Bioinformatics

Exam Topics:

1. Nucleic Acids: DNA, RNA structure, translation, transcription, sequencing technologies
2. Producing and Analyzing Sequence Alignments: principles of sequence alignment & scoring alignments, nucleic acid vs amino acid level alignments, variant calling
3. Pairwise Sequence Alignment and Database Searching: substitution matrices and scoring, dynamic programming algorithms, indexing and scanning whole-genome sequences, BLAST
4. Patterns, Profiles and Multiple Alignments: sequence logos, profile HMMs, sequence pattern discovery
5. Building Phylogenetic Trees: comparative genomics, evolutionary distance, generating tree topologies, evaluating tree topologies
6. Revealing Genome Features: gene prediction in genome, splice site detection, genome annotation, epigenetic features
7. Protein Spatial Structures: definition of secondary structure, secondary structure prediction models (neighbor models, HMM, NN), protein 3D structure measurement and analysis
8. Proteome and Gene Expression Analysis: analyzing microarray (expression, methylation, SNP) data, analyzing gel electrophoresis data
9. Clustering Methods and Statistics: data normalization, distance metrics for clustering, clustering algorithms (KNN, Hierarchical clustering, SOM), statistical significance tests
10. Human Genetics, SNPs, and Genome Wide Associate Studies

Reading material:

Baum, Jeremy O._ Zvelebil, Marketa - Understanding Bioinformatics; Garland Science Taylor (2008)

Additional resources:

Phillip Compeau, Pavel Pevzner: Bioinformatics Algorithms 1-2, Active Learning Publ. (2015)
Prof.ManolisKellis: ComputationalBiology:Genomes,Networks,Evolution; MIT course 6.047/6.878
http://ocw.mit.edu/ans7870/6/6.047/f15/MIT6_047F15_Compiled.pdf

Carbon nanostructures

1) The role of hybridization (sp^2, sp^3 hybridization, band structure of diamond and graphite-graphene)

2) Isolated cage like molecules (discovery of fullerenes, symmetries, Euler's rule, isolated pentagon rule, endohedral fullerenes)

3) Crystalline fullerenes (preparation in large quantities, crystal structure, phase transitions)

4) Electronic structure of C_{60} molecule (symmetry analysis, use of the character table of icosahedral point group)

5) Band structure of fullerenes (electric and optical properties, Van Hove singularities)

6) Vibrational properties of fullerenes (infrared spectroscopy, Raman spectroscopy)

7) Doping of fullerenes (effect of doping on electric and optical properties, superconductivity)

8) Fullerene polymers (covalent bonds between fullerene molecules, various polymer structures)

9) Carbon nanotubes (discovery, electric-, optical-, and vibrational properties, functionalization)

10) Graphene and related materials (discovery, fundamental properties, nanoribbons)

Recommended reading:

a) M.S. Dresselhaus, G. Dresselhaus and P.C. Eklund: Science of Fullerenes and Carbon Nanotubes (Academic Press, New York, 1996)

b) S. Reich, Ch. Thomsen, J. Maultzsch, Carbon Nanotubes: Basic Concepts and Physical Properties (Wiley-VCH, Berlin, 2004)

c) M.I. Katsnelson: The Physics of Graphene (Cambridge University Press, 2020)

Chaotic Systems

1. Strange attractors and fractal dimension.
   (Measure and the spectrum of D_q dimensions, pointwise dimension, fractal dimension in experiments, embedding.)
2. Dynamical properties of chaotic systems.
   (Symbolic dynamics, linear stability of periodic orbits, stable and unstable manifolds, Lyapunov exponents, Kolmogorov-Rényi entropies.)
3. Chaotic repellors.
   (Fractal basin boundaries, final state sensitivity, chaotic scattering, dimensions of chaotic repellors and their stable and unstable manifolds.)
4. Quasiperiodicity.
   (Frequency spectrum of attractors, the circle map, attractors of quasiperiodically forced systems, phase locking of coupled oscillators.)
5. Chaos in Hamiltonian systems.
   (Hamiltonian systems, perturbation of integrable systems, chaos and KAM tori, higher dimensional and strongly chaotic systems.)
6. Chaotic transitions.
   (The period doubling cascade and the intermittency routes to chaos, the Lorenz system, bifurcations to chaotic scattering.)
7. Multifractals.
   (The singularity spectrum $f(\alpha)$, the partition function formalism, Lyapunov partition functions, unstable periodic orbits and the natural measure, advection by Lagrangian chaotic flows.)
8. Control and synchronization of chaos.
   (Control of chaos, controlling and targeting of a steadily running chaotic process.)
9. Synchronization of chaotic systems.
   (Stability of a chaotic set on an invariant manifold, generalized synchronization of coupled chaotic systems, phase synchronization of chaos.)
10. Quantum chaos. (The energy level spectra and wavefunctions of chaotic, bounded, time independent systems, temporally periodic systems.)

Recommended reading: Edward Ott, Chaos in Dynamical Systems (Cambridge University Press)

Classical optical instruments

1) Image formation of plane, convex and concave mirrors
2) Image formation of convex and concave lenses
3) Image formation of lens systems
4) Refractive (lens) telescopes
5) Reflective (mirror) telescopes
6) Mosaic giant telescopes
7) Adaptive optical telescopes
8) Optical microscope
9) Phase contrast microscope
10) Polarization microscope
11) Schlieren optical system
12) Refractometers
13) Spectroscopes, spectrometers

Suggested literature

I) Daniel Malacara Hernández (ed.): Fundamentals and Basic Optical Instruments (CRC Press 2019)

II) R. P. Feynman, R. B. Leighton, M. Sands https://www.feynmanlectures.caltech.edu/I_toc.html Chapters 26-38.

III) N. Subrahmanyam, Brij Lal, M. N. Avadhanulu (2004) A Text Book of Optics. S. Chand Limited, p. 668, ISBN 8121926114

Computer Simulations in Statistical Physics

Exam Topics:

1. Computational vs. analytic approach. Number representation, errors & uncertainties in computations
2. Deterministic randomness, random number generation, random walks, self-avoiding walks
3. Monte Carlo integration, Variance Reduction Method, Importance Sampling, von Neumann Rejection
4. Chaotic maps, nonlinear dynamics, chaos, bifurcation, chaos in phase space, attractor
5. Fractals & Statistical Growth Models, Diffusion-Limited Aggregation
6. Cellular automata, classification of 1D automata, Lattice-Boltzmann model
7. Metropolis Algorithm,
8. Ising model, phase transition, boundary conditions, simulation speed-up methods
9. Simulated annealing, numerical optimization methods
10. Feynman Path Integral, lattice path integral
11. Molecular Dynamics Simulations, Connection to Thermodynamic Variables

Reading material:

Rubin H Landau, Manuel J Paez, & Cristian Bordeianu: Computational Physics - Problem Solving with Python (Wiley 2015)

Additional resources:

Kurt Binder, Dieter W. Heermann: Monte Carlo Simulation in Statistical Physics - An Introduction (Springer International Publishing 2019)

Environmental Physics

1. The composition and layers of the athmosphere
The thermal inversion, planetary boundary layer, air flow systems, cyclon, anticyclon, meteorological fronts

2. Oceanic current systems
The composition and layers of the oceans, drive of the Golf-stream, global conveyor belt, coupled oceanic-athmospheric processes, oscillations in Atlantic Ocean, El Niño, La Niña, beach up and down streams, tropical cyclons

3. Interaction of the solar radiation with the Earth
Global energy balance, solar constant, albedo, irradiation, spectral properties, processes in the global balance, green house effect, ozone layer, ozone hole, effects of ultraviolet radiation

4. Glodal wind systems
transport processes, their drive force, thermal convection, cell structure, surface wind systems, wind power

5. Athmospheric electromagnetism
Lightning, magnetospheres of the Earth, shielding properties, van Allen belts, aurora borealis

6. Athmospheric optics
rainbow, halos, polarization of the scattered skylight

7. Basic physical concepts and environmental impact of the application of the renewable energies
Solar energy, hydropower, wind power, biomass, wave energy, geothermal energy, tide waves

8. Nuclear energy production and its environmental impact
physics of fission, nuclear power plants, radioactive wastes

9. Energy of the population
Fossil, mineral energy sources, energy production processes, energy density in alternativ energy production possibilities, feasibility of different solutions, EROEI

10. Propagation, dispersion and analytics of environmental pollutants

11. Natural radioactivity
Uranium series, thorium series, cosmic radiation, muon flux, journey of triton and radiocarbon on Earth, application of these isotopes

12. Radon in our environment
The journey of radon atom sin nature. Radon sources, radon potential, doses of the radon and its daughters, radondetectors, radioactivity in the rain

Recommended reading

John Monteith, Mike Unsworth:
Principles of Environmental Physics, Academic Press 2013
ISBN 9780080924793

Egbert Boeker, Rienk Van Grondelle
Environmental Physics: Sustainable Energy and Climate Change, 2011 John Wiley & Sons, Ltd
ISBN 9780470666753

David JC MacKay:
Sustainable Energy, 2009, UIT Cambridge Ltd.
ISBN 978-0-9544529-3-3

Evolutionary Biology

1. Evolution as a history
2. Theory of selection
3. Competitive exclusion and coexistence
4. Lotka-Volterra equations
5. Epidemic models
6. Diploid genetics
7. Multilocus genetics
8. Molecular evolution
9. Adaptive dynamics and speciation
10. Kin selection
11. Evolutionary game theory
12. Evolutionary transitions
13. Origin of life
14. Origin of humans

Readings

- N. H. Barton, D. G. Briggs, J. A. Eisen, D. B. Goldstein & N. H. Patel: Evolution. Cold Spring Harbor Laboratory Press, 2007
- L. Pásztor, Z. Botta-Dukát, G. Magyar, T. Czárán & G. Meszéna: Theory-based Ecology: a Darwinian approach. Oxford University Press, 2016

Growth phenomena, pattern formation

1. The fundamentals of fractal geometry: definitions, types of fractals, rules involving dimensions, examples for self-similar fractals
2. Self-affine and fat fractals: definitions, relation of exponents to dimension, examples exponents
3. Fractal measures (multifractals): definitions, information dimension, examples
4. Cluster growth models (local growth models, percolation, indefinitely growing random walks)
5. Cluster growth models: Diffusion-limited growth, models, dimension, fractal measure, deposition, scaling of the cluster size distribution
6. Growth of self-affine surfaces: dynamic scaling of roughening, exponents, models
7. Computer simulation of the non-local continuum equations of growth
8. Experiments on fractal pattern formation
9. General considerations about patterns: Deterministic vs. probabilistic descriptions in physics, Instabilities and symmetry breakings in homogeneous systems, notion of effective long-range interactions far from equilibrium.
10. Patterns from stability analysis: Linear stability analysis. stationary (fixed) points of differential equations. Examples (Lotka-Volterra, Hopf bifurcation, Brusselator,
11. Landau-Ginzburg equation, Competing dynamics and nonequilibrium phase transitions.
12. Patterns from moving fronts: examples, velocity selection, population dynamics, wavelength selection, precipitation patterns

Courses: Fractal growth, Nonlinear Dynamics and Pattern Formation

Recommended reading:

Fractal growth phenomena, (by T.Vicsek, 1991, World Scientific, http://hal.elte.hu/~vicsek/downloads/Fractal_Growth_Phenomena/)

W. van Saarloos, *Front Propagation into Unstable State,* Physics Reports **386**, 29-222 (2003).

http://cgl.elte.hu/~racz/Patterns-2009.ppt, http://cgl.elte.hu/~racz/Fronts-2009.ppt

Physics of Macromolecules and Membranes

1. Theoretical description of conjugated carbon chains, one-dimensional instabilities.
2. Structures and properties of conjugated carbon polymers, insulator → metal transition induced by doping.
3. Structures of biological polymers (cellulose, proteins, DNA).
4. Molecular structure of polymers (constitution, configuration, conformation).
5. Segment model, ideal chain models, thermodynamic basis of flexibility.
6. Interaction of distant monomers, Flory model, theta temperature.
7. Polymer dynamics (Rouse model, Zimm model), physical basis of electrophoresis.
8. Scaling laws (polymer fibers confined to small spaces, surface adsorption, polymer solutions, reptation).
9. Physical properties of lipid membranes, elastic models, shapes of membrane vesicles.
10. Monge representation, thermal fluctuations, surface tension.
11. Membrane tubes.
12. Membrane-membrane and membrane-surface adhesion.
13. Transmembrane proteins (topography, topology, structure and function).

Recommended reading:

- M. Rubinstein, Ralph H. Colby: Polymer Physics (Chemistry), Oxford (2003)
- Siegmar Roth, David Carrol: One-Dimensional Metals: Conjugated Polymers, Organic Crystals, Carbon Nanotubes , Wiley-VCH (2004)
- M. Doi: Introduction to Polymer Physics, Oxford University Press (1996)
- P.-G. De Gennes: Scaling Concepts in Polymer Physics, Cornell University Press (1979)
- U. Seifert: Configurations of Fluid Membranes and Vesicles, Adv. Phys. 46, 13-137 (1997)
- R. Lipowsky and E. Sackmann: Structure and Dynamics of Membranes: I. From Cells to Vesicles / II. Generic and Specific Interactions, North Holland (1995)
- D. Frishman: Structural Bioinformatics of Membrane Proteins, Springer (2010)

Many-Body Theory

1. Second quantization.
   (Fock-space, creation and annihilation operators)
2. Operators in second quantized forms.
   (One- and two-particle operators, field operators, examples)
3. Temperature Green's functions.
   (The Green's functions used at finite temperature; calculation of thermodynamic quantities from the exact Green's functions, Properties of the temperature Green's functions, non-interacting Green's functions)
4. Perturbation theory for the exact Green's function.
   (Feynman-diagrams; Feynman-rules; Dyson-equation)
5. Useful approximations and methods.
   (Random Phase Approximation (RPA), classical limit, the sum for the effective interaction)
6. Quasiparticles, collective excitations.
   (Spectral function; retarded Green's function; density fluctuation operator; calculation of collective excitations)
7. Application for superfluid Fermi gases.
   (Cooper-instability. BCS-theory, calculation of the gap, critical temperature of BCS phase transition)

Recommended reading:

1.) A.L.Fetter, J.D. Walecka: "Quantum theory of many particle systems" (McGrow-Hill Inc., New York, 1971).
2.) L.D. Landau and E.M. Lifshitz,"Course of Theoretical Physics, Vol. 9; Statistical Physics, Part 2." (Pergamon,Oxford,1981).

Mesoscopic systems

1) Fabrication of two dimensional electron systems and their properties (Experimental techniques)

2) Important quantities in mesoscopic transport

3) Electronic phase coherence

4) The Landauer–Büttiker formalism, mesoscopic ballistic transport

5) Conductance from transmission, transmission function, S-matrix and Green's functions

6) The quantum Hall effect

7) Localization and fluctuations, Aharonov-Bohm effects

Recommended reading:

I) Supriyo Datta: Electronic Transport in Mesoscopic Systems (Cambridge University Press, 1995, 2013)

II) Thomas Heinzel: Mesoscopic Electronics in Solid State Nanostructures, 3rd Edition (WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim 2007)

Molecular Biophysics

Exam Topics:

1. Theoretical fundamentals: Diffusion and Brownian motion. Stochastic theory of reaction rates. Kramers Theory. Michaelis–Menten kinetics.
2. Theoretical fundamentals: Molecular interactions and chemical bonds: covalent bonds, ionic interactions, Van der Walls interaction, hydrogen bonds and hydrophobic interactions.
3. Theoretical fundamentals: Statistical physics of macromolecules: freely jointed chain model, the concept of persistence length, stretching a random coil and the concept of an entropic spring.
4. Structure and function of biomolecules: DNA structure: single and double stranded DNA, base-paring, stacking and tertiary structures of DNA. DNA replication.
5. Structure and function of biomolecules: RNA structure: functional role of RNA secondary structure, rRNA, mRNA, siRNA.
6. Structure and function of biomolecules: Protein structure: Protein synthesis, primary, secondary and tertiary structure. Ramachandran plots. Protein Stability. Protein folding.
7. Structure and function of the Cell: Biomembranes: membrane composition and function: phospholipid bilayers, sterols and membrane fluidity, the fluid mosaic model. Cellular vs. organelle membranes.
8. Structure and function of the Cell: Membrane transport. Ion channels and ion pumps. Membrane proteins their structure and functions.
9. Structure and function of the Cell: Structure and dynamics of the cytoskeleton. Molecular motors, actin/myosin, tubulin/kinesin.
10. Computational methods in Molecular Biophysics: Molecular dynamics simulations. Predicting protein fold.

Reading material:

Molecular and Cellular Biophysics by Jack A. Tuszynski
ISBN-13: 978-1-4200-1172-2 (CRC Press)

Molecular and Cellular Biophysics by Meyer B. Jackson
ISBN-13: 978-0-511-34472-5 (Cambridge University Press)

Phase Transitions and Critical Phenomena

(1) Basic concepts of thermodynamics: intensive and extensive state variables, fundamental equations and thermodynamic potentials. Thermodynamic phases and their stability. The solid (cristallic or glassy) and the fluid (gaseous or liquid) phases. Multicomponent systems (solutions, alloys, etc.). Phase coexistense. Gibbs's phase rule.

(2) Classification of phase transitions. First order and continuous phase transitions. The characterization of first order phase transitions. The Clausius-Clapeyron equation. The Van der Waals theory of the liquid-gas transition and the Maxwell construction. The generic properties of the solid-liquid-gas phase diagram for a simple one-component system. The triple point and the critical point. The special case of the phase diagram of pure water. Freezing-point depression and boiling-point elevation of dilute solutions.

(3) Special cases of phase transfomations:
The low-temperature phases of ordered magnetic materials: ferromagnets and antiferromagnets. The transition to this phases from the paramagnetic phase at the Curie and the Néel temperatures.

Ferroelectricity and structural phase transitions.

Liquid crystals.

Surface phase transitions.

Phase transitions in polymeric systems (DNA melting, protein folding problems, sol-gel transition, …).

Phase transitions in disordered systems. Diluted magnetic systems and spin glasses. The percolation problem.

The normal to superfluid transition in liquid He_4.

(4) The critical state. The singularity of thermodynamic functions at the critical point: generalized homogenuous functions. The definitions of critical indexes. The scaling hypothesis for the specific free energy. Correlations at and around the critical point, the definition of the correlation length. Definition of critical exponents related to correlations. Scaling hypothesis for the correlation function. Universality and the concept of the order parameter. Scaling laws for the critical exponents.

Critical dynamics: critical slowing down and the dynamic critical exponent. Dynamical scaling hypothesis. Phenomenological models for critical dynamics. Dynamical generalization of the Ising model.

(5) Model systems for the study of critical phenomena. The lattice-gas and the Ising model for the study of the liquid-gas critical point and the Curie point of uniaxial ferromagnets. The Heisenberg model and its generalization: the n-component spin model. The spherical model. Antiferromagnetic models and tricritical phenomena. The Potts model.The percolation problem as a special limit of the Potts model. Effective Landau-Ginzburg-Wilson field theories to study the vicinity of the critical point and calculate critical indexes.

(6) Early theories and results in the study of critical phenomena. Mean-field theory of the liquid-gas system (Van der Waals) and the paramagnet-ferromagnet transition (Weiss). The Landau-theory and the introduction of the idea of the order parameter. Classical critical exponents resulting from this mean-field-like approaches.

Exact solution of the 2-dimensional Ising model by Onsager and other exact results. Approximation methods for the calculation of critical exponents: high-temperature and low-temperature series. Estimation of critical parameters by numerical simulations (Monte Carlo method and molecular dynamics) and direct measurements in different materials near to the critical point. A comparison of the exact and approximate results for the critical exponents with the corresponding classical values.

(7) The modern theory of critical phenomena: Wilson's renormalization group. Kadanoff''s block spin construction. The basic steps of the renormalization group. Fixed points and linearization around the fixed point: relation to critical exponents. Renormalization of thermodynamic and correlation functions: derivation of the scaling hypothesis. Universality classes and multicritical points. Real- and momentum-space renormalization. Perturbative renormalization group around the upper critical dimension. Epsilon expansion and 1/n expansion of critical parameters.

(8) Field-theoretic renormalization group. The Landau-Ginzburg-Wilson effective action for the study a system in the critical region. Different schemes of ultraviolet renormalization. Renormalization group equations, the beta-function and fixed points. Epsilon expansion in higher orders and resummation of the series. A comparison of the two renormalization methods, field-theoretic vs. Wilson's one.

(9) Phase transitions in disordered systems. Percolational problems. Diluted magnetic materials. Annealed and quenched disordered systems. The replica method for studying quenched systems.

Spin glasses: The Edwards-Anderson model and the spin glass order parameter. Mean field theory of spin glasses: the Sherrington-Kirckpatrick model and the Thouless-Anderson-Palmer equations. The Almeida-Thouless spin glass transition in an external magnetic field. Beyond mean field theory: replicated Landau-Ginzburg-Wilson field theory and numerical simulations on special dedicated computers.

The physics of the structural glass transition in supercooled liquids.

<u>Suggested literature:</u>

(I) H.E. Stanley: Introduction to phase transitions and critical phenomena (Oxford U. P., New York; 1971)

(ii) Shang-Keng Ma: Modern theory of critical phenomena (W.A. Benjamin, Inc., Reading, MA; 1976)

Physical methods in biology

1. Förster resonance energy transfer (FRET) spectroscopy
2. X-ray crystallography
3. NMR spectroscopy
4. Membrane investigation methods and electrophysiology Langmuir-Blodgett (LB), black lipid membrane (BLM), and patch-clamp.
5. Optical microscopes. Phase contrast and fluorescent microscopes. Confocal and two-photon microscopes. Point spread function: PSF, diffraction limit.
6. Atomic force microscopy (AFM)
7. X-ray CT: computed tomography
8. MRI: magnetic resonance imaging
9. PET: positron emission tomography
10. Surface investigation methods. QCM, SPR, OWLS, GCI

Recommended reading:

I) M.C. Leake, Biophysics: Tools and Techniques (CRC Press Taylor and Francis Group, 2016)

II) N.R. Zaccai, I.N. Serdyuk, Joseph Zaccai, Methods in Molecular Biophysics: Structure, Dynamics, Function for Biology and Medicine (Cambridge University Press, 2017)

Low Temperature Plasma Physics

1. Plasmas in the Universe and in the laboratory, their applications in industry (surface processing, etching, deposition, light sources).
2. Basic plasma characteristics: coupling parameter, ideal/non-ideal plasmas, Saha equation, plasma frequency, Debye shielding.
3. Single particle motion in electric and magnetic fields.
4. The physics of binary collisions: cross sections, rate coefficients, scattering angle, energy transfer. Elementary processes in gas discharge plasmas.
5. Kinetic theory: Vlasov and Boltzmann equations, two-term approximation, derivation of moment equations, drift-diffusion approximation.
6. Plasma waves: perturbation approach based on moment equations: phase and group velocities, cold/warm electrostatic plasma waves, ion acoustic waves.
7. The plasma/surface boundary: sheath formation, Bohm velocity. Plasma-surface interaction: elementary processes at the interface.
8. Gas breakdown and formation of direct-current gas discharges at low pressure. The structure and modeling of direct-current gas discharges.
9. Physics of capacitively and inductively coupled radiofrequency plasmas sources.
10. Basics of plasma diagnostics: Langmuir probes (measurement of electron density, electron temperature, electron energy distribution function) and elements of plasma spectroscopy.
11. Fundamentals of dusty plasmas: particle charging, self-organization, transport and collective effects

References:

A. Piel: “Plasma Physics (An Introduction to Laboratory, Space, and Fusion Plasmas)”, Springer (2010)

M. A. Lieberman and A. J. Lichtenberg: “Principles of Plasma Discharges and Materials Processing”, Wiley (2005)

Quantum Optics and Lasers

1. Classical description of light – matter interaction: the Maxwell-Lorentz equations. Introduction of electromagnetic potentials, gauges, gauge transformations, the Standard Lagrangian of classical electrodynamics, the Euler-Lagrange equations for charged particles and electromagnetic fields.

2. Tranforming the Standard Lagrangian of classical electrodynamics to the Standard Hamiltonian. Identification of the canonical variables. Quantization of the electromagnetic field, quantum electrodynamics in the Coulomb gauge.

3. Elementary processes of quantum electrodynamics: photon absorption, emission, graph representation, Einstein's A and B coefficients.

4. The Wigner-Weisskopf theory of spontaneous emission. Lamb-shift, the spectra of the emitted light (homogeneous width of spectral lines).

5. Practical application of the theory of ligh-atom interaction: long wavelength (dipole) approximation. Rotating wave coordinate system, rotating wave approximation, Rabi frequency, Rabi oscillation.

6. The quantum theory of dissipation for atomic states. Excitation of a two-level atom with a nearly resonant laser field: representation in the Bloch sphere, dynamics of the Bloch vector.

7. Light pulse propagation in dielectric media: the slowly varying envelope approximation. The Beer-Lambert law of attenuation. The McCall-Hahn area theorem, propagation of π-pulses.

8. Resonant, multimode wave propagation phenomena: the electromagnetically induced transparency, the slow down of light pulses and coherent quantum memory.

9. Description of the quantum states of the electromagnetic field: Glauber's coherence functions. Measurement of the second order coherence function: the Hanbury Brown – Twiss and Hong-Ou-Mandel interference experiments.

10. Two-level atoms in a cavity: the Jaynes-Cummings model. The Purcell-effect, weak and strong coupling between the cavity modes and atoms, cavity losses.

11. Cooperative radiation of an ensemble of two-level atoms: the Dicke model and super-radiance.

12. The theory of continuous wave lasers: application of the density operator formalism to the coupled atom-field system inside a resonator. Amplification, laser threshold, below threshold and above threshold oparation.

13. Multimode and pulsed lasing. QSwitching. Multimode laser oscillation. Phase-locked oscillators. Mode locking. Amplification of short pulses. Amplified spontaneous emission. Ultrashort light pulses.

14. Laser resonators and Gaussian beams. The ray matrix. Resonator stability. The paraxial wave equation. Gaussian beams. The ABCD law for Gaussian beams. Hermite – Gaussian and Laguerre – Gaussian beams. Diffraction by an aperture. Diffraction theory of resonators. Beam quality. Unstable resonators for high-power lasers. Bessel beams.

15. Specific lasers and amplifiers. Electron-impact excitation, excitation transfer. He – Ne Lasers. Rate equation model of population inversion in He – Ne lasers. CO2 electric-discharge lasers. Gas-dynamic lasers. Chemical lasers. Excimer lasers. Dye lasers. Optically pumped solid-state lasers. Ultrashort, superintense pulses. Fiber amplifiers and lasers.

Recommended readings:

[1] Jonathan Keeling: Light-Matter Interactions and Quantum Optics (https://www.st-andrews.ac.uk/~jmjk/keeling/teaching/quantum-optics.pdf)

[2] Marlan O. Scully and M. Sughail Zubairy: Quantum Optics (Cambridge University Press)

[3] Peter W. Milonni and Joseph H. Eberly: Laser Physics (Wiley-Blackwell)

Reactor physics and radiation protection

1. The types of the fission reactors and the basic physical concepts of their operation.
2. Nuclear reactions in reactors,
3. Nuclear energy production
4. The neutron life cycle, the physical aspects of its calculation, delayed neutrons
5. Neutron transport theory
6. Nuclear fuel cycle, radioactive waste treatment
7. Interaction of radiation with matter and human cells
8. Radiation dose, the risk models, and their background
9. The radiation dose load of the population from artificial and natural sources
10. Radiation safety system, shielding,
11. Operation mechanisms of the dosimeters

Recommended readings:

- Robert E. Masterson, Introduction to Nuclear Reactor Physics
- Weston M. Stacey, Nuclear Reactor Physics, 3rd Edition, ISBN: 978-3-527-81230-1

Signal Processing (Data Processing and Informatics)

Reading material:

Steven W. Smith; The Scientist and Engineer's Guide to Digital Signal Processing; (2011) ; Available online: http://www.dspguide.com/

Additional resources:

Rafael C Gonzalez, Richard E. Woods; Digital Image Processing; Pearson (2017)
Anastasia Veloni, Nikolaos I. Miridakis, Erysso Boukouvala; Digital and Statistical Signal Processing; CRC Press (2019)
Dimitris G. Manolakis, Vinay K. Ingle; Applied Digital Signal Processing: Theory and Practice; Cambridge University Press (2012)
K. Deergha Rao, M. N. S. Swamy; Digital Signal Processing. Theory and Practice; Springer (2018)

Exam Topics:

1. Linear systems: Transfer function. Fourier series. Fourier series of some simple signals. Discrete Fourier transform with uniform sampling. Wiener filters and properties.

2. Fourier transform: Properties of the Fourier transform. The Fourier transform in two (or more) dimensions. Correlation functions. Cross-correlation function. Autocorrelation function. Properties of the autocorrelation function. Measurement of the amplitude of a known waveform, matched filter.

3. Frequency spectrum, energy and power spectrum. Frequency spectrum of a square signal. Dirac-delta frequency spectrum. Matrix analyzer, the concept of the combined density function. Examining a transfer function with correlation functions. Image processing with DFT: correlation, homomorphic filtering, convolution in two dimensions.

4. The concept of weight function and convolution. System's weight function. Weight function of simple RC parts. The universal test signal. Distribution functions of continuous and sampled signals. Autocorrelation functions of random signals. Relationship between energy spectrum and autocorrelation function. Wiener-Khinchin theorem. Measurement of trigger-bound signals in the presence of noise, comb filter.

5. The convolutional integral, convolution in Fourier space. Convolution in two dimensions. Representation of images, convolution of images. AD converters. Importance of band limiting in AD conversion. Quantization noise. The wavelet transform.

6. Linear and periodic convolution. Averaging, smoothing, edge detection, image sharpening. Basic concepts of digital filters (AD, DA, delay). FIR (finite impulse response) filters. Recursive filters. Low and high pass digital filters. Connection of low-pass RC and digital filter.

7. Deconvolution. Distortion - distortion. Sampling law in the time domain and in the frequency domain. Image digitization: CCD, TV video signal properties. DA converter correction in the frequency space. Channel capacity, information content, maximum information flux.

8. Phase and time delay properties. RC low pass filter phase flow. Ideal low-pass, ideal pulse transmission on an ideal low-pass filter. Filter types (Bessel, Butterworth, Chebyshev), jump function transfer, overshoot. Enlarging images, interpolation, practical application of Bessel filter. Principal component analysis.

9. Transmission of a step function through an ideal low-pass filter. Integration identities. The Nyquist theorem. Noise characteristics, noise and disturbance. White noise properties with noise reduction integration. FFT - the Fast Fourier Transform. The CT algorithm, butterfly operation, bit reversal. Convolution with FFT, circular convolution. Application of window functions.