The Curriculum[1] of the

Doctoral School of Physics, University of Pécs

Pécs, 2025.

1 Study requirements at the Doctoral School of Physics, PTE TTK

The study requirements and administrative procedures are set out in the Organizational and Operational Regulations of the Doctoral School of Physics at the University of Pécs, in accordance with university regulations.
A brief summary is provided below:
1) The doctoral programme lasts 8 semesters.
2) Doctoral training is carried out in two stages:
   i) The first is a "training and research phase" lasting 4 semesters.
   ii) The second is a "research and dissertation phase" also lasting 4 semesters.
3) The total number of credits that must be earned during the doctoral programme is 120+120=240.
4) Credits can be earned in the doctoral programme through various activities:
   i) participation in training ("study credits"),
   ii) teaching,
   iii) research work,
   iv) reviewing professional literature,
   v) publication of research results,
   vi) written reports summarizing the student's activities.
5) Compulsory courses in doctoral training by curricula:

Quantum Optics and Quantum Informatics curriculum	**Laser physics, nonlinear optics and applied physics** curriculum	**Scholar-Teacher Training Programme** curriculum
Scientific communication (Zoltán Tibai)		
Quantum Optics I. (Péter Ádám)	Modern Optics (János Erostyák)	Teaching Physics I. (Classical Physics) (László Pálfalvi)
Quantum Informatics I. (Péter Ádám)	Laser Physics (János Hebling)	Teaching Physics II. (Modern Physics) (László Pálfalvi)

Students enrolled in the **Quantum Optics and Quantum Informatics**, **Laser Physics, Nonlinear Optics, and Applied Physics** programmes may choose from the subjects listed in sections 3.1 and 3.2 to fulfil their compulsory credit requirements. Students enrolled in the **Scholar-Teacher Training** programme may choose from the subjects listed in Chapter 3.3 to fulfil their compulsory credit requirements. A maximum of 30% of the credits may be earned from subjects listed in Chapters 3.1 and 3.2.

[1] Prepared in accordance with Level 8 of the Hungarian Qualifications Framework (HuQF, in Hungarian: Magyar Képesítési Keretrendszer - MKKR).

6) The subjects of the comprehensive exam:

- For the **Quantum Optics and Quantum Informatics** programme: the main and minor subjects are selected from the subjects listed in Chapter 3.1 based on the consensus of the supervisor and the head of the Doctoral School.
- For the **Laser Physics, Nonlinear Optics and Applied Physics** programme: the main and minor subjects are selected from the subjects listed in Chapter 3.2 based on the consensus of the supervisor and the head of the Doctoral School.
- For the **Scholar-Teacher Training** programme: the main and minor subjects are selected from among the subjects listed in Chapter 3.3 based on the consensus of the supervisor and the head of the Doctoral School.

7) Requirements for credits that can be earned through each type of activity:
   i) In semesters 1-4:
   Total credits to be earned: 120

	Number of credits		**Comments**	**Method of certification**
	Minimum	**Maximum**		
Study	30	48	For courses completed based on the supervisor's recommendation, one class per week in one semester is worth 2 credits. Credits may also be earned by taking courses in other programmes or at other universities, based on the supervisor's recommendation and with the programme director's approval.	Completion of the course is certified by the course director.
Teaching	8	32	One class per week in one semester is worth 2 credits.	The teaching activity is certified by the head of teaching at the Institute of Physics.
Review of professional literature	0	24	The literature to be reviewed is designated by the supervisor. 0, 2, 4, or 6 credits may be awarded per semester.	Certified by the supervisor.
Research	6	32	0, 2, 4, 6, or 8 credits per semester.	Confirmed by the supervisor.
Final report at the end of the first two semesters	3	12	For the presentation or written report summarizing the doctoral student's activities to date in no more than 15 pages. 3, 6, 9, or 12 credits may be awarded based on the supervisor's recommendation.	Supervisor certifies.

ii) In semesters 5-8:
Total credits to be earned: 120

	Credit number		Comments	Method of verification
	Minimum	**Maximum**		
Study	0	16	For courses completed based on the supervisor's recommendation, one class per week in one semester is worth 2 credits. Credits may also be earned by taking courses in other programmes or at other universities, based on the supervisor's recommendation and with the programme director's approval.	Completion of the course is certified by the course director.
Education	0	24	One class per week in one semester is worth 2 credits	The teaching activity is certified by the Director of Education at the Institute of Physics.
Review of professional literature	0	12	The literature to be reviewed is designated by the supervisor. 0, 2, 4, or 6 credits may be awarded per semester.	Certified by the supervisor.
Research	0	16	0, 2, 4, 6, or 8 credits per semester.	Certified by the supervisor.
Publication	72	96	A maximum of 30 credits can be awarded for publications in international peer-reviewed journals, a maximum of 20 credits for presentations at international conferences, a maximum of 15 credits for posters, and a maximum of 10 credits for other publications, which can be validated by the student in any semester following the acceptance of the publication.	Completion is certified by the programme director each semester based on the supervisor's recommendation.

2 Doctoral school programmes and research areas

This chapter lists the doctoral school's programmes and their characteristic research topics. The current doctoral topics are available at http://www.doktori.hu. The Physics Doctoral School Council (PDSC, in Hungarian: Fizika Doktori Iskola Tanácsa - FizDIT) is responsible for reviewing, developing, and expanding the quality of the topics.

2.1 Quantum Optics and Quantum Informatics Programme

Head: *Péter Ádám, PhD,* associate professor

2.1.1 Quantum optics

- Application of quantum trajectory methods to the description of quantum optical systems
- Coherent control in atomic systems
- Coherent control and manipulation of quantum systems with phase-modulated laser pulses
- Slow light with frequency-modulated laser pulses: Applications to quantum information and resonant nonlinear optics
- Collective optical excitations of ultracold atomic gases
- Study of the interaction between light and bound-state ions
- Propagation of electromagnetic fields in photonic crystal-optical fibers
- Analog Hawking radiation in moving Bose-Einstein condensates
- Properties of quantum random walks, their role in quantum information systems and quantum optical implementations
- Multiphoton scattering of electrons
- Dependence on the absolute phase of interactions with few-cycle femtosecond pulses
- Gauge-invariant Wigner functions of charged particles
- S-wave Wigner functions in arbitrary higher dimensions
- Computer modelling of biomolecular systems from the molecular mechanics approach to the quantum treatment

2.1.2 Quantum informatics

- Behavior of entanglement in various physical systems and processes, like, e.g, quantum optical setups and solid-state systems
- Realization of quantum computers. Problems related to specific platforms, such as, e.g., atomic, ionic and optical implementations
- Foundations of quantum mechanics in view of information theory: measurement theory, nonlocality, Bell inequalities, interpretations
- Strongly correlated systems in two dimensions
- Fractional quantum Hall effect
- Employing decohering quantum systems in quantum information protocols
- Practical applications of nonclassical light
- Investigation of error-free capacities of quantum channels

2.2 Laser physics, nonlinear optics and applied physics programme

Head: *Professor Gábor Almási,* university professor

- "Time-resolved" spectroscopic investigation of molecular interactions on the fs-ns scale
- Development and application of integrating spheres on studying low cross-section transitions
- Investigation of LiTaO3 crystals having high optical damage threshold
- Development and critical investigation of the theories of Z-scan measurement
- Generation of high intensity ultrashort THz pulses by optical rectification
- Investigation of transient dynamics induced by THz pulses
- THz pump-probe measurements
- Investigation of the physical properties of graphene
- Investigation of nonlinear photonic crystals
- High resolution spectroscopy of rare earth element doped optical crystals
- Development of optical and opto-electronic devices based on periodically poled LiNbO3 crystals

- Development of ultrashort pulse OPOs and OPAs
- Simulations of the interaction of high intensity electromagnetic fields with charged particles by PIC methods
- The role of hydroxide ion sin nonlinear optical crystals
- Thermal fixing of hologram sin photorefractive crystals
- ESR investigation of transition metals in LiNbO3
- Experimental and theoretical investigation of capillary z-pinch soft-X-ray lasers
- Experimental and theoretical investigation of capillary z-pinch optical waveguides
- Nonlinear optics with soft-X-ray lasers
- Measurement of aerosols with lasers: determination of particle site and concentration
- Investigation of biological effects of aerosols
- Energy transfer and fluorescence quenching in guest-host complexes of cavitands
- Surface characterization by interferometric methods
- Modelling and development of particle counters
- Laser based methods in the determination of atmospheric parameters
- Studying the physical parameters of ferroelectric crystals

2.3 Scholar-teacher training programme

Head: *Professor László Pálfalvi*, university professor

- Educational videos for teaching physics
- Competence-based assessment in secondary school physics education
- Microcontrollers in physics education
- Using simulations to prepare experiments in the topic of electricity
- Electromagnetic fields and radio waves in secondary school physics education
- Methods and effects of science communication in science education
- Environmental physics in physics education
- Interpreting measurement results and making decisions based on them: applying probability theory and statistics in secondary school physics education
- The role and development of general cognitive skills in university and secondary school physics education
- Analogies in physics
- Talent development and physics competitions
- Synthesis of advanced physics and mathematics knowledge in competition tasks
- Optimization problems in physics tasks
- Complex, selected classical physics problems related to public education
- The ball model revisited: computer molecular modeling
- Failed attempts in the history of physics
- The development of physics as an interplay of chance and necessity

3 Doctoral school courses

This chapter lists the courses offered by the doctoral school, grouped according to thematic programmes. Based on the recommendations of the programme directors, the Physics Doctoral School Council (PDSC) determines the courses offered each semester. The PDSC is responsible for reviewing, improving, and expanding the course list. Doctoral students enrolled in a given programme may also take courses offered in other programmes according to their specific interests and research topics (see Chapter 1 and Section 5). According to Section 14 of the Organizational and Operational Regulations of the Doctoral School of Physics, students may also earn academic credits by auditing courses offered in other programmes or at other universities.

3.1.1 Scientific communication (Zoltán Tibai)

- The role of scientific communication: publication pressure, impact factor, and citation systems
- The structure of scientific articles: introduction, methods, results, and conclusions
- How to write effective abstracts and titles
- Literature search, reference management, and citation methods
- Scientific conferences: abstract submission, oral presentation, and poster preparation
- Effective PowerPoint use and presentation techniques
- Writing a dissertation: structural and stylistic principles
- The scientific peer review process: handling reviewers' comments and formulating responses
- Intellectual property protection: patent applications and utilization of research results
- Ethical issues in scientific publications: plagiarism, authorship, and data management

Recommended reading:

Day, R. A., & Gastel, B. "How to Write and Publish a Scientific Paper" (Cambridge University Press, 2016)

Alley, M. "The Craft of Scientific Presentations: Critical Steps to Succeed and Critical Errors to Avoid" (Springer, 2013)

Peat, J., Elliott, E., Baur, L., & Keena, V. "Scientific Writing: Easy When You Know How" (BMJ Books, 2002)

3.2 Quantum Optics and Quantum Informatics Programme

3.2.1 Quantum Optics I. (Péter Ádám)

- Quantized electromagnetic field, modes
- Density operator and phase space
- Operator ordering, operator functions
- The Wigner function, characteristic functions, quasi-probability distribution functions
- Quantum states of the EM field: thermal, coherent, squeezed states
- The phenomenon of entanglement, Einstein-Podolsky-Rosen pairs.

Recommended reading:

A. Yariv: Quantum Electronics (John Wiley, New York, 1988)

W. H. Louisell: Quantum Statistical Properties of Radiation (John Wiley, New York, 1990)

S. M. Barnett, P. M. Radmore: Methods in Theoretical Quantum Optics (Clarendon Press, 1997)

M. O. Scully, M. S. Zubairy: Quantum Optics (Cambridge University Press, 1997)

3.2.2 Quantum Optics II. (Péter Ádám)

- Passive optical elements: beam splitters, phase shifters, multiports
- The theory of photodetection, photon counting
- Homodyne and heterodyne detection
- Statistical and quantum theory of coherence
- Nonlinear optical processes
- Active optical elements: amplification, optical parametric oscillators

- Description of losses, noise and attenuation in quantum optics

Recommended reading:
L. Mandel, and E. Wolf: "Optical Coherence and Quantum Optics" (Cambridge University Press, 1995)
S. M. Barnett, and P. M. Radmore: "Methods in Theoretical Quantum Optics" (Clarendon Press, 1997)
U. Leonhardt: "Measuring the quantum state of light" (Cambridge University Press, 1997)

3.2.3 Quantum optical experiments (Tamás Kiss)

- Generation and detection of non-classical light
- Reconstruction of quantum states, quantum tomography
- Verification of quantum mechanical models in optics
- Quantum state teleportation
- Atomic trapping, atomic optics

Recommended reading:
Hans-A. Bachor, and T. C. Ralph: "A Guide to Experiments in Quantum Optics"

3.2.4 Quantum Informatics I: Theory (Péter Ádám)

- Classical and quantum information theory (Shannon and Neumann entropy, channel capacity)
- Quantum bit dynamics (Unitér evolution, quantum operations, Neumann measurement, POVM measurement, quantum logic networks)
- The theory of entanglement (Typical entangled states (EPR, GHZ, W, Werner, etc.). Measures of entanglement, entanglement witnesses in general and on special states. Multi-part entanglement.)
- Quantum communication protocols (teleportation, cloning, supercompression, encryption)
- Quantum algorithms (Shor, Grover, quantum random walk, error correction codes)

Recommended reading:
M.A. Nielsen, I.L. Chuang: Quantum Computation and Quantum Information (Cambridge University Press, 2000)

3.2.5 Quantum Informatics II: Experimental Aspects, Applications (Mátyás Koniorczyk)

- General quantum computer models, quantum simulations
- Decoherence, conditions for the operation of quantum computers, fault tolerant quantum computing
- Ion trap quantum computers
- Quantum simulators and quantum computers based on cold trapped atoms
- Photonic quantum computers, photonic quantum communication (polarization qubits, coherent-state qubits, Gaussian states)
- NMR quantum computers, quantum dots
- Application of quantum information science results in other areas of physics (DMRG as a variational method in quantum information science, phase transitions and quantum information)

Recommended reading:
M. A. Nielsen, and I. L. Chuang: "Quantum Computation and Quantum Information" (Cambridge University Press, 2000)

3.2.6 Computational methods in quantum information science (Mátyás Koniorczyk)

- Quantum bits, pure and mixed states of quantum bits
- Unitér time evolution, projective measurement
- Multipartite quantum systems: tensor product, partial imprinting
- General quantum mechanical time evolution: CP mappings, POVM measurements
- Schmidt decomposition, entanglement, EPR, GHZ, W states
- Bound entanglement, PPT, NPT states
- Quantum mechanical entropies
- Two-part entanglement, competition
- Monogamy of entanglement, tangle, CKW inequalities
- Localizable entanglement, cluster states

Recommended reading:

John Preskill: "Lecture notes for Physics 229: Quantum information and computation" (California Institute of Technology, 1998)
Michal Horodecki, Pawel Horodecki, and Ryszard Horodecki: "Mixed state entanglement and quantum communication" (Quantum Information: An Introduction to Basic Theoretical Concepts and Experiments, Springer-Verlag, 2001)
M. Hein, W. Dür, J. Eisert, R. Raussendorf, M. Van den Nest, and H.-J. Briegel: "Entanglement in Graph States and its Applications" (https://arxiv.org/abs/quant-ph/0602096)

3.2.7 Quantum mechanical paradoxes (Mátyás Koniorczyk)

- Einstein-Podolsky-Rosen paradox
- Non-locality, Bell inequalities
- Greenberger-Horne-Zeilinger correlations
- Correlations and entangled states of light fields
- Single-photon interferometry, complementarity, duality
- Two-photon interferometry, quantum erasure
- Non-destructive quantum mechanical measurement
- Pre- and post-selective quantum mechanics

Recommended reading:
J. S. Bell: "Speakable and Unspeakable in Quantum Mechanics"
H. Paul, and I. Jex: "Introduction to Quantum Optics: From Light Quanta to Quantum Teleportation"

3.2.8 Fundamentals of quantum electrodynamics (Sándor Varró)

- Classical field theory, conservation laws
- Spaces and particles, creation and annihilation operators
- Canonical quantization
- Perturbation theory, Wick's theorem, Feynman diagrams
- Quantization of gauge theories: electrodynamics
- Spontaneous emission, Lamb shift, Casimir effect, multiphoton absorption

Recommended reading:
P. W. Milonni: "The Quantum Vacuum: An Introduction to Quantum Electrodynamics"
C. Cohen-Tannoudji, J. Dupont-Roc, and G. Grynberg: "Photons and Atoms - Introduction to Quantum Electrodynamics" (Wiley, New York 1989)

3.2.9 Resonant light-matter interaction (Péter Ádám)

- Light scattering on atoms, spontaneous emission
- Semiclassical theory, coupled Maxwell-Bloch equations
- Propagation of coherent pulses
- Resonance fluorescence
- Electrodynamics in resonators
- The Jaynes-Cummings model
- The micromaser
- Quantum theory of lasers

Recommended reading:
L. Allen, J.H. Eberly: Optical Resonance and Two Level Atoms (Dover Publications, 1987)
C. Cohen-Tannoudji, J. Dupont-Roc, G. Grynberg: Photons and Atoms - Introduction to Quantum Electrodynamics
M. O. Scully, M. S. Zubairy: Quantum Optics (Cambridge University Press, 1997)
Fundamentals of Quantum Electronics, ed. Sándor Varró, lecture notes

3.2.10 Quantum Statistics of Open Systems (Péter Domokos)

- Density matrix, von Neumann equation and measurement, entropy
- Quantum system in a heat reservoir, Markov approximation
- Master equation, quantum regression theorem
- Zwanzig projector operator method

- Phase space methods, Wigner function, Fokker-Planck equation
- Heat reservoir in non-thermal state
- Quantum Langevin equations, generalized Einstein relations
- Stochastic differential equations Ito and Stratonovich interpretations
- Theory of photodetection
- Monte Carlo wave function method for describing the time evolution of open systems
- Quantum optical applications

Recommended reading:
C. W. Gardiner: "Handbook of Stochastic Methods" (Springer-Verlag, 2004)
H. Carmichael: "An Open Systems Approach to Quantum Optics" (Springer-Verlag, 1993)

3.2.11 Laser cooling and trapping of atoms (Péter Domokos)

- Mechanical effects of light on neutral particles, historical overview
- Characteristic time scales, separation of internal and external degrees of freedom, fundamentals of semiclassical theory
- The mechanical effect of lasers on stationary atoms: radiation pressure and dipole force
- The work of the radiation field, energy balance
- Electromagnetic field fluctuations, diffusion in atomic motion
- Mechanical effect of lasers on moving atoms, Doppler cooling
- Optical molasses, introduction of Langevin equations and the concept of temperature
- The mechanical effect of lasers on multi-level atoms
- Magneto-optical trap
- Polarization gradient cooling, Sisyphus effect
- Quantized motion of atoms, velocity-selective population trapping
- Cooling trapped atoms with sideband excitation

Recommended reading:
H. J. Metcalf, and P. Van Der Straten: "Laser Cooling and Trapping" (Springer-Verlag 1999)
C. Cohen-Tannoudji, J. Dupont-Roc, and G. Grynberg: "Photons and Atoms - Introduction to Quantum Electrodynamics" (Wiley, New York 1989)

3.2.12 Bose-Einstein condensation in rare gases (Tamás Kiss)

- Non-interacting Bose gas: phase transition, critical temperature, condensed fraction
- Trapping: quadrupole, TOP, Ioffe-Pritchard, optical and magneto-optical traps
- Cooling: Doppler, Sisyphus and evaporative cooling
- Interacting gases: scattering, scattering length
- Gross-Pitayevsky equation, Thomas-Fermi approximation, healing length
- Hydrodynamic approximation
- Elemental excitations, Bogoliubov transformation
- Finite temperature, Hartree-Fock approximation
- Correlations, coherence, atom laser

Recommended reading:
C. J. Pethick, and H. Smith: "Bose-Einstein Condensation in Dilute Gases" (Cambridge University Press, 2002)
L. P. Pitaevskii, S. Stringari, and L. Pitaevskii: "Bose-Einstein Condensation" (Oxford University Press, 2003)
H. J. Metcalf, and P. Van Der Straten: "Laser Cooling and Trapping" (Springer-Verlag, 1999)

3.2.13 Coherent control (Zsolt Kis)

- Electromagnetic field interaction with idealized two-level atoms
- Control of atomic electron states, Bloch equations
- Adiabatic control of electron states in two-level systems
- Dissipative processes, the role of dissipation in the controllability of atomic levels
- Interaction of three-level systems with coherent electromagnetic fields
- Stimulated Raman adiabatic transition in a three-level system
- Interaction of degenerate atomic systems with electromagnetic fields, selection rules

- Stimulated Raman adiabatic transition in degenerate three-level systems
- Applications in atomic physics
- Interaction of molecular electron clouds with electromagnetic fields
- Control of vibrational wave packets in diatomic molecules
- Femto chemistry: influencing chemical reactions with femtosecond laser pulses

Recommended reading:

R. Loudon: "The Quantum Theory of Light" (Oxford University Press, 2000)
C. Cohen-Tannoudji, J. Dupont-Roc, and G. Grynberg: "Photons and Atoms - Introduction to Quantum Electrodynamics" (Wiley, New York 1989)
M. O. Scully, and M. S. Zubairy: "Quantum Optics" (Cambridge University Press, 1997)
P. W. Brumer, and M. Shapiro: "Principles of the Quantum Control of Molecular Processes" (Wiley, 2003)

3.2.14 The latest results and applications of density functional theory (Gábor Paragi)

- A summary overview of time-independent ground state DFT (Hohenberg-Kohn theorems, Kohn-Sham picture, basic exchange and correlation functionals)
- New exchange and correlation functionals in DFT.
- Extension of the basic DFT theory to time-dependent cases (TD-DFT). The Runge-Gross and van Leeuwen theory.
- The time-dependent Kohn-Sham picture. The ALDA method and further exchange and correlation functionals in TD-DFT.
- Linear response theory in TD-DFT; calculation of excited states using time-dependent DFT.
- Density matrix functional theory.
- Semiempirical DFT: Density Functional Based Tight Binding (DFTB)
- Strongly interacting electrons and DFT.

Recommended reading:

1. Carsten A. Ulrich: Time-Dependent Density Functional Theorem. Oxford University Press (2012), ISBN 978-0-19-956302-9
2. Topics in Current Chemistry (368): Density-Functional Methods for Excited States (ed.: N. Ferré, M. Filatov, M. Huix-Rotllant) Springer (2016) ISBN 978-3-319-22080-2, doi 10.1007/978-3-319-22081-9
3. P. Gori-Giorgi "Density-Functional Theory for Strongly Interacting Electrons" Phys.Rev.Lett. 103, 166402 (2009), doi: 10.1103/PhysRevLett.103.166402
4. Elstner, M.; Porezag, D.; Jungnickel, G.; Elsner, J.; Haugk, M.; Frauenheim, Th.; Suhai, S.; Seifert, G. (1998). "Self-consistent-charge density-functional tight-binding method for simulations of complex materials properties". Physical Review B. 58 (11): 7260–7268. doi:10.1103/PhysRevB.58.7260
5. Yang; Yu, Haibo; York, Darrin; Cui, Qiang; Elstner, Marcus (2007). "Extension of the Self-Consistent-Charge Density-Functional Tight-Binding Method: Third-Order Expansion of the Density Functional Theory Total Energy and Introduction of a Modified Effective Coulomb Interaction". The Journal of Physical Chemistry A. 111 (42): 10861–10873. doi:10.1021/jp074167r

3.2.15 Advanced Methods in Molecular Modelling (Gábor Paragi)

- Main differences between quantum mechanical (QM) and molecular mechanical (MM) studies of molecules. Levels of organization of biologically interesting molecular systems.
- Fundamentals of QM studies of molecules: Born-Oppenheimer approximation, potential energy surfaces, Hartree-Fock and post-Hartree-Fock methods.
- Fundamentals of density functional theory, energy decomposition methods, implicit solvent models, charge analysis methods
- Theoretical background of MM simulation. Traditional and polarizable force fields. Molecular dynamics (MD) simulations. Theoretical background of numerical solutions used in MD: Verlet algorithm and its main variants.
- Ligand-Target Study I: Free Energy Calculation Methods. MMGBSA Method, Umbrella Sampling Method, Thermodynamic Integration Method.
- Ligand-Target Analysis II: QM/MM Methods

- Ab Initio MD calculation.
- Familiarization with the most important software packages (AMBER, GROMACS, DESMOND, Gaussian, Orka, Octopus)

Recommended reading:
1. A R Leach: Molecular modeling Principles and applications, 2nd ed.
2. Computational Biochemistry. Edited by Tamás Körtvélyesi Szeged, Hungary: Digital Textbook Library (2013)
3. AMBER, GROMACS, Desmond, Gaussian, etc. user manuals

3.2.16 Selected chapters from quantum informatics I. (János Bergou)

- Introduction and motivation: representing information with quantum states, qubit and Bloch representations, quantum gates, quantum circuits, Deutsch algorithm.
- Density matrix, mixed states of qubits and Bloch vector representation, Schmidt decomposition, state purification.
- Entanglement, the non-local nature of quantum mechanics, Bell and Wigner inequalities, measures of entanglement and testing. Entanglement as a resource for quantum information protocols: teleportation and dense coding.
- Generalized quantum dynamics: quantum operations, quantum mappings, Kraus representations. Quantum channels. Impossible mappings: quantum cloning and the impossibility of quantum communication faster than light.
- Quantum theory of measurements: projective and generalized measurements, Positive Operator Valued Measure (POVM), Neumark's theorem. Strategies for distinguishing between quantum states.
- Quantum communication: protocols for quantum distribution of encryption keys, quantum cryptography, proof of the unbreakability of quantum codes.

Recommended reading:
1. J. A. Bergou, M. Hillery, and M. Saffman: Theory of Quantum Information Processing: Theory and Implementation (2nd Edition, Graduate Texts in Physics, Springer, 2021).
2. Preskill notes on the website www.theory.caltech.edu/people/preskill/ph229
3. M. A. Nielsen and I. L. Chuang, Quantum Computation and Quantum Information (Cambridge University Press, 2000).
4. G. Benenti, G. Casati and G. Strini, Principles of Quantum Computation and Quantum Information, (World Scientific, Singapore, 2004)

3.2.17 Selected chapters from quantum informatics II. (János Bergou)

- Quantum algorithms: Deutsch-Jozsa algorithm, Grover search algorithm, period determination, Shor factorization algorithm.
- Quantum machines: quantum copier, devices operating with finite probability, programmable devices.
- Decoherence: the influence of the environment, decoherence-free alters.
- Error correction: stabilizer formalism and the Gottesman-Knill theorem.
- If time permits, or if the course spans two semesters, the following topics are also recommended:
- The application of information theory in quantum information science: entropic measures of information (Shannon and Neumann), Schumacher's noise-free coding theorem, mutual information, accessible information, and the Holevo bound.
- Physical systems for implementing quantum information protocols

Recommended reading:
1. J. A. Bergou, M. Hillery, and M. Saffman: Theory of Quantum Information Processing: Theory and Implementation (2nd Edition, Graduate Texts in Physics, Springer, 2021).
2. Preskill notes on the website www.theory.caltech.edu/people/preskill/ph229
3. M. A. Nielsen and I. L. Chuang, Quantum Computation and Quantum Information (Cambridge University Press, 2000).
4. G. Benenti, G. Casati and G. Strini, Principles of Quantum Computation and Quantum Information, (World Scientific, Singapore, 2004)

3.2.18 Approximation theory, special functions and their applications in physics (Margit Pap)

- Introduction to approximation theory, best approximation norms and metrics, Hilbert spaces. Polynomial approximation, rational approximation
- Orthogonal polynomials and spectral approximation Orthogonal polynomials: Legendre, Chebyshev, Laguerre, and Hermite polynomials. Orthogonal bases and the Gram-Schmidt process
- Special functions and their applications in physics, Bessel functions, Legendre polynomials and spherical harmonics, Hermite functions, Laguerre functions, Zernike functions
- Approximation in complex analysis and physical systems Malmquist-Takenaka systems and rational approximation
- Application of approximation methods in quantum mechanics and wave optics

Recommended reading:

Szegő, G. (1975). Orthogonal Polynomials (4th ed.). American Mathematical Society.
Schipp Ferenc, Approximation Theory, University Lecture Notes, ELTE, Budapest, 2006
https://numanal-old.inf.elte.hu/~schipp/Jegyzetek/AprxElm.pdf
Andrews, G. E., Askey, R., & Roy, R. (1999). Special Functions. Cambridge University Press. ISBN-13: 978-0521576046.
Chant, R. F., & Cooke, T. P. (2016). Mathematical Methods for Physicists: A Concise Introduction. Cambridge University Press.

3.2.19 Wavelet Analysis and Applications (Margit Pap)

- Wavelet basics: Discrete and continuous affine wavelet transforms, orthogonal and bi-orthogonal wavelets.
- Haar wavelets, Daubechies wavelets, Morlet and Coiflet wavelets
- Multiresolution analysis: Data compression, denoising, signal processing, and image processing.
- Gabor wavelets, Gabor transform (Short Time Fourier transform) and their applications
- The relationship between affine and Gabor transforms and group representations, and their joint generalization to voice transforms
- Hyperbolic wavelets and hyperbolic wavelet transforms
- Applications in physics: Application of wavelets in quantum mechanical systems, signal processing, noise filtering techniques in physical measurements.

Recommended reading

Mallat, S. (2009). A Wavelet Tour of Signal Processing (3rd ed.). Academic Press.
Daubechies, I. (1992). Ten Lectures on Wavelets. SIAM.
Schipp Ferenc, Wavelets, University Lecture Notes, ELTE, Budapest, 2003 https://numanal-old.inf.elte.hu/~schipp/Jegyzetek/Waveletek.pdf
Margit Pap, Hyperbolic Wavelet Transforms and Applications MTA Doctorate (Dissertation)134 p. 2022 MTMT: 36043865 https://real-d.mtak.hu/1356/7/Pap%20Margit_doktori_mu.pdf

3.3 Laser Physics, Nonlinear Optics and Applied Physics

3.3.1 Fluorescence spectroscopy (János Erostyák)

- Basic concepts of fluorescence spectroscopy
- Measurement methods and measuring equipment: direct methods, sampling techniques, time-correlated single photon counting, transient signal measurements, phase fluorimetry
- Convolution, deconvolution, decay functions, lifetime functions
- Fluorescence polarization, steady-state and time-resolved anisotropy
- Fluorescence quenching
- Types of energy transfer
- Reversible two-state reactions
- Solvent relaxation
- Methods for evaluating steady-state and time-resolved measurement results

Recommended reading:
J. R. Lakowicz (ed.): "Principles of Fluorescence Spectroscopy" (Springer, Singapore, 2006)
J. R. Lakowitz (ed.): "Topics in Fluorescence Spectroscopy Vol. 1-3." (Plenum Press, New York, 1991)
B. Valeur, and J. C. Brochon (eds.): "New Trends in Fluorescence Spectroscopy. Applications to Chemical and Life Sciences." (Springer, Berlin, 2001)
Szalay L., and Damjanovich S. (eds.): "Luminescence in Biology and Medicine" (Akadémiai Kiadó, Budapest, 1983)

3.3.2 Modern Optics (János Erostyák)

- Geometric optics (mirrors, lenses, prisms, lens systems)
- Optical instruments (magnifying glasses, microscopes, telescopes, projectors, the human eye)
- Matrix optics
- Electromagnetic waves, wave equations. Absorption. Dispersion and group velocity
- Interference phenomena. Coherence. Interferometers.
- Waveguides. Optical fibers
- Gaussian beams
- Fraunhofer and Fresnel diffraction. Fourier optics
- Polarization. Double refraction.
- Nonlinear optics. Electro-optics. Acousto-optics.

Recommended reading:
E. Hecht: Optics. Pearson Education Limited, 2017.
B.E.A. Saleh, M.C. Teich: Fundamentals of Photonics. John Wiley and Sons, 2019.
R. Guenter: Modern Optics, John Wiley and Sons, 1990.
A. Nussbaumm, R.A. Phillips: Modern Optics, Műszaki Könyvkiadó, 1982.

3.3.3 Determination of nonlinear optical parameters using the Z-scan method (László Pálfalvi)

- Description of light propagation using matrix optics
- Diffraction, Gaussian beams
- Elements of nonlinear optics and crystal optics, third-order optical nonlinearity
- The Z-scan theory for thin samples, possibilities for determining the nonlinear refractive index and nonlinear absorption
- Extension of the Z-scan method to thick samples, limitations of the individual theories
- Application of the Z-scan method to light pulses, time-resolved Z-scan measurements
- Simplified model of photorefraction
- Thermo-optical nonlinearity
- Investigation of LiNbO3 using the Z-scan method

Recommended reading:
R. L. Sutherland: "Handbook of Nonlinear Optics" (New York: Marcel Dekker, 1996)

M. G. Kuzyk, and C. W. Dirk: "Characterisation Techniques and Tabulations for Organic Nonlinear Materials" (Marcel Dekker, pp. 655-692, 1998)
R. Guenther: "Modern Optics" (John Wiley and Sons, 1990)

3.3.4 Plasma Physics (Sergei Kuhlevsky)

- Basic parameters of plasmas. Different types of plasmas
- Excitation and ionization of atoms, ions, and nuclear nuclei to energy levels using chemical, electrical, electromagnetic (light), and nuclear energy. Electron-ion recombination
- Fundamental optical processes in plasmas. Modeling of the plasma spectrum.
- Production of plasma using chemical, electrical, electromagnetic (light) and nuclear energy
- The zeroth-order (simplest) (plasma as a hot ideal gas)
- First-oder (microscopic) model of plasma
- Second (kinetic) model of plasma
- Third (MHD) model of plasma
- Plasma waves. EM waves in plasma. Plasma-based wave guides
- Scientific and industrial applications of plasmas

Recommended reading:
Kuhlevszkij Szergej (S.V. Kukhlevsky), "Plasma Physics (online lectures)" PTE TTK, Institute of Physics, 2025
F.F. Chen, Introduction to Plasma Physics and Controlled Fusion (3rd ed.). Switzerland: Springer International Publishing (2016)
U.S. Inan, M. Golkowski: Principles of Plasma Physics for Engineers and Scientists. Cambridge University Press, 2011
Paul M. Bellan: Fundamentals of Plasma Physics. Cambridge University Press, 2006.
J. A. Bittencourt: Fundamentals of Plasma Physics. Springer, 2004.
L.A. Arcimovics, R.Z. Szaggyejev, Plasma Physics for Physicists, Akadémiai kiadó, Budapest (1985)
Iván Abonyi, The Fourth State of Matter. Introduction to Plasma Physics, Gondolat Publishing House, Budapest (1971).
W. B. Thompson, Introduction to Plasma Physics, Müszaki Könyvkiado, Budapest, 1970

3.3.5 X-ray lasers (Sergei Kuhlevsky)

- Basic definitions and fundamental physical concepts of laser physics.
- The X-ray range of the electromagnetic spectrum
- Fundamental optical processes in the X-ray spectral region
- Physical fundamentals of X-ray lasers
- Excitation of multiply ionized ions in X-ray lasers
- Plasmas as sources of multiply ionized ions
- Characteristics of X-ray lasers
- Soft X-ray Ar+8 laser at the University of Pécs. Experiments and theories
- Alternative coherent X-ray sources
- Scientific and technological applications. Biological and medical applications

Recommended reading:
Kuhlevszkij Szergej (S.V. Kukhlevsky), "X-ray lasers (online lectures)" PTE TTK, Institute of Physics, 2025
D. Attwood, Soft x-rays and extreme ultraviolet radiation. Principles and applications. Cambridge University Press, London, 1999
R. Elton, X-ray lasers, Academic Press, London, 1990
W. J. Sarjeant, R.E. Dollinger, High-power electronics, TAB Professional and Reference Books, Blue

3.3.6 Wave guide optics (Sergei Kuhlevsky)

- Optical waveguides in geometric (ray) optics
- Optical waveguides in wave optics
- Description of optical waveguides using the solution of the differential wave equation
- Description of optical waveguides using integral wave equations (Kuhlevsky model)
- Description of optical waveguides by direct solution of the Faraday and Ampere equations
- TE and TM modes of waveguides. Linearly polarized (LP) modes: TE, TM, hybrid EH and hybrid HE modes.
- General model of distortion caused by group velocity dispersion of a wave packet (light pulse)
- Four types (mechanisms) of delay time dispersion: Multi-mode dispersion Polarization dispersion. Material dispersion. Waveguide dispersion.
- Continuous index waveguides. Plasma-based waveguides. TE, TM, hybrid EH and hybrid HE modes
- Delay time caused by dispersion characteristics of continuous index fibers. Multi-mode dispersion. Relationship between dispersion and transmission capacity. Examples: Multi-mode and single-mode waveguides.
- Applications of waveguides.

Recommended reading:

Kuhlevszkij Szergej (S.V. Kukhlevsky), "Waveguide Optics (online lectures)" PTE TTK, Institute of Physics, 2025

K. Okamoto, Fundamentals of Optical Waveguides (Optics and Photonics Series, Academic Press (1995)

B.E.A. Saleh, M.C. Teich, Fundamentals of Photonics, Wiley-Interscience (1991)

A. Yariv, Quantum Electronics, John Wiley, New York (1988)

J.D. Jackson, Classical Electrodynamics (Wiley, New York, 1999)

S. V. Kuhlevsky, "Optical waveguide fields as free-space waves," Europhysics Letters, 54, 461 (2001)

3.3.7 Optical spectroscopy (János Hebling)

A brief history of spectroscopy
The most important parameters of spectroscopic instruments
Basic relationships of the Fourier transform
Convolution, cross-correlation and autocorrelation, energy spectrum, power spectrum
Description of linear, shift-invariant systems. Impulse response function. Transfer function.
Diffraction. Fundamentals of Fourier optics.
Spectroscopic instruments with angular dispersion
Interferometers
Fourier transform spectrometers
Multilayer dielectric coatings. Spectroscopic instruments based on double refraction.
General theory of spectroscopic instruments
Detector types, detector characteristics

Recommended reading:

F. A. Jenkins, and H. E White: "Fundamentals of optics" (McGraw-Hill, 1976)

W. Demtröder: "Laser Spectroscopy: Basic Concepts" (Springer, Berlin, Heidelberg, New York, 2008)

J. Hebling, and Zs. Márton: Theory of spectroscopic devices" JOSA A 23, 966-972 (2006)

3.3.8 Laser Physics (János Hebling)

- Introduction. Properties of lasers, their structure, basic principles of operation, main types.
- Photon-matter interaction.
- Laser amplifiers.
- Matrix optics. Resonators.
- Gaussian beam.
- Generation of short laser pulses 1. Relaxation oscillation. Long-cavity laser.
- Generation of short laser pulses 2. Q-switched lasers. Mode synchronization.
- Nonlinear optics.

- Free-electron lasers.
- Applications of lasers.

Recommended reading:
J.T. Verdeyen: Laser Electronics, Prentice-Hall Inc. ISBN: 0-13-706666-X
K.F- Renk: Basics of Laser Physics, Springer, ISBN: 978-3-642-23564-1

3.3.9 Introduction to Terahertz Science and Technology (János Hebling)

- Introduction
- Continuous terahertz (THz) sources
- THz detectors. Terahertz imaging. Security, medical and other applications
- Single-cycle (broadband) THz pulse sources I. Photoconductive antenna.
- Temporal measurement of THz fields with photoconductive antennas. Time-domain THz spectroscopy (TDTS).
- Single-cycle (broadband) THz pulse sources II. Optical alignment. Electro-optical sampling.
- Velocity matching with pulse front detection.
- Single-cycle (broadband) THz pulse sources III. Laser-induced gas plasma.
- THz optics: focusing lenses and mirrors, polarizers, etc. Dielectric properties of materials in the THz range.
- High-intensity THz science and technology. Nonlinear THz optics. Nonlinear THz spectroscopy. Keldysh parameter. Other applications of high-intensity THz pulses.
- Generation and application of THz pulses with extremely high energy and field strength.
- THz spectroscopy of solids.
- THz spectroscopy of liquids.

Recommended reading:
Yun-Shik Li, Principles of Terahertz Science and Technology, Springer, New York, ISBN: 978-0-387-09539-4 978-0-387-09540-0

3.3.10 Physics of ultrashort light pulses (György Tóth)

- Overview of the subject. Description of ultrashort pulses.
- Propagation of ultrashort pulses in dispersive media, propagation of Gaussian pulses.
- Dispersion properties of optical elements (dielectrics, gases, optical fibers, dispersion of interferometric structures: Fabry-Perot, Gires-Tournois interferometers, chirped mirrors)
- Dispersion properties of optical elements (slits, prisms, gratings, pulse compressors, lenses). Propagation of light in anisotropic media
- Angular dispersion and its effects: pulse front deflection, spatial chirping
- Ultra-short pulse lasers

Recommended reading:
W. Kaiser: Ultrashort Laser Pulses and Applications (Topics in Applied Physics, 1988)
Jean-Claude Diels: Ultrashort Laser Pulse Phenomena, Academic Press, 2006.
B. E. Saleh, M. C. Teich: Fundamentals of Photonics. Wiley&Sons, 1991.
R. D. Guenther, Modern Optics, Wiley&Sons, 1990

3.3.11 Nonlinear Optics (György Tóth)

- Nonlinear susceptibility
- Nonlinear wave equation.
- Sum-difference frequency and second harmonic generation.
- Phase matching. Quasi-phase matching.
- Parametric amplification. Optical parametric amplifiers and oscillators.
- Optical rectification

- Nonlinear refractive index: self-phase modulation, self-focusing. Measurement of nonlinear refractive index using the z-scan method.
- Measurement of ultrashort pulses: autocorrelation, FROG, GRENOUILLE, SPIDER.
- Modeling nonlinear optical processes.

Recommended reading:
Jean-Claude Diels: Ultrashort Laser Pulse Phenomena, Academic Press, 2006.
Robert W. Boyd: Nonlinear Optics, Academic Press, 2003.
R. D. Guenther, Modern Optics, Wiley&Sons, 1990
R. Trebino: Frequency-Resolved Optical Gating: The Measurement of Ultrashort Laser Pulses
R. L. Sutherland: Handbook of nonlinear optics (New York: Marcel Dekker, 2003)

3.3.12 Free electron lasers (Zoltán Tibai)

- Types of free electron lasers
- Undulators and wobblers
- Free electron lasers with pulse repetition frequency modulation
- X-ray free electron lasers
- Inverse free electron lasers
- Carrier-envelope phase-controlled attosecond pulse generation
- Presentation of software used for free electron lasers
- Electron manipulation using numerical software
- General Particle Tracer, Elegant, CSRTrack, Genesis

Recommended reading:
Peter Schmüser, Martin Dohlus, Jörg Rossbach: Ultraviolet and Soft X-Ray Free-Electron Lasers, Springer, ISBN 978-3-540-79571-1

3.3.13 Physics and Applications of Electric Gas Discharges (Péter Hartmann)

- Natural and technological plasmas.
- Thermal and non-equilibrium plasmas. Fundamentals of plasma physics.
- Transport of charged particles in gases. Collision cross sections.
- Kinematics of two-particle collisions.
- Transport equations: Boltzmann equation. Derivation of fluid equations.
- Monte Carlo particle simulation method. Determination and relaxation of the velocity distribution function in a homogeneous electric field.
- Phenomena in direct current gas discharges: breakdown, self-sustaining processes, modes of operation, structure.
- Operation and technological relevance of capacitively coupled radio frequency gas discharges.
- Plasma diagnostics: electrical probes, optical spectroscopy.
- Strongly coupled plasmas / Powder plasmas.
- Applications of low-temperature plasmas.

Recommended reading:
Iván Abonyi: "The Fourth State of Matter, Introduction to Plasma Physics" (Gondolat, Budapest, 1971)
Alexander Piel: "Plasma Physics: An Introduction to Laboratory, Space, and Fusion Plasmas" (Springer, 2017)
N St J Braithwaite: "Introduction to Gas Discharges" (Plasma Sources Sci. Technol. 9 (2000) 517–527, https://home.sandiego.edu/~severn/intro_gas_discharges.pdf)

3.3.14 High-intensity laser-atom interactions (Márk Aladi)

- Generation of high-intensity laser light
- Properties of ultrashort laser pulses
- Generation of attosecond pulses and their applications

- Construction of optical and optomechanical systems
- Construction of vacuum systems
- Fundamentals of plasma physics
- Detection of charged and neutral particles
- Particle acceleration with lasers, applications
- Laser-induced nuclear reactions, applications
- "Exotic" processes in extremely high electric and magnetic fields

Recommended reading:
B. E. A. Saleh and M. C Teich: FUNDAMENTALS OF PHOTONICS (2019 by John Wiley & Sons, Inc.)
Shalom Eliezer: The Interaction of High-Power Lasers with Plasmas (IOP Publishing Ltd 2002)
Leonida Antonio Gizzi, Ralph Assmann, Petra Koester, Antonio Giulietti: Laser-Driven Sources of High Energy Particles and Radiation (Springer Nature Switzerland AG 2019)

3.3.15 Classical and Nonlinear Vibrational Spectroscopy (Miklós Veres)

- Molecular vibrations, normal vibrations, group theory
- Fundamentals of vibration spectroscopy
- Raman scattering and Raman spectroscopy (measurement principle, instruments, data processing)
- Surface-enhanced Raman scattering (SERS)
- Infrared spectroscopy (measurement principle, instruments, data processing)
- Nonlinear vibration spectroscopy (stimulated Raman scattering (SRS), coherent anti-Stokes Raman scattering (CARS))
- Vibrational imaging using SRS and CARS methods
- Time-resolved techniques
- Photothermal infrared spectroscopy

Recommended reading:
D. N. Sathyanarayana: "Vibrational Spectroscopy: Theory and Applications" (New Age International, 2004)
J. M. Chalmers, P. R. Griffiths (Editors): "Handbook of Vibrational Spectroscopy" (John Wiley and Sons, 2006)
E. Smith, G. Dent: "Modern Raman Spectroscopy: A Practical Approach" (John Wiley and Sons, 2019)
J.-X. Cheng, W. Min, Y. Ozeki, D. Polli (Editors): Stimulated Raman Scattering Microscopy: Techniques and Applications (Elsevier, 2022)

3.3.16 Laboratory practice: Laser measurements (Gyula Polónyi)

- Work safety, preparation and planning of experiments, report writing, basic evaluation, necessary Matlab skills
- performance measurement, spectrum measurement, measurement with photodiode and digital oscilloscope, beam profile measurement with CCD camera
- reading and evaluating measured data using Matlab
- Measurement control and automation using Matlab
- Application of acquired knowledge in more complex experiments: Determination of the orientation of zinc blende-type semiconductors using second harmonic generation

Recommended reading:
Yun-Shik Li, Principles of Terahertz Science and Technology, Springer, New York, ISBN: 978-0-387-09539-4 978-0-387-09540-0

3.3.17 Laboratory exercise: Characterization of ultrashort pulse laser beams (Gergő Krizsán)

- Overview of measurement methods
- spectrum measurement with a spectrometer
- pulse length measurement with an autocorrelator and FROG

- Determination of beam size using the knife-edge measurement method
- measurement of transverse intensity distribution with a CCD camera
- measurement of the M2 parameter of the beam

Recommended reading:
Rullière, Claude (Ed.). Femtosecond Laser Pulses: Principles and Experiments. Springer, 2005.
2. Diels, Jean-Claude, and Wolfgang Rudolph. Ultrashort Laser Pulse Phenomena. Academic Press, 2006.
3. Trebino, R. Frequency-Resolved Optical Gating: The Measurement of Ultrashort Laser Pulses. Springer, 2002.
4. Siegman, A.E. Lasers. University Science Books, 1986.

3.3.18 Laboratory exercise: Construction, optimization, and characterization of terahertz pulse sources (Gergő Krizsán)

- Semiconductor-based sources
- Source construction with collinear and tilted pulse front pumping
- Determination of terahertz energy as a function of the pulse front tilt angle
- Measurement of generated terahertz energy and generation efficiency as a function of pump energy and intensity
- Measurement of the electric field strength of generated terahertz pulses by electro-optical sampling
- Lithium niobate-based source:
- Construction of conventional and microstructured sources pumped with a tapered pulse front
- Determination of terahertz energy as a function of the pulse front angle of inclination
- Measurement of generated terahertz energy and generation efficiency as a function of pumping energy and intensity
- Measurement of the electric field strength of generated terahertz pulses by electro-optical sampling
- Comparison of the parameters of terahertz pulses generated by the sources.

Recommended reading:
1. Y. S. Lee (2009). Principles of terahertz science and technology (Vol. 170). Springer Science & Business Media.
2. J. A. Fülöp, S. Tzortzakis and T. Kampfrath (2020). Laser-driven strong-field terahertz sources. Advanced Optical Materials, 8(3), 1900681.

3.3.19 From femtosecond lasers to attophysics (Péter Dombi)

- Introduction to nonlinear optics
- Laser pulse generation, mode-locking in the time and frequency domains.
- Mode-locking and its basic methods (active vs. passive). Kerr-lens mode-locking.
- Broadband laser materials and mode-synchronized lasers. Oscillator architecture, dispersion compensation, chirped mirrors.
- Amplification of femtosecond pulses. Regenerative and multi-path amplifiers, phase-modulated pulse amplification (chirped pulse amplification, CPA). Optical parametric amplification.
- Mode-synchronized oscillators as frequency combs, the concept of carrier-envelope phase. Laser frequency metrology.
- Other applications of femtosecond lasers: femtochemistry, coherent control, material processing, spectroscopy.
- The attosecond time domain, typical electron processes.
- Generation of high-order harmonics.
- Generation of attosecond pulse trains and single pulses, phase of harmonics, and its measurement.
- Attosecond metrology and spectroscopy

Recommended reading:

R. L. Sutherland: "Handbook of Nonlinear Optics" (New York: Marcel Dekker, 1996)
R. Guenther: "Modern Optics" (John Wiley and Sons, 1990)

3.3.20 Fourier analysis and its application in signal processing and physics (László Tóth)

- Fourier series and Fourier transform
- Fourier series: series expansion of periodic functions using orthogonal trigonometric basis functions.
- Fourier coefficients and convergence issues (Dirichlet and Fejér theorems).
- Fourier transform: determination of the frequency spectrum of non-periodic signals.
- Discrete Fourier transform (DFT) and fast Fourier transform (FFT)
- Sampling theorem (Shannon-Nyquist theorem).
- Spectral analysis of DFT and periodic signals.
- FFT algorithm and its efficiency in numerical calculations.
- Application of Fourier analysis in physics and signal processing.

Recommended reading:
Elias M. Stein and Rami Shakarchi – Fourier Analysis: An Introduction
Publisher: Princeton University Press, 2003.
Ronald N. Bracewell – The Fourier Transform and Its Applications
Publisher: McGraw-Hill Science/Engineering/Math, 1999.
Gerald B. Folland – Fourier Analysis and Its Applications
Publisher: American Mathematical Society, 1992.
M. D. Adams, Lecture Slides for Continuous-Time Signals and Systems (Ver-
2013-09-11), University of Victoria, Victoria, BC, Canada, Dec. 2013,
286 slides, ISBN 978-1-55058-517-9 (paperback), ISBN 978-1-55058-518-6
https://www.ece.uvic.ca/~frodo/sigsysbook/downloads/lecture_slides_for_continuous_time_signals_and_systems-2013-09-11-uvic-v2.pdf
Ferenc Schipp, Fourier Analysis, University Lecture Notes, ELTE, BUDAPEST, 2006S
The notes are from MKM 367/94, https://numanal-old.inf.elte.hu/~schipp/FourierAnal/Fourier_Anal.pdf

3.3.21 Ultrafast optics and laser oscillators. Confocal and nonlinear 3D microscopy. (Róbert Szipőcs)

- Ultrafast optics: the concept of dispersion, basic phenomena and fundamental relationships. Description of ultrafast laser pulses in the time and frequency domains.
- Ultrafast optics (achromatic lenses, prisms, gratings) and ultrafast optical coatings.
- Propagation of ultrafast pulses in optical fibers, the split-step Fourier method.
- The relationship between group delay and stored energy in 1D and 2D dielectric structures.
- Design of dispersion-compensating optical fibers. The finite element method (FEM).
- Photonic crystal optical fibers, optical fiber transmission systems for ultrafast lasers.
- Ultrafast solid-state lasers (main types, structure and operation).
- Ultrafast optical lasers (main types, structure and operation).
- Ultrafast optical parametric oscillators (OPO).
- Confocal and nonlinear (2P, SHG, CARS, etc.) 3D microscopes: structure and operation.
- Some typical applications of nonlinear microscopes in brain research, dermatology, and pharmacology.
- Structure of fluorescence lifetime imaging (FLIM) systems and some of their most important applications in the life sciences.

Recommended reading:
U. Keller: Ultrafast Lasers (Springer Nature, 2021)
H.A.Macleod: Thin Film Optical Filters (Taylor&Francis, 2001)
G.P. Agrawal: Nonlinear Fiber Optics (Academic Press, 2001)
A. Diaspro: Confocal and two-photon microscopy (Wiley-Liss, 2002)

3.4 Scholar-teacher training programme

3.4.1 Use of optical design programs in education (Szabolcs Turnár)

- Introduction to the user interfaces of TracePro and GeoGebra
- Object definition and editing
- Properties of surfaces and optical media, Boolean operations
- Elements of matrix optics, theoretical foundations
- Ray tracing (simulation of simple and complex optical paths, error checking, tracking accuracy adjustment)
- Refraction and reflection from flat and curved surfaces, multiple reflections and scattering
- Lenses and lens errors
- Light propagation in media with a variable (gradient) refractive index
- Resonator modelling
- Caustics
- Overview of other optical design programs (OSLO, Beam4, Zemax)

Recommended reading:
https://lambdares.com/hubfs/TracePro_User_Manual.pdf
Warren J. Smith: "Modern Optical Engineering – The Design of Optical Systems" (McGraw-Hill, 4th ed., 2007)
J. E. Greivenkamp: "Field Guide to Geometrical Optics" (SPIE Press, 2004)

3.4.2 The history of physics education in Hungary and worldwide (László Pálfalvi)

- The development of physics education in Hungary and worldwide over the past 50 years
- Major centers and workshops of physics education in Hungary over the past 50 years
- The popularization of physics in the past and today, the role of associations, the media
- The development of the admission system
- Famous Hungarian experimenters and methodological innovators
- Modernization of physics teaching
- Physics competitions and the development of talent management in Hungary and worldwide
- The impact of curriculum changes and education policy decisions: the effects of the National Core Curricula (1995, 2003, 2020) on physics education
- Practical challenges

Recommended reading:
P. Tibor: The history of physics education in Hungary in the 20th and 21st centuries (Budapest: Akadémiai Kiadó, 2020)
B. Varga: József Öveges and the renewal of physics education in Hungary (Typotex, Budapest, 2018)
Sas Elemér: Physics in school and on screen (Műszaki Könyvkiadó, 1995)

3.4.3 Analogies in Physics (László Pálfalvi)

- The role of analogies in thinking and problem solving
- Conceptual and structural analogies in physics
- Analogies used in mathematical descriptions
- Analogies between translational motion and rotation around an axis
- Analogies in harmonic oscillations (optics, electromagnetism)
- Damped and forced vibrations and analogies (electromagnetism)
- Analogies to Fermat's principle
- Radioactive decay and analogies
- Analogies between electrostatic and gravitational fields
- Analogies between medium resistance forces proportional to speed and its various powers and linear and multiphoton absorption
- The anharmonicity of the pendulum and nonlinear optics
- The Schrödinger equation and paraxial Gaussian beams

Recommended reading:
G. B. Arfken, H. J. Weber, Mathematical Methods for Physicists, 7th Edition, Academic Press, 2013.
D. Halliday, R. Resnick, J. Walker, Fundamentals of Physics, 10th Edition, Wiley, 2013.
Feynman, R. P., The Feynman Lectures on Physics, Volume 1-3, Basic Books, 2011.

3.4.4 Teaching Physics I. (László Pálfalvi)

- The central role of physics in shaping scientific literacy and thinking; physics as an integrating discipline in STEM education.
- Pedagogical foundations of physics teaching: learning theory background, teacher roles, motivational and activating strategies in physics lessons.
- The structure and construction of the conceptual system of physics: precise definitions of key concepts (e.g., mass, force, energy, temperature) and difficulties in learning them.
- Inductive and deductive thinking in the transmission of physical knowledge; logical models of knowledge construction in teaching.
- Methodology of illustration in the 21st century: digital visualization, simulations, and the role of interactive demonstrations in understanding.
- Mathematics as the language of physics: teaching mathematical formalism and the difficulties this poses for students.
- The inclusion of the axiomatic and structural approach in public education content: when, how, and to what depth?

Recommended reading:
Arons, A. B. (1997). Teaching Introductory Physics. Wiley.
Fűzfa Balázs (2019): The pedagogy of teaching physics. ELTE Eötvös Publishing House.
Duit, R., & Treagust, D. F. (2003). Conceptual change: A powerful framework for improving science teaching and learning. International Journal of Science Education, 25(6), 671–688.

3.4.5 Teaching Physics II. (László Pálfalvi)

- The characteristics of physics as a subject: complexity, abstractness, layers of representation. Selecting and adapting teaching strategies for different groups of learners.
- Conservation laws as systemic organizing principles of physical thinking: conservation of momentum, energy, and charge, and methodological principles for teaching them.
- Particularly difficult and abstract concepts: inertial systems, waves, the second law of thermodynamics, entropy, special theory of relativity – didactic challenges and management strategies.
- Dealing with student misconceptions and alternative concepts: research results and intervention options.
- The language and representational repertoire of physics: graphical representation, mathematical symbols, use of analogies and metaphors in education.
- The role of the history and philosophy of science in physics education: strengthening context and reflectivity.
- Modern assessment methods: formative assessment, alternative assessment, conceptual diagnostics, portfolios.
- International trends and frameworks (e.g., IB, NGSS) – lessons for domestic practice.
- Opportunities for teacher development at doctoral level: curriculum development, teaching experiments, utilization of educational research results.
- Teaching physics in digital and multimodal learning environments.

Recommended reading:
Knight, R. D. (2004). Five Easy Lessons: Strategies for Successful Physics Teaching. Addison-Wesley.
Varga Péter (ed.) (2020): Physics Education in the 21st Century – Theories, Trends, Practices. Typotex.
McDermott, L. C., & Redish, E. F. (1999). Resource Letter: PER-1: Physics Education Research. American Journal of Physics, 67(9), 755–767.

3.4.6 Physics competitions and talent development (László Pálfalvi)

- The concept of talent, its components, and possibilities for development
- Organizational framework for talent development, talent development workshops
- Talent development from primary school to university
- Domestic physics competitions in the past and today (from regional to the most prestigious)
- Organizations behind the competitions
- The Secondary School Mathematics Journal
- The International Physics Olympiad and its history
- International physics competitions, contests and talent development around the world
- The European Physics Olympiad
- Student Olympiad preparation clubs, selection competitions
- Measurement at competitions

Recommended reading:
http://www.leoweypecs.hu/mikola/fordulok.html
http://eik.bme.hu/~vanko/fizika/eotvos.htm
http://eik.bme.hu/~vanko/fizika/ipho.htm

3.4.7 Problem-based physics teaching (László Pálfalvi)

- The theory and models of problem solving
- The didactic role of tasks in physics education
- The use of mathematical tools in solving physics problems
- Dimensional analysis
- Creative thinking and intuition in solving physics problems
- Problems based on analogies
- Special techniques in problem solving (coordinate transformations, symmetry principles, decomposition into elements, conformal mapping)
- Real-life problems
- The role of simulations and numerical models in problem solving
- Cooperative problem solving
- Problem solving and scientific reasoning

Recommended reading:
Polya, G. (1945). How to Solve It: A New Aspect of Mathematical Method. Princeton University Press.
Heller, P., Keith, R., & Anderson, S. (1992). "Teaching problem solving through cooperative grouping. Part 1: Group versus individual problem solving." American Journal of Physics, 60(7), 627-636.
Radnóti K. (2014). Thought-provoking tasks in physics teaching. ELTE Eötvös Publishing House.

3.4.8 Action-centered physics teaching I. (Schnider Dorottya)

- Action-centered physics education – general pedagogical and methodological foundations
- Action-oriented talent development (IYPT, data analysis competition, etc.)
- Competence-developing physics teaching
- Thought-provoking theoretical and playful physics tasks
- Physics escape rooms
- Project-based physics education
- Flipped classroom
- Assessment and evaluation – science operators

Recommended reading
Schnider, D. (2022). Varied work forms, playful tasks that develop thinking in physics lessons. Új Pedagógiai Szemle. 72(9-10), 98-115.
Schnider, D. and Hömöstrei, M. (2021). Competence-based physics teaching. Fizikai Szemle. 71(12), 421-429.

Hunya, M. (2009). Project-based learning in the 21st century I. New Pedagogical Review, no. 11, 75-96.
Larmer, J. & Mergendoller, J. R. (2010). The Main Course, Not Dessert. How Are Students Reaching 21st Century Goals? With 21st Century Project Based Learning. Buck Institute for Education. https://files.ascd.org/pdfs/onlinelearning/webinars/webinar-handout1-10-8-2012.pdf
Faletic, S. et al. (2021). YPT Toolkit – A guide for implementing YPT-inspired activities in class and prepare teams for YPT competitions. https://fiztan.phd.elte.hu/files/kiadvanyok/Projektfeladatok.pdf

3.4.9 Action-oriented physics teaching II. (Mihály Hömöstrei)

- Student measurements, methods of cognition, data analysis and evaluation
- Images and videos in physics lessons. Image and video analysis tasks
- Sound analysis
- Use of simulations in concept formation and practice (Phet, Vascak, etc.)
- Smartphones in physics lessons (from student videos to Phyphox)
- Differential equations in Excel
- Python
- Competence development with Arduino

Recommended reading

Schnider, D. and Hömöstrei, M. (2021). Competence development in physics teaching. Fizikai Szemle. 71(12), 421-429.
Schnider, D. & Hömöstrei, M. (2024). Arduino-supported kinematics measurements. Physics Education. 59(5). https://doi.org/10.1088/1361-6552/ad672a
Banda, H. J. & Nzabahimana, J. (2021). Effect of integrating physics education technology simulations on students' conceptual understanding in physics: A review of literature. Physical Review Physics Education Research. DOI: 10.1103/PhysRevPhysEducRes.17.023108
Carroll, R. & Lincoln, J. (2020). Phyphox app in the physics classroom. Phys. Teach. 58. https://doi.org/10.1119/10.0002393
Fauzi, A. (2017). Integrating numerical computation into the undergraduate education physics curriculum using spreadsheet excel. J. Phys.: Conf. Ser. DOI 10.1088/1742-6596/909/1/012056
Srnec, M. N., Upadhyay, S., & Madura, J. D. (2017). A Python Program for Solving Schrödinger's Equation in Undergraduate Physical Chemistry. Journal of Chemical Education. 94(6). https://pubs.acs.org/doi/10.1021/acs.jchemed.7b00003

3.4.10 Differential Equations and Their Applications in Physics (Margit Pap)

- Introduction to differential equations: Simple differential equations and physical examples. Linear and PTE Quality Policy references: nonlinear differential equations Initial and boundary value problems.
- First, second, and higher order differential equations.
- Linear differential equation systems.
- Eigenvalue problems and operators
- Partial differential equations (PDEs)
- Special functions and transformation methods for solving differential equations
- Physical applications and numerical methods

Recommended reading

Boyce, W. E., DiPrima, R. C.: Elementary Differential Equations and Boundary Value Problems, Wiley, 2017.
Strauss, W. A.: Partial Differential Equations: An Introduction, Cambridge University Press, 2008.
Arfken, G. B., Weber, H. J.: Mathematical Methods for Physicists, Elsevier, 2012.
Eisner Tímea, Differential Equations, Lecture Notes, University of Pécs, 2011
https://tamop412a.ttk.pte.hu/files/diffegyenletek_vegleges_2011_06_28.pdf
D. Curran, A. Sövegjártó, L. Szili and M. Vicsek , Numerical Solutions of Ordinary Differential Equations, (Initial Value Problems)
1997, 167 pages https://numanal-old.inf.elte.hu/~szili/Okt_anyag/Num_Sol_ODE.pdf

3.4.11 Probability Theory and Statistical Analysis and Their Applications in Physics (Zsolt Hetesi)

- Fundamentals of probability theory. Different types of probability distributions (normal, Poisson, binomial, etc.). Conditional probabilities, Bayes' theorem and its applications.
- Statistical methods Descriptive statistics: mean, standard deviation, variance, correlation. Sampling, dispersion, and confidence intervals.
- Estimation: point estimation, interval estimation. Hypothesis testing: null hypothesis and alternative hypothesis, p-value, statistical significance.
- Statistical modeling in physics Least squares method and its application to modeling physical experimental data. Application of Monte Carlo simulations in physical systems. Stochastic processes and their application in physical and quantum mechanical systems.
- Applications in physics

Recommended reading:

Keller, E. L., & Roberts, T. W. (2013). Statistics for Physicists. Springer.
Rice, J. A. (2007). Mathematical Statistics and Data Analysis (3rd ed.). Duxbury Press.
Bovenschen, T. F. (2014). Principles of Statistical Physics. Springer.
Schulz, W. (2020). Statistical Methods in Quantum Physics. Springer.