qubit was in the state $|0\rangle$. Then when we apple the Hadamard Gate to this qubit $\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix}\begin{bmatrix}1\\ 0\end{bmatrix}$ then we get $\frac{1}{\sqrt{2}}\begin{bmatrix}1\\ 1\end{bmatrix}$. Which brings the likelihood of a one or a 0 is a $\frac{1}{2}$. For every Quantum Computation we would like to do involving Superpositions. We need to use the Hadamard Gate.

INPUT		PROCESS		
q_0	q_1	q_0	$q_0 \oplus q_1$	$q_0\, q_1$
0	0	0	0	00
1	0	1	1	11
0	1	0	1	01
1	1	1	0	10

An example of the CNOT gate and Hadamard Gate in action is here:
We put both qubits into a superposition using the Hadamard gate. Meaning the q_0 and q_1 are in the conditions $\frac{}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$. Then we apply the CNOT gate, then measure. Now, using a truth table, we can see what is going on. We can conclude that the results all have a 25% probability of being correct.

Pauli Gates

Pauli Gates are matrices that are useful for calculating the change in a spin for an electron by rotating the state around the x, y, and z-axis

X Gate

This is the gate equivalent of negation in classical computing. Therefore, it corresponds to the NOT gate (sometimes referenced as the quantum NOT gate). In quantum computing, it is used to flip the spin states of a qubit, a bit-flip. The matrix used is:

$\begin{bmatrix}0 & 1\\ 1 & 0\end{bmatrix}$ which can be applied mathematically to any qubit to flip the state.

This gate is majorly used in error-correcting when a qubit is found to be corrupted, and therefore needs to be flipped. Here is an example of the X gate mathematically.

$$X|0\rangle = \begin{bmatrix}0 & 1\\ 1 & 0\end{bmatrix}\begin{bmatrix}1\\ 0\end{bmatrix} = \begin{bmatrix}0\\ 1\end{bmatrix} = |1\rangle$$

Y and Z Gate

The Z Gate flips the phase of the qubit by rotating the qubit 180 degrees around the z-axis. This means that it maps 1 to -1 however leaves 0 unchanged. The flip in the phase is only significant when a qubit is in Superposition. If not, then a single qubit measured with a phase of either 1 or -1 will be measured as 1. The matrix is $\begin{bmatrix}1 & 0\\ 0 & -1\end{bmatrix}$

This means that to apply the Z Gate to a qubit, you would need to use a Hadamard Gate first to superpose the qubit between two states. For example, a qubit set to 0 is then superposed using a Hadamard Gate. If we then apply the Z Gate to flip the phase, apply the Hadamard Gate again, then measure. The qubits state should be in the opposites state of 1.

This idea of flipping the phase is present in the Y Gate too. The Y gate flips the phase of the qubit about the y-axis. Inevitably this would result in complex solutions. The matrix is $\begin{bmatrix}0 & -i\\ i & 0\end{bmatrix}$.

Quantum Algorithms

Quantum Speedup and Query Complexity

Quantum Computing's revolution does not mean that it will be the new technology that surpasses the classical way of life, for example, using them as our desktop computers instead. This is an inaccurate assumption, as Quantum Computing can only speed up certain specific tasks. Most algorithms are superior to do on a classical computer. However, the minority of tasks that are inferior on a classical Computer have significant ramifications.

There are two main types of speedup - polynomial and exponential speedup. Usually, the exponential speedups found can be used by small scale quantum computers. Meaning that current quantum technology can evaluate these algorithms.

Polynomial speedups may not seem that revolutionary, let us take the example of trying to find a specific unique value in an unordered list. The only way to do this classically is to force search of the entire list – searching every value consecutively until we find the right one. Let's says, on average. It takes 1 million steps. If we use Grover's Algorithm on a quantum computer, the time taken to search the list is, on average, a thousand steps. The way of measuring the efficiency of an algorithm by the amount the questions we need to ask is Query Complexity. This shows the importance that Quantum Computers have in the near future.

Complexity classes help designate algorithms and problems into sets based on the amount of resource and time is needed. One of the classes is ‘P ‘. ‘P’ classifies problems that are solvable in deterministic polynomial time, usually decision-based problems such as a forced search. A classical computer can generally solve these problems with ease. However, there are circumstances e.g., cryptography, where it still cannot be solved without a significant amount of computational time.

Another example of a complexity class is ‘NP.’ ‘NP’ problems are solvable in non-deterministic polynomial time, which includes issues that are solved usually in exponential. These are problems that can be verified in polynomial time, e.g., finding prime factors of a number. Due to these problems being non-deterministic, many different actions could be performed on a single input, like simulations. Classical computers find it hard to solve these problems effectively. However, Quantum computers have the power to solve some NP problems polynomials.

Error Correction

When transferring data across locations classically, certain bits will be corrupted and changed. These changes could have dire consequences on the message being sent. In a quantum system, qubits are more prone to the encoded information being lost in transmission. We call the amount of environmental interference that the qubit may suffer the amount of noise in a communication channel. Theoretically, we can never have no noise communication channel. So there will always be a chance of errors in our qubits. To avoid this, we try to choose the least error-prone type of qubit. However, incorporating error correction tools when transmitting qubits is essential for the confidence of the qubit's preservation. This is called noise suppression.

Repetition Code

A way to recognise qubit errors is called Repetition Code. Where each qubit is repeated three times consecutively, e.g. 010 would be repeated as 000111000. Therefore, if I sent a message to Bob, he would expect to receive a sequence of three 0s and 1s. However, if he received a 101, he knows that an error has occurred. It should have been either 000 or 111. If it was 111, then one error must have happened, and if it was 000, then two errors must have occurred. By balance of probability, it is more likely that one error occurred than two. Therefore, Bob corrects that qubit to 1 for it to become 111.

This method is fine for a Classical system but not for a Quantum one as we cannot read the qubits without them jumping to a state. A way to get around this is to perform Parity Tests.

Imagine Bob receives three bits (b_1, b_2, b_3). He expects them all to be the same. We cannot measure the qubits to see whether they are the same, so instead, we put them through the CNOT gate. This is because a CNOT gate returns a 1 when two qubits are different values from one another.

$b_0 \oplus b_1 = 0$ and $b_0 \oplus b_2 = 0$ then together 00 Bob will flip nothing

$b_0 \oplus b_1 = 0$ and $b_0 \oplus b_2 = 1$ then together 01 Bob will flip b_2

$b_0 \oplus b_1 = 1$ and $b_0 \oplus b_2 = 0$ then together 10 Bob will flip b_1

$b_0 \oplus b_1 = 1$ and $b_0 \oplus b_2 = 1$ then together 11 Bob will flip b_0

Quantum Bit Flip Correction

This builds on the previous idea. We add two more qubits called Ancilla qubits into the algorithm. The Ancilla qubits are qubits used to test the authenticity of qubits without measuring them. This is done by collecting information about the noise in the communication channel. They are not fundamentally needed when finding errors; however, it is necessary when fault-tolerant methods are required.

Imagine Alice needs to send a qubit of information to Bob. She does it the previous way and sends three copies of the same qubit to Bob, e.g. she would like to send the qubit $|0\rangle$, it goes to the state $\alpha|0\rangle + \beta|1\rangle$ then to $\alpha|000\rangle + \beta|111\rangle$.

Once Bob has received the qubit, he introduces a pair of ancilla bits. He first carries out CNOTs from the first and second received qubits to the first ancilla qubit, then from the first and third received qubits to the second ancilla bit.

For there to be no errors, we should see $|00\rangle$, therefore if we see anything else we can assume that an error has occurred in transmission. We can use Pauli's X Gate to flip any wrong bits.

If 00 then do nothing If 01 then apply the X gate to the third qubit If 10 then apply the X gate to the second qubit If 11 then apply the X gate to the first qubit

The outcomes to this are -

$\alpha|000\rangle + \beta|111\rangle$ the ancilla qubits should be $|00\rangle$
$\alpha|001\rangle + \beta|110\rangle$ the ancilla qubits should be $|01\rangle$
$\alpha|010\rangle + \beta|101\rangle$ the ancilla qubits should be $|10\rangle$
$\alpha|011\rangle + \beta|100\rangle$ the ancilla qubits should be $|11\rangle$
$\alpha|100\rangle + \beta|011\rangle$ the ancilla qubits should be $|11\rangle$
$\alpha|101\rangle + \beta|010\rangle$ the ancilla qubits should be $|10\rangle$
$\alpha|110\rangle + \beta|001\rangle$ the ancilla qubits should be $|01\rangle$
$\alpha|111\rangle + \beta|000\rangle$ the ancilla qubits should be $|00\rangle$

The downside to this method of correction is that it is only designed to succeed whenever either none or just one qubit is corrupted by transmission. This is because it assumes the anomaly in the qubits is

from one error and not two. Therefore, a qubit meaning to be 111 could be corrupted to 010, and the error correction would assume that the error is in the second qubit and flip it to 000.

Database Searching and Grover's Algorithm

A database is where data is collected, stored, and organised in a contextual way that fits the database's purpose. It can also be accessed and searched. But what if the database has a million items to search? Wouldn't that take a significant amount of time? People have made algorithms to counter this, for example, Binary Search.
Which takes the midpoint of the data and, depending on whether the value query is above or below the median value, discards the half of the data that is not needed and repeats the process. This delivers a significant time improvement compared to checking every value in order until it is found (called a Linear Search). In terms of time complexity, it's O(n) for linear search and O(log n) for binary search, the importance of this speedup can be seen in the graph here.

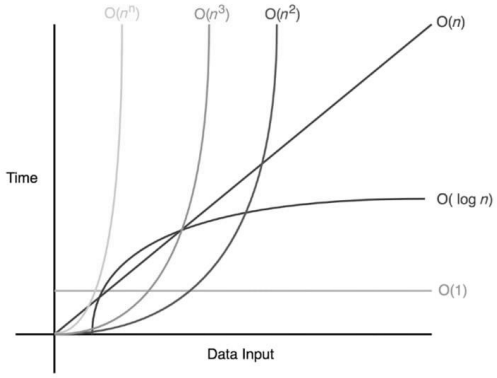


Figure 14

However, a binary search assumes that the list is ordered. What if it is not? What if you did not know whether the list was ordered or not? The time complexity for linear search is so significant that searching unordered lists is impossible with a large data set and a time constraint.

Therefore, Grover's algorithm is essential. Let us say we have four strings that hold the values 00,01,10,11. Then we have a function that returns one of the strings as true and three false. Let us say that it was 01 returned the true value. Because this is a Query Complexity algorithm, we need to make the function the oracle, and we are asking what value returned true.

Now let have two qubits in a superposition of all possible values using a Hadamard Gate. Every state would have the same probability amplitude of $\frac{1}{\sqrt{2^n}}$, where n depends on the length of the string. This means that each amplitude would be $\frac{1}{\sqrt{4}}$ then equals $\frac{1}{2}$. We then apply the which flips the amplitude of the queried value amplitude from $\frac{1}{2}$ to -$\frac{1}{2}$. But still, if we measure, the queried value and other values will bring up the same answer $(\frac{1}{2})^2 = (-\frac{1}{2})^2 = \frac{1}{2}$. To further differentiate the queried value, we use Grover's Diffusion Operator, which amplifies the amplitude. This is done by 'inversion about the mean'. Where we take the mean of the amplitudes, find the difference between the value and the mean, if the value is below the mean, flip it upwards by adding the mean and the difference. If above the mean, then flip downwards by subtracting the difference from the mean. For example, if we have four numbers [1,1,1,-1] (one flipped as it's the queried value), the mean would be $\frac{1}{2}$. The difference for 1 -$\frac{1}{2}$ = $\frac{1}{2}$ and the value 1 is above the mean $\frac{1}{2}$ Meaning we need to flip it below the mean; it now becomes 0. For the value -1, the difference between the mean is $\frac{3}{2}$ and the value is below the mean, so we need to flip upwards. It now becomes 2. We have amplified the amplitude for our value.

Now looking back at our binary string, it is Superposition would be represented as:

$\frac{1}{2}|00\rangle + \frac{1}{2}|01\rangle + \frac{1}{2}|10\rangle + \frac{1}{2}|11\rangle$

We then flip the queried value:

$\frac{1}{2}|00\rangle + \frac{1}{2}|01\rangle$ - $\frac{1}{2}|10\rangle + \frac{1}{2}|11\rangle$

Then we flip the probability amplitudes

$0|00\rangle + 0|01\rangle + 1|10\rangle + 0|11\rangle$ which equals $|10\rangle$

For a bigger data set, you would need to repeatedly amplify the amplitudes to get your value.

Even though there is a quadratic speedup of using Grover's algorithm in comparison to linear search, the implementation in the real world is challenging. We need to implement the oracle, making sure it's reversible and no information is lost – this can sometimes result in the algorithm being slower than a 'classical' algorithm.

Uses of Quantum Computing

In classical Computing, we are finding the best solution to a problem that involves different pathways and outcomes by consecutively testing each pathway until the preferred outcome has been found. This method is incredibly inefficient when scaling up the problem to involve millions of pathways and outcomes – however, there is no other way to find solutions accurately and rapidly. Yes, there is a way to tweak algorithms to disregard pathways that heuristically are ridiculous to test. However, the exponential time complexity involved makes it impossible for classical computers to find solutions to problems in an accurate time scale.

Therefore, the development of Quantum Computing is promising. The ability to have qubits superposed and entangled in many positions at once. This means, in theory, that we can do one calculation, and the qubit is manipulated into travelling through all pathways at once. This speedup is revolutionary. It is opening the gates to engineering capabilities that can change the world.

Quantum Chemistry Modelling

Everything is comprised of bonds, and how these bonds are formed and change the characteristics of that molecule are paramount when discussing Material Science and Medicine manufacturing. When trying to find the most optimal molecular composition for a substance and the outcomes that molecule has in a particular it is hard for classical computers today to accurately simulate chemical reactions.

The purpose use of molecular simulation is about finding the compounds ground state – this is the molecules lowest energy state, and this depends on finding the most stable configuration of the electrons. For computers, this is difficult, as it must simulate all the possible configurations and energy levels of the electrons in each atom interacting with others that also have mutliple configurations, along with the separate outcomes of Quantum Mechanics, which would also affect

events that occur. This problem is easy to see becoming exponentially difficult in time complexity as the size of the atom or compound increases. "If you have 125 orbitals and you want to store all possible configurations, then you need more memory in your classical computer than there are atoms in the universe," says Matthias Troyer. He develops algorithms and applications for quantum computers at Microsoft Research in Zurich. In comparison, a Quantum Computer with 250 qubits could model this system.

Therefore, the idea of simulating molecules with a Quantum Computer is appealing. There is a view that a computer that operates under the Quantum Model would also make it easier to accurately simulate the Quantum Model.

Tech giants such as Google have backed this idea. Their 54 superconducting qubit computer called Sycamore achieved quantum supremacy in 2019. It carried out a calculation that would be impossible for a classical computer to perform in a reasonable amount of time. This simulated the molecule called diazene, which consists of two nitrogen and two hydrogen atoms. The problem took 200 seconds to complete when in comparison, Google stated that the world's fastest current classical computer called the Summit would take 10,000 years to solve the same problem.

What would this be used for? A quantum simulation could provide a deeper insight into how molecules interact with each other and what those outcomes would look like – which a classical computer could never have the capabilities to attempt. These simulations can be more accurate, not needing to approximate value for the complex structures of electrons for a classical processor to cope.

Examples of use include enabling a full understanding of the enzymes that underlie photosynthesis and the nitrogen cycle, which could aid in the development of catalysts for clean energy and renewable chemical manufacturing, power the discovery of high-temperature superconductors and new materials for solar cells, and much more.

Cryptography

Following from previous ideas of classical computing methods, the exponential query complexity of checking every pathway possible is impossible when problems are difficult to find a solution to. This is why Cryptography has thrived.

When sensitive data is sent over an open connection from Alice to Bob – we want to make sure that no one can know what this data entails. If we send the raw file, then someone (let us call this person Eve) can intercept the transmission. Read and copy it. Then transmit it to Bob. There is no way Alice or Bob can know whether it has been intercepted.

Therefore, the norm for sending data over the internet is to 'encrypt' it. This means that a message containing 0110 can be converted using a secret key that only Alice and Bob know to be Ae8K. If Eve does intercept the message, all she gets is Ae8K – this is called Ciphertext. She does not know what key it was encrypted with – so she cannot read the message at all even though she has intercepted it. When Bob receives the Ae8K, he uses his correlating key to decrypt it back into 0110. Standards keys are usually 128 to 256 bits long, making it impossible for computers to try and 'crack' the encryption process. Trying every combination possible for a 128-bit key is 2128 possibilities. This is 340,282,366,920,938,463,463,374,607,431,768,211,456 different combinations. If we tried to brute force crack this key (try every combination possible until we found our answer), a normal computer

that could test 240 different combinations a day would crack this key for 847,904,136,496,835,804,725,427 years. For a supercomputer, it would still take millions of years. This shows that encryption can be ridiculously secure.

One of encryption is RSA keys. These are based on two prime keys and an auxiliary value; note that the two prime numbers are incredibly large and are hidden from the public. The prime numbers are the only way that the encrypted data can be decoded but finding out what they are is incredibly difficult. This is known as the factoring problem.

Quantum Key Distribution

This is a method of constructing and transporting an encryption key to ensure confidentiality and security over previous methods. Let's say Alice and Bob would like to share information over a secured line, and each will get a stream of photons entangled with each other. If Alice measured one of her qubits, Bob would get the opposite result in his corresponding qubit. Therefore, they shared a shared key. Now we need to get the stream of qubits.

When received, both Alice and Bob now form the key. Each qubit has it is one spin property unknown to either Alice or Bob. As the stream of qubits is received, Alice and Bob independently chose a random scheme, either the Rectilinear scheme or the Diagonal scheme. When a qubit passes through the rectilinear scheme, the qubit will either have the polarisation as $|\uparrow\rangle$ or $|\rightarrow\rangle$ when passing through the Diagonal scheme the qubit becomes either $|\nwarrow\rangle$ or $|\nearrow\rangle$. Alice and Bob will note down a 1 for $|\uparrow\rangle$ or $|\nearrow\rangle$ in terms of degrees. This is 90° and 45° and will note down a 0 for 45° and 0°.

Imagine when the qubits are in transport, they were intercepted by an eavesdropper such as Eve. She wants to know the secret key but needs to measure the qubit to do so. She can pass the qubits through a filter to measure, but she does not know which filter Alice and Bob will use. Additionally, bypassing qubits through filters, Eve risks altering the spins of the qubits by passing them through the wrong filter. Laws of probability states that she will get it wrong about 50% of the time. After you pass the photons through the filters, Alice and Bob can talk to one another and discuss which scheme was used for which qubit. They do not tell each other what the spin was or if it signified a 0 or a 1. If Alice and Bob used the right filters, then it is kept. If not, then it is discarded. By the end, you would have around 50% left of your string. This can be done over an insecure line because even if Eve was still listening in, she could not tell what the spin of the photon was by which scheme. Let's say Alice and Bob both used the Rectilinear scheme, so the qubit is not discarded, and Eve used Diagonal. She still does not know whether the qubit represents a 0 or 1, so it does not help her. The only time she would know that she has the same answer is when all of them are measured in the same direction, but that's only a third of the time which is useless for figuring out the key. We have now successfully transported and gifted two keys securely.

Shor's Algorithm

However, the rise of Quantum Computing puts these forms of classical encryption at risk. Algorithms like Shor's Algorithm have been seen to put the industry of cryptography at risk in the next couple of years. Imagine we have an arbitrarily big number N we need to find the factors of. We guess a random number 'a' that might be a factor of N (providing $a < N$). The number g is likely not to be a factor of N, however $a^{r/2} + 1$ is much likely going to be a factor on N.

$$a^r - 1 = (a^{r/2} - 1)(a^{r/2} + 1)$$

Figure 16

E.g. the powers of three
- 3,9,27,81,243,729,2187,6561
Modulus to 20
- 3,9,7,1,3,9,7,1
Has a period of 4 (r)

When multiplying g by a factor of x and then modulus of N ($a^x \ mod \ N$), there will be a periodic sequence associated with it.

This by itself is useless. However, with Euclid's algorithm, we might have shared common prime factors. By using the identity above, you are much more likely to find the factors rather than brute force. The table below shows how trying to find the factors of N = 15 can still garner results even though the guess a is not a factor.

a	Period r	$\gcd(15, a^{r/2}-1)$	$\gcd(15, a^{r/2}+1)$
1	1		
2	4	3	5
4	2	3	5
7	4	3	5
8	4	3	5
11	2	5	3
13	4	3	5
14	2	1	15

Figure 17

Finding the periods of a function can be implemented on a classical computer. However, using the Quantum Fourier Transform is responsible for the quantum speedup.

To find the periods of a function on a Quantum computer, you need to create a superposition of the states. Usually, this is done by applying Hadamard gate to every qubit. Instead, we use the Quantum Fourier Transform. These speeds up the algorithm by only using O((log(N)^2)) gates. QFT acts on an input qubit and maps it to a vector y_k in accordance with the formula.

$$y_k = \frac{1}{\sqrt{N}} \sum_{j=0}^{N-1} x_j \omega_N^{jk}$$

Figure 18

Other Areas for Quantum Computing

Other than Medicine, Material Science and Cryptography, Artificial Intelligence will also benefit from Quantum computing. Artificial Intelligence (AI) is the future of the world and is one of the most compelling and debated topics in science today. But how does Quantum computing fit into this? AI is achieved by having and combining massive amounts of data together and utilising algorithms that are iteratively asking the same questions millions of times. This allows the software to find patterns and connections in the data set. An example of this is face recognition, where you give a computer a wide range of photos and learns by trial and error which pictures match the face. Quantum AI is already being utilised, with Google announcing TensorFlow Quantum (TFQ), which is an open-source library for machine learning that helps model quantum systems.

Another area is in the military. The Ministry of Defence has been looking into Quantum Computers and their applications in the military. Quantum Information Processing (QIP) could help speed up security and defensive systems. Other examples the research paper introduces is AI with 'pattern matching and 'situational understanding'.

Will they ever go mainstream?

Firstly, we would need to define what mainstream means. Is it them being in our homes for personal use? Or the adoption for commercially viable industries to perform complex tasks. The need for extended computer power originates from industry, so that is what we will define it as.

For companies, the association to this industry alone is profitable. According to IDC predictions, 25 percent of the Fortune Global 500 will gain a competitive edge from quantum computing by 2023. The uses for Quantum Computing have gained traction from Tech companies. Most notably, IBM and Google have already started making their own computers in in a race towards Quantum Supremacy.

This feat will put them in an advantageous position compared to others in developing lucrative industrial solutions using Quantum Computing. It is expected that Quantum Computing will transform some industries.

Will they ever be in our homes? Most probably not soon. The vast computing power of Quantum Computers would never be needed for opening a Word Document. The sheer cost and size of Quantum Computers now mean is not feasible to be ever used for personal use. Additionally, classical computers do not have the restrictions of needing reversible gates and or the ability to clone qubits, making them often more advantageous. Another consideration is that with current technology, the interference and degradation of qubits are too significant to be of use. Also, with the need for the computer cooler to go to temperatures lower than in outer space, it is not practical.

However, other ideas for people to use a Quantum computer include a cloud service. Quantum computing in the cloud could allow people utilise the powers of Quantum Computing without needing the extra cost and hassle of maintaining a Quantum Computer in their home. Companies such as Rigetti Computing, has been providing a 31-qubit computer on a cloud service for some time. Additionally, IBM has set up an online IDE (Integrated Development Environment) which allows users to make their own Quantum Algorithms as an aid to learning about Quantum Computing.

The true indication of the potential of Quantum Computing is the investment in the technology. There is increased investment in the field from companies and from Governments around the World. The UK Government has launched a 10-year investment scheme into building multiple quantum network hubs to propel and grow the industry in the UK.

My Experiences

Whilst researching this project I thought about how this technology would affect me and my family. Both my father and I have Primary Lymphoedema which is caused by the FOXC2 gene mutation. In July we took part in an international study which aims to understand the mechanism of this gene mutation. Following on from this I looked into how Quantum Computing could help study genetic diseases. There has been a proof of concept of quantum computing being used for genetic classification by researchers at the Virginia School of Medicine in the USA. In the study it was reported that "*if they used all four building blocks of DNA for the classification, a conventional computer would execute 3 Billion operations to classify the sample. The new quantum algorithm would only need 32.*"

Quantum computing will help speed up sifting through data and hence speed up efforts to find solutions for genetic diseases such as mine.

Conclusion

Conducting the research for this project has opened my eyes to the new and appealing world of Quantum Computing. The theorised ways to change the world are ground-breaking; However, further research and development into the mainstream market are needed. This comes with time and patience, yet new developments are happening every day, and I will be looking forward to following the advancements.

As mentioned previously, the projected uses for Quantum Computing will introduce many societal changes that we will need to be prepared for. Especially in the cybersecurity sector, as forming and breaking mainstream encryption methods has ethical issues relating to people's personal private data. There needs to be discussion of what should be encrypted to the new highest level of encryption. Another ethical issue is related to the aid of the development of Artificial Intelligence and the link to unemployment and poverty.

By deciding to have this project be in a Research Essay Format, I have been able to thoroughly discuss, explain and form opinions on each topic in my project. However, I recognise that this format of a project can limit my creativity and any practical work that could have been accomplished alongside. I feel that I have still maintained and managed to do some form of creative, practical work from researching this project and going on to use the IBM Quantum Experience. This will be a method of education that will supersede my conclusion of this project. I will be able to create and form my own Quantum Algorithms and see the outcomes on every individual qubit in real-time.

If I were to do this project again, I would like to focus more on the algorithms and discuss them in more detail and how they relate to their expected uses. I have discussed some encryption Algorithms like Shor's Algorithms and Error Correction. But I would have liked to discuss other algorithms, like Grover's Algorithm, which speeds up searching for items in unsorted databases. This is because I feel that it would help people understand Quantum Computing adaptations into different industries and recognise how they would be beneficial in those sectors. I look forward to educating myself on other types of algorithms, along with IBM Quantum Experience.

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Figure 7:
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Figure 17 & 18:
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Activity Log

Date	Activity	Duration	No.
03/09/2020	Reading and researching topics for my project and setting up documents/folders for organisational purposes - looked at random Physics topics that interested me and noted them in a word document. After I had a deep dive into them, I could see how much depth I could talk about a topic and whether it still interested me	2 hours	2.00
09/09/2020	I started to look into one topic - Quantum Computing in more detail and started looking at different articles in my Study Period. I also started to create a plan of sub-topics relating to Quantum Computing that I could delve into	1 Hour	1.00
11/09/2020	Setting up more documents for links and References - also looked up how to reference and cite documents properly. Then started to research different articles and papers about Quantum Computing.	30 Minutes	0.50
13/09/2020	I was searching up more in-depth detail about Quantum Mechanics and the scope of what Quantum computing could take us compared to the limitations of 'Normal' computing. This was done by watching YouTube videos. Whilst watching a video from an IBM representative, he mentioned how the IBM quantum computer could be accessed online, so I looked and realised I am able to make my own Quantum gates.	2 Hours 30 Minutes	2.50
14/09/2020	Researching the development of Quantum computing - and somewhat refining my plan of what subjects I would like to cover in my project, and to plan what I need to research further into	2 Hours	2
14/09/2020 (after school)	Refining my plan of what I will cover further, using my notes that I've taken from watching the lectures yesterday	1 hour	1
15/09/2020	I had my first E&E session, where we talked about how to take notes from lectures and how to research. Then in the last 30 minutes of my E&E session in school, I started to read, highlight and note down points in Quantum Computing For Everyone	1 Hour and 30 Minutes	1.5
19/09/2020	Read the first 2 Chapters of 'Quantum Computing for Everyone', highlighting points that would be interesting to write about - I also learned about how Qubits work in terms of polarisation and spin of electrons.	1 Hour	1
20/09/2020	Read the 3rd chapter of the book, noting and highlighting points that I could expand upon in my projects	30 Minutes	0.5
25/09/2020	Going over Paul Dirac's Notation in detail to understand it properly	1 Hour	1
26/09/2020	Making notes on Paul Dirac's notation and looking at the Double Slit experiment	1 Hour	1
29/09/2020	Continuing to make notes on the mathematics seen in Chapter 3	2 Hours	2
06/10/2020	Watching Q2B lectures and thinking about what I can write about in my Write-Up	1 Hour	1
07/10/2020	Learning about BB84 Protocol - understanding how it came to be and how it works.	1 Hour 30 Minutes	1.5
10/10/2020	Learning about IBM Quantum Experience and read more on Quantum. Then I watched an hour out of an hour and half lecture on Quantum Computing	2 Hours	2
12/10/2020	Reading on Quantum Computing and doing notes. Reading random Quantum articles online to see where we are in today in terms of development	1 Hour and 30 Minutes	1.5

13/10/2020	Reading and noting down about Bell's Inequality. Looked at Uncertainty principle in further detail and wave functions - finding a link to this and the Double Slit Experiment and to Superposition of spins	1 Hour 30 Minutes	1.5
20/10/2020	Bell's Inequality and Einstein's explanation in a Classical Model. How Einstein did not believe in the Quantum model and how his theory of local realism was debunked via Bell's Inequality. Thus showing a disconnect between the Quantum and the classical realm	1 Hour 30 Minutes	1.5
24/10/2020	Ekert Protocol in relation - to Bell's Inequality. Looking at how I can integrate the development of cryptography in Quantum Computers	2 hours	2
10/11/2020	Started planning out my Write-up, about what I would like to include and what I need to look deeper into and noting about Logic Gates and Boolean algebra.	2 Hours	2
10/11/2020	Looking into Quantum Gates - Pauli's Gates and the equivalent in classical computing. Additionally, how to work mathematically to change the spin of the qubit too.	1 hour	1
11/11/2020	Learning more about Quantum Gates and trying to understand Super coding and then started to plan my write up even further.	1 Hour	1
12/11/2020	Looking more at Super coding, Quantum Teleportation and a bit on Error Correction	2 Hours	2
13/11/2020	Looked deeper into Error Correction to understand how it affects the efficiency of Computers. And how to try and limit it	1 Hour	1
15/11/2020	Looking at Quantum Gates, about X, Y and Z gates and how they are implemented into circuits	1 Hour	1.5
16/11/2020	Looking a Quantum Entanglement in Photosynthesis and carrying on looking a Deutsh Gates	1 Hour	1
20/11/2020	Understanding on the different particles Qubit's can be made out of - and the different aspects that can determine what particles are used.	1 Hour	1
21/11/2020	Starting to write up and learnt more about Quantum Biology and how Quantum computers can help transform the biology sector when they can accurately simulate molecules.	2 Hours	2
22/11/2020	Making the contents and started to write the Introduction and about planning my project	1 Hour	1
23/11/2020	Writing up about Double Slit Experiment and thought about and other areas that I should discuss about	1 Hour	1
24/11/2020	Writing up about what spin is and how it links to Quantum Computing. Additionally started to talk about the mathematical representations of spin and qubits	2 Hours	2
25/11/2020	Writing up about Reversible Gates and what is thought about when choosing component for qubits and how they are made	2 Hours	2
28/11/2020	Watching more Q2B lectures	1 Hour	1
29/11/2020	Write-up about Quantum gates and the basics of them in Classical Computing	2 Hour	2
30/11/2020	Write-up & looking more at entanglement	1 Hour	1
01/12/2020	Write-up & looking at Hadamard gates and how they are implemented into	1 Hour 30 Minutes	1.5
02/12/2020	Write-up continued	1 Hour	1
03/12/2020	Write-up continued	2 Hours	2
07/12/2020	Write-up continued	2 Hours	2
08/12/2020	Write-up continued	2 Hours	2
12/01/2021	Write-up continued	1 Hour	1
19/01/2021	Write-up continued	1 Hour	1

15/02/2021	Write-up continued	1 Hour 30 Minutes	1.5
22/02/2021	Write-up and starting to organise my references	1 Hour 30 Minutes	1.5
13/04/2021	Writing up my references	1 Hour	1
23/06/2021	References & Write-up continued	2 Hours	2
31/06/2021	References & Write-up continued	2 Hours	2
01/07/2021	References & Write-up continued	2 Hours	2
16/08/2021	References & Write-up continued	1 Hour	1
18/08/2021	References & Write-up continued	1 Hour	1
19/08/2021	Starting to edit and correct errors in my write-up and references whilst also still doing the finishing touches to my write-up, this includes finalising my conclusion	1 Hour	1
21/08/2021	I finished editing and making a final draft of my project & started and completed my CREST student profile with my mentor	3 Hours	3
		Hours in Total	**76.00**