PHYS 139/239: Quantum Science and Technology

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Zoom Lecture: TuTh 12:30 PM - 1:50 PM PST	Outdoor classroom: Revelle North
Office Hours: TBD	https://ucsd.zoom.us/my/barreiro
TA: Paul Lauria, plauria@ucsd.edu	
Discussion session: TBD	https://ucsd.zoom.us/

Course Description

Self-contained course on quantum science and technology. Although quantum devices are implemented using a number of technologies, the fundamental quantum mechanical structure underpinning them is the same as that of the quantum optics of atoms and light. *Atoms* may be genuine atoms or engineered systems, e.g. superconducting systems, and *light* may be of any wavelength from UV to microwave regimes. This course will cover the foundations of quantum optics, the most powerful and convenient *theoretical and experimental* toolbox for the understanding of quantum devices, such as quantum computers and sensors.

Qiskit: We will use qiskit as playground and for some of the homework. Plans in progress, including other platforms.

Course References

Course will refer to chapters/sections from the following books:

- Gardiner & Zoller, *The quantum world of ultra-cold atoms and light, Book I: Foundations of Quantum Optics*, Imperial College Press (2015).
- Gardiner & Zoller, *The quantum world of ultra-cold atoms and light, Book II: The Physics of Quantum-Optical Devices*, Imperial College Press (2015).
- Schumacher & Westmoreland, *Quantum Processes, Systems, & Information*, Cambridge Univ. Press (2010).
- Wiseman & Milburn, *Quantum Measurement and Control*, Cambridge Univ. Press (2010).
- Nielsen & Chuang, *Quantum Computation and Quantum Information*, Cambridge Univ. Press (2000).

- Fox, *Quantum Optics, An Introduction*, Oxford Univ. Press (2006).
- Gerry & Knight, *Introductory Quantum Optics*, Cambridge Univ. Press. (2005).
- Moore/Davis/Coplan/Greer, *Building Scientific Apparatus*, Cambridge Univ. Press (2009).
- Bachor & Ralph, *A Guide to Experiments in Quantum Optics*, Wiley-VCH (2004).
- Bouwmeester & Ekert & Zeilinger, *The Physics of Quantum Information*, Springer (2000).

Suggested prerequisites

PHYS 139. Prerequisite: PHYS 130B.
PHYS 239. Prerequisite: PHYS 212B.

Grading

Weekly homework (40%), Two midterm oral exams (20%), final paper report and presentation (40%).

Tentative course outline

Part I. Quantum Computing, Mechanics, and Information

1. Quantum Computing for the very curious
   - The state of a qubit
   - Logic gates
   - Universal quantum computing
   - DiVincenzo criteria for a practical quantum computer
2. Quantum Mechanics distilled (Part 1/2)
   - Postulates of quantum mechanics
   - Bell inequalities
3. Quantum information theory (Part 1/2)
   - Entanglement, Schmidt decomposition with pure states
   - Transferring QI: No-cloning thm, quantum teleportation
   - Quantum dense coding (Information theory)
4. Quantum Mechanics distilled (Part 2/2)
   - Beyond state vectors
   - Open systems
5. Quantum information theory (Part 2/2)
   - Entanglement with density matrices,
   - Reduced density operators
   - Schmidt decomp for mixed states
   - Entropy of entanglement

  - Multipartite entanglement

Part II. Quantum Science and Technology. Covered in various degrees of depth.

1. Qubits from physical quantum systems (QED, harmonic oscillator, atoms)
   - A particle in space
   - Spins
   - Ladder systems (two-level nonlinear oscillators)
   - Superconducting quantum devices
   - Many particles
   - Atoms (bound states in 3-D, central potentials, two-level atoms)
   - Topological systems
2. Preparation/Initialization, uncovering quantum features: intro to cooling (laser and thermalization, dilution fridge)
3. Processing the quantum state of the system (Quantum Control)
   - Coherent manipulation of two-level systems
   - Coherent manipulation of multilevel systems
   - Cavity QED
   - Trapped ions: optical manipulation, the quantum computer
   - Circuit QED, quantum circuit theory
4. Environment/Isolation/Compensation (Noise and Decoherence)
   - Two-level systems including atomic motion
   - Dissipative dynamics of driven atoms
   - Modelling real atoms
   - Laser cooling (IV), untrapped atoms/ions
   - Error correction
5. Quantum sensors
   - Rev. Mod. Phys. **49**, 035002 (2017).
6. Measuring the final state of the system
   - Foundations and formalism of quantum measurement
   - Continuous measurement
   - Phase-sensitive quantum optics: Homodyne measurement, squeezing, correlations and amplifiers Homodyne and Heterodyne Measurements
7. Distributing quantum information (Quantum Networks, optical and microwave Cavity QED)
   - Cavity quantum electrodynamics networks
   - The dark-state ensemble quantum memory
   - Spatially extended atomic ensembles