QUANTUM SUPREMACY

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Abstract - *Quantum supremacy demonstrates that a programmable quantum device can solve a complex problem which is infeasible to solve by a classical computer. Recently, in October 2019, Google researchers officially claimed that its 54-qubit Sycamore processor performed a calculation much faster just in 200 seconds that would have taken the world's most advanced supercomputer 10,000 years, though some critics and competitors like IBM called that a gross exaggeration. In this paper, we will learn about the basics of quantum computing and also its impact in the upcoming future. Although quantum supremacy is still in its infancy, experiments have been carried out on smaller number of qubits to demonstrate quantum power which can dominate the classical computer in the upcoming 5-10 years.*

Key Words: Quantum supremacy, quantum computer, classical computer, Moore law, qubit, superposition, entanglement

1. INTRODUCTION

In the early 1980s, Paul proposed quantum model of the Turing machine. Later Richard Feynman and Yuri Manin demonstrate to simulate things that a classical computer could not. Despite number of ongoing experimental progress since late 1990 most scientists believe that fault tolerant quantum computers are distant dreams. However, on 23 October 2019, Google researchers, in partnership with NASA announced to have achieved quantum supremacy. While its chief rival, IBM, said it hasn't.

The nature at fundamental level works in a quantum way. As we know at subatomic level things can exist in many different states at the same instant. Classical computers works in ones and zeros so it's an imperfect way to simulate nature since nature works differently. Quantum computing allows understanding the world in more deeper way i.e. we can simulate nature in better way means simulating molecular structures which can help in discovering better drugs and understanding climate in deeper way, so that we can predict weather patterns and tackle climate change. We can design better batteries and nitrogen fixation which is process by which fertilizers are made, accounts for 2% of carbon emissions and the process hasn't changed for a long time. Quantum computer allows us the hope that we can make process more efficient.

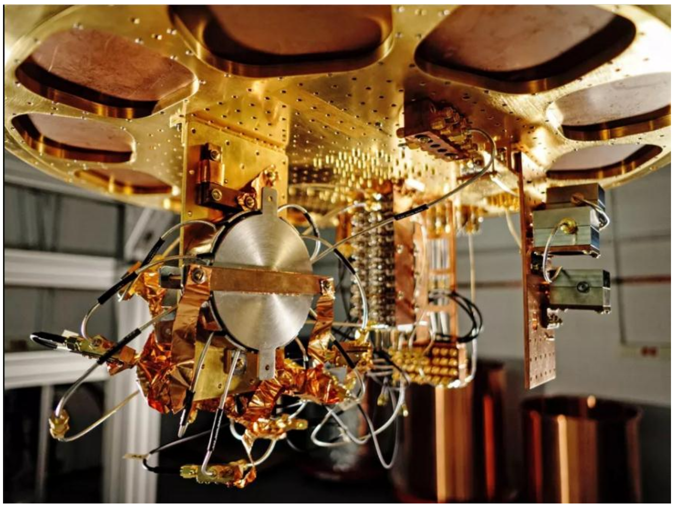

Fig-1: Model of Google quantum computer

So, it is very profound to dealing with the end of Moore's law. Quantum computing could be one of the tools in Arsenal by which Moore's law can continue to evolve in 5 to 10 years of time frame.

2. CLASSICAL COMPUTER

Classical computing is the name given to binary computing. This follows traditional approach of computing, information is stored in bits that are logically represented by either a 0 or a 1. Here zero represents OFF state and one represents ON state i.e. these computer uses bit which can be either ON or OFF at any instant of time. These computer works on Boolean operations and compute in the same way that people compute by hands .Transistors are used to build and engineer the logic required to solve a traditional or conventional computer. Processors such as x86 and ARM processor support classical computing.

3. QUBITS

Quantum A classical computer performs operations using classical bits, which can be either zero or one. In contrast, a quantum computer uses quantum bits or qubits. Qubits can exist in the form, zero and one at same time which give super computing power to quantum computers. There are a number of physical objects that can be used as a qubit like a single photon, a nucleus or an electron such as outermost electron in phosphorus as a qubit.

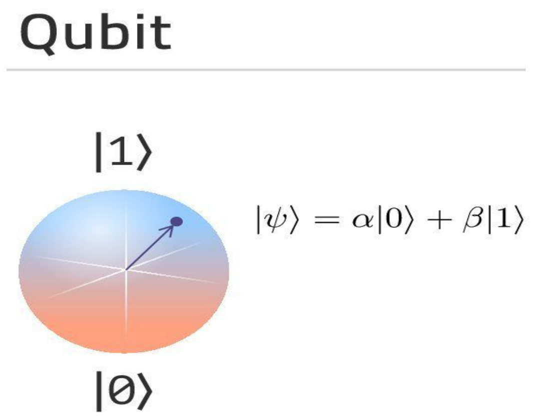

Fig-2: Qubit

All electrons have magnetic fields, so they are basically like tiny bar magnets and this property is called spin. If we place them in a magnetic field they will align with that field, just like a compass needle lines up with the magnetic field of the earth. This is lowest energy state so it is called zero state or spin down. When it moves to other way it is called one state or spin up, but that takes some energy. The funny things about quantum objects are that they can exist in both the states at once which is called quantum superposition.

3.1 How qubits work?

To understand the working let take an example of outermost electron in phosphorus as a qubit.

The single phosphorous atom is embedded in a silicon crystal right next to a tiny transistor. Now the electron has a magnetic dipole called its spin. And it has two orientations, up or down, which are like classical one and zero. Now to differentiate the energy state of the electron when it is spin up and down we need to apply strong magnetic field and to do that superconducting magnet which is large solenoid is used. It is a coil of superconducting wire that sits inside the vessel that is full of liquid helium. So now electron will line up with its spin pointing down. That is in its lowest energy state. And it would take some energy to put into the spin up state. But actually not that much energy is needed if it were at room temperature. As the electron would have so much thermal energy that it would be bouncing around, from spin up to spin down and so we need to cool down the whole apparatus to only few hundredths of a degree above absolute zero. That way we know that electron will definitely spin down. There is not enough thermal energy in the surrounding to flip it other way .Now if we want to write information on to qubit , we can put the electron into the spin up state by putting it with a pulse of microwaves. But that pulse need to be of very specific frequency and that frequency depends on the magnetic field that the electron is sitting in i.e. that frequency must be in resonance frequency of electron.

So the electron is a little bit like radio that can only tune to one station. And when that station is broadcasting, the electron gets all excited and turns to the spin up state. But we can stop at any point. To read out this information we can use the transistor that this phosphorous atom is embedded next to it.

4. QUANTUM COMPUTING

Quantum computing uses quantum-mechanical phenomena such as superposition, entanglement and interference to manipulate the state of a qubit in order to perform complex computation. Superposition is the ability of a quantum system to be in multiple states at the same time which cannot be exhibit by classical system. Quantum entanglement is the physical phenomenon that occurs in quantum system when a pair or group of particles is generated, interact, or share spatial proximity in such a way, the quantum state of each particle of the pair or group cannot be described independently of the state of the others, even when the particles are separated. Computing devices that perform quantum computation are called quantum computers.

There are a few different ways to create a qubit which is used by quantum computing devices. One method uses superconductivity to create and maintain a quantum state. To work efficiently with these superconducting qubit for extended periods of time, they should be kept very cold. Any heat in the system commonly known as noise can introduce error, that is why quantum computers operate at temperatures close to absolute zero, almost colder than the vacuum of space.

Quantum computers can be able to solve certain difficult computational problems, such as integer prime factorization (which is used in RSA encryption), significantly faster than classical computers.

5. CLASSICAL COMPUTING VERSES QUANTUM COMPUTING

Table -1: Comparison between Classical and Quantum computing

S. No.	Classical Computing	Quantum Computing
1.	It is large scale integrated multi-purpose computer.	It is high speed parallel computer based on quantum mechanics.
2.	Information is stored in bits which can be either zero or one.	Information is stored in quantum bits which can be both 0 and 1 at the same time.

3.	There are discrete numbers of possible states.	There are infinite, continuous numbers of possible states.
4.	Calculations are deterministic, meaning repeating the same input results in the same set of output.	Calculations are probabilistic, meaning there are multiple possible outputs to the same set of inputs.
5.	Circuit can be easily implemented in fast, scalable and macroscopic technologies such as CMOS.	Circuit uses microscopic technologies that are slow, fragile and not yet scalable, e.g. NMR (nuclear magnetic resonance).
6.	Data processing is carried out by logic and in sequential manner.	Data processing is done by Quantum logic at parallel instances.
7.	Operations are defined by the Boolean Algebra i.e. zero(0) and ones (1).	Operations are defined by the linear algebra over Hilbert space.
8.	Circuit behavior is defined by classical physics.	Circuit behavior is defined by quantum mechanics.

The diagram shown below illustrates the problem space that can be solved by different computing devices.

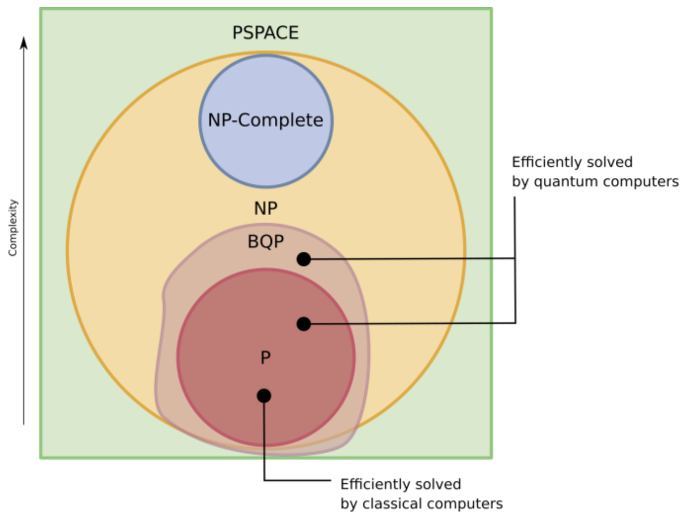

Fig-3: Problem space Classical computer verses quantum computer

6. APPLICATIONS OF QUANTUM COMPUTING

Quantum computers can be used anywhere, where there's a exponentially large, uncertain complicated system that needs to be simulated. That could range from predicting the financial markets, to improving weather forecasts, to modeling the behavior of individual electrons: using quantum computing to understand quantum physics.

There are various application of quantum computing due to its faster and parallel computation power. Some of them are given below.

- Cyber security
- Drug Development
- Financial Modeling
- Better Batteries
- Cleaner Fertilization
- Traffic Optimization
- Weather Forecasting and Climate Change
- Artificial Intelligence
- Solar Capture

7. CHALLENGES TO QUANTUM COMPUTING

As always there are few challenges with the new emerging technology. Similarly, some major challenge for the quantum computing has discussed below.

- Quantum computer's infrastructure is complex and designing is arduous task. It is very difficult to engineer, build and program these computers.
- Quantum computing could break the modern encryption used for cryptography in much smaller time which can be threat to national security.
- A little noise in the environment may cause quantum de-coherence that result in the loss of quantum computing.
- Difficult to scale up the large number of qubits within a quantum chip as it requires multiple control wires or multiple lasers to create each qubit.

8. Is quantum computers are replacement of classical computers?

No, they are not. They are not universally faster. They are only faster for special type of calculations where you can use the fact that you have all these quantum superposition available at the same time i.e. to do some kind of computational parallelism. For an example, if you just want to watch a video in high definition or browse the internet or write some document work they are not going to give you any particular improvements. For this we need to use a classical algorithm to get the result. So, quantum computer cannot make every operation faster.

But it is the computer where the number of operations required to arrive at the result is exponentially small. So the improvement is not in the speed of the individual operation. It is the total number of operations that you need to arrive the result which is why it is not replacement of classical computer.

9. CONCLUSIONS

Quantum computing is a revolutionary technology that uses the bizarre properties of quantum mechanics like superposition and entanglement to solve certain problems much faster than regular classical computers can. Those problems include the worlds of complex mathematics problems to retail business, and physics to finance. If we use quantum technology rightly, the benefits will lift the entire economy and enhance competitiveness which can be beneficial for human beings.

Quantum computing is demanding technology of future. Quantum computing will break encryption as we know it today but we can also do quantum encryption. As always there are challenges with any new emerging technology. Also combination of AI and Quantum will help to tackle some of the biggest problems. Quantum computing will also help in protein unfolding which is very complex and nearly infeasible to do with classical computers.

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