Phys 315 (Fall 2011)—Course Learning Goals

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At the end of the course, the student will be able to do the following things.

1 Structure of the PTE

- Describe the basic structure of the periodic table of the elements (PTE).
- Explain the difference between a group, a period, and a block on the PTE.
- List a minimum of three groups on the PTE.

2 Properties of the PTE

- Describe how the fundamental properties (e.g., atomic radii, ionization energies, electro-affinities) evolve within a group and within a period on the PTE.
- Explain why elements in the same group on the PTE have similar properties.
- List a minimum of three properties of the noble gases.
- Explain how electronegativity of the atoms involved determines the bonding type (i.e., ionic versus covalent).

3 General

- Write down simple chemical reaction formulas (e.g., $2H_2 + O_2 = 2H_2O$).
- Convert between frequency, energy, wavelength, and wave vector.

4 Maxwell-Boltzmann distribution

- Write down the Maxwell-Boltzmann distribution function.
- Identify the physical circumstances under which the Maxwell-Boltzmann distribution function is used.
- Calculate the occupational probability for simple two-level systems using the Maxwell-Boltzmann distribution.
- Explain how degeneracy is incorporated into the Maxwell-Boltzmann distribution.

5 Degrees of freedom and excitations

- Define the term *degree of freedom.*
- List a minimum of three examples of degrees of freedom.
- Interpret the role of degrees of freedom in determining a system's thermal properties and state of matter.
- Describe several excitations in condensed matter.

6 Materials science

- Define the word *material.*
- Define the term *materials science.*
- Demarcate *physics of materials* from other aspects of materials science.
- List multiple ways by which materials may be classified (e.g., state of matter, hardness, conductivity, magnetic properties, and so on).
- Categorize various pieces of matter into *actual material* or *not.*

7 Bonding types

- List and define all the bonding types, and provide examples for each.
- Compare the relative strengths of the different types of bonds.

8 The electron shell

- Describe why different isotopes behave similarly in their chemistry.
- Summarize the role of the outermost electrons in chemical bonding.
- Highlight the difference between the Bohr and the Schrödinger model of the atom with a sketch.

9 The Schrödinger equation

- Write down the time-dependent and time-independent Schrödinger equations.
- Identify the components of Schrödinger equation.
- Provide an example of a quantum mechanical state.
- Summarize, in qualitative terms and with classical mechanical concepts in mind, how a Hamiltonian is constructed.

10 Solutions of Schrödinger's equation for atoms

- Identify the eigenstates of the time-independent Schrödinger equation.
- Write down the Coulomb potential.
- Sketch the energy levels associated with the Coulomb potential.
- Define the word *degeneracy*.

11 From Schrödinger's equation to the PTE

- Use the notion of degeneracy to explain why often several quantum numbers are necessary to describe the state of a system.
- Illustrate how the PTE is constructed according to different quantum numbers.
- State the Pauli Exclusion Principle.
- Summarize how electron-electron interactions shuffle the energy levels in many multi-electron atoms.

12 Symmetries in physics

- Explain what is meant by (and come to appreciate) the expression "More is different."
- Contrast the symmetry of physical laws to the symmetry of the resulting physical systems.
- Provide an example of each kind of the above symmetries.

13 Structural properties of polymers

- Identify the "backbone" of various polymers.
- Highlight the importance of carbon in complex matter.
- Define the term *conformational isomer*.
- Calculate the thermal population for the two conformational isomers of a butane molecule.

14 Modeling the viscoelastic properties of polymers

- Write down the simple, linear differential equation relating stress to strain for a spring and a dashpot.
- Define the word *viscoelasticity*.
- List the two basic, viscoelastic elements that can be constructed out of a spring and a dashpot.
- Construct the differential equations corresponding to the above viscoelastic elements.
- Solve the above equations for given initial conditions.
- Identify the serial/parallel analogy of the above viscoelastic elements to LRC electrical components.

15 Forces acting in liquids

- Identify the typical forces acting between the molecules of a solid.
- Write down the formula that describes the van der Waals force.
- Compute the strength of the van der Waals force between two molecules.

16 Structure of liquids

- Define the term *pair distribution function*.
- Explain how the pair distribution function is used to describe short-range order in a liquid.
- Summarize how available degrees of freedom change upon a phase transition.

17 Metastability

- Define the term *local minimum* with respect to the potential energy of a physical system.
- Define the word *metastability*.
- Explain why glass is in a metastable state.

18 Non-ideal solids

- Define the word *frustration*, with respect to the structural properties physical systems.
- Distinguish amorphous solids, glasses, and liquids using the terms *metastability*, *frustration*, and *time scale*.

19 Structural properties of liquid crystals

- Describe the base constituent of a liquid crystal.
- List molecular rotations as an additional degree of freedom in liquid crystals.

20 Optical properties of liquid crystals

- Define the word *birefringence*.
- Describe an experiment involving polarized light that could identify a birefringent material.
- Explain why liquid crystals are birefringent.
- Sketch the setup of a liquid crystal display (LCD) and explain how it works.

21 Maxwell equations

- Write down the four Maxwell equations (MEs), in differential and integral form.
- Summarize, in words, what each of the four MEs means.
- Explain the difference between the microscopic and macroscopic MEs.

22 Macroscopic Maxwell equations and susceptibilities

- For the macroscopic MEs, write down the relationship between the electric field, the dielectric displacement and the polarization.
- Define the terms *dielectric constant* and *electric susceptibility.*
- For the macroscopic MEs, write down the relationship between the magnetic induction, the magnetic field strength and the magnetization.
- Define the terms *magnetic permeability* and *magnetic susceptibility.*
- Discriminate between dia-, para-, and ferromagnetism.

23 Spontaneous order

- Discriminate between spontaneous and induced order.
- List several examples of spontaneous order.
- Infer the order parameter when a given type of order is present.

24 Capacitors

- Identify which physical quantities are used to characterize a capacitor.
- Explain how the dielectric material between its plates can affect a capacitor's capacity.

25 Nuclear magnetic resonance

- Provide a formula that describes the splitting of energy levels in a magnetic field due to the nuclear magnetic moment.
- Summarize the basic principle of nuclear magnetic resonance.
- State the range of typical frequencies used in magnetic resonance imaging.

26 Ferromagnetism

- Define the term hysteresis, in the context of non-ideal ferromagnets.
- Sketch and explain the domains in a typical, untreated ferromagnet.

27 First and second order phase transitions

- Contrast a first- from a second-order phase transition, based on the behavior of the order parameter across the transition temperature.
- List several examples of both first- and second-order phase transitions.

28 Phase diagrams

- Sketch the phase diagram of water.
- Define the terms *triple point* and *critical point*, with water's phase diagram in mind.

29 Thermodynamic potentials

- Assign appropriate thermodynamic potentials to various physical systems.
- Define the term *specific heat at constant volume and at constant pressure*, using the corresponding thermodynamic potentials.

30 Landau theory

- Describe how a Taylor series expansion of the corresponding potential is used to empirically explain second-order phase transitions in Landau theory.
- Apply Landau theory in simple cases to calculate the behavior of the order parameter at the transition temperature.

31 Basic definitions for crystal structure

- Define the term translation.
- Define an idealized lattice structure.
- Contrast an idealized lattice structure to an amorphous solid using the terms *long- and short-range order*.
- Discriminate between the continuous translation symmetry of free space and the discrete translation symmetry of a crystal lattice.

32 Bravais lattices

- Define the term *primitive vectors*.
- Define the term *Bravais lattice* using a formula that explains how all possible linear combinations of the primitive vectors yield the lattice.
- List three examples of Bravais lattices in 2D and 3D.
- Identify the set of primitive vectors that make up a particular Bravais lattice.
- Define the term *coordination number*.

33 Lattices with a basis

- Distinguish a lattice as being either a Bravais lattice or not.
- Define the terms *basis* and *primitive unit cell*, for lattices which are more complicated than a Bravais lattice.

34 Wigner-Seitz cell as a particular primitive unit cell

- Define the Wigner-Seitz unit cell of a Bravais lattice.
- Construct the Wigner-Seitz unit cell for a given 2D Bravais lattice.
- State the Mermin-Wagner-Berezinskii theorem.

35 Bragg's law

- Explain Bragg's law.
- Write a formula describing Bragg's condition for constructive interference (diffraction).
- Explain Bragg's condition for constructive interference (diffraction).

36 Reciprocal lattice

- Define the reciprocal lattice of a Bravais lattice.
- Describe the Laue formulation of diffraction.
- Construct the primitive unit vectors of the reciprocal lattice out of the primitive unit vectors of the Bravais lattice.
- Define the first Brillouin zone (BZ), with the relationship between the real lattice and reciprocal lattice in mind.

37 Lattice planes

- Define the terms *lattice plane* and *family of lattice planes*.
- Sketch how lattice planes and families of lattice planes are constructed.
- Summarize the relationship between a family of lattice planes and an appropriate reciprocal lattice vector.

38 The Ewald sphere construction

- Define *the Ewald sphere*.
- Illustrate how the Ewald sphere can be used to estimate for which angles diffraction will occur.
- Explain how diffraction can be used to monochromatize a beam.

39 Structure and form factors

- Explain how a structure factor is used to describe scattering from a lattice with basis.
- Explain how a form factor is used to describe x-ray scattering from electron clouds.

40 Measuring lattice vibrations

- Compare and contrast the momentum and energy of a photon to that of a neutron, assuming that both are in a plane wave state have the wave vectors $\mathbf{k}$.
- Contrast elastic scattering against inelastic scattering.
- Sketch a three-axis neutron spectrometer and explain the different components.

41 Equation of motion in monatomic chains

- Write down the coupled, homogeneous, linear second-order differential equations for a one-dimensional chain of identical, equally spaced atoms (1D Bravais lattice) coupled with harmonic forces.
- Define the Born-von-Karman (periodic) boundary condition.
- Outline how the differential equation given in the two learning goals above can be solved.

42 Dispersion relation

- Sketch the dispersion relation for the one-dimensional chain.
- Identify the constituents of the vibrational modes in the one-dimensional chain.
- Construct an expression for the allowed wave vectors in the one-dimensional chain.

43 Lattice vibrations in a chain with basis

- Propose reasonable changes that would occur when moving from a monatomic to a polyatomic basis (i.e., more than one atom per unit cell).
- Define the terms *acoustic phonon* and *optical phonon*.
- Sketch the atomic displacement patterns for both acoustic and optical phonons.
- Write down the differential equations for the two inequivalent atoms in a diatomic basis (by analogy to the Bravais lattice case).
- Contrast lattice vibrations in 1D to those in 3D.

44 Failure of classical mechanics

- Calculate the specific heat of a simple system according the Dulong-Petit law.
- Describe how the heat capacity predicted by the Dulong-Petit law deviates from a system's actual heat capacity at low temperatures.

45 Harmonic quantum oscillators

- Define the term *excitation energy*.
- Explain how modes become excited.
- List the energy levels of a quantum harmonic oscillator.
- List an exemplary quantum harmonic oscillator with each mode.

46 Correspondence between quantum oscillators and phonon modes

- Interpret the different energy levels in a quantum harmonic oscillator in terms of phonons present in the mode.
- Use the Maxwell-Boltzmann distribution to determine the probability to find a certain number of phonons in a particular mode.
- Write down the expression for the average number of phonons in a given mode.

47 Specific heat in quantum mechanics model

- Construct an expression for the total internal energy U of the crystal, using the expression for the average number of phonons in a certain mode.
- Construct an expression of the specific heat Cv, using U.
- Outline how the above expression can be simplified to explain the suppression of Cv at low temperature.

48 Definitions related to black-body radiation

- Define the term *blackbody radiation.*
- List at least five examples of objects with the radiation characteristics of a black body.
- List at least five examples of objects which radiate with the characteristics unlike that of a black body.

49 Analogy to phonons

- Derive the radiation energy per mode in a blackbody cavity.

50 Necessity of quantum mechanics in the ultraviolet catastrophe

- Compare and contrast the phonon distribution established in a crystal lattice of equal shape as a given blackbody cavity.
- Describe the ultraviolet catastrophe.
- Explain how quantum mechanics helps to resolve the ultraviolet catastrophe.
- Argue why the ultraviolet catastrophe can not occur in a phonon system (even in the classical picture).

51 Physical particles with different statisitics

- Define the words *fermions* and *bosons.*
- List the main differences between the physical laws obeyed by fermions, bosons, and classical particles.
- Sketch the Maxwell-Boltzmann and the Fermi-Dirac distribution, at the same temperature.
- Explain why the electronic specific heat is much lower than for a classical gas, at the same temperature.

52 Drude model of a metal

- Describe the Drude model.
- State the shortcomings of the Drude model in describing the free electron gas.

53 Electronic states in a box potential

- Write down an expression for the discrete set of allowed wave vectors (considering free electrons enclosed in a "box with periodic boundary conditions" and using the analogy to lattice vibrations).
- Describe how the wave vectors above can be represented in reciprocal space.
- Define the terms *Fermi surface*, *Fermi momentum* and *Fermi energy*.

54 Density of states

- Define the term *density of states*.
- Describe the functional dependence of the density of states in 3D.
- Derive a formula for the density of states for a free electron gas.
- State the power law with which temperature varies for the electronic and phononic specific heats.

55 Electrons in a periodic potential

- List several drawbacks of the free electron picture (e.g., when trying to explain why certain materials are metals and others are insulators).

56 Bloch theorem and solutions to the single electron Schrödinger equation

- Write down Bloch's theorem.
- Explain Bloch's theorem.
- Write down a general solution of Schrödinger's equation for an electron in a periodic potential.

- Explain the above general solution of Schrödinger's equation for an electron in a periodic potential.

57 Energy bands

- Explain why there are energy bands in a solid.
- Defend why it is sufficient to consider only the solutions in the first Brillouin zone.
- Describe what happens to band gaps at the BZ boundary in a finite periodic potential.
- Contrast metals, insulators, and semiconductors, with the banc picture in mind.
- Summarize phenomena which can be explained within the free electron picture and others that require the band picture.

58 Photoemission

- Describe the principle of photoemission.
- Explain how photoemission can be used to measure the shape of electronic bands.

59 Band paramagnetism

- Explain the occurrence of paramagnetism, with the band picture in mind.
- Explain why the application of a magnetic field leads to a net total magnetization.
- Derive an expression for the above effect.