Information: Quantum or Classical?

The twenty first century has often been hailed as the “Age of Information”; such degree is justified as computers have indeed changed the human way of life in this era. With data and information being such an integral part of our lives, it is really important that we all know what they truly mean. In this article, I aim to explain the two types of information: classical and quantum - and present a brief introduction into the field of Quantum Information and Quantum Computation. This article is written with the intent of introducing Quantum Computing in a “not so math heavy” and intuitive way.

While I believe most of our understanding of the meaning of “information” may be fairly accurate, I think it is safe to say that Rolf Landauer, German-American physicist, said it best when he said, “ Information is physical”. Landauer’s insight into the meaning of information tells us a lot about our natural world; In three simple words, he has portrayed the universe, as we know it, as a computer, where each observable is what we call information.

Under such a premise, it is only obvious that the most common definition of information, i.e. computer memory/storage, is nothing but the physical state of some transistor. Information is indeed physical. Now, it is only natural to ask - Is information classical or can it be quantum? The answer to this question is both. However, so far in this age of information we have mostly been dealing with information that is classical in nature. Classical information is binary- 0 or 1, true or false, yes or no - hence transistors, which can be in two distinct states, are an ideal physical realization of classical information. Using 800 of such transistors and a handful of logic gates and a current source, the first “transistorized” computer was built in January of 1952.

We have made quantum leaps in terms of speed and power of computers ever since the birth of the first “transistorized” computer. However, it is to be noted that in terms of core technology not much has changed. Modern computers still run using such transistors but use more of them (billions of them in fact!), and the types of logic gates used are more or less the same. This leads one to ask, “How are the modern computers so much more powerful then?”: the answer- efficiency. Computers, nowadays, are much more spatially and functionally efficient thanks to innovations in electrical engineering and material sciences, but most of the credit of such increase in power is attributed to the shrinking size and growing numbers of transistors. This phenomenon is so prominent that Gordon Moore, the co-founder of Fairchild Semiconductor, conjectured the claim that the number of transistors in a dense integrated circuit doubles about every two years. This observation about the exponential growth of computing power that Moore back in the 1970s has proved to be prophetic. Starting around 2010, however, Moore’s Law began to break down and many today are asking if this “Age of Information” is coming to an end with silicon chips approaching the size of a silicon atom.

This is where the “Age of Quantum Information” will begin. Quantum computation and quantum information is the study of the information processing tasks that can be accomplished using quantum mechanical systems. So what exactly is quantum mechanics again? Quantum Mechanics is the study of the small and probabilistic building blocks of the universe. It is a mathematical framework that physicists use for the construction of physical theories to model reality. This may be very redundant for those of us who have taken one or two quantum classes, but what seems very unintuitive is how can such a physical theory be used for computation. The key insight to solving this problem comes from history. In the past, we created classical computers by thinking physically about computation and now to create quantum computers, we should think computationally about physics.

We all know ‘bit’ as being the fundamental concept of classical computation. The world of quantum information has been built on an analogous concept called the quantum bit (qubit). Similar to how a classical bit has a state - 0 or 1, a qubit also has a state. It in fact has two states $|0\rangle$ and $|1\rangle$ which correspond to their classical counterparts respectively, moreover, it also has a state which is a superposition of these two states.

$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle \tag{1}$$

If you have taken a course in quantum mechanics, you can tell that this equation looks eerily similar to that of the expression of a time dependent Schrodinger equation as a linear combination of its stationary states.

$$\Psi(x,t) = \sum_{n=1}^{\infty} c_n \psi_n(x) e^{\frac{-iE_n t}{\hbar}} \tag{2}$$

This is no coincidence, as it is such behavior of quantum systems that enable it to carry out information processing. In the equation for the qubit system, the square of the coefficient for the states represent the probability of finding the qubit in that certain state. For example, if $\alpha = 0.5$ and $\beta = \sqrt{0.75}$, this would tell us that the probability of finding the qubit in state $|0\rangle$ would be $0.5^2 = 0.25$ and that of state $|1\rangle$ will be 0.75. (Note how the normalization condition still apply). With that being said, however, whenever we measure the state of a qubit it will only exist in a state of $|0\rangle$ or $|1\rangle$, and will continue to be in that state for consecutive repeated measurements made shortly afterwards.

This lack of this direct correspondence and inclusion of probabilities does make it difficult to intuit the behavior of quantum systems; however, there is an indirect correspondence, for qubit states can be manipulated and transformed in ways which lead to measurement outcomes which depend distinctly on the different properties of the state. The ability of a qubit to be in a superposition state runs counter to our ‘common sense’ understanding of the physical world around us. A classical bit is like a coin: either heads or tails up. By contrast, a qubit can exist in a continuum of states between landing on its “head” and “tail” side– until it is observed. Such phenomenon may sound strange, but in practice, qubits are very real, their existence and behavior extensively validated by experiments.

A fun problem that I would like to pose to you guys is to theorize a physical system that can be used to realize qubits. It’s a problem that I think a lot about in my free time and it is also a burning research question. Do send me an email with any idea that you may have.