Quantum Computing: Principles, Apps & Teleportation

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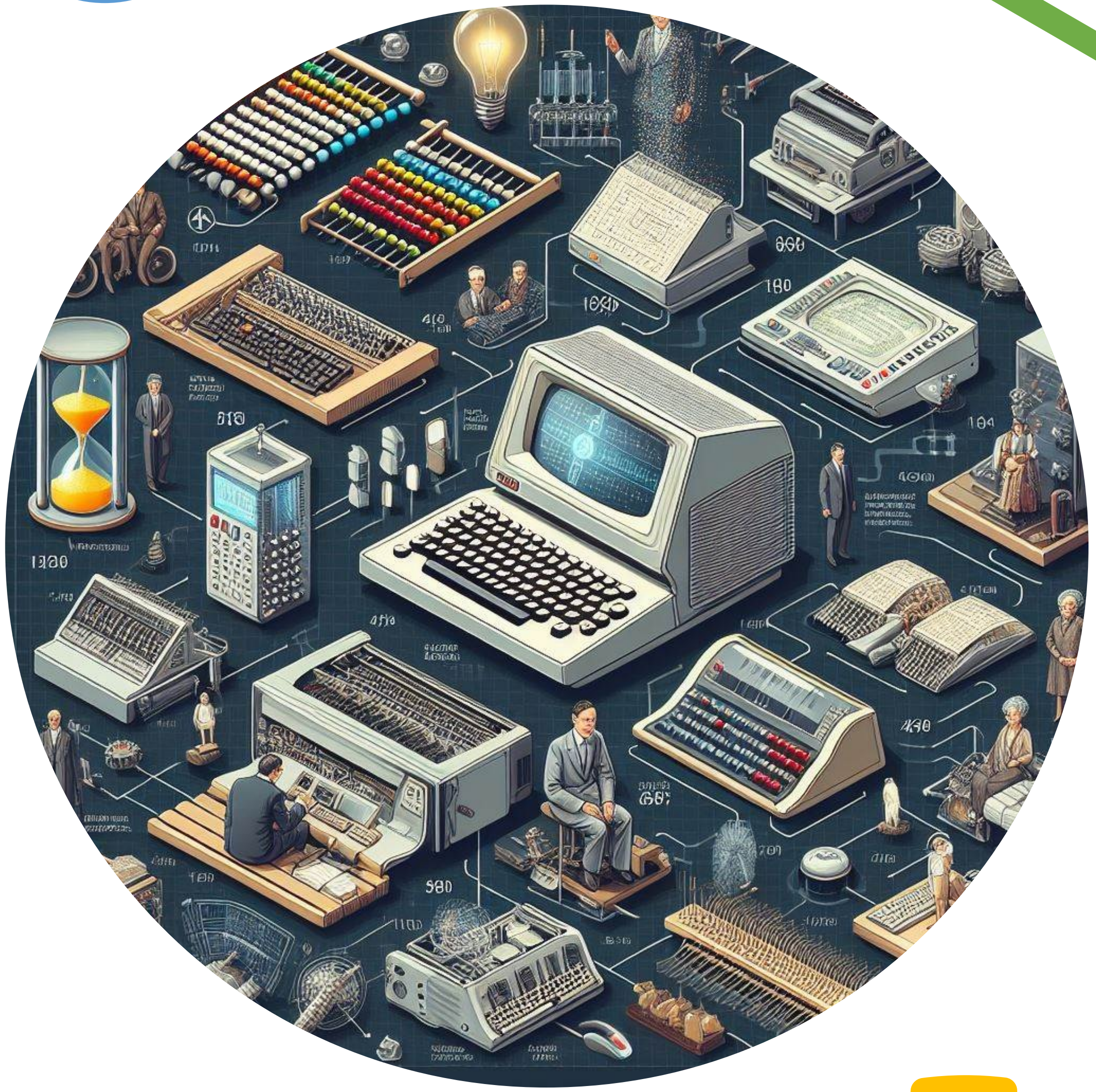
Agenda

- Classical Computers
- Understanding Quantum
- Types of Quantum Computers
- IBM Quantum Computer Architecture
- Potential Applications
- Q&A

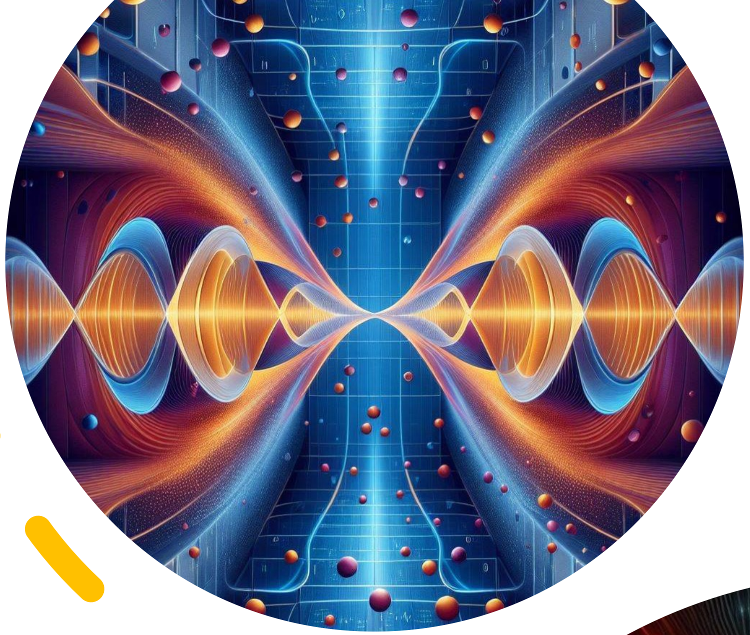
- Qubits
- Basic Gates (One and Two Qubits)
- Quantum Teleportation Algorithm
- Current Frontiers
- Q&A



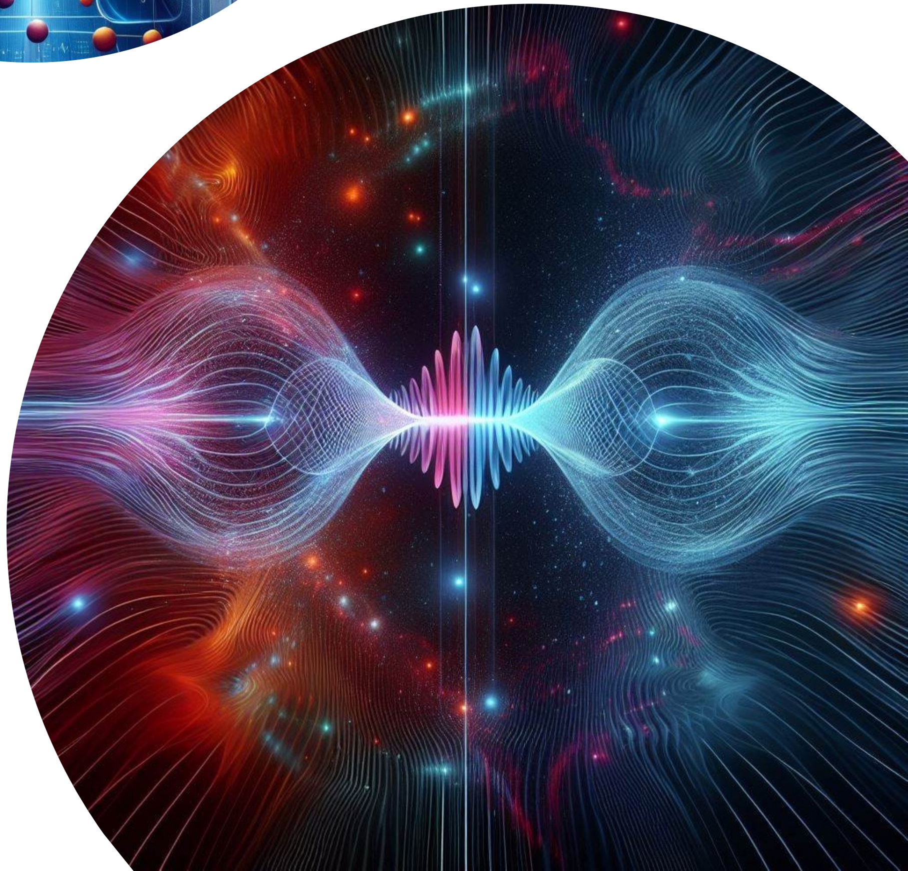
Classical Computers

- *Generations of Computer*
- *Bits – Unit of information .* 2^n possible states, <u>only one at a time</u>
- *Gates Operation (AND, OR, NOT)*

Understanding Quantum



- Quantum – the smallest amount of something
- Role of Photons (wave packets- Quantum of light)
- Wave-Particle Duality (Double-slit experiment*)



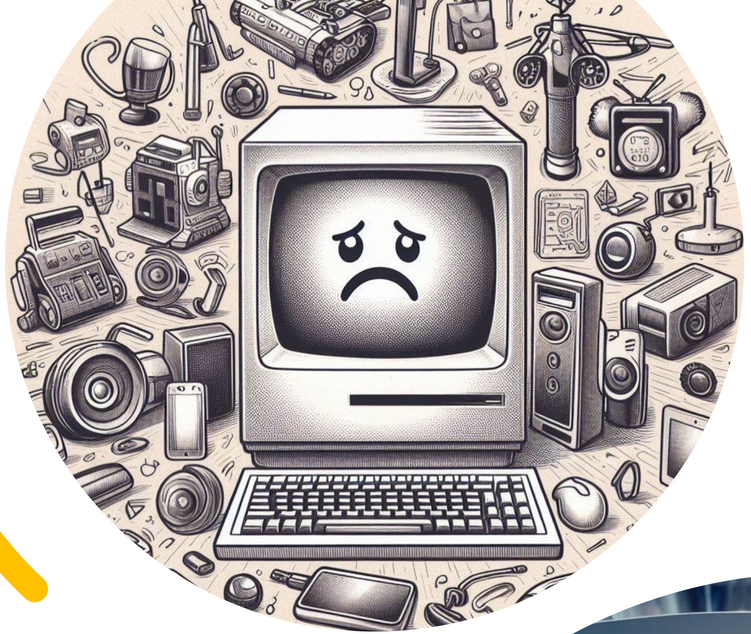
* https://en.wikipedia.org/wiki/Double-slit_experiment

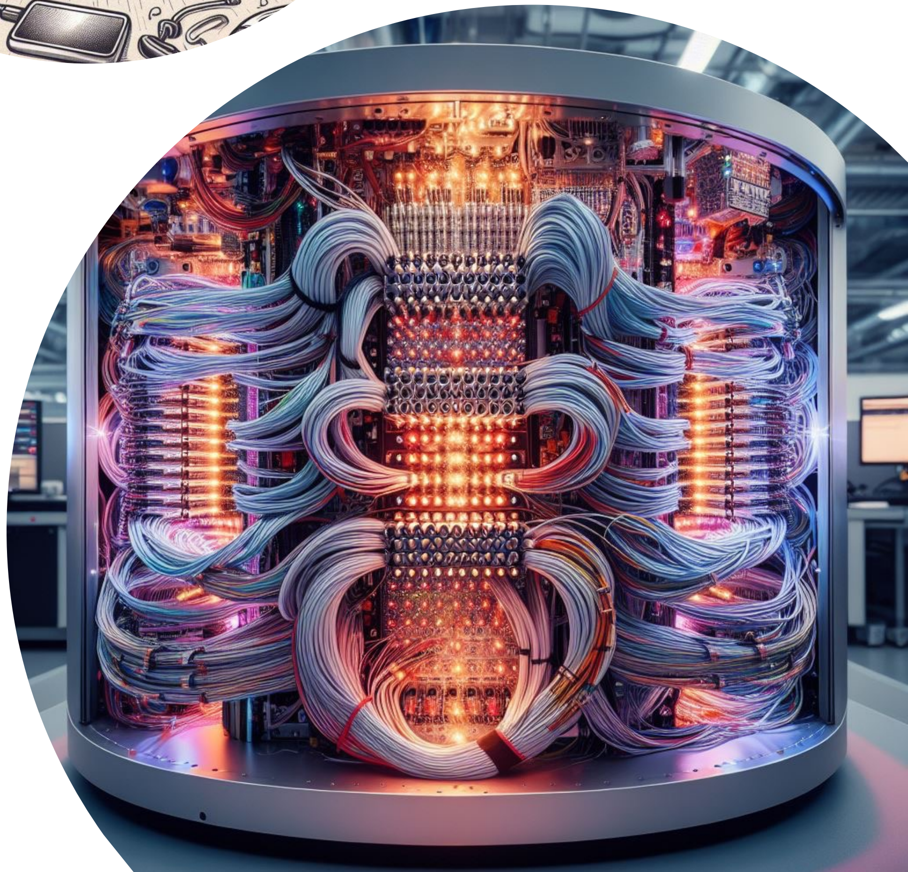
Quantum Properties

- Superposition - An object that is not being observed exists in all possible states (a combination of all the possible states)
- Entanglement - Any two quantum particles interact, they are entangled, and it means that their quantum states are interdependent. There's a correlation between them, so that if one is in one particular state, then the other one has to have some other particular state across space and time
- Decoherence – Loosing its quantum nature (measurements / external environment)
- Probabilistic *in Nature*
- Qubit - *Basic unit of Info (Quantum Bit)*

Why Quantum Computing?

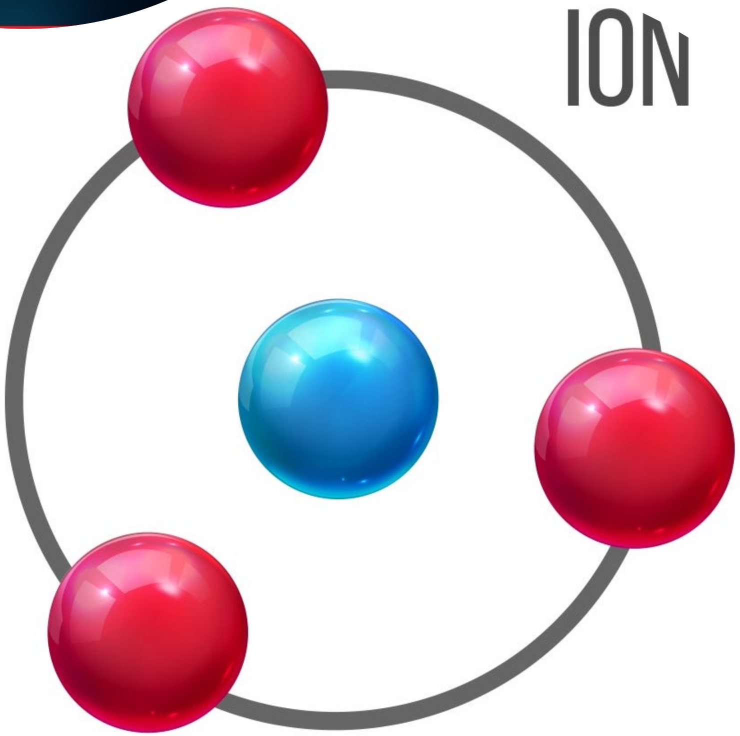
- Limitations of Classical Computers
- Complex problems (e.g., Large number factorisation)
- Quantum Parallelism
- Speed & Efficiency





Types of Quantum Computers*

- ***Superconducting Qubits QC-*** Use of superconducting materials, emphasizing quantum coherence E.g, IBM Quantum, Google Sycamore
- ***Trapped Ion QC*** Qubits are individual ions trapped and manipulated using electromagnetic fields. E.g, IonQ, HoneyWell
- ***Photonic QC****: Uses photons (particles of light) to represent qubits. E.g, Xanadu Quantum Technologies*
- ***Adiabatic QC****:* Uses quantum annealing to find the lowest energy state of a system representing the solution to a problem. E.g, D-Wave Systems
- ***Topological QC****:* Utilizes anyons(Quasiparticle), exotic particles that exist in certain two-dimensional materials. *E.g, Microsoft Quantum*



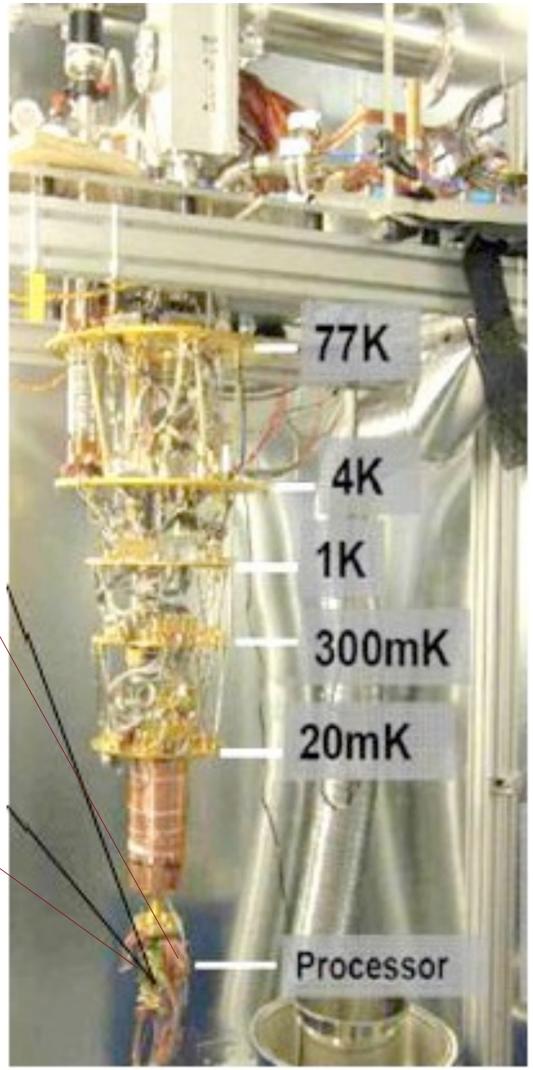
* Naming a few, as it's an exhaustive list

Quantum Computer Physically

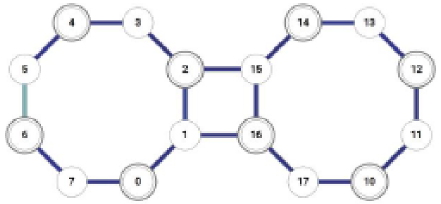
Superconducting Qubits

- Cooled to .015 Kelvin temperature, approximately 180 times colder than interstellar space.
- Shielded to 50,000 times less than the earth's magnetic field.
- Placed in a high vacuum: 10 billion times lower than atmospheric pressure.
- Placed on a low vibration floor

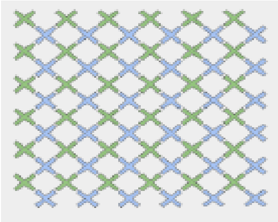
Quantum Processor



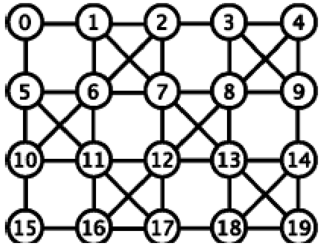
Dilution Refrigerator



Rigetti



Google

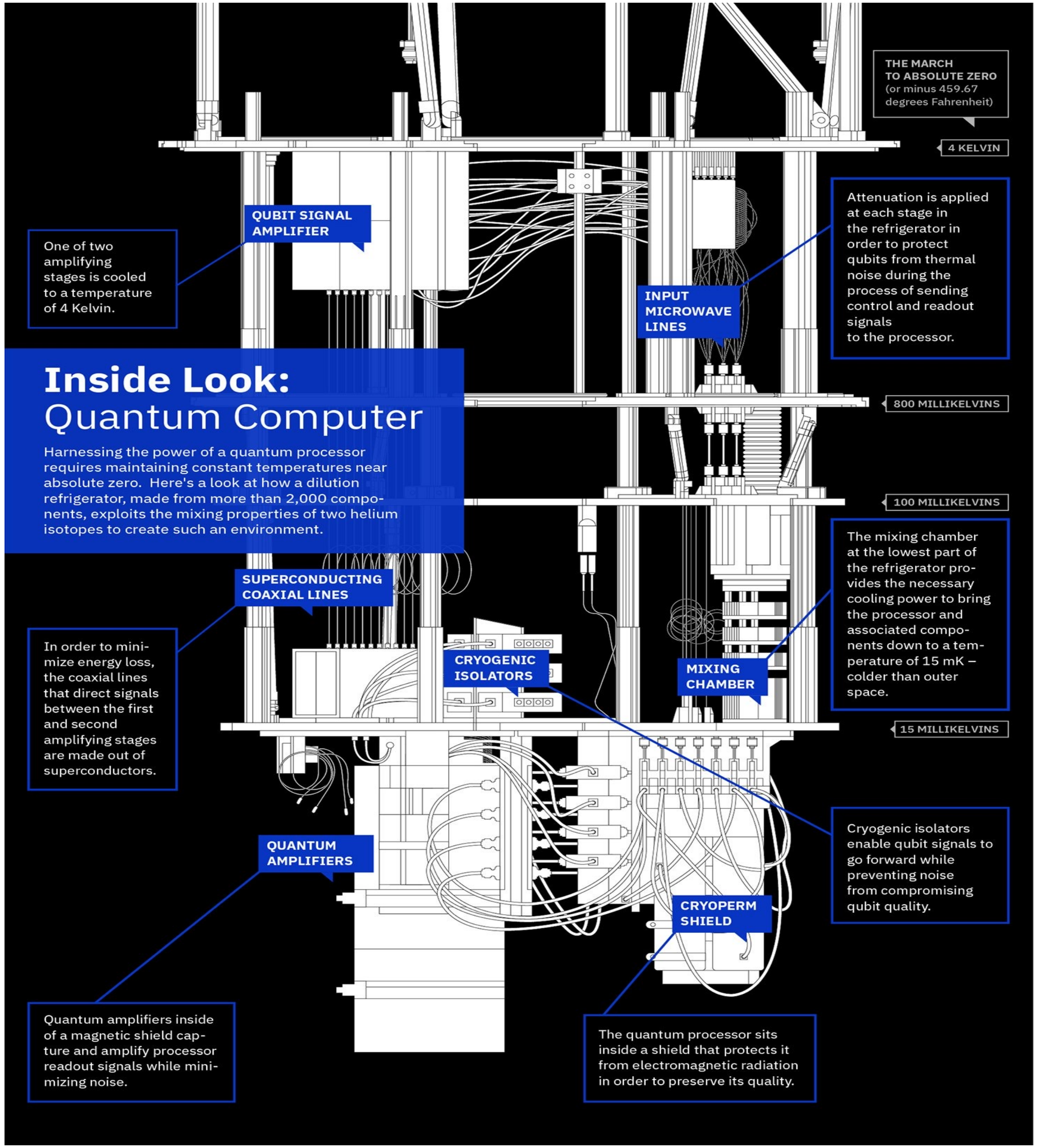


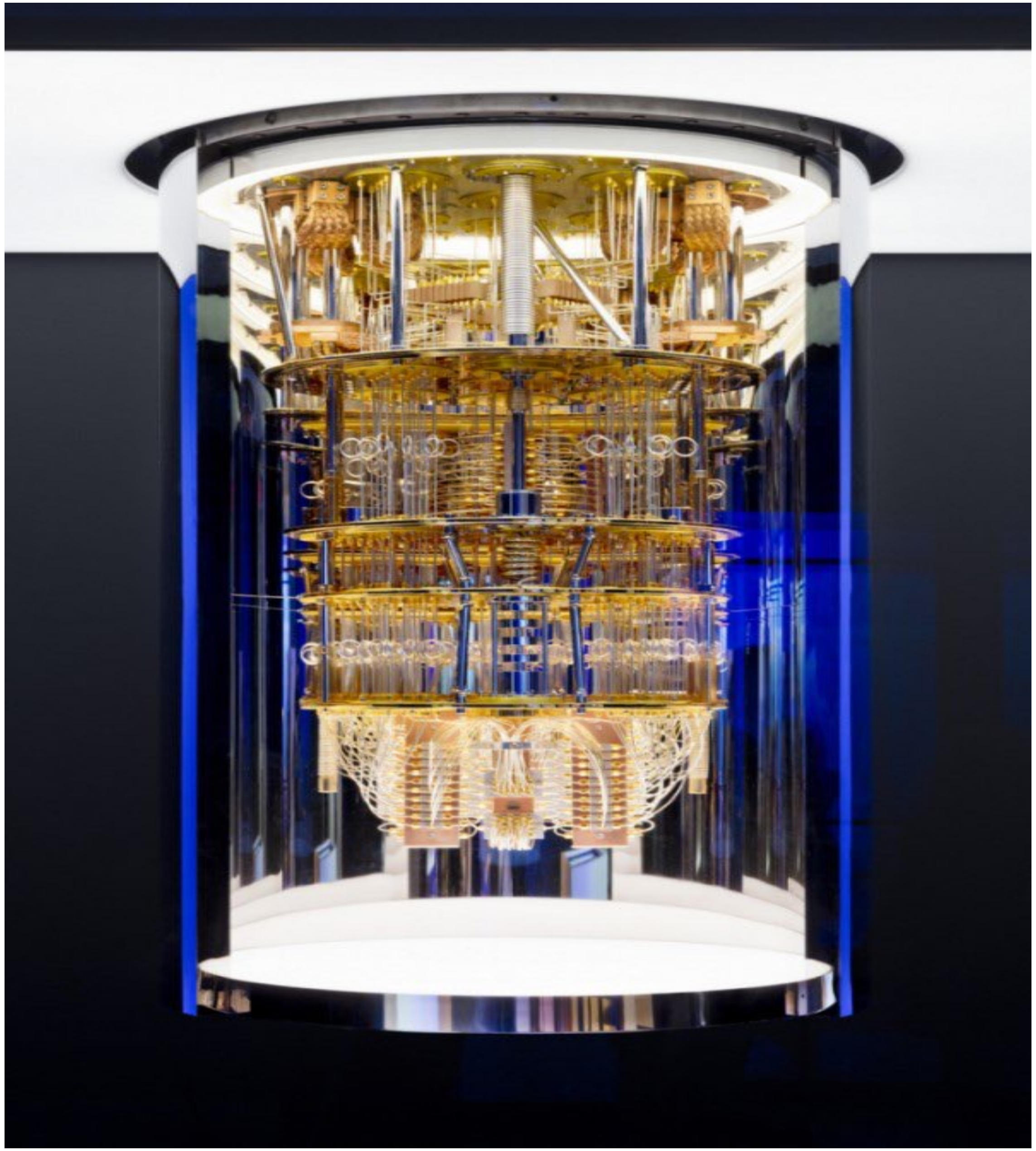
IBM

Intel

Source: Gartner

Real Quantum Computer Architecture (IBM)





Landscape

- *Major Players (IBM, Google, Microsoft and startups)*
- Collaborative initiatives between academia, industry, and government
- The National Quantum Mission (NQM) is a program by the Indian government with a budget of Rs. 6003.65 crore (approximately USD 740 million) over eight years, from 2023-24 to 2030-31

Potential Applications

- Cryptography and Security
  - Shor's algorithm: Breaking classical cryptographic system
- Optimization Problems
  - Traveling Salesman Problem (TSP) and other NP-hard problems
- Drug Discovery and Material Science
  - Simulating molecular structures with quantum algorithms

Real-world Impact

- Machine Learning and Artificial Intelligence
  - Quantum-enhanced machine learning algorithms (QML)
  - Speeding up training processes for complex models
- Financial Modeling
  - Portfolio optimization and risk analysis
  - Speeding up complex financial simulations
- Climate Modeling
  - Simulating complex climate models for accurate predictions
  - Addressing global challenges through quantum computation

Challenges and Future Developments

- *Quantum Decoherence*
- *Error Correction*
- *Quantum Algorithms*
- *Qubit Scaling (as of 2023 IBM Condor 1121 qubits)*

Q&A So far…

Qubits

- QBits are the unit of information in Quantum computers.

- Representation
  - Vectors
  - Matrices
  - Block Sphere (3D)

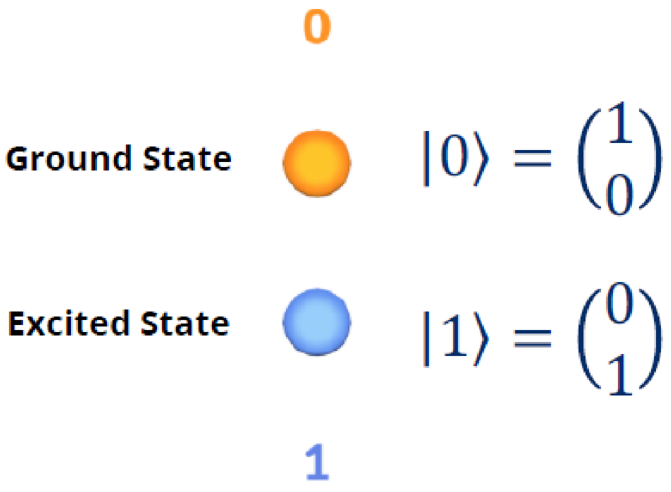
  (Ket Notation) |0> is represented as $\begin{matrix}1\\0\end{matrix}$ matrix.

  (Ket Notation) |1> is represented as $\begin{matrix}0\\1\end{matrix}$ matrix.

  (Ket Notation) |+> is represented as $\begin{matrix}1\\1\end{matrix}$ matrix.

  (Ket Notation) |-> is represented as $\begin{matrix}1\\-1\end{matrix}$ matrix.

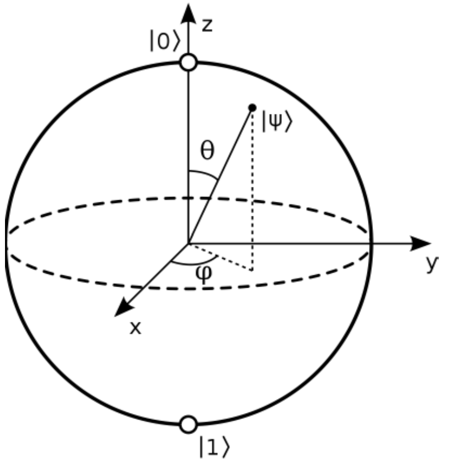
- Qubit: $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$
  - Here α & β are the amplitudes of the wave function of the qubit.



Representing Qubits Mathematics using Bloch sphere

- Just as we manipulate Bits for classical computation, we need to manipulate Qubits i.e. quantum states.
- To do so, we use **quantum gates**, which are represented as Unitary matrices!
    - Square matrix (Row = Columns)
    - $XX^T = I$

$$\boldsymbol{X} = \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{pmatrix}$$

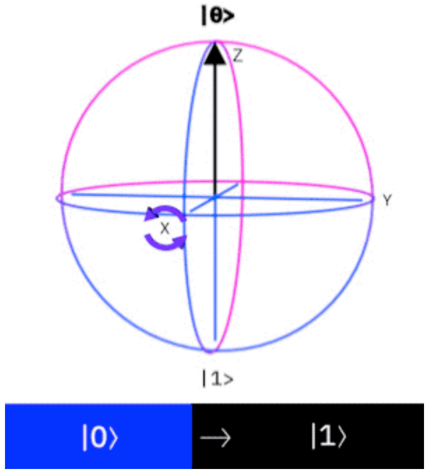


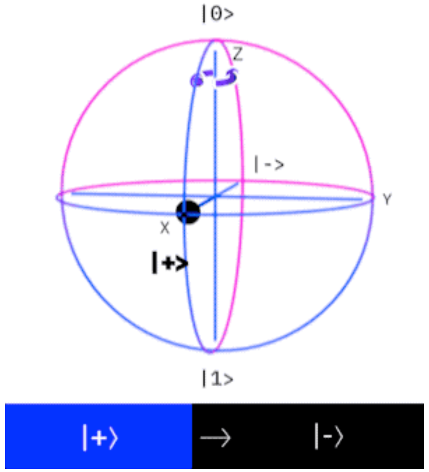
- Measurement of quantum state is done on some axis also called **Basis**.
- A Bloch-sphere is a representation of all positions of the ‘Normalized’ quantum particle in 3D space.
- The spin of the Qubit is measured along Z-axis as $|0\rangle$ and $|1\rangle$.

Qubit Operations- 1-qubit Pauli Gates

X $\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$ Bit-Flip Gate

Z $\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$ Phase-Flip Gate



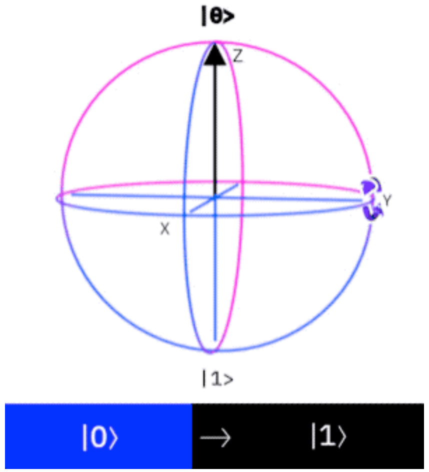


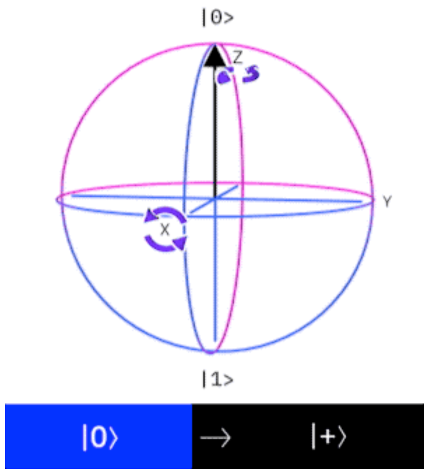
Input	Output of X gate
0	1
1	1

Input	Output of Z gate
0	0
1	-1

Y $\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$ Bit & Phase-Flip Gate

H $\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$ ***Superposition Gate***





Y Gate	Output of Y Gate
0	i1
1	-i0

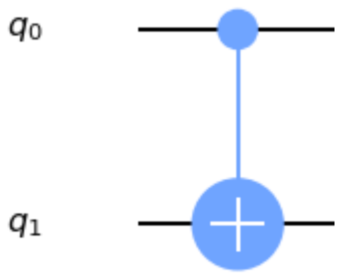
Input	Output of H gate
0	0+1/√2
1	0-1/√2

Qubit Operations- 2-qubit Basic Gates

CNOT

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}$$

Entanglement Gate



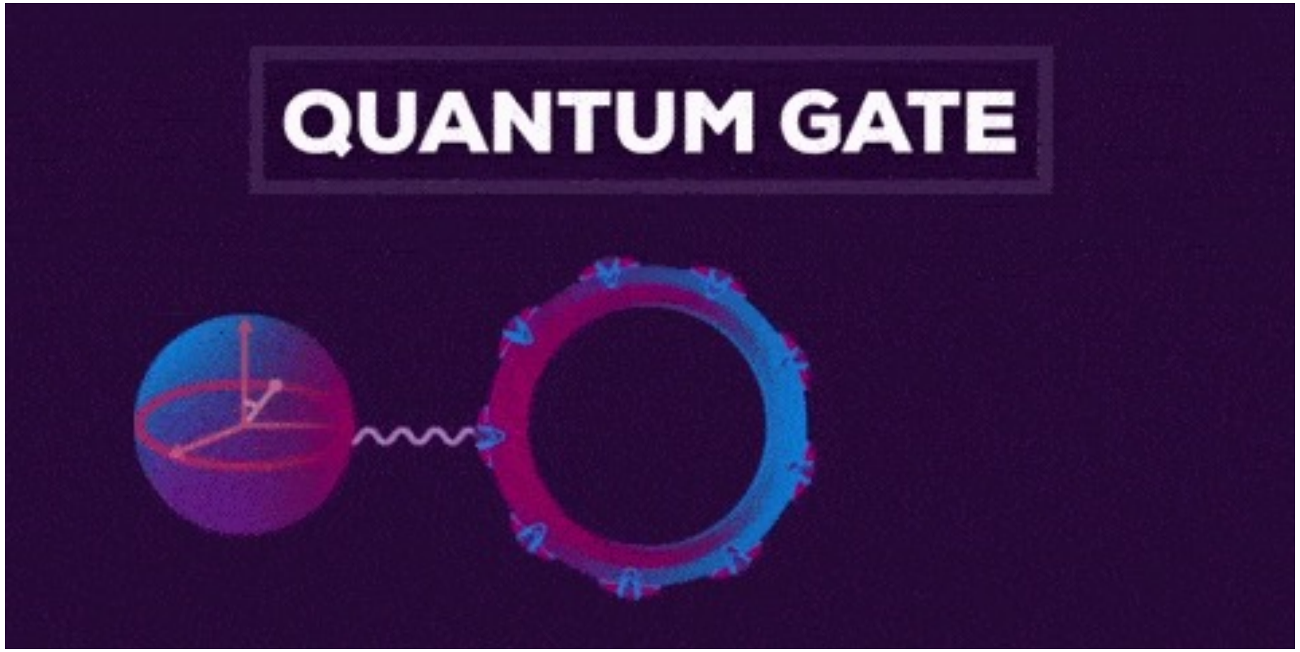
Input (t,c)	Output (t,c)
00	00
01	11
10	10
11	01

SWAP

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Gate Operation

$$\underset{X}{\begin{bmatrix}0 & 1\\ 1 & 0\end{bmatrix}}\ \underset{|0\rangle}{\begin{bmatrix}1\\ 0\end{bmatrix}} = \begin{bmatrix}0\text{x}1 + 1\text{x}0\\ 1\text{x}1 + 0\text{x}0\end{bmatrix} = \underset{|1\rangle}{\begin{bmatrix}0\\ 1\end{bmatrix}}$$

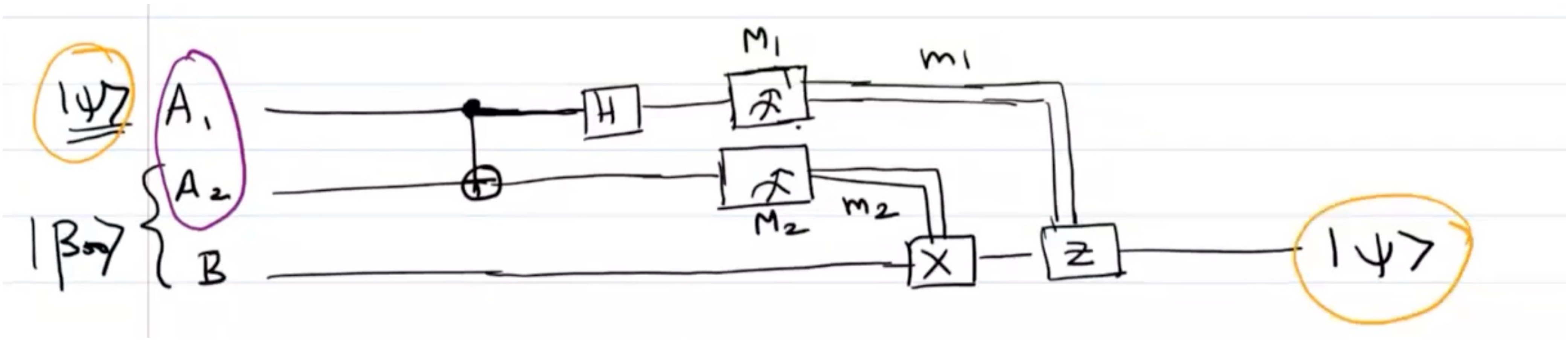


$$\underset{X}{\begin{bmatrix}0 & 1\\ 1 & 0\end{bmatrix}}\ \underset{X^T}{\begin{bmatrix}0 & 1\\ 1 & 0\end{bmatrix}} = \begin{bmatrix}0\text{x}0 + 1\text{x}1 & 0\text{x}1 + 1\text{x}0\\ 1\text{x}0 + 0\text{x}1 & 1\text{x}1 + 0\text{x}0\end{bmatrix} = \begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}$$

I = Identity Matrix

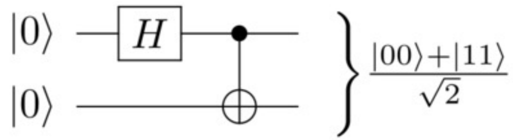
Quantum Teleportation Algorithm

Phenomena exhibit while transferring a state of information (qubit) from A->B. During such transfer the information at A will be destroyed and received at B , *i.e, without the qubit being transmitted through the intervening space.*



A1 = Source
A2 = Provided an entanglement between A and B
B = Destination

$|\beta_{00}\rangle =$



STEP 1

Assume A_1 ← Some Arbitary State $\Rightarrow \alpha|0\rangle + \beta|1\rangle$.

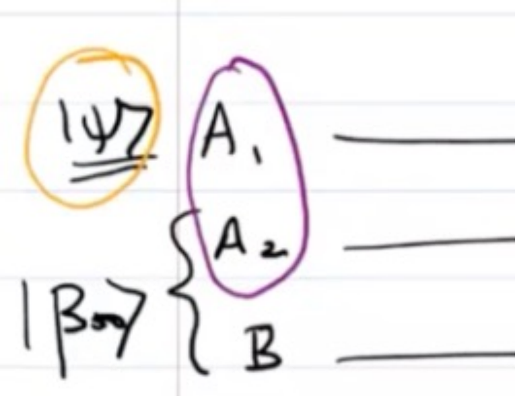
$$A_2 = \frac{1}{\sqrt{2}}\left(|00\rangle + |11\rangle\right)_{A_2 B}.$$

STEP 1

$A_1 \otimes A_2$.

$$\left[\alpha|0\rangle + \beta|1\rangle\right]_{A_1} \otimes \left[\frac{1}{\sqrt{2}}\left(|00\rangle + |11\rangle\right)_{A_2 B}\right]$$

$$\Rightarrow \frac{1}{\sqrt{2}}\left[\alpha|000\rangle + \alpha|011\rangle + \beta|100\rangle + \beta|111\rangle\right]_{A_1 A_2 B}$$



STEP 2 (CNOT)

STEP 2: APPLY CNOT b/w A_1 & A_2

$\Rightarrow$ e.g. $\alpha|000\rangle_{A_1A_2B} \Rightarrow \alpha|0_{A_1}\, 0_{A_2}\, 0_B\rangle \Rightarrow \alpha|000\rangle$

Control Target

Remember. CNOT gate control & target flip.

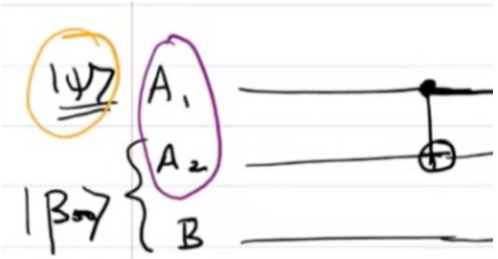
C	T	
0	0 => 0	0
0	1 => 0	0
1	0 => 1	1
1	1 => 1	0

Lets apply CNOT now.

$$\Rightarrow \frac{1}{\sqrt{2}}\left[\alpha|000\rangle + \alpha|011\rangle + \beta|100\rangle + \beta|111\rangle\right]_{A_1A_2B}$$

Become

$$\Rightarrow \frac{1}{\sqrt{2}}\left[\alpha|000\rangle + \alpha|011\rangle + \beta|1\underset{\text{change}}{\underline{1}}0\rangle + \beta|\underset{\text{change}}{101}\rangle\right]$$



STEP 3 (Hadamard)

Step 3 Apply H on A_1

Splitting A_1 alone

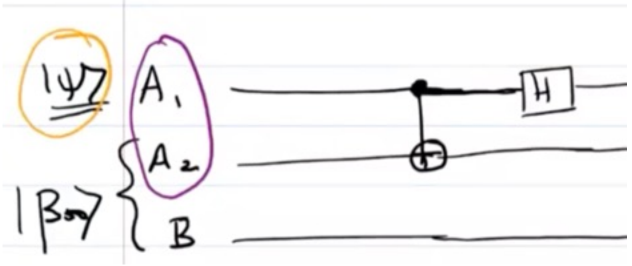
$$\Rightarrow \frac{1}{\sqrt{2}}\Big[\alpha|0\rangle_{A_1}|00\rangle_{A_2B} + \alpha|0\rangle_{A_1}|11\rangle_{A_2B} + \beta|1\rangle_{A_1}|10\rangle_{A_2B}$$

$$+ \beta|1\rangle_{A_1}|01\rangle_{A_2B}\Big]$$

Apply H on A_1

$$\Rightarrow \frac{1}{\sqrt{2}}\Big[\alpha|00\rangle_{A_2B}\left[\frac{|0\rangle+|1\rangle}{\sqrt{2}}\right]_{A_1} + \alpha|11\rangle_{A_2B}\left[\frac{|0\rangle+|1\rangle}{\sqrt{2}}\right]_{A_1} + \dots$$

$$+ \dots \beta\left[\frac{|0\rangle-|1\rangle}{\sqrt{2}}\right]_{A_1}|10\rangle_{A_2B} + \beta\left[\frac{|0\rangle-|1\rangle}{\sqrt{2}}\right]|01\rangle_{A_2B}\Big)$$



STEP 4 (Taking common factors)

$$\Rightarrow \frac{1}{2}\Big[\alpha|000\rangle + \alpha|100\rangle + \alpha|010\rangle + \alpha|111\rangle$$

$$+\beta|010\rangle - \beta|110\rangle + \beta|001\rangle - \beta|101\rangle\Big]_{A_1A_2B}$$

$$\Rightarrow \frac{1}{2}\Big[|00\rangle\,[\alpha|0\rangle + \beta|1\rangle] + |01\rangle\,[\alpha|1\rangle + \beta|0\rangle]$$

$$+|10\rangle\,[\alpha|0\rangle - \beta|1\rangle] + |11\rangle\,[\alpha|1\rangle - \beta|0\rangle]$$

$$\Rightarrow \frac{1}{2}\Big[|00\rangle_{A_1A_2}\,\underline{[\alpha|0\rangle + \beta|1\rangle]}_B + |01\rangle_{A_1A_2}\,[\underline{\alpha|1\rangle + \beta|0\rangle}]_B$$

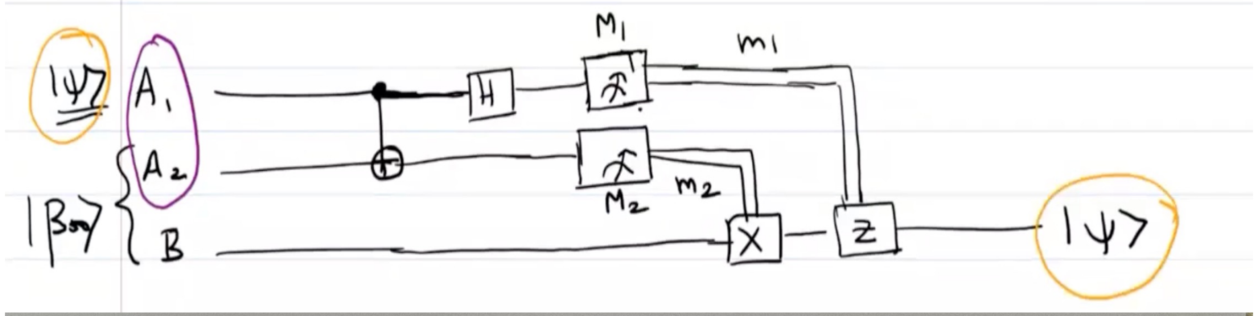
$$+|10\rangle_{A_1A_2}\,[\underline{\alpha|0\rangle - \beta|1\rangle}] + |11\rangle_{A_1A_2}\,[\underline{\alpha|1\rangle - \beta|0\rangle}]_B$$

STEP 5 (Applying Conditional Gates)

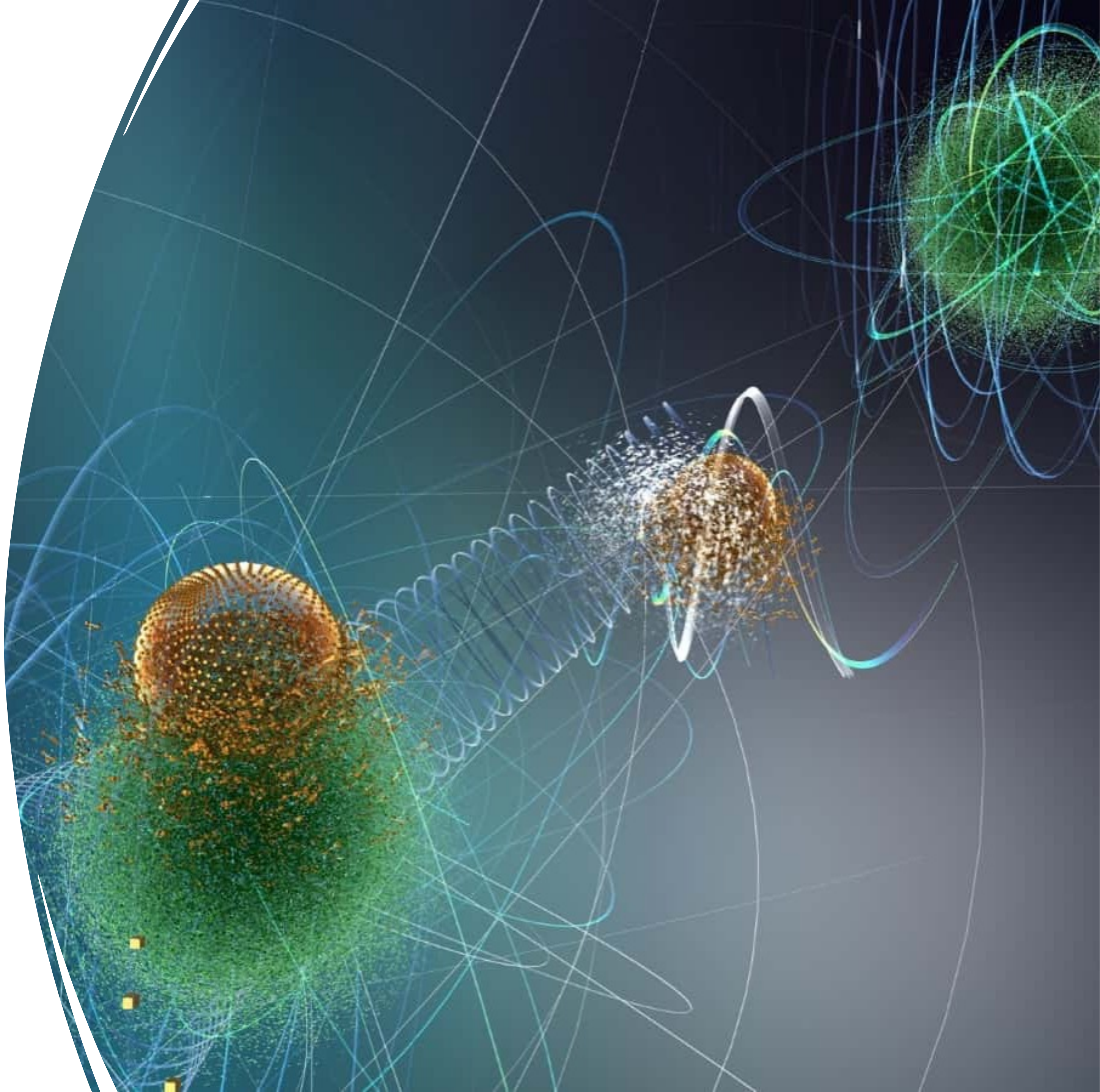
Now, using the 2 classical bit from A_1 & A_2 That are measure. we will perform Certain below operations to retrieve $|\psi\rangle$ on B.

A_1	A_2	Gate operation on B	
0	0	I	$\alpha|0\rangle + \beta|1\rangle$
0	1	X - Gate	$\alpha|0\rangle + \beta|1\rangle$
1	0	Z - gate	$\alpha|0\rangle + \beta|1\rangle$
1	1	Z - X gate	$\alpha|0\rangle + \beta|1\rangle$

Thus the original value of State $|\psi\rangle$ has been destroyed at A & retreived at B.



How hard is to teleport an atom?



- ❖ Photons have very few pairs of parameters: colour, duration, amplitude, phase, beam size, and polarisation. That's about it.
- ❖ Recent discoveries have led to the teleportation of photons.
- ❖ So, with further development in technology, it wouldn't be tough enough to teleport the atom shortly

Research Credits: Biswajit Pratihari

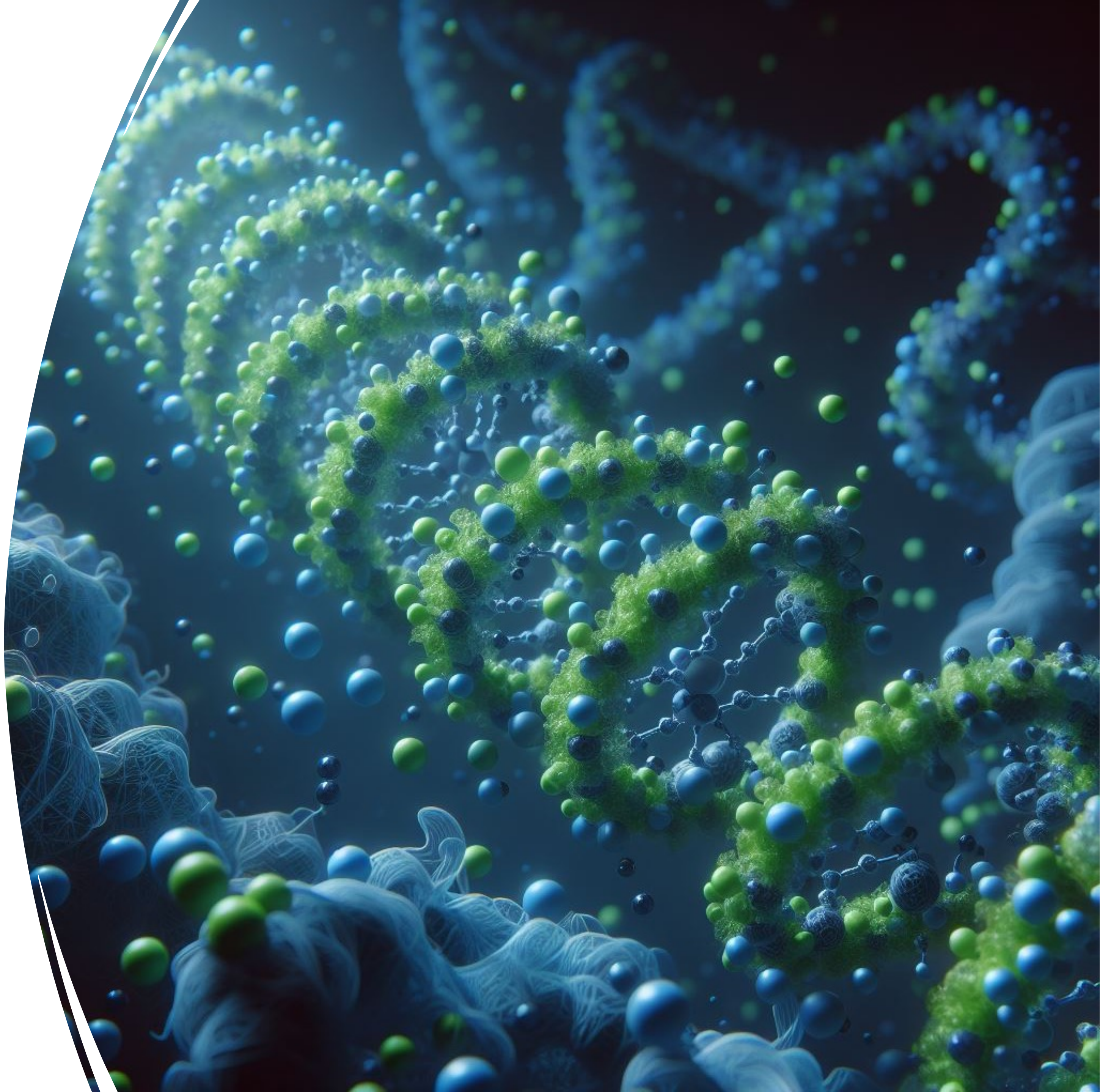
How hard is to teleport a Living organism ?

- To date, there are a few science experiments that have created life. The smallest living organism is the viroid. Some are as small as 10,000 atoms.

- So far scientists have teleported only one pair of information.

- Teleporting a viroid is 100*10,000 times (10^6 times) harder= roughly a million times.

Research Credits: Biswajit Pratihari



How hard is to teleport a human ?

- There are about 10^{27} atoms in a person.
- With 100 parameter pairs per atom, we have about $10^{29 \text{ pair}}$ of information (10^{29} times harder)
- For a person to be transported, a machine would have to be built that can pinpoint and analyse all of 10^{27} atoms that make up the human body

Research Credits: Biswajit Pratihari

Developments so far…

- **In 2002**, some researchers at the Australian National University successfully teleported a laser beam.
- **In 2004**, researchers from the University of Vienna and the Austrian Academy of Science teleported particles of light over a distance of 600m using Optical Fibre.
- **In Oct 4,2006,** at the Neil Bohr's Institute, Denmark, Dr. Polzik and his team teleported information stored in a laser beam into a cloud of atom across 1.6 feet. It involves teleportation between light and matter, two different objects.

- **In May 2010**, a team of 15 Chinese researchers from Tsinghua University in Beijing and the Hefei National Laboratory achieved secure quantum-key distribution over 16 kilometres of free-space.
- **In April 2011**, physicist at University of Tokyo, teleported a complex set of quantum information from one point to another.
- **In May 2012**, an international research team including several scientists from the University of Waterloo has achieved quantum teleportation over a record-breaking distance of 143 kilometres through free-space between the two Canary Islands of La Palma and Tenerife off the Atlantic coast of North Africa.

Research Credits: Biswajit Pratihari

Q&A

Reference materials

- Quantum Computation and Quantum Information – Nielsen and Chuang (A Quantum Bible)
- “Quantum Computing and Quantum Information” Youtube Playlist by Prabha Mandayam
- Get Start with Qiskit- IBM Quantum Programming way
- Get Start with Q# - Microsoft Azure Quantum way