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An overview of Quantum Computing

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1. INTRODUCTION

Computers, no doubt has been a revolutionary machine which transformed and bettered our lives in so many ways. But what is the most important underlying factor, which is making the computer so useful? It is the data processing speed of the computer. In other words, computers are so useful because of a simple fact that they can perform calculations, perform instructions such as finding data etc. much faster than a normal human being. The question now comes is how fast the computer can get? To answer this question, in 1965, Gordon Moore formulated an observation that number of transistors in an integrated circuit will double every 2 years, in other words, speed of a computer will double every 2 years. Then further questions arise like is there any limit to Moore's law? What about the problems that need to be solved now, but will take very long time to solve for a classical computer? Will we have to wait for years till the speed is fast enough? A similar question was asked by Richard P Feynman in his paper "Simulating physics with computers"[1] in 1981. He asked, what kind of computers will be used to simulate physics? He argued, that for accurately simulating quantum mechanical systems, we need a computer which is built on quantum mechanical principles as it was impossible for classical computers to do so. This was the first time, possibilities of a new type of computer got introduced.

This new technology has immense potential and opens up new possibilities. The goal of this research paper is to understand the motivation behind quantum computers, its basic elements, how it is different from the computers we are using today and what lies in the future.

2.1 Why Quantum?

Richard P Feynman in his paper doubted if physics can be accurately simulated using a classical computer. If we want to do that, we will have to assume that a finite number of elements and operations are involved in a certain event as classical computers can't compute infinite elements. But in reality. Physics allows to break an event into infinitely small parts. Even if we want to get approximate results, the computer will have to process a huge amount of data, which very time consuming if not impossible for a classical computer. For example, let's say if we want to simulate time, we will have to discretize it to a scale of 10^{-27} seconds or below. Thus, even for simulating 1 second, the classical computer will have to process a huge amount of data. Another argument he presented in the paper is that of simulating probability. Quantum mechanics is highly dependent on probability. Let's say if we want to find the state of a particle at an instance, and the particle is having a probability half of being A and half of being B. If we measure it, we will find it either A or B. Whether the state of particle will be A or B is determined randomly. This randomness is something a classical computer cannot simulate. It can generate pseudo random numbers but that is also based on some kind of seed. Also, there remains a problem of reversibility. Many of the quantum mechanical operations are reversible in nature, that is, from input we can get output and from output we can get the input. But classical computers are made of non-reversible elements. Thus, quantum physics cannot be simulated in a classical computer. Thus come the idea of building a computer which will be made of quantum mechanical elements following quantum mechanical laws.

2.1. Basic elements of a quantum computer:

As discussed earlier, for a computer to be able to simulate quantum mechanics accurately, it is important to build a computer with quantum mechanical elements itself, which are characterized by being reversible in nature. Richard P Feynman in his paper (1985) have discussed 3 reversible elements that can be used to make a quantum computer.

- **NOT gate or Pauli X gate:** this element is reversible in the sense that if we use 2 NOT gates simultaneously, we get the original input back.

  It can be represented with the matrix,

$$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

- **Controlled NOT gate:** If we provide 2 inputs to this gate a and b, the value of b gets reversed if a is 1 otherwise b retains the same value. This operation is reversible in the sense, if we measure the value of a and b after this operation, we know what the original values of a and b was.

  It can be represented with the matrix,

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

- **Controlled Controlled NOT gate / Toffoli gate:** If we provide 3 inputs to it such as a, b and c, then the value of c is reversed only if both a and b is 1.

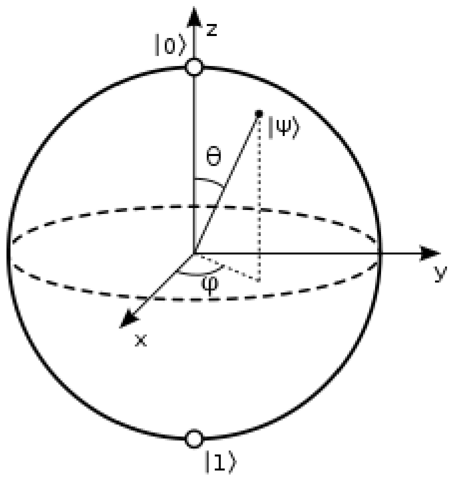
  It can be represented with the matrix,

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

2.2. Difference between classical and quantum bit

The equivalent of a bit in a classical computer is Qubit in a quantum computer. The basic difference is a bit has only 0 or 1, but a qubit can exist in superposition of both 0 and 1 state simultaneously.

The qubits are represented as bloch spheres.



Thus, a qubit can be represented like, $\mathbf{|\Psi> = \cos\Theta/2\ |0> + e^{i\varphi} \sin\Theta/2\ |1>}$

If we represent a classical bit in bloch sphere, it can only point at either the location |0> ot location |1>. But a qubit can point to any location on the sphere. In the given equation of qubits, $\cos\Theta/2$ and $e^{i\varphi} \sin\Theta/2$ are square root of the probability of the qubit being |0> and |1> respectively upon measuring. Thus, we can see that probability plays a very important role in qubits. The quantum gates rotate the qubit in the bloch sphere in a particular position.

Qubits can be created in several ways. Some of them are:

- **Superconductor based:** where the 2 states of a harmonic oscillator are considered as 0 and 1.
- **Optical photon based:** it is possible to control energy levels of a photon. Thus, higher and lower energy levels of photos are considered as 1 and 0. By the

application of quantum gates, the photon can be placed between the 2 energy levels.

- **Ion trap based:** In this case, qubits are represented by atomic spins. The spins are controlled to form various qubit states.
- **Nuclear magnetic resonance (NMR) based:** here, molecules are considered as qubits. We know, many molecules are dipole and the polarity is controlled as qubit states.

3. CONCLUSION

Quantum computing is an active research area and is thought to have a huge potential. It has applications in the field of chemistry simulation, physics simulation, cryptography, machine learning, finance etc. Though there are certain concerns about quantum computing. One big concern is that our internet security system might be easily breached with quantum computers and thus post quantum cryptography is a huge research area right now. But in the field of simulations and algorithm optimization, future of quantum computing looks promising. Quantum computing algorithms can reduce time complexity of NP hard problems. If quantum computers can simulate real life chemistry and physics conditions accurately and in a reasonable time, then testing of different chemicals, medicines, vaccines etc. will be much easier and faster. Quantum machine learning is also a field with great promises and it is aiming at solving the problem of speed in training machine and deep learning models.

In this paper, we saw how the quantum computing came into picture and explored some of the basic uniqueness of it. Classical mechanics have taken humanity to great heights and now we will see what quantum mechanics has to offer.

4. **References**

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