IMPORTANT:
Please refer to the USC Center for Excellence in Teaching for current best practices in syllabus and course design. This document is intended to be a customizable template that primarily includes the technical elements required for the Curriculum Office to forward your proposal to the UCOC.

EE539 –Engineering Quantum Mechanics

Units: 4
Term: Fall 2022

Lectures: Tuesday and Thursday, 9:00am - 10:50am

Location: ZHS 360

Instructor: Tony Levi
Office: KAP 132
Office Hours: Tuesday and Thursday, 7:45am – 8:45am

Contact Info: alevi@usc.edu, 213-740-7318 (office),

Teaching Assistant: Zeyu Wang
Office: PHE 223
Office Hours: 9.00am – 10.00am
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IT Help: USC Information Technology Services
Hours of Service: Around the clock
Contact Info: 213-740-5555

Course Description

Quantum mechanics is the basis for understanding physical phenomena on the atomic and nano-meter scale. There are numerous applications of quantum mechanics in biology, chemistry and engineering. Those with significant economic impact include semiconductor transistors, lasers, quantum optics and photonics. As technology advances, an increasing number of new electronic and opto-electronic devices will operate in ways that can only be understood using quantum mechanics. Over the next twenty years fundamentally quantum devices such as single-electron memory cells and photonic signal processing systems will become commonplace. This course aims to develop intuition as well as quantitative tools and methods for developing models of physical systems that operate according to quantum mechanics. Applications explored include electron transport in devices and the laser diode.

Learning Objectives

After completing this course, the student will have a solid foundation in the tools and methods of quantum mechanics. The intent is that this understanding will enable intuition, insight, and contributions to future, as yet unknown, applications.

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Prerequisite: See recommended preparation.
Co-Requisite: None
Concurrent Enrollment: None
Recommended Preparation: *Mathematics*: A basic working knowledge of differential calculus, linear algebra, statistics, and geometry. *Computer skills*: An ability to program numerical algorithms in MATLAB and display results in graphical form. *Physics background*: Basic understanding of Newtonian mechanics, waves, and Maxwell's equations.

Course Notes

This course has 25 lectures, 11 homeworks, 1 midterm exam, and one comprehensive final exam covering all the material learned. A letter grade will be derived from all the homeworks and exams. When appropriate, examples will be used to connect the theorical material presented with its practical applications.

Technological Proficiency and Hardware/Software Required

The course is offered in a traditional classroom setting.

Required Readings and Supplementary Materials

The required text is *Applied Quantum Mechanics*, A.F.J. Levi, Cambridge University Press Paperback: ISBN: 978-0-521-18399-4.
Optional supplementary material available as a free download for USC students is:
Essential Classical Mechanics for Device Physics, A.F.J. Levi, IoP, ISBN: 9781681744124
Essential Semiconductor Laser Device Physics, A.F.J. levi, IoP, ISBN: 978-1-6432-7029-6
and
Essential Electron Transport for Device Physics, A.F.J. Levi, AIP, ISBN: 978-0-7354-2158-5

Description and Assessment of Assignments

Homeworks related to the material covered are assigned and given to the students. The homeworks are due one week after they are assigned. The homeworks will then be graded and returned to the students one week after they were received. All assignments must be completed individually by the students.

Grading Breakdown

Assessment Tool (assignments)	% of Grade
11 Homeworks	10
One Midterm Exam	35
Final Exam	55
TOTAL	100

Homework Submission Policy

Homework assignments are due before the deadline given, usually at the beginning of a class.

Grading Timeline

The homeworks will be graded and returned to the students one week after the submission deadline.

Additional Policies

No late submissions of homeworks or computer codes are allowed. It is expected that the students will attend all classes in person, as opposed to just watching a recorded version of the lectures, if available.

Course Schedule: A Weekly Breakdown

Lecture	Topics
	Introduction
1-2	REVIEW OF CLASSICAL CONCEPTS Extended discussion to include material from the book "Essential classical mechanics for device physics". The linear and nonlinear oscillator. Electromagnetism. Mechanical model of light-matter interaction due to Lorentz.
3	TOWARDS QUANTUM MECHANICS – PARTICLES AND WAVES Diffraction, interference, and correlation functions for light. Black-body radiation and evidence for quantization of light. Photoelectric effect. THE PHOTON PARTICLE The existence of the photon particle. The photon at a beam splitter. Stochastic computing. Secure quantum communication.
4-5	WAVE-PARTICLE DUALITY The link between quantization of photons and quantization of other particles. Diffraction and interference of electrons. When is a particle a wave? THE SCHRÖDINGER WAVE EQUATION The wave function description of an electron of mass m0 in free-space. The electron wave packet and dispersion. The Bohr model of the hydrogen atom. Calculation of the average radius of an electron orbit in hydrogen. Calculation of energy difference between electron orbits in hydrogen. Periodic table of elements. Crystal structure. Three types of solid classified according to atomic arrangement. Two-dimensional square lattice, cubic lattices in three-dimensions. Electronic properties of semiconductor crystals. The semiconductor heterostructure.
	Using the Schrödinger wave equation
6-7	INTRODUCTION The effect of discontinuities in the wave function and its derivative WAVE FUNCTION NORMALIZATION AND COMPLETENESS INVERSION SYMMETRY IN THE POTENTIAL Particle in a one-dimensional square potential well with infinite barrier energy NUMERICAL SOLUTION OF THE SCHRÖDINGER EQUATION Matrix solution to the discretized Schrödinger equation. Non-transmitting boundary conditions. Periodic boundary conditions CURRENT FLOW Current flow in a one-dimensional infinite square potential well. Current flow due to a traveling wave

	DEGENERACY IS A CONSEQUENCE OF SYMMETRY Bound states in three-dimensions and degeneracy of eigenvalues BOUND STATES OF A SYMMETRIC SQUARE POTENTIAL WELL Symmetric square potential well with finite barrier energy TRANSMISSION AND REFLECTION OF UNBOUND STATES Scattering from a potential step when effective electron mass changes. Probability current density for scattering at a step. Impedance matching for unity transmission PARTICLE TUNNELING Electron tunneling limit to reduction in size of CMOS transistors THE NONEQUILIBRIUM ELECTRON TRANSISTOR
	Scattering in one-dimension: The propagation method
8	THE PROPAGATION MATRIX METHOD Writing a computer program for the propagation method TIME REVERSAL SYMMETRY CURRENT CONSERVATION AND THE PROPAGATION MATRIX
9	THE RECTANGULAR POTENTIAL BARRIER Tunneling RESONANT TUNNELING Transmission threshold. Multiple potential barriers THE POTENIAL BARRIER IN THE □-FUNCTION LIMIT ENERGY BANDS IN PERIODIC POTENTIALS: THE KRONIG-PENNY POTENTIAL Bloch's theorem. Propagation matrix in a periodic potential. Real and imaginary band structure
10	THE TIGHT BINDING MODEL FOR ELECTRONIC BAND STRUCTURE Nearest neighbor and long-range interactions. Crystal momentum and effective electron mass USE OF THE PROPAGATION MATRIX TO SOLVE OTHER PROBLEMS IN ENGINEERING THE WKB APPROXIMATION Tunneling
	Related mathematics
11-12	ONE PARTICLE WAVE FUNCTION SPACE PROPERTIES OF LINEAR OPERATORS Hermitian operators. Commutator algebra DIRAC NOTATION MEASUREMENT OF REAL NUMBERS Time dependence of expectation values. Indeterminacy in expectation value. The generalized indeterminacy relation THE NO CLONING THEOREM DENSITY OF STATES Density of states of particle mass m in 3D, 2D, 1D and 0D. Quantum conductance. Numerically evaluating density of states from a dispersion relation. Density of photon states
	The harmonic oscillator
13	THE HARMONIC OSCILLATOR POTENTIAL CREATION AND ANNIHILATION OPERATORS The ground state. Excited states HARMONIC OSCILLATOR WAVE FUNCTIONS Classical turning point

	TIME DEPENDENCE The superposition operator. Measurement of a superposition state
14	Time dependence in the Heisenberg representation. Charged particle in harmonic potential subject to constant electric field ELECTROMAGNETIC FIELDS Laser light. Quantization of an electrical resonator. Quantization of lattice vibrations. Quantization of mechanical vibrations
	Fermions and Bosons
15	INTRODUCTION The symmetry of indistinguishable particles. Slater determinant. Pauli exclusion principle. Fermion creation and annihilation operators – application to tight-binding Hamiltonian FERMI-DIRAC DISTRIBUTION FUNCTION Equilibrium statistics. Writing a computer program to calculate the chemical potential and Fermi-Dirac distribution at finite temperature BOSE-EINSTIEN DISTRIBUTION FUNCTION CURRENT AS FUNCTION OF VOLTAGE BIAS Semiconductor heterostructure diode structures in the depletion approximation. Metal-insulator-metal. Reduced dimensions
	Midterm
16	Review
17	Midterm exam
	Fermions and Bosons, continued.
18-19	PHOTON FOCK STATES The Mandel effect. n-photons at a beam splitter. *n*-photons at a FP resonator THE MANDEL EFFECT Dual photon source. Fiber-optic beam splitter and delay line. Photon counting and correlation
	Time-dependent perturbation theory and the laser diode
20	FIRST-ORDER TIME-DEPENDENT PERTURBATION THEORY Abrupt change in potential. Time dependent change in potential CHARGED PARTICLE IN A HARMONIC POTENTIAL FIRST-ORDER TIME-DEPENDENT PERTURBATION FERMI'S GOLDEN RULE IONIZED IMPURITY ELASTIC SCATTERING RATE IN GaAs The coulomb potential. Linear screening of the coulomb potential. Correlation effects in position of dopant atoms. Calculating the electron mean free path
21	EMISSION OF PHOTONS DUE TO TRANSITIONS BETWEEN ELECTRONIC STATES Density of optical modes in three dimensions. Light intensity. Background photon energy density at thermal equilibrium. The golden rule for stimulated optical transitions. The Einstein A and B coefficients. Occupation factor for photons in thermal equilibrium in a two-level system. Derivation of the relationship between spontaneous emission rate and gain THE SEMICONDUCTOR LASER DIODE Spontaneous and stimulated emission. Optical gain in a semiconductor. Optical gain in the presence of electron scattering

	DESIGNING A LASER CAVITY Resonant optical cavity. Mirror loss and photon lifetime. The Fabry-Perot laser diode. Rate equation models
22	NUMERICAL METHOD OF SOLVING RATE EQUATIONS The Runge-Kutta method. Large-signal transient response. Cavity formation NOISE IN LASER DIODE LIGHT EMISSION Effect of photon and electron number quantization. Langevin and semiclassical master equations QUANTUM THEORY OF LASER OPERATION Density matrix. Single and multiple quantum dot, saturable absorber
	Time independent perturbation theory
23	NON-DEGENERATE CASE Hamiltonian subject to perturbation *W*. First-order correction. Second-order correction. Harmonic oscillator subject to perturbing potential in x, x2 and x3 DEGENERATE CASE Secular equation. Two states. Perturbation of two-dimensional harmonic oscillator. Perturbation of two-dimensional potential with infinite barrier
	Angular momentum, the hydrogenic atom, and bonds
24	ANGULAR MOMENTUM Classical angular momentum. The angular momentum operator. Eigenvalues of the angular momentum operators L_z and L^2. Geometric representation SPHERICAL HARMONICS AND THE HYDROGEN ATOM Spherical coordinates and spherical harmonics. The rigid rotator. Quantization of the hydrogenic atom. Radial and angular probability density
25	ELECTROMAGNETIC RADIATION No eigenstate radiation. Superposition of eigenstates. Hydrogenic selection rules for dipole radiation. Fine structure BONDS. The hydrogen molecule ion. The hydrogen molecule covalent bond. Valence bond description. Molecular orbital description. The ionic bond.
FINAL EXAM	All material Refer to the final exam schedule in the USC *Schedule of Classes.* classes.usc.edu.

Statement on Academic Conduct and Support Systems

Academic Conduct:
Plagiarism – presenting someone else's ideas as your own, either verbatim or recast in your own words – is a serious academic offense with serious consequences. Please familiarize yourself with the discussion of plagiarism in SCampus in Part B, Section 11, "Behavior Violating University Standards" policy.usc.edu/scampus-part-b. Other forms of academic dishonesty are equally unacceptable. See additional information in SCampus and university policies on scientific misconduct, policy.usc.edu/scientific-misconduct.

Support Systems:
Counseling and Mental Health - (213) 740-9355 – 24/7 on call
studenthealth.usc.edu/counseling
Free and confidential mental health treatment for students, including short-term psychotherapy, group counseling, stress fitness workshops, and crisis intervention.

National Suicide Prevention Lifeline - 1 (800) 273-8255 – 24/7 on call
suicidepreventionlifeline.org
Free and confidential emotional support to people in suicidal crisis or emotional distress 24 hours a day, 7 days a week.

Relationship and Sexual Violence Prevention Services (RSVP) - (213) 740-9355(WELL), press "0" after hours – 24/7 on call
studenthealth.usc.edu/sexual-assault
Free and confidential therapy services, workshops, and training for situations related to gender-based harm.

Office of Equity and Diversity (OED) - (213) 740-5086 | Title IX – (213) 821-8298
equity.usc.edu, titleix.usc.edu
Information about how to get help or help someone affected by harassment or discrimination, rights of protected classes, reporting options, and additional resources for students, faculty, staff, visitors, and applicants.

Reporting Incidents of Bias or Harassment - (213) 740-5086 or (213) 821-8298
usc-advocate.symplicity.com/care_report
Avenue to report incidents of bias, hate crimes, and microaggressions to the Office of Equity and Diversity |Title IX for appropriate investigation, supportive measures, and response.

The Office of Disability Services and Programs - (213) 740-0776
dsp.usc.edu
Support and accommodations for students with disabilities. Services include assistance in providing readers/notetakers/interpreters, special accommodations for test taking needs, assistance with architectural barriers, assistive technology, and support for individual needs.

USC Campus Support and Intervention - (213) 821-4710
campussupport.usc.edu
Assists students and families in resolving complex personal, financial, and academic issues adversely affecting their success as a student.

Diversity at USC - (213) 740-2101
diversity.usc.edu
Information on events, programs and training, the Provost's Diversity and Inclusion Council, Diversity Liaisons for each academic school, chronology, participation, and various resources for students.

USC Emergency - UPC: (213) 740-4321, HSC: (323) 442-1000 – 24/7 on call
dps.usc.edu, emergency.usc.edu
Emergency assistance and avenue to report a crime. Latest updates regarding safety, including ways in which instruction will be continued if an officially declared emergency makes travel to campus infeasible.

USC Department of Public Safety - UPC: (213) 740-6000, HSC: (323) 442-120 – 24/7 on call
dps.usc.edu
Non-emergency assistance or information.

Office of the Ombuds - (213) 821-9556 (UPC) / (323-442-0382 (HSC)
ombuds.usc.edu
A safe and confidential place to share your USC-related issues with a University Ombuds who will work with you to explore options or paths to manage your concern.