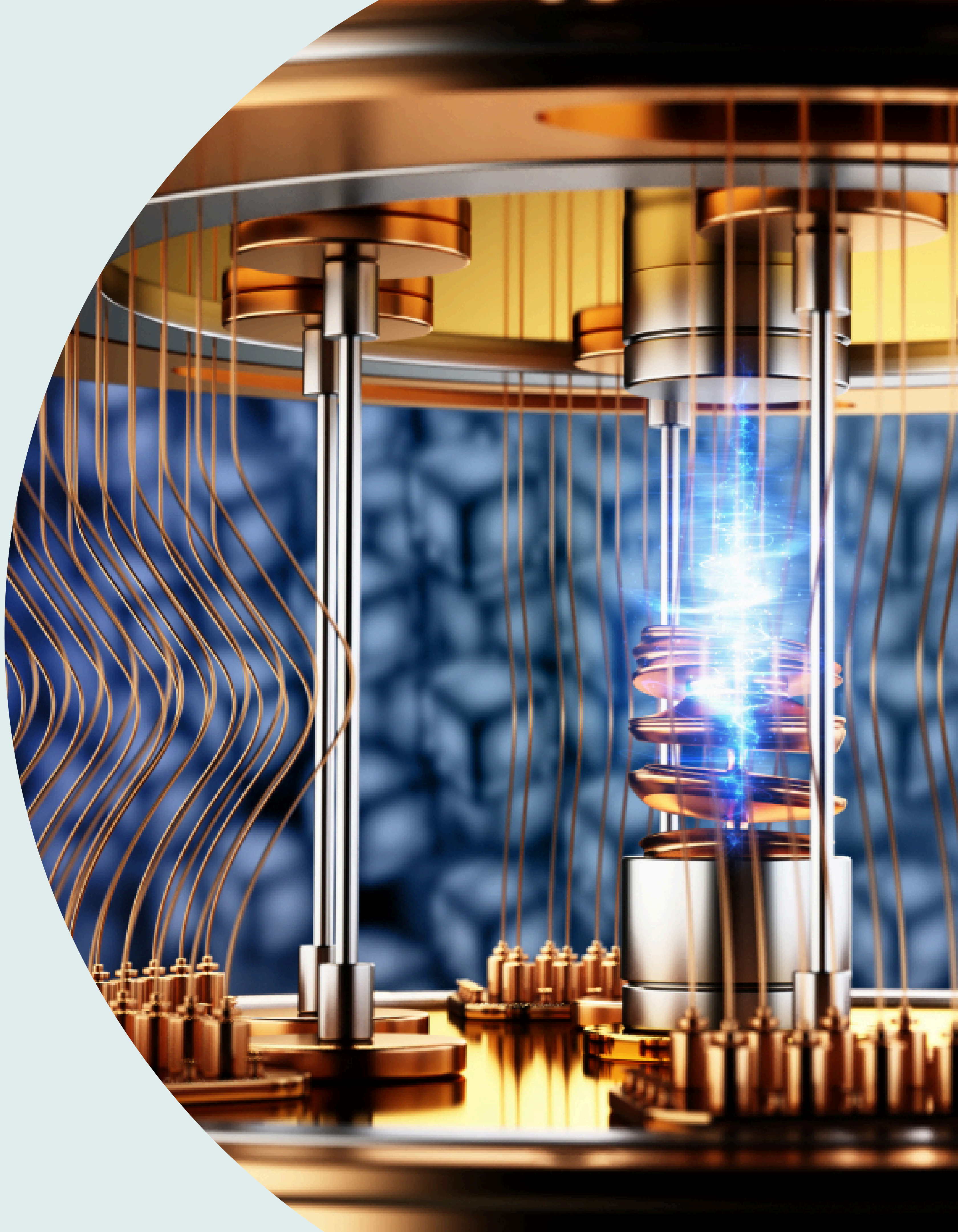
MODULE 1 : INTRODUCTION TO QUANTUM COMPUTING



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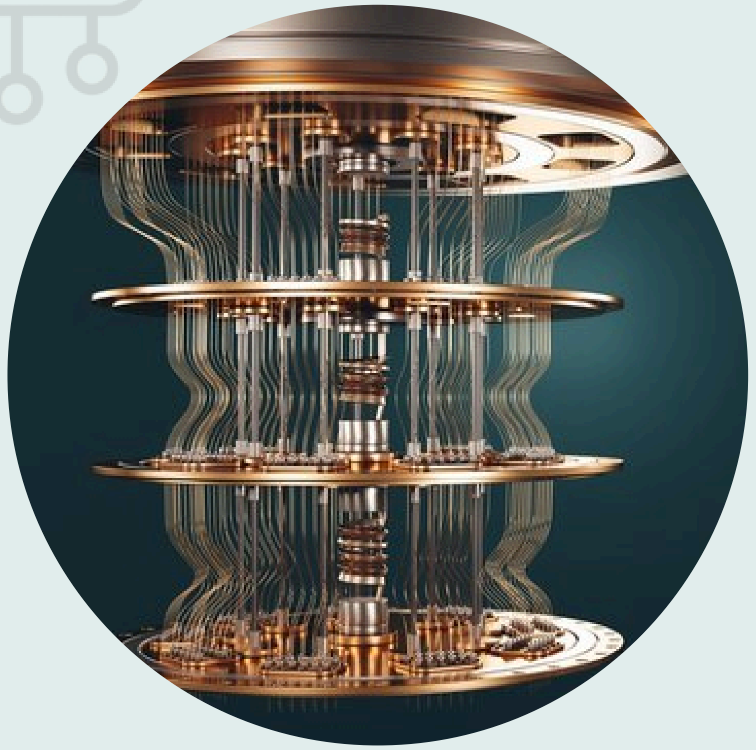
1.1 What is Quantum Computing?



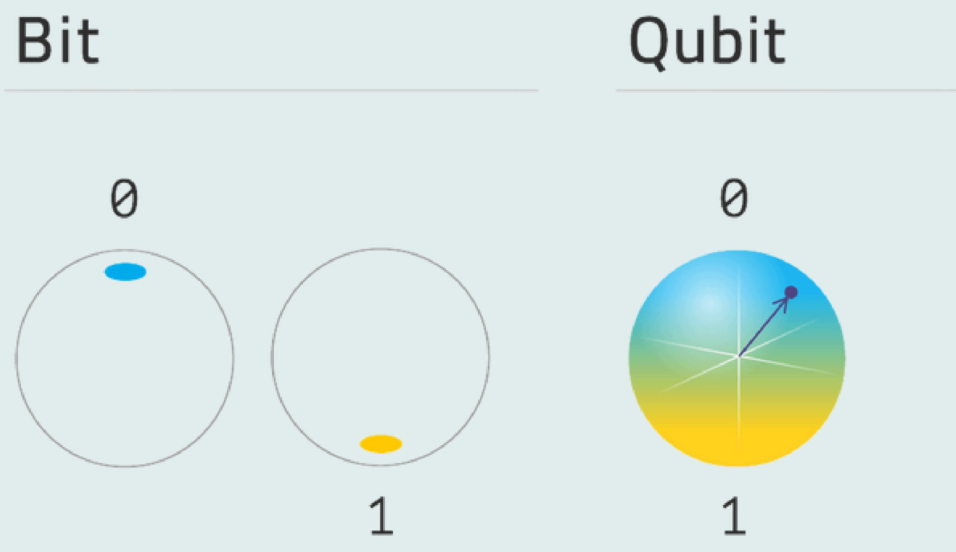
Quantum computing is an emergent field of cutting-edge computer science harnessing the unique qualities of quantum mechanics to solve problems beyond the ability of even the most powerful classical computers.

Quantum Building Blocks

Quantum Bit(Qubit):

A qubit is the basic unit of information in quantum computing, just like a bit is in classical computing.
Unlike classical bits, qubits can exist in multiple states simultaneously.
The Measurement collapses a qubit to $|0\rangle$ or $|1\rangle$.

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



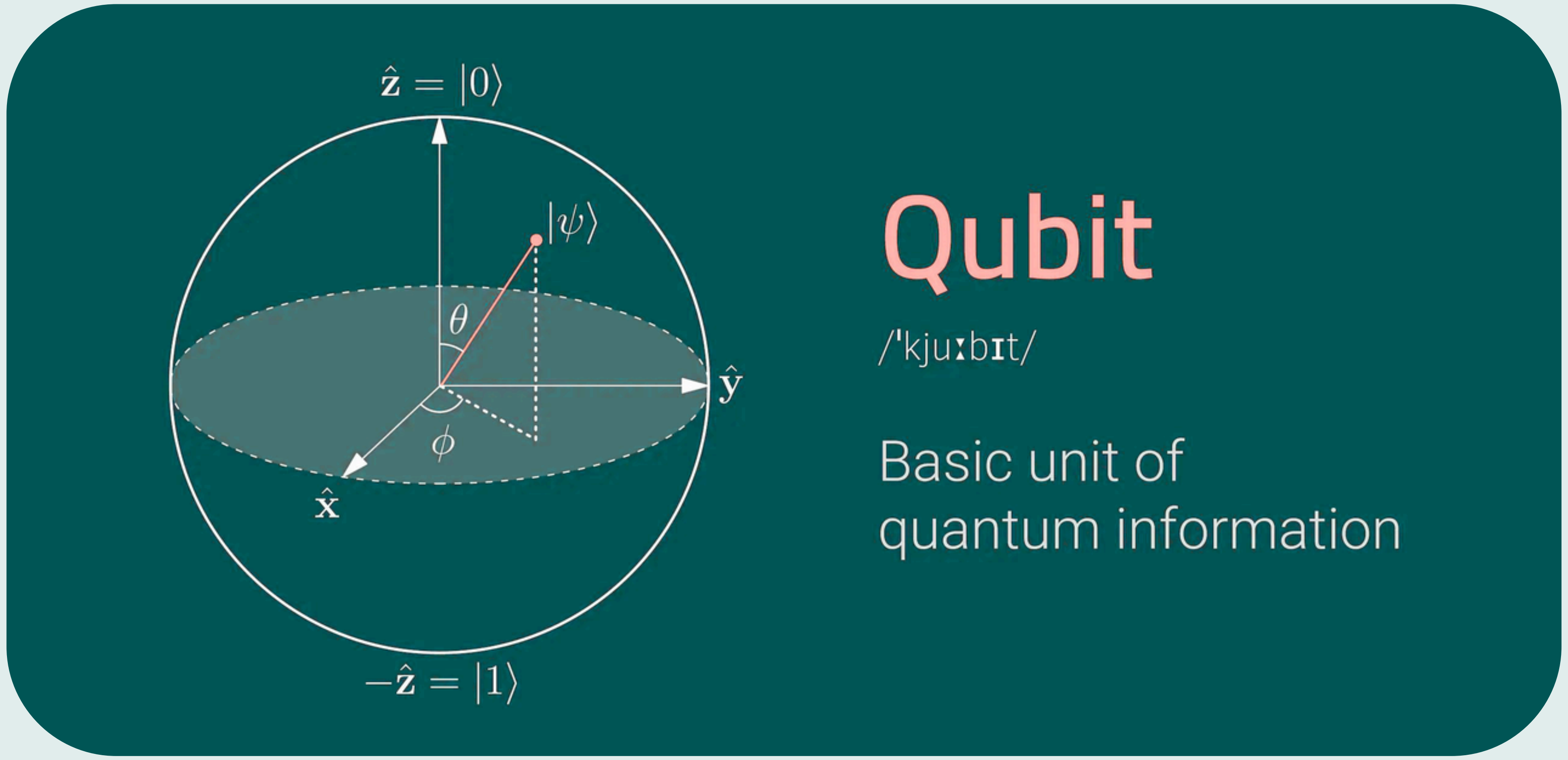
Key Properties:

Superposition: Qubits can be in a mix of states, allowing multiple computations at once.

Entanglement: Qubits can become linked so that the state of one instantly affects the other.

Measurement: Measuring a qubit collapses its state to either $|0\rangle$ or $|1\rangle$, probabilistically based on $|\alpha|^2$ and $|\beta|^2$.

Quantum Gates: Qubits are manipulated using quantum gates like Hadamard, Pauli-X, etc.



Computational Basis:

The computational basis is the standard basis used to describe quantum states of qubits. It's directly analogous to how binary (0 and 1) is used in classical computing.

$$|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \quad |1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

Multiple Qubits:

Multiple qubits, or multi-qubit systems, are essential for quantum computing because they enable quantum entanglement and allow for complex computations that classical computers cannot perform efficiently. These systems are represented using tensor products and allow for the creation of entangled states, which are crucial for various quantum algorithms

A few of the more common types of qubits in use are as follows:

Superconducting qubits: Fast, controllable qubits made from superconductors at ultra-low temperatures.

Trapped ion qubits: Ions held in place, offering long coherence and high measurement accuracy.

Quantum dots: Semiconductor-based qubits using single electrons; good for scaling.

Photons: Light particles used for long-distance quantum communication.

Neutral atoms: Laser-controlled atoms, suitable for scalable quantum systems.

1.2 What is Qubit State Space & Why Qubit State Space is 4D?

What is Qubit State Space?

The qubit state space is the mathematical space that contains all possible states a qubit can be in.
A qubit is a quantum bit that can exist in a superposition of the classical bit values 0 and 1. Its general state can be written as:

- 1 qubit → state in a 2D space: $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$
- 2 qubits → state in 4D space: $|\psi\rangle = \alpha_{00}|00\rangle + \alpha_{01}|01\rangle + \alpha_{10}|10\rangle + \alpha_{11}|11\rangle$
- n qubits → state in 2^n D space: $|\psi\rangle = \sum_{i=0}^{2^n-1} \alpha_i|i\rangle$, where $\sum |\alpha_i|^2 = 1$

Why Qubit State Space is 4D?

Even though a qubit is described using 2 complex numbers (α,β), each complex number has two real parts (real and imaginary).

- $\alpha = a_1 + i b_1$
- $\beta = a_2 + i b_2$

There are total of four Real Numbers.

$(a_1, a_2, b_1, b_2) \Rightarrow$ 4D real space $\mathbf{R}^4$

1.3 Classical vs Super vs Quantum Computing

Category	Classical computing	Super computing	Quantum computing
Unit of Information:	Bits	Bits	Qubits(Quantum Bits)
Possible States:	Discrete (0 or 1)	Discrete (0 or 1)	0, 1 or superposition (any proportion of 0 and 1)
Calculations:	Deterministic (same input always equals same output)	Deterministic (same input always equals same output)	Deterministic (same input always equals same output)
Operations:	Boolean algebra	Boolean algebra	Linear algebra over Hilbert space
Processors:	One to Several	Thousands to millions	One

1.4 History of Quantum Computing

History:

1981

Richard Feynman proposed quantum computers to simulate quantum systems, which classical computers couldn't handle efficiently.

1994

Peter Shor developed Shor'salgorithm, showing quantum computers could factor large numbers exponentially faster,threatening RSA encryption.

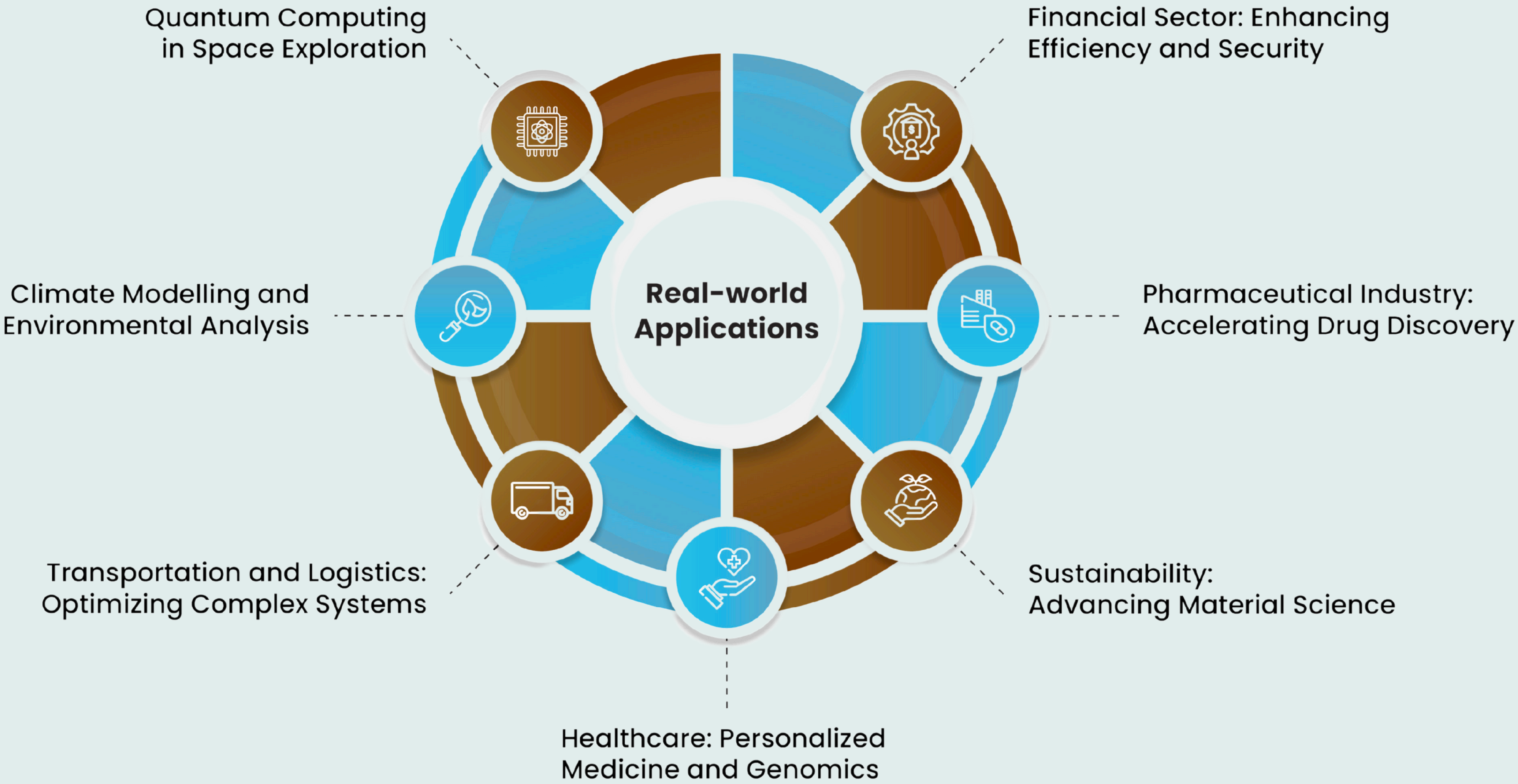
2019

Google claimed "quantum supremacy" with its Sycamore processor, solving a specific problem faster than any classical supercomputer.

2020s

IBM, Microsoft, and others advance quantum hardware and software, making quantum computing more accessible.

Quantum Computing's Real-world Applications



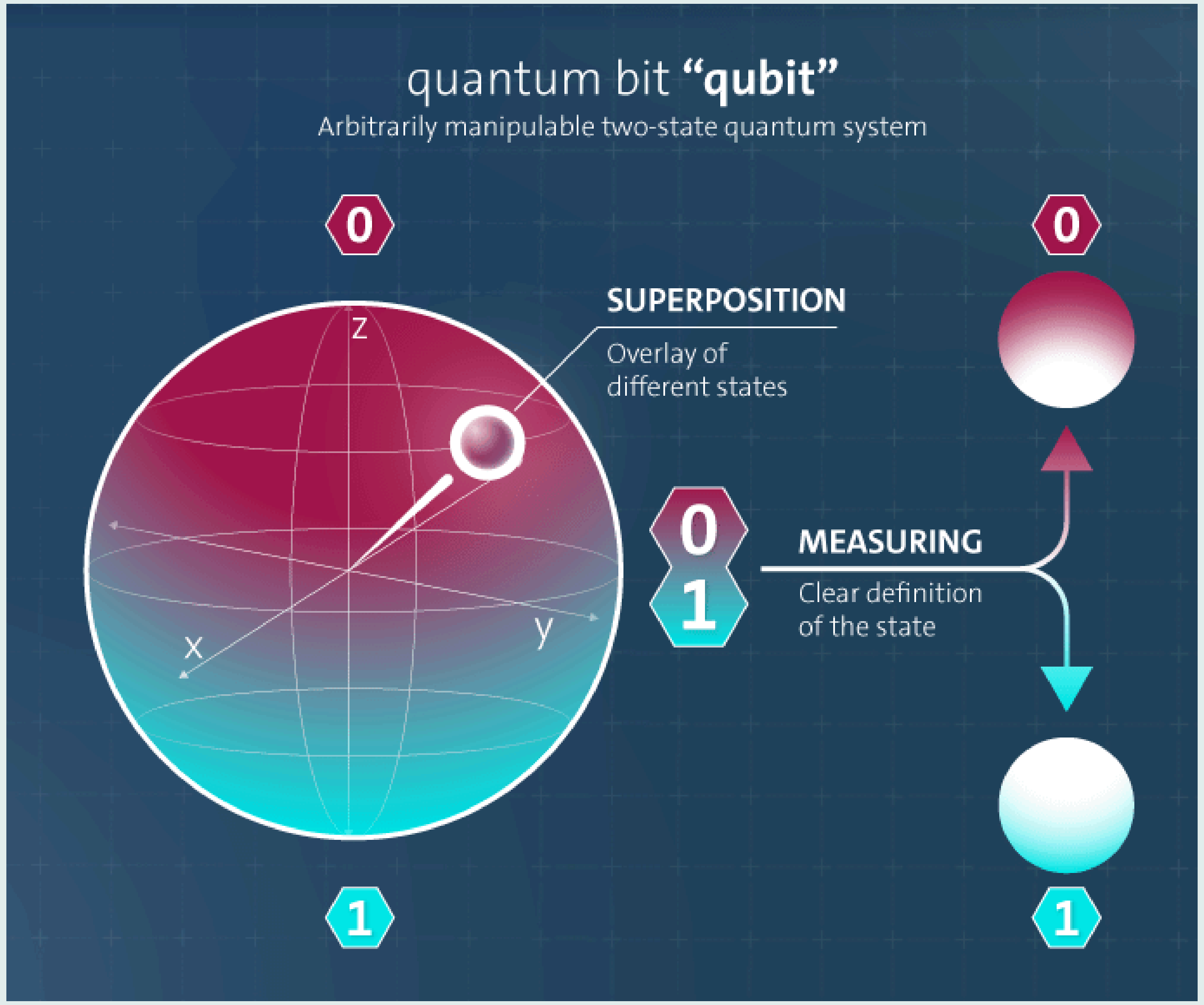
1.5 Basic Concepts: Superposition

Definition:

Superposition is the state in which a quantum particle or system can represent not just one possibility, but a combination of multiple possibilities.

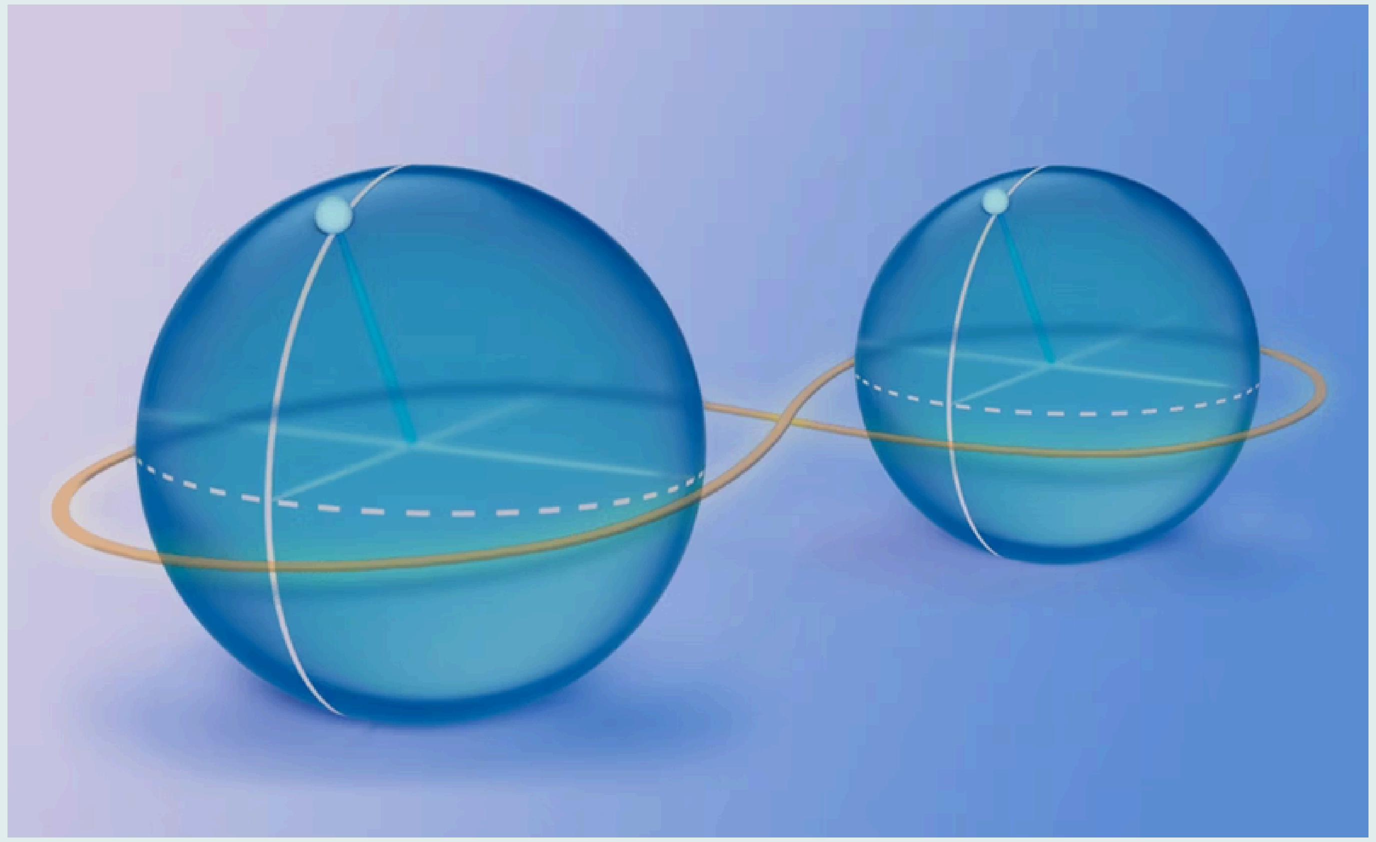
It allows quantum computers to evaluate multiple outcomes simultaneously, enabling faster problem-solving through quantum parallelism.

Example: A qubit in state $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, where α and β are complex numbers and $|\alpha|^2 + |\beta|^2 = 1$, represents a superposition of heads (0) and tails (1).



Entanglement

Entanglement is the ability of qubits to correlate their state with other qubits. Entangled systems are so intrinsically linked that when quantum processors measure a single entangled qubit, they can immediately determine information about other qubits in the entangled system.

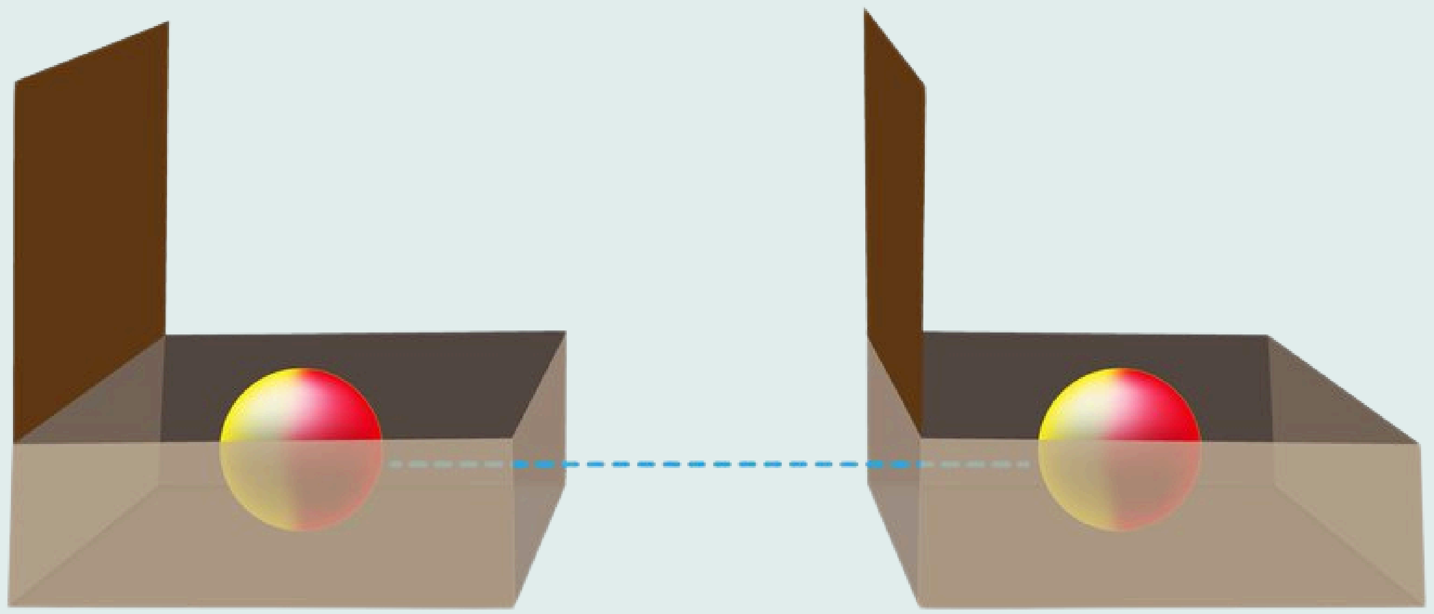


Example state:

$(|00\rangle + |11\rangle)/\sqrt{2}$, where measuring one qubit as $|0\rangle$ forces the other to be **$|0\rangle$**, and **$|1\rangle$** forces **$|1\rangle$**. Entanglement Described as "**spooky action at a distance**" by Einstein.

Key Points:

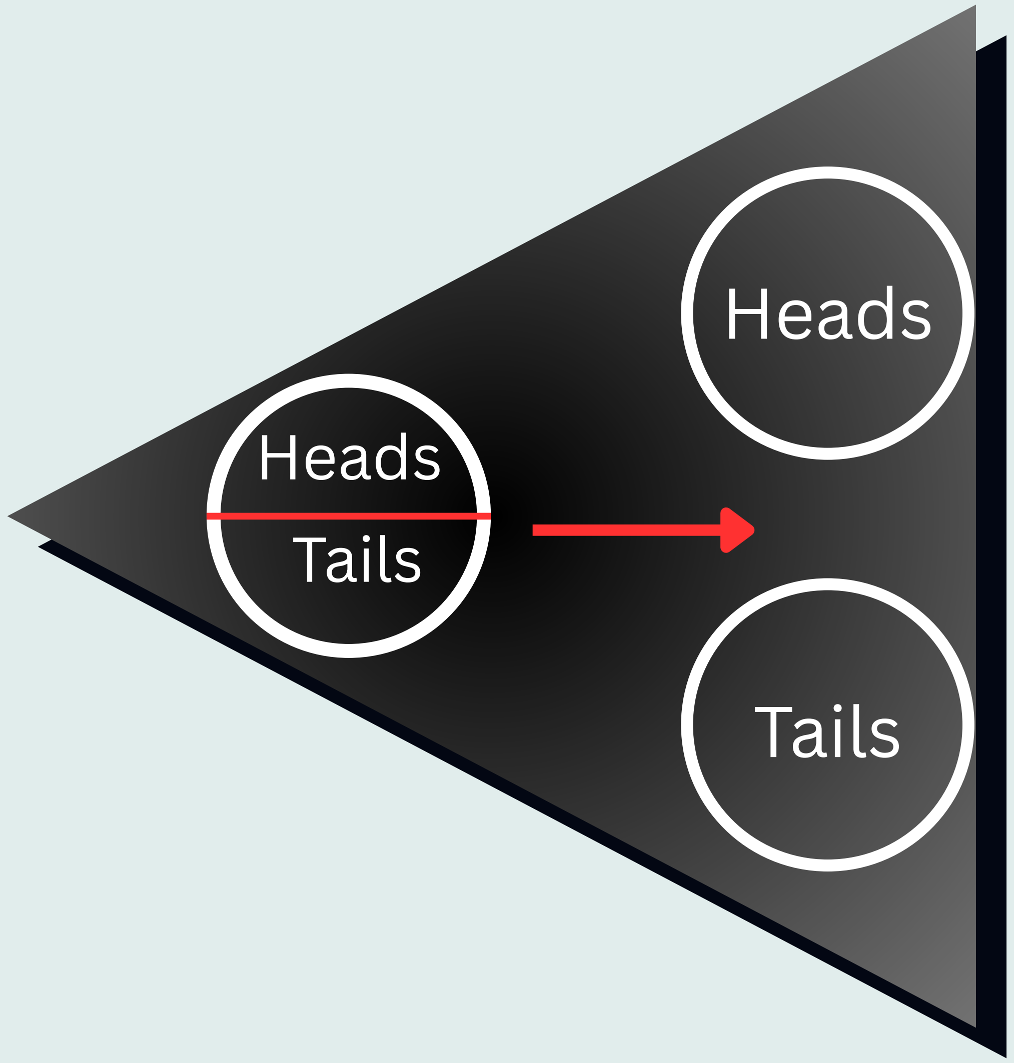
- If two qubits are entangled, measuring the state of one instantly gives information about the other.
- Entanglement enables quantum parallelism, which is a major advantage in quantum algorithms.
- It's used in quantum teleportation, superdense coding, and quantum error correction.



Decoherence

Definition:

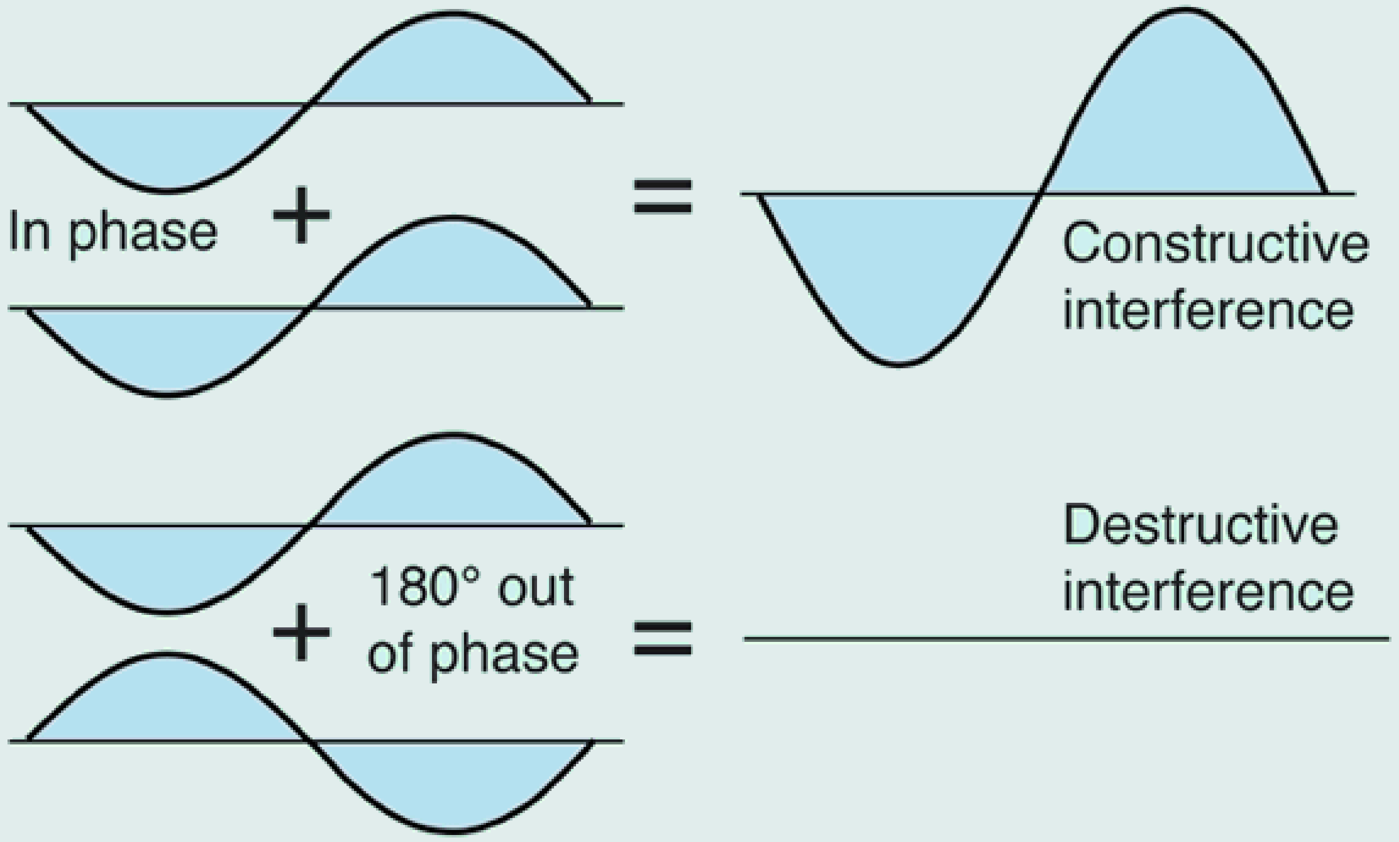
Decoherence in quantum computing **refers to the loss of quantum properties (like superposition and entanglement) in a qubit due to its interaction with the environment**. This interaction introduces noise and errors, hindering the accurate execution of quantum computations. It's a major challenge in building practical quantum computers.



Interference

Definition:

Quantum interference is the phenomenon where probability amplitudes (not probabilities) of quantum states combine—constructively or destructively—to influence the outcome of a measurement.



1.6 Introduction to Qiskit & IBM Quantum Lab

What is Qiskit?

Qiskit (Quantum Information Software Kit) is an open-source quantum computing SDK developed by IBM.

It allows users to create, simulate, and run quantum programs on real quantum hardware or simulators.

Written in Python, making it accessible for students and developers.

Qiskit Core Components:

qiskit.circuit: Create quantum circuits.

qiskit.aer: Run simulations locally.

qiskit.transpile: Optimize circuits for hardware.

qiskit.execute: Execute circuits on backend.

Qiskit Installation

Qiskit

Prerequisites:
Python 3.8 or later installed
pip (Python package installer)
Recommended: Use a virtual environment

Steps:

Step 1:
Install the core Qiskit package for quantum computing.
C:\>pip install qiskit

Step 2:
Install optional Qiskit modules for simulation, IBM Quantum access, and visualization.
C:\>pip install qiskit-aer qiskit-ibmq-provider qiskit[visualization]

Step 3:
Verify Qiskit installation by printing its version.
C:\>python -c "import qiskit; print(qiskit.__version__)"

IBM Quantum Lab

https://quantum.ibm.com/

What is IBM Quantum Lab?

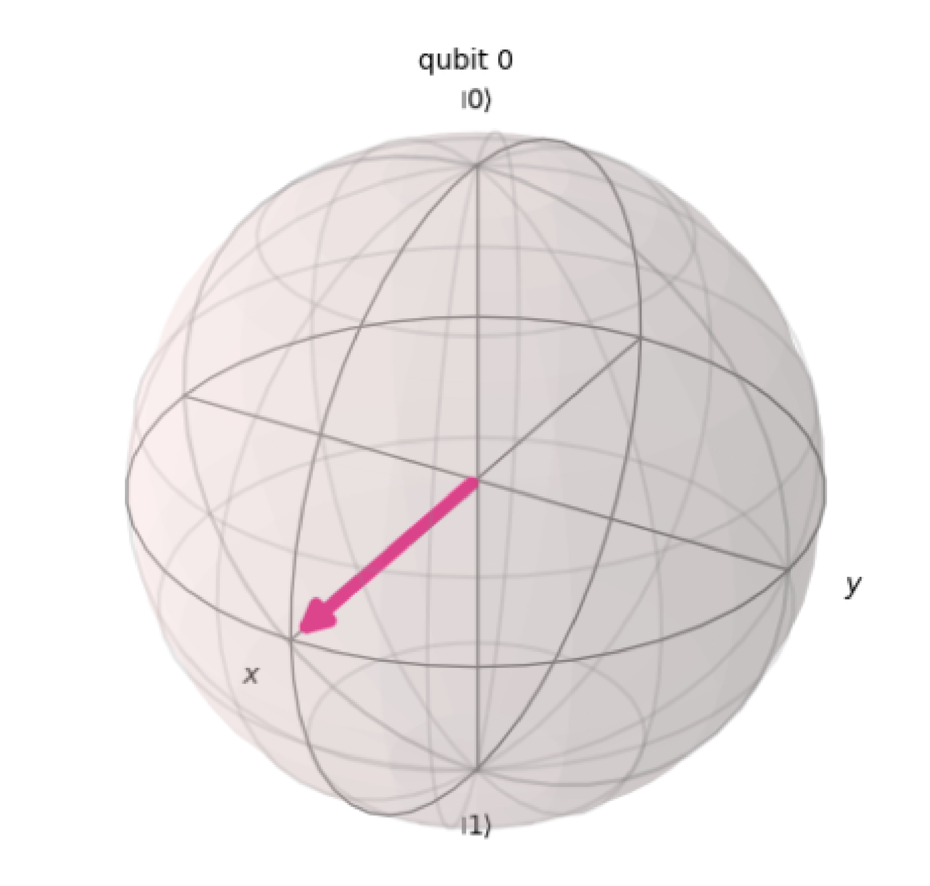
A cloud-based platform to write and run quantum programs using Qiskit.
Offers access to real IBM quantum computers from anywhere.
Includes Jupyter Notebook interface, simulators, and visualization tools

Why Use IBM Quantum Lab?

No installation required — works in the browser.
Run experiments on real quantum devices.
Great for learning, research, and prototyping.

1.7 Basic Quantum State Visualization: Visualize qubit states using Qiskit

To visualize qubit states using Qiskit, we can create a simple Python script that initializes a qubit in a superposition state and visualizes it on a Bloch sphere. Qiskit is a powerful quantum computing framework, and its visualization tools, like plot_bloch_vector, are great for representing qubit states.



1.8 Writing & Measuring a Qubit as a Specific State

Writing a Qubit as a Specific State

Yes, it is possible to prepare (or write) a qubit in a specific state using quantum gates. A qubit can be initialized and transformed to any desired pure state through the application of unitary operations.

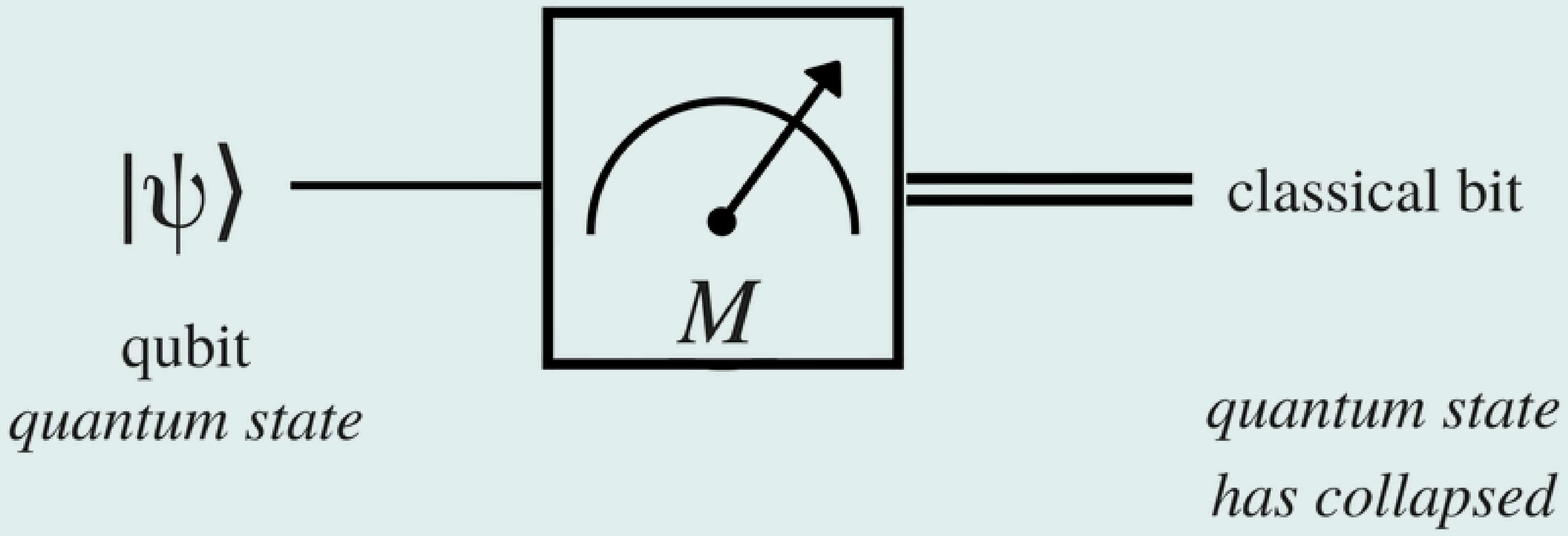
Measuring a Qubit as a Specific State

No, you cannot measure a qubit deterministically into a specific quantum state.
Measurement collapses a qubit to either $|0\rangle$ or $|1\rangle$ in the computational basis.

1.8 Writing & Measuring a Qubit as a Specific State

Qubit Measurement and Probabilistic Outcomes:

Measuring a qubit involves probabilistic outcomes. When a qubit is in a superposition of $|0\rangle$ and $|1\rangle$, the probability of measuring it as $|0\rangle$ is $|\alpha|^2$, and the probability of measuring it as $|1\rangle$ is $|\beta|^2$, where α and β are the complex amplitudes of the superposition.



Thank You..!