

UNIT 1: INTRODUCTION TO QUANTUM THEORY AND TECHNOLOGIES

1)The transition from classical to quantum physics:

The transition from **classical to quantum physics** marked one of the most profound revolutions in the history of science. It occurred primarily in the early 20th century, as physicists encountered phenomena that classical physics couldn't explain. Here's an overview of this transformation:

🌟 1. Classical Physics Overview

Classical physics, based on Newtonian mechanics, Maxwell's electromagnetism, and thermodynamics, worked well for describing:

- Motion of macroscopic objects
- Planetary dynamics
- Electricity and magnetism
- Heat and energy transfer

However, it began to **fail at microscopic scales** (atoms, electrons, photons).

⚠️ 2. Key Failures of Classical Physics

Classical theories could not explain:

Phenomenon	Classical Prediction	Actual Observation
Blackbody Radiation	Infinite energy at short wavelengths ("ultraviolet catastrophe")	Energy peaks and drops at high frequencies
Photoelectric Effect	Light energy depends on intensity	No electrons emitted below a certain frequency, regardless of intensity
Atomic Spectra	Continuous spectrum	Discrete spectral lines (e.g., hydrogen)
Stability of Atoms	Electrons should spiral into nucleus	Atoms are stable in nature

💡 3. Birth of Quantum Theory (Key Milestones)

Year	Scientist	Discovery
1900	Max Planck	Proposed energy quantization: $E = h\nu$
1905	Albert Einstein	Explained photoelectric effect using photons (quantum of light)

Year	Scientist	Discovery
1913	Niels Bohr	Quantized orbits in hydrogen atom
1924	Louis de Broglie	Wave-particle duality of matter
1926	Erwin Schrödinger	Developed wave mechanics (Schrödinger equation)
1927	Werner Heisenberg	Introduced uncertainty principle
1928	Paul Dirac	Combined quantum mechanics and relativity (Dirac equation)

🔗 4. Fundamental Differences

Aspect	Classical Physics	Quantum Physics
Nature	Deterministic	Probabilistic
Energy	Continuous	Discrete (quantized)
Wave-Particle Duality	Separate concepts	Unified dual nature
Measurement	Does not affect system	Observer affects outcome
Position & Momentum	Known simultaneously	Uncertainty principle applies

📦 5. Philosophical Implications

- **Quantum superposition:** A particle can exist in multiple states at once.
- **Entanglement:** Particles can be connected instantly across distance.
- **Observer effect:** Measurement collapses the wave function to a definite state.

These led to deep philosophical questions and interpretations (e.g., Copenhagen interpretation, Many-Worlds, etc.).

🚀 6. Impact and Applications

Quantum theory laid the foundation for:

- Semiconductors and electronics
- Lasers
- MRI and other medical imaging
- Quantum computing and cryptography
- Understanding of atomic and subatomic particles

2) Fundamental principles explained conceptually: Superposition, Entanglement, Uncertainty Principle, Wave-particle duality, Classical vs Quantum mechanics – theoretical comparison, Quantum states and measurement:

Here's a **conceptual explanation** of the **fundamental principles of quantum physics**, comparing them with classical physics where needed. Each concept is broken down simply and clearly:

◆ 1. Superposition

🔗 Concept:

- In quantum mechanics, a system (like an electron or photon) can exist in **multiple possible states at once** until it is measured.
- This is called a **superposition** of states.

□ Analogy:

- Imagine a spinning coin: before it lands, it's **both heads and tails** — only when you observe it (measure) does it become one or the other.

□ Example:

- An electron in an atom doesn't have a single fixed location; it exists in a **cloud of probabilities** until you look for it.
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◆ 2. Entanglement

🔗 Concept:

- Two quantum particles can become **entangled**, meaning their states are **strongly correlated**, no matter how far apart they are.
- Changing one instantly affects the other — even if they are light-years away.

□ **Analogy:**

- Like a pair of gloves in separate boxes: if you open one and see a left glove, you **instantly** know the other box has the right glove — but with entanglement, it's more than this — the states aren't decided **until** one is observed.

□ **Weird but true:**

- Entanglement defies classical ideas of locality. It was famously called “**spooky action at a distance**” by Einstein.
-

◆ 3. Uncertainty Principle (Heisenberg's)

🔗 **Concept:**

- You cannot know both the **position** and **momentum** of a particle **exactly at the same time**.
- The more precisely you measure one, the less precisely you can know the other.

□ **Analogy:**

- Like trying to photograph a fast-moving car: if you get a clear photo of the car's location (still frame), it blurs the speed. If you capture speed (motion blur), you lose the exact position.

∞ **Formula:**

$$\Delta x \cdot \Delta p \geq h4\pi \Delta x \cdot \Delta p \geq \frac{h}{4\pi}$$

◆ 4. Wave-Particle Duality

🔗 **Concept:**

- Particles like electrons and photons can **behave like particles and waves**.
- They don't just travel like marbles; they can **interfere** and **diffract** like ripples in water.

□ **Analogy:**

- Like light being both a beam and a ripple, depending on how you observe it.

□ **Double-Slit Experiment:**

- If you shoot one photon at a time through two slits, it creates a wave interference pattern — **as if it went through both slits simultaneously** — until you measure it.

◆ 5. Classical vs. Quantum Mechanics – Theoretical Comparison

Feature	Classical Mechanics	Quantum Mechanics
Determinism	Predictable outcomes	Probabilistic outcomes
State	Well-defined (e.g., position, velocity)	Described by wavefunction
Measurement	Does not affect system	Collapses wavefunction
Particles/Waves	Separate concepts	Unified (duality)
Scales	Macroscopic (planets, projectiles)	Microscopic (atoms, photons)
Causality	Local cause-effect	Nonlocal correlations (entanglement)

◆ 6. Quantum States and Measurement

🔗 Concept:

- A **quantum state** describes all possible information about a system (via a wavefunction).
- When measured, this state **collapses** to one specific outcome.

□ Analogy:

- Like a spinning roulette wheel with all possibilities. Measurement is like the ball landing on one number — the outcome is real **only** after you observe it.

★ Key Ideas:

- Before measurement: system is in a **superposition** of states.
 - After measurement: system collapses into a **definite state**.
 - The act of observing **changes** the system.
-

✓ Summary Table

Principle	Key Idea	Classical View	Quantum View
Superposition	Many states at once	One state only	All possible states until measured
Entanglement	Linked particles	No long-distance influence	Instant connection regardless of distance
Uncertainty	Limits of knowledge	Know everything precisely	Built-in fuzziness in nature
Wave-Particle Duality	Dual behavior	Either particle or wave	Both, depending on observation
Measurement	Observing a system	Passive action	Actively affects the system
Quantum State	Complete description	Precise numbers	Probabilities encoded in wavefunction

3) Nature Of Observation, Overview Of Quantum Systems:

Here's a **clear and conceptual explanation** of the **nature of observation** in quantum physics and an **overview of quantum systems**:

🔍 Nature of Observation in Quantum Physics

🔪 1. Observation Is Not Passive

In classical physics, observing something (like a planet) doesn't affect it. But in quantum physics, **observation changes the system**.

💡 2. Wavefunction Collapse

- A quantum particle exists in a **superposition** — multiple possible states.
- When you **measure** it, the wavefunction **collapses** into a single definite state.
- You don't just **discover** what was there — you actually **decide** what it becomes.

□ **Analogy:**

- Like a spinning dice that shows all numbers at once — but once you look, it “chooses” just one number.

🌀 **3. Role of the Observer**

- The observer doesn’t have to be a human. Even a **detector or measuring instrument** counts as an observer.
- The key idea: **interaction** with the system defines the outcome.

⚠️ **4. Quantum Measurement Paradox**

- Example: Schrödinger’s Cat is **both alive and dead** until observed.
- This highlights how strange and unintuitive the quantum world is compared to everyday experience.

📖 [Overview of Quantum Systems](#)

Quantum systems are **physical systems** that behave according to **quantum mechanics** — they are typically very small (atoms, electrons, photons, etc.) and display non-classical behaviors.

◆ **1. Basic Components of a Quantum System**

Element	Description
Quantum state	Describes all possible information (via wavefunction ψ)
Wavefunction	Mathematical function giving probabilities for outcomes
Observable	Measurable quantities (position, momentum, energy, spin)
Operator	Mathematical tool used to get values of observables
Hilbert space	Abstract space in which quantum states "live"

◆ 2. Types of Quantum Systems

System	Example	Behavior
Two-level system	Spin-½ particle, qubit	Only two possible states (e.g., up/down)
Harmonic oscillator	Vibrating atom or molecule	Discrete energy levels like a quantum spring
Multi-particle system	Electrons in an atom	May be entangled, obey Pauli exclusion
Quantum field	Photons in a field	Infinite degrees of freedom (used in QFT)

◆ 3. Quantum Behaviors in Systems

Feature	Description
Superposition	System exists in multiple possible states at once
Entanglement	Parts of a system become inseparably linked
Quantization	Energy, momentum, etc., come in discrete units
Tunneling	Particle can pass through barriers it classically shouldn't
Non-locality	Instant correlations between distant parts (entanglement)
Interference	Probabilities from different paths can combine constructively or destructively

◆ 4. Applications of Quantum Systems

Field	Application
Quantum Computing	Qubits use superposition and entanglement for faster computing
Quantum Cryptography	Unbreakable encryption using entangled photons
Quantum Sensing	Ultra-sensitive sensors for magnetic or gravitational fields
Quantum Chemistry	Predicting molecular behavior with quantum models
Lasers and Electronics	Based on transitions in quantum energy levels

✓ Summary

□ Nature of Observation

- Observation causes a **change** (collapse of wavefunction).
- **Observer interaction defines reality** in quantum terms.

✿ □ Quantum Systems

- Built on **wavefunctions**, **operators**, and **probabilities**.
- Behave in non-intuitive ways (superposition, entanglement, tunneling).
- Form the foundation of modern technologies like **quantum computing** and **nanotech**.

4. Electrons, Photons, Atoms, The Concept Of Quantization: Discrete Energy Levels, Why Quantum? Strategic, Scientific, And Technological Significance, A Snapshot Of Quantum Technologies:

Here's a **comprehensive yet clear conceptual explanation** of the topics you asked for, ideal for academic notes, presentations, or general understanding:

✿ □ Electrons, Photons, Atoms – The Quantum World's Building Blocks

◆ Electrons

- **Subatomic particles** with negative charge.
- Exhibit **wave-particle duality** — behave like both particles and waves.
- Cannot be pinned to a single location; exist in **orbitals**, not orbits.
- Have **spin**, a purely quantum property (not literal spinning).

◆ Photons

- **Quantum particles of light** or electromagnetic radiation.
- Massless but carry energy $E = h\nu$ and momentum.
- Always move at the speed of light.
- Show **quantum behaviors** like interference, entanglement, and the photoelectric effect.

◆ Atoms

- **Basic units of matter**, composed of a nucleus (protons & neutrons) and electrons.
 - Electrons occupy **quantized energy levels** — they can jump between levels but not exist in between.
 - Atoms form the basis for understanding matter, chemistry, and light-matter interaction.
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◆ The Concept of Quantization: Discrete Energy Levels

🔗 What Is Quantization?

- Quantization means certain properties (like energy, angular momentum) can **only take specific values**, not any value.
- Think of it like **stairs**, not a **ramp** — electrons jump from one step to another but can't be in between.

📖 Example: The Hydrogen Atom

- Electrons around the nucleus can occupy **only specific orbits** (energy levels).
- When an electron jumps to a lower level, it emits a **photon** of a particular frequency.
- This explains **atomic spectra** — unique for each element.

🎯 Why It Matters

- Quantization explains:
 - Atomic stability
 - Spectral lines
 - Semiconductor behavior
 - Laser operation
-

? Why Quantum? Strategic, Scientific & Technological Significance

🌐 Strategic Importance

- Quantum tech is a **global race** — nations are investing heavily due to its defense and cybersecurity applications.
- Quantum communication enables **ultra-secure data transfer**, immune to hacking.
- Quantum sensors can detect changes at scales classical instruments cannot — vital for **navigation, surveillance, and intelligence**.

Scientific Significance

- Helps us understand the **fundamental nature** of reality.
- Essential in **modern physics, chemistry, biology, and materials science**.
- Explains phenomena that classical theories fail to.

Technological Significance

- Powers innovations in:
 - **Computing**: solving complex problems in seconds
 - **Cryptography**: unhackable communication systems
 - **Imaging**: more precise medical scans
 - **Sensors**: atomic-scale sensitivity for navigation, geology, etc.

A Snapshot of Quantum Technologies

Quantum Technology	What It Does	Real-World Use
Quantum Computing	Uses qubits to perform many calculations simultaneously	Drug discovery, AI, cryptography
Quantum Cryptography	Provides secure communication using entangled photons	Military-grade data encryption
Quantum Sensors	Detect minuscule changes in magnetic/gravitational fields	Submarine navigation, medical imaging
Quantum Simulators	Mimic complex systems (like molecules) to study their behavior	Material science, molecular chemistry
Quantum Imaging	Uses quantum properties of light to improve resolution	Biomedical imaging, low-light vision
Quantum Internet	Networks using entangled states for ultra-secure data transmission	Secure national and international communication infrastructure

📄 Summary

Concept	Key Idea
Electrons, Photons, Atoms	Quantum objects with wave-particle duality
Quantization	Physical properties exist in discrete levels, not continuous values
Why Quantum?	Drives scientific understanding, national security, and next-gen technologies
Quantum Technologies	Includes computing, communication, sensors, and more — transforming multiple industries

5. Computing, Communication, and Sensing, National and global quantum missions: India's Quantum Mission, EU, USA, China

Here is a **clear and structured explanation** of:

1. **Quantum applications in Computing, Communication, and Sensing**
2. **National and global quantum missions**, including India's Quantum Mission and efforts by the EU, USA, and China.

📄 Quantum Applications: Computing, Communication, and Sensing

◆ 1. Quantum Computing

- **Uses qubits** instead of classical bits (0 or 1).
- Qubits can be in **superposition** (0 and 1 at once) and **entangled** with others.
- **Massive parallelism** allows solving certain problems exponentially faster than classical computers.

Applications:

- Drug discovery and protein folding (e.g., pharma)
- Optimization in logistics and finance
- Breaking classical encryption (long-term risk)
- AI and machine learning acceleration

◆ 2. Quantum Communication

- Based on **quantum entanglement** and **quantum key distribution (QKD)**.
- Any attempt to eavesdrop **destroys the entanglement**, alerting the users.
- Enables **unbreakable encryption** and **secure networks**.

Applications:

- Military & diplomatic communication
 - Secure banking and finance transactions
 - Future **quantum internet**
-

◆ 3. Quantum Sensing

- Uses quantum effects (superposition, entanglement, tunneling) to detect ultra-small changes.
- More sensitive and accurate than classical sensors.

Applications:

- GPS-free navigation (e.g., in submarines)
 - Medical imaging (e.g., brain scans)
 - Geological exploration
 - Detection of gravitational waves or magnetic fields
-

National and Global Quantum Missions

IN India: National Quantum Mission (NQM)

- **Launched:** April 2023, by the Government of India
- **Budget:** ₹6003 crore (approx. \$730 million)
- **Timeframe:** 2023–2031 (8 years)
- **Objective:** Position India among top nations in quantum technologies

Key Targets:

- Develop **quantum computers** with up to 1000 qubits by 2031
 - Build **secure quantum communication** systems
 - Develop **quantum sensors** for precision navigation, health, and defense
 - Set up **four Thematic Hubs (T-Hubs)** in leading institutions (IITs, IISERs, etc.)
-

EU European Union: Quantum Flagship

- **Launched:** 2018
- **Budget:** €1 billion over 10 years
- **Goal:** Strengthen Europe's position in quantum technologies

Key Areas:

- Quantum computing platforms (hardware & software)
 - Quantum simulation
 - Secure quantum communication (e.g., EuroQCI – quantum internet)
 - Quantum metrology and sensors
-

US USA: National Quantum Initiative (NQI)

- **Launched:** 2018 (signed into law by Congress)
- **Agencies involved:** NSF, NIST, DOE, and private sector (Google, IBM, etc.)
- **Goal:** Maintain US leadership in quantum R&D

Key Efforts:

- National Quantum Coordination Office
 - \$1.2+ billion funding
 - Multiple **Quantum Centers** across national labs and universities
 - Public-private partnerships in **quantum computing and networking**
-

CN China: Quantum Development Roadmap

- **Strong government investment** and world leadership goals
- World's first **quantum satellite (Micius)** launched in 2016 for quantum communication
- Built the **longest quantum communication network** (Beijing–Shanghai)
- Leading in **quantum supremacy experiments** (e.g., Jiuzhang photonic computer)

Focus Areas:

- Quantum cryptography and national security
 - Quantum computing and cloud access
 - Quantum metrology and satellites
 - Global quantum infrastructure dominance
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✓ Summary Table

Country/Region	Mission	Focus Areas	Budget
India IN	National Quantum Mission (NQM)	Computing (1000-qubit goal), QKD, sensors	₹6003 Cr (~\$730M)
EU EU	Quantum Flagship	All quantum pillars: compute, sense, secure	€1 billion
USA us	National Quantum Initiative	Research centers, workforce, industry	\$1.2+ billion
China CN	National Strategy	Satellite QKD, supremacy, infrastructure	Est. \$10+ billion

Qubit using spin :- UNIT-2 :-

→ Electrons behave like tiny magnets with "spin": up = 0, down = 1;

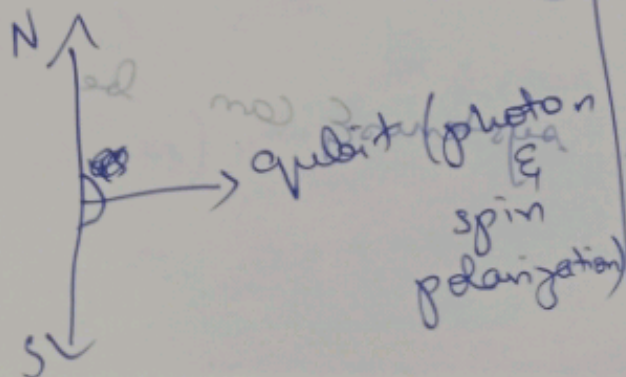
Quantum rules allow spin to be blend of up & down @ same time (Superposition)

Qubit using photon polarization :-

Light waves can be allow horizontal / vertical vibrations called "polarisation": hori = 0; vert = 1

A qubit can be tilted b/w N & S (or) to show spin

polarised diagonally
photon polarization



Scientists use different "carriers of quantum information"

① Trapped ions:

Single atoms held in place using electromagnetic "traps".

Each atom has internal energy levels where

ground state: 0; excited state: 1

Shining lasers at the ions, they can be put into

superposition.

② Superconducting Circuits:

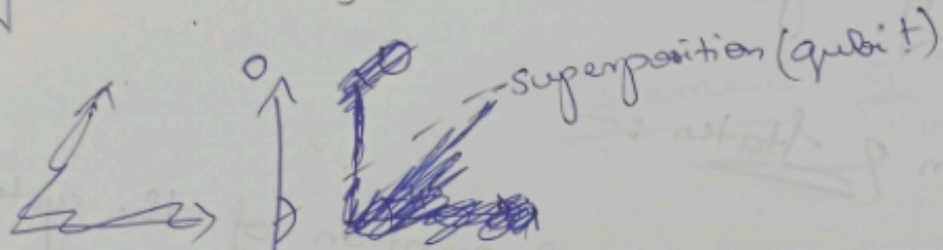
→ Tiny electrical circuits made from non-resistant materials (close to absolute zero) carry current (0) & current (1) (or a mix)

of both in quantum systems & can be

controlled using microwave pulses to excite them into different states.

Photons:

↳ Tiny particles of light that travel super fast & rarely interact with the environment.



Quantum Coherence & Decoherence:-

For a qubit to stay in a delicate balance b/w 0 & 1, it exists in superposition also known as "Coherence". ~~The~~ In real life, qubits interact with their environment (air, heat, vibrations) which "disturb" the delicate balance causing the superposition to collapse known as "Decoherence".

Theoretical Concepts:

1. Hilbert Space :-

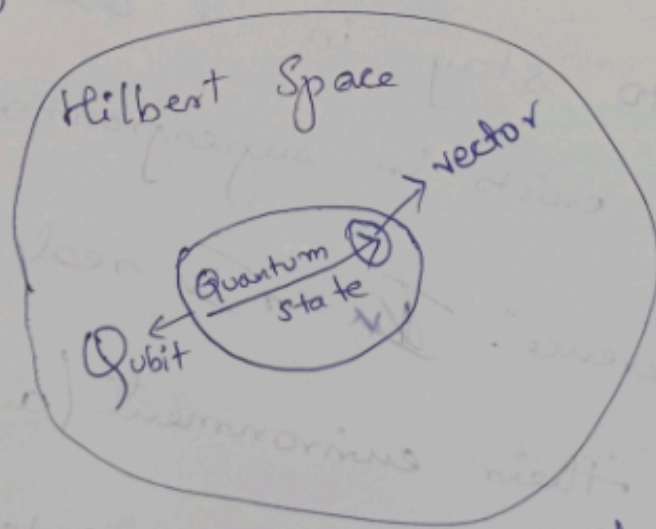
↳ The space where all possible quantum states live.

↳ Arena of possibilities.

2. Quantum States :-

↳ It is one specific description of the system

@ a given time.



The vector is in a state of superposition.

3. Operators:

↳ They are the rules/actions that change states & act & produce on quantum states inside Hilbert space & produce new states.

Eg:- Rotation, Flipping.

The role of Entanglement & non-locality

in systems :-

Entanglement - Quantum Connections;

→ In quantum mechanics, 2 particles can become entangled (states are linked despite their distance); if one particle is measured & found to be in state 0, the other particle will instantly "know" it must be 1.

Entanglement - 1 - - - 2 - - - invisible thread of correlation that ties particles together.

Non-locality - spooky action @ a distance:

↳ These entangled particles can show instant correlations even when separated by huge distances.

Eg:- 2 different gloves in 2 different boxes in " " cities. Opening one box will reveal the glove inside as well as the other glove in the other box @ the other city.

Quantum Info

Classical Info

Qubit

↳ Bit

↳ Not secure (cloning)

↳ Can copy exactly.

↳ Secure (no cloning)

No cloning.

↳ One step @ a time.

Parallel possibilities via superposition.

↳ Independent bits

Entangled bits.

Philosophical Implications:-

↳ Randomness in Quantum mechanics:

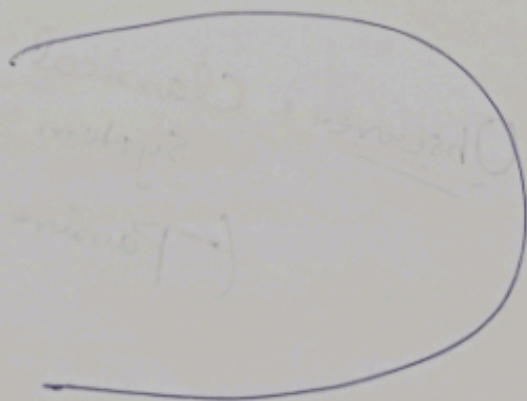
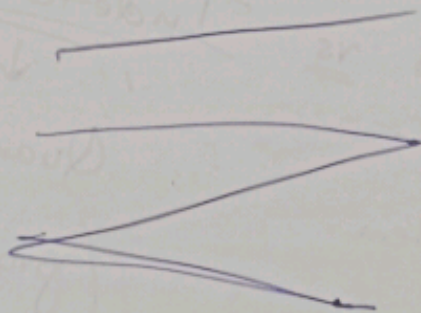
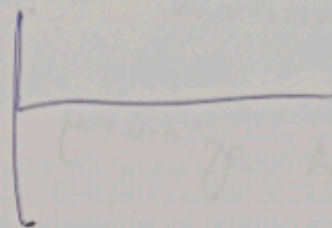
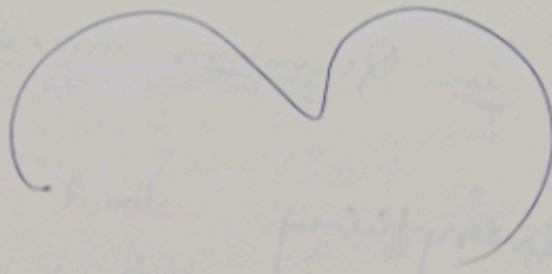
↳ Even if everything about a system is already known, outcome of a particle/system measurement is "fundamentally random". Eg: A spinning coin.

↳ Determinism vs Indeterminism:

↓
Classical System
(predicted outcomes)

↓
Quantum Systems
(probabilistic Outcomes)

↳ Role of the Observer: Classical System (Passive) Quantum System (Active)



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What is required to build a quantum computer?

Conceptual Overview:-

It has 3 components. They are:

- Qubits (Quantum Bits) [INFORMATION CARRIERS]

↳ It is a physical system that can represent 0, 1, (or) 0 & 1 (Superposition).

↳ Can be trapped ions (atoms held with lasers),
Superconducting Circuits (Tiny electrical loops @ near-zero temp),

Photons / light particles with polarization states)

- Initialization [STARTING POINT]

↳ Starting state usually is 0 [Hilbert Space]

- Quantum Gates [INSTRUCTIONS]

↳ Quantum computers need quantum gates to

↳ Flip a qubit ($0 \rightarrow 1$)

↳ Put it into superposition

↳ Entangle multiple qubits.

• Quantum Coherence [DELICATE HARMONY]:

↳ Qubits must stay in their quantum state

long enough to compute their results/states.

• Error Correction [SAFETY NET]:

↳ Qubits are very fragile - even small disturbances

(heat, noise, vibrations) cause errors.

↳ Spl techniques are needed to detect & correct these errors without destroying the quantum info.

• Read out (Measurement) [FINAL SCORE]:

↳ Measure qubits to get usable results (0 & 1)

which collapses the superposition into definite outcomes.

Environment & Infrastructure:-

↳ Quantum computers need very controlled environments:

1. Near ~~zero~~ absolute zero temperatures (for superconducting qubits)
2. Ultra high vacuum & lasers (for trapped ions)
3. Optical Networks (for photons)

Quantum Computer = Qubits +

Control + Protection.

Fragility of Quantum Systems:-

1. Decoherence - losing "Quantumness"

Quantum particles existing in superposition
faces decoherence when the environment

peeks @ the system & forces it to behave classically.

2. Noise:

Random unwanted changes that affect the quantum system.

Types: Temperature fluctuations, electromagnetic signals from nearby devices, imperfections in materials used to build quantum device.

3. Control:

Quantum computers need precise control signals to manipulate qubits; but too much control can disturb the system.

Quantum ~~advantage~~^{advantage} relies on coherence;
if decoherence/noise/control errors ruin the
system, quantum computers lose their power to survive.

Qubits need below conditions to ~~be~~^{survive}

1. Supercold temp (near absolute zero).

2. Isolation chambers (Shielding from
vibrations & radiation)

3. Error Correction Techniques.

Quantum systems are fragile because their
special states are easily disturbed by:
the environment (decoherence), random
disturbances (noise), & even imperfect human

handling (control issues).

Conditions for a functional quantum

System:

1. Isolation:

Keep the quantum system separated from the noisy outside world.

How is this achieved in labs?

↳ Ultra-cold freezers.

↳ Shielding from magnetic / electric interference.

↳ Vacuum chambers to keep out atoms / molecules.

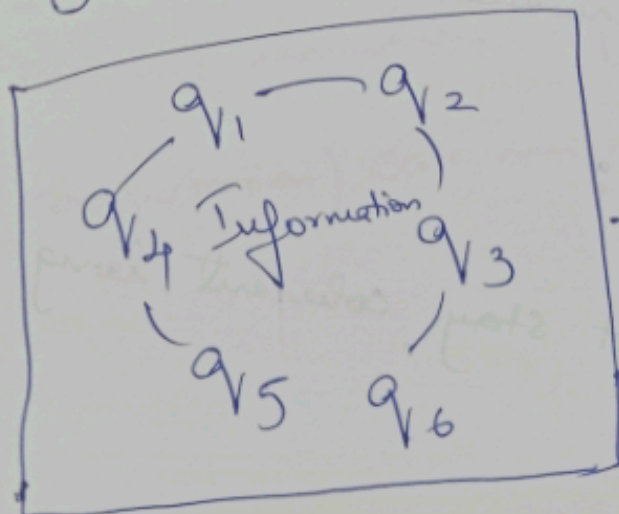
2. Error Management:-

Detect & fix mistakes caused by decoherence & noise because quantum

systems are prone to making more errors than classical systems.

How is this achieved in labs?

↳ Quantum error correction codes - using many physical qubits to protect the information of a single "logical qubit" (combination of many physical qubits that ^{work together as a} ~~are~~ team to protect one piece of information.)



→ Logical Qubit.

↳ Constant monitoring (without destroying the quantum state).

3. Scalability:

↳ Build ~~not~~ many ~~qubits~~ qubits at once that work together; but more qubits mean more chances for errors & more difficulty in keeping them isolated & controlled.

↳ It is needed for drug discovery, secure communication & climate modeling.

4. Stability:

↳ Qubits must stay coherent long enough to

perform calculations because if they lose their state too quickly, the computation fails before it finishes.

It's improved by using:

- Better materials
- Designing qubits with longer "coherence" times.
- Carefully timed control pulses to keep qubits stable.

"A functional quantum system needs isolation, error management, scalability & stability so that its delicate performance (quantum computation) can succeed."

Theoretical Barriers:

* Why is maintenance of entanglement difficult?

↳ Entanglement is ultra-delicate:

• Entangled particles share a special link.

• But even the tiniest interaction with the environment can break it.

↳ Environmental issues:

• Entanglement only works if the system stays isolated.

- But the environment (air molecules, heat, light, vibrations) is constantly "bumping into" particles.

↳ Noise:

- Real-world systems are noisy because of:
 - * Temperature fluctuations.
 - * Material defects.
 - * Electromagnetic Interference.
- Noise scrambles the delicate quantum state.

↳ Scaling:

- Entanglement with just 2 particles can be achieved & tested.
- But for many particles, (100 (or) even 1000 (or) more) keeping them all entangled is exponentially harder.

Shielding:

↳ Environment can be protected from noise / disturbances by:

- Cooling to near absolute zero.
- Vacuum chambers to keep particles away from air.
- Error-correcting codes.

But no shield is perfect - environment always leaks a little.

* Diff b/w Short lived entanglement & long lasting entanglement help quantum

Computing easier to understand.

Entanglement

Short lived ← → Long lasting

↳ Easy to create.

Very hard to maintain

↳ Flickers out fast

Can last throughout
computations.

↳ Good for demo.

Needed for quantum
computers.

↳ Happens naturally in
certain experiments.

Doesn't happen naturally
in any experiments.

How to turn short lived entanglement
into long lasting entanglement?

↳ Cooling:

* Heat makes atoms & particles jiggle

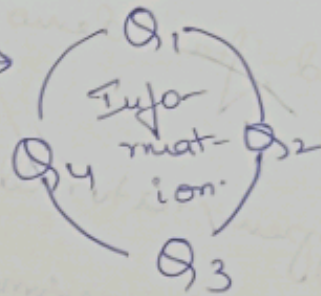
randomly. That random motion destroys
entanglement.

↳ Error Correction:

- Even with cooling, tiny mistakes creep in. (i.e., particles slip out of sync)
- Use quantum error correction, which means combining many physical qubits so they "vote" together to protect the information of

one logical qubit

↓
Combination of many physical qubits that work together as a team to protect one piece of information.



↳ Shielding:

- External noise like vibration, stray particles & electromagnetic waves constantly interfere.
- Shield the system with vacuum chambers, magnetic shields & vibration isolation platforms.

"Scientists stretch short-lived entanglement into long lasting entanglement by cooling the system, error correction and shielding"

Error Correction as a theoretical necessity:

• Fragile Building blocks:

↳ Qubits are inherently error-prone.

↳ Sources of errors:

1. Decoherence (Qubits losing their quantum state)

2. Noise (Unwanted signals)

3. Imperfect control (Tiny mistakes in laser/microwave pulses)

↳ Without correction, these errors pile up so fast that no meaningful calculation can finish; even the best built qubit can't avoid errors forever which makes error correction necessary and not optional.

↳ Classical bits are very stable in contrast to quantum bits which can flip randomly ϵ/p lose their state in fractions of a second.

↳ Without error correction, a quantum computer collapses into useless noise.

• Threshold Theorem:

↳ The quantum error correction threshold theorem

says:

"If we can keep error rates below a certain level (THRESHOLD), then error correction can allow a quantum computer to run computations as long as we like."

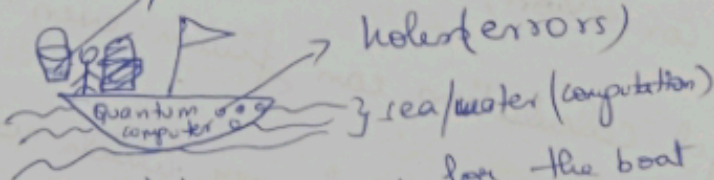
↳ That is, error correction is necessary for

quantum computing to be theoretically

feasible.

A closed room is full of dust despite blocking all air vents.

Analogy:



The bucket (error correction) is necessary for the boat (quantum computer) to sail smoothly to its destination. (computation & results)

"Error Correction is important to quantum computing as

Memory Storage is to classical computing".

Quantum Hardware Platforms:

↳ Superconducting circuits:

↳ Uses tiny electrical loops @ ultra-cold temperatures to behave like qubits. These kind of circuits are well developed & have fast operations but needs extreme cooling & decoherence happens quickly.

↳ Trapped ions:

↳ Individual ions are held in place by electric/magnetic fields & manipulated with lasers; they are like beads floating in space, with lasers acting as tweezers to move & connect them.

↳ They are very accurate & such qubits have long coherence times but operations are slower & its not ^{easy} ~~hard~~ to add many ions.

↳ Photons:-

Qubits are carried by light particles (photons) through optical circuits like sending secret notes.

through beams of light in a fibre-optic cable.

↳ It is great for communication (cryptography, quantum internet) and works @ room temperature.

↳ But its hard to make photons interact strongly and requires special detectors.

↳ Neutral Atoms:-

Neutral (uncharged) atoms are trapped in place by laser beams & manipulated individually like arranging

marbles in a grid with invisible tweezers.

↳ They can create large, regular arrays & is promising for long term systems. but its still in early stages compared to ions / superconductors.

↳ Topological Qubits :-

↳ It "braids" exotic particles to store information in a way that's naturally protected from errors; it is like tying information into a knot which won't unravel unless cut. This method could reduce need for error correction & very stable (in theory).

Superconducting Circuits, Trapped ions, 3 methods

Photonics : These 3 properties 3 features are most competitively for building qubits.

Each method is like trying to make the world's most delicate ice sculpture: the tools differ, but the goal is same.

↳ Superconducting Circuits: (IBM, Google, Rigetti)

• Vision/Weaknesses:

- They are noisy: qubits "forget" quickly. (microseconds)
- They require giant refrigerators.
- They can be fabricated using microchip technology.

• Reality/Strengths:

- Already demonstrated hundreds of qubits.
- Operations are very fast. (nanoseconds)
- Can be fabricated using microchip technology (scalable in principle)

↳ Trapped Ions: (IonQ, Quantinuum)

• Strengths: (Reality):

→ Very stable and accurate qubits (can keep memory for seconds (or) even minutes)

→ High fidelity operations (fewer mistakes)

• Weaknesses: (~~Vision~~):

→ Operations are slow (milliseconds & not nanoseconds)

→ Scaling is hard because controlling & laser pointing @ thousands of ions is like trying

to choreograph ^{millions of} ~~every~~ qubits one by one.

↳ Photonic Qubits: (Xanadu, Psi Quantum)

• These kind of qubits use photons traveling in optical circuits as qubits. (Beam splitter ^{superposition} $\begin{cases} P(0) \\ P(1) \end{cases}$ only)

• Strengths: went on upper side (0) (or) lower side (1)
observation will decide Photon

→ They don't interact much with the environment;

they are naturally resistant to noise.

→ Easy to send photons across fiber optics;
great for quantum networks / communication

• Weaknesses:
(guided path, low loss, noise protection, ease of use & good for time & polarization qubits) doesn't let photons escape

→ Hard to make photons interact strongly with each other as it is needed for computation.

→ Current systems are more like demonstrations (showing small-scale circuits) rather than large quantum processors.

↳ Vision vs Reality:

• Vision - A universal quantum computer with millions of error-corrected qubits, solving real world problems; (Drug Discovery, Finance; Cryptography) small, compact and even room temperature someday.

• Reality - Devices have tens to, ^{few} hundred noisy qubits, they are experimental, huge & power hungry (fridges, lasers, optic tables).

↳ Algorithms run, but they cannot yet beat classical supercomputers for most useful tasks.

↳ Right now, Noisy Intermediate Scale Quantum (NISQ) era is in the rule where there are powerful prototypes but no practical machines are built yet.

The role of Quantum Software in managing theoretical complexities is extremely high as it helps in:

↳ Error Mitigation:

• Hardware mistakes are spotted by software algorithms through patterns and "smooth them out", even if complete error correction is not possible.

(eg: correction of spelling in phone; addition of new words in phone dictionary; increase of use in text)

↳ Optimization for

• Real life qubits are limited; so s/w has to adapt

algorithms to what's realistically possible (instead of millions of qubits, only few hundred qubits are computed/manipulated)

↳ translation from human logic to quantum

logic:

- Software translates programmer instructions into a sequence of quantum operations

understandable by the hardware.
(Human logic $\xrightarrow{\text{code}}$ Binary/Quantum logic)

↳ Simulation & hybrid approaches:

- Quantum s/w often mixes quantum & classical computing called hybrid algorithms where classical computers handle the heavy lifting (hardware), while quantum chips tackle the complexity of the problem (software).

Eg: phone: calculator $\longleftrightarrow$ scientific calculator.



Quantum Information | Classical Information

→ Information is stored in:

Qubits (0 & 1, 70% (0),
30% (1) called
superposition)

Bits (0/1)

→ Qubits can be entangled.

→ Bits cannot be entangled.

→ Copying, reading, photocopying
is ~~simple~~ not simple.

→ ~~Not simple~~ Simple.

→ No cloning.

→ Cloning is easy.

→ Quantum info. is fragile
measuring it (collapses)
it into either 1/0.

→ Measuring it does not
change the
final value.

→ Observer effect.

→ No observer effect.

→ Eg:

A spinning coin is in
space (superposition).

A spinning coin
lands on either
heads / tails (known
phenomenon)

Basics of Quantum Communication:

→ It uses quantum properties like entanglement & superposition to send messages more securely than classical methods.

- Quantum states as messengers: Instead of sending a regular pulse of electricity/light, qubits are sent.

- Fragility as a feature: Anyone trying to eavesdrop on a quantum system inevitably disturbs the qubits, which makes quantum communication inherently secure.

- Entanglement Distribution: Using entangled qubits, secret key can be securely sent between 2 people (or) verify the security of a message.

Quantum Key Distribution (QKD):

↳ It is the most practical application of quantum communication today.

↳ It is a method to create a secret key b/w 2 people so they can encrypt & decrypt messages securely.

↳ In classical encryption, keys are exchanged using math which could be broken by future quantum computers.

↳ In QKD, keys are exchanged using quantum physics laws, which no amount of computing power can "cheat".

↳ Quantum states of the photons/particles used in QKD can be in different states.

Carry the information of the qubit (either 0 & (or) 1).

Eg:- Electron & photon polarization.

QKD methods:-

• BB84 protocol: [First & most famous]

• This protocol is one of the oldest protocols used and also famous QKD protocol.

• It was invented in 1984 by Bennett and Brassard.

Person A

• A sends photons to person B, each photon

polarized in one of four ways:

$\rightarrow 0^\circ (0) \rightarrow 90^\circ (1) \rightarrow \pm 45^\circ (0) \rightarrow -45^\circ (1)$

(Horizontal)

(Vertical)

Diagonal base

Rectilinear base

bit / either

- Person A randomly chooses a basis & a bit value for each photon. (horizontal/diagonal) (0/1)

• After transmission of photons, person B randomly chooses a basis and assumes the bit value for it. (h/d) (0/1)

• If during transmission, person 3 tries to intercept the message, the person 3 has to guess & send a basis & a bit to person 1 the basis & bit of person 1

2 to avoid doubt on either side.

↳ After completion of transmission of photons from sender to receiver, both sides compare their basis (not bits which can be overheard by anyone in proximity) and keep only the shared correct answers.

$\rightarrow$ If there are more errors than normal, it means the message is manipulated / intercepted by third party.

$\rightarrow$ Eg:-

A $\xrightarrow{\quad}$ B
 i am sending a message } photon form (horizontal/diagonal)

In photon format:

$i = \rightarrow$ $i = \rightarrow$ $a = \uparrow$
 $a = \uparrow$ $n = \leftarrow$ $g = \searrow$
 $m = \downarrow$ $g = \searrow$ $e = \uparrow$
 $s = \leftarrow$ $a = \uparrow$
 $e = \uparrow$ $m = \downarrow$
 $n = \downarrow$ $e = \uparrow$
 $d = \searrow$ $s = \leftarrow$
 $s = \leftarrow$

So, (am) (sending) (a)
 $\begin{matrix} \uparrow \downarrow \leftarrow \uparrow \downarrow \rightarrow \leftarrow \downarrow \uparrow \uparrow \\ \leftarrow \uparrow \downarrow \leftarrow \uparrow \downarrow \rightarrow \leftarrow \downarrow \uparrow \uparrow \end{matrix}$
 (message)

In case, someone intercepts, they will guess the basis (h/d) & thus miss the message in

$\downarrow$

B/w

- The receiver will see
- After basis creation

Eg:
 only directions of photons are shared via public bit rate

Based Key

general, thus alerting both parties (sender & receiver) that some third party is intercepting the message.

B/w Sender & receiver:

• The receiver (person 2) might not understand the message correctly as soon as it is transmitted.

• After transmission, they share the basis the receiver has correctly guessed & create a raw key.

Eg: (I) → (a) (m) (s) e x x i x g (a) -
only directions of photons are shared via phone, not bit values.
Raw key (I am seig a)

Based on the raw key, the final key is understood by both parties without any interference.

BB84 protocol summary: (1) no one is intercepting the message)

Step 1:

A $\xrightarrow{\rightarrow, \leftarrow, \searrow, \nearrow, \dots}$ B
(Sender) (Receiver)

(Transmission of photons)
(u/d)

Step 2:

A $\xrightarrow{\text{phone call}}$ B [Keep only the photons
order if they match
b/w sender & receiver]

A: $\rightarrow (I)$ } keep as part of raw key.

B: $\rightarrow (I)$ }

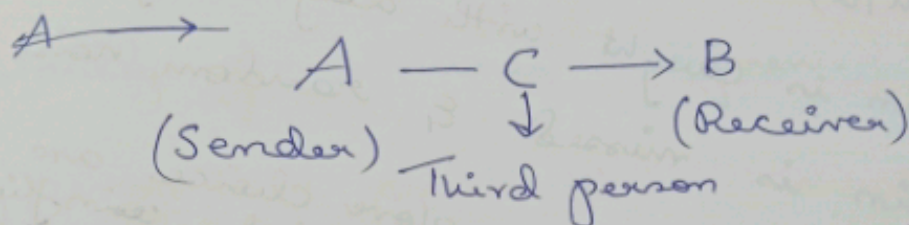
A: $\leftarrow (a)$

B: $\leftarrow$ guess
random noise
(no answer)

} remove from raw key.

Ca. If anyone is intercepting the message:

Step 1:



The 3rd person doesn't know what A wanted to send, so they will guess a random basis & send the information to B to avoid doubt on both sides. This will lead in errors in comparison of basis values on both values.

Step 2: A $\xrightarrow[\text{call}]{\text{phone}}$ B A: → } x multiple times
 B: ↗ (guess)

which alerts both sides that a 3rd party is trying to interfere & intercept the message.

Eg: Coins & gloves; if horizontal flipped
(h/d) (h/d)

coin is caught with diagonal glove,
coin is missed & random noise

is created. later glove choices are
which coin flips
compared to figure the secret key

both parties understood & create

a raw key to understand the secret

key.

E91 protocols: (Entanglement-based)

→ Inventor: Artur Ekert, 1991.

→ Idea: Instead of sending photons
directly, both parties receive photons
from a source that creates entangled
pairs.

This is more, than BB84 as disturbing
secure & less
the entanglement ^{complicated} will alert both parties
instantly of someone's interference.

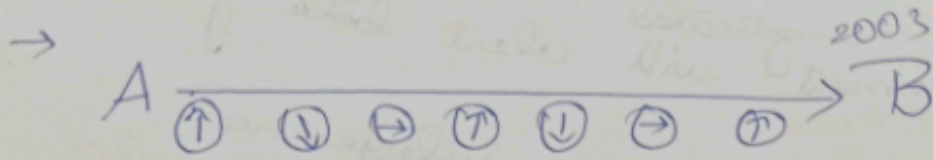
Eg: person 1 person 2

a pair of magic dice which are
entangled with each other to
give ^{same} opposite results when rolled.

$\Rightarrow$ person 1 gets 1, person 2 gets 6.
" " 2, " " 2.5
 $\rightarrow$ balancing between them

and so on. Interfering between them would require guessing the value of any one's (person 1 / person 2) value which would confuse both parties & alert both parties of the interference.

Decoy State Protocol : (Upgrade of BB84)



Expectation of ~~the~~ quantum key

transmission.

↳ In real life, making a source that spits out exactly one photon at a time

is hard & expensive; thus, many real

QKD systems use weak laser pulses

instead.

→ In theory, QKD works best if A sends

1 photon @ a time to B. Because one photon

can only be measured once, if anyone

tries to intercept it, the photon's state changes. ↳ T

- A weak laser pulse is like a very faint flash of light.
- On average, it contains less than 1 photon, but sometimes it contains 0, 1, (or) 2+ photons.

→ The person trying to eavesdrop will try to steal one photon & let other photons pass. This ensures photon loss & successful eavesdropping without letting either side get suspicious for loss of a photon is not enough to raise suspicion and is instead considered to be lost / misinterpreted by both sides.

→ Therefore, the sender sends real signals mixed with ~~fake~~ fake signals with weaker intensity.

↳ After transmission, both sides compare based on the no. of fake & guess if there's an attack on the information shared.

↳ Quantum rules ensure that no one's able to eavesdrop without being caught in some way (or) the other.

Continuous Variable QKD (CV-QKD):-

→ Instead of sending single photons, person A sends continuous waves of light.

laser/light of: intensity & timing
~~laser~~ (strong/weak) (no. of seconds that the laser is lighted)

Analogy / Eg: piano tunes timing & loudness.

→ These pulses are sent down the optical fiber channel attenuates (damps) the signals and adds noise.

→ Person B measures the incoming pulse through a tuning fork.

Person A $\xrightarrow[\text{continuous}]{\begin{matrix} (l/s) \\ (s/w) \end{matrix}} \text{light waves} \rightarrow \text{Person B}$

Strong	weak signals	(Pitch)
loud	slow signals	(Loudness)
less		

In light waves, these concepts are understood as intensity & length of the light waves which can be measured (Amplitude) (loudness) (phase timing)

In CV-QKD context, Amplitude = strength of the light wave and phase = position of the wave in its cycle.

Role of Entanglement in Communication

Entanglement has 2 particles that are connected so strongly that knowing one particle's outcome ~~also~~ decides the outcome of the other connected particle, despite their distance.

- Instant Correlation: Entanglement does not send messages faster than light, but it ensures that 2 distant particles can

share perfectly linked information.

- Unbreakable Security: Anyone trying to measure/interfere with the entangled particles breaks the link between them and alerts both parties involved.

- Teleportation of Information: Entanglement allows teleportation of a particle's state to another place.

The Idea of the Quantum Internet -

Secure Global Networking:

→ The classical internet sends information as bits: 0's and 1's, carried by light signals in optical fibers but quantum

- internet will send qubits which can be:
- 0 & 1 @ the same time (Superposition)
 - Entangle with other particles for a specified time limit.

Why Quantum Internet?

→ Unhackable Communication: It doesn't allow eavesdropping / interference without being caught.

→ Global Quantum Keys: QKD uses entanglement to share secret keys worldwide.

→ Distributed Quantum Computing: Small quantum computers are connected to work as a giant super-quantum computer.

Eg: Self-destructing letters in cases of tampering (Quantum physics)

(Classical physics - letters sealed in envelopes which can be still opened secretly!)

Introduction ^{to} Quantum Computing:

→ Unlike natural computers which use bits (0/1), quantum computers use 0,1/21 both @ once. (Superposition)

→ 3 Key Quantum Powers:

• Superposition - lets quantum computers test many possibilities in parallel.

• Entanglement - Qubits can be linked so that changing one qubit's outcome affects the other qubit's instantly & makes teamwork b/w qubits extremely powerful.

• Interference - Quantum states can add up (or) cancel out like waves which helps highlight the ^{right} answer & cancel wrong ones.

Why Quantum Computers Matter:

- Breaking codes: Can solve problems much faster.
- Medicine Discovery: Can stimulate molecules perfectly (new drugs).
- Optimization: Better airline routes, supply chains (or) stock predictions.
- AI Boost: Trains ML models way faster.

"If classical computers are like reading every book in a library one by one, then quantum computers are like reading all books at once, then keeping only the pages needed".

Quantum Parallelism (Many States at once):

Classical

Computers

→ Bit (0/1); ^{the value} ~~they~~ ~~check~~
is only either 0 or 1.

→ They don't have superposition i.e., they do not ~~have~~ follow quantum physics laws.

Quantum

Computers

Qubit (0 & 1) is in

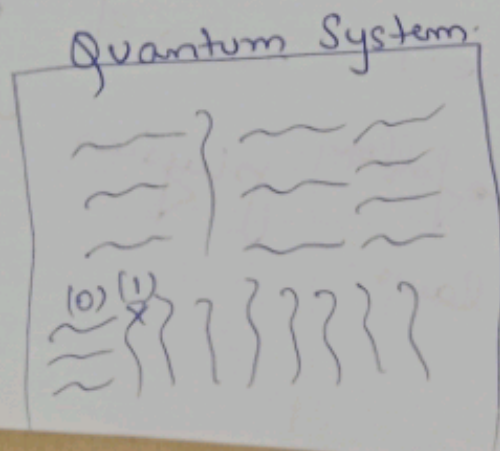
Superposition.

They follow all rules of quantum physics laws.

→ A quantum computer can test many possibilities at the same time because qubits exist in multiple states simultaneously.

→ The ability of a quantum computer to explore many solutions in parallel is called quantum parallelism.

→ If quantum computers only used superposition, they would just explode into a cloud of random possibilities when measured which is not useful, therefore, interference is necessary.



$|0\rangle \sim |1\rangle$

~~noise~~

$\left. \begin{matrix} (0) \\ (1) \end{matrix} \right\}$ gives value 1 or 0.

• AND :

• OR :

• NOT :

Classical (Vs) Quantum Key & Gates:

Q. How does your computer know what to do when a key is pressed?

A. Classical computers break every task into tiny yes/no questions called "BITS".

Classical Gates:

→ Both 0's and 1's are used to switch on & off a function (pressing a key → 1, ~~not~~ vice versa → 0) very quickly.

→ These decisions to use/not use these bits are done by logic gates:

- AND: Both ~~switches~~ ^{inputs} ON.
- OR: At least one if ON.
- NOT: Flips from ON → OFF and vice versa!

→ These gates are deterministic: Given the same input, the output remains unchanged
Eg: - AND, NOT, OR, NOR - - -

Quantum Gates:

→ Here, instead of bits, they have qubits which are in superposition.

→ Quantum gates are machines that manipulate superposition because:

- They don't just flip ON/OFF.
- They rotate, entangle and interfere with qubits states.

→ The best part is that quantum gates are reversible & manipulate probability waves rather than definite states.

* ANALOGY: classical: railway tracks with fixed direction

Quantum: water waves which can overlap, cancel (or) reinforce with each other

Key

process

some

do. E

Class

Clas

→ Wor

→ Tr

(O/P
back to

→ 1) etc

result

→ Eg: -

ged. Key Idea: Quantum Gates allows for processing of many possible answers @ once, something which classical computers cannot do. Eg: Superposition, Entanglement, Interference.

~~Classi~~ Eg: X, H, Z

Classical Gates

Quantum Gates

→ Works with bits (0/1)

Works with Qubits (0/1, ~~0&1~~ 0&1)

→ Irreversible.

(O/p does not change)
back to i/p.

Reversible.

(O/p can be changed
back to i/p).

→ Deterministic (same
result in every case)

Probabilistic (results
depend on measurement)

→ Eg:- follows a single road
at a time.

Explores multiple roads
at a time.

NOT Classical

Quantum

→ Gates:

NOT: flips $0 \rightarrow 1$

AND: needs both 1's

OR: either 1 works

No equivalent classical gate is found.

Note: Superposition is denoted by

$$\alpha |0\rangle + \beta |1\rangle \quad \text{and} \\ (|1\rangle) \quad (|1\rangle)$$

definite quantum states are ~~denoted~~ denoted by

$$|0\rangle \text{ \& \& } |1\rangle!$$

$|1\rangle \rightarrow$ ground/starting state of a qubit

X : flips $|0\rangle \rightarrow |1\rangle$
(Pauli-X) (written in bracket notation)
(Quantum NOT)

CNOT: flips only if quantum state (controlled NOT) first value is $|1\rangle$.

H: allows both 0 & 1 (Hadamard gate) $\rightarrow$ (superposition matrix)
(a) once

Z: flips direction ($+$ to $-$) (Pauli-Z) (180° rotation) only of quantum state $|+1\rangle$ to $|-1\rangle$

→ This gate lets quantum computers explore many possibilities in parallel.

(c) Pauli-Z Gate : (Phase flip)

→ leaves 0 ~~un~~ unchanged, but "flips" the "sign" of 1.

(d) CNOT gate : (CONTROLLED NOT - Entanglement maker)

→ Works on 2 qubits.

→ If first qubit = 0 → 2nd qubit stays ⁱⁿ the same quantum state.

→ " " " = 1 → 2nd qubit's quantum state is flipped.

Eg:-

→ Start with both qubits at 0.

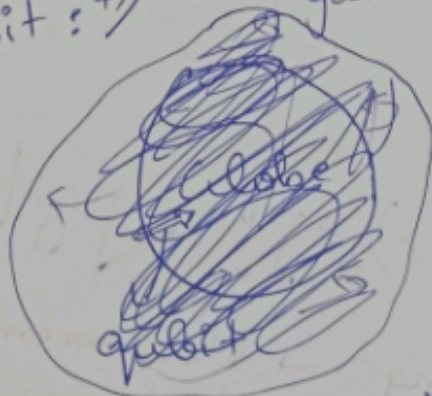
→ By applying Hadamard gate on the first gate (i.e., definite 0 → 0/1) then apply

CNOT because 1st qubit = 0 & 1, 2nd qubit's quantum state is flipped from 0 $\rightarrow$ 1, thus changing both qubits to 0 & 1 and 0 & 1 (1st) (2nd) (superposition), thus creating an entangled pair. This is called the "BELL STATE" (a building block for quantum teleportation and cryptography)

(e) Rotation gates: (R_x, R_y, R_z)

$\rightarrow$ These gates rotate the qubit's state around different axes.

Eg:- Qubit: $\nearrow$ $\xrightarrow{\text{rotation gate}}$ $\searrow$



$\rightarrow$ They allow very fine control over probabilities.

(f) Toffoli gate (CCNOT):

→ It works on 3 qubits.

→ If the first 2 (qubits quantum states) are 1, it flips the third.

→ Important for universal quantum computation

[Toffoli + Hadamard = Quantum Algorithm]

— — — (Continuation of challenges: decoherence)
Consequences:

→ Computations lose quantum advantage & errors accumulate rapidly.

Error types:

→ Bit-flip ($|0\rangle \rightarrow |1\rangle$), → phase flip ($|+0\rangle \rightarrow |-0\rangle$)

→ Amplitude damping → ~~Measurement errors~~ leakage in quantum environment.

Quantum Error Correction (QEC):

→ Core idea: Encode a logical qubit into many physical qubits so errors can be detected and corrected without measuring the logical state directly.

Eg: Shor code & surface code.

• Shor code: (Backup in layers)

→ A message is always in danger of being messed / interfered / copied by

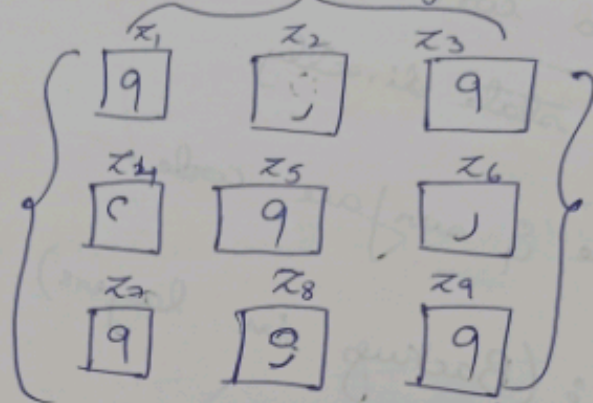
third party sources.

→ First quantum error correcting codes.

(1995, Peter Shor)

→ $\mathbb{I}$ is used for protection of information by creating multiple backups of a qubit's information.

→ Eg:-



$\mathbb{I}$ prevents bit flip errors ($0 \leftrightarrow 1$) and phase flip ($+0 \leftrightarrow -0$) errors.

$z_1 - z_3 \rightarrow$ same quantum state, then no bit flip has occurred.

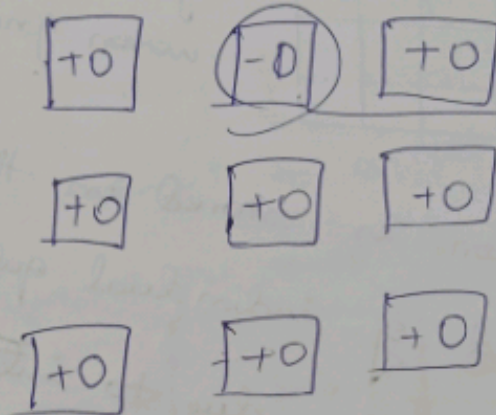
$$(z_1, z_2, z_3) = (9, 9, 9) \Rightarrow \checkmark$$

$$z_1, z_2, z_3 = (9, \text{random noise}, 9) \Rightarrow \text{understand some interference has happened \& make value as 9.}$$

Similarly, phase flips are also checked using Hadamard gates.

$$H|0\rangle = \frac{|0\rangle + |1\rangle}{\sqrt{2}}, \quad H|1\rangle = \frac{|0\rangle - |1\rangle}{\sqrt{2}}$$

Eg:-



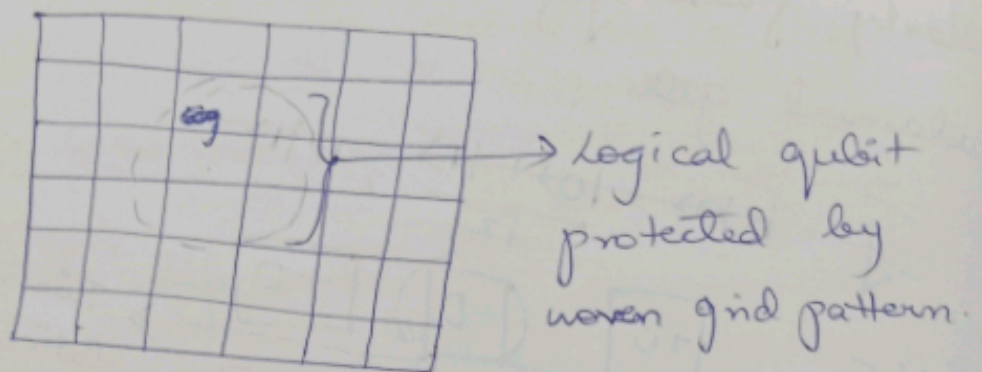
This is detected as phase flip ($+\rightarrow-$) and changed to $+$ again.

• Steane code:

→ It is an improvement on shor code by using 7 qubits instead of 9 qubits to store and protect information.

• Surface codes: (Topological codes)

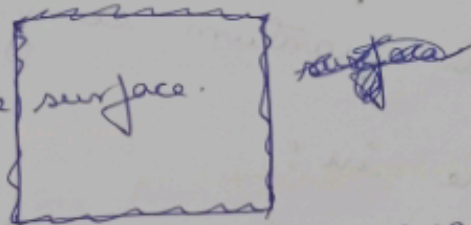
→ It is modern and most practical for real hardware (used by google, IBM, etc.)



- The information is stored in the surface pattern, instead of individual qubits which can lose information due to interference.
- This ensures security and privacy better than above 2 methods as it is easy to steal (or) guess a piece of information stored in qubits, but guessing / stealing a entire surface pattern is impossible because each small grid carries only a part of the entire pattern but without

knowing the pattern as a whole, it is impossible to guess which grid part represents which part of the surface pattern.

→ In case of any flip errors, the nearest neighbours interact to correct the errors; the logical qubits are ~~used~~ represented by loops across the surface.



→ But, here 100's of qubits are used to protect 1 logical qubit's information, so it is preferred by larger networking systems.

→ "Goal of error correction is to detect & correct errors without measuring (or) destroying the qubit's state".

Real world importance and future potential:

Real world Importance:

→ Quantum computing can revolutionize areas where classical computers fail (or) take too long.

→ In real life, there are many areas in which quantum computing plays a huge role in:

• Healthcare and Drug Discovery:

→ Quantum computers can simulate molecules exactly as they behave in nature.

→ Helps design new drugs (cancer, COVID etc.) by predicting reactions faster & cheaper.

→ Pharma companies do not need human subjects/animal subjects.

• Material Science:

→ Helps discover new materials for batteries, solar cells, superconductors.

Eg: Volkswagen uses quantum computers to design better lithium-ion batteries.

• Logistics & Optimization:

→ Optimizes delivery routes, flight schedules & warehouse operations.

→ Quantum algorithms can find the best solution among billions of options faster than classical computers.

• Finance & Risk Modeling:

→ Quantum systems can simulate stock markets, optimize investment portfolios and detect fraud in real-time.

Eg: Goldman Sachs and JP Morgan use quantum algorithms for risk analysis.

• Artificial Intelligence:

- Quantum machine learning (QML) can process huge datasets quickly.
- Enables smarter AI for language processing, pattern recognition and data mining.

• Energy production:

- Quantum elements help create new materials for clean energy and superconductors.

• Space and Navigation:-

- The quantum machines are used to create quantum environments which represent real life space and realities and calculations of quantum states help understand space in more detail.

→ Quantum computing allows multiple routes to be explored parallelly to facilitate best optimized routes.

India's role in the Quantum Future:

→ India is actively investing in quantum technology.

- National Quantum Mission (2023-2030)

→ 6000 crores initiative is done to develop 50-100 qubit quantum computers.

→ The key idea is to build quantum communication n/w's across major cities.

→ Encourage startups in quantum tech like

Boson Q Psi, QpiAI).

→ Create new quantum education & research programs.

- Academia & Industry partnerships :

→ ISRO, DRDO are all working on quantum sensors, quantum communication and quantum computers.

→ There are many collaborations between IBM, Microsoft and google quantum programs.

CNT-5

Real world Application domains:

1. Healthcare (Drug discovery):

→ The quantum computer can naturally represent quantum states of molecules, which makes simulating molecular structures and electronic properties exponentially more efficient for certain hard problems.

→ Real-term impact: Quantum-inspired algorithms speed up parts of simulation and error-mitigated small quantum processors help validate models.

2. Material Science:

→ Quantum computers help create accurate simulation of electronic structure, defects

and excited states in materials which is crucial for batteries, superconductors, catalysts.
→ It helps in discovering better battery electrodes, modeling defects in semiconductors, designing materials with targeted optical/electronic properties.

3. Logistics & Optimization:

- Quantum algorithms can tackle combinatorial optimization problems faster.
- Vehicle routing, supply chain optimization, traffic flow are some of the uses of quantum computing.
- Hybrid algorithms (classical + quantum system) are the future pathway.

4. Quantum Sensing & Precision timing:

- Sensors exploiting quantum coherence & entanglement produce measurements with much higher ~~sensitivity~~ sensitivity (or) resolution.
- It helps in detection of weak signals, medical imaging ~~and~~ enhancements, magnetic and electric field sensing at nanoscale levels.
- Such applications can be deployed to enable new measurement capabilities.

5. Cryptography and communications:

- Quantum key distribution and post quantum cryptography provide alternatives (surface code) to shor's code which could be widely used to break public key cryptosystems in large, fault-tolerant quantum computers.

→ Its used for secure communication links in governments, finance, critical infrastructure and aids in long-term confidentiality.

Industrial Case Studies:

1. IBM:

→ Approach: Build superconducting-qubit h/w, open cloud access to quantum processors and a full s/w stack with emphasis on ecosystem, developer access & incremental h/w scaling.

2. Google:

→ Approach: Topological qubits vision, extensive s/w, more platform/developer ecosystem focus, cloud integration.

3. PsiQuantum:

→ Approach: photonics based quantum computing

aimed at scalability & room-temperature components with focus on fault-tolerant, high volume manufacturing.

"All large scale companies use different q/w approaches (superconducting, photonic & trapped ions, topological) ~~and~~ ^{into} business strategies to move from ~~short~~ short-term commercial value through s/w, hybrid services & sensing rather than large quantum machines."

Ethical, Societal & Policy considerations:

1. Security & privacy:

~~Future quantum compute~~

1. Security & privacy

(Post quantum cryptography, data protection timelines)

2. Equity & access

(cloud access to all, open research)

3. Workforce & economic disruption

(Human need is decreased as AI increases in accuracy)

4. Dual use & misuse

(Transparent research practices)

5. Research ethics • (Ethics training for researchers, open toolchains).

Challenges to adoption:

→ Cost: Hardware, photonics manufacturing & error correction overheads are expensive.

→ Skills gap: Shortage of engineers, physicists & software developers who understand quantum algorithms, hardware engineering & hybrid systems.

→ Standardization & Interoperability: Diverse software platforms mean lack of standards for qubit metrics, benchmarks, software APIs which in turn slows industry uptake.

→ Error rates & scale: Current qubits are noisy, fault-tolerant quantum computing requires orders of magnitude more physical qubits per logical qubit.

→ Integration with classical systems: Real benefit often requires hybrid-classical quantum pipelines and new s/w tooling.

Emerging careers in quantum - Roles, Skills, and how to prepare.

1. Quantum algorithm developer
2. Quantum hardware engineer
3. Quantum s/w engineer / stack developer
4. Quantum applications / domain specialist

5. Quantum systems/ integration engineer.

6. Quantum product manager/ policy analyst,
ethics lead.

All these roles specifically need:

→ Basic understanding of quantum
physics, programming languages,
automation in various fields.

→ Linear algebra, complex numbers &
probability.

→ Classical algorithms & optimization, numerical
methods.

→ Ability to learn software development
kits. (Qiskit, Cirq, Q#, PennyLane)

analyst)
Preparation for these positions can
be done by:

- Short courses → University programmes
- Hands-on practice → Internships
- Collaborations → Cross training

Educational & Research Landscape -

India's opportunity:

→ India's strengths:

- Strong STEM talent pool.
- Manufacturing & photonic capabilities.
- IT ecosystem.
- Growing startup & research environments.

→ Strategic focus areas:

- Workforce development at scale.

- Industry-academia consortia.
- Targeted applications domains
- Quantum sensing & metrology
- Quantum s/w and cloud services.
- Manufacturing & component supply chain
- Policy, standards, and cryptotransition.

→ Institutional actions:

- Creation of centers of excellence with shared hardware & multi-disciplinary teams.
- Public sector pilots use public infrastructure (transport, energy, healthcare) as labs to trial quantum-inspired optimization.
- Scholarships & fellowships to help quick spread of quantum disciplines.