Quantum Computers: A new Era in State-of-the-Art Technology - 1

Nowadays everybody hears all the cool words used to describe Quantum Computers, like superposition, entangled particles, qubits, and so on. When it is about something mathematically complicated and philosophically amazing, the word "quantum" shows itself. At the end of the day, among many explanations, no one understands exactly the theme. On the other hand, as a physicist it was not easy for me to ignore being from one of those guys who try to demystify the puzzle. So, this article discusses what exists behind this state of the art technology: Quantum Computers (QC).

Since the 1900's physicists have been struggling with the bizarre behaviour of subatomic particles. Following Max Planck's black body radiation, Einstein's photoelectric effect and Rutherford's spectacular atomic model, a new era was born in science. Especially discovery of electron orbitals pushed the scientists to understand the nature of atoms. This new unusual mathematical frame was called quantum physics.

Quantum concepts helpt physicists manipulate the behaviour of subatomic particles like electrons. Many breathtaking technological developments such as diodes and transistors took place. Transistors are probably one of the most astonishing discoveries of mankind. In the mobile phone you hold or in the laptop you read this article there are probably hundreds of millions of tiny transistors. The transistors are literally in every electronic device we use. But how do they work?

The basic principles of transistors are actually very simple. They act like a switch in an electric circuit and control the flow of electric current. They can be "off", so we call that the 0 state, or they can be "on", the "1" state. This is how all digital information is stored and processed as zeros and ones: "bits" of electric currents.

The difference between a regular switch and a transistor is that the transistors are incredibly small and they do not require a human controller, thanks to the semiconductor technology.

Transistors are combined to create logic gates which still do very simple tasks. For instance an OR gate sends an output of 1 if one of the inputs is 1, and an output 0 otherwise. Combination of logic gates form purposeful modules like arithmetical operations. A large enough of modules can compute anything from cosmology or string theory to virus simulations.

Transistors are made up of doped silicon crystals. Applying (not applying) a positive potential to the gate of a transistor, switches on (off) the current. Thus, without any mechanical moving part, the electric current can be controlled. The size of an advanced transistor is about 15 nanometers, which is almost the size of 30 silicon atoms.

Processing speed of the electronic products is directly linked to the number of transistors on chips. The famous Moore's Law points out that every two year the number of transistors on integrated circuits doubles. The law has worked until this very day. The problem arises from the size of transistors. It will not be possible in the very near future to build smaller transistors any more. Because of a quantum mechanical effect called Tunneling, it is getting harder and harder to control electric current flow in those nano transistors.

In a transistor, the gate blocks the electron flow between electrodes (the source and the drain) and the gate behaves as a barrier. That is how we control current and use the gate as a switch. But if the size of the gate approaches atomic level, the electrons cross the barrier and literally jump between the electrodes. This is called quantum tunneling.

Essentially what determines whether the transistor works or not, is whether we can stop electrons effectively. At some point, quantum mechanics becomes the problem! Even if there is a potential barrier between the electrodes, electrons can still flow because of this quantum tunneling effect. Electrons go through the walls! In essence the whole challenge for modern microelectronics (should we say nanoelectronics!) is to keep pursuing Moore's law. But it is not our technological capabilities that limit us, it is nature itself!

At this critical point, quantum mechanics itself becomes the solution. Here instead of a classical transistor, we need just another option which includes two different states to be 1 and 0 and we need to be able to control these states. Quantum physics is full of these types of state couples. Recently, scientists are trying to use the unusual quantum features to their advantage. For example an electron has two angular momentum values that we call spin up and spin down states. Or we can use horizontal or vertical polarized photons as zeros and ones.

Instead of classical bits, QC uses quantum bits, or qubits which can also be set to one of two values. A qubit can be any 2-level quantum system, such as a magnetic field, polarization of a photon, or spin of an electron. In the quantum world these qubits do not have to be just 1 or 0, they can be any proportions of both states at once! This odd property is called superposition. But as soon as the state of the qubit is tested (detected), qubit has to choose one of the either state, 0 or 1.

Before detecting, the qubit is in a superposition of probabilities for 0 and 1 and no one can predict which it will be. The measurement makes it instantly collapse into one of the two states. So why is this so-called superposition thing a game changer?

If we place an electron in a magnetic field, it aligns with that field just like as a bar magnet. In that magnetic field without any outside-effect the electron would be in the lowest energy level, we could call it the zero state or spin down state. After taking some energy from outside the electron changes its state to spin up, or 1.

So far this is basically like a classical bit. It has got two states: spin up and spin down which are similar to classical 1 and 0. But the weird thing about quantum objects is that they can be in both states at once. The electron can exist in a superposition. Let us formulize the spin up and down probabilities with an example:

$$\text{The state of electron} = 0{,}75\ u + 0{,}25\ d$$

The coefficients indicate the relative probability of finding the electron in u state or in d state. Here the probability of the electron being in up state is 75%, being in down state is 25%.

In order to be able to imagine how qubits enable the incredible power of QCs, we consider two interacting qubits. The notation is familiar to physics students and easy to understand. Assume we have two electrons. There are four different possibilities:

$|uu\rangle$: both in spin up state
$|dd\rangle$: both in spin down state

|ud> : first in spin up, second is in spin down state
|du> : vice versa.

This is like the two bits of a classical computer: 11, 00, 10 and 01 states of two bits of information. But the difference is that quantum mechanics allows us to make superposition of each one of those four quantum states. So we can write a quantum mechanical state as a multiplication of the coefficients of the four states. In short, we need to give four numbers (four coefficients) to determine the state of this 2-spin system. Whereas in the classical example of two transistors we have only two bit information. In quantum systems, two qubits actually contain four bits of information. If we have three qubits, 8 numbers can determine the state of this 3-qubit system, so it contains 8 bits of information. If we keep going, what we find is that the amount of classical information contained by N qubits is equal to 2^N bits. The power of exponential numbers tells us, as an example, that if we have 300 qubits then we have so many classical bits of information which are as many as the particles in the whole Universe.

It may seem unbelievably effective but there are other problems in using qubits. Although the qubits can exist in any combination of states, they must fall into one of the states when we measure them. It means all the other information before the measurement is lost. It comes to a conclusion that the QCs are not faster for every algorithm. Instead, they are faster for very specific calculations where we can use all those quantum superpositions available at the same time to do some kind of parallel computation. So the advantage of QCs is not the speed of the individual operation, it is in the total amount of operations we need to arrive at the end as a result.

In conclusion, QCs will not replace classical computers. At least, to say, for the following decades, we can expect to use QCs in a narrow field of research. It is not realistic to hope a QC as a laptop that we download 4K movies.