Course Work: Doctoral Programmes in Physics at IMSc

There are two streams leading to the Doctoral degree in Physics at IMSc: PhD stream for students who join after finishing their masters degree and integrated PhD stream for students who join after finishing their Bachelor's degree. . The course work for the PhD program is for two semesters [**Semester III** & **IV** in **Table 1**] while that for the integrated PhD is for four semesters [**Semester I-IV** in **Table 1**]. Students in the integrated Ph.D. and Ph.D. programs earn **123 credits** and **60 credits** respectively at the end of the coursework completion.

Table 1:

Semester I [30 Credits] (11) Classical Mechanics **[9]** (12) Quantum Mechanics I **[9]** (13) Electromagnetic Theory **[6]** (14) Mathematical Methods I **[6]**	**Semester II [33 Credits]** (21) Quantum Mechanics II **[9]** (22) Computational Physics **[6]** (23) Condensed Matter Physics I **[9]** (24) Statistical Mechanics I **[9]**
Semester III [30 Credits] (31) Quantum Field Theory I **[9]** (32) Mathematical Methods II **[6]** (33) Statistical Mechanics II (**9**) (34) Particle Physics I **[6]**	**Semester IV [30 Credits]** Project **[12]** Two Electives **[9+9]**: (41) Quantum Field Theory II **[9]** (42a) Cosmology and Gravitation **[9]** (42b) Particle Physics II **[9]** (43) Advanced Condensed Matter Physics **[9]** (44a) Nonlinear Dynamics **[9]** (44b) Quantum Information and Computation **[9]** (44c) Statistical Field Theory **[9]** (45) Computational Physics **[6+3]** (same as 22)

Detailed syllabus

(11) Classical Mechanics (4.5 hours class work per week, 9 credits)

- **Lagrangian formulation and the action principle:**
  Configuration space, generalized coordinates Constrained systems, holonomic constraints as coordinate transformations, motion in a central field, including Kepler problem, Rutherford scattering, Small oscillations, normal modes, total time derivatives, non-uniqueness of Lagrangian, Noether's theorem, Conservation laws;
- **Rigid body kinematics and dynamics:**
  Kinematics, rotational kinetic energy, moments of inertia, inertia tensor, Euler angles, angular momentum, Free rigid body motion, axisymmetric tops;
- **Hamiltonian formulation:**
  The Legendre transformation, canonical momentum Poisson brackets, Phase space reduction, cyclic coordinates, Phase space description and evolution, surfaces of section, periodically driven systems, Liouville's theorem, Poincare recurrence;

- **Canonical transformations, Hamilton-Jacobi theory, perturbation theory:**
  Definition; point transformations; time-independent transformations; symplectic transformations and time-dependent transformations, Invariants of canonical transformations, Generating functions Hamilton-Jacobi equation, action-angle variables, Perturbation theory as a sequence of canonical transformations of a perturbed integrable system;
- **Relativistic mechanics (including Lagrangian formulation):**
  Space-time, 4-vectors, Lorentz transformations, basic relativistic kinematics and dynamics.

Textbooks:

1. L. Landau and E. Lifshitz, Mechanics : Course of Theoretical Physics, Vol.1, Pergamon, 1974.
2. W. D. McComb, Dynamics and Relativity, Oxford University Press, 1999.
3. V. I. Arnold, Mathematical Theory of Classical Mechanics, Springer, 1977.
4. M. Tabor, Chaos and Integrability in Nonlinear Dynamics, Wiley, 1989.
5. H. Goldstein, Classical Mechanics, Narosa, 1990.
6. I. Percival and D. Richards, Introduction to Dynamics, Cambridge, 1991
7. J.V. Jose and E.J. Saletan, Classical dynamics: A contemporary approach, Cambridge, 1998.

(12) Quantum Mechanics I: (4.5 hours class work per week, 9 credits)

- **Fundamentals of Quantum Theory:**
  The breakdown of classical physics, the polarization of photons, Wave-particle duality: Particle properties of photons and wave properties of electrons, Schrodinger evolution, Hamiltonian, examples: free particle, one-dimensional potential well, potential barrier, harmonic oscillator, etc., Hilbert space formulation of Quantum Mechanics: states, observables, measurement, evolution, the collapse of the wave function, uncertainty relation and its interpretation, Discrete and continuous spectra, canonically conjugate observables, Schrodinger, Heisenberg and interaction pictures, Virial theorem, Ehrenfest's theorem, semi-classical quantization;
- **Theory of spin-1/2 systems:**
  Stern-Gerlach experiment for the existence of spin Quantum Mechanics of two-level systems
- **Spherically symmetric potentials:**
  Schrodinger equation for spherically symmetric potentials, Orbital angular momentum and spherical harmonics, Hydrogen atom problem and three-dimensional harmonic oscillators;
- **Symmetries and conservation laws:**
  What is symmetry, Wigner's theorem, Continuous transformations, Rotation, Euclidean and Galilean groups, Transformations and invariances;

- **Angular momentum theory in Quantum Mechanics:**
  Orbital and spin angular momenta, Raising and lowering operators, Addition of angular momenta, Clebsch-Gordon coefficients, Schwinger oscillator model, Spherical tensors and Wigner- Eckart Theorem, Spin-orbit coupling
- **Exactly solvable models:**
  Charged particle in a magnetic field, Landau levels, Quantum Hall effect;
- **Time-independent perturbation theory:**
  Non-degenerate and degenerate cases, An-harmonic oscillator, Van der Waal's force, Dipole interactions for spin-1/2 systems, Stark effect, Zeemann effect;
- **Time-dependent perturbation theory:**
  Approximate solution of Schrodinger equation, Sinusoidal perturbation of two-level system: resonance phenomenon, Coupling with states of continuous spectrum, Fermi's golden rule, Interaction of atom with electromagnetic wave

Textbooks:

1. C. Cohen-Tannoudji, B. Diu and F. Laloe, Quantum Mechanics, Vols. I and II, Wiley, 1970.
2. J. J. Sakurai, Modern Quantum Mechanics, Addisson Wesley, 1995.
3. Leslie E. Ballentine, Quantum Mechanics: A Modern Development, World Scientific, 1998.

(13) Classical Electromagnetism: (3 hours class work per week, 6 credits)

- **Electrostatics and Magneto-statics:**
  Mathematical preliminaries, boundary value problems using Green function techniques, special techniques for calculating potentials, electrostatics of dielectric media, magnetic vector potential and the gauge problem, Biot-Savart law, magnetic dipole moment and the Larmor precession, magnetic susceptibility and permeability, ferromagnetism;
- **Maxwell Electrodynamics:**
  Motion of charges in external fields, electromagnetic waves in vacua and propagation through continuous media, gauge transformations, Lorentz covariant formulation of electrodynamics, energy-momentum of electromagnetic field and Poynting's theorem, Lagrangian and Hamiltonian formulation of electrodynamics;
- **Radiation Theory:**
  Advanced and retarded Green functions, Lienard-Wiechert potentials, dipole radiation and Larmor's formula, spectral resolution and angular distribution of radiation from a relativistic point charge, synchrotron radiation, Rayleigh and Thomson scattering;
- **Classical Electron Theory:**
  Radiation reaction, acausality and preacceleration, incompleteness of Maxwell electrodynamics;

Textbooks:

1. D. J. Griffiths, Introduction to Electrodynamics, Prentice Hall, 1981.
2. L. Landau and E. Lifshitz, The Classical Theory of Fields, Pergamon, 1979.
3. J. D. Jackson, Classical Electrodynamics, Wiley Eastern, 1986.

(14) Mathematical Methods I (3 hours class work per week, 6 credits)

- **Linear Algebra:**

  Linear Vector spaces, Determinants & Matrices, Special matrices: orthogonal, hermitian, unitary, Eigenvalue problem: matrix diagonalization, Canonical Forms, Infinite-dimensional vector spaces: Hilbert space & Hermitian operators, Numerical solution of linear equations;

- **Complex Analysis:**

  Complex algebra, analytic functions, infinite sequences and series, tests of convergence, Weier- strass theorem, Taylor and Laurent series, classification of isolated singularities, poles & cal- culus of residues, contour integration, residue theorem and applications;

- **Differential and Integral Equations:**

  Ordinary differential equations, linear differential equations up to second order, orthogonal polynomials and functions, Integral transforms: Laplace and Fourier transforms, partial differ- ential equations, classification of PDEs, Laplace and wave equations, boundary value problems, Special functions, Integral equations and Green functions, Ideas about nonlinear equations, Approximation methods: WKB approximation (at the level of Mathews-Walker);

Textbooks:

1. J Mathews and R L Walker, Mathematical Methods for Physicists, Benjamin, 1964
2. G Arfken, Mathematical Methods for Physicists, Academic Press, 1995.

(21) Quantum Mechanics II (4.5 hours class work per week, 9 credits)

- **Quantum theory of identical particles:**

  Symmetrization of wave functions, Pauli's exclusion principle, Bosons and fermions, Spin- statistics theorem, Second quantization formalism, Quantum theory of many-electron atoms, Electron gas: application to solids;

- **Approximation methods:**

  WKB approximation, Variational methods, Absorption and stimulated emission of radiation;

- **Scattering theory:**

  Lipmann-Schwinger equation, Born approximation, Partial waves, The optical theorem, Determination of phase-shifts, Hard sphere scattering, Low energy scattering, Resonances;

- **Path integral approach to Quantum Mechanics:**

  Kernel of wave-packet evolution, Feynmann's approach, Examples of free particle and harmonic oscillator, Path-integral approach to spin systems, Aharonov-Bohm effect, The adiabatic theorem, Berry's phase;

- **Relativistic Quantum Mechanics:**

  Dirac and Klein-Gordon equations and their solutions, Relativistic invariance, Space reflection and time reversal, Idea of spin, Helicity, Hydrogen atom, fine structure of spectral lines;

- **Phase-space description of Quantum Mechanics:**
  Coherent states, squeezed states and thermal states, Wigner's phase-space quasi-probability distribution, Glauber-Sudarshan's P-representation, Husimi distribution, Symplectic transformation and covariance matrix, Non-classical states of light;
- **Foundations of Quantum Mechanics:**
  Density operators formalism, Contradiction of Quantum Theory with local realism, The causality issue.

Textbooks:

1. C. Cohen-Tannoudji, B. Diu and F. Laloe, Quantum Mechanics, Vols. I and II, Wiley, 1970.
2. J. J. Sakurai, Modern Quantum Mechanics, Addisson Wesley, 1995.
3. Marlan O. Scully and M. Suhail Zubairy, Quantum Optics, Cambridge University Press, 1997.
4. W. Greiner, Relativistic Quantum Mechanics: Wave Equations, Springer, 1997.
5. Leslie E. Ballentine, Quantum Mechanics: A Modern Development, World Scientific, 1998.
6. S. D. Bjorken and J. D. Drell, Relativistic Quantum Mechanics, McGraw-Hill Science/Engineering/Math, 1998.

(22) Computational methods in Physics - I (3 hours class work per week, 6 credits)

- **Solving of ordinary differential Equations:**
  Using Runge-Kutta methods, and using to solve Laplace's equation (1D) in electrodynamics and Schr¨odingers equations in quantum mechanics.
- **Solving Partial Differential Equations**
  Diffusion equation in the context of heat propagation, time evolution in Schr¨odingers equation, Laplace's equation in 2 and 3 dimensions in electromagnetism, wave equation, Navier-Stokes's equation (hydrodynamics) in 1+1 and 2+1 D. Discussion of different techniques including symplectic integrators and also basics of finite element method.
- **Various techniques of Numerical Integration.**
- **Linear Algebra and Eigensystem:**
  LU decomposition, eigenvalue solvers like the Ritz method, Lanczos and comparison. Iterative methods like Jacobi or Gauss-Seidel methods for solving systems of linear equations. Eigenvalue solvers can be discussed with examples in quantum mechanics, classical mechanics and electrodynamics (TEM modes).
- **Monte Carlo methods for numerical integration:**
  statistical mechanics, Metropolis and over-relaxation algorithm with a special example of solving Ising model. Generating random numbers.
- **Data Processing and Plotting:**
  Fast-Fourier transform, Spline interpolation of data, chi-square distribution and numerical error analysis. Theory of distribution functions and generating trial data using normal,log-normal and exponential functions.
- **Basics of Parallel programming using MPI, OPEN-MP**

- **Language: C/C++, Fortran, Python**

Recommended books:

1. Numerical Recipies 3rd Edition: The art of scientific computing by W. H Press, S. A. Teukolsky, W. T. Vetterling.
2. Computational Physics by Mark E.J. Newman
3. Numerical methods for Scientists and Engineers by H. M. Antia.
4. Numerical Methods for Partial Differential Equations by Sandip Mazumder.
5. Data Reduction and Error Analysis for the Physical Sciences by Philip R.

Additional Resources

1. Practical Statistics for Astronomers by Christine R. Jenkins, J. V. Wall,C. R. Jenkins
2. Statistical Mechanics: Algorithms & Computations by Werner Krauth.
3. Finite Element Methods: Theory, Implementation and Applications by M. J. Larson & F. Bengzon.
4. The Lanczos and Conjugate Gradient Algorithms: From Theory to Finite Precision Computations by By Gerard Meurant.
5. Parallel Scientific Computing in C++ and MPI - Volume 1, G. Karniadakis, R. M. Kirby.

(23) Condensed Matter Physics I (4.5 hours class work per week, 9 credits)

- **Introduction:**

  Length, time and energy scales in condensed matter, soft and hard condensed matter, examples of materials properties, bonding and interactions, van der Waals interaction, hydrogen bonding;

- **Condensed matter systems:**

  Crystals: Lattice, basis, 2-d and 3-d crystals, point and space groups, symmetries, experimen- tal determination of structure, scattering, lattice with basis, Miller indices, structure factor, form factors, defects in crystals; Liquids and glasses, Liquid crystals, Polymers, Quasicrystals;

- **Electronic Properties:**

  Jellium model: Single electron model, density of states, Fermi surface and quasiparticles;Thermodynamic properties: Review of thermodynamics, statistical mechanics of non-interacting electrons, Sommerfeld expansion, specific heat, magnetic susceptibility;Transport properties: Drude Model, electrical conductivity, thermal conductivity thermoelec- tric phenomena. Band theory; Electrons in periodic potentials, Bloch’s theorem, Kronig-Penney model, Brillouin zones, nearly free and tightly bound electrons, Fermi surfaces, band theory, effective mass, Wannier functions and tight binding, survey of the periodic table;

- **Lattice vibrations:**

  The cohesion of solids, mechanical properties, elasticity, constitutive relations; Modes of lattice vibrations. Quantization and phonons. Statistical mechanics of phonon gas, Einstein and Debye models, umklapp processes, thermal expansion, Kohn anomalies, charge- density waves; Electron phonon interactions;

- **Semiconductor Physics:**
  Introduction: Valence and conduction bands. Doping and the Fermi level; Band diagrams, metal interfaces, work functions, Schottky barrier, diodes and transistors; Nano-electronics: heterostructures, quantum wells, quantum wires and quantum dots;
- **Optical Properties:**
  Optical properties of metals, optical properties of semiconductors, direct and indirect band gaps, polarization, Clausius-Mosotti relation, polarons, point defects and color centres, metals at low frequencies, anomalous skin effect, plasmons, Brillouin and Raman scattering;
- **Superfluidity and Superconductivity:**
  Superfluidity of Helium, BEC, Landau argument, two-fluid model, BEC in atomic gases, superconductivity, phenomenology including Meissner effect, type-I and type-II superconductors;
- **Magnetism:**
  Atomic magnetism, Hunds rules, Curie's law, Pauli paramagnetism, Landau diamagnetism, quantum mechanics of interacting moments, Heisenberg model, spin waves;

Textbooks:

1. N. Ashcroft and N. Mermin, Solid State Physics, Holt, Rinehart and Winston, 1976.

(24) Statistical Mechanics I (4.5 hours class work per week, 9 credits)

- **Fundamental principles :**
  Elements of probability theory, algebra and calculus of random variables, binomial, Poisson and Gaussian distributions, moments and cumulants of probability densities, the central limit theorem, the basic postulate of statistical mechanics, first discussion of ergodicity and mixing;
- **Thermodynamics:**
  Macroscopic definition of thermodynamic variables, temperature, pressure, work and heat, the Carnot cycle and empirical definition of entropy, free energy and other thermodynamic potentials, convexity of entropy and thermodynamic potentials, thermodynamic potentials as Legendre transforms of the entropy, thermodynamic relations of Maxwell, Gibbs and Duhem, Clausius and Clapeyron, and Clausius and Mosotti, the third law of thermodynamics;
- **The Gibbs distribution:**
  Gibbs definition of entropy, the Gibbs distribution as maximisation of entropy subject to constraints, connection with Legendre transforms, connection to thermodynamics, the three canonical distributions, the Maxwell-Boltzmann

distribution, the probability distribution of a classical and quantum harmonic oscillator;

- **Non-interacting systems I:**
  Classical ideal gas, the Boltzmann distribution and classical statistics, the counting approach to the Boltzmann distribution, free energy and equation of state of the ideal gas, the law of equipartition, ideal gases with internal degrees of freedom, diatomic and polyatomic gases, the magnetism of an ideal gas;
- **Non-interacting systems II:**
  Fermi distribution, Bose distribution, counting approach to Fermi and Bose distributions, Fermi and Bose gases of elementary particles, the degenerate electron gas, the specific heat of the degenerate electron gas, magnetism of an electron gas, the degenerate Bose gas, black body radiation;
- **Non-interacting systems III:**
  Solids at high temperature and the Dulong-Petit law, solids at low temperatures and Einstein's theory of specific heat, the Debye interpolation formula, thermal expansion of solids;
- **Interacting systems I :**
  Deviations of gases from ideality, van der Waals equation, the conditions of phase equilibrium, the Clausius-Clapeyron equation, the critical point, law of corresponding states, virial and cluster expansions, the method of correlation functions, the Ornstein-Zernike relation;

Textbooks:

1. L. D. Landau and E. M. Lifshitz, Statistical Physics, 3rd Edition, Butterworth-Heinmann, 1980.
2. H. B. Callen, Thermodynamics and an Introduction to Thermo-statistics, 2nd Edition, Wiley, 1985.
3. D. Chandler, Introduction to Modern Statistical Mechanics, Oxford Univ. Press, 1987.
4. M. Plischke and B. Bergersen, Equilibrium Statistical Mechanics, World Scientific, 1994.
5. R. K. Pathria, Statistical Mechanics, Butterworth-Heinmann, 1996.
6. M. Kardar, Statistical Mechanics of Particles, Cambridge Univ. Press, 2007.
7. F. Reif, Fundamentals of Statistical and Thermal Physics, Waveland Pr. Inc., 2008.

(31) Quantum Field Theory I (4.5 hours class work per week, 9 credits)

First two-third portion of the course is meant for all students, while a bifurcation is made at the end of this for separately orienting students towards HEP and LEP, during the remaining one-third portion of the course. Thus the common section has 32 lectures, the other two parts have 16 to 18 lectures. Part II and part III will run concurrently,

1. QFT I part I:

(Common to all students. Knowledge of Relativistic Quantum Mechanics, i.e., Dirac equation and KG equation is expected. Some basic notions of the Lorentz group and Poincare group are also expected)

- **Elements of Classical Field theory:**
  Lagrangian and Hamiltonian densities, quantization of KG and Dirac and electromagnetic fields, propagators for KG, Dirac and vector (photons) ;
- **Perturbation theory:**
  Wick's theorem and Wick expansion, Feynman diagrams, cross sections and S matrix. Feynman rules for scalars, spinors and gauge fields (Abelian) ;
- **Elementary processes in QED:**
  electron-positron annihilation, Compton scattering, Bhabha scattering, crossing symmetry etc. ;
- **Radiative corrections for scalar theory:**
  loop corrections, regularization and renormalization, dimensional regularization. elemen- tary ideas of the systematics of renormalization ;
- **Functional method techniques:**
  Scalar field theory quantization (with, if time permits, some discussion of critical phenomena in this approach) ;
- **Non-interacting electrons:**
  Tight binding models, the many body ground state, quasi-particle and quasi-hole excita- tions. Partially filled bands and Fermi surface kinematics ;

2. QFT 1 part II: (For HEP students)

- **LSZ formalism:**
  one loop diagrams in QED, Ward Takahashi identities, regularization in QED ;
- **Path integral/Functional method**
  Quantization in spinor and vector (gauge) theories ;
- **Systematics of renormalization:**
  Power counting, idea of counter terms, structure of one loop and beyond in scalar and QED. (no explicit 2 loop calculations etc.) ;

3. QFT I part III: (Many Body Theory for Condensed Matter/LEP students)

- **Second quantization in operator formalism (non-relativistic):**
  Diagrammatic perturbation theory, Retarded Greens functions, Spectral function, quasi- particle lifetimes, Angle resolved photoemission spectroscopy (ARPES) ;
- **Linear response theory and Kubo formulae ;**
- **Interacting bosons:**
  Symmetry breaking, semi-classical spectrum. Applications to cold atoms and superfluids ;
- **Mean field theory:**
  BCS hamiltonian and superconductivity ;
- **Magnetism:**
  Heisenberg models. Spin waves. Coherent states and path integrals for spin systems. Non-linear sigma models ;

Textbooks:

1. M. E. Peskin and D. V. Schroyder, Quantum Field Theory, Sarat Book House, 2005.

2. G. D. Mahan, Many-Particle Physics, Springer, 2010.

(32) Mathematical Methods II (3 hours classwork per week, 6 credits)

- **Numerical interpolation techniques (including Lagrange method)**
- **Advanced Complex Analysis:**
  Analytic continuation, branch cuts, Multivalued functions, Riemann surfaces, Conformal Mapping, Method of steepest descent;
- **Group theory:**
  Discrete and continuous groups;
- **Numerical methods:**
  Numerical solution of integrals, Numerical solution of ODEs, Numerical solution of PDEs: finite difference Monte Carlo method (especially solving integrals), Spectral techniques (in- cluding FFT) Numerical minimization techniques;
- **Probability and statistics:**
  Brief survey of probability theory and statistical distributions, Bayesian probability Data analysis;

Textbooks:

1. C. M. Bender and S. A. Orszag, Advanced Mathematical Methods for Scientists and Engineers:Asymptotic Methods and Perturbation Theory (vol. 1), Springer, 1999.
2. T. W. Gamelin, Complex Analysis, Springer, 2001.
3. E. T. Jaynes and G. L. Bretthorst, Probability Theory: The Logic of Science (vol. 1), Cam- bridge Univ. Press, 2003.
4. M. Tinkham, Group Theory and Quantum Mechanics, Dover, 2003.
5. R. Gilmore, Lie Groups, Lie Algebras, and Some of Their Applications, Dover, 2006.
6. J. H. Mathews and R. W. Howell, Complex Analysis for Mathematics and Engineers, Jones and Bartlett, 2006.
7. N. G. Van Kampen, Stochastic Process in Physics and Chemistry, 3rd Edition, North Holland, 2007.

(33) Statistical Mechanics II (4.5 hours class work per week, 9 credits)

- **Introduction to critical phenomena:**
  Survey of experimental results, scaling hypothesis and empirical scaling relations, self-similarity and fractals;
- **Interacting systems:**
  Critical phenomena and continuous phase transitions, symmetry and the order parameter, Landau theory, introduction to the Ising model, Curie-Weiss mean field theory, the absence of phase transitions in one dimension;
- **Criticality in spin systems:**
  The Ising model in one dimensions, solution using transfer matrices, the lack of phase transitions in one dimensions, the Landau-Peirls argument. The Ising model in two dimensions, Wannier's calculation of the critical temperature, mean

field solutions of the Ising model, survey of principle results of Onsager's exact solution;

- **Criticality in classical field theories:**
  Landau-Ginzburg theory, the Landau-Ginzburg functional as an effective Hamiltonian, calcu- lation of correlation functions, exponents and thermodynamic quantities, mean field and RPA closures, the problem of divergences;
- **Introduction to the renormalisation group:**
  Historical survey, integration of short-wavelength degrees of freedom, classification of fixed points, flow equations, illustration with Kadanoff block spins in the 1d Ising model;
- **perturbative renormalisation in momentum space:**
  Philosophy of the perturbative RG scheme, significance of the upper critical dimension, diagrammatic expansion in momentum space, the ε expansion, exponents and thermodynamic quantities in powers of ε, comparison with mean field approximations;
- **Non-perturbative renormalisation in real space:**
  Kadanoff block spins, techniques of approximate non-perturbative renormalisation, numerical renormalisation in the Ising model;
- **Broken Symmetry:**
  Continuous symmetry groups and effective Hamiltonians, the consequences of broken symmetry, Goldstone modes and fluctuations, elastic variables, topological defects, fluctuation destruction of long-range order, the Mermin-Wagner and Landau-Peirles arguments, the disclination and dislocation unbinding transitions;
- **Disorder:**
  Disorder in physical systems, quenched and annealed disorder, the Parisi solution for quenched disorder, illustrative examples;
- **Dynamics of fluctuations:**
  Linear response in physical systems, the regression of fluctuations and Onsager's hypothesis, symmetry of kinetic coefficients, the Fokker-Planck and Langevin descriptions of fluctuations, the fluctuation-dissipation theorem;

Textbooks:

1. L. D. Landau and E. M. Lifshitz, Statistical Physics, 3rd Edition, Butterworth-Heinmann, 1980.
2. H. E. Stanley, Introduction to Phase Transitions and Critical Phenomena, Oxford Univ. Press, 1987.
3. D. Chandler, Introduction to Modern Statistical Mechanics, Oxford Univ. Press, 1987.
4. M. Plischke and B. Bergersen, Equilibrium Statistical Mechanics, World Scientific, 1994.
5. R. K. Pathria, Statistical Mechanics, Butterworth-Heinmann, 1996.
6. S.-k. Ma, Modern Theory of Critical Phenomena, Westview Press, 2000.
7. P. M. Chaikin and T. C. Lubensky, Principles of Condensed Matter Physics, Cambridge Univ. Press, 2000.

(34) Particle Physics I (three hours classwork per week, 6 credits) Standard Model, Part I :

- **Symmetries and Quarks :**

  Discrete symmetries, isospin-SU(2), G-parity, SU(3)-classification of mesons and baryons, mass formula, magnetic moments, motivation for colour as an internal symmetry;

- **Scattering Processes :**

  Relativistic kinematics, phase space, lifetimes and cross-sections, Golden rule; scattering of a spinless charged particle by electromagnetic field, scattering of electrons by electromagnetic field, $e - \mu$ scattering, Moller scattering, electron-proton scattering and form factors, higher order corrections, vacuum polarization, charge renormalization, Lamb shift, $g - 2$;

- **Parton Model and QCD :**

  Deep inelastic scattering (DIS) of electrons on nucleons, structure functions and scale invariance, parton model; quantum chromodynamics : Lagrangian, symmetries; Standard Model, Part II :

- **Early Developments :**

  Beta-decay, μ-decay, parity violation, $V - A$ theory of weak interactions, conserved vector current (CVC) hypothesis;

- **Strange particle decay, mixing of neutral K-mesons, Cabibbo theory, current-current interaction, PCAC and current algebra;**

- **CP Problem**:

  C,P,T transformations, CP violation;

- **Electro-Weak Unified Theory :**

  Spontaneous symmetry breaking, Higgs mechanism, $SU(2) \times U(1)$ theory, electroweak unification, neutral current phenomena, W,Z bosons;

- **Current Phenomenology :**

  New flavours, KM-matrix and associated phenomenology, neutrinos, masses and mixing, neutrino oscillations.

Textbooks:

1. T. D. Lee, Particle Physics and Field Theory, Harwood, 1981.
2. F. Halzen, A.D. Martin, Quarks and Leptons, Wiley, 1984.

(41) Quantum Field Theory II (4.5 hours classwork per week, 9 credits)

- **Functional Methods in Quantum Field Theory :**

  Quantization of the Klein-Gordon and Dirac fields and their interactions, derivation of the Feynman rules of covariant perturbation theory, quantization of the Maxwell field, issues of gauge fixing, BRST invariance and QED Ward identities;

- **Functional Integral Quantization of Non-abelian Gauge fields :**

  Faddeev-Popov method of gauge fixing, BRST invariance and Slavnov-Taylor identities, Gribov ambiguities, loop computations in non-abelian gauge theories and renormalizability;

- **Renormalization Group and its Applications :**

The Gell-Mann, Low and Wilson approaches to the renormalization group, Callan-Symanzik equations and fixed points of the beta function, asymptotic freedom of non-abelian gauge theories, applications to perturbative QCD;

- **Anomalies in Abelian and Non-abelian Gauge Theories :**

  The axial vector anomaly in QED and its implications, non-abelian anomalies, anomaly freedom vs renormalizability and unitarity, Fujikawa's approach to anomalies;

- **Topological Solutions :**

  Soliton solutions and their implications, Polyakov-'t Hooft magnetic monopole and the BPS limit, instantons and tunneling in quantum field theory;

Textbooks:

1. S. Coleman, Aspects of Symmetry, Cambridge University Press, 1985.
2. R. Rajaraman, Solitons and Instantons, Elsevier, 1986.
3. M. Peskin and D. Schroeder, An Introduction to Quantum Field Theory, Addison-Wesley, New York, 1995.
4. S. Weinberg, Quantum Theory of Fields, Vols. I and II, Cambridge University Press, 1996.

(42a) Cosmology and Gravitation (4.5 hours class work per week, 9 credits)

- **Principle of relativity, principle of equivalence, tensors, tensor calculus on Riemannian manifolds, symmetries of Riemannian manifolds, hypersurfaces, extrinsic curvatures, Gauss-Codazzi equations;**
- **Einstein's field equations:**

  Newtonian limit, tests of general relativity, gravitational radiation;

- **Solutions of Einstein's equations :**

  Schwarzschild solution, Kerr solution, black holes;

- **Tetrad formulation of gravity, generalizations to arbitrary dimensions;**
- **Hamiltonian formulation :**

  For metric gravity, for tetrad formulation, canonical quantization and path integral quantization;

- **Cosmology : Robertson-Walker model, early universe;**
- **Singularity theorems;**

Textbooks:

1. S. Weinberg, Gravitation and Cosmology, Wiley, 1972.
2. R. Wald, General Relativity, Chicago, 1987.

(42b) Particle Physics II (4.5 hours class work per week, 9 credits)

- **Basic Ingredients of the Standard Model :**

  Yang-Mills fields, Higgs mechanism, asymptotic freedom;

- **Electroweak Sector :**

  Weinberg-Salam Model, phenomenological consequences, families and flavours, anomaly cancellations, radiative corrections and precession tests;

- **Quantum Chromodynamics (QCD) :**

Lagrangian, perturbative QCD, Altarelli-Parisi equations, nonperturbative QCD and colour confinement models, strong CP problem, chiral perturbation theory, heavy quark effective theory, Skyrme model;

- **Neutrino Physics :**
  Solar neutrinos, double beta decay, neutrino masses and mixing models;
- **CP Violation :**
  CP violation in $K0 - \bar{K}0$ system, $B0 - \bar{B}0$ system, models of CP violation;
- **Supersymmetry:**
  Hierarchy problem, construction of the supersymmetric standard model, search for SUSY signals;
- **Other Approaches beyond the Standard Model : Grand unified theories;**

Textbooks:

1. T Cheng and L. Li, Gauge Theory of Elementary Particles, Oxford University Press, 1984.

(43) Advanced Condensed Matter Physics (4.5 hours class work per week, 9 credits)

- **Correlated Electron Physics:**
  Second quantization review, Hubbard model, Heisenberg model; Material phenomenology, magnetic phases, CDW states; Quantum magnetism, Stoner criterion, double exchange; Superconductivity, Cooper argument, BCS, gap equation, Bogoliubov-de Gennes equations, strong coupling theory, RVB and modern approaches to superconductivity in correlated systems;Quantum Hall effect, integer and fractional, edge states, Laughlin and Jain wave functions, topological defects; Luttinger liquids, Bethe ansatz; Mesoscopic physics; Disordered electronic systems and metal insulator transitions;
- **Soft Condensed Matter**
  Physics Interactions in soft matter, entropic interactions, fluctuation-induced interactions, hard-sphere statistical mechanics and crystallization; Self-assembly of amphiphiles, phases, theoretical approaches; Colloids, self-assembly, the freezing transition; Polymers, polymer structure, self-avoidance, Edwards model, osmotic pressure, Flory-Huggins theory, screening, semi-flexibility, persistence length; Membranes, biological membranes, lipid bilayers, physical properties, de Gennes-Taupin length, tethered membranes; Liquid crystals, nematic, cholesteric and smectic, order parameters, Frank free energy, Landau-de Gennes model defects, defect phases; Survey of hydrodynamics, hydrodynamic approaches to soft matter physics, dynamical properties of polymers, membranes, colloids; Soft matter away from equilibrium, shear-induced phases; Optional: Granular media and Glasses;

Textbooks: For Strongly Correlated Systems:-

1. M. P. Marder, Condensed Matter Physics, Wiley-Interscience, 2000.
2. A. Altland and B. Simons, Condensed Matter Field Theory, Cambridge University Press, 2006.
3. G. D. Mahan, Many-Particle Physics, Springer, 2010.

For Soft Condensed Matter:-

1. P. M. Chaikin and T. C. Lubensky, Principles of Condensed Matter Physics, 1st Edition, Cambridge University Press, 2000.

(44a) Quantum Information and Computation (4.5 hours class work per week, 9 credits)

- **Resume of Quantum Mechanics:**
  Composite quantum systems and tensor product Hilbert spaces, Subsystems and density oper- ators, From Schr ̈odinger to Liouville evolution; completely positive maps as quantum channels; From projective measurements to POVMs; State estimation;

- **Entanglement and its applications:**
  EPR argument and Bell inequalities; Separability vs. entanglement; Positive unphysical maps witnessing entanglement; Partial transpose criterion for checking separability; Other entanglement detection criteria; Multi-partite entanglement; Quantum teleportation, dense coding, entanglement swapping;
- **Connection with Shannon information theory:**
  Shannon's noiseless coding theorem and Schumacher's quantum counterpart; Accessible information and Holevo's bound; Shannon's noisy channel coding theorem and HSW theorem; Quantum channel capacities; Decoherence and quantum error correction;
- **Measures of entanglement:**
  Thermodynamic considerations of entanglement under LOCC; Entanglement concentration and dilution; Several measures of entanglement; Majorization;
- **Quantum Cryptography:**
  Basics of classical cryptography; RSA cryptosystem; Quantum key distribution; Security of quantum key distribution;
- **Entanglement in continuous variable systems:**
  Gaussian states; Role of Wingner description and symplectic transformations; Quantum information processing with continuous variable systems;
- **Quantum computation:**
  Classical and quantum computers; Circuit complexity; One- and two-qubit gates; Universality of gates; Deutsch-Jozsa algorithm; Grover's search algorithm; Quantum Fourier transform and Shor's factorization algorithm;
- **Implementations:**
  Quantum key distribution experiments; Unconditional quantum teleportation using continuous variable systems; Implementations of quantum computers using NMR, trapped ions, Josephson junctions, linear optical devices, etc.;

Recommended readings:

1. Quantum Computation and Information, Michael A. Nielsen and Issac L. Chuang (Cambridge University Press, 2000);
2. John Preskill's Lectures on Quantum Information and Computation, available at: http://theory.caltech.edu/people/preskill/ph229/♯lecture;

3. David Mermin's Lectures on Quantum Computation, available at: http://people.ccmr.cornell.edu/ mermin/qcomp/CS483.html;
4. The Physics of Quantum Information: Quantum Cryptography, Quantum Teleportation, Quantum Computation, Dik Bouwmeester, Artur Ekert, Anton Zeilinger (eds.) (Springer, 2000);
5. Elements of Information Theory, Thomas M. Cover and Joy A. Thomas (John Wiley & Sons, 1999);
6. Contemporary review articles available at:- http://xxx.imsc.res.in/archive/quant-ph

(44b) Nonlinear Dynamics (4.5 hours class work per week, 9 credits)

• Hamiltonian formulation :

Iterative maps, fixed points, Lyapunov exponents, Integrable systems, Perturbed integrable systems, Poincar ́e-Birkhoff construction (illustration with driven pendulum);

• Deterministic Nonlinear Dynamics :

Discrete dynamics and maps, differentiable dynamics: dissipative systems, non-dissipative systems, Hamiltonian systems;

• Integrability Aspects of Hamiltonian Dynamics : Liouville-Arnold theorem, KAM theory;

• Chaos:

In discrete dynamical systems, in Hamiltonian systems, in dissipative systems;

• Semiclassical Analysis :

Berry-Tabor theory, Gutzwiller Theory;

• Quantum Aspects.

Textbook:

1. M. Tabor, Chaos and Integrability in Nonlinear Dynamics, Wiley, 1989.
2. M. C. Gutzwiller, Chaos in Classical and QUantum Mechanics, Springer, 1990.
3. I. Percival and D. Richards, Introduction to Dynamics, Cambridge, 1991.
4. L. Reichl, A Modern Course in Statistical Physics, Wiley, 1998.
5. S.H. Strogatz, Nonlinear dynamics and Chaos: Applications to Physics, Biology, Chemistry and Engineering, Cambridge, 2001.
6. M. Lakshmanan and S. Rajasekar, Nonlinear Dynamics, Springer, 2003.
7. L. Reichl, The transition to Chaos, Springer, 2004.

(44c) Statistical Field Theory (4.5 hours class work per week, 9 credits)

• Review of quantum statistical mechanics, functional integration representation of partition function, scalar field, charged scalars and Bose-Einstein condensation, Fermions, interactions and diagrammatic techniques, self-coupled scalar field theory, Yukawa theory, QED, renormalization and loop corrections to ln Z.

• Spontaneous symmetry breaking and Higgs model QCD, deconfinement phase transitions.

• Salem-Weinberg model and symmetry restoration, early universe, nuclear matter and pion condensates, neutron stars.

Textbook:

1. P. Kapusta, Finite Temperature Field Theory, Cambridge University Press, 1989.