PHYSICS SUBJECT BOARD – CORE COURSES

Integrated M.Sc. - Ph.D. Programme
P-101 / C-201 : Mathematical Methods
P-102 / C-203 : Numerical Methods and Algorithms in Chemical Physics
P-103 : Classical Mechanics
P-105 / C-202 : Quantum Mechanics – I
P-106 : Classical Electrodynamics – I
P-107 : Experimental Methods
+ All Core courses of Ph.D. Programme

Ph.D. Programme
P-202 : Numerical Methods
P-204 /C-103 : Statistical Mechanics – I
P-205 : Quantum Mechanics II / Advanced Quantum Mechanics
P-206 : Classical Electrodynamics – II
P-207 : Advance Experimental Methods

CHEMISTRY SUBJECT BOARD – CORE COURSES

Integrated M.Sc. - Ph.D. Programme
C-101 : Physics & Chemistry of materials: Bulk to Nano
C-102 : Organic Chemistry and Inorganic Chemistry
C-103 / P-204 : Statistical Mechanics – I
+ All Core courses of Ph.D. Programme

Ph.D. Programme
C-201 / P-101 : Mathematical Methods
C-202 / P-105 : Quantum Mechanics - I
C-203 / P-102 : Numerical Methods and Algorithms in Chemical Physics
C-204 / B-203 : Biophysics
C-205 : NMR Spectroscopy

BIOLOGY SUBJECT BOARD – BASIC COURSES

Ph.D. Programme
B-201 : Cell Biology
B-202 : Cell Physiology and Cell signaling
B-203 / C-204 : Biophysics
B-204 : Basic Mathematics for Biologists
B-205 : Fluorescence Methods in Cellular Biophysics

ELECTIVE COURSES	
E-201 : Scientific Communication	E-405 : Soft Matter: Equilibrium and Dynamics
E-202 : Error Analysis and Statistical Inference in Experiments	E-406 : Advanced Mathematical Physics
E-203 : Computer Programming using Python language	E-407 : Advanced continuum Mechanics
E-204 : Advanced Topics in Organic Chemistry and Inorganic Chemistry	E-408 : Field Theory
E-301 : Optics	E-409 : Nonlinear Dynamics
E-302 : Condensed Matter Physics	E-410 : Intense laser matter interactions
E-303 : Atomic & Molecular Physics	E-411 : Solid State NMR
E-401 : Advanced Computational Methods	E-412 : Principles in Cancer & Cancer Stem cell biology
E-402 : Advanced Dynamics	E-413 : Biological thermodynamics
E-403 : Advanced Statistical Mechanics / Statistical Mechanics – II	E-414 : Mechanobiology of cells and molecules
E-404 : Phase Transitions, Ordering and Dynamics	

Note: Core / Basic courses from other disciplines may be taken as electives and the credits are allocated as per the subject board guidelines under which the student is admitted / registered. The course work for registration must be as per the requirement of respective subject boards.

P-101 / C-201: Mathematical Methods **4 Credits**

- Determinants and Matrix Algebra: Properties of determinants and matrices, Linear transformation, Eigenvector-Eigenvalue problems, Similarity and unitary transformations
- Differential Equations: Separable, Exact, and First-order homogeneous linear differential equations, Sturm-Liouville eigenvalue problem, Legendre polynomials and properties, Spherical harmonics, Bessel equations and properties
- Vector Algebra: Gradient, Divergence, Curl, Gauss and Stokes theorem, Curvilinear coordinates, Tensor analysis
- Complex Analysis : Cauchy-Riemann conditions, Analytic functions, Contour integrals, Taylor and Laurent series, Singularities, Residue theorem, Gamma and Beta function, Method of steepest descent, Stirling series, asymptotic series, Convergence tests
- Integral Transforms : Fourier series, Fourier transform, Laplace transform, Solution of initial boundary-value problem, Convolution
- Error Analysis

P-102 / C-203: Numerical Methods and Algorithms in Chemical Physics **4 Credits**

Part – 1 Foundation Topics

- **Computers**
  - ❖ Linux - system commands.
  - ❖ Fortran90 - basics, style, usage.
  - ❖ Python - trends in modern programming.
  - ❖ Numerical libraries - BLAS, LAPACK/Numpy, Scipy
- **Examples from physical chemistry**
  - ❖ Equations of states: molar volume, heat capacity, virial coefficients
  - ❖ Solving equations of chemical equilibria, balancing stoichiometric equations
  - ❖ Principal coordinate system, moment of inertia

  Math topics:
  - ❖ Error analysis: Algorithms and error propagation
  - ❖ Data analysis: Data modeling, principal component analysis
  - ❖ Roots of equations: Newton-Raphson
  - ❖ Numerical methods: Overview

Part - 2 Topics in Molecular Quantum Mechanics

- **Time-independent variational problems**
  - ❖ Vibrational Schrödinger equation: Harmonic oscillator, Morse oscillator, diatomic molecules, Dimensionless normal coordinates, potential energy surface fitting
  - ❖ Electronic problems: Hückel molecular orbital method, Ground electronic state of Helium atom, Hartree-Fock approximation
  - ❖ NMR spectrum of AX spin system

Math topics:

- ❖ Partial Differential Equations: Basis set representation
- ❖ Numerical integration: Gaussian quadrature, Monte Carlo
- ❖ Eigensolvers: Jacobi, inverse iteration, Lanczos
- ❖ Linear systems of equations: Least squares polynomial fitting, matrix inversion, condition number, direct and iterative linear solvers

- **Time-dependent problems**
  - ❖ Time-evolution of a non-stationary state, wave packets
  - ❖ Bound states by imaginary time propagation
  - ❖ Survival probability, correlation spectra
  - ❖ Equation of motion of a harmonic oscillator, Coupled-rate equation for Lindemann-Hinshelwood mechanism, Bloch equations

  Math topics:
  - ❖ Ordinary differential equations: Euler's method, Runge-Kutta, Predictor-Corrector
  - ❖ Fourier series and Fourier transform. Fourier transform pairs in ab-initio quantum chemistry
  - ❖ Laplace transform, connection to integral equations

Part – 3 Topics in Molecular Classical Mechanics

- **Introduction to Molecular Dynamics simulation**
  - ❖ Initialization of system, Force calculation from classical potential, Implementation of periodic boundary condition, Integration schemes of Newtonian equation of motion. Simple monoatomic liquids as the test system.

  Math topics:
  - ❖ Ordinary differential equations: leap frog, verlet and velocity verlet
- **Introduction to Monte Carlo simulation**
  - ❖ Initialization of system, Implementation of metropolis algorithm, Translational and rotational monte carlo moves. Generation of Neighbor list (verlet and linked list). Simple monoatomic liquids as the test system.

  Math topics:
  - ❖ Probability and detailed balance, Sorting
- **Calculation of static and dynamic property**
  Equation of state of a liquid, Pair correlation function and Static structure factor. self-diffusion constant from Monte Carlo and Molecular Dynamics simulation. Handling long range electrostatics using ewald summation.

  Math topics:
  - ❖ Correlation functions and Histograms
  - ❖ Fourier Transform.

P-103: Classical Mechanics 4 Credits

- **One and Two-dimensional dynamical systems :** Newton's laws of motion, Harmonic oscillator, Over-damped oscillator, Simple pendulum, Time period of oscillations, Fixed points, simple bifurcations, Phase plane/space.
- Lagrangian formalism Elements of calculus of variations, Generalised coordinates, Principle of least action, Euler-Lagrange equations, Constraints, Lagrangian for a free particle and system of particles, Conservation laws, Mechanical similarity

- Central force fields and Collisions Motion in one dimension, Reduced mass, Motion in a central field, Kepler's problem, Elastic collisions, Scattering
- Small Oscillations : Free and forced oscillations, Vibrations of molecules, Damped oscillations, Resonance, Parametric resonance, Regular perturbation theory, Anharmonic oscillator, Motion in a rapidly oscillating field
- Hamiltonian formalism Hamilton's equation, Poisson brackets, Canonical transformation, Liouville's theorem, Hamilton-Jacobi theory, Action-Angle variables Integrable and NonIntegrable systems, Adiabatic invariants, and elements of time-dependent perturbation theory.

P-105 / C-202: Quantum Mechanics I **4 Credits**

- The need for QM: Movies on Davisson & Germer electron diffraction; Young's 2-slit with photons. Ideas from de Broglie, Bohr, Heisenberg, Schroedinger, Born. 'First' quantized momentum & position, and commutator. Heuristic argument for Schroedinger's equation, starting from free particle.
- Quantum Concepts : Wave-functions and bra-ket notation; ortho-normality; completeness, unitary transforms; local continuity for probability density; special role of hermitian operators; uncertainty principle; symmetry operators, common eigenfunctions, degeneracies; Pauli exchange and fermions/bosons; Slater determinants.
- Bound States: Non-bound wave-functions e.g. 1D square barrier. Bound states of 1 D & 3D square well; 1D circle and 3D spherical-well; Angular momentum algebra and eigenfunctions. 1D simple harmonic oscillator (SHO), minimum uncertainty product in ground state; 1D SHO re-visited: operator approach. Hydrogen atom, Rung-Lenz degeneracy. Hund's Rules, L.S coupling; spectroscopic level notation; Periodic Table, and filling of atomic levels.
- Molecules and bonding: Born-Oppenheimer approx; Heitler-London valence bonds versus Mulliken molecular orbitals; bonding/ anti-bonding states; qualitative ideas of \sigma, \pi bond-overlaps; sp3 hybridization. [Handout: Shape, Structure Molecules by C A Coulson.]
- Approximation Methods: Variational methods (e.g. attractive delta function and Gaussian trial). Time-independent perturbation theory for single/ degenerate energy levels (e.g. Zeeman/ Stark effects). Selection rules for electric dipole matrix elements. [Handout: Time-dependent perturbations and decay rates.]

P-106: Classical Electrodynamics – I **4 Credits**

- Single charged particles in E and B fields
- Electrostatic fields, potentials, energy and forces
- Analytical and numerical ways of solving electrostatic potential problems
- Idealized and real charge distributions and their potentials
- Current distributions and magnetic fields
- Magnetic materials
- Maxwell's equations, EM waves and their propagation in free space and in media.
- EM waves in confined spaces

P-107: Experimental Methods **8 Credits**

- e/m Experiments. (1credit)
- Frank-Hertz experiment. (1credit)
- Michelson Interferometer. (1credit)
- Zeeman effect. (1credit)
- Plank Constant measurement. (1credit)
- Fiber coupling and profile mapping. (1credit)
- 4-probe conductivity measurement. (1credit)
- Basic Labview experiment. (1credit)

P-202: Numerical Methods **4 Credits**

- Elements of Computer Programming: Flow-charts, Basic of C language (arrays, pointers, functions), Add/Subtract/Multiply/division, Round of errors with some examples, Data analysis using Matlab, python, gnuplot
- Linear algebra: Gauss elimination, Gram-Schmidt orthogonalization, Eigenvalue problem, Examples using lapack.
- Differentiation and Integration: numerical schemes for differentiation (finite differences and spectral methods) and integration (Trapezoidal, Simposon's 1/3, Gaussian Quadratures).
- Ordinary Differential Equations: Euler, Runge-Kutta time integration and velocity verlet scheme, Example elucidating Newton's equation of motion.
- Partial Differential Equation: Diffusion Equation, Advection equation, Advection-diffusion equation, Laplace, Poisson equation, Helmholtz equation.
- Conjugate gradient method. Least square method of fitting data to different functions. Linear, polynomial and non-linear functions (Levenberg-Marquardt algorithm), Interpolation (Linear, polynomial, spline, etc.).
- Advanced topics: Introduction to Molecular Dynamics/Monte Carlo, Lattice Boltzmann and Navier-Stokes Equations

P-204 / C-103: Statistical Mechanics - I **4 Credits**

- Brief overview of Equilibrium Thermodynamics: Equilibrium states, Extensive and intensive variables, Laws of thermodynamics, Entropy and free energy, Chemical potential, Phase equilibria
- Ensembles in Statistical Mechanics: Introduction to microcanonical, canonical and grand canonical ensembles, Partition functions and connections to thermodynamic quantities
- Fluctuations, correlations and response: Correlation functions for liquids and magnets, Relation between fluctuations and response to external fields, Long range order
- Application of Statistical Mechanics to the Classical ideal gas, Rotational and vibrational spectra, Heat capacity of crystals, Spin systems, Chemical reactions, Polymer chains.
- Quantum Statistics: Fermi and Bose statistics, Ideal Fermi gas and Ideal Bose gas, recovering the classical limit, Fermi gases at low temperature, Bose-Einstein condensation.

- Statistical Mechanics of Interacting Systems 1: Interactions as perturbations: High temperature expansions, Virial expansions.
- Statistical mechanics of interacting systems 2: Simple liquids and magnets: the lattice gas model, Change of state, mean field theory.
- Applications of computer simulation: Introduction to Monte Carlo methods, Connection with statistical mechanics, Simulations of model polymers and magnets

P-205: Quantum Mechanics – II / Advanced Quantum Mechanics **4 Credits**

- Addition of angular momenta
- Spin and identical particles
- Time independent perturbation theory and Variation Method: Applications to atomic and molecular physics
- WKB approximation
- Scattering theory: Integral equation and Born approximation, Partial wave expansion, Applications to atomic and nuclear physics
- Time dependent perturbation theory: Semi-classical theory of radiation
- Relativistic quantum mechanics
- Second quantization of Schrodinger equation
- **Special topics:**
  - ❖ Radiation from uniformly accelerated charges.
  - ❖ Lasers and nonlinear optics, novel optical phenomena
  - ❖ Astrophysical phenomena like cosmic ray acceleration

P-206: Classical Electrodynamics - II **4 Credits**

- Special relativity and relativistic kinematics
- Covariant (Lagrangian) formulation of electrodynamics
- Motion of charges and electromagnetic fields: Leinard Weichert potentials
- Charges in electromagnetic fields: radiation from an accelerated Charge, Bremsstrahlung, Cherenkov, Synchrotron and Transition.
- Radiation reaction: energy loss mechanisms
- Electromagnetic fields propagating through matter: scattering, diffraction

P-207: Advance Experimental Methods **12 Credits**

- Study the hyperfine spectrum of Rb. (2 credits)
- Molecular Spectroscopy using Raman +FTIR+UV-Vis + Photoluminescence measurements (2 credits)
- Heterogeneous Electron Transfer Studies (2 credits)
- Magneto-Resistance Measurement on thin films (2 credits)
- Earth field NMR/ 300 MHz. (2 credits)
- Contact Angle Measurement (2 credits)

C-101: Physics & Chemistry of Materials: Bulk to Nano **4 Credits**

Pre-requisites: P-105 / C-202

- Introduction to semiconductors: Metal, Semiconductor and Insulator, Formation of Energy bands, carrier concentration and transport phenomena, electrochemical potential & Fermi-Dirac statistics, metal-semiconductor contacts (ohmic & Schottky). P-N junction characteristics, Transistors-Uni polar and bi-polar, Metal-oxide-semiconductor characteristics, MOSFETs. Scaling down effects - properties at the nano-scale: change in density of states due to confinement.
- Introduction to magnetism: Classifications - dia, para, ferro and anti-ferromagnetism. Domain wall theory,Magnetic anisotropy, exchange interactions, Introduction to meanfield approximation, periodic table of magnetic materials, magnons, and demagnetization factor, Size effects in magnetism.
- Nano-materials & nano-probes : Synthesis of nanomaterials - top-down & bottom-up approaches, characterization tools - optical and electron spectroscopy & microscopy, and mechanical analysis, introduction to electrochemistry.
- Nanofabrication & Nano-devices: Basics of fabrication techniques: photo-lithography, Ebeam lithography, etching techniques. Nano-devices–molecular electronics, resonant tunneling devices, single electron transistors.
- Extra-components: Guest lectures, Lab tour & Student presentations (covering important characterization methods / device physics).

C-102 : Organic Chemistry and Inorganic Chemistry **4 Credits**

- **Functional Group Interconversion**
  - ❖ Introduction to Functional group interconversion including protecting group strategy
  - ❖ Conversion of Alcohols to different functional groups
  - ❖ Introduction of different Functional group in selective positions of un-activated carbon centers
  - ❖ Inter conversion of carboxylic acid derivatives
  - ❖ Installation and removal of protecting groups
  - ❖ Applications: solid phase peptide synthesis and bio-conjugation reactions
- **Addition and reduction reactions of unsaturated homo- and hetero-nuclear bonds**
  - ❖ Metathesis of homo- and hetero-nuclear sigma bond with different substituent's across unsaturated homo- and hetero-nuclear bonds.
  - ❖ Hydroalumination, carboalumination, hydrozirconation reactions
  - ❖ Hydrogen addition reactions and catalytic hydrogenations using transition metal catalyst. Reductions using DIBAL-H, L-selectride, K-selectride, and Red-Al reagents including elective reduction.
- **Reactive Intermediates**
  - ❖ Carbonium ions, carbanions, and radicals: formation and rearrangement
  - ❖ Technique and strategy for isolation and trapping of reaction intermediates
  - ❖ Overview of some the reaction mechanism based on reaction intermediates
- **Methodologies for the construction of 3-7 membered rings**

- Diels-Alder reactions
- Metal catalyzed cyclopropanation reactions (including Simmons Smith reaction)
- [2+2] and [2+2+2]-cycloaddition reactions
- Nazarov cyclizations
- Ring expansion and ring contraction reactions
- Aza macrocycle synthesis
- Baldwin' rules for ring-closing reactions
- Special topic: Coordination Complexes in Inorganic Chemistry

- **Basics of Organometallic chemistry**
  - dn electron counting
  - Elimination and Addition Reactions involving transition metal complexes and their consequence on catalytic process
  - Syntheses and application of organometallic reagents
  - Coupling reactions: Kumada coupling, Suzuki-Miyaura coupling, Hiyama coupling, Sonogashira coupling, Negeshi coupling, Stille coupling, Buchwald-Hartwig Coupling, Heck reaction, Click Reactions.
- **Asymmetric Synthesis**
  - Sharpless epoxidation and dihydroxylation, Jacobsen's epoxidation
  - Corey's oxazaborolidine catalyzed reduction
  - Noyori's BINAP reduction
  - SAMP, RAMP, Evans oxazoline.
- **Principles of retrosynthetic analysis and Multistep synthesis**
  - Linear and convergent synthesis
  - Synthesis under steric control, Regio- and stereoselective synthesis
  - Application of chiral auxiliaries
- **Chemistry of Main group Elements (involving their usual oxidation states)**
  - Group 13, 14, and 15 elements: Boranes, Siloxanes, cyclophosphazenes,
  - cyclophosphazanes, poly silanes, and poly phosphazenes.
  - Group 16 elements: Sulfur and selenium
- **Chemistry and Applications of f-block elements**
  - Organo-lanthanide reagents
  - Applications in fluorescence imaging
- **Special Topics**
  - Homogeneous catalysis and catalysts: Alkene isomerization. Hydrogenation, Hydroformylation, Monsanto acetic acid process, Alkene polymerization, Cross coupling reactions, Metathesis, C-H activation and functionalization, Oxidation of olefins, Metal Clusters and catalysis.
  - Supramolecular constructs and metal-organic frameworks
  - Combinatorial approaches to synthesis
  - Light induced reactions
  - Synthesis in engineered micro-organisms

C-204/ B-203: Biophysics **4 / 3 Credits**

- Introduction: Biomolecules, Cells, Multicellular Organisms
- Intermolecular forces: Van der waals, Hydrophobic etc.
- Hemoglobin: allostery etc.
- Basic Electrostatics: Debye-Huckel, dielectric constant etc.
- Basics of polymer statistics
- DNA as a polyelectrolyte (Ion condensation etc)
- Motor Proteins
- Membranes
- Metabolic Control theory
- Biological Physics: (switch, repressilator, chemotaxis etc.)

C-205: NMR spectroscopy **4 Credits**

- Basic concepts in NMR spectroscopy
- Biomolecular structure determination using NMR
- Two-dimensional NMR
- Multiple quantum NMR
- Heteronuclear NMR
- Three-dimensional NMR
- Protein structures by NMR
- Nucleic acid structures by NMR
- Study of metabolism using NMR
- Magnetic resonance imaging (MRI)

B-201: Cell Biology **3 Credits**

- Physical and chemical processes regulating cellular function - Mechanobiology, effects of substrate stiffness and mechanical forces on cell fate and development, chemical modifications of DNA and histone proteins regulating gene expression (Epigenetics), phosphorylation cascades that regulate chromatin function and DNA repair. Works of Ingber, Discher, Allis and others to be discussed.
- Roles of the cytoskeleton and associated motor proteins - structure of actin, microtubules, cytoskeletal intermediate filaments, nuclear intermediate filaments (lamins), discovery of myosin and kinesin. Pioneering works of Spudich, Vale and others to be discussed.
- Basic processes of transcriptional and translational regulation, endocytosis, exocytosis and protein export, RNA splicing and export - Biochemical processes in specific cellular organelles like the endoplasmic reticulum, golgi, mitochondria, nucleus and nucleolus and the plasma membrane. Works of Rothman, Schekman, Sharp, Malhotra and others to be discussed. Books: Molecular Biology of the Cell by Alberts et al, Physical Biology of the Cell by Phillips etal, Genes by Lewin.

B-202: Cell physiology and cell signaling **3 Credits**

- **Diffusion, osmosis and cell volumes:** Understand how electrolytes and non-electrolytes change the cell volume in closed and open system under different experimental conditions. Provide examples for each experimental condition, how intra-cellular and extracellular permeants and impermeants change the flow-volume and ultimately the cell-volume. Know the similarities and differences between diffusion and osmosis. Provide examples to calculate the cell volume and osmotic pressure under different experimental conditions. Understand the difference between, molarity, osmolarity, equivalence and milli-equivalence. Explain why body fluids are measured in Osmolarity or milli-equivalence.
- **Body fluid volume:** Learn the composition of body fluids; Intra-cellular Fluid (ICF), Extra-cellular Fluid (ECF), Interstitial Fluid (IS), Plasma volume (PV). Discuss how fluid loss changes the body fluid composition and the cell volume (ex: vomition, diarrhoea, sweating, etc.). Explain how body fluid volume could change the normal homeostasis and cell signaling.
- **Membrane Transport system:** Know the similarities and differences between diffusion, facilitated diffusion, primary and secondary active transport, co-transport and counter transport. Provide examples of each type of transport. Understand the energy source which drives each type of transport. Understand the difference between pores, channels and pumps.
- **Ionic equilibrium, current voltage diagrams and membrane potential:** Explain how chemical and electrical potential is getting developed in the cell and why cell maintains negative membrane potential? Explain and derive Nernst potential equation. Understand the importance of Na2+, K+,Cl-and Ca2+ions and Na2+/K+ pump in the context of membrane potential. Provide examples to calculate membrane potential from Nernst potential. Explain ionic current, conductance and permeability to understand the current-voltage (I-V) relationship and membrane potential. Give introduction to patch-

clamp technique to measure the membrane potential and channel activity. Summarize Nernst potential, membrane potential, chord conductance equation and the resting membrane potential. Classify different types of ion channels

- **Generation and transmission of Action potential:** Explain the resting membrane potential, sub threshold potential, threshold potential and refractory period. Understand the sequence of events in the action potential, ion channels involved and transmission of action of potential. Explain the cable theory in comparison with neuronal signal transmission. Explain how depolarization and repolarization in cardiac myocytes measure as electro cardiogram (ECG).
- **Neuromuscular junction (NMJ) and central synapses:** Learn the structure of a neuromuscular junction and the sequence of events that lead to neurotransmission. Understand end plate potential, miniature end plate potentials and spontaneous end plate potentials. Understand the properties of acetylcholine receptor and their importance in depolarization. Differentiate NMJ and central synapses.
- **Neurotransmitters in cell signaling:** Learn different neurotransmitters involved in central and peripheral nervous system. Understand the signaling mechanism how it modulated ion channel and membrane proteins as a signaling molecules. Know differention channel blockers and its toxicological effect and pharmaceutical usage by in modulating cell signaling.
- **Mitochondrial electron transport system and ATP production:** Learn the structure and mitochondrial membrane potential. Understand the electron transport process and the respiratory enzyme complexes. Understand the mechanism of ATP synthesis using proton gradient and mitochondrial energy metabolism. Understand the importance of mitochondrial Ca2+signaling. Learn about mitochondrial uncoupling protein (UCP) and mitochondrial calcium uniporter (MCU). Learn how UCP involved in hibernation. Learn how to image mitochondria using fluorescent dye.
- **Ca2+signaling:** Understand the important roles of calcium as a secondary messenger. Learn about Ca2+ channels (voltage gated Ca2+channel, Store operated Ca2+ channel (SOC), etc.) and pumps (SERCA and PMCA). Know more about endoplasmic reticulum, intracellular and extracellular Ca2+signaling. Learn Ca2+ imaging techniques using Fluo-4 and Fura-2.
- **Reactive oxygen species (ROS) signaling:** Learn the mechanism of ROS generation in mitochondria and plasma membrane. Understand the physiological and pathological significance of ROS signaling.
- **Cell signaling pathways (cell survival and cell death signaling):** Learn the basic principles and classification of cell signaling pathways. Know about various types of receptor and cell stimuli involved in cell signaling. Understand different cell signaling pathways and proteins involved; PIP pathway, Akt /PI3K, MAP kinase, GPCRs, cAMP, cGMP, PKA, PKC, PLC etc. Learn apoptotic and anti-apoptotic proteins and the signaling mechanism. Differentiate apoptosis, necrosis and autophagy. Understand different caspase proteins and their roles. Explain the relationship between Ca2+ signaling in apoptosis.

B-204: Basic Mathematics for Biologists **3 Credits**

- Permutations and combinations
- Binomial theorem, Probability and statistics.
- Calculus: derivatives, integration,
- Simple differential equations.

B-205: Fluorescence Methods in Cellular Biophysics **3 Credits**

- Basics of fluorescence - Jablonski diagrams, Stokes shifts, structures of fluorophores, quantum yields, fluorescence instrumentation - fluorescence microscopy and spectroscopy, light sources, filters, and detectors (PMTs, APDs and camera technologies - CCD, EMCCD, CMOS, sCMOS etc.)
- Forster Resonance Energy Transfer (FRET), Time-Correlated Single Photon Counting (TCSPC), fluorescence lifetime, quenching - theoretical ideas, technical details behind measurements and applications. Fluorescence polarization measurements - steady-state and time-resolved fluorescence anisotropy - theory, instrumentation and technical details.
- Widefield microscopy, effects of objective numerical aperture on resolution, diffraction limit of resolution of light microscopy, single molecule imaging of mRNA as an example, basics of flow cytometry.
- Confocal microscopy - point-scanning and spinning disk confocal microscopy; light sheet microscopy; Total Internal Reflection Fluorescence (TIRF) microscopy; considerations for temporal resolution; multiphoton microscopy.
- GFP technology and dynamics measurements in live cells - Single Particle Tracking (SPT), Fluorescence Correlation spectroscopy (FCS) - both APD and camera-based, Fluorescence Recovery After Photobleaching (FRAP), live cell mRNA dynamics measurements
- Super-resolution microscopy methods - stimulated emission depletion (STED), structured illumination microscopy (SIM), stochastic optical reconstruction microscopy (STORM), photo activated localization microscopy (PALM), point accumulation for imaging in nanoscale topography (PAINT) and others.

E-201: Scientific Communication 2 Credits

- **How to read a scientific paper**
- **How to present work: students will do**
  - ❖ Short talks (10 mins) + poster sound – bites
  - ❖ Journal club presentations of work published by others
  - ❖ Presentations of own research aimed at both a specialist and a non - specialist audience
- **Scientific Writing**
  - ❖ A journal article (bring drafts of current papers)
  - ❖ A research proposal
  - ❖ An article for the popular press
- **Video presentations**
  - ❖ An idea + experiment/demonstration in less than 4 minutes
  - ❖ A description of personal research goals and interests (interview others)
- **Scientific literacy and ethics, including**
  - ❖ What constitutes ownership of an idea
  - ❖ Proper referencing and credit attribution
  - ❖ What constitutes plagiarism

E-202: Error Analysis and Statistical Inference in Experiment 2 Credits

- **Errors in experimental science:** Errors as uncertainties. Inevitability of uncertainty. Importance of knowing the uncertainties. Estimating uncertainties in repeatable measurements.
- **How to report and use uncertainties:** Best estimate ± Uncertainty. Significant figures. Discrepancy. Comparison of measured and accepted values. Comparison of two measured numbers. Fractional uncertainties. Significant figures and fractional uncertainties. Multiplying two measured numbers.
- **Propagation of uncertainties:** Uncertainties in direct measurements. Sums and differences, products and quotients. Independent uncertainties in a sum. Arbitrary function of one variable. General formula for error propagation.
- **Statistical analysis of random uncertainties:** Random and systematic errors. The mean and standard deviation. The standard deviation as the uncertainty in a single measurement. The standard deviation of the mean.
- **The normal distribution:** Histogram and distributions. Limiting distributions. The normal distribution. The standard deviation as 68% confidence limit. Justification of the mean as the best estimate. Justification of addition in quadrature. Standard deviation of the mean. Confidence.
- **Averaging data:** Weighted averages
- **Rejection of data:** The problem of rejecting data. Chauvenet's criterion.
- **Least-square fitting:** Maximum likelihood and Fitting data to a straight line.
- **The binomial distribution and the Poisson distribution:** Probabilities in dice throwing. Definition of the binomial distribution. Properties of binomial distribution. Definition of the Poisson distribution. Properties of Poisson distribution

- **The χ 2 test for a distribution:** Introduction to χ 2 . General definition of χ 2 . Degrees of freedom and reduced χ 2 . Probabilities of χ 2 .
- **Some special topics:** Use of covariance. Confidence limits on estimated parameters.

E-203: Computer Programming using Python language **2 Credits**

- Simple programs with input and output
- Variables, operations, expressions, statements
- Numbers, characters, strings
- Tuples, lists, dictionaries, sets
- Functions
- Scoping
- Conditionals
- Iteration
- Manipulating text
- Files
- Packages
- Computing with random numbers Along the way, we will learn some simple algorithms.

E-204: Advanced Topics in Inorganic and Organic Chemistry **4 Credits**

- **First Row Main Group Elements:** Activation of Hydrogen by Lewis pairs, Hydrogenation and Dehydrogenation reactions (catalytic-non catalytic) involving main group reagents. Boryl Lithium, Borylene, Boron based nucleophile and Lewis Base. Classical and Non Classical Carbocation synthesis and structure, Bonding of C2 molecule, Hyper coordinated carbon and some unusual carbon based systems including carbenes.
- **Heavier Main Group Elements:** Mg(I) Compound. Mg(I) as a Reducing Reagents. Chemistry of compounds involving Low-Valent Low-Coordinate Aluminum, Silicon, Germanium, Tin, Lead, Phosphorous, Arsenic, Antimony, and Bismuth. Bonding description of disilenes and disilynes and its comparison with alkenes and alkynes.
- **Transition Metals:** Compounds involving metal metal bonding (including zinc) and its reactivity. Transition metal hydrides and fluorides. Some aspects of transition metals in bio inorganic chemistry.
- **Organic Synthesis:** Halonium ions in organic chemistry. Cascade reactions. Flow reactions. Selective oxidation-reduction, and epoxidation. Wittig reagent. Application of boron and silicon compounds in organic synthesis. Modern approach in natural product synthesis.

E-301: Optics **4 Credits**

Pre-requisites: --

- **Basic properties of EM field:** Electro-magnetic field, Maxwell's equations, boundary conditions, energy law of EM field; Scalar waves, plane, spherical and harmonic waves, phase and group velocity; Vector waves, EM plane wave, harmonic EM plane wave; elliptic polarization, characterization of state of polarization, Stokes parameters, Poincaré sphere representation; Reflection and refraction of plane waves, Fresnel formulae, reflectivity and transmissivity, polarization on reflection, total reflection.
- **Theory of interference and interferometers:** Interference of two monochromatic waves, wave-front and amplitude division interferometers, fringes with quasi monochromatic sources, visibility of fringes, coherence; multiple beam interference and interferometers.
- **Theory of diffraction:** Huygens-Fresnel principle, Kirchhof's diffraction theory, Fraunhofer and Fresnel diffraction; Fraunhofer diffraction at apertures and in optical instruments, Fresnel diffraction at a straight edge.
- **Interference and diffraction with partially coherent light:** Polychromatic fields, correlation function of light beams van-Cittert –Zernike theorem; polarization properties of quasi monochromatic light, coherency matrix, degree of polarization.
- **Optics of metals:** Wave propagation in a conductor, reflection, refraction at a metal surface, elementary electron theory
- **Optics of crystals:** Dielectric tensor of anisotropic medium, monochromatic wave in an anisotropic medium, phase and ray velocity, Fresnel's formulae, index ellipsoid, uniaxial and biaxial crystals, measurements.
- **Advanced topics:** Beam shifts, cylindrical vector beams, optical angular momentum, advances in microscopy.

E-302: Condensed Matter Physics **4 Credits**

Pre-requisites: --

- Elementary excitations in solids
- Electrons in metals: Drude model
- Electrons in metals: Sommerfeld model
- Describing periodicity: Crystal lattices
- Electrons in periodic crystals: Bloch states & Bands
- Electrons in metals: Fermi surfaces
- Vibrations of periodic crystals: phonons
- Electrons & phonons: Scattering or binding
- From atoms to solids: Periodic Table
- Messing up periodicity: Defects in crystals

E-303: Atomic & Molecular Physics **4 Credits**

Pre-requisites: --

- Interaction of one-electron atoms with electromagnetic radiation.
- One-electron atoms: fine structure, hyperfine structure and interaction with external electric and magnetic fields.

- Two-electron atoms: Para and ortho states, Independent particle model, Excited states of two-electron atoms.
- Many electron systems: Thomas-Fermi model, the Hartree-Fock method, LS- and jj-couplings.
- The interaction of many-electron atoms with electromagnetic fields. Selection rules, Atoms with several optically active electrons. Zeeman effect and quadratic Stark effect.
- Molecular structure. The Born-Oppenheimer separation for diatomic molecules, rotation and vibration of diatomic molecules. Structure of polyatomic molecules.
- Molecular spectra: Rotational energy levels of diatomic molecules, Vibrational-rotational spectra, electronic spectra, Electronic spectra and Hund's cases, nuclear spin.

E-401: Advanced Computational Methods **4 Credits**

Pre-requisites: P-202

- Programming primer - C Vs. Fortran Arrays, Memory allocation, Functions and Subroutines, What NOT to do while handling arrays, Debuggers
- Advection equation - Finite difference, Spectral, Boundary conditions
- Diffusion equation - Finite difference, Spectral , Boundary conditions
- Examples of Advection-Diffusion equation - Inviscid and Viscous Burgers equation, Chemical reactions: Advection-Diffusion-Reaction equation (Fisher equation)
- Poisson equation - Matrix diagonalization , Fast solvers
- A "real" problem: 2D Navier-Stokes simulation in a box - Lid-driven cavity problem, Introducting obstacles: Volume penalization
- A new approach to fluid dynamics: Lattice Boltzmann method - Boltzmann equation and its discretization, From Boltzmann equation to Navier-Stokes: Chapman-Engskok expansion, 2D Navier-Stokes with variety of boudary conditions
- MPI programming of Navier-Stokes and Lattice Boltzmann
- If possible: Invited presentations
    - ❖ Rahul Pandit on Navier-Stokes simulations in 3d
    - ❖ Mahendra Verma/Abhik Basu MHD simulations.
    - ❖ Dhrubaditya Mitra on solar MHD simulations.
    - ❖ Samriddhi Sankar Ray on Tigers in Burgers equations. (after Advection-Diffusion)
    - ❖ Rama Govindarajan on stability problems. (after Poisson equation)

E-402: Advanced Dynamics **4 Credits**

Pre-requisites: P-101 / C-201 , P-202

- low-order systems of ordinary differential equations
- maps
- linear stability
- bifurcations
- routes to chaos
- Navier-Stokes and continuity equation, some simple shear flows
- Flow stability: Kelvin-Helmholtz, Rayleigh-Benard, Taylor-Couette
- Routes to turbulence

- Elastic instabilities

E-403: Advanced Statistical Mechanics / Statistical Mechanics - II 4 Credits

Pre-requisites: P-204 / C-103

- A quick summary of different ensembles. Non-interacting Classical Systems - magnetic systems, ideal gas and Harmonic oscillator, Statistical mechanics for interacting systems: Cluster expansion.
- Interacting Magnetic Systems, Ising and Heisenberg Model, Mean Field Theory, Transfer Matrix Method, Phase Transitions: Order Parameter, First and Second Order Phase Transitions, Landau-Ginzburg Theory, Scaling, Critical exponents and Universality class, Generalized Homogeneous function, Hyper Scaling relation, Kadanoff Construction, Renormalization Group Transformation, Momentum Space RG.
- Dynamical systems, Linear Response, Fluctuation-Dissipation Theorem, Brownian Motion, Langevin Equation, Fokker-Planck Equation.

E-404: Phase Transitions, Ordering and Dynamics 4 Credits

Pre-requisites: P-204 / C-103

- Ordered Phases and Phase Transitions: Phenomenology; Models; Correlation Functions; Mean field theory
- General Results on Ordering: Absence in 1-d; Peierls argument; Spin waves; Lower critical dimension; Mermin-Wagner theorem
- Critical Phenomena: Fluctuations and their growth; Ornstein-Zernike theory; Scaling; Universality; Upper critical dimension, Ginzburg criterion
- Renormalization Group: Basic idea; Real-space RG; Epsilon expansion; Multicriticality Specific Systems: XY Model; Polymers
- The framework of time-dependent statistical mechanics: Linear response theory, fluctuation-dissipation theorem, Kubo formulae
- Brownian motion: Langevin and Fokker-Planck approaches
- Microscopic stochastic dynamics: Kinetic Ising models; Master equation
- Coarse-grained stochastic dynamics: Generalised Langevin equations; Fluctuating hydrodynamics of broken-symmetry systems; dynamics of critical phenomena
- Field-theoretic methods and models: Functional integrals for statistical dynamics; dynamical renormalization group; application of these techniques to selected models at and away from thermal equilibrium.

E-405: Soft Matter and Biological Physics 4 Credits

Pre-requisites: P-204 / C-103, P-403

Polymers, Glass Formation and Jamming

- Polymers: Introduction to polymers; Ideal polymer chains; Real Chains: Excluded Volume; Polymer Solutions; Electrostatics; Polyelectrolytes; Networks and gelation; Polymer Dynamics; Rheology of Polymers; Protein Folding

- Glass Formation and Jamming: Glass transition phenomenology; Crystal nuclation and glass forming ability; Description of dynamics; Mode Coupling Theory; Energy landscape approach; Spin glasses; Random First Order Transition theory; Dynamic Heterogeneity; Jamming; Glassy Rheology

E-406: Advanced Mathematical Physics **4 Credits**

Pre-requisites: P-101 / C-201

- Vectors in 3-d; addition, products; transformation under rotations; active and passive transformations; invariants; compact formulation via isotropic tensors; vectors in diverse dimensions; polar and axial vectors in 3-d;Euler angles.
- Vector fields and vector calculus; div and curl; various identities of vector calculus; electrodynamics as illustration of 4-d; electrodynamics in diverse dimensions; applications to fluid dynamics and elasticity; line, surface and volume integrals.
- Gauss's theorem, Stoke's theorem, Green's theorem, Helmholtz theorem and Alfven's theorem; coherence in quantum optics.
- Matrices; nilpotent and idempotent matrices; diagonalisation; upper and lower triangular matrices; orthogonal, unitary and Hermitian matrices; normal matrices; LUdecomposition; direct product matrices; eigenvalues and eigenfunctions; generalized eigenvectors; geometric and algebraic multiplicities; defective matrices ; left and right eigenvectors; Schur canonical form; Jordan canonical form; Singular value decomposition; Schmidt decomposition.
- Tensor calculus
- Group theory; rotations and translations; generators and their algebra; unitary unimodular groups in physics; Lorentz and Poincare groups; group representations
- Transformations and symmetries; coordinate transformations; invariances and symmetries; Noether's two theorems
- Finite groups; order of the group, order of the element, periods, rearrangement theorem, multiplication tables, subgroups and cosets; Lagrange's theorem; quotient group; conjugacy classes; group characters;
- Permutation groups and their properties; cyclic groups and their properties; the continuous groups SO(2), SO(3), SU(2) and SU(N)
- **10.**Representations of groups
- Probability theory; discrete and continuous random variables; mean, variance and higher moments; dependent and independent random variables - joint, marginal and conditional probabilities; uniform distribution, gaussian distribution; uniform distribution on group manifolds; Bayesian approach to probability.

E-407: Advanced Continuum Mechanics **4 Credits**

Pre-requisites: P-101 / C-201

- Hydrostatics, Surface tension, continuity equation, Euler equation, Bernoulli's theorem. Vorticity equation, inviscid, simple vertical flows, shear stress, simple channel flow. Navier-Stokes, non-dimensionalisation, Stability theory

- The elastic continuum, broken symmetry. Simple elastic free energies of meso-phases and solids. Defects, Volterra constructions, Defect dynamics and elasticity. Time dependent elastic moduli. Elements of plasticity.

E-408: Field Theory 4 Credits

Pre-requisites: P-105 / C-202, P-101 / C-201, P-205

- Resume of classical mechanics, resume of quantum mechanics, path integral formulation of quantum mechanics, connections to classical statistical mechanics.
- Relativistic quantum mechanics: spin, Klein paradox, antiparticles. Inevitability of many particles even in single particle descriptions. Dirac sea. Simple relativistic processes.
- Fermi sea, particles and holes, nonrelativistic many-body systems, 'relativistic' behaviour in non-relativistic systems, graphene.
- Point particles to fields. Classical fields in Lagrangian and Hamiltonian formulations, symmetries and conservation laws.
- Electromagnetic and Gravitational fields. Elasticity as field theory. Hydrodynamics and Field theory, Field theory of liquid crystals.
- Quantisation of scalar fields. Overview of Quantum Electrodynamics. Why atoms radiate? Casimir effect. Examples from Quantum Optics.
- BCS theory of superconductivity. Pions and superconductivity. Higgs bosons and superconductivity.
- Asymptotic freedom in QCD. Kondo effect - asymptotic freedom in condensed matter physics.
- Singular potentials in QM as a guide to renormalisation. Scaling and critical phenomena.

E-409: Nonlinear Dynamics 4 Credits

Pre-requisites:

The course will consist mainly of homework and project work, with few lectures. The book "Nonlinear dynamics and chaos" by Steven Strogatz will be broadly followed and home-work assignments will be based on this.

Apart from this, each student (or pair of students) will be assigned a Separate project on a particular aspect of NLD.

E-410: Intense laser matter interactions 4 Credits

Pre-requisites: E-301 / E-303

- Conditions for producing a Laser – Population inversions, Gain and Gain Saturation
- Laser Oscillation above Threshold
- Requirements for obtaining Population inversions
- Laser Pumping requirements and techniques
- Laser Cavity Modes
- Stable Laser Resonators & Gaussian Beams
- Introduction to the Theory of Field-Induced Atomic Transitions
- Multiphoton Stimulated Bremsstrahlung

- Multiphoton Compton Scattering and Ponderomotive Forces in an Inhomogeneous Light Field
- Free-Electron Lasers

E-411: Solid State NMR **4 Credits**

Pre-requisites: C-202 / P-105, C-205

- Principles of solid-state NMR: Spin interactions, anisotropy of interactions, Frame transformations, magic-angle spinning, heteronuclear spin decoupling, cross polarisation
- Sensitivity enhancement in spins-1/2: Cross polarisation, theory and pulse schemes, transient oscillations, dipolar coupling information, spectral editing, adiabatic /ramped CP, Scalar coupling transfers in solids.
- Resolution enhancement in spins-1/2: Decoupling, various pulse schemes, experimental strategies, refocussed and non-refocussed transverse relaxation times
- Distance and Geometry information via recoupling: Separated local field experiments, pulse schemes based on symmetry of spin interactions, applications to correlation/distances/bond and torsional angles/assignments
- Quadrupolar spins: Introduction to half-integer and integer spin quadrupolar nuclear spins, comment on resolution and sensitivity issues, applications
- Solid-state NMR for bio-molecular applications.

E-412 : Principles in Cancer & Cancer Stem cell biology **3 Credits**

Pre-requisites: --

- Normal Cell Vs. Cancer Cell
- How are tumours derived?
- Carcinogens and Tumourigensis
- Cell immortalization
- How do viruses cause cancer
- Oncogenes and tumour suppressor genes
- Maintenance of genore integrity and development of cancer
- Invasion and metastasis – epithelial to mesenchymal transition
- Cancer stem cells – Basics and how to target cancer stem cells
- Rationale treatment of Cancer
- Special emphasis on few important cancers which are prevalent in India – Breast cancer, Oral cancer etc.

E-413 : Biological thermodynamics **3 Credits**

Pre-requisites: --

- Introduction to Thermodynamics. Zeroth Law. Concept of different types of thermodynamic systems. Temperature, work, and heat. Energy transformation.
- First law of thermodynamics. Energy conservations, thermodynamic states, and paths. Concept of equilibrium. Reversible and Irreversible Processes. Heat engines. Maxwell relations.

- Second law of thermodynamics. Entropy (Boltzmann and Clausius). Efficiency of heat engine. Third law of thermodynamics.
- Thermodynamics and statistical thermodynamics. Maxwell's demon, minus first law of thermodynamics, and information theory. Concept of ensembles, partition functions, Boltzmann distribution, and calculation of thermodynamic quantities from partition function. Diffusion. Analysis of thermodynamic data. Multistate equilibrium.
- A mid-term test, on the laws of thermodynamics.
- Phase transition. Phase Equilibria. Clausius-Clapeyron Equation.
- Gibbs free energy: theory and applications. Chemical potential. Standard States and Gibbs-Duhem equation. Ionic solutions. Equilibrium constant. Acids and bases. Redox reactions. Chemical coupling. Glycolysis and citric acid cycle. Oxidative phosphorylation and ATP hydrolysis. Osmosis, dialysis, and membrane potential. Donnan equilibrium. Enzyme–substrate interaction. Protein stability and reaction. DNA melting and polymerase chain reaction (PCR).
- Quiz on the theory and applications of Gibb's free energy.
- Binding equilibria and reaction kinetics. Single-site model. Scatchard and Hill plots. Rate constant and order of reaction. First and second order reactions. Transition state theory.
- Energy, information, and life. A discussion on non-equilibrium thermodynamics and living systems.
- Oncogenes and tumour suppressor genes
- Maintenance of genore integrity and development of cancer
- Invasion and metastasis – epithelial to mesenchymal transition
- Cancer stem cells – Basics and how to target cancer stem cells
- Rationale treatment of Cancer
- Special emphasis on few important cancers which are prevalent in India – Breast cancer, Oral cancer etc.

E-414 : Mechanobiology of cells and molecules **3 Credits**

Pre-requisites: --

- **Introduction:** On growth and form. Historical overview of mechanobiology and its importance. Cell biology in terms of important numbers. Different forces and stresses in cell biology. Frequently used solid and fluid mechanics concepts.
- **Tools for experiments:** Traction force microscopy and monolayer stress microscopy. Molecular force sensors. Optogenetic methods. Förster resonance energy transfer (FRET). Atomic force microscope. Micropipette aspiration. Magnetic tweezes. Rheological measurements within a cell. Popular methods for providing physical perturbations to a cell. Photo- and soft-lithography based micropatterning and related mechanobiological examples. Brief overview of microfluidics with examples.
- **Force-sensitive cellular structures:** Cell structure. Cytoskeleton and its components. Actin filaments and actomyosin network. Actomyosin contractility and example of muscle cell contraction. Microtubules and their force-sensitive participation in cell division. Diversity of cytoplasmic and nuclear intermediate filaments and their role in cancer. Nuclear force transduction. Force sensitive molecular complexes including focal adhesions and adherens junctions. Extracellular matrix mechanics. Stiffness effect on

cellular differentiation. Force transmitting proteins or mechanotransducers including cadherins and integrins.

- **Mechanobiology of physiological processes:** Single cell to multicellular composites. Mechanobiology of single and collective cell migration. Introduction to developmental biology. Forces during development and organogenesis. Differential adhesion hypothesis. Mechanobiology of cardiovascular system and bronchial tissue. Stem cell mechanics. Mechanobiology of cancer. Mechanical considerations for biomaterials and tissue engineering. Open questions.