1. Explain the Concepts of Superposition and entanglement with suitable real-world analogies.

Ans:- **Superposition** :- Superposition means a quantam system can be in multiple states at the same time until it is measured. Once measured, it "collapses" into one definite state.

Equation:- $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$

$$|\alpha|^2 + |\beta|^2 = 1$$

Ex:- When the coin is spinning in the air, it is not strictly heads or tails - it is a blend of both. Only when you catch it and look does it Collapse into either heads or tails.

Entanglement :- Entanglement is a connection between two Quantam particles such that the state of one instantly determines the state of the other, even far apart.

Equation :-

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

Ex:- Lab partners always writing the same answer without talking. Hostel friends choosing the same food without planning.

2. Compare classical mechanics and Quantam mechanics in terms of principles, information systems and measurement.

Ans:-

Classical Mechanics	Quantam Mechanics.
1. If we know initial state, we can Predict the future exactly.	1. Describes the probability of finding a particle in a given state, not certainty.
2. Have definite positions, Velocities and energies at all times.	2. Can exist in superpositions of multiple states simultaneously.
3. Variables like energy, space and time continuous.	3. Quantities like energy are quantized.
4. The smallest unit of information is a bit, which can be either 0 or 1	4. The smallest unit of information is a qubit, which can exist in superposition.
5. A system can only be in one definite state at a time	5. Multiple Qubits can be linked, giving correlations stronger than classical systems.
6. Classical computers manipulate bits through logic gates	6. Quantam computers use Quantam gates to manipulate qubits

7. Measuring a property does not alter the system	7. Measuring a system changes its state (collapse of wavefunction)
8. Properties exist before measure-ment, we just reveal them	8. Some pairs of properties cannot be known simultaneously with perfect accuracy.

3. What is qubit? Illustrate using polarization of light and compare it with a classical bit.

Ans:- **Qubit:-**

A Qubit is the fundamental unit of information in Quantam mechanics.

→ unlike a classical bit, a Qubit can exist in a superposition of both states at the same time

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

Polarization is the electromagnetic field with a specific direction that a photo carries. In a polarization Qubit, the polarization state represents the Quantam state.

The Quantam states $|0\rangle$ & $|1\rangle$ can be represented as horizontal (H) and vertical (V) polarization, respectively.

$$|0\rangle = |H\rangle, \quad |1\rangle = |V\rangle$$

$$|D\rangle = \frac{1}{\sqrt{2}}(|H\rangle + |V\rangle) = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

$$|A\rangle = \frac{1}{\sqrt{2}}(|H\rangle - |V\rangle) = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$$

These polarization states form valid bases for representing Qubit states in Quantam optics.

classical bit Vs Qubit:-

Feature	classical bit	Qubit.
Values	0 or 1	Superposition of 0 & 1
Storage	One value at a time	Multiple states simultaneously.
Measurement	Exact (0 or 1)	Probabilistic outcome
Processing power	Limited by binary	Exponential scaling.
Real world analogies	light switch	spinning coin, polarized light.

4. Define and explain Quantam Coherence and decoherence. Why are they important for Quantam technology?

Ans:- Quantam Coherence :-

It is the property of a Quantam System to exist in a superposition of states with well defined relative phases between them.

Coherence is like the magical balance that allows a quantam system to stay in a superposition without collapsing.

Ex:- Guitar string.

When you pluck a guitar string, it vibrates smoothly. The vibration → wave → superposition. As long as there is no disturbance, the note is clear and stable.

Quantam Decoherence :-

Quantam Decoherence occurs when a quantam system interacts with environment, leading to the destruction of superposition. It marks transition from Quantam to classical behavior.

Ex:- Spilling Tea.

Importance :-

1. Coherence allows Qubits to perform Quantam logic
2. Decoherence destroys quantam information which leads to errors and loss of Quantam power.

5. Discuss the role of entanglement and non-locality in Quantam information systems.

Ans:- The role of entanglement :-

Entanglement is a special Quantam correlation between two or more particles.

If two particles are entangled, the state of one cannot be described independently of the state of the other.

Measuring one particle immediately Tells you something about the other, no matter how far apart they are.

Mathematical Example :-

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

This means :- With 50% chance of A = 0 & B = 0

With 50% chance of A = 1 & B = 1

but never be A = 1, B = 0 & A = 0, B = 1

non-locality :-
The principle of locality, fundamental to classical physics, states that an object is influnced only by its immediate surroundings. The phenomenon of nonlocality highlights strange, interconnected relationships between distanct quantam objects. Non-locality is the idea that entangled particles can show correlations that can't be explained by classical physics or any "local hidden Variables".

6. Write short notes on Hilbert space, Quantam states and operators in context of Quantum Theory.

Ans: Hilbert space :-
It is a mathematical space that provides the stage on which Quantam mechanics is built.
→ It is a vector space equipped with an inner product, which allows us to define lengths and angles of vectors.
→ Quantam states are represented as vectors in this space.

Quantam states :-
A Quantam state fully describes the condition of a quantam system. Represented by a state vector $|\psi\rangle$ in Hilbert space.
→ Can be a pure state or a mixed state
→ Superposition is possible :- $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$
→ Measurement "collapses" a Quantam state into one of the basis states with certain probabilities.

Operators :-
An operators is a mathematical rule that acts on a quantum state to produce another Quantam state or a measurable number.

1. Linear operator :-
An operator $\hat{A}$ is linear if scaling and adding states works same way before and after applying the operator.
$$\hat{A}(a|\psi\rangle + b|\phi\rangle) = a\hat{A}|\psi\rangle + b\hat{A}|\phi\rangle$$

2. Hermitian operator :-
It corresponds to observables - their eigenvalues are real numbers
&
$$\langle\psi|\hat{A}\phi\rangle = \langle\hat{A}\psi|\phi\rangle$$

3. Unitary operator :- They preserve the length of state vectors → Used for time evolution & quantam gates.
$$U^{\dagger}U = UU^{\dagger} = \hat{I}$$

7. What are the essential requirements for building a Quantum computer? Explain in terms of isolation, error management, scalability and stability.

Ans:- Isolation:- Qubits are extremely sensitive to their surroundings. Any interaction with the environment causes decoherence.
Keep Qubits isolated enough to maintain coherence times long enough to perform computations.
Error management:- Unlike classical bits, qubits cannot be simply copied due to the no-cloning theorem. Errors from decoherence and imperfect gates accumulate quickly.
Achieve fault tolerance - the ability to run large computations despite errors.
Scalability:- small prototypes exist, but useful Quantum computing requires thousands to millions of Qubits.
Build large-scale machines where Qubits can interact reliably & efficiently.
Stability:- Qubits must remain in coherent superpositions long enough for computations. The ratio of coherence time to operation time determines how many gates can be applied before errors dominate.
Ensure Qubits are stable and gate operations are highly accurate.

8. Describe the challengers posed by decoherence and noise in building functional Quantum systems.

Ans:- Challenges of decoherence and noise in Quantum systems:-
Decoherence:- It is when a quantum system interacts with its environment and loses its coherence.
effect:-
1. Superposition collapses into a classical mixture.
2. Entanglement between Qubits breaks down
3. Useful Quantum information is lost

Noise:-
Noise refers to unwanted random fluctuations from the environments or imperfect control signals.
effects:-
1. Even if Qubits are well isolated, tiny noise sources can corrupt data
2. Quantum states are so delicate that even very low noise levels matter

9. Explain the philosophical implications of Quantam mechanics in terms of randomness, determinism and the observer's role.

Ans:- Randomness :-

In classical physics, randomness is usually apparent. If we know all initial conditions, we could, in principle, predict the outcome exactly.

In Quantum physics, ~~ram~~ randomness is fundamental. Even if we know the complete state of a qubit, we only predict probabilities.

For instance, a qubit in the state

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

Determinism :-

classically, the universe behaves like a clockwork machine: the future is fully determined by the present.

In Quantum mechanics, wave function evolves ~~dynami~~ deterministi-cally according to the schrodinger equation. However, measurement outcomes are probabilistic.

Observer Role :-

In classical physics, the observer is passive. Observing a system does not significantly affect it.

In Quantum physics, the observer plays an active role. Measurement disturbs the system.

10. What are three main areas of Quantum technologies? Briefly describe each a. Quantum computing b. Quantum communication c. Quantum sensing and metrology.

Ans:- a. Quantum computing :- Uses principles of superposition and entangl-ement to perform computations with Qubits.

→ Quantam computers can solve certain problems much faster

b. Quantum communication :- Uses Quantum states to transmit information securely.

→ Guarantees unbreakable encryption, since eavesdropping disturbs the Quantum states.

→ Transfer of Quantum information without ~~making~~ moving the particle itself.

c. Quantum ~~Comput~~ sensing and metrology :- Uses quantum effects to make ultra-precise measurements.

→ Medical imaging and brain scanning.

→ Detecting gravitational waves and underground minerals.