Physics Courses Syllabus

CP1. Physics 1

Newton's law of motion. Mechanics of particles in one dimension. Energy, work and impulse. Conservation of linear momentum including problems where the mass changes, e.g. the motion of a rocket ejecting fuel. Conservation of energy.

Vector formulation of Newton's law of motion. Time-dependent vectors and differentiation of vectors.

Mechanics of particles in two dimensions. Equations of motion in Cartesian and plane polar coordinates. Simple cases of the motion of charged particles in uniform E and B fields.

Projectiles moving under gravity, including such motion subject to a damping force proportional to velocity. Dimensional Analysis.

Systems of point particles. Centre of mass (or momentum) frame and its uses. Torque and angular momentum. Conservation of angular momentum. Two-body collisions.

Central forces. Importance of conservation of energy and angular momentum. Classification of orbits as bound or unbound (derivation of equation for $u=1/r$ not required; explicit treatment of hyperbolae and ellipses not required). Inverse square central forces. Examples from planetary and satellite motion and motion of charged particles under the Coulomb force. Distance of closest approach and angle of deviation.

Calculus of variations. Principle of stationary action (Hamilton principle). The Euler-Lagrange equation. Constraints. Application to particle motion in one and two dimensions. Small oscillations, normal coordinates. Compound pendulum. Conservation laws. Noether's theorem. The Hamiltonian and energy conservation.

Moment of inertia of a system of particles. Use of perpendicular- and parallel-axis theorems. Moment of inertia of simple bodies. Simple problems of rigid body dynamics. Angular impulse, collision and rolling. The concept of principal axes. Angular momentum and total energy in rigid body rotation.

Special Relativity

Special theory of relativity restricted throughout to problems in one or two space dimensions. The constancy of the speed of light; simultaneity. The Lorentz transformation (derivation not required). Time dilation and length contraction. The addition of velocities. Invariance of the space-time interval. Proper time.

Energy, momentum, rest mass and their relationship for a single particle. Conservation of energy and momentum and the use of invariants in the formation sub-atomic particles. Elementary kinematics of the scattering and decay of sub-atomic particles, including photon scattering. Relativistic Doppler effect (longitudinal only).

CP2. Physics 2

The treatment of electromagnetism is restricted to fields in vacuo. Vector operator identities required will be given on the data sheet. Complicated manipulations of vector operators will not be set.

Electromagnetism

Coulomb's law. The electric field E and potential due to a point charge and systems of point charges, including the electric dipole. The couple and force on, and the energy of, a dipole in an external electric field. Energy of a system of point charges; energy stored in an electric field. Gauss' Law; the E field and potential due to surface and volume distributions of charge (including simple examples of the method of images), no field inside a closed conductor. Force on a conductor. The capacitance of parallel-plate, cylindrical and spherical capacitors, energy stored in capacitors.

The forces between wires carrying steady currents. The magnetic field B, Ampere's law, Gauss' Law ("no magnetic monopoles"), the Biot-Savart Law. The B field due to currents in a long straight wire, in a circular loop (on axis only) and in straight and toroidal solenoids. The magnetic dipole; its B field. The force and couple on, and the energy of, a dipole in an external B field. Energy stored in a B field.

The force on a charged particle in E and B fields.

Electromagnetic induction, the laws of Faraday and Lenz. EMFs generated by an external, changing magnetic field threading a circuit and due to the motion of a circuit in an external magnetic field, the flux rule. Self and mutual inductance: calculation for simple circuits, energy stored in inductors. The transformer.

Charge conservation, Ampere's law applied to a charging capacitor, Maxwell's addition to Ampere's law ("displacement current").

Maxwell's equations for fields in a vacuum (rectangular co-ordinates only). Plane electromagnetic waves in empty space: their speed; the relationships between E, B and the direction of propagation.

Circuit Theory

EMF and voltage drop. Resistance, capacitance, inductance and their symbolic representation. Growth and decay of currents in circuits, time constant. The concept of complex impedance in steady-state AC circuit analysis.

Ideal Op-amp: inverting and non inverting amplifier circuits; summation, integration and differentiation circuits.

Optics

Elementary geometrical optics in the paraxial approximation. Refractive index; reflection and refraction at a plane boundary from Huygens' principle and Fermat's principle; Snell's Law; total internal reflection. Image formation by reflection at a spherical boundary; concave and convex mirrors. Real and virtual images. Magnification. Image formation by refraction at a spherical boundary and by converging and diverging thin lenses. Derivation of the expression for the focal length of a thin lens. [Non-examinable: Image formation by systems of thin lenses or mirrors as illustrated by: a simple astronomical telescope consisting of two convex lenses, a simple reflecting telescope, a simple microscope.]

Simple two-slit interference (restricted to slits of negligible width). The diffraction grating, its experimental arrangement; conditions for proper illumination. The dispersion of a diffraction grating. (The multiple-slit interference pattern and the resolution of a diffraction grating are excluded.) Fraunhofer diffraction by a single slit. The resolution of a simple lens.

Note: the above electromagnetism syllabus is also that for the Physics and Philosophy Part A paper A2P (Electromagnetism), excluding the sections on Circuit Theory and Optics.

CP3. Mathematical Methods 1

Differential equations and complex numbers

Complex numbers, definitions and operations. The Argand diagram; modulus and argument (phase) and their geometric interpretation; curves in the Argand diagram. De Moivre's theorem. Elementary functions (polynomial, trigonometric, exponential, hyperbolic, logarithmic) of a complex variable. (Complex transformations and complex differentiation and integration are excluded.)

Ordinary differential equations; integrating factors. Second-order linear differential equations with constant coefficients; complementary functions and particular integrals. Application to forced vibrations of mechanical or electrical resonant systems, including the use of a complex displacement variable; critical damping; quality factor (Q), bandwidth, rms, peak and average values. [Physical interpretation of complex impedance and power factor is not assumed]

Vector algebra

Addition of vectors, multiplication by a scalar. Basis vectors and components. Magnitude of a vector. Scalar product. Vector product. Triple product. Equations of lines, planes, spheres. Using vectors to find distances.

Matrices

Basic matrix algebra: addition, multiplication, functions of matrices. Transpose and Hermitian conjugate of a matrix. Trace, determinant, inverse and rank of a matrix. Orthogonal, Hermitian and unitary matrices. Vector spaces in generality. Basis vectors. Scalar product. Dual vectors. Linear operators and relation to matrices. Simultaneous linear equations and their solutions. Determination of eigenvalues and eigenvectors, characteristic polynomial. Properties of eigenvalues and eigenvectors of Hermitian linear operators. Matrix diagonalisation.

CP4. Mathematical Methods 2

Elementary ideas of sequences, series, limits and convergence. (Questions on determining the convergence or otherwise of a series will not be set.) Taylor and MacLaurin series and their application to the local approximation of a function of one variable by a polynomial, and to finding limits. (Knowledge of and use of the exact form of the remainder are excluded.) Differentiation of functions of one variable including function of a function and implicit differentiation. Changing variables in a differential equation, integration of functions of one variable including the methods of integration by parts and by change of variable, though only simple uses of these techniques will be required, such as $\int x \sin x \, dx$ and $\int x \exp(-x2) dx$ The relation between integration and differentiation, i.e. $\int dx \;\; b \; a$ (df/dx) and d/dx ($\int f(x') dx' \; x \; a$).

Differential calculus of functions of more than one variable. Functions of two variables as surfaces. Partial differentiation, chain rule and differentials and their use to evaluate small changes. Simple transformations of first order coefficients. (Questions on transformations of higher order coefficients are excluded.) Taylor expansion for two variables, maxima, minima and saddle points of functions of two variables.

Double integrals and their evaluation by repeated integration in Cartesian, plane polar and other specified coordinate systems. Jacobians. Probability theory and general probability distributions. Line, surface and volume integrals, evaluation by change of variables (Cartesian, plane polar, spherical polar coordinates and cylindrical coordinates only unless the transformation to be used is specified). Integrals around closed curves and exact differentials. Scalar and vector fields. The operations of grad, div and curl and understanding and use of identities involving these. The statements of the theorems of Gauss and Stokes with simple applications. Conservative fields.

Waves

Coupled undamped oscillations in systems with two degrees of freedom. Normal frequencies, and amplitude ratios in normal modes. General solution (for two coupled oscillators) as a super-position of modes. Total energy, and individual mode energies. Response to a sinusoidal driving term.

Derivation of the one-dimensional wave equation and its application to transverse waves on a stretched string. D’Alembert’s solution. Sinusoidal solutions and their complex representation. Characteristics of wave motion in one dimension: amplitude, phase, frequency, wavelength, wavenumber, phase velocity. Energy in a vibrating string. Travelling waves: energy, power, impedance, reflection and transmission at a boundary. Superposition of two waves of different frequencies: beats and elementary discussion of construction of wave packets; qualitative discussion of dispersive media; group velocity. Method of separation of variables for the one-dimensional wave equation; separation constants. Modes of a string with fixed end points (standing waves): superposition of modes, energy as a sum of mode energies.

Data Analysis and Statistics

A- level Maths plus the bridging material in (a) data analysis and statistics and (b) computing are assumed. Qualitative introduction explaining what experiments are, what they are used for in science, and other relevant concepts such as hypothesis or model testing. The fundamental origins of experimental uncertainty, e.g. shot and Johnson noise Examples throughout the course, from contemporary physics or famous discoveries, discussing experimental design, technique, and instrumentation as well as data analysis Uncertainties in measurements including dominant error, random and systematic errors, accuracy and precision, derivation and use of error propagation formulae assuming independent, normally distributed errors (ie no covariance matrices). Gaussian and Poisson distributions (as the distributions found in first year practicals), central limit theorem, least squares fitting (including weighted), meaning of residuals, confidence limits, simple statistical tests. Practical implementation of the above in software and in data presentation, including a) How to produce a plot (e.g. labels, units, title, expression of uncertainties etc.). b) How to describe and present a numerical answer sensibly, with appropriate precision. c) Other useful skills in physics such as estimation. A pragmatic approach to data analysis should be stressed.

This first year material is taught through a short lecture course and the practical course. It is continually assessed through practical work (i.e. through log book assessment, lab reports, and discussion with demonstrators). As is usual, knowledge of the first year syllabus will be assumed in the second year, where it can be examined and/or encountered in practicals.

A1. Thermal Physics

Kinetic Theory

Maxwell distribution of velocities: derivation assuming the Boltzmann factor, calculation of averages, experimental verification. Derivation of pressure and effusion formulae, distribution of velocities in an effusing beam, simple kinetic theory expressions for mean free path, thermal conductivity and viscosity; dependence on temperature and pressure, limits of validity. Practical applications of kinetic theory. Heat transport

Conduction, radiation and convection as heat-transport mechanisms. The approximation that heat flux is proportional to the temperature gradient. Derivation of the heat diffusion equation. Generalization to systems in which heat is generated at a steady rate per unit volume. Problems involving sinusoidally varying surface temperatures. Thermodynamics

Zeroth & first laws. Heat, work and internal energy: the concept of a function of state. Slow changes and the connection with statistical mechanics: entropy and pressure as functions of state. Heat engines: Kelvin's statement of the second law of thermodynamics and the equivalence and superiority of reversible engines. The significance of dQ/T=0 and the fact that entropy is a function of state. Practical realization of the thermodynamic temperature scale. Entropy as dQ (reversible)/T. Enthalpy, Helmholtz energy and Gibbs energy as functions of state. Maxwell relations. Concept of the equation of state; thermodynamic implications. Ideal gas, van der Waals gas. Reversible and free expansion of gas; changes in internal energy and entropy in ideal and non-ideal cases. Joule–Kelvin expansion; inversion temperature and microscopic reason for cooling. Impossibility of global entropy decreasing: connection to latent heat in phase changes. [Non-examinable: Constancy of global entropy during fluctuations around equilibrium.] Chemical potential and its relation to Gibbs energy. Equality of chemical potential between phases in equilibrium. Latent heat and the concepts of first-order and continuous phase changes. Clausius–Clapeyron equation and simple applications. Simple practical examples of the use of thermodynamics. Statistical mechanics

Boltzmann factor. Partition function and its relation to internal energy, entropy, Helmholtz energy, heat capacities and equations of state. [Non-examinable: Quantum states and the Gibbs hypothesis.] Density of states; application to: the spin-half paramagnet; simple harmonic oscillator (Einstein model of a solid); perfect gas; vibrational excitations of a diatomic gas; rotational excitations of a heteronuclear diatomic gas. Equipartition of energy. Bosons and fermions: Fermi–Dirac and Bose–Einstein distribution functions for non-interacting, indistinguishable particles. Simple treatment of the partition function for bosons and fermions when the particle number is not restricted and when it is: microcanonical, canonical and grand canonical ensemble. Chemical potential. Hightemperature limit and the Maxwell–Boltzmann distribution. [Non-examinable: Simple treatment of fluctuations.] Low-temperature limit for fermions: Fermi energy and low-temperature limit of the heat capacity; application to electrons in metals and degenerate stars. Low-temperature limit for boson gas: Bose–Einstein condensation: calculation of the critical temperature of the phase transition; heat capacity; relevance to superfluidity in helium. The photon gas: Planck distribution, Stefan–Boltzmann law. [Non-examinable: Kirchhoff's law.]

A2. Electromagnetism and Optics

Electromagnetism

Electromagnetic waves in free space. Derivation of expressions for the energy density and energy flux (Poynting vector) in an electromagnetic field. Radiation pressure.

Magnetic vector potential. [Non-examinable: The change of E and B fields under Lorentz transformations in simple cases.]

Dielectric media, polarisation density and the electric displacement D. Dielectric permittivity and susceptibility. Boundary conditions on E and D at an interface between two dielectrics. Magnetic media, magnetisation density and the magnetic field strength H. Magnetic permeability and susceptibility; properties of magnetic materials as represented by hysteresis curves. Boundary conditions on B and H at an interface between two magnetic media. Maxwell's equations in the presence of dielectric and magnetic media.

Electromagnetic wave equation in dielectrics: refractive index and impedance of the medium. Reflection and transmission of light at a plane interface between two dielectric media. Brewster angle. Total internal reflection. [Non- examinable: Fresnel equations] The electromagnetic wave equation in a conductor: skin depth. Electromagnetic waves in a plasma; the plasma frequency. Dispersion and absorption of electromagnetic waves, treated in terms of the response of a damped classical harmonic oscillator.

Treatment of electrostatic problems by solution of Poisson's equation using separation of variables in Cartesian, cylindrical or spherical coordinate systems.

Theory of a loss-free transmission line: characteristic impedance and wave speed. Reflection and transmission of signals at connections between transmission lines and at loads; impedance matching using a quarter-wavelength transmission line.

[Non-examinable: Rectangular loss-less waveguides and resonators.]

Optics

Diffraction, and interference by division of wave front (quasi-monochromatic light). Questions on diffraction will be limited to the Fraunhofer case. Statement of the Fraunhofer condition. Practical importance of Fraunhofer diffraction and experimental arrangements for its observation. Derivation of patterns for multiple slits and the rectangular aperture using Huygens-Fresnel theory with a scalar amplitude and neglecting obliquity factors. (The assumptions involved in this theory will not be asked for.) The resolving power of a telescope. Fourier transforms in Fraunhofer diffraction: the decomposition of a screen transmission function with simple periodic structure into its spatial frequency components. Spatial filtering. [Non-examinable: The Gaussian function and apodization.] The resolving power of a microscope with coherent illumination.

Interference by division of amplitude (quasi-monochromatic light). Two-beam interference, restricted to the limiting cases of fringes of equal thickness and of equal inclination. Importance in modern optical and photonic devices as illustrated by: the Michelson interferometer (including its use as a Fourier-transform spectrometer); the Fabry–Perot etalon (derivation of the pattern, definition of finesse).

Distinction between completely polarized, partially polarized and unpolarized light. Phenomenological understanding of birefringence; principles of the use of uniaxial crystals in practical polarizers and wave plates (detailed knowledge of individual devices will not be required). Production and analysis of completely polarized light. Practical applications of polarized light.

Basic principles of lasers and laser action: population inversion, Einstein coefficients, pumping.

[Non-examinable: Properties of laser radiation; brightness compared to conventional sources; coherence length measured using the Michelson Interferometer. Measurement and use of transverse coherence. Propagation of light in optical fibres.]

Electronics

Non-ideal Operational amplifiers with finite, frequency dependent gain. Bipolar Junction transistors and simple one-transistor amplifiers. Extension to long-tailed pairs and current mirrors.

A3. Quantum Physics

Probabilities and probability amplitudes. Interference, state vectors and the bra-ket notation, wavefunctions. Hermitian operators and physical observables, eigenvalues and expectation values.

The effect of measurement on a state; collapse of the wave function. Successive measurements and the uncertainty relations. The relation between simultaneous observables, commutators and complete sets of states.

The time-dependent Schroedinger equation. Energy eigenstates and the time-independent Schroedinger equation. The time evolution of a system not in an energy eigenstate. Wave packets in position and momentum space.

Probability current density.

Wave function of a free particle and its relation to de Broglie's hypothesis and Planck's relation. Particle in one-dimensional square-well potentials of finite and infinite depth. Scattering off, and tunnelling through, a one-dimensional square potential barrier. Circumstances in which a change in potential can be idealised as steep; [Non examinable: Use of the WKB approximation.]

The simple harmonic oscillator in one dimension by operator methods. Derivation of energy eigenvalues and eigenfunctions and explicit forms of the eigenfunctions for n=0,1 states.

Amplitudes and wave functions for a system of two particles. Simple examples of entanglement.

Commutation rules for angular momentum operators including raising and lowering operators, their

eigenvalues (general derivation of the eigenvalues of L2 and Lz not required), and explicit form of the spherical harmonics for l=0,1 states. Rotational spectra of simple diatomic molecules.

Representation of spin-1/2 operators by Pauli matrices. The magnetic moment of the electron and precession in a homogeneous magnetic field. The Stern–Gerlach experiment. The combination of two spin-1/2 states into S=0,1; [non-examinable: Derivation of states of well-defined total angular momentum using raising and lowering operators]. Rules for combining angular momenta in general (derivation not required). [Non-examinable: term symbols.]

Hamiltonian for the gross structure of the hydrogen atom. Centre of mass motion and reduced particle. Separation of the kinetic-energy operator into radial and angular parts. Derivation of the allowed energies; principal and orbital angular-momentum quantum numbers; degeneracy of energy levels.

Functional forms and physical interpretation of the wavefunctions for n<3.

First-order time-independent perturbation theory, both non-degenerate and degenerate (questions will be restricted to systems where the solution of the characteristic equation can be obtained by elementary means). Interaction of a hydrogen atom with a strong uniform external magnetic field. The linear and quadratic Stark effects in hydrogen.

Exchange symmetry for systems with identical fermions or bosons; derivation of the Pauli principle. Gross-structure Hamiltonian of helium. Implications of exchange symmetry for wavefunctions of stationary states of helium; singlet and triplet states. Estimation of the energies of the lowest few states using hydrogenic wavefunctions and perturbation theory.

The variational method for ground-state energies; application to helium.

The adiabatic and sudden approximations with simple applications.

Time-dependent perturbation theory. The interaction of a hydrogen atom with an oscillating external electric field; dipole matrix elements, selection rules and the connection to angularmomentum conservation. Transition to a continuum; density of states, Fermi's golden rule.

[Non-examinable -Classical uncertainty in quantum mechanics: pure and impure states. The density matrix and trace rules. Time-evolution of the density matrix. Measurement and loss of coherence.]

B1. Flows, fluctuations and complexity

Fluxes and conservation principles, The Navier-Stokes equation Solution for Poiseuille flow, Reynolds's experiment. Dynamical similarity, the Reynolds number. Phenomena of instability, chaos and turbulence.

Vorticity, Kelvin's circulation theorem. Ideal fluid flows without vorticity. Bernoulli's theorem, lift force, hydraulic jumps. Boundary layers. Very viscous flows: Stokes' law, biological motility at low Reynolds number. Sound waves, shocks.

Flows in phase space and Liouville's theorem. Fixed points, stability, attractors, bifurcations. Strange attractor, aperiodicity and predictability in simple chaotic systems, Lyapunov exponents.

Convective instability, Rayleigh-Bénard convection. Lorenz system as a simple model of RayleighBénard convection. Simple scaling arguments for turbulence.

Simple stochastic processes, Einstein's theory of Brownian motion as an example of the fluctuationdissipation theorem. Random walk, diffusion equation.

Examples of stochastic processes in biology: fluctuations and gene expression; molecular machines for active transport, the freely-jointed chain model of the mechanical properties of biopolymers. Biophysical single-molecule measurements.

B2. Symmetry & relativity

Transformation properties of vectors in Newtonian and relativistic mechanics; 4-vectors; proper time; invariants. Doppler effect, aberration. Force and simple motion problems. Conservation of energy-momentum; collisions. Annihilation, decay and formation; centre of momentum frame. Compton scattering.

Transformation of electromagnetic fields; the fields of a uniformly moving charge. 4-gradient.The electromagnetic potential as a four-vector; gauge invariance, the use of retarded potentials to solve Maxwell's equations (derivation of functional forms of potentials not required).

Equations of particle motion from the Lagrangian; motion of a charged particle in an electromagnetic field.

Field of an accelerated charge; qualitative understanding of its derivation; radiated power, Larmor's formula. The half-wave electric dipole antenna.

3-d and 4-d tensors; polar and axial vectors; angular momentum; the Maxwell field tensor $F_{\mu\nu}$; Lorentz transformation of tensors with application to E and B. Energy-momentum tensor of the electromagnetic field, applications with simple geometries (e.g. parallel-plate capacitor, long straight solenoid, plane wave).

2-spinors: rotation, Lorentz transformation and parity; classical Klein-Gordon equation [Nonexaminable: Weyl equations; Dirac equation.]

B3. Quantum, atomic and molecular physics

Multi-electron atoms and the central field approximation. Electron configurations, shell structure and the Periodic Table. Atoms with 1 or 2 valence electrons. Residual electrostatic interaction, singlet and triplet terms, LS-coupling. Spin-orbit interaction (fine structure).

Simple ideas of atomic spectra and energy levels. Term symbols. Selection rules for electric dipole radiation. Magnetic dipole hyperfine structure; weak and strong magnetic field phenomena in both fine and hyperfine structure. Inner shell transitions and X-ray notation, Auger transitions.

Basic ideas of molecular physics, Born-Oppenheimer approximation, vibrational (simple harmonic oscillator) and rotational (rigid rotor) energy levels for heteronuclear diatomics.

Two-level system in a classical light field: coherent light and Rabi oscillations. Einstein A&B coefficients and thermal radiation. Decaying states and Lorentzian lineshape, incoherent light and rate equations. Homogeneous and inhomogeneous broadening of spectral lines.

Optical gain and absorption. Minimum conditions for laser operation, population inversion, 3- and 4level laser systems. Specific intensity, the optical gain cross section, rate equations governing population inversion and growth of laser radiation. Saturated absorption and saturated gain.

B4. Sub-atomic Physics

Knowledge of the special relativity in the Prelims paper CP1 will be assumed

Concept of a scattering cross section, Quantum mechanical scattering; The Born approximation. Feynman rules in quantum mechanics. Yukawa potential, propagator, virtual particle exchange. Resonance scattering, Breit-Wigner; decay widths. Fermi's golden rule. Use of invariants in relativistic particle decay and formation.

Elastic and inelastic scattering; form factors. Structure of the nucleus: nuclear mass & binding energies; stability, radioactivity, α and β decay; Fermi theory, the (A,Z) plane; basic fission and fusion reactions (U-235 fission, proton- proton fusion).

Quark model of hadrons: the light meson and baryon multiplets; nucleons as bound states of quarks; quarkonium; the ratio of cross sections (e+e- to hadrons) to (e+e- to muons); phenomenology of deep inelastic scattering.

The Standard Model: quark and lepton families, fundamental interactions and flavour mixing. The strong interaction and qualitative discussion of confinement. Weak interaction, parity violation, Cabibbo mixing, properties and decays of W and Z boson. The width of the Z and the number of neutrino types.

B5. General relativity and cosmology

Newtonian gravity, examples of two body and spherical configurations; Gravitational and inertial mass; the Einstein equivalence principle.

Accelerating frames, metrics, covariant derivatives and the geodesic equation; connection between metric and the Newtonian potential; the Newtonian limit. [Non examinable: GPS.]

Gravity and light: gravitational redshift, deflection of light, lensing. Curvature of spacetime; the curvature tensor; Ricci tensor and scalar.

Einstein field equations: the Einstein tensor, symmetries, the energy-momentum tensor, the conservation of energy, relation of curvature and energy; Poisson's equation in the Newtonian limit. Properties of the Schwarzschild metric.

Linearized gravity. Simple treatment of gravitational radiation.

Experimental tests of General Relativity: precession of perihelion of Mercury; binary pulsar. Homogeneous isotropic spacetimes, Friedmann equations, redshift, scale factor, luminosity distance.

The expanding universe: its contents and energy-momentum tensor. Closed and open universes.

Cosmological distance ladder; Hubble constant; deceleration and acceleration; observational evidence for acceleration from high-z supernovae.

Thermal history of the universe. Formation of the CMB; decoupling between photons and baryons; cosmological parameters from CMB observations; formation of the light elements.

B6. Condensed-matter physics

Structure and types of condensed matter. Bonding of atoms: ionic, covalent, van der Waals, metallic [Non examinable: hydrogen bonding].

Introduction to crystals; lattice, basis, Bravais lattices, unit cell (primitive and conventional), Wigner–Seitz cell, crystal systems, lattice planes, interplanar spacing, crystal directions, Miller indices. Reciprocal lattice, reciprocal lattice vectors, Brillouin zones (in 1-, 2- and 3- dimensions). (Crystal systems with orthogonal conventional axes only).

Diffraction including Bragg and Laue equations, structure factor, systematic absences, atomic form factor and nuclear scattering length. Neutron and x-ray diffraction.

Normal mode dispersion for monatomic and diatomic linear chains (harmonic approximation, nearest neighbours only), acoustic and optic modes, group velocity. Born von Karman boundary conditions, density of states (in 1-, 2- and 3- dimensions). Lattice quantization, phonons. Lattice heat capacity, Einstein and Debye models. Elasticity and thermal expansion (simple case of anharmonic oscillator only).

The free-electron theory of metals. Electron density of states, Fermi energy, Fermi surface. Electrical conductivity and Ohm's law. Electronic heat capacity of metals. Experimental determination of electron mobility and mean free path in a metal (from carrier density and conductivity), and density of states at the Fermi level (heat capacity). Second-order non-degenerate and first-order degenerate perturbation theory to model 1-dimensional electron dispersion in the presence of a weak periodic potential. Tight binding model (1-dimensional treatment only). Band gaps. Qualitative generalisation to 2- and 3- dimensions. The distinction between metals, semiconductors and insulators.

Direct and indirect gap semiconductors, band structures near the band edges in Si, Ge and GaAs. Optical absorption, effective mass, holes. Temperature dependence of carrier concentration (parabolic bands only), law of mass action. Impurity binding energy, thermal ionisation of donors and acceptors. Mobility and Hall effect in systems with one dominant carrier type. Experiments that determine the band gap (temperature dependence of conductivity or Hall resistance), direct band gap (optical absorption), sign and concentration of the majority carrier (Hall effect), and mobility of the majority carrier (Hall resistance and conductivity). [Non-Examinable: Semiconductor devices, including p-n junction and transistor]

Magnetic susceptibility, diamagnetism (descriptive treatment only), application of Hund's rules to determination of magnetic ground states of isolated ions, paramagnetism of isolated atoms/ions (temperature dependence of magnetization, Curie's law), Pauli paramagnetism. Magnetic ordering . Weiss molecular field theory of ferromagnetism, Curie temperature, Curie–Weiss susceptibility, exchange interactions. Ferromagnetic domains, domain (Bloch) walls. [Non-examinable: antiferromagnetism, ferrimagnetism, itinerant ferromagnetism, Hubbard model].

Special Options

S01. Functions of a complex variable

Complex differentiation and definition of analytic functions, Cauchy-Riemann equations, orthogonal families of curves and complex mapping, conformal transformations and applications.

Complex integration, Cauchy's integral theorem and integral formula, Taylor series, isolated singularities and Laurent series, residue theorem and evaluation of real integrals, Jordan's lemma and other types of integral, branch points, branch cuts and Riemann surfaces, integration with cuts or with removable singularities, other selected applications of complex calculus.

S07. Classical Mechanics*

Calculus of variations: Euler--Lagrange equation, variation subject to constraints.

Lagrangian mechanics: principle of least action; generalized co-ordinates; configuration space. Application to motion in strange co-ordinate systems, particle in an electromagnetic field, normal nodes, rigid bodies. Noether's theorem and conservation laws.

Hamiltonian mechanics: Legendre transform; Hamilton's equations; examples; principle of least action again; Liouville's theorem; Poisson brackets; symmetries and conservation laws; canonical transformations.

[Non-examinable: Hamilton--Jacobi equation; optico-mechanical analogy and derivation of Hamilton's principle from path integral. Action-angle variables.]

*Note: the above S7. Classical Mechanics syllabus is also that for B7. Classical Mechanics, the Physics and Philosophy paper but includes the non-examinable material.

S10. Medical Imaging and Radiation Therapy

The physics that is applied in imaging, diagnostics, therapy and analysis in medicine: Interaction of Xrays with matter (Photoelectric, Compton, Pair Production); X-ray imaging (scintillation and diode detection) and Computed Tomography; Magnetic resonance fundamentals, basic imaging & slice selection, functional imaging (diffusion-weighted imaging, dynamic contrast-enhanced imaging, spectroscopy); Ultrasound and its application to imaging, including Doppler imaging; Use of radioisotopes: Gamma cameras, SPECT, PET & radionuclide therapy; Radiotherapy: microwave linacs, bremsstrahlung, beam collimation, portal imaging; Introduction to radiotherapy planning: CT simulation, conformal therapy, IMRT, charged particle therapy; Radiation Dosimetry (ionisation chambers, film, diodes, TLDs); Safety considerations; Comparisons between imaging methods.

S12. Introduction to Biological Physics

Introduction to biological molecules, the structures and processes of life: organisms, organs, cells, molecules and molecular machines. DNA and RNA; the double helix, the "central dogma" and DNA code, DNA processing in cells, genes, inheritance. Proteins; the importance of water, amino acids and their properties, forces in protein folding, primary, secondary, tertiary and quaternary structure, methods of structure determination, proteins as catalysts and machines. Lipid bilayer membranes; self-assembly of lipids, vesicles, electrical properties, ionic solutions and Nernst potential. Biological membranes; ion channels and other membrane proteins.

Proteins as nanotechnology: importance of thermal energy, selfassembly, examples of protein nanomachines.

S14. History of Physics

Medieval natural philosophy: the basic Aristotelian scientific views that dominated learned thought until the Seventeenth Century, and why the system became increasingly implausible by the end of the Sixteenth Century.

The instrumental origins of the Scientific Revolution: how in the first three decades of the Seventeenth Century there was a transformation in the way that researchers understood nature, such that for the first time it became conceivable that experiments and scientific instruments could give improved evidence about the natural world.

The Mathematization of Nature: the introduction by Galileo and Newton of new and immensely powerful mathematical approaches to nature, the ways in which they argued for these approaches and the response to them.

The Evidential Basis of the Newtonian system: the experimental and observational corroboration of the Newtonian system in the Eighteenth Century, including the shape of the Earth, the prediction of the return of Halley's comet in 1759, and the triumph of celestial mechanics.

Electromagnetism from Oersted to Maxwell: the work of Oersted, Faraday, Maxwell and Heaviside, and resulting contemporary technological innovations.

Carnot's Inheritance and the Creation of Thermodynamics: Carnot's analysis of Watt engines, his idealisation of a perfect engine by means of the Carnot cycle, and the later work of Joule, William Thomson, and Clausius leading to the concept of energy.

Small Particles and Big Physics from Marie Curie to CERN: the twentieth century elaboration of the structure of matter, from the pioneering work of Wilson, JJ Thomson, and Rutherford, the work of Marie and Pierre Curie, Moseley's use of X-Ray spectroscopy to demonstrate the physical foundation of the Periodic Table, to the beginnings of particle physics

Einstein's Universe: Finding Evidence for the General Theory of Relativity from Eddington to LIGO.

S16. Plasma Physics

Saha Equation. Heat Capacity of a Plasma. Debye Length.

Plasma frequency. The plasma parameter and 'good' plasmas. Single particle motion: Larmor orbits, guiding centre drift, drift of particles in electric and gravitational fields, grad-B drift. First adiabatic invariant. Analysis of subset of electrostatic and electromagnetic waves in unmagnetized and magnetized cold plasmas. Coronal Equilibrium. Plasma dispersion and Faraday Rotation and application to simple astrophysical problems.

Concept of collisionless plasmas and collective effects. Collision times and the Coulomb Logarithm. The fluid approximation, Bohm-Gross frequency. The Vlasov equation and Landau damping (integration in the complex plane not required). The Lawson criterion. Simple concepts of magnetic confinement fusion. Inverse bremsstrahlung absorption.

Rayleigh-Taylor Instability and simple concepts of inertial confinement fusion.

S25. Physics of Climate Change

This course outlines the basic physics underlying our understanding of how the global climate system responds to increasing greenhouse gas levels and its implications for the future. We cover: the distinction between weather and climate in a chaotic system; planetary energy balance; atmospheric temperature structure and its role in the greenhouse effect; forcing, feedbacks and climate sensitivity; the role of the oceans in the transient climate response; the global carbon cycle; simple coupled ODE models of global climate change; how we use observed climate change to quantify what is causing it and to constrain climate projections; simple climate change economics, including the principles and pitfalls of benefit-cost maximisation; and the prospects and risks of geoengineering. In addition to the lectures, participants will be asked to undertake a small-group exercise using a simple (Excel-based) Integrated Assessment Model, devise their own global climate policy and defend it to the rest of the class.

S30. Exoplanets

Overview of the main planet detection methods: radial velocities (Keplerian orbits and the radial velocity equation, spectroscopy and Doppler shift measurement basics), transits (basics of stellar photometry, unique solution of transit light curve), astrometry (astronomical distance and angular scales, astronomical coordinate systems, parallax and proper motion), direct imaging (blackbody emission, planetary albedo, expected contrast, spatial resolution of ground-based telescopes and the concept of seeing, basics of adaptive optics and coronography), and microlensing (microlensing equation, probability of microlensing event, timescale for planetary microlensing signals). Comparison of the biases and limitations of the different techniques, key instruments/missions at present and in medium term future.

Formation, dynamics and statistics: standard model of star formation, accretion discs basics, introduction to planet formation models (core accretion / gravitational instability). Torque exerted by the disk on the planet (planet migration). Star-planet interaction (tides). Overview of statistics of the exoplanet population (mass, semi-major axis, eccentricity and radius distribution, properties of the host stars) and comparison to theoretical expectations.

Evolution and atmospheres: evolution of a pure H/He sphere in the absence of heat source. Energy budgets and mass-radius relation for different kinds of planets, qualitative introduction to the effect of external heating (stellar irradiation). Hydrostatic equilibrium, atmospheric scale height, key constituents of planetary atmospheres, key features of atmospheric spectra. Effects of small particles (Rayleigh scattering). Habitable zone: definition, location for different star types. Biosignatures: notion of chemical (dis-) equilibrium, techniques and prospects for detection of extraterrestrial life.

S31. Numerical Methods

Types of partial differential equations (elliptical, hyperbolic, parabolic); finite difference approximations for partial differential equations: discretization on a grid, Taylor series and accuracy of discretization, stability analysis of linear PDEs (one-dimensional heat conduction equation, scalar advection equation), physical meaning of stability criterion.

Collisionless N-body dynamics: Poisson-Vlasov system; Monte-Carlo approach to N-body dynamics; Time integration schemes for advancing positions and velocities of particles (e.g. explicit Euler method, Runge-Kutta methods, leapfrog method); symplectic integration schemes; gravitational force calculation: direct summation, particle mesh methods (mass assignment schemes, Fourier methods, relaxation solvers), tree algorithms.

Lagrangian versus Eulerian hydrodynamics; Smooth Particle Hydrodynamics: kernel interpolation; constructing derivatives from discrete tracer points; basic equations of smooth particle hydrodynamics; artificial viscosity and shock capturing.

Grid-based hydrodynamics: Euler equations as a set of hyperbolic conservation laws; conservative versus primitive variables; solution to linearized Euler equations and Riemann problem; solving nonlinear conservation laws: shocks and rarefaction waves.