MODULE 6:
ERROR CORRECTION
&
NOISE IN QUANTUM

CONTENTS

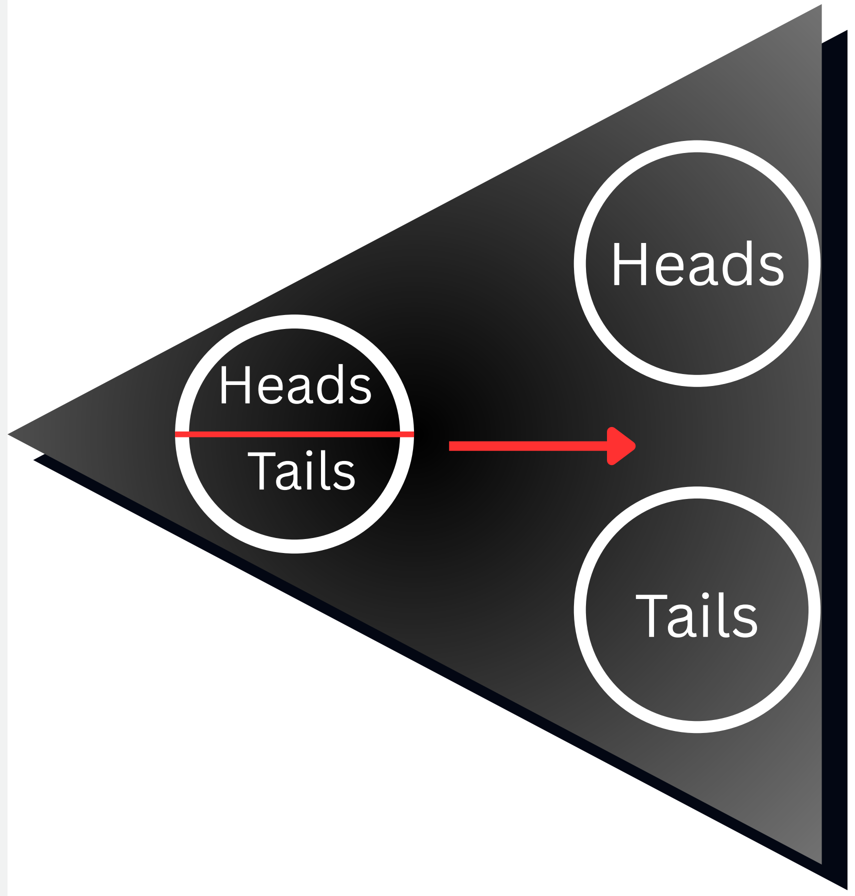
6.1 QUANTUM DECOHERENCE AND NOISE

Quantum Decoherence:

Quantum decoherence can be understood through the example of a spinning coin. While it's spinning, it's like a quantum system in superposition—existing in multiple states at once.

When the environment interacts with the system, it's similar to someone touching the coin mid-air, forcing it to land early.

As a result, the system loses its quantum behavior and settles into a definite, classical state.



Causes of Decoherence:

Environmental Interactions

Quantum systems interact with external systems leading to entanglement with the environment rather than within the system itself.

Thermal Fluctuations

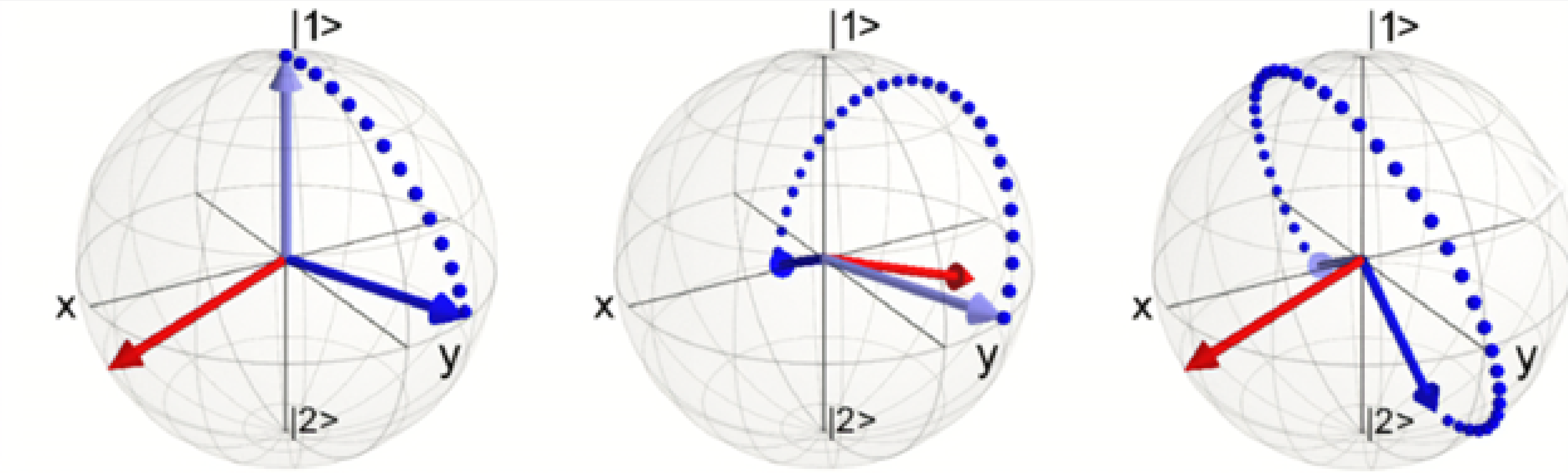
Temperature variations can introduce random energy changes, disrupting quantum states.

Imperfect Control

Errors in applying quantum gates or maintaining qubits can cause unintended state changes.

What is Quantum Noise?

Quantum noise in quantum computing refers to unwanted disturbances that negatively impact qubit states and computations, leading to errors. It's a significant hurdle in building large-scale, fault-tolerant quantum computers. Sources of quantum noise include thermal fluctuations, electromagnetic interference, imperfections in quantum gates, and interactions with the environment.



The graphic above depicts a few rotations of a qubit, with the blue arrows pointing to various points before and after a rotation (various rotations are implemented via gates representing algorithm commands) and the red arrow showing the axis of rotation. The ending position of the blue arrow contains important and precise information but can move incorrectly due to several noise factors.

1. Environment Sensitivity:

Qubits are highly sensitive to temperature changes, stray electromagnetic fields, and even cosmic radiation — all of which can degrade quantum information.

2. Crosstalk:

Lasers or microwaves used to control one qubit can unintentionally affect nearby qubits, leading to interference.

3. Quantum Decoherence:

Qubits lose their quantum state very quickly (in fractions of a second), requiring computations to be completed rapidly.

4.Implementation Errors:

Imperfect gate operations (e.g., rotating 179° instead of 180°) can introduce inaccuracies in quantum algorithms.

Types of Quantum Noise:

Noise Type	Description	Operator
Bit-flip	Flips qubit state between	0〉 and
Phase-flip	Flips phase between	+〉 and
Bit-phase-flip	Combines both bit and phase flip	Y
Depolarizing	Qubit becomes a random mixed state	Random
Dephasing	Relative phase between qubit states is lost	—
Amplitude Damping	Qubit loses energy (e.g.,	1〉 decays to

6.2 QUANTUM ERROR CORRECTION BASICS

Why is Error Correction Necessary?

Quantum states are extremely sensitive to noise. Even minor disturbances can destroy useful information. Since direct copying of quantum data is not possible (due to the no-cloning theorem), we need indirect techniques for error detection and correction.

Quantum vs Classical Error Correction:

Feature	Classical Error Correction	Quantum Error Correction
1. Error Types Handled	Bit-flip errors (0 ⇔ 1)	Bit-flip, phase-flip, and bit-phase-flip errors
2. Redundancy Mechanism	Repetition of bits (e.g., 111 for ‘1’)	Encoding logical qubits into multiple entangled physical qubits
3. Measurement Impact	Measurement is safe and non-destructive	Direct measurement collapses quantum state — uses syndrome measurement
4. Error Detection	Uses parity checks or comparison	Uses ancilla qubits to detect error syndromes without destroying data
5. Correction Method	Majority voting or flipping bits based on error location	Applies unitary operations (like X, Y, Z) based on detected error

6.3 QUANTUM ERROR CORRECTING CODES

What Are QECCs?

Quantum Error Correcting Codes are structured techniques that encode quantum information into a larger quantum system to protect it from errors caused by decoherence, noise, or imperfect operations. These codes allow us to detect and correct quantum errors without collapsing the quantum state.

Purpose of QECCs

- Preserve quantum information during computation and communication.
- Detect and correct bit-flip, phase-flip, and combined errors.
- Enable fault-tolerant quantum computing — computation that can continue correctly even in the presence of some errors.

Examples of Quantum Error Correcting Codes:

Code Name	Qubits Used	Corrects	Description
Bit-Flip Code	3	Bit-flip errors (X)	Encodes logical qubit as `
Phase-Flip Code	3	Phase-flip errors (Z)	Uses Hadamard gates to convert phase errors into bit errors, then applies bit-flip code
Shor Code	9	Bit-flip and phase-flip errors	First QECC; combines bit- and phase-flip correction by nesting 3-qubit codes
Steane Code	7	Any single-qubit error (X, Y, Z)	Based on classical [7,4,3] Hamming code; corrects all types of single-qubit errors
Five-Qubit Code	5	Any single-qubit error	Smallest possible code to correct arbitrary 1-qubit errors; also called the "perfect code"

6.4 FAULT-TOLERANT QUANTUM COMPUTATION

What is Fault Tolerance in Quantum Computing?

Fault-tolerant quantum computing (FTQC) refers to the ability of a quantum computer to perform computations reliably and accurately even in the presence of errors and faults. This is crucial because qubits, the fundamental units of quantum information, are inherently susceptible to noise and decoherence. FTQC aims to achieve this reliability through various techniques, most notably quantum error correction (QEC).

Key Techniques for Fault-Tolerant Quantum Computing

1. **Transversal Gates**
   - Operate on corresponding qubits across code blocks (e.g., apply X to each qubit individually).
   - Prevent error propagation across the system.
2. **Logical Qubits**
   - Encode one logical qubit using many physical qubits.
   - Provides protection by isolating errors within code blocks.

3. Syndrome Extraction:

- Detects where and what kind of error occurred.
- Uses ancilla qubits to avoid collapsing the quantum state.

4. Concatenated Codes:

- Apply multiple layers of quantum codes (code within a code).
- Increases the system’s ability to handle multiple errors simultaneously.

6.5 REAL-WORLD APPLICATIONS OF QEC

Why Quantum Error Correction is Important?

The Problem with Quantum Hardware:

- Quantum computers are extremely sensitive to their environment.
- Qubits can easily lose their quantum state due to noise, decoherence, and gate imperfections.
- Unlike classical bits, qubits can’t be copied or refreshed easily.

Consequences Without QEC:

- Quantum computations become unstable and unreliable over time.
- Algorithms like Shor’s (for factoring) and Grover’s (for search) fail without error control.
- Scalability is not achievable without robust error correction methods.

Real-World Implementations of QEC

1. **Google's Sycamore Processor:**
    - Used repetition codes to correct bit-flip errors in real-time.
    - Demonstrated quantum supremacy in specific tasks.
    - Validated that QEC can be embedded in quantum circuits.
2. **IBM Quantum:**
    - Employs superconducting qubits with built-in error detection circuits.
    - Working toward implementing surface code-based QEC for future fault-tolerant systems.
3. **Topological Codes:**
    - Qubits arranged in a 2D lattice interact only with neighbors.
    - Enables local error correction, which is scalable and hardware-efficient.

THANK YOU