# Quantum Bit(Qubit) and quantum states

**Quantum Bit or Qubit** is the fundamental unit of quantum information that represents subatomic particles such as atoms, electrons, etc. as a computer's memory while their control mechanisms work as a computer's processor. It can take the value of 0, 1, or both simultaneously. It is a million times more powerful than today's strongest supercomputers. Production and management of qubits are tremendous challenges in the field of engineering. They acquire both, digital as well as analog nature which gives the quantum computer their computational power. Their analog nature indicates that quantum gates have no noise limit and their digital nature provides a norm to recover from this serious weakness. Therefore, the approach of logic gates and abstractions created for classical computing is of no use in quantum computing. Quantum computing may adopt ideas only from classical computing. But this computing needs its own method to overcome the variations of processing and any type of noise. It also needs its own strategy to debug errors and handle defects in design.

Qubit has two quantum states similar to the classical binary states. The qubit can be in either state as well as in the superposed state of both states simultaneously.

There is a representation of these quantum states also known as Dirac notation [6]. In this notation, the state label is kept between two symbols | and ⟩. Therefore,

states are written as |0⟩ and |1⟩ which are literally having analog values and both are participating to give any value between 0 and 1 given that sum of probability of occurrence of each state must be 1.

## Concept of qubit and its properties

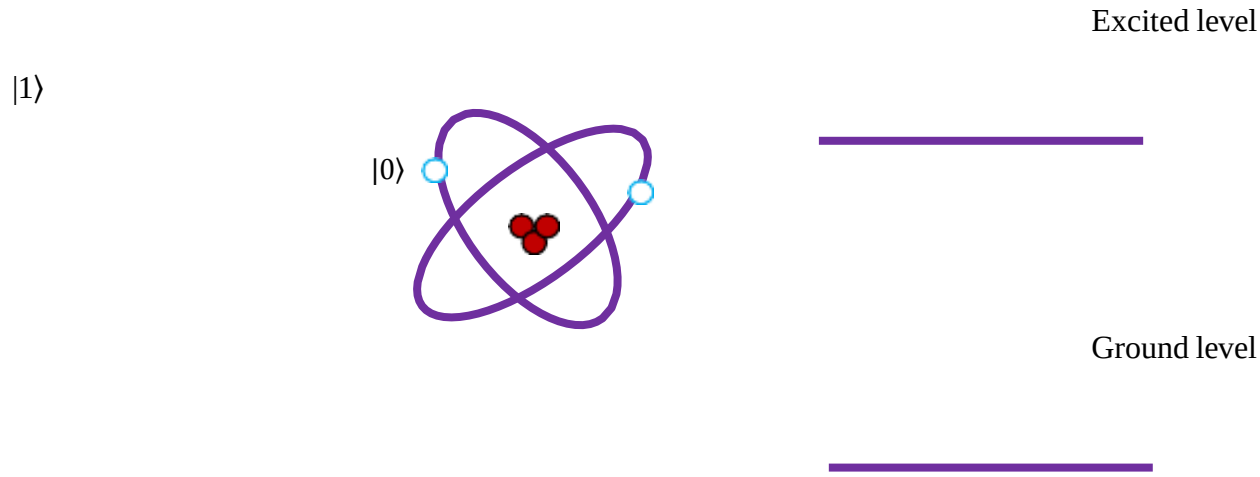
### From bits to qubit

**Bit:** A digital computer stores and processes information using bits, which can be either 0 or 1. In modern computing and communications, bits are represented by the absence or presence of an electrical signal, encoding "0" and "1" respectively

**Qubit** is the physical carrier of quantum information. It is the quantum version of a bit, and its quantum state can be written in terms of two levels, labelled |0⟩ and |1⟩. | ⟩ this notation is known as 'ket' notation and □ | is known as 'brac' notation. Both are together called as **Dirac notations** 'Ket' is analogous to a column vector.

The qubit can be in any one of the two states as well as in the superposed state simultaneously

In quantum computation two distinguishable states of a system are needed to represent a bit of data. For example, two states of an electron orbiting a single atom is shown in the following figure. Spin up is taken as |1⟩ and spin down is taken as |0⟩. Similarly ground state energy level is |0⟩ and excited state level is |1⟩




Qubit represented by two electronic levels in an atom

# Superposition of two states

The difference between qubits and classical bits is that a qubit can be in a linear combination (superposition) of the two states |0⟩ and |1⟩. For ex, if □ and □ are the probability amplitudes of electron in ground state (ie, in |0⟩ state) and in excited state (ie, in |1⟩ state) then the linear combination of two states is

$|\psi\rangle = \alpha |0\rangle + \beta|1\rangle$

The numbers α and β are complex but due to normalization conditions

$|\propto|^2 + |\beta|^2 = 1.$

Here $|\propto|^2$is the probability of finding $|\psi\rangle$ in state |0⟩ and $|\beta|^2$is the probability of finding $|\psi\rangle$ in state |1⟩. So, we have to keep in mind that when a qubit is measured, it only gives either '0' or '1' as the measurement result – probabilistically

This means that with 50% probability the qubit will be found in |0⟩ state as well as in |1⟩ state. The superposed states are also called as **space states** where as |0⟩ and |1⟩ are called **basis states**.

## Properties of qubits

1. Qubits make use of discrete energy state particles such as electrons and photons
2. Qubits exists in two quantum state |0⟩ and |1⟩ or in a linear combination of both states. This is known as superposition. This property allows for *exponentially many logical states* at once (and no classical computer can achieve it)
3. Unlike classical bits, qubit can work with the overlap of both 0 & 1 states. For ex, a 4-bit register[1] can store one number from 0 to 15 (because of $2^n = 2^4$=16), but 4-qubit register can store all 16 numbers
4. When the qubit is measured, it collapses to one of the two basis states |0⟩ or |1⟩
5. Quantum entanglement and quantum tunnelling are two exclusive properties of qubit
6. State of the qubits is represented using Bloch sphere

After studying the physics of qubits it is now time to look at the mathematics of qubits. Let us start with the representation of qubit using Bloch sphere in a vector space. Later on we proceed towards single qubit, multi qubit, tensor operation, operators and matrix representation

expressed as a two-state linear combination each with its own complex coefficient

i.e. $|w\rangle = x\,|0\rangle + y\,|1\rangle$ where x and y are coefficients of both the states. The probabil-ity of the state is directly proportional to the square of the magnitude of its coeffi-cient. $|x|^2$ is the probability of identifying the qubit state 0 and $|y|^2$ is the probability of identifying the qubit state 1. These probabilities when summed up must give a total of 1 or say 100% mathematically, i.e. $|x|^2 + |y|^2 = 1$.

**Understanding qubits**

While quantum technologies do use binary code, the quantum data derived from a quantum system—such as a qubit—encodes data differently from traditional bits, with a few remarkable advantages. Researchers have established various ways to either create qubits or use naturally occurring quantum systems as qubits. However, in nearly all instances, quantum computers require extreme refrigeration to isolate qubits and prevent interference.

Theoretically, any two-level quantum system can be used to make a qubit. A quantum system is described as two-level when certain system properties can be measured in binary positions, such as up or down. Multilevel quantum systems can be used to create qubits when two aspects of that system can be effectively isolated to produce a binary measurement.

Just as traditional computers can use multiple types of bits—such as electrical current, electrical charge or holes punched (or not punched) in a piece of paper for punch-card computing. They rely on different physical representations. Quantum computers, likewise, can use multiple types of bits. Certain bits are better suited to certain functions and an advanced quantum computer will likely use a combination of bit types to achieve different operations.

Because each bit can represent either a 0 or a 1, by pairing two binary digits of information, we can create up to four unique binary combinations:

1. 0 0
2. 0 1
3. 1 0
4. 1 1

While each bit can be either a 0 or a 1, a single qubit can be either a 0, a 1 or a *superposition*. A quantum superposition can be described as both 0 and 1 or as all the possible states between 0–1 because it represents the probability of the qubit's state.

On the quantum level, qubit probability is measured as a wave function. The probability amplitude of a qubit can be used to encode more than one bit of data and perform complex calculations when combined with other qubits.

When processing a complex problem, such as factoring a large prime number, traditional bits become bound up by holding large quantities of information. Quantum bits behave differently. Because qubits can hold a superposition, a quantum computer that uses qubits can calculate a larger volume of data.

As a helpful analogy for understanding bits versus qubits, imagine you are standing in the center of a complicated maze. To escape the maze, a traditional computer must "brute force" the problem, trying every possible combination of paths to find the exit. This kind of computer would use bits to explore new paths and remember which ones are dead ends.

Comparatively, a quantum computer might, figuratively speaking, at once derive a bird's-eye view of the maze, testing multiple paths simultaneously and revealing the correct solution. However, qubits do not "test multiple paths" at once. Instead, quantum computers measure the probability amplitudes of qubits to determine an outcome.

As these amplitudes function like waves, they also overlap and interfere with each other. When asynchronous waves overlap, it effectively eliminates possible solutions to complex problems and the realized coherent wave or waves present the solution.

## What is a Quantum State?

A **quantum state** is the fundamental mathematical description of a physical system in quantum mechanics. It serves as a complete "container" for all the information that can potentially be known about that system, such as its energy, position, momentum, or spin.

In classical computing, the state of a bit is deterministic—it is either a 0 or a 1. In contrast, a **quantum state** is probabilistic. Until it is measured, it exists as a superposition of potential outcomes. Think of a classical state like a coin resting on a table (clearly Heads or Tails), while a quantum state is like a coin spinning in mid-air—it embodies the potential for both outcomes simultaneously, defined by a precise probability distribution.

## Types of Quantum States in a Quantum System

To accurately describe a **quantum system**, physicists categorize states into two primary types depending on how much information is known about the system.

- Pure States: A pure state describes a system where we have perfect knowledge of its quantum wavefunction. It is typically represented by a "ket" vector (e.g., $|\psi\rangle$) in Dirac notation. In quantum computing, ideal operations assume we are manipulating pure states.
- Mixed States: In the real world, systems interact with their environment (noise), leading to a loss of information. A mixed state represents a statistical ensemble of pure states—essentially, we know the system is in one of several states, but we don't know which one. Mixed states are described using a density matrix rather than a simple vector.
- Entangled States: When two or more qubits are linked such that the state of one cannot be described independently of the other, they form an entangled state. This correlation is stronger than anything possible in classical physics and is a key resource for quantum algorithms. (See also: Entanglement)

## Quantum Phase and Its Role in Computation

One of the most critical components of a **quantum state**—and one that has no equivalent in classical logic—is the **quantum phase**.

If we write a qubit's state as $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, the numbers $\alpha$ and $\beta$ are complex numbers. The relationship between them involves a phase angle. While the probabilities of measuring 0 or 1 depend only on the magnitude of these numbers, the *phase* controls how states interfere with one another.

"Quantum algorithms work by manipulating the quantum phase to create constructive interference for the correct answer and destructive interference for wrong answers."

Mastering phase control is essential for high-fidelity operations. If the phase drifts randomly due to environmental noise (dephasing), the computation fails. This is why coherence time is such a vital metric for any **qubit** technology.

## Measuring a Quantum State: Quantum State Tomography

A fundamental rule of quantum mechanics is that you cannot observe a quantum state directly without collapsing it. If you measure a qubit in **superposition**, it snaps to either 0 or 1, destroying the complex quantum information it held.

So, how do researchers verify that they have created the correct state? They use a process called **quantum state tomography**.

Similar to how a medical CT scan builds a 3D image from many 2D X-rays, quantum state tomography reconstructs the quantum state by repeating the same experiment thousands of times. By measuring the system along different axes (X, Y, and Z bases) across many identical runs, researchers can statistically piece together the full density matrix of the system. This technique is crucial for calibrating hardware and verifying gate fidelity.

### Applications of Quantum States in Quantum Computing

The ability to prepare, manipulate, and read out **quantum states** enables all quantum applications.

- **Simulation:** Mapping the quantum state of a molecule onto a quantum computer to predict chemical reaction rates.
- **Optimization:** Encoding a complex logistics problem into the ground state of a Hamiltonian.
- **Cryptography:** Using the "no-cloning theorem"—which states you cannot copy an unknown quantum state—to create unhackable communication channels.

Different hardware approaches face different challenges in preserving these states. For instance, **superconducting qubits** often struggle with short coherence times (states degrade quickly), requiring complex error mitigation.

### The QuEra Angle: High-Fidelity States With Neutral Atoms

At QuEra, we utilize neutral atoms (specifically Rubidium) to define our quantum states. This approach offers distinct advantages for state preparation and preservation:

- **Nature's Perfection:** unlike manufactured circuits where every qubit is slightly different, every Rubidium atom is identical. This allows us to define the **quantum state** with extreme precision using the atom's internal energy levels (Rydberg states).
- **Long Coherence:** Neutral atoms are naturally isolated from the environment. They are not coupled to a noisy solid-state chip, allowing their quantum states to persist for very long durations (seconds), which is orders of magnitude longer than many other modalities.

## properties of quantum computing

In quantum physics, the quantum object does not exist in an entirely determined state. It looks like a particle but behaves like a wave when not being observed. This dual nature of particles leads to interesting physical phenomena. The state of any quantum object is expressed as a sum of possible participating states or a wave-function. Such states are coherent due to the interference of all the participating states either in a constructive or a

destructive manner. Observation of quantum objects when they interact with some larger physical system results in the extraction of information. Such observation of quantum objects is called quantum measurement. Measurement can also result in the loss of information by disrupting the quantum state. These are some of the properties of quantum objects. Quantum objects referred here are the qubits in the case of quantum computing. The progress of any quantum system is regulated by Schrodinger's equation that tells us about the change in the wave-function of the system due to the energy environment. This environment is the system Hamiltonian which is a mathematical description of energies experiencing from all forces felt by all components of the system. To control any quantum system, there is a need to control this environment by isolating the system from the forces of the universe that cannot be controlled easily and by assigning energy within this isolated area only. A system cannot be completely isolated. However, energy and information exchanges can be minimized. This interaction with the outside environment can lead to loss of coherence and can result in "Decoherence"

The properties are the conceptual rules and mathematical manifestations that describe the behavior of the particles. Quantum computers use three fundamental properties of quantum mechanics to store, represent, and perform operations on data in such a way so that it can compute exponentially faster than any classical computer. The three properties are given as follows

## Superposition

Superposition in quantum mechanics states that any two quantum states can be summed up (superposed) resulting in another valid quantum state. It is a fundamental principle of quantum mechanics. Oppositely we can say that any quantum state is the sum of two or more than two other unique states.

Superposition in quantum computing refers to the ability of a quantum system where quantum particle or qubit can exist in two different positions or say, in multiple states at the same time. It provides high-speed parallel processing in an unbelievable way and is very different from their classical equivalents that have binary constraints. The quantum computer system holds the information that exists in two states simultaneously. Qubits are brought into a superposition by influencing them with the help of lasers so that it can simultaneously store 0 and 1 at the same time. In classical computing, if there are 2 bits, the total possible values after combining we get are 4, out of which only 1 value is possible at any instant. But on the other hand, if there are 2 qubits in the quantum computer. The total possible values after combination are 4 and all are possible at once. It looks like unthinkable

because it is not like gravity that can be proved easily just by looking at the falling of an apple. The laws of classical physics fail here because superposition only exists in the territory of quantum particles.
For example, when solving a puzzle-like maze, a quantum particle can decide to take the various paths at the same time using superposition. This process matches the function of the parallel computer. Due to this property, the qubit is able to navigate the maze in exponentially less time than a classical bit.

## Entanglement

Entanglement in quantum mechanics is a physical phenomenon where two or more quantum objects are inherently linked such that measurement of one rules the possible measurement of another. In other words, a pair or a group of particles interacts or share spatial locality such that the quantum state of each particle cannot be characterized independently of the other particle's state in the same group even when they are separated by a large distance

Entanglement is one of the important properties of quantum computing. It refers to the strong correlation existing between two quantum particles (physical proper-ties of systems) or qubits. Qubits are linked together in a perfect instantaneous connection, even if they are isolated at any large distances such as located at the opposite ends of the Universe. They are entangled or defined with reference to each other. The fact is that the state of one particle influences the state of the other. It creates strong communication between qubits. Once they got entangled, they will stay connected even after separated at any distance. In classical computers, if bits are doubled, computational power also gets doubled. But in the case of Entanglement, adding extra bits to a quantum computer can increase its computational power exponentially.
Quantum computer uses this property in a sort of quantum daisy chain.

Some examples of entanglement can be seen in nature such as electrons separated from each other at some distance inside an electron cloud are massively entangled with one another. If one electron is at both the states of spin-up and spin-down with each state having a probability of ½, a similar case is with the other electron.