Biophysics

1. Structure and function of proteins and nucleic acids
2. Reaction thermodynamics and kinetics
3. Bioenergetics (redox processes, oxidative phosphorylation, photosynthesis, chemiosmosis)
4. Biological membranes (structures, properties)
5. Membrane potential, ion transport, nerve signaling
6. Ion transport, molecular motors
7. Cell communication, signal transduction, cell locomotion
8. Biophysics of sensation (vision, hearing)
9. Collective behavior (motion, synchronization)
10. Biological networks
11. Evolutionary biology (population dynamics, population genetics)
12. Biophysical techniques

Recommended reading:

- Glaser: Biophysics
- Nelson: Biological Physics: Energy, Information, Life
- Cotterill: Biophysics - An Introduction
- Phillips, Kondev, Theriot, Garcia: Physical Biology of the Cell
- Berg, Stryer, Tymoczko: Biochemistry
- Alberts et al.: Molecular Biology of the Cell

Networks

(Structure and dynamics of complex networks)

1. **Graph types**. Directed, un-directed graphs, weighted graphs, bi-partite graphs. Adjacency matrix and its properties. Dense and sparse networks.

2. **Basic node properties**. Degree, strength, clustering co-efficient. Distance and algorithms for calculating the shortest path length. The small world property.

3. **Centrality measures**. Closeness and shortest path betweenness. Eigenvector centrality and Page-rank.

4. **Degree distribution and the scale-free property**. Degree distribution of the Erdős-Rényi random graph compared to real networks. Scale-free degree distribution, divergence of the higher moments.

5. **Degree correlations**. Assortative and disassortative networks. Statistical description of the degree correlations. Average nearest neighbours degree and the assortativity coefficient.

6. **Network models I.** The Erős–Rényi model and its main properties. The Watts–Strogatz model and small-world networks.

7. **Network models II.** The Barabási–Albert model. Derivation of the degree decay exponent. Variations of the Barabási–Albert model: uniform and multiplicative fitness and the Holme-Kim model.

8. **Network models III.** The configuration network ensemble. Hidden variable models for constructing degree correlated random networks.

9. **Network robustness**. Percolation transition in the Erdős–Rényi graph and the giant component. Resilience of networks against random node removal. Targeted attack of scale-free networks.

10. **Spreading phenomena on networks**. The SIS and SIR models. Behaviour of the SIS model in homogeneous networks. SIS model in scale-free networks.

11. **Motifs and communities**. Network motifs in directed networks and the motif significance profile. The concept of communities. The Girvan-Newman algorithm and modularity. Modularity optimisation.

Recommended textbooks:

- Albert-László Barabási: Network science. (Cambridge University Press, 2016).
  `http://networksciencebook.com/`

- M. E. J. Newman, A.-L. Barabási, D. J. Watts: The Structure and Dynamics of Networks. (Princeton University Press, Princeton, 2006).

Optics

1) Electromagnetic theory of light, propagation of light

2) Diffraction

3) Interference and interferometers

4) Polarization and crystal optics

5) Optics of thin layers

6) Geometrical optics based on wave optics (eikonal, non-light optics)

7) Analytical ray tracing, matrix optics and optical aberrations, fiber optics

8) Rainbow and other atmospheric optical phenomenon

9) Electro-optics, nonlinear optics, elements of quantum optics, lasers and laser light

Recommended reading:

I) Eugene Hecht: Optics (Addison-Wesley Longman, Inc.; 4 edition, August 12, 2001)

II) E. Wolf and M. Born: Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light (Cambridge University Press; 7th edition, October 13, 1999)

Extra: Pierre Meystre and Murray Sargent III: Elements of Quantum Optics (Springer, Berlin, Heidelberg, 1998, 2007)

Quantum Mechanics, Atomic and Molecular Physics

1) Foundation of quantum mechanics (founding experiments, operators, Schrödinger equation, particle in box, harmonic oscillator, angular momentum, hydrogen atom, many-particle wave function, entanglement)

2) Basic theoretical principles in atomic- and molecular physics (hydrogen like ions, separating the center of mass motion in the two-body problem, Rydberg constant, atomic units, virial theorem, perturbation theory, variation theory, Eckart's inequality, linear variation, Löwdin's orthogonalization, Born--Oppenheimer approximation, Hellmann--Feynman theorem)

3) He atom (ground state: screening, Cb-integral, comparison of various approximations, Hartree-Fock method for the ground state of He, Hylleraas-solution, Pekeris-solution, various types of correlation; excited states: exchange integral, ortho-He, para-He, two-electron Slater determinants, Fermi-hole, Coulomb-hole)

4) Dirac-equation (application of the Dirac-equation for H atom, the spin in electric and/or magnetic field, the spin-orbit coupling, Zeeman-effect, g-factor of electron, hyperfine interaction)

5) Many-electron atoms (periodic table, Hartree-Fock method, Koopmans' theorem, Hund's rules, atomic term symbols, LS-coupling, the role of configurational interaction, jj-coupling, Grotrian diagram)

6) H_2^+ molecular ion (description with various approximate (and exact) methods, molecular orbitals, LCAO method, the role of E_{kin} and E_{pot} in the formation of a chemical bond on the example of the H_2^+ molecular ion)

7) H_2 molecule (description with various approximate methods, comparison of the MO and VB methods)

8) Diatomic molecules (correlation diagram, avoided crossing, N_2 and O_2 molecule, paramagnetism of O_2)

9) Polyatomic molecules (molecular symmetries and the use of character tables: H_2O, NH_3, CH_4, benzene, hybridization, conjugated π-systems, C_{60}, Jahn-Teller theorem)

10) Molecular rotations and vibrations (infrared spectrum, Raman-spectrum, selection rules, nuclear statistics, rotation-vibration, anharmonicities, Coriolis-forces, inversion doubling)

11) Electric and magnetic properties of molecules (electric polarizability, optical activity, magnetic susceptibility, chemical shift in nuclear magnetic resonance)

12) Quantum information theory (qubit, quantum logical gates, quantum cryptography, quantum computing, physical implementations, the decoherence issue)

13) Experimental quantum mechanics (interferometry, ion- and atom traps, one- and two-photon experiments, superconducting circuits)

Recommended reading:

a) P.W. Atkins, R. Friedman: Molecular Quantum Mechanics, Oxford University Press 2010
b) I. Mayer: Simple Theorems, Proofs, and Derivations in Quantum Chemistry, Springer Science+Business Media New York 2003
c) H. Haken, H.C. Wolf: Atomic and Quantum Physics, Springer-Verlag Berlin Heidelberg 1987
d) H. Haken, H.C. Wolf: Molecular Physics and Elements of Quantum Chemistry, Springer-Verlag Berlin Heidelberg 2004
e) Nielsen-Chuang: Quantum Computation and Quantum Information, Cambridge 2012

Statistical Physics

1. Basic principles of statistical physics.
   (quantum Liouville theorem and microcanonical distribution, the law of entropy growth, grand canonical distribution, thermodynamic relations.)

2. Ideal gases.
   (Boltzmann distribution and classical statistics, equation of state, equipartition, ideal Fermi and Bose gases, degenerate electron gas, photons.)

3. Condensed matter.
   (Debye theory, Bose liquid, superfluidity, phonons in a Bose liquid, degenerate interacting Bose gas, Fermi liquids, electron liquid in metals.)

4. Superconductivity.
   (Cooper instability, energy spectrum of superconductors, thermodynamics of superconductors, Ginzburg–Landau theory.)

5. Phase transitions and critical phenomena.
   (Mean-field theory of magnetism, fluctuations of the order parameter, scaling.)

6. Linear response.
   (Linear response to mechanical perturbation, electrical conductivity and magnetic susceptibility, dispersion relations.)

7. Kinetic equations.
   (Boltzmann equation, H-theorem, quantum kinetic equations, electron–phonon interaction, electron–electron interaction.)

8. Basics of the modern theory of many-particle systems.
   (Quasi-particles and Green's functions, Feynman diagrams for many-particle systems, Dyson equation, effective interaction and dielectric screening, Green's functions at finite temperatures.)

Recommended reading: Michael V. Sadovskii, Statistical Physics (De Gruyter)