Alistair Drew

10567887

Quantum Supremacy

What does it mean? How does it work? And how does Google do it?

# Introduction:

Quantum Supremacy is defined as the aim of solving a problem no classical computer can solve irrespective of any reasonable amount of time (Arute et al., 2019). This is achieved through the manipulation of quantum mechanics such as superposition, entanglement, and parallel computation in what is known as quantum computing. Using these quantum computers could potentially utilise quantum speedup, a process to exponentially increase the rate of computation of complex tasks (Harrow and Montanaro, 2017). Although it seems far away companies such as Google have declared that they have achieved quantum supremacy (Gibney, 2019). This paper investigates what quantum supremacy is about, how it fits into quantum computing, its criticisms and ultimately what does it mean to achieve quantum supremacy?

# Quantum Supremacy’s History and its place in Quantum Computing

## History of quantum supremacy:

The history of quantum computing and quantum supremacy can be traced back to the 1980s when Paul Benioff an American physicist used Alan Turing’s paper to propose the feasibility of quantum computing (Benioff, 1980). This was arguably one of the first steps to proving the feasibility of quantum computing despite the technology for it not existing at the time. The purpose of this was to show that you could theoretically simulate quantum systems.

Shor's algorithm This is a polynomial-time quantum computer algorithm invented by Peter Shor, a US-based mathematician in 1994 to be used in integers factoring (Chen, 2016). It is used unofficially in solving the problem below: With the, find its prime factors. In addition to the algorithms presented above, the Shor’s algorithm is also used in quantum computing. In this case, factoring an involves the algorithm running in polynomial time (the time taken is polynomial in, the size of the integer given as input). Shor’s algorithm assumes quantum gates of order by use of fast multiplications, consequently indicating that the problem of integer-factorization can be solved resourcefully on quantum computers and is thus in the complexity class BQP. This way, it is faster than the most effective identified classical factoring algorithms such as the general number field sieve (runs in sub-exponential time: . Shor's algorithm is that efficient because of the efficacy of the modular exponentiation and quantum Fourier transform by repeated squaring (Chen, 2016). The algorithm has been a huge motivator for designing and constructing quantum computers as well as studying new quantum-computer algorithms. The Shor’s algorithm is said to have aided in the research on post-quantum cryptography, a group of new cryptosystems that are protected from quantum computers.

## Quantum Computing:

Quantum computing is the exploitation of multiple quantum states such as superposition, parallelism, and entanglement to perform computation (Menon and Ritwik, 2014). Particularly the use of parallel computation is the source of the exponential computational abilities of quantum computers (Arute et al., 2019). The difference between classical computers and quantum computers are the use qubits and quantum gates in quantum computers as compared to binary states and logic gates in classic computers. A Qubit represents a superposition of multiple states of a bit, whereas similarly a quantum gate is a generalisation of a logic gate. It describes the change one or more qubits will experience after the gate is applied to them, given their initial state.

A qubit in a quantum system as represented in figure 1 can exist in a linear superposition of base states (“eigenstates”) The north and south pole of the Bloch sphere are normally chosen to correspond the standard basic vectors |0> and |1>. These might represent the spin-up and spin-down states of an electron. The points on the surface of the Block sphere represent pure states of the system and the interior points are the mixed states (Vogel, 2011). Figure 1 could also represent an n-level quantum system.

A picture containing night sky

Description automatically generated

Figure 1 - Topology of pure state qubit

The Schrodinger equation is a linear partial differential equation that outlines the wave function, a mathematical description of the quantum state of an isolated quantum system. It gives the evolution over time of a wave function and as such can be used to derive information from quantum systems and is typically written up in matrices.

## Measurements and State Collapse

When prepared in some state, a quantum system changes the state over time following its dynamic equation, starting in a pure state it always stays in a pure state. Pure states can be written as superpositions of base states, a base state gets mapped to a mix of base states. Each base state leads to a set of coefficients for the mix.

If undisturbed, a superposition will develop all base states in parallel. Quantum systems can be in >1 state at the same time, however measurements are incompatible with this at a macro scale since they collapse the state to one base state when interfered with. With the probabilities determined by the coefficients, afterwards the system is in that base state (spin up/down) and the mechanism is assumed to be a ‘purely’ random process since it cannot be observed. This is demonstrated in figure 2.

A picture containing logo

Description automatically generated

Figure 2 - State collapse representation

# Main issues – (Quantum Decoherence, Measurement and Hardware)

The main issues with quantum supremacy can be split into 3 different topics.

## Quantum Decoherence

Quantum decoherence is one of the greatest challenges that quantum computing faces, the interaction of outside forces with the superposition of the qubits causes the quantum system to decohere. The result of the quantum decoherence in a quantum system is an impact on the superposition state of the qubits. Interference, (Arute et al., 2019) highlights the use of new error-correcting algorithms that can address the issue of decoherence. However, the use of the error-correcting algorithms comes with challenges that hinder the advancement of quantum supremacy, this uses lot of qubits which impacts the performance of the wave function. Another method to reduce the error rate in quantum computers through the application of Noisy Intermediate-Scale Quantum algorithms. Since the process of error-correcting qubits ends up affecting the computation durations the NISQ algorithms allow the use of qubits that are not error-corrected and use the limited coherence durations to conduct computational tasks.

## Hardware

The creation of a quantum computer is very difficult, Although the potential of quantum supremacy was initially discussed in the 1980’s, it has yet to be fulfilled. One of the problems behind this is because it is because of the very tough to meet the engineering challenges when crating and programming quantum computers. This is a result of how extremely fragile the qubits in superposition are, by changing any number of variables it could offset the result.

Consequently, quantum computers are usually weakened by errors in the form of faults, noise and loss of quantum logic which is important to their operations. This makes them fall apart before any nontrivial programs can be ran completely.

## The measurement Problem

The measurement problem considers how if or when a state collapse occurs, according to Schrodinger’s equation the wave function is meant to evolve deterministically applying to Schrodinger’s equation as a liner superposition of different states. However, despite this we do not view the changes of state on the macro-scale as it always settles into a definite state. As such you would not be able to observe any of the other states. Quantum decoherence resolves the issue of the measurement problem (Joos and Zeh, 1985), the main concept is that the environment interacts with the wave function so that it causes the appearance we see ‘normally’. Decoherence also makes it so that by analysing it you can see how the macro world and the quantum microworld interact.

Quantum computers are much more susceptible to errors than classic computers due to decoherence and noise.

# Discussion and Conclusion

Main point to be learnt from the investigation and what are the problems that still need to be understood and worked out?

More recently in 2019 Google announced that they had achieved quantum supremacy, this is despite roadblocks that are in the way of this. It is mentioned that they carried out a specific calculation that is beyond the practical capabilities of ‘classical’ machines. To do so they produced the Sycamore Processor a quantum computer with an array of 54 qubits. Any proposal for quantum supremacy must fulfil four criteria (Harrow and Montanaro, 2017), firstly a well-defined computational task, secondly a plausible algorithm for the problem, thirdly an amount of time/space for any classical competitor and four a complexity theoretic assumption. For Google to achieve quantum supremacy they would need to cover these criteria. The computational task that they carried out fulfils the criteria “The same calculation would take even the best classical supercomputer 10,000 years to complete, Google estimates” (Gibney, 2019). They completed this task in under 200 seconds. The algorithm used by Google is the Schrodinger’s algorithm which simulates the full wave function of a quantum state. This was used in conjunction with a hybrid algorithm Schrodinger-Feyman algorithm, it this was for larger qubit numbers as it splits the circuit in two so that each section can be analysed with the Schrodinger algorithm individually before reconnecting. Allow for any classic competitor and furth the complexity theoretic assumption.

After Google officially made the claim of achieving quantum supremacy there was a lot of scepticism in the industry. Michelle Simmons, a quantum physicist at the University of New South Wales in Sydney, Australia quoted “While it did give the first experimental evidence that quantum speedup is achievable in a real-world system” (Gibney, 2019). The biggest drawback that Google came across was the limited application of the new quantum computer, despite advancements in technology. Going forward the practical application of quantum computers needs to be improved upon.

# Bibliography