- Binary Logic: Classical computers are built upon Boolean algebra, using binary values (`0` and `1`) to represent logical states.

- Classical Logic Gates: Devices such as AND, OR, NOT, NAND, NOR, XOR, and XNOR perform basic logical operations. These gates are constructed from transistors.

- Transistor Physics: Transistors operate via classical electrodynamics and solid-state physics, particularly:

  - Semiconductors that can be doped to create p-type and n-type materials.
  - PN junctions that allow or block current based on voltage polarity.
  - Voltage thresholds that determine when a gate flips from `0` to `1`.

- Classical gates behave in a deterministic manner: given the same inputs, the outputs are always the same.

- Moore's Law: the number of transistors on a chip doubles approximately every two years.

- As transistors shrink to the nanometer scale, quantum effects like tunneling and superposition become non-negligible, and heat dissipation and power leakage issues emerge due to the density and sensitivity of circuits.

- At scales below ~10 nanometers, electrons can tunnel through barriers that classical physics would forbid. This undermines the reliability of classical logic gates, which rely on sharp voltage thresholds.

- Quantum Mechanics governs the behavior of particles at atomic and subatomic scales:

- Superposition: A quantum system can exist in multiple states simultaneously until measured.

- Entanglement: Two or more qubits can become correlated, such that the state of one immediately influences the other—no matter the distance.

- Quantum systems evolve via reversible operations governed by unitary matrices (unlike classical logic gates, which are not always reversible).

Quantum Bits (Qubits)

- A qubit is the quantum analog of a classical bit. It can be in state `|0⟩`, `|1⟩`, or any linear combination (superposition.

- Qubits can be implemented using:

    - Spin states of electrons
    - Polarization of photons
    - Superconducting circuits
    - Ion traps

- Measurement collapses the superposition, revealing a `0` or `1` probabilistically.

- Operate on qubits and are described by unitary matrices. Unlike classical gates, all quantum gates are reversible.

- Common single-qubit gates:

    - Pauli-X (quantum NOT)
    - Hadamard (H): Creates superposition
    - Phase (S, T) gates

- Two-qubit gates:

    - CNOT (Controlled-NOT): Entangles qubits; crucial for universality
    - CZ (Controlled-Z)

- These gates are combined to create quantum circuits analogous to classical logic circuits.

- Parallelism via Superposition: A quantum computer with *n* qubits can represent 2^n states at once, allowing massive computational parallelism.
- Shor's Algorithm: Factors large integers exponentially faster than classical algorithms.
- Grover's Algorithm: Searches unsorted databases in $\sqrt{N}$ time vs. N time classically.
- Error Correction: Due to the fragile nature of quantum states (subject to decoherence), quantum error correction and fault-tolerant computing are critical to building scalable systems.
- Non-Cloning Theorem: Quantum states cannot be perfectly copied, which makes direct duplication and classical fan-out techniques inapplicable.