Quantum Computing

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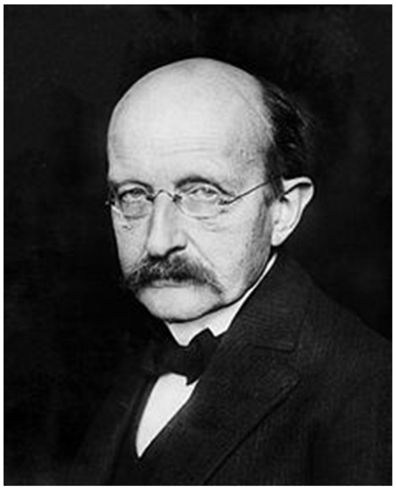
"A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it.“

Max Planck

Max Planck



http://en.wikipedia.org/wiki/Max_Planck

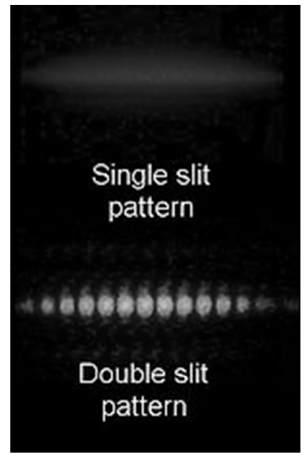
- Father of Quantum Physics
- Nobel Prize 1918
- Proposed that radiant energy could exist only in discrete quanta which were proportional to the frequency
- $E=h\nu$, $h = 6.62606957 \times 10^{-34}$ m^2 kg / s

"in recognition of the services he rendered to the advancement of Physics by his discovery of energy quanta".

“h” is the Planck constant – he called it the quantum of action

The Double Slit Experiment

- Often called Young's experiment – established the wave nature of light
- If light was a particle, we would expect the pattern to be a discrete line in the pattern of the slits

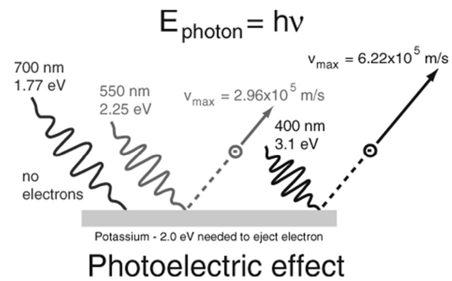


http://en.wikipedia.org/wiki/Double-slit_experiment

Newton believed in the corpuscular theory of light. This theory said that light was made up of small discrete particles called corpuscles which travel in a straight line with a finite velocity and possess kinetic energy.

The Photoelectric Effect

- the emission of electrons by substances, especially metals, when light falls on their surfaces
- the maximum energy of the electrons is not dependent on the intensity of the light, but rather the frequency
- Photons have now been described



http://hyperphysics.phy-astr.gsu.edu/hbase/mod1.html

According to classical theory, when light, thought to be composed of waves, strikes substances, the energy of the liberated electrons ought to be proportional to the intensity of light. Experiments showed that, although the electron current produced depends upon the intensity of the light, the maximum energy of the electrons was not dependent on the intensity. Moreover, classical theory predicted that the photoelectric current should not depend on the frequency of the light and that there should be a time lag between the reception of light on the surface and the emission of the electrons. Neither of these predictions was borne out by experiment.

The remarkable aspects of the photoelectric effect when it was first observed were:

1. The electrons were emitted immediately - no time lag!
2. Increasing the intensity of the light increased the number of photoelectrons, but not their maximum kinetic energy!
3. Red light will not cause the ejection of electrons, no matter what the intensity!
4. A weak violet light will eject only a few electrons, but their maximum kinetic energies are greater than those for intense light of longer wavelengths!

Wave-Particle Duality

Depending on the circumstances light can be both a wave and a particle at the exact same time, with the properties of both.

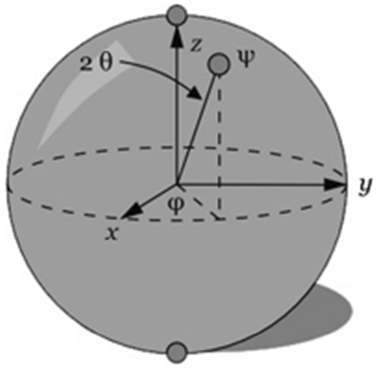
Quantum Mechanics provides a mathematical description of much of the dual *particle-like* and *wave-like* behavior and interactions of energy and matter.

Today, physicists accept the dual nature of light. In this modern view, they define light as a collection of one or more photons propagating through space as electromagnetic waves. This definition, which combines light's wave and particle nature, makes it possible to rethink Thomas Young's double-slit experiment in this way: Light travels away from a source as an electromagnetic wave. When it encounters the slits, it passes through and divides into two wave fronts. These wave fronts overlap and approach the screen. At the moment of impact, however, the entire wave field disappears and a photon appears. Quantum physicists often describe this by saying the spread-out wave "collapses" into a small point.

Quantum mechanics deals with "nature as She is – absurd."

--Richard Feynman

The Qubit



- Quantum equivalent of a bit
- May be 0, 1, or a superposition of both
- The classic representation of its states is the Bloch sphere
- represent atoms, ions, photons or electrons and their respective control devices that are working together to act as computer memory and a processor

http://computer.howstuffworks.com/quantum-computer1.htm

A bit is the basic unit of computer information. Regardless of its physical realization, a bit is always understood to be either a 0 or a 1. An analogy to this is a light switch— with the off position representing 0 and the on position representing 1.
A qubit has a few similarities to a classical bit, but is overall very different. Like a bit, a qubit can have two possible values—normally a 0 or a 1. The difference is that whereas a bit *must be* either 0 or 1, a qubit *can be* 0, 1, or a superposition of both.
The possible states for a single qubit can be visualised using a Bloch Sphere(see diagram). Represented on such a sphere, a classical bit could only be at the "North Pole" or the "South Pole", in the locations where and are respectively. The rest of the surface of the sphere is inaccessible to a classical bit, but a pure qubit state can be represented by any point on the surface. For example the pure qubit state would lie on the equator of the sphere, on the positive y axis.
The surface of the sphere is two-dimensional space, which represents the state base of the pure qubit states. This state space has two local degrees of freedom. It might at first sight seem that there should be four degrees of freedom, as α and β are complex numbers with two degrees of freedom each. However, one degree of freedom is removed by the constraint . Another, the overall phase of the state, has no physically observable consequences, so we can arbitrarily choose α to be real, leaving just two degrees of freedom.
But qubits are fickle things, having a tendency to lose superposition under observation (recall S cat). Until this latest breakthrough, qubits had only been successfully created in large vacuum chambers.

Registers

Classical

- Take a 3-bit register may contain any number from 0 to 7 – 1 distinct value.
- A 4-bit register may contain any number from 0 to15 – 1 distinct value.
- An n-bit register may contain any number from 0 to n-1 – 1 distinct value.

Quantum

- A 3-qubit register may contain all numbers from 0 to 7 at the same time – 8 or 2^3 values.
- A 4-qubit register may contain all numbers from 0 to 15 at the same time – 16 or 2^4 values.
- An n-qubit register may contain all numbers from 0 to n-1 at the same time – n or 2^n values.

The Features

- Superposition
- Interference
- Entanglement
- Non-determinism
- Non-clonability
- Non-locality

1. Superposition is a fundamental principle of quantum mechanics that holds that a physical system—such as an electron—exists partly in all its particular, theoretically possible states (or, configuration of its properties) simultaneously; but, when measured or observed, it gives a result corresponding to only one of the possible configurations –application quantum database search
2. Interference– because it can work on multiple computations at the same time, we can cause them to interfere and influence each other. Application Quantum parallelism –can extract a joint property of all of the solutions to a problem.
3. Entanglement– if 2 or more are made to interact, they can emerge in a joint quantum state which can be expressed as a product. This can cause them to retain an instantabneous influence on each other. App—quantum factoring allows a repeating sequence of numbers whose period can be used to reveal the factors of large numbers.
4. Non-determinism– inability to predict the state it will collapse into when measured -- App key distribution—guarantees that eavesdropping will be detected

5. Non-clonability – cannot be copied if state is unknown App – cryptography, guarantees security
6. Non-locality-- Quantum nonlocality is the phenomenon by which the measurements made at a microscopic level necessarily refute one or more notions (often referred to as local realism) that are regarded as intuitively true in classical mechanics. Rigorously, quantum nonlocality refers to quantum mechanical predictions of many-system measurement correlations that cannot be simulated by any local hidden variable theory. Many entangled quantum states produce such correlations when measured, as demonstrated by Bell's theorem. – quantum teleportation

The Progress

- 1998—Los Alamos and MIT
- 2000—Los Alamos
- 2001—IBM and Stanford
- 2005 -- Institute of Quantum Optics and Quantum Information at the University of Innsbruck
- 2006 -- Waterloo and Massachusetts
- 2007 – Canadian company D-Wave
- 2013 -- Stanford University and IBM Research
- 2013 -- Princeton

1998
Los Alamos and MIT researchers managed to spread a single qubit across three nuclear spins in each molecule of a liquid solution of **alanine** (an amino acid used to analyze quantum state decay) or **trichloroethylene** (a chlorinated hydrocarbon used for quantum error correction) molecules. Spreading out the qubit made it harder to corrupt, allowing researchers to use entanglement to study interactions between states as an indirect method for analyzing the quantum information.
2000
announced the development of a 7-qubit quantum computer within a single drop of liquid. The quantum computer uses nuclear magnetic resonance (NMR) to manipulate particles in the atomic nuclei of molecules of trans-crotonic acid, a simple fluid consisting of molecules made up of six hydrogen and four carbon atoms. magnetic field allow the quantum computer to mimic the information-encoding of bits in digital computers.
Led by Dr. Isaac Chuang, the IBM team was able to solve in one step a mathematical problem that would take conventional computers repeated cycles. The problem, called **order-finding**, involves finding the period of a particular function, a typical aspect of many mathematical problems involved in cryptography.
2001
Scientists from IBM and Stanford University successfully demonstrated **Shor's Algorithm** on a quantum computer. Shor's Algorithm is a method for finding the prime factors of numbers (which plays an intrinsic role in **cryptography**). They used a 7-qubit computer to find the factors of 15. The computer correctly deduced that the prime factors were 3 and 5.
2005
The Institute of Quantum Optics and Quantum Information at the University of Innsbruck announced that scientists had created the first **qubyte**, or series of 8 qubits, using **ion traps**.
2006
Scientists in Waterloo and Massachusetts devised methods for quantum control on a 12-qubit system. Quantum control becomes more complex as systems employ more qubits.
2007
Canadian startup company D-Wave demonstrated a 16-qubit quantum computer. The computer solved a sudoku puzzle and other pattern matching problems. The company claims it will produce practical systems by 2008.
2013
ability to control qubits at room temperature. Until recently, temperatures near absolute zero were required, but new diamond-based materials allow spin qubits to be oper-ated on a table top, at room tempera-ture. (*Sci-ence*, 2013).
The second big development is the ability to con-trol these qubits for several seconds before they lapse into classical behaviorAt Princeton, Lyon and his team demonstrated the control of spin in billions of electrons, a state known as coherence, for several seconds by using highly pure silicon-28.