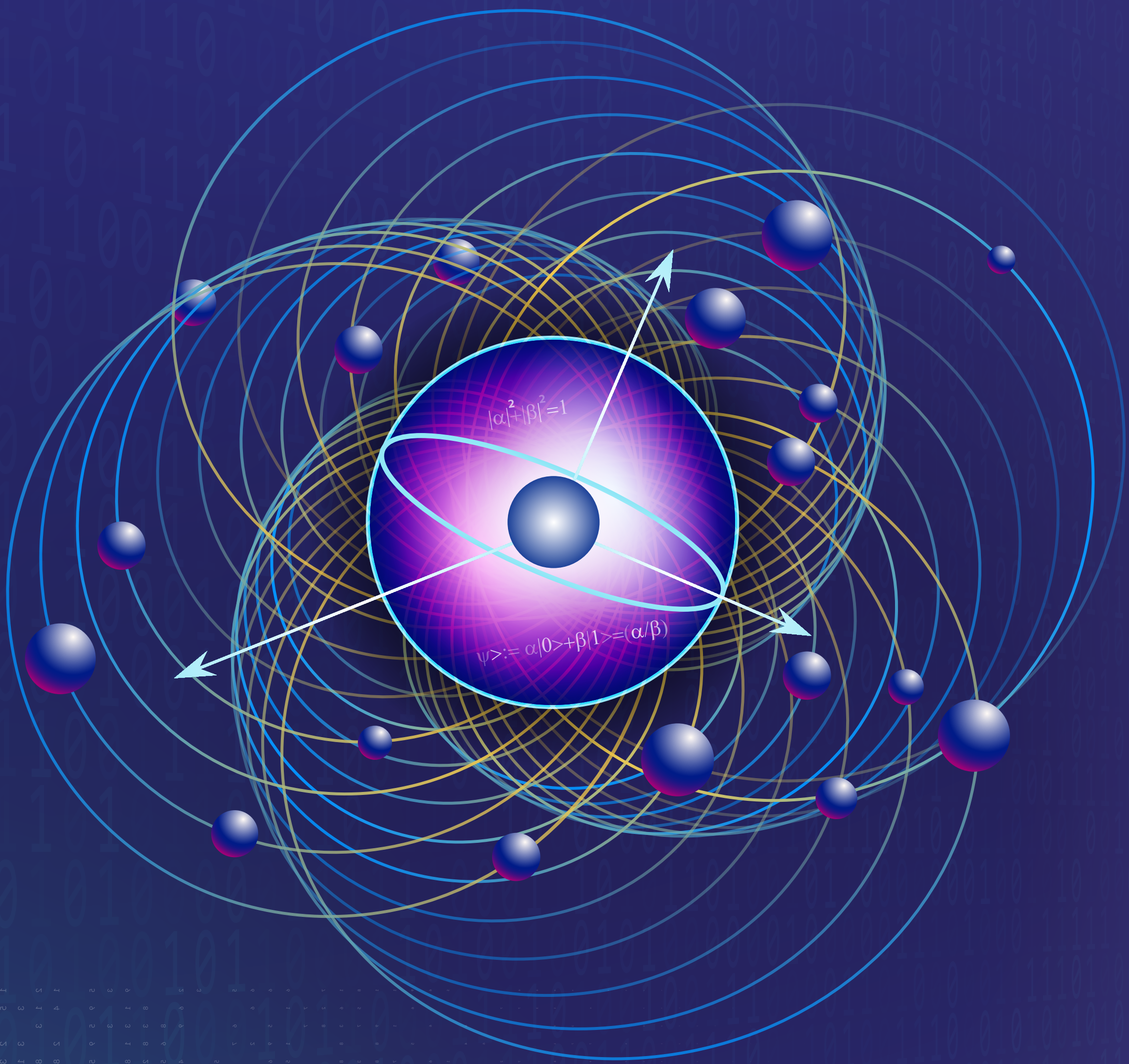
Ready-to-run
Quantum Software



Qubits

The Heart of Quantum Computing

Quantum Computing Inc. | (703) 436-2161 | quantumcomputinginc.com

Quantum Computing and the Qubit

A quantum computer performs quantum computations using the principles of quantum mechanics. The quantum processing units (QPUs) manipulate the quantum states of qubits in a controlled way to perform computations, such as algorithms.

A qubit is a quantum bit of information. It's typically created by a particle that demonstrates the properties of quantum mechanics, versus the Newtonian deterministic physical laws that define our world. So qubits come in particles like electrons, neutrons, photons and ions versus apples, bears or cars.

The qubit can be viewed as the heart of quantum computers. It is the quantum mechanical version of a classical bit. A qubit is a two-state (or two-level) quantum-mechanical system, one of the simplest quantum systems displaying the peculiarity of quantum mechanics.

Yes, I said it can exist in two states. As one of our lead quantum experts says, "Qubits have unique personalities and they are feisty." Two-states is just one example of that.

The All Powerful Qubit

The ability of a qubit to represent quantum mechanics principles is what gives quantum computing its power.

Let's take a look at the principle of Superposition first.

In classical computing, data is encoded in bits, where each bit can have the value zero or one. In quantum computing, the data is encoded in qubits, with each qubit able to be encoded as both 0 and 1, or in a linear combination of both states. This is the phenomenon known as superposition.

That's a hard one to wrap your head around. Here's a simple real world corollary.

In our everyday world, a coin facing up has a known state: a head or a tail. You don't have to flip the coin over to know that it has both states. In quantum computing, the situation is similar; the material properties of things (qubits) do not exist until they are measured. Until you "look" (measure the particular property) at the coin, as it were, it has no fixed face up. Yet it's known to be in two states.

Now let's apply this to quantum superposition. In quantum physics, electrons demonstrate a quantum feature called spin, a type of intrinsic momentum. In the presence of a force (aka a magnetic field, laser beam etc.,) the electron may exist in two possible spin states, usually referred to as spin up and spin down. Each electron, until it is measured, will have a finite chance of being in either state. Only when measured is it observed to be in a specific spin state. The potential is always there for both states.

Superposition is what makes quantum computers operate as parallelized systems. That's why a quantum computer can work on a million computations at once, while your desktop PC works on one.

Now let's look at the quantum principle of entanglement.

Qubits are extremely sensitive to measurement.

- When you measure the state of a classical bit electronically, you do not disturb its state. It remains coherent and continues to process.
- When you attempt to measure a qubit directly, it loses its coherence and disrupts the state of superposition. It literally dissipates. That's not too useful if you can't measure the value.

Entanglement is used in two ways in Quantum Computing: entanglement with the measurement apparatus (for the final readout, this is the way quantum scientists are able to measure qubits indirectly) and entanglement with other qubits (to perform non-linear i.e., useful computations.)

While the term seems complex, it's really not if you start with a simpler example.

Take a set of square and round pegs. They can be independent, or entangled.

Independent

- Imagine that these square and round pegs always come in pairs, and that they can be combined in any fashion.
- That gives us 4 possible outcomes: Square and Square, Round and Round, Round and Square, Square and Round.
- The pegs are said to be "independent" if knowing the "state" of the first peg in no way gives us any information about the state of the second peg.
- In this example, the statistical chance of all four options is equal - 25%. So they are independent.

Entangled

- With the same pegs, imagine now that they have to be in the same combination of two pegs; square and square, round and round.
- In this case, the pegs are said to be "entangled" because information about one gives us information about the other.

- We therefore know that if the first peg is round, the 2nd MUST be round. And the same with squares.

In the quantum computing world, independent states are known to be rare exceptions. Whenever particles interact, the interaction naturally creates correlations between them. Here's why.

- In quantum physics, if you apply an outside "force" (aka an electromagnetic field, laser etc.) to two atoms (aka qubits), it can cause them to become entangled.
- The second atom can take on the properties of the first atom.
- The instant it is disturbed, it chooses one spin, or one value; and at the same time, the second entangled atom will choose a spin direction that is consistent with the way they are entangled.

This behavior allows us to know the value, or state, of the qubits without actually looking at them. This behavior is also how quantum computers are able to process extremely complex computations and simulations, providing a diversity, or range, of results. This is also where the challenge of scaling quantum computing (aka the number of qubits) lies. We have to be able to isolate our fragile qubits from unwanted entanglement with the surrounding (noise) e.g., a microwave warming a pizza next door.

As you can see, qubits are quite powerful and picky, yet have the potential to change the way we simulate and process our information, and our world.

The Many Faces of a Qubit

There are a variety of qubit types that are coming into the market, as quantum computing vendors explore various technologies to exploit the full force of quantum mechanics for our complex computations and simulations.

Is there a Standard Qubit?

Not today. Physically, qubits can be any two-level system. For example, the polarization of a proton, or the spin of an electron.

Early quantum hardware vendors have implemented qubits in several physical representations, each seeking to identify the best qubit for solving problems with scale and accuracy. Some use semiconductors, other electrons or atoms (ions), still others use light or photons. Some of these qubits require supercooled environments and complete isolation, others work at room temperature and are less finicky.

The Holy Grail is to define the best qubit for processing complex problems, a qubit which can be connected to scale up to be able to solve large production problems. The challenge then becomes how to scale with accuracy - since scaling qubits results in noise and more errors, in some qubit types. Some are limited in scale due to their connections with other qubits, some by the noise they create, other simply because of the architecture that is used to connect subsets of qubits, missing full connectivity.

The jury is still out on which qubit, or qubits, will be the ultimate winner. Many believe that different qubits will become the defacto standard for different problem types. The reality is, we still don't have the answers. But we do have a variety of powerful options.

Types of Qubits Available Today

We are currently in what's known as **noisy intermediate-scale quantum (NISQ) era.** What does that mean, other than we are in the early stages of quantum computing and have so many more amazing innovations to come?

- Noisy refers to the current state of quantum processors. They are very sensitive to the world around them and easily experience decoherence (aka the qubit gradually loses the quantum information it encodes.) They also aren't mature enough to include error correction.

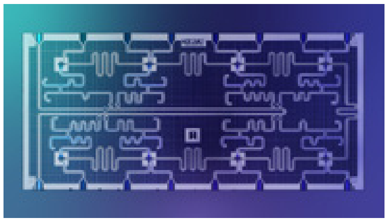
- Intermediate-scale refers to the volume of qubits that they can connect and use, which as of today ranges from 50 to ~150 qubits.

Several types of qubits are in the market today. These innovative approaches to implementing quantum mechanics within a qubit are all part of the exploration of quantum computing to better understand which implementations will best deliver results for specific use cases.

What are the leading Qubit types as of today?

Superconducting Qubits, or Transmons

These qubits, made from superconducting electrical circuits, are already in use in early stage NISC quantum computers made by Google, IBM, and others.



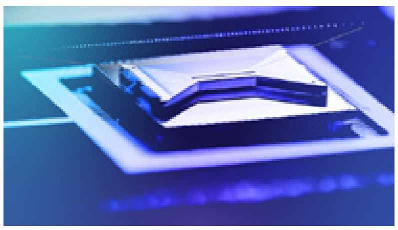
A **superconductor** is a material that changes from a normal state when it is cooled to a superconducting state where there is essentially no resistance to the flow of direct electrical current. This behavior makes superconductors an option for qubits in quantum computing.

Advantages: Superconducting qubits demonstrate fast operation times, meaning computations can be performed faster than on other qubits. This is important since quantum computations may have millions of operations that require speed. Another benefit is that superconducting qubits take advantage of existing printable circuit processes that are efficient and available. It's the most straightforward approach to creating a quantum computer than with other, more innovation-driven, methods.

Disadvantages: Superconducting qubits quickly experience decoherence. They are very short-lived and therefore demand **error correction techniques**. Superconducting qubits are connected to the qubits next to them, limiting the size and depth of the circuit that can be run. They only operate in very cold environments, (below 100mK, or 0.1 degrees above absolute zero.) Anyone who remembers chilled mainframe rooms will also remember the cost and complexity of building and maintaining such cold environments. Finally, due to fabrication, each superconducting qubit is different from others and therefore requires continuous calibration for operations.

Trapped Atoms and Ions

When atoms, or charged atoms (ions) are trapped in place by lasers they behave as qubits. Quantum computing companies with ion trap qubits include Ion Q, Alpine Quantum Technologies (AQT,) Eleqtron, and Quantiniuum.



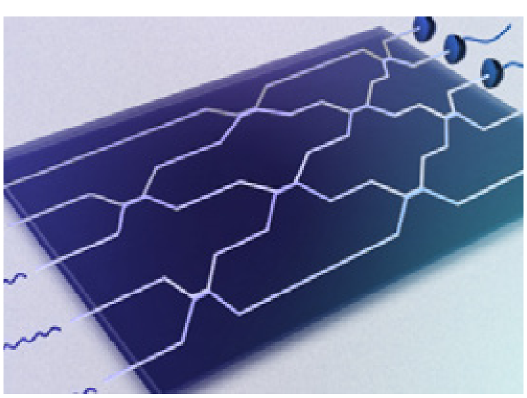
Ion trap qubits literally trap ions (charged atoms) using magnetic fields and hold them in place. The outermost particle, an electron, orbiting the nucleus demonstrates superposition and can be used as a qubit. Trapped ion qubits encode quantum information in the electronic energy levels of ions as they are suspended in vacuum.

Advantages: Ion traps are more stable than other qubits; the qubits display a significantly longer time to decoherence than seen in superconducting qubits. An ion trap can operate at room temperature, although users will find better performance if the ions are cooled to somewhere around 4K, which is much easier to maintain than superconducting qubits. Ion trap quantum computers are also reconfigurable, meaning individual qubits interact with other qubits in the QPU.

Disadvantages: Ion trap computers were previously benchmarked to be slower than their superconducting counterparts. Recent benchmarks suggest that disadvantage is becoming an advantage as we speak. Then there's the vacuum required to hold, or trap, the ions. This technology is not as mature as fabricating superconductors.

Photonic Qubits

Photonic qubits use particles of light to carry and process information. Xanadu and PsiQuantum are developing a unique type of quantum computer, based on photonics.



Linear Optical Quantum Computing or Linear Optics Quantum Computation (LOQC) represents the common approach to photonic quantum computing. It relies on qubits that are individually based on a single photon. The computer manipulates the photons with mirrors, beam splitters, and phase shifters. Single photon detectors read the results. The problem is that single photons are difficult to experiment with, generally limiting this strategy to a handful of photons.

Xanadu is taking the next step beyond employing a single photon generator. Instead, the Xanadu quantum system relies on so-called “squeezed states” which are comprised of multiple photons in superposition.

Squeezed states take advantage of Heisenberg’s uncertainty principle, which states you cannot measure a feature of a particle, such as its position, with certainty without measuring another feature of that particle, like its momentum, with less certainty. Squeezed states take advantage of this tradeoff to “squeeze” or reduce the uncertainty in the measurements of a given variable while increasing the uncertainty in the measurement of another variable the researchers can ignore.

Advantages: Photonic qubits can operate at room temperature. Photons are also much less sensitive to their environment, which means they can retain their quantum state for much longer and over long distances. They also easily integrate into existing optical—based infrastructures. This holds the potential to connect multiple QPUs together over networks. Using a “multiplexing” approach, photonic quantum computers can theoretically scale to millions of qubits and beyond.

Disadvantages: Photonic qubits are emerging in the quantum computing market. While individual quantum “logic gates” for photons exist, a challenge is to construct large numbers of gates and connect them in a reliable fashion to perform complex calculations. Innovations in the market appear to be addressing this challenge.

The Bottom Line

Quantum computing is in an exciting stage of its evolution. There are so many exciting and powerful applications and opportunities to be explored.

The qubit is the heart of a quantum computer, the component that brings the laws of quantum mechanics to bear on the complex challenges of our society, for business, health, environment, government and more.

The variety of options is exciting. As we move forward, we’ll have the opportunity to explore these and potentially new innovations, all with the potential to change the way we think, make decisions and act. Not to mention discovering new ways of thinking and exploring that expand our business and personal worlds.

Here’s to the mighty qubit for bringing these opportunities to us, in all its forms!