Unlocking a world of boundless possibilities of quantum computers

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The recent advancements in computer technology have been incredible. During the early stages of computer development in 1950, computers occupied an entire room. However, now they have shrunk to the size of smartphones that fit in our hands, and their computing speed has significantly increased. In the future, computers may undergo further evolution. The new computer is called a quantum computer, built on a different mechanism from conventional computers. When quantum computers are put to practical use, they are expected to solve complex problems that were unsolvable by conventional computers. Before explaining how a quantum computer works, let's first briefly describe how your computer operates. Have you ever heard that computers are made of 0s and 1s? That's actually true. Computers use 0s and 1s, called "bits," to represent all numbers and characters. Why do we use only 0s and 1s? That is because handling continuous values in a computer is challenging, and we want to keep data as simple as possible. Typically, 0 and 1 in a bit is represented by the amount of the voltage. For example, if the voltage is 0 V, it represents 0; if it's 5 V, it represents 1. The value of the voltage may deviate slightly due to noise, like 4.9 V or 5.1 V, but we can still determine the value bit represents based on the presence or absence of the voltage. By limiting the number of the representation of information, we can tolerate voltage fluctuations caused by the noise. This is called "digital" information. On the other hand, information that can take continuous values is called "analog" information.

Let's explain quantum computers next. Like the computers we commonly use, quantum computers also represent information using 0s and 1s. What makes them different from traditional computers is the use of something called "quantum bits" or “qubits,” which can simultaneously represent 0 and 1. Suppose we flip a coin and say that if it lands on heads, it represents 0, and if it lands on tails, it represents 1. In this case, we can expect a 50% chance of getting 0 and a 50% chance of getting 1. The fascinating thing about qubits is that we can freely manipulate these probabilities of getting 0 or 1. With conventional bits, when we represent 0 or 1 using voltage levels, the probabilities are obviously either 0% or 100%. However, qubits can change these probabilities to any value between 0% and 100% and maintain that state during calculation. If you have one qubit, you can manipulate the probabilities of two states: 0 and 1. If you have two qubits, you can manipulate the probabilities of four states: 00, 01, 10, and 11. As you increase the number of qubits, the number of values of probabilities that can be stored doubles. This allows quantum computers to handle an enormous amount of information that could not be handled by conventional computers.

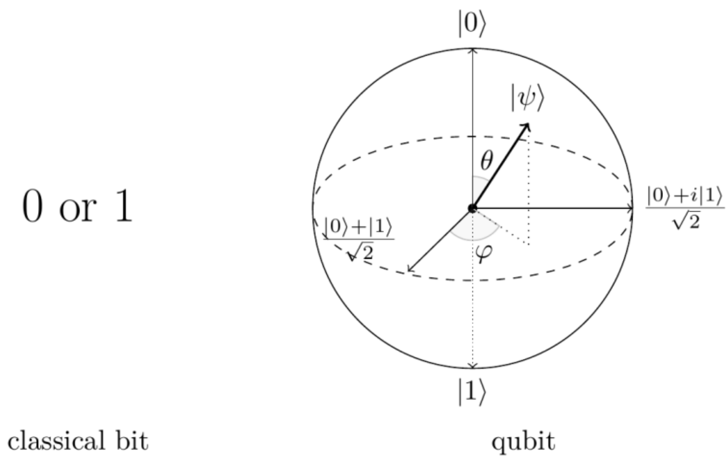

Fig. 1. The difference between classical bit and qubit. Classical bits can represent only 0 or 1, but qubits can be a superposition of 0 and 1.

However, these qubits are susceptible to noise. Current existing quantum computers cannot perform calculations properly due to the influence of noise. Furthermore, the issue of noise is a deeply rooted problem. Remember the unique property of qubits that they can change the probability of obtaining 0 or 1 to any percentage? These probabilities are analog. Being analog, due to the noise, a 10% probability, for example, can turn into 11%, 10.1%, or any probability during the computation. Scientists have been facing a challenge in distinguishing meaningful analog data from noise, which has been a persistent problem. The situation changed with the introduction of quantum error correction codes by Peter Shor in 1995 [1]. Shor showed that this analog error could actually be expressed in terms of a digital error and that the noise can be canceled simply by performing some predetermined error correction operations depending on the noise. The occurrence of noise is assumed to be random and causes some qubits to perform incorrect calculations among the qubits that successfully executed correct calculations. Shor’s idea is to solve this issue by simultaneously performing the same calculation on multiple qubits and taking a majority vote. If we can reduce the frequency of noise occurrence to a sufficient level, the number of qubits that performed correct calculations will be significantly greater than the number of qubits with incorrect calculations. Therefore, by inserting operations that detect noise during the computation and correcting the results, we should be able to eliminate the noise. Many scientists got excited about this new invention. After this breakthrough, scientists figured out that if the probability of noise occurrence is lower than a certain threshold, quantum computers can work perfectly without any errors. Although the probability of noise occurrence is still high for practical computations using current quantum computers, scientists and engineers continue their efforts to reduce this probability, dreaming of achieving the goal someday.

The invention of Shor's quantum error correction code was a significant breakthrough that showed how a perfect quantum computer, which was previously thought to be challenging to achieve, could be feasible with efforts to suppress noise. Scientists currently interested in quantum computers are primarily focused on two things. One is the development of practical quantum computers. Various forms of quantum computers have been devised and designed based on different materials, such as light, electrons, and atomic nuclei, all of which can function as qubits. The other focus is on developing quantum algorithms. There are problems in materials science, finance, machine learning, and optimization that are expected to benefit significantly from the computational power provided by quantum computers. As a result, scientists from various fields, not just quantum mechanics experts, are getting involved in the development of quantum algorithms.

Reference

[1] P. W. Shor, Scheme for Reducing Decoherence in Quantum Computer Memory, Phys. Rev. A **52**, R2493 (1995).

Acknowledgments

I would like to thank Dr. Kate Harris, Dr. Ravindra Palavalli Nettimi, and Mr. Yuki Nakamura for their invaluable input and insightful suggestions regarding my essay.