Getting Started With Quantum Computation: Experiencing The Quantum Experience

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Getting Started With Quantum Computation: Experiencing The Quantum Experience

A Brief Introduction To Quantum Computation

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Quantum computation is an emerging field of research at the intersection of computer science, information theory and quantum physics. With applications in cryptography, simulation of complex quantum mechanical systems, artificial intelligence, weather forecast and market prediction, quantum computers will be indispensable in the future. Recent years have seen immense progress on the experimental front, with IBM Quantum Experience (IBM QE) real quantum computers are within reach for anyone. We introduce here the basic concepts of quantum computation in order to get ready for IBM QE, which can be started with the knowledge of matrix multiplication.

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Introduction

There is a certain class of problems called non-polynomial (NP) problems which cannot be solved efficiently on the current "classical" computers. The phrase "cannot be solved efficiently" means that as the size of input parameter increases, the time required to solve the problem increases exponentially. Consider the travelling salesman problem; a salesman has to visit n different cities, in what order should he visit them so that the total distance travelled by him is minimum? For number of cities as small as 10 there are 10!/2 =1814400 possible ways in which he can visit them. A classical computer will systematically calculate the total distance for each possible configuration and then compare them to find an optimal solution. The time required to solve this problem increases exponentially with number of cities, thus for a sufficiently large number of cities the computer will take forever to find solution.

One way to deal with this limitation is to make bigger computers i.e., to have more transistors on a chip. Although the problem is still non-polynomial, a bigger computer solves a problem of given size in less time. In order to tackle problems of bigger and bigger size in less and less time, the transistors will have to get smaller, so small that eventually there are only a few silicon atoms. At this stage a new problem comes up, due to the small size we are no longer in classical regime. Quantum effects start to dominate. Due to the inherent uncertainty of quantum world we may get random results.

1. Origin of Randomness

To understand how quantum uncertainty comes up at microscopic scale, consider an example of plane polarized light incident on a polarizer. The state of polarization parallel to optical axis is denoted by $|x\rangle$[1] and the state perpendicular to it is denoted by $|y\rangle$. These two states form a complete and orthonormal basis which means any other polarization state can be described as a linear combination of these two states.

[1] This is a more general notation for vectors. For simplicity $|c\rangle$ and $\langle r|$ can be considered as generalizations column and row vectors respectively.Thus $\langle r|c\rangle$ becomes the generalized dot product.

$$\langle x|x\rangle = \langle y|y\rangle = 1, \langle x|y\rangle = \langle y|x\rangle = 0 \qquad \text{Orthonormality} \tag{1}$$

$$|x\rangle\langle x| + |y\rangle\langle y| = I \qquad \text{Completeness} \tag{2}$$

When light in arbitrary state of polarization $\cos(a)|x\rangle + \sin(a)|y\rangle$, travelling along z axis, is incident on a polarizer it is observed that transmitted intensity is $\cos^2(a)I_0$, where I_0 is incident intensity and a is angle between plane of polarization and optical axis. However, if the intensity of the incident light is reduced to the extent that only single photon is incident at a time, then the photon will either pass through or it will be absorbed. What decides whether the photon will pass through polarizer or not? Passing photon through polarizer constitutes a measurement and according to Copenhagen interpretation of quantum mechanics the state of the system collapses to one of the basis states upon measurement. This collapse is totally random and all we can talk about a priory is the probability with which the photon will collapse to given basis state. An analogy of coin toss will be helpful to understand the idea of superposition-measurement-collapse. When the coin is in air it is neither heads nor tails, it is in superposition. As it hits the ground it lands on heads or tails at random. The probability that an incident photon in state $\cos(a)|x\rangle + \sin(a)|y\rangle$ will collapse to state $|x\rangle$ is given by $\cos^2(a)$ and that of state $|y\rangle$ is $\sin^2(a)$. Note that the sum of probabilities i.e., $\sin^2(a) + \cos^2(a)$ is 1. Thus out of n incident photons $\cos^2(a).n$ are randomly found in state $|x\rangle$ and thus the transmitted intensity is $\cos^2(a)I_0$. This analysis at microscopic scale is totally consistent with macroscopic intensity law (Malu's Law). If we rotate the analyzer such that the optical axis is parallel to plane of polarization (rotation of measurement basis) then the photon is in state $|x\rangle$. Now $\cos^2(a) = 1$, thus every photon that arrives at polarizer passes through. There is no random behaviour. We see that randomness arises when the system is in superposition of measurement basis states.

Randomness arises when the system is in superposition of measurement basis.

2. The Power of Superposition

Interestingly, the same superposition which leads to randomness also allows for performing operations on all possible states at once. This leads to Quantum parallelization i.e. unlike classical computer which has to process one input at a time a computer based on quantum principles a "Quantum Computer" can process all possible inputs at once. Although quantum parallelization offers a large speedup over classical computers, the result may still be random, so the whole idea is to design the operations in such a way that the probability of getting correct answer is enhanced. For problems which are beyond reach of classical computers a probabilistic answer is better than no answer at all. Fortunately in some cases, although the solution is difficult to find it is easy to check a given solution. For example, finding out prime factors of a number is a NP problem, but given a prime factor of a number it is just matter of easy multiplication to check whether they are really the prime factors or not. Thus a probabilistic answer can be checked and if found incorrect, the process can be rerun to find

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another answer.

3. Quantum Computer

The information storage and processing in classical computers occurs via classical bits (cbit). These bits can be only in state 0 or 1. Unlike classical bits which are described using numbers (scalars) the quantum bits or qubits are described by vectors. Physically a qubit can be any quantum system that can be described using two basis vectors $|0\rangle$ and $|1\rangle$ for example, trapped ions, superconducting junctions, NMR etc. Unlike cbit a qubit can be in superposition of $|0\rangle$ and $|1\rangle$. Since the qubits are vectors the natural language of quantum computation is linear algebra. The transformations applied to change the input state of qubit to output state are nothing but matrices. Thus a quantum computer essentially consists of a series of qubits, each of which is a quantum system described using two dimensional vector space. The qubits are prepared in known state say $|0\rangle$ then a transformation is applied on them to which puts them in superposition. Once in superposition a series of transformations are applied which act on every possible input. Mathematically these transformations are rotation matrices. A measurement is then done to retrieve the answer.

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4. A Brief History Of Quantum Computation

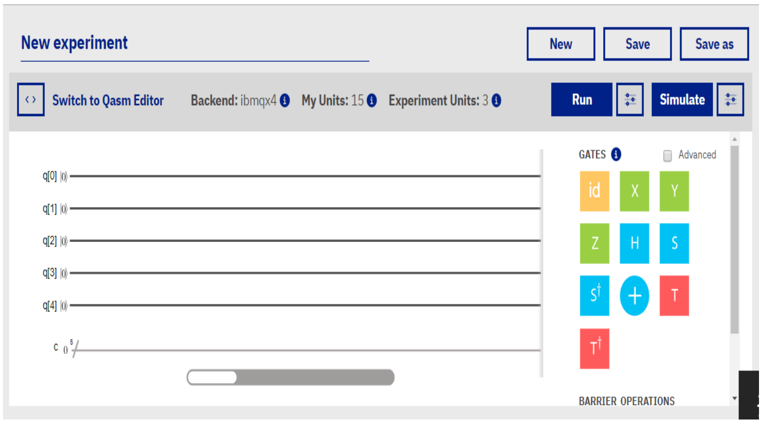
The first idea in the field of Quantum information was ”Quantum Money” proposed by Stephen Wiesner in 1970. The quantum money is based on the “No Cloning Theorem” which states that quantum information cannot be copied. Thus quantum money cannot be forged. In 1981 Richard Feynman had realized that the inability of computers to simulate quantum mechanical systems is because their working principles are classical. He proposed that a computer used for simulation of quantum mechanical systems should be based on Quantum principles. From late 60s to late 90s the research in the field led to formation of theoretical framework for quantum information. The most factorization algorithm by Shor (1994) and list search algorithm by Grover (1996) demonstrated the power of quantum computer. The first experimental demonstration of quantum algorithm was done in 1998 by Jonathan A. Jones and Michele Mosca at Oxford University. Since then experimental side has progressed tremendously. Linear optics, superconducting junction, Nuclear magnetic resonance and trapped ions have been used as qubits. Recently IBM has made 3 quantum computers public, providing an opportunity everyone to work with quantum computers.

5. IBM Q Experience

Since its inception in May 2016 IBM Q Experience has proven to be a valuable asset for researchers working in the field of quantum computation. More than 80 academic papers have been published based on the research carried out with help of IBM Q Experience. Through this platform researchers, students and enthusiasts get access to a real quantum processor and a simulator. The qubits used are superconducting Josephson junctions. They are stored at very low temperature, only a few milikelvin above absolute zero, in order to protect them from the thermal noise. A $^{3}He/^{4}He$ dilution refrigerator is used to achieve the low temperature required. The state of a qubit is changed by shooting it with microwave radiation of predetermined frequency and phase. On the other hand measurement of the state of a qubit is done by measuring its response to certain microwave radiation.

As of November 2018, IBM has made available two 5 qubit and one 14 qubit quantum computers. These devices can be remotely accessed using IBMs online platform called IBM Quantum Experience. The composer (Fig1) is a friendly graphic user interface used to write an algorithm. Along with composer the online platform includes a beginner's guide, a full user's guide and a forum to share ideas and reach out for help. The typical process of writing and running an algorithm is as follows: first all the qubits in composer are in state $|0\rangle$, appropriate gates are taken from side panel and dropped on a qubit to change the state of qubit. The

Figure 1. The composer of IBM Q Experience. Image Credit:IBM Q Experience.



information processing occurs when state of one qubit is conditionally evolved based on the state of some other qubits. Finally measurements are done to know the states of all or some qubits and the result is stored in a classical register and displayed as a bar chart. For example a two qubit algorithm can have four possible outcomes 00, 01, 10 and 11. So the result of a two qubit algorithm gives probability of getting each one of these as output. As we know for a particular run, the result is random but when we run the algorithm many times we may find that a certain result occurs more often than other. The whole idea is to apply transformations (gates) in such a way that the probability of getting desired output is enhanced.

To start building quantum circuits one first needs to visit IBM Q Experience website and register with email addresses. Then go to composer and start a new circuit. There is an option to choose to run the circuit on real quantum computer or simulate the results using custom topology. A circuit sent to run on real device is queued and the process takes time. Thus it is advisable to use custom topology for trial and error and for testing the circuit prior to sending it to real device.

6. Conclusion

In this article we have seen that a paradigm shift from classical to quantum computation allows us to solve problems which could not be solved efficiently before. There are a lot of problems for which quantum algorithms are yet to be designed. With the help of IBM Q Experience anyone can participate in the effort to take the research in quantum computation forward.

Suggested Reading

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