DAY 1

Quantum Computing

Introduction to Quantum Computing Workshop Day 1 - Bits, Qubits, and Quantum Computing

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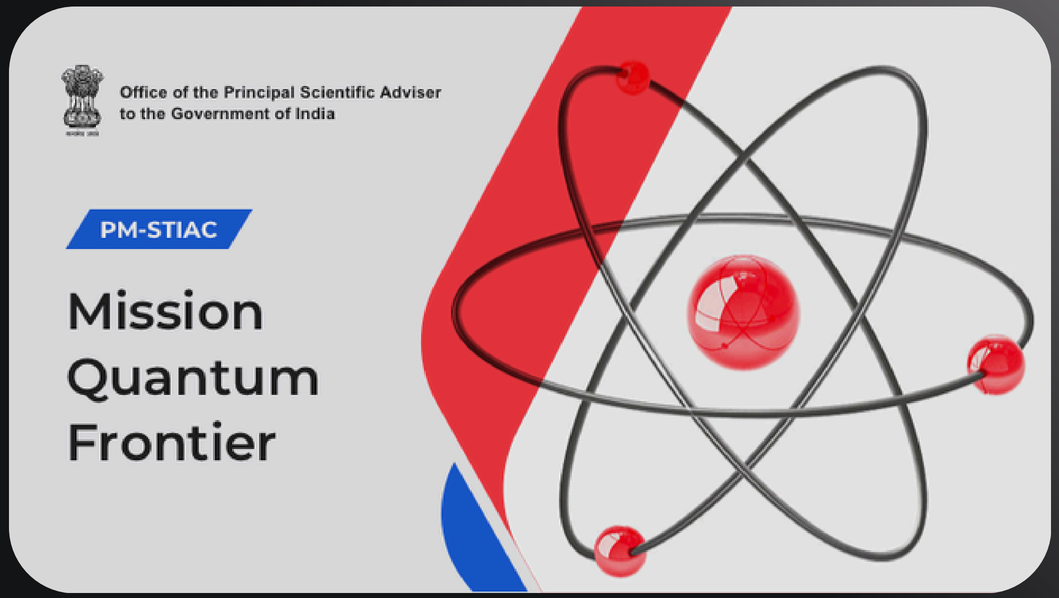
Workshop Content

- India and Quantum
- Bits & Qubits
- Quantum vs Classical Computing
- Introduction to Qiskit
- Quantum States
- Bloch Sphere
- Quantum Gates
- Quantum Circuits
- Superposition & Entanglement
- Introduction in Qiskit

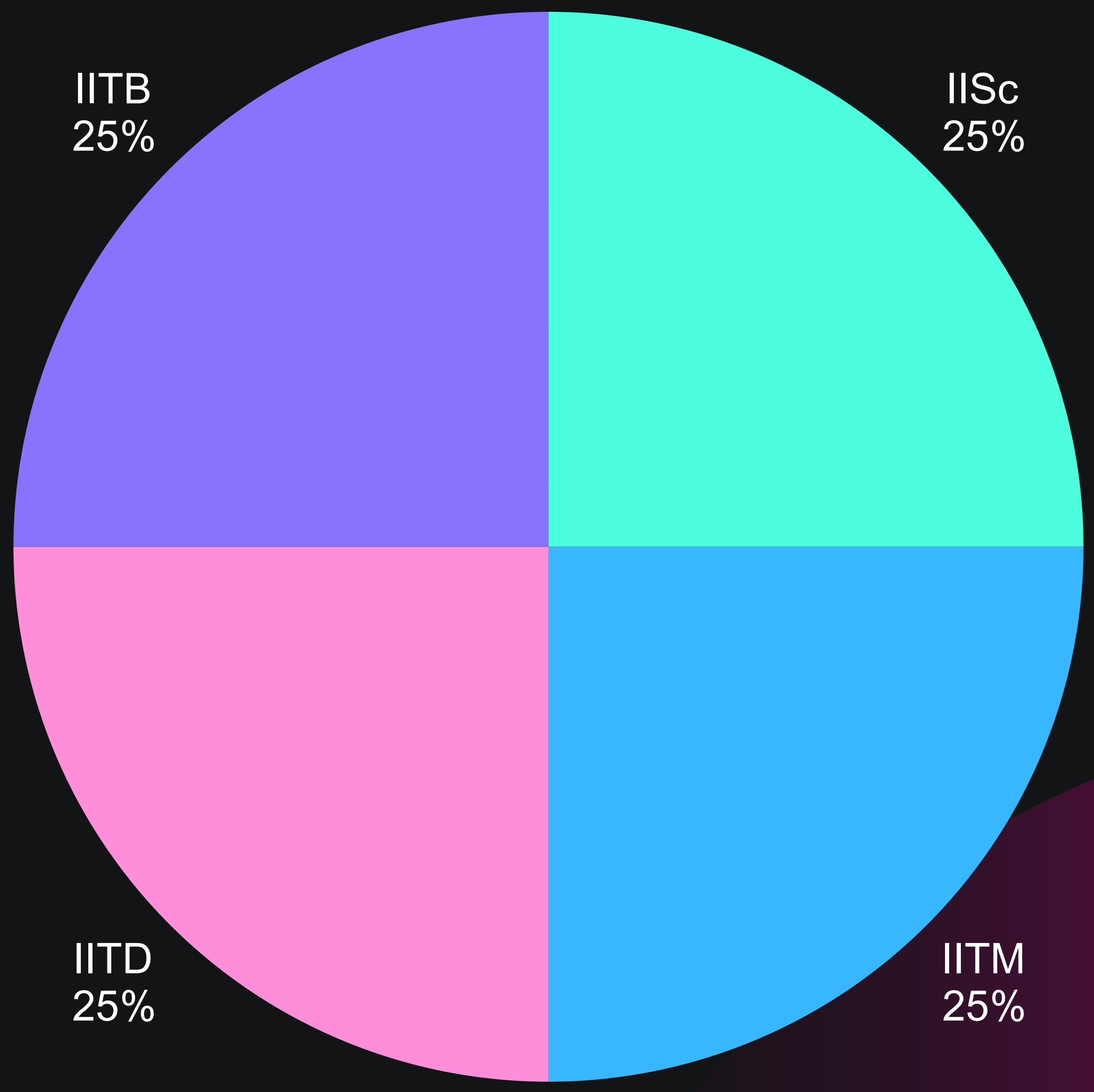
National Quantum Mission(NQM)

- Quantum Valley
- 4 Thematic Hubs
- Undergraduate Minor Course
- ₹6,003.65 crore (2023–2031)
- 8 NQM backed quantum startups
- IIT Delhi (with DRDO support): 1 km free-space entanglement based secure link demo
- Other research, startup, education schemes to push quantum in India



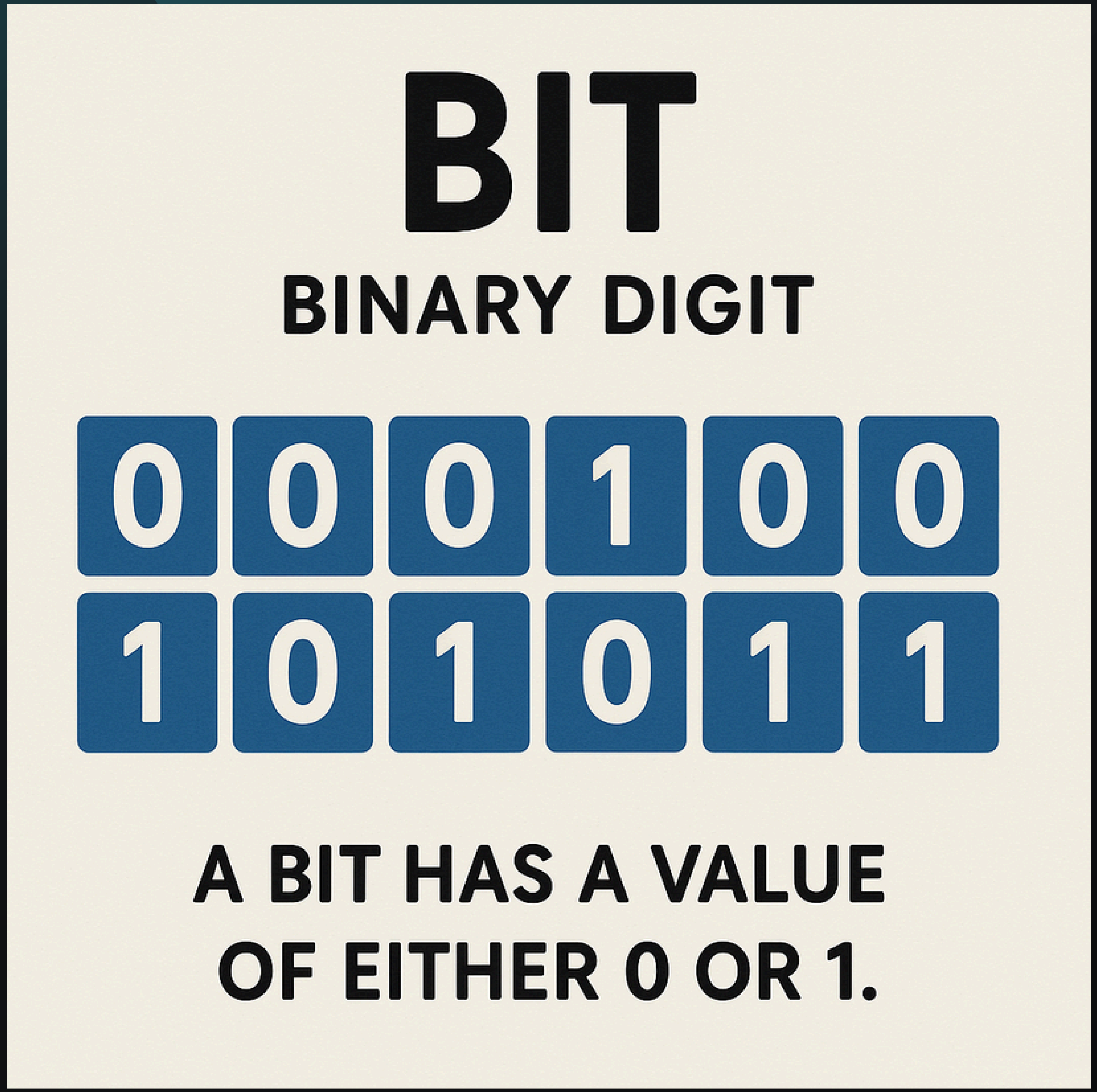
4 Thematic Hubs

1. IISc - Quantum Computing
2. IIT Madras - Quantum Communication
3. IIT Bombay - Quantum Sensing & Metrology
4. IIT Delhi - Quantum Materials & Devices



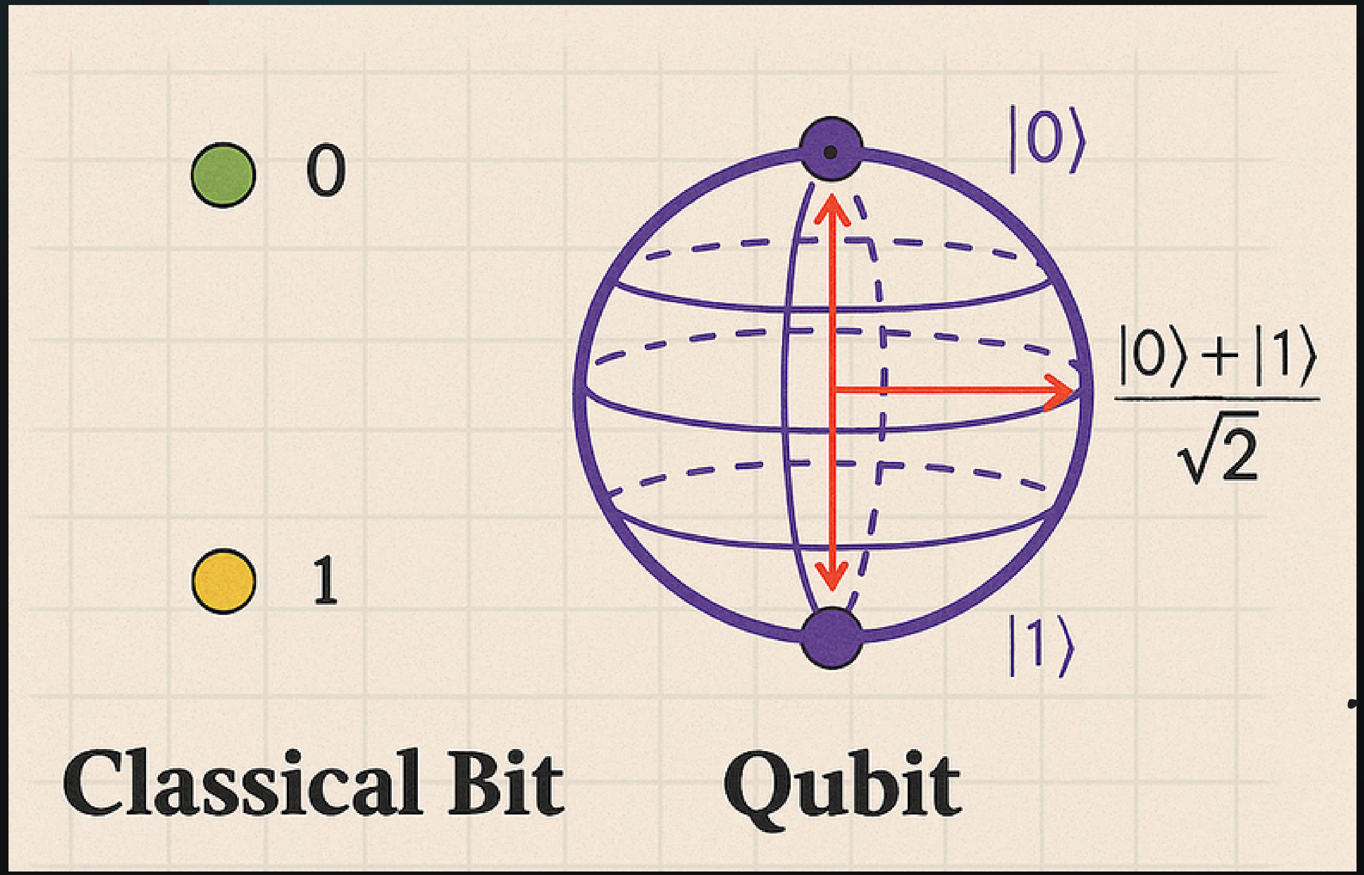
Bits

- A bit is the smallest unit of data in computing.
- It can have only two possible values: 0 or 1.
- 0 usually represents OFF, false, or low voltage, and 1 represents ON, true, or high voltage.
- Multiple bits can be combined to represent more complex data:
- 8 bits = 1 byte
- 16 bits = 2 bytes
- Forming larger data structures (like integers or floating-point numbers).
- All digital data (text, images, videos, etc.) is ultimately represented using bits.



Qubits

- A qubit is the basic unit of quantum information
- Unlike a classical bit, a qubit can exist in a superposition of both $|0\rangle$ and $|1\rangle$ states simultaneously.
- A qubit's state is described by:
- $|\psi\rangle=\alpha|0\rangle+\beta|1\rangle$ where α and β are complex probability amplitudes satisfying |α|2+|β|2=1.
- Measurement collapses a qubit's superposition to either 0 or 1, with probabilities determined by |α|2 and |β|2.
- The squared magnitudes of these amplitudes give the probabilities of measuring the qubit in state $|0\rangle$ or $|1\rangle$ states.
- Qubits can be implemented using various physical systems: trapped ions, superconducting circuits, photons, etc.



Bloch Sphere

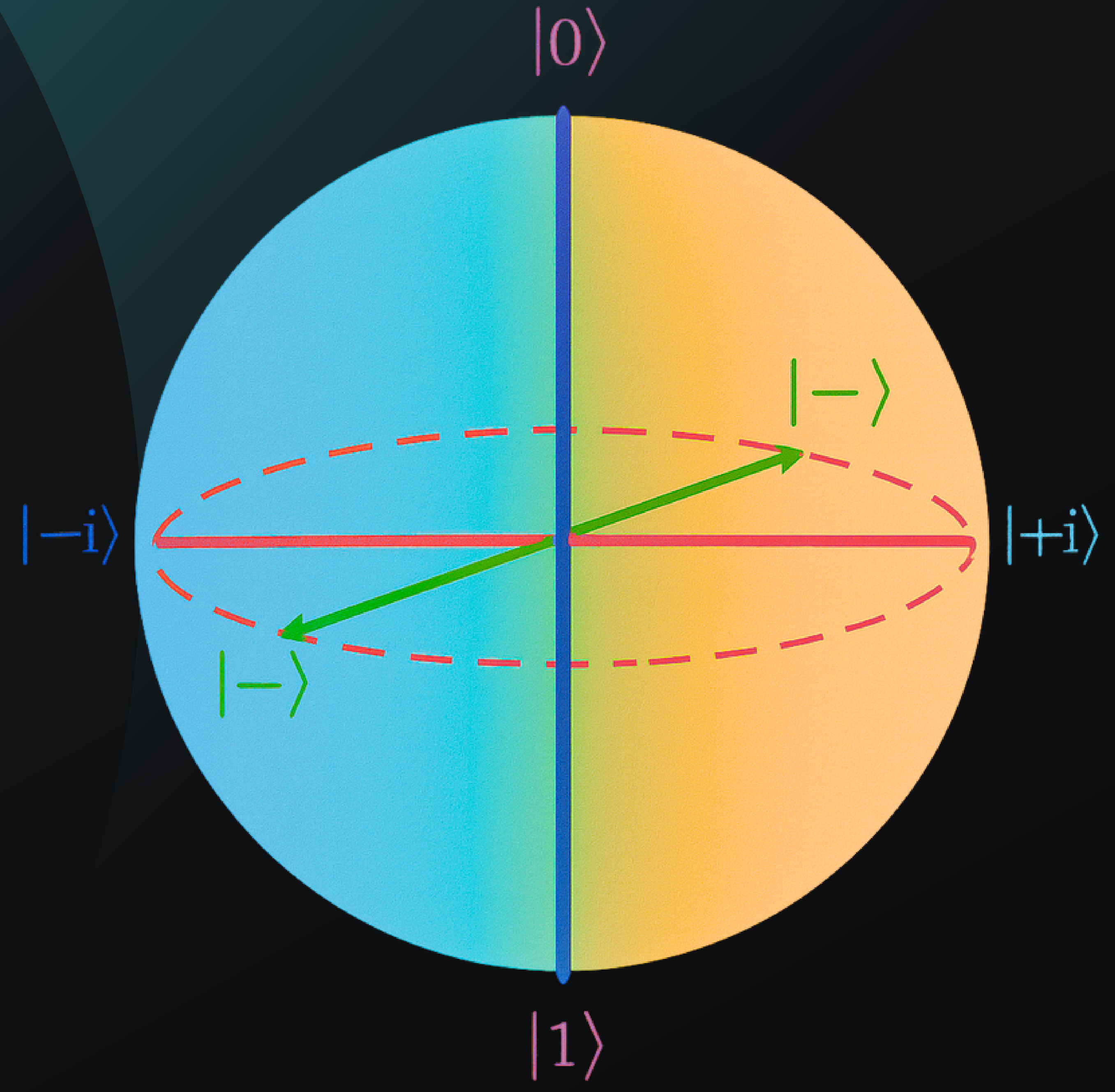
- The Bloch Sphere is a 3D geometric representation of the state of a single qubit.
- Any pure qubit state can be written as:

$$|\psi\rangle = \cos(\theta/2)|0\rangle + e^{i\phi}\sin(\theta/2)|1\rangle$$

- The north and south poles represent the classical states $|0\rangle$ and $|1\rangle$, while points on the equator represent equal superpositions.

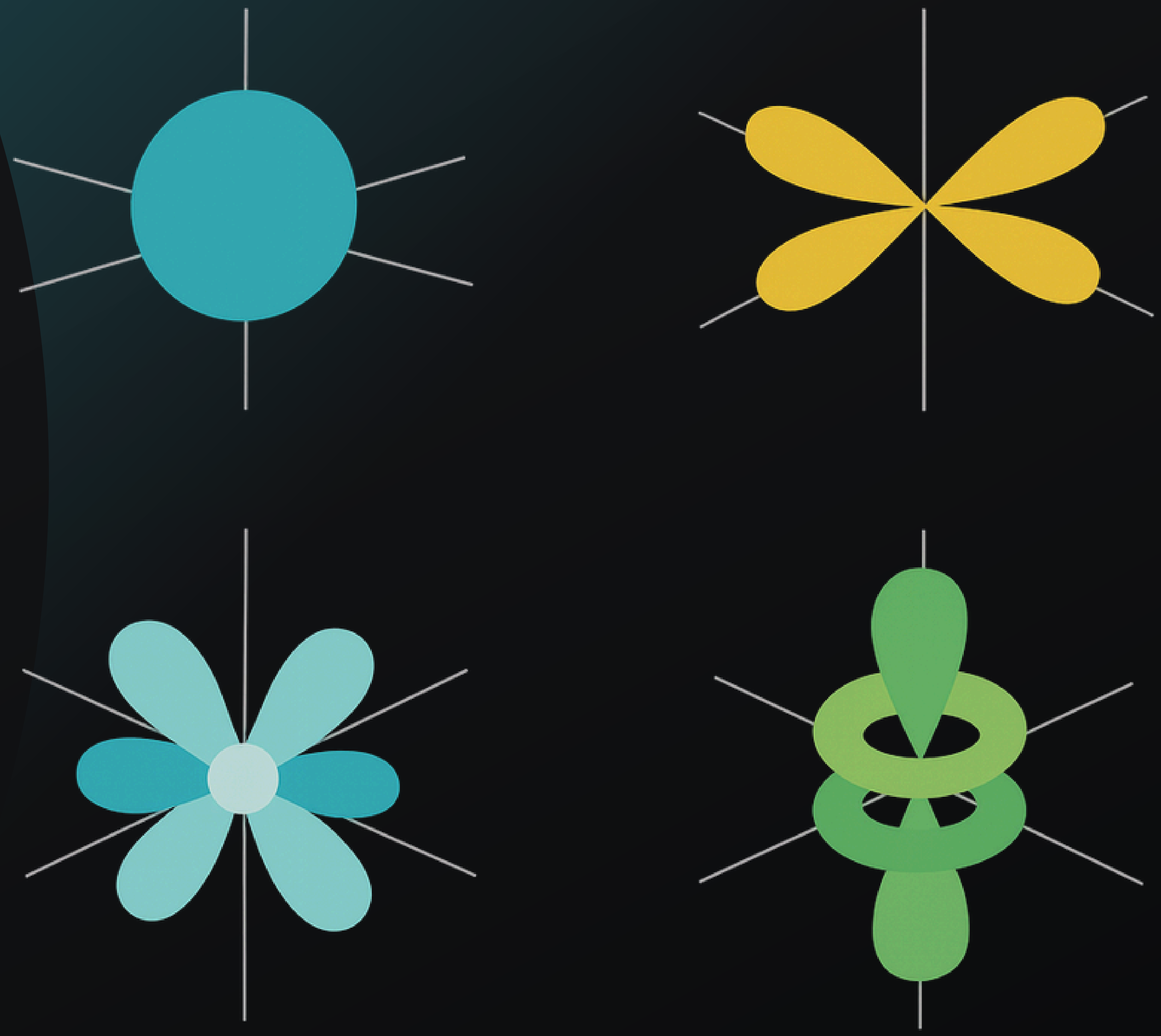
- Quantum gates (like Pauli or Hadamard) can be visualized as rotations on the Bloch Sphere.

- The Bloch Sphere provides intuitive insight into quantum superposition, phase, and qubit evolution over time.



Superposition

- Superposition is a fundamental principle of quantum mechanics allowing a quantum system to exist in multiple states simultaneously.
- A qubit in superposition is written as: $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$ where α and β are complex amplitudes satisfying $|\alpha|^2 + |\beta|^2 = 1.$
- Measurement collapses a qubit's superposition to either 0 or 1, with probabilities determined by $|\alpha|2$ and $|\beta|2$.
- The squared magnitudes of these amplitudes give the probabilities of measuring the qubit in state $|0\rangle$ or $|1\rangle$ states.
- Superposition enables quantum parallelism. A quantum computer can process many possible outcomes at once, unlike classical computers.
- Quantum gates like the Hadamard gate (H) are used to create and manipulate superposition in quantum circuits.
- 1s → 2s → 2p → 3s → 3p → 4s → 3d → 4p → 5s → 4d → 5p → 6s → 4f → 5d → 6p → 7s → 5f → 6d → 7p



Maze Example

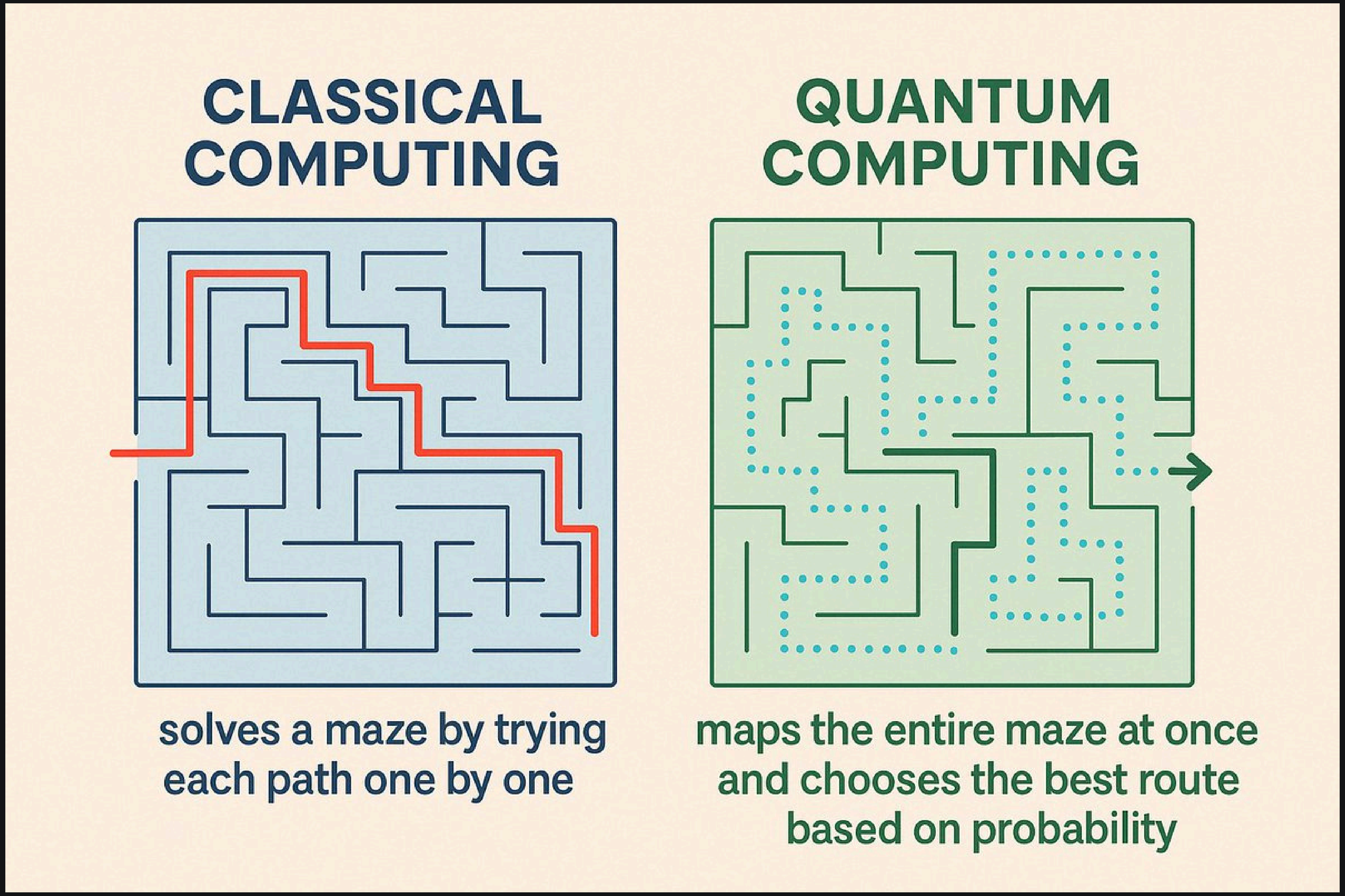
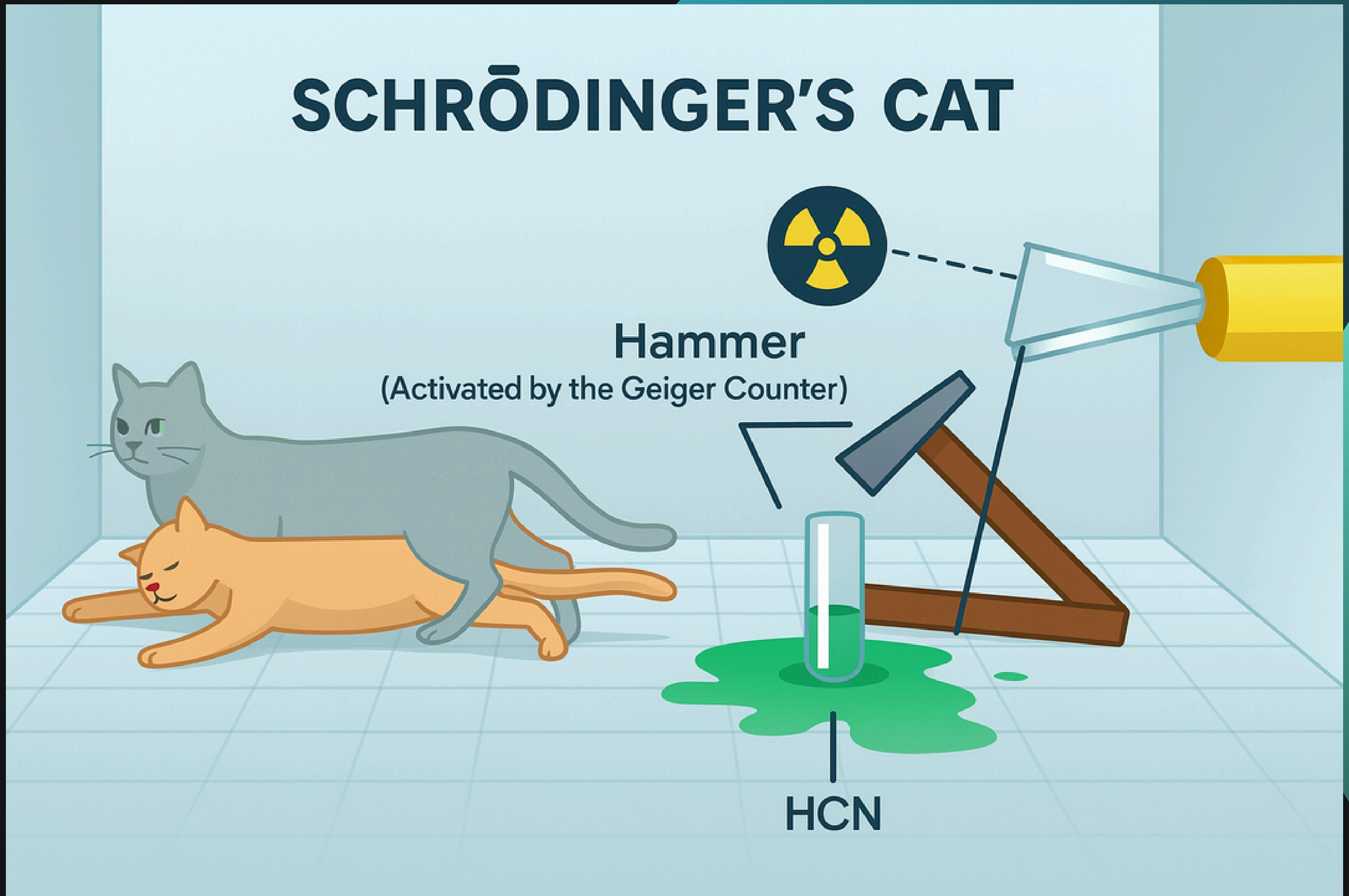


Image Source: https://x.com/DesFrontierTech/status/1912870018527736054

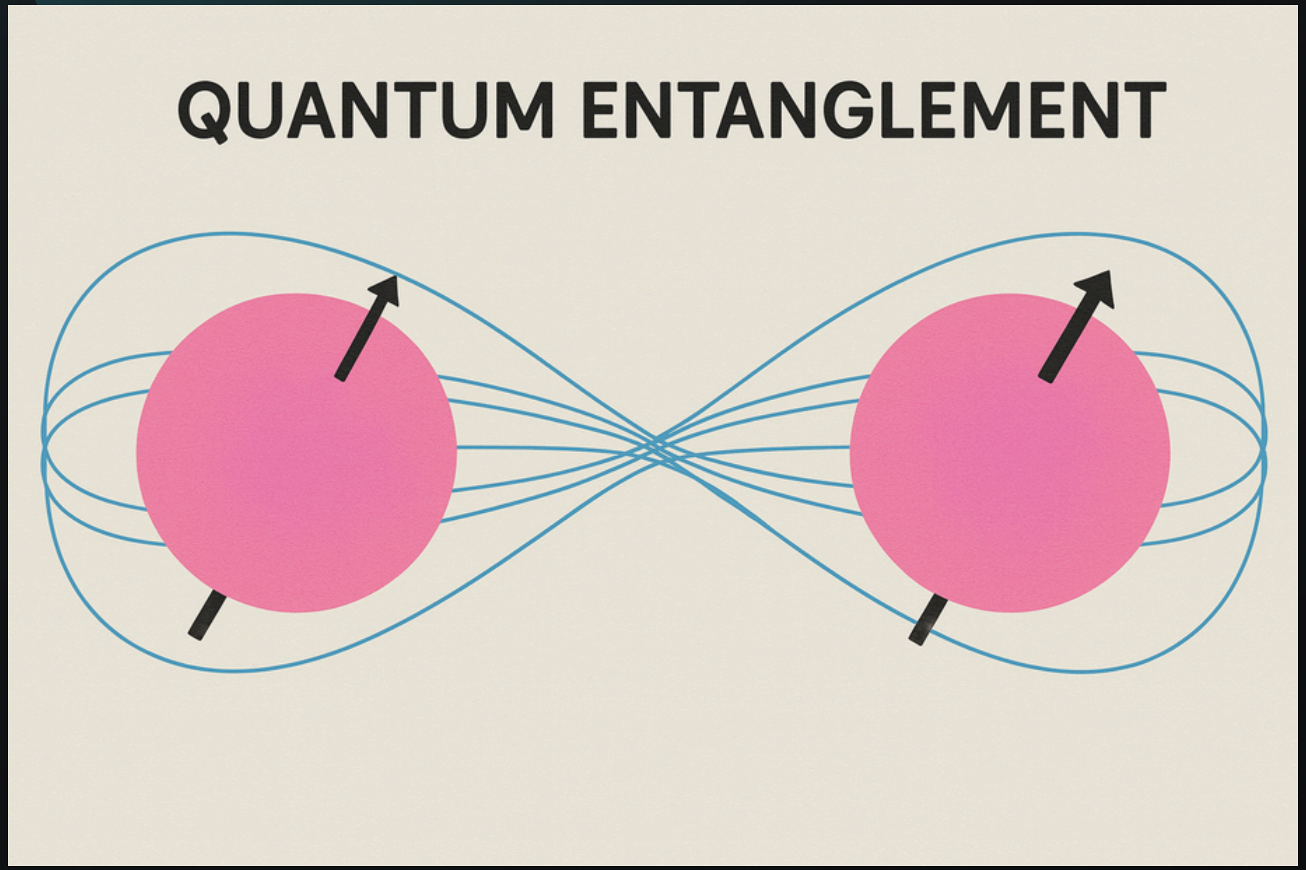
Schrodinges's Cat



- Schrödinger's Cat is a thought experiment illustrating quantum superposition and the measurement problem.
- A cat in a sealed box is linked to a quantum event (radioactive decay) that can make it alive and dead at the same time until observed.
- It highlights how quantum systems can exist in multiple states simultaneously, but measurement forces a definite outcome.
- Schrödinger designed it to criticize the Copenhagen interpretation when applied to macroscopic objects.
- The experiment raises questions about the role of the observer, wavefunction collapse, and the boundary between quantum and classical worlds.

Entanglement

- Entanglement is a quantum phenomenon where two or more particles become correlated such that the state of one instantly affects the state of the other(s), no matter how far apart they are.
- A classic example of a two-qubit entangled state is the Bell state. Measuring one qubit immediately determines the outcome of the other.
- Entanglement enables quantum teleportation, superdense coding, and is a key resource in quantum computing and quantum cryptography.
- In practice, entanglement is fragile and can be disrupted by decoherence or interaction with the environment.
- Entangled states are widely used in quantum networks, quantum key distribution (QKD), and quantum error correction.

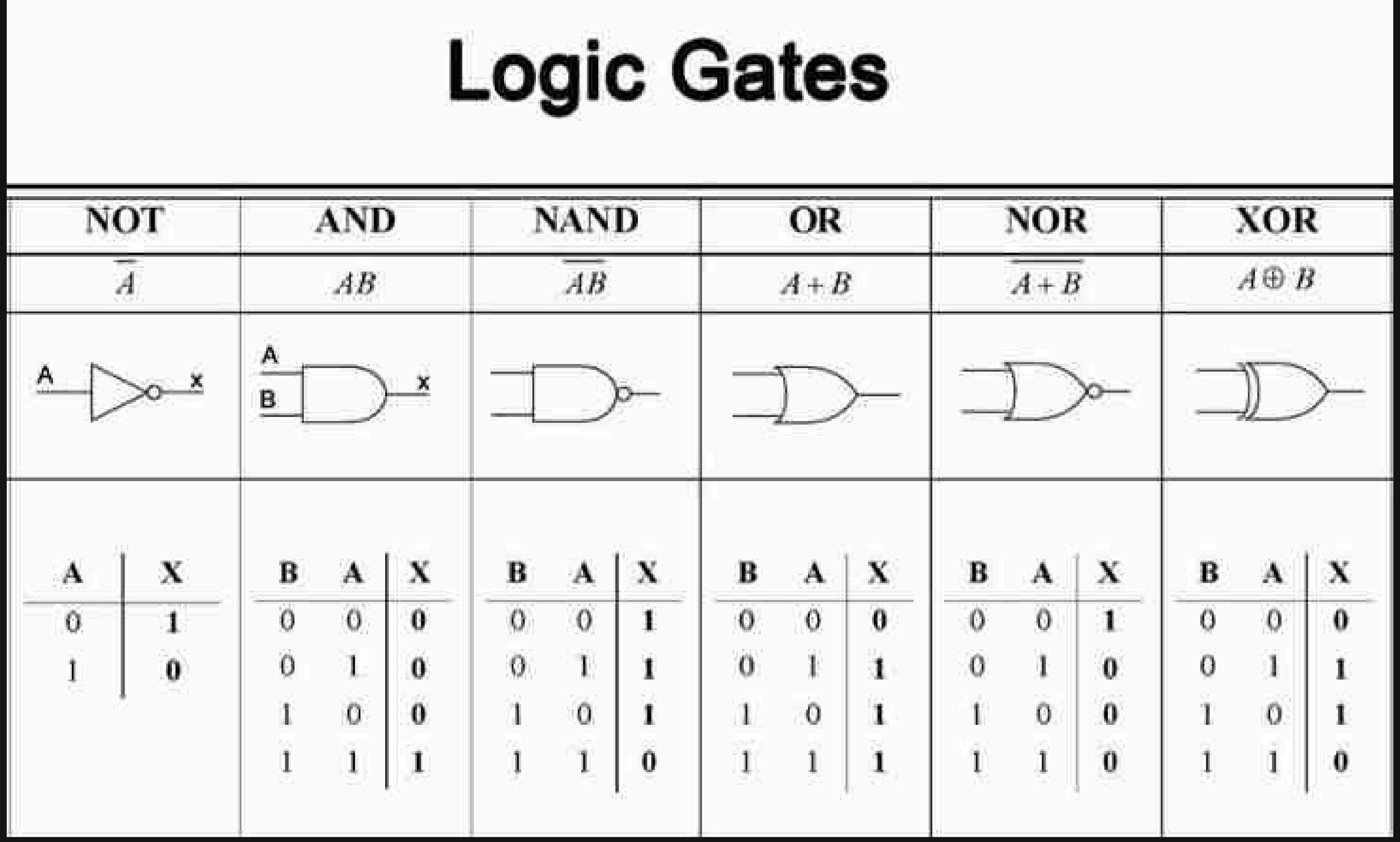


Why Quantum Computing?

- Transistors are the fundamental building blocks of modern computers they act as tiny on/off switches that control the flow of electrical current.
- Traditionally, they follow the rules of classical physics, where electrons behave like tiny, localized particles.
- But as we shrink transistors to just a few nanometers (1 nanometer = 1 billionth of a meter), we’re approaching the scale of individual atoms and at this point, quantum mechanics kicks in.

Classical Gates

- Classical logic gates are the building blocks of digital circuits, processing binary inputs (0 and 1) to produce binary outputs.
- Common gates include AND, OR, NOT etc.
- These gates follow Boolean algebra, using logical operations to perform computation.



Logic Gates

NOT	AND	NAND	OR	NOR	XOR
$\overline{A}$	AB	$\overline{AB}$	$A+B$	$\overline{A+B}$	$A \oplus B$

NOT

A	X
0	1
1	0

AND

B	A	X
0	0	0
0	1	0
1	0	0
1	1	1

NAND

B	A	X
0	0	1
0	1	1
1	0	1
1	1	0

OR

B	A	X
0	0	0
0	1	1
1	0	1
1	1	1

NOR

B	A	X
0	0	1
0	1	0
1	0	0
1	1	0

XOR

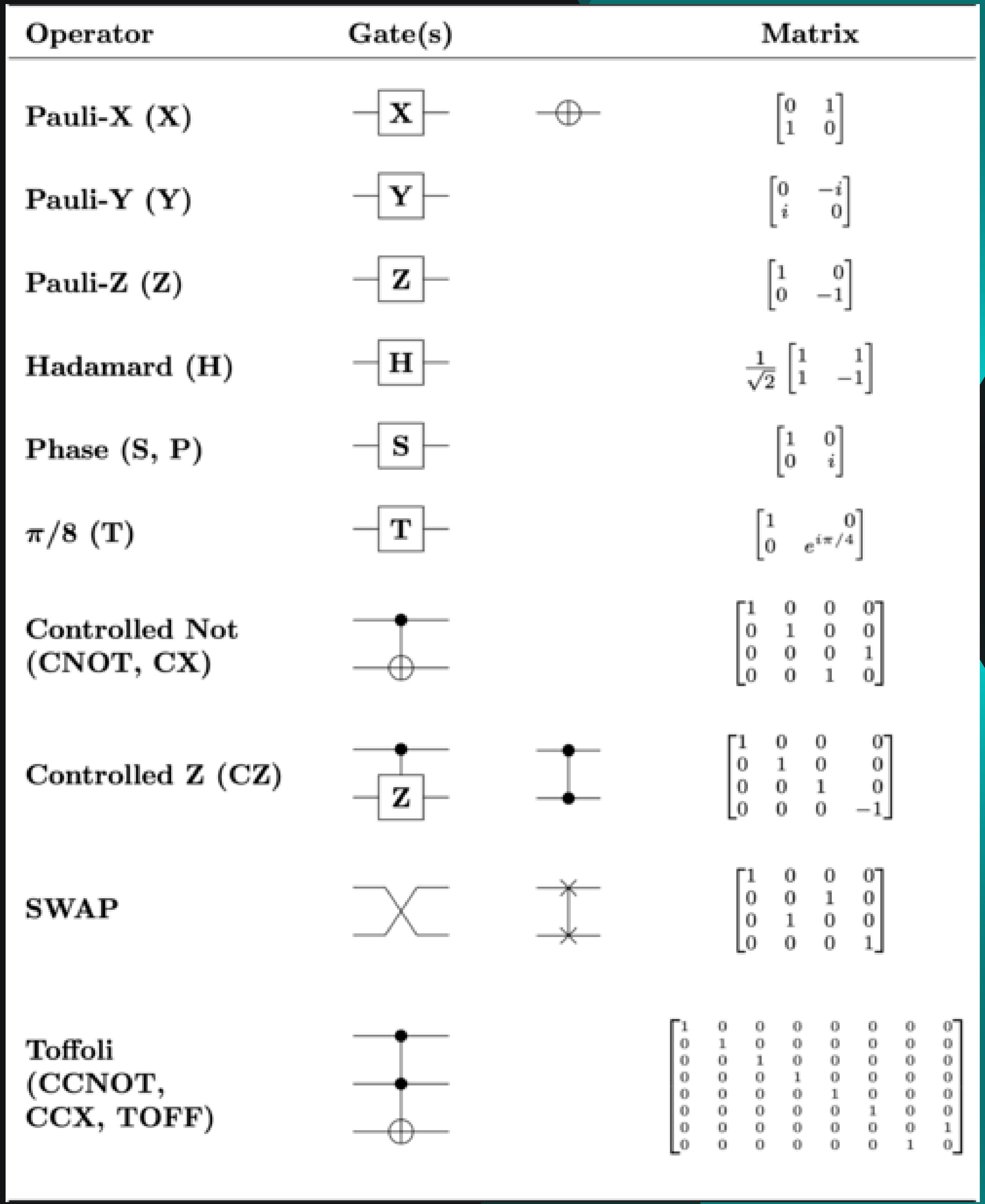
B	A	X
0	0	0
0	1	1
1	0	1
1	1	0

- Classical gates are irreversible (except for NOT); you can't always deduce the inputs from the output.
- They are implemented using transistors in modern CPUs and digital devices to execute all logical and arithmetic operations.

Image Source: https://hgmin1159.github.io/quantum/quantum2_eng/

Quantum Gates

- Quantum gates are the fundamental operations on qubits, governed by quantum mechanics.
- Unlike classical gates, quantum gates are unitary (reversible) and operate on superpositions, preserving the total probability.
- Common single-qubit gates include: X gate (quantum NOT): flips |0⟩ ↔ |1⟩,H (Hadamard) gate: creates superposition, Z gate: applies a phase flip
- Y gate: combines bit and phase flip,Rx, Ry, Rz gates: rotation gates on Bloch sphere axes.
- Multi-qubit gates like the CNOT gate entangle qubits and are essential for quantum algorithms and circuits.
- Quantum gates enable operations like superposition, entanglement, and interference, powering algorithms such as Shor’s and Grover’s.



Operator	Gate(s)	Matrix
Pauli-X (X)	X	$\begin{bmatrix}0 & 1\\1 & 0\end{bmatrix}$
Pauli-Y (Y)	Y	$\begin{bmatrix}0 & -i\\i & 0\end{bmatrix}$
Pauli-Z (Z)	Z	$\begin{bmatrix}1 & 0\\0 & -1\end{bmatrix}$
Hadamard (H)	H	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$
Phase (S, P)	S	$\begin{bmatrix}1 & 0\\0 & i\end{bmatrix}$
$\pi/8$ (T)	T	$\begin{bmatrix}1 & 0\\0 & e^{i\pi/4}\end{bmatrix}$
Controlled Not (CNOT, CX)		$\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&0&1\\0&0&1&0\end{bmatrix}$
Controlled Z (CZ)	Z	$\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&-1\end{bmatrix}$
SWAP		$\begin{bmatrix}1&0&0&0\\0&0&1&0\\0&1&0&0\\0&0&0&1\end{bmatrix}$
Toffoli (CCNOT, CCX, TOFF)		$\begin{bmatrix}1&0&0&0&0&0&0&0\\0&1&0&0&0&0&0&0\\0&0&1&0&0&0&0&0\\0&0&0&1&0&0&0&0\\0&0&0&0&1&0&0&0\\0&0&0&0&0&1&0&0\\0&0&0&0&0&0&0&1\\0&0&0&0&0&0&1&0\end{bmatrix}$

Image Source: https://en.wikipedia.org/wiki/Quantum_logic_gate

Quantum Circuits

- Quantum circuits are sequences of quantum gates applied to qubits, designed to perform specific quantum computations or algorithms.

Key components include:

- **Qubits:** The basic units of quantum information.
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- **Quantum gates:** Operations that manipulate qubit states (e.g., X, H, CNOT).
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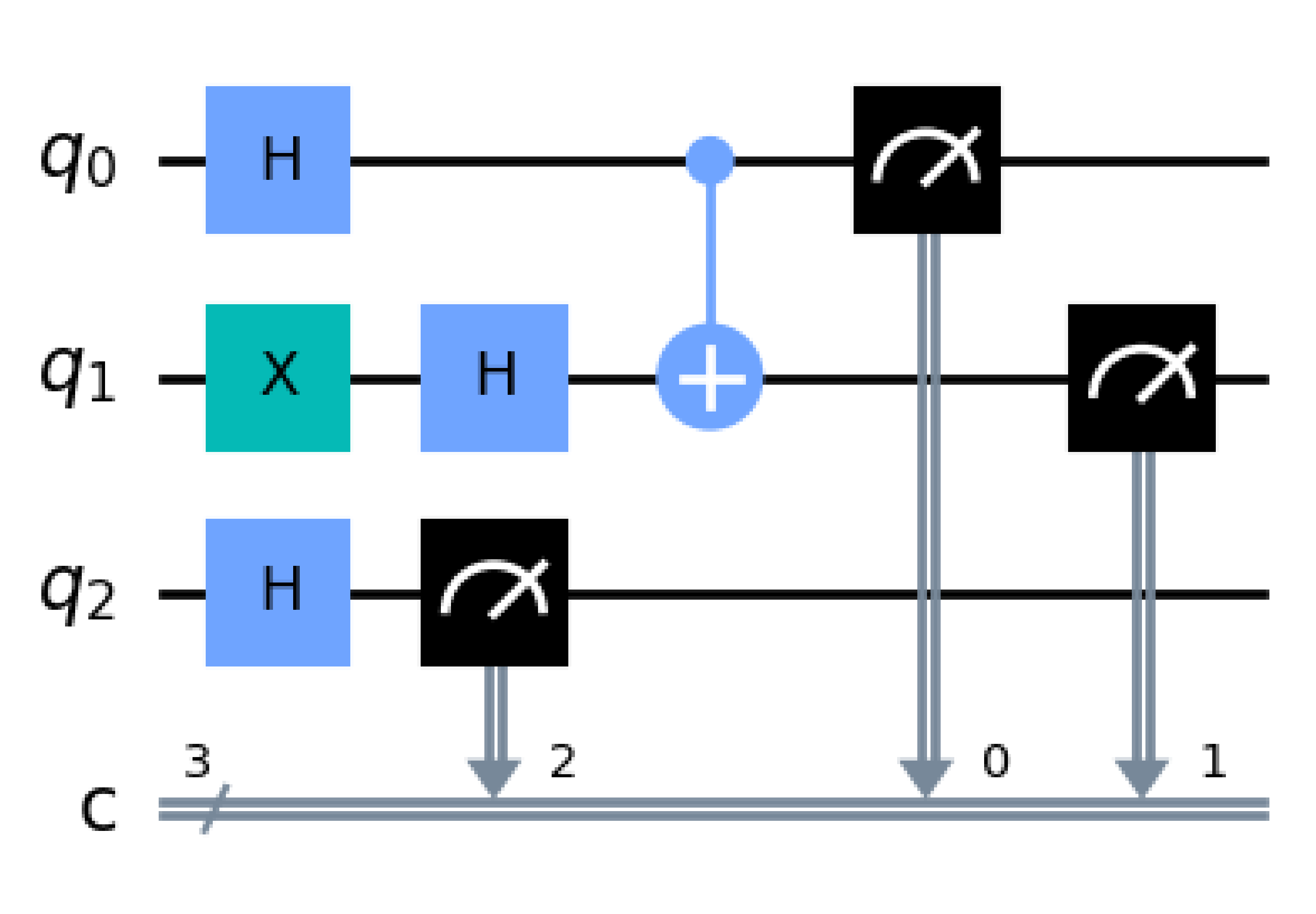
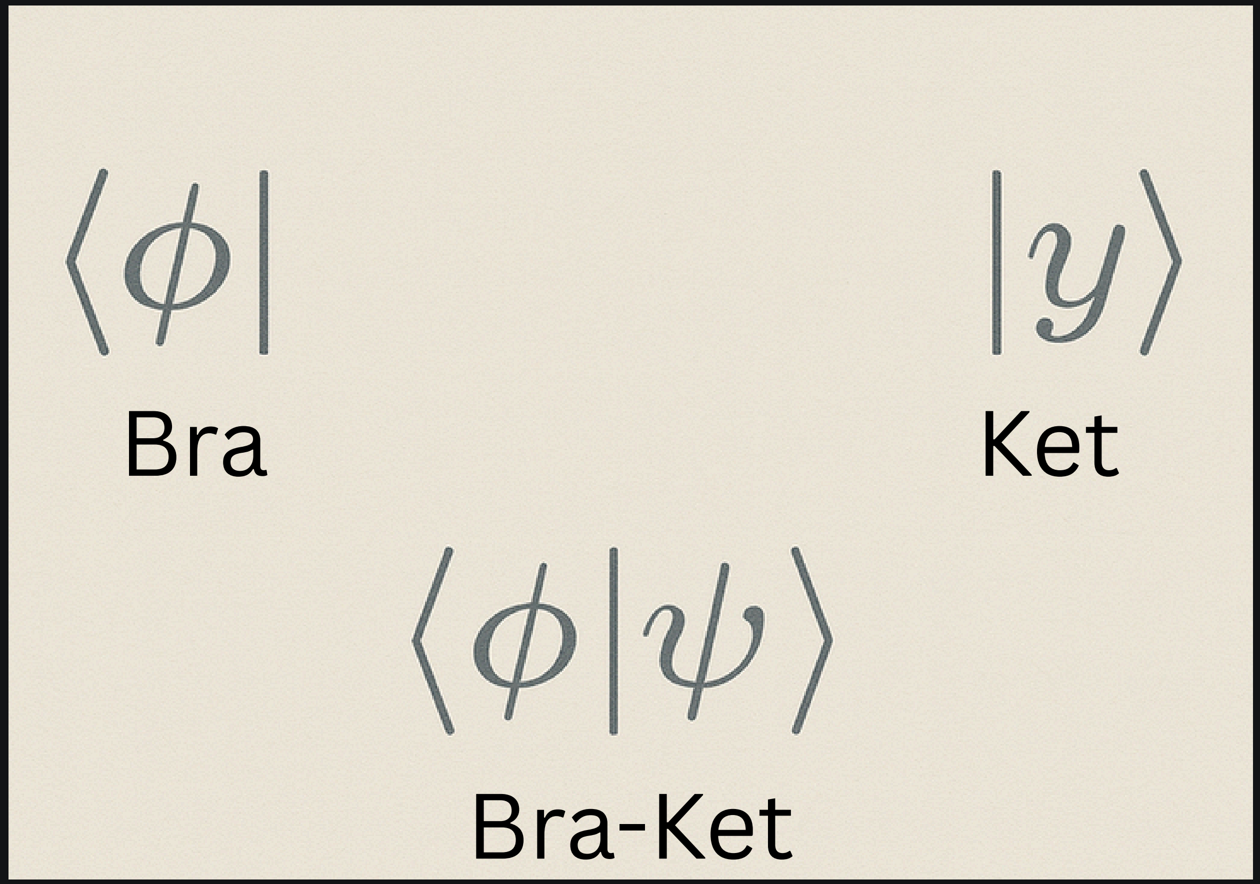
- **Measurement:** Final step that collapses qubit states into classical bits.



Bra-Ket Notation

- Bra-ket notation, introduced by Dirac, is a standard way to represent quantum states:
- Ket $|\psi\rangle$ denotes a quantum state (a column vector), Bra $\langle\psi|$ is its dual (a row vector).
- The inner product $\langle\phi|\psi\rangle$ gives the probability amplitude of finding state $|\psi\rangle$ in state $|\phi\rangle$, and its squared magnitude gives the probability.
- The outer product $|\psi\rangle\langle\phi|$ represents an operator, often used in constructing quantum gates or projectors.



Programming a Quantum Computer

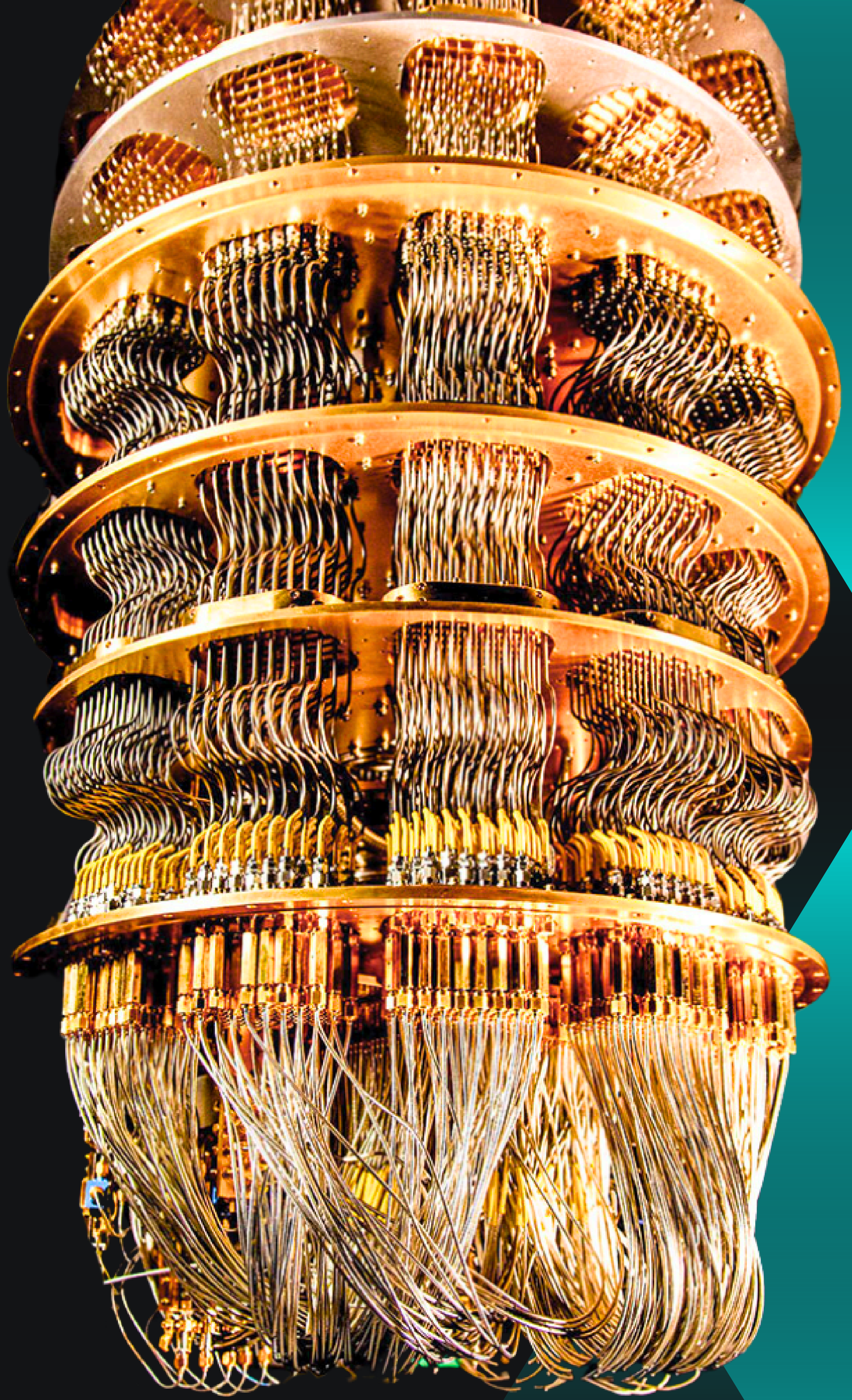
1. **Define Qubits & Initialize Circuit**
   Use a quantum programming language (like Qiskit, Cirq, or PennyLane) to create qubits and set up your quantum circuit.

2. **Apply Quantum Gates**
   Add operations (e.g., Hadamard, CNOT, Pauli gates) to manipulate qubits and build the quantum algorithm.

3. **Measure & Run**
   Measure the qubits to extract classical outcomes, then execute the circuit on a quantum simulator or real quantum hardware (e.g., IBM Quantum or IonQ).

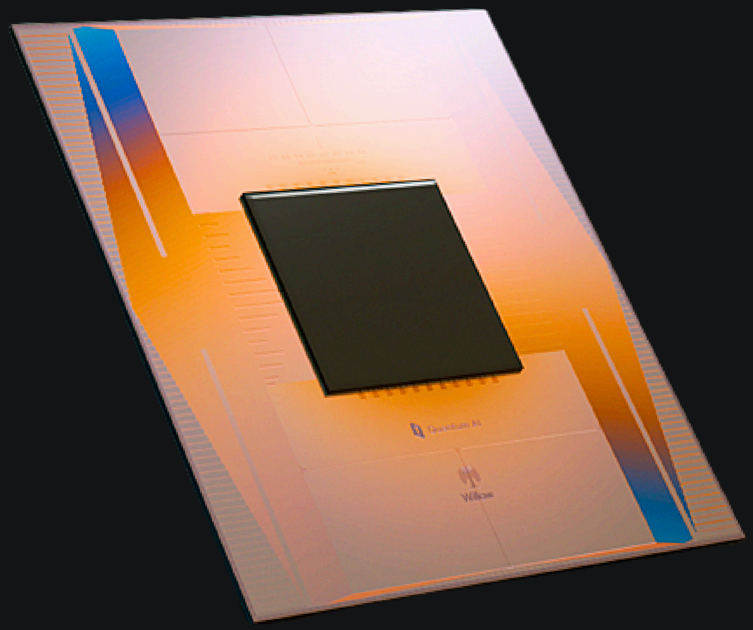
Quantum Computers

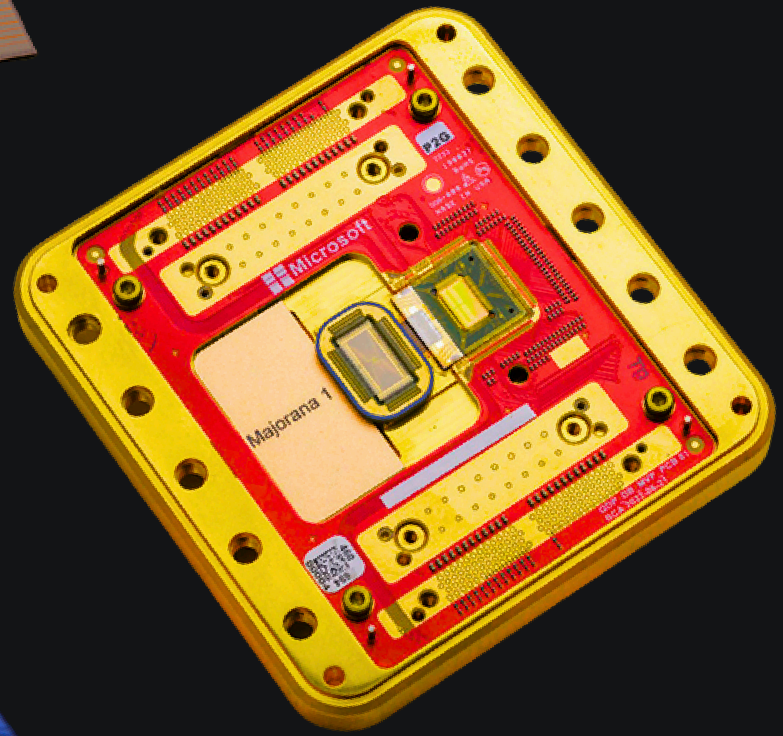
- Quantum computers use qubits and quantum effects to solve problems classical computers can’t.
- They operate at ultra-cold temperatures using dilution refrigerators to preserve quantum states.
- They often look like golden chandeliers, housing the quantum processor and control systems.

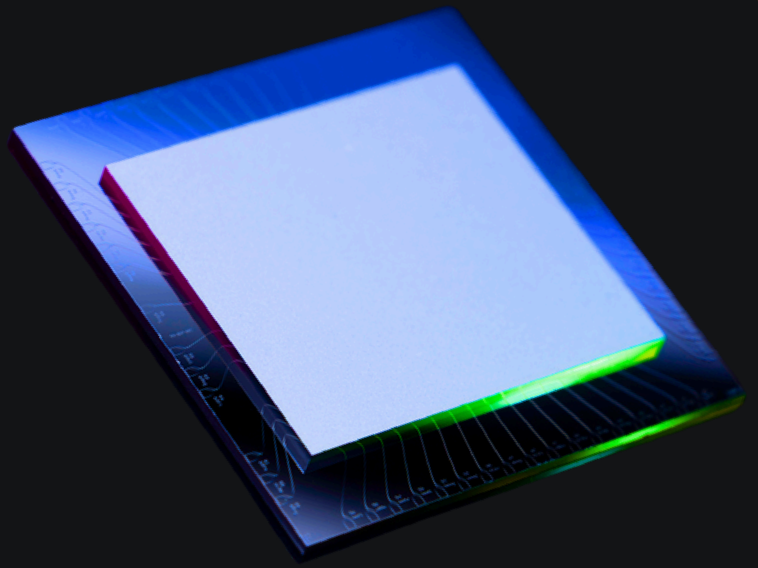


Quantum Chips

- Quantum chips contain qubits and quantum circuits for performing quantum computations.
- They are made using platforms like superconducting circuits, trapped ions, or photonics.
- Operate at cryogenic temperatures to maintain coherence and reduce noise.







Types of Quantum Computers

Superconducting Qubits

Use circuits cooled to near absolute zero to exhibit quantum behavior. Fast gate operations and widely used by IBM, Google, and Rigetti.

Neutral Atoms

Qubits are individual neutral atoms trapped using optical tweezers. Highly scalable and reconfigurable; used by companies like QuEra and PASQAL.

Photonic

Use single photons as qubits, manipulated via beam splitters and phase shifters. Room-temperature operation and good for quantum communication tasks.

Trapped-Ion

Qubits are individual ions trapped and manipulated using lasers. High fidelity and long coherence times, used by IonQ and Quantinuum.

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