Engineering Quantum Mechanics. Fall 2015.
TTh 9.30 a.m. – 10.50 a.m., VHE 210.

Web site: http://www.usc.edu/alevi
Web site: http://classes.usc.edu/term-20153/classes/ee

EE539: Abstract and Prerequisites

<table>
<tr><td>Instructor: Tony Levi
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Email: alevi@usc.edu</td><td>Office Hours:
TTh 8:00 a.m. - 9:15 a.m.
or by appointment</td></tr>
<tr><td>Grading:
Midterm 35%
Homework 10%
Final Exam 55%</td><td>Final Exam:
11:00 a.m. - 1:00 p.m.,
Thursday, December 10, 2015, VHE 210
First day of class – Tuesday, August 25, 2015
Last day of class – Thursday, December 3, 2015</td></tr>
<tr><td colspan="2">Required Text:
Applied Quantum Mechanics, A.F.J. Levi, Cambridge University Press
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:
Optimal Device Design, Cambridge University Press, ISBN: 0521116600</td></tr>
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Abstract
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. 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 SCHRÖDINGER 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 SCHRÖDINGER EQUATION

Matrix solution to the descretized 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 POTENIAL 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-EINSTIEN DISTRIBUTION FUNCTION

CURRENT AS FUNCTION OF VOLTAGE BIAS

Semiconductor heterostructure diode structures in the depletion approximation.

Metal-insulator-metal.

Reduced dimensions

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

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