Engineering Quantum Mechanics. Fall 2016.
TTh 9.30 a.m. – 10.50 a.m., VHE 210.

Web site: [http://www.usc.edu/alevi](http://www.usc.edu/alevi)
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EE539: Abstract and Prerequisites

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| Office Hours:             |
| TTh 8:00 a.m. - 9:15 a.m. or by appointment |

| Grading:                     |
| Midterm: 35%                |
| Homework: 10%               |
| Final Exam: 55%             |

| Final Exam:                 |
| 11:00 a.m. - 1:00 p.m.      |
| Thursday, December 8, 2015, VHE 210 |
| First day of class – Tuesday, August 23, 2016 |
| Last day of class – Thursday, December 1, 2016 |

| Required Text:              |
| Paperback: Call Cambridge University Press at (845) 353-7500 and ask for the "Print on demand version" ISBN: 978-0-521-18399-4 |

| Optional Text:              |

Abstract
Quantum mechanics is the basis for understanding physical phenomena on the atomic and nanometer 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. The purpose of this course is to cover a few selected applications and to provide a solid foundation in the tools and methods of quantum mechanics. The intent is that this understanding will enable insight and contributions to future, as yet unknown, applications.

Prerequisites
Mathematics:
A basic working knowledge of differential calculus, linear algebra, statistics, and geometry.

Computer skills:
An ability to program numerical algorithms in MATLAB or similar language and display results in graphical form.

Physics background:
Should include a basic understanding of Newtonian mechanics, waves, and Maxwell’s equations.
Introduction: Lectures 1 - 3

Lecture 1

**REVIEW OF CLASSICAL CONCEPTS**
- The linear and nonlinear oscillator
- Electromagnetism

**TOWARDS QUANTUM MECHANICS – PARTICLES AND WAVES**
- Diffraction, interference, and correlation functions for light
- Black-body radiation and evidence for quantization of light
- Photoelectric effect and the photon particle

Lecture 2

- Secure quantum communication
- The link between quantization of photons and quantization of other particles
- Diffraction and interference of electrons
- When is a particle a wave?

Lecture 3

**THE SCHRODINGER WAVE EQUATION**
- The wave function description of an electron of mass $m_0$ 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: Lectures 4 - 6

Lecture 4

**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 SCHRODINGER EQUATION**
- Matrix solution to the discretized Schrödinger equation
- Nontransmitting 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
Lecture 5

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

Lecture 6

PARTICLE TUNNELING
Electron tunneling limit to reduction in size of CMOS transistors

THE NONEQUILIBRIUM ELECTRON TRANSISTOR

Scattering in one-dimension: The propagation method: Lectures 7 - 10

Lecture 7

THE PROPAGATION MATRIX METHOD
Writing a computer program for the propagation method

TIME REVERSAL SYMMETRY

CURRENT CONSERVATION AND THE PROPAGATION MATRIX

Lecture 8

THE RECTANGULAR POTENTIAL BARRIER
Tunneling

RESONANT TUNNELING
Localization threshold
Multiple potential barriers

THE POTENTIAL BARRIER IN THE δ-FUNCTION LIMIT

Lecture 9

ENERGY BANDS IN PERIODIC POTENTIALS: THE KRONIG-PENNY POTENTIAL
Bloch’s theorem
Propagation matrix in a periodic potential
Real and imaginary band structure

Lecture 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: Lecture 11 - 12

Lecture 11

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

Lecture 12

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: Lectures 13 - 14

Lecture 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

Lecture 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: Lecture 15 - 16

Lecture 15

INTRODUCTION
The symmetry of indistinguishable particles. Slater determinant
Pauli exclusion principle. Fermion creation and annihilation operators – application to tight-binding Hamiltonian

Lecture 16

**FERMI-DIRAC DISTRIBUTION FUNCTION**
Equilibrium statistics
Writing a computer program to calculate the chemical potential and Fermi-Dirac distribution at finite temperature

**BOSE-EINSTEIN DISTRIBUTION FUNCTION**
Current as function of voltage bias
Semiconductor heterostructure diode structures in the depletion approximation.
Metal-insulator-metal.
Reduced dimensions

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**Time dependent perturbation theory and the laser diode:** Lectures 17 - 21

Lecture 17

**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

Lecture 18

**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

Lecture 19

**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
Fermi’s 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

Lecture 20

**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
Lecture 21

**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

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**Time independent perturbation theory:** Lectures 22 - 23

Lecture 22

**NON-DEGENERATE CASE**
Hamiltonian subject to perturbation $W$
First-order correction. Second order correction
Harmonic oscillator subject to perturbing potential in $x$, $x^2$ and $x^3$

Lecture 23

**DEGENERATE CASE**
Secular equation
Two states
Perturbation of two-dimensional harmonic oscillator
Perturbation of two-dimensional potential with infinite barrier

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**Angular momentum and the hydrogenic atom:** Lectures 24 - 26

Lecture 24

**ANGULAR MOMENTUM**
Classical angular momentum
The angular momentum operator
Eigenvalues of the angular momentum operators $L_z$ and $L^2$
Geometric representation

Lecture 25

**SPHERICAL HARMONICS AND THE HYDROGEN ATOM**
Spherical coordinates and spherical harmonics
The rigid rotator
Quantization of the hydrogenic atom
Radial and angular probability density

Lecture 26

**ELECTROMAGNETIC RADIATION**
No eigenstate radiation
Superposition of eigenstates
Hydrogenic selection rules for dipole radiation
Fine structure
Hybridization