The Quantum Leap
June 23, 2023

The Quantum Leap's Beginner Guide to "Qubits"

This is the second in a planned series of "Quantum Leap Beginner Guides", aimed at audiences without physics training and using only the most basic math (and even then, only when necessary). The first post in this series described "Quantum" (see it here) and today's post will cover "Qubits".

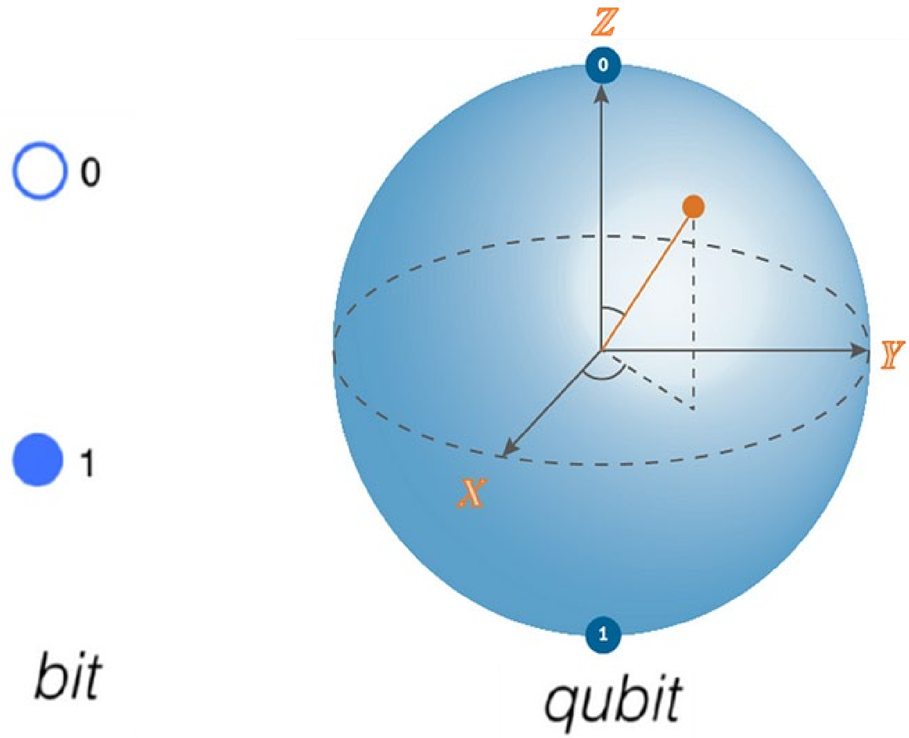
What is a Qubit?

Classical computers use "binary digits" more commonly known as "bits" as their most fundamental processing unit. A bit is simply an "on-off" switch taking one of two states…it is either "on" or it is "off", so it is referred to as a binary system.

Each bit on a computer is measured by electricity flow on tiny switches called transistors (ultimately replaced by integrated circuits). I am writing this on a Dell OptiPlex which has 64 GB of operating memory, meaning there are 64 billion bytes. Each byte is comprised of 8 bits, so my computer has 512 billion individual on-off switches. Wow, that's a lot! As readers know, today's personal computers are extremely powerful, fast and can do amazing things like stream high-definition video, browse the Internet and process complex spreadsheets among other functions.

Quantum bits, commonly referred to as "qubits," are quantum's most fundament processing unit but are quite different from bits, with the primary difference being that qubits are 3- dimensional objects. This can be seen in the picture below with a classical bit represented on the left, showing only two possible states, and a qubit on the right with the orange dot depicting the state of the qubit. It may help to imagine that the qubit is a globe where "0" represents the North Pole and "1" represents the South Pole. The qubit value can be any location anywhere on the surface of the globe and its position can be described as a combination of its three spatial dimensions (X, Y and Z).

While the graphic on the right may seem a bit daunting with the various dotted lines and angles drawn in, don't let that intimidate you. It simply indicates the three-dimensionality of the qubit (and for those familiar with trigonometry, suggests there are basic formulas to describe the specific orientation of the qubit at a given moment).



How are Qubits Made?

There are a variety of current modalities for making qubits, but they are generally comprised of one of three fundamental particles: either atoms, photons or electrons. Each of these particles has binary properties which can be measured, such as "spin-up" or "spin-down" of an electron or "left" or "right" polarization of a photon. Atomic qubits are generally one of two types, either "trapped ions" or "neutral atoms". In both cases, individual atoms are isolated and oriented and lasers are used to nudge the atoms. Photonic qubits, as the name suggests, use photons as their fundamental unit and electrons are used via a number of modalities including superconducting (which uses cryogenics to induce quantum properties along a circuit loop), quantum dots (which uses electrons trapped in a semiconductor), and NV Centers (where electrons are trapped in the cavity of a diamond crystal). There are at least seven broad types of qubits currently in use by over 100 different companies and academic institutions with various pros and cons among them. The table below provides a representative overview of the current qubit landscape:

Qubit Type	Sub-Category	Core Modality	Select Players
Atom	Trapped Ion	Ions carry charges which are used to isolate the atoms	IonQ; Quantinuum; AQT; Oxford Ionics; Universal Quantum
	Neutral Atom	Lasers are used to trap and thereby cool the atoms	Infleqtion; Atom Computing; QuEra; Pasqal; planc
Electron	Superconducting	Cryogenics enable Josephson Junctions to circulate electrons	Rigetti; Google; IBM; QuTech; IQM; QCI
	Quantum Dot	Electrons trapped in a semiconductor	Intel; Origin; SQC; dirac; Quantum Motion
	NV Center	Designed faults in diamonds isolate electrons	Quantum Brilliance
	Topological	Quasi-particles in superconducting nanowires	Microsoft
Photon	Photonic	Photons circulating in waveguides	PsiQuantum; ORCA; Xanadu; Quandela;

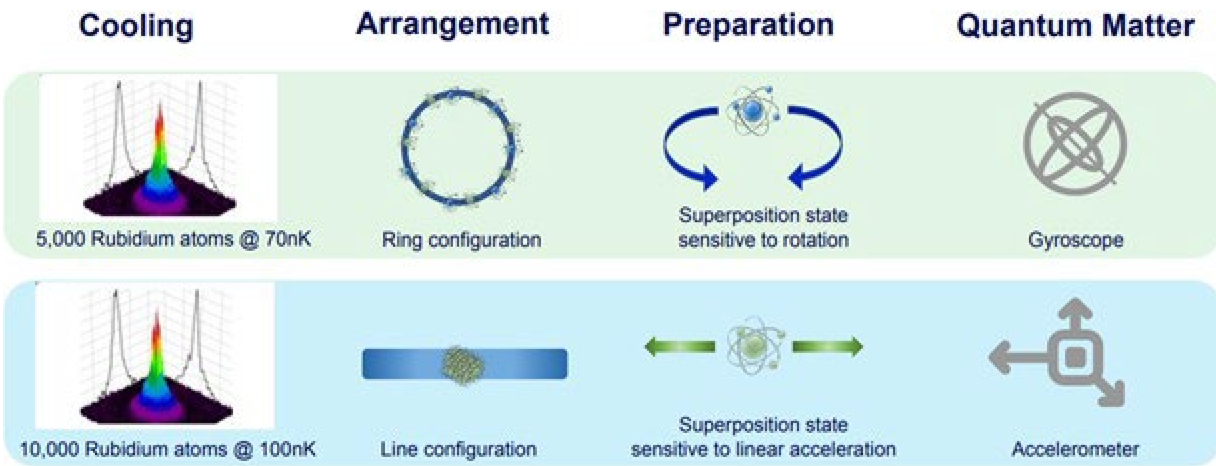
The above chart is not meant to be all-inclusive. In fact, the tracks over 130 organizations pursuing 169 different qubit projects.

What can Qubits be Used For?

Today, these qubits generally have two broad use cases: Sensors and Computers.

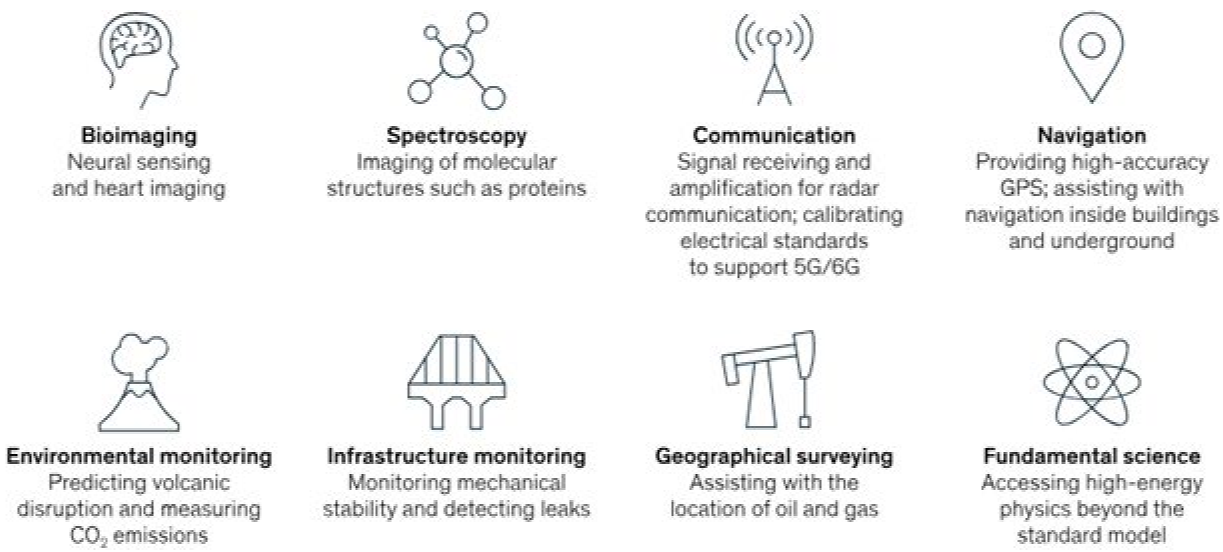
As previously described, the creation of a qubit involves exquisite control. Recall that the companies noted in the chart above are isolating individual fundamental particles, often “freezing” them in place and then controlling, manipulating, and measuring them.

Accordingly, these particles are extremely sensitive to any and all environmental inputs including gravity, vibrations, electromagnetism, temperature fluctuations and even interference from subatomic particles from outer space. This ultra-vulnerability to external forces makes qubits particularly powerful sensors. The graphic below depicts two examples of how these ultra-sensitive qubits (in this case, neutral rubidium atoms) can be arranged in certain geometries which can then sense the most minute changes in things like rotation or acceleration.



Source: Infleqtion (f/k/a ColdQuanta)

McKinsey & Company has described eight applications where quantum sensing has distinct advantages over alternative technologies as highlighted below:



In order to make quantum computers functional, a number of qubits must be arranged in a coordinated fashion, so that various quantum computer programs (or algorithms) can be executed. Because of some of the principles of quantum mechanics such as “superposition”, “entanglement”, and “wave-particle duality” [these properties will be described in future Quantum Leap Beginner Guides], phenomenally powerful quantum computers could be created with a relatively modest number of qubits if the qubits could be sufficiently controlled, made immune to environmental disruptions, and made to all interact will each other.

However, because of the sensitivity of the qubits to environmental “noise”, today’s quantum computers are generally referred to as “NISQ” meaning “noisy intermediate-scale quantum”. In this NISQ era various noise suppression techniques are being developed, generally using many of the qubits for noise reduction overhead as opposed to computational power.

Therefore, today's quantum computers have modest capabilities although advances in noise- suppression techniques as well as ever-increasing numbers of qubits suggest that quantum computing power can begin surpassing that of classical computers in the next few years.

Summary

As we learn to tame the quantum properties of elementary particles, we are finding that profound new things can be done including the creation of ultra-powerful sensors and computers. Given that these advances represent entirely new paradigms, it is daunting to follow and understand the developments. In coming posts, I hope to further describe and explain some of the fundamental properties and use-cases in ways that all readers can understand and appreciate. Stay tuned to the next few Quantum Leap Beginner Guides where I will describe Superposition, Entanglement and Wave-Particle Duality and explain why taming these quantum principles can yield profound new powers.

References:

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Batra, Gschwendtner, Ostojic, Queirolo, Soller and Wester, "Shaping the long race in quantum communication and quantum sensing", McKinsey & Company, December 21, 2021.

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