25SC806 Advanced Quantum Computation 3-1-0-4

Objective:

To equip students with an advanced understanding of quantum computational principles, qubit technologies, entanglement, error correction, and quantum communication systems.

Unit – I Quantum Foundations and Measurement

Motivation for quantum technologies, overview of quantum physics, quantum measurement postulates, standard quantum limits, types of measurements — direct and indirect, orthogonal and non-orthogonal, quantum non-demolition measurements. Introduction to decoherence, decoherence as measured by the environment, characterizing decoherence in qubits, open-loop control and stabilization of qubit states.

Unit – II Qubits, Quantum Gates and Superconducting Architectures

DiVincenzo criteria, single and multi-qubit gates, quantum circuits, Rydberg and neutral atoms, quantum dot, topological qubits and superconducting qubits; charge qubits including Cooper pair box and transmon qubits, phase qubits using Josephson junctions as artificial atoms, flux qubits involving superconducting loops and flux-based quantum states, fluxonium qubits with large inductance and enhanced anharmonicity, circuit quantum electrodynamics (cQED), interaction of qubits with resonators, Hamiltonian modeling of superconducting qubits, photonics-based qubits including conventional linear optical setups and integrated photonics, Rydberg atoms and their strong dipole interactions for quantum control and gate implementation.

Unit – III Entanglement and Quantum Correlations

Bipartite and multipartite entanglement, Bell, GHZ and W states, measures of entanglement — von Neumann entropy, concurrence, negativity. Entanglement witnesses, entanglement dynamics under decoherence, quantum monogamy, area laws, entanglement as a resource in quantum information theory.

Unit – IV Noise, Decoherence and Quantum Error Correction

Noise models — Markovian and non-Markovian channels, Kraus operator formalism, quantum process tomography, quantum error correction codes — bit flip, phase flip, Shor, Steane, and surface codes. Fault-tolerant quantum computation, threshold theorems, stabilizer formalism, decoherence-free subspaces, dynamical decoupling techniques.

Unit – V Quantum Algorithms and Cryptography

Foundations of quantum algorithms, quantum parallelism and speedup, basic algorithms — Deutsch-Jozsa, Grover's algorithm, introduction to Shor's algorithm (conceptual), Overview of quantum complexity classes — P, NP, BQP, QMA, QIP; oracle separations; comparisons with classical complexity classes. Quantum key distribution protocols — BB84, E91, no-cloning theorem, eavesdropping strategies, Holevo bound, privacy amplification, quantum channel capacity.

Unit – VI Quantum Communication and Sensing

Quantum teleportation, entanglement swapping, superdense coding, quantum repeaters, optical fiber and free-space quantum communication channels. Overview of experimental achievements in quantum communication. Basics of quantum sensing, photon generation and detection, quantum-limited amplifiers, superconducting resonators, applications in gravimetry, atomic clocks, and magnetometry.

Textbooks:

1. M.A. Nielsen and I.L. Chuang, Quantum Computation and Quantum Information, Cambridge University Press, 2010 (10th Anniversary Edition)
2. John Preskill, Ph219/CS219 lecture notes, Caltech.
3. Scott Aaronson, lecture notes

References:

Horodecki, R., Horodecki, P., Horodecki, M., & Horodecki, K. (2009). Quantum entanglement. *Reviews of Modern Physics, 81*(2), 865–942.

Outcomes:

CO	Course Outcomes
CO01	Understand quantum foundations including measurement theory, decoherence, and the physical principles underlying qubit control and readout.
CO02	Analyze and compare physical qubit implementations such as superconducting, photonic, and Rydberg-based architectures in realistic quantum systems.
CO03	Evaluate quantum entanglement and its applications using appropriate quantitative measures and theoretical frameworks.
CO04	Apply quantum error correction methods and fault-tolerant strategies to mitigate noise and decoherence in quantum systems.
CO05	Demonstrate conceptual and technical knowledge of foundational quantum algorithms, cryptographic protocols, and state-of-the-art quantum communication and sensing technologies.

Evaluation Pattern:

Category	Marks
Quizzes(3)	30
Assignments(2)	20
End-sem	50