DEPARTMENT OF COMPUTER SCIENCE & ENGINEERING

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MC46XX30 : Quantum Computing

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Course Description An introduction to quantum computation focused primarily on foundations, theory, and rigor, rather than specific hardware implementations or heuristic applications. We will begin with the axioms of quantum mechanics and the most common formulation of quantum computation based on quantum circuits. We will then develop the core primitives in the quantum algorithms toolkit (such as quantum Fourier transforms, phase estimation, and Trotterization/quantum simulation) and establish some elementary complexity-theoretic results (including some oracle separations, and various lower and upper bounds), as well as work through the crown jewel of quantum algorithms to date—Shor's factoring algorithm. Along the way, we will see some of the more curious aspects of quantum information facilitated by quantum entanglement (such as Grover search, quantum teleportation, superdense coding, Bell violations). The last portion of the course will develop the basic theory of quantum error-correcting codes and the fault tolerance problem. In particular, you may want to note that I do not plan to cover quantum optimization, quantum machine learning, or post-quantum cryptography in any depth (if at all).

Prerequisites: linear algebra, quantum mechanics

Course Outcomes:

After completing the course, successful students should be able to do the following:

Sl.No	Outcome	Mapping to PO
1	Formulate the axioms of quantum mechanics and all relevant definitions.	PO1, PO2
2	Explain what it means for a quantum computer to solve a problem, and efficiently solve a problem as well as some of the limitations of quantum computers, both theoretical and practical.	PO2, PO3, PO5
3	Describe the essential role that measurement plays in quantum computation.	PO3, PO4
4	Define several examples of impressive things that quantum computers can do when compared to classical computers.	PO4, PO7

5	Understand the fault tolerance problem, and how quantum error-correction works to partially address it.	PO1, PO12

Unit 1: [6]

Introduction to information theory: Classical Information, Information Content in a Signal, Entropy and Shannon's Information Theory, Why Quantum Computing?, Postulates of Quantum Mechanics, Qubits and Bloch Sphere, Vector Spaces, Hilbert spaces, Basis and Dimension, Inner Products, Orthonormality, Bra-Ket Formalism

Unit 2: [8]

Observables, Pauli Operators, Outer Products, Hermitian, Unitary, and Normal Operators, Eigenvalues and Eigenvectors, The Trace of an Operator, Projection Operators, Positive Operators, The Heisenberg Uncertainty Principle, Tensor product: The Density operator.

Unit 3: [10]

Quantum Measurement: Distinguishing Quantum States and Measurement, Projective Measurements, Measurements on Composite Systems, POVM; Entanglement: Bell's Theorem, Bipartite Systems and the Bell Basis, Entanglement Fidelity; Quantum gate and quantum circuits, Quantum No Cloning Theorem and Teleportation, Dense coding.

Unit 4: [12]

Deutsch Algorithm, Deutsch-Jozsa Algorithm, Simon Problem, Grover's Search Algorithm, Quantum Fourier Transform, Period Finding, Method of Continued Fraction, Shor's Factorization Algorithm, Quantum Error Correction Codes, Classical Information Theory: Shannon Entropy, Von Neumann Entropy

Unit 5: [6]

Classical Cryptography, RSA Algorithm, Basic Quantum Cryptography, An Example Attack: The Controlled NOT Attack, BB84 protocol, B-92 and Eckart protocol, Quantum noise and error correction.

Reference Books:

1. McMahon, D. (2007). Quantum Computing Explained. Germany: Wiley.
2. Nielsen, M. A., Chuang, I. L. (2010). Quantum Computation and Quantum Information: 10th Anniversary Edition. (n.p.): Cambridge University Press.

3. Woody III, L. S. (2022). Essential Mathematics for Quantum Computing: A Beginner's Guide to Just the Math You Need Without Needless Complexities. United Kingdom: Packt Publishing.
4. Mermin, N. D. (2007). Quantum Computer Science: An Introduction. (n.p.): Cambridge University Press.