ECE 305 – QUANTUM SYSTEMS I

Simeon Bogdanov, Eric Chitambar, and Kejie Fang

Overview

Quantum information science (QIS) is a rapidly developing field that aims to revolutionize computation and communication technology. This course introduces the basic principles of quantum mechanics and its applications in quantum information science. The experimental and mathematical concepts of quantum mechanics are introduced in terms of quantum bits, or qubits, and the students will learn how qubits are used for computing and communication. Topics include: wave-particle duality, interferometry and quantum sensing, spin systems, atomic transitions and Rabi Oscillations, bra/ket notation, quantum communication and entanglement, quantum computation and algorithms, and continuous systems. The primary objective is to provide the conceptual and quantitative foundations for higher-level courses in quantum information science and nanoelectronics.

Prerequisites

Math 257 and Phys 214, or junior standing.

Structure

Course textbooks:

B. Schumacher and M. Westmoreland, Quantum Processes Systems, and Information, 2010 (Primary).
D. Miller, Quantum Mechanics for Scientists and Engineers, Cambridge, 2008 (Supplemental).

Instructor

Prof. Eric Chitambar (echitamb@illinois.edu)

Office Hours

Office hours will be held once a week for 60 minutes. The TA will also hold weekly office hours for 120 minutes.

Grading

This course will have homework assignments given every two weeks, three midterm exams, and a final exam. Their relative contribution to the overall grade is as follows:

Homework: 25%
Midterm Exams 1, 2, & 3: 25% each
Final Exam: 25%

Outline

Introduction	Lecture 1	**Bits and Information**	S-W 1.1 **(1 Hour)**
	Lecture 2	**Quantum Systems and Wave-Particle Duality** (complementarity, quantum probabilities)	S-W 1.2 **(2 Hours)**

Qubits	Lecture 3	**The Mach-Zehnder Interferometer** (phase shifters, beam splitters, matrix representations, quantum sensing)	S-W 2.1 **(3 Hours)**
	Lecture 4	**Spin 1/2 particles** (Stern-Gerlach experiment, bra-ket notation, Bloch sphere, measuring spin)	S-W 2.2 **(2 Hours)**
	Lecture 5	**Two-level atoms** (time evolution, unitary operators and the Hamiltonian, transition probabilities)	S-W 2.3 **(2 Hours)**
Mathematical structure of quantum states and observables	Lecture 6	**Hilbert space and Linear Operators** (Pauli matrices, eigenvalues, spectral decomposition)	S-W 3.1-3.3 **(3 Hours)**
	Lecture 7	**Observables** (Expectation values, incompatible observables, uncertainty principle)	S-W 3.4-3.5 **(3 Hours)**
Quantum measurements and evolution	Lecture 8	**Quantum Communication** (Distinguishability, projection axiom, Holevo’s bound, QKD)	S-W 4.1-4.3 **(3 Hours)**
	Lecture 9	**Quantum Dynamics** (Unitary evolution, Schrodinger's equation, atomic clocks)	S-W 5.1-5.2 **(2 Hours)**
Quantum entanglement and computation	Lecture 10	**Entanglement** (Tensor products, interaction Hamiltonians, nuclear spin entanglement, quantum steering, and Bell's theorem)	S-W 6.1-6.6 **(5 Hours)**
	Lecture 11	**Quantum Computation** (Quantum circuits and algorithms, NMR quantum computing, decoherence, spin-echo effect)	S-W 18.1-18.5 **(5 Hours)**
	Lecture 12		

Wave functions and continuous-variable systems		**Continuous Systems** (The continuum limit, wave functions, continuous observables, position and moment, Fourier transformations)	S-W 10.1-10.5 **(4 Hours)**
	Lecture 13	**Dynamics of a free particle** (Schrodinger equation, Heisenberg uncertainty principle, wave packets, particle in a box, quantum harmonic oscillator)	S-W 11.1-11.4 **(5 Hours)**

Learning Objectives

By the end of the course, the student will be able to

- Explain how information can be encoded and decoded into bits.
- Compute probabilities for measurements performed on quantum systems.
- Use matrices and matrix multiplication to represent the behavior of photons in a Mach-Zehnder interferometer.
- Explain principles of quantum measurement using sequential Stern-Gerlach experiments.
- Compute expectation value and variance of different quantum observables.
- Apply principles of quantum measurement to describe simple communication protocols.
- Derive the time evolution of quantum systems using Schrodinger's equation.
- Differentiate between entangled and unentangled quantum systems; show how entanglement can be used in quantum computation.
- Describe the different components of NMR quantum computing and how they realize quantum logical gates.
- Understand the difference between discrete and continuous quantum systems and how the two are related.
- Compute the wave function for a continuous system under different types of Hamiltonians.