DEPARTMENT OF
ENGINEERING SCIENCE

Fourth Year Syllabus

The fourth year is devoted to specialist topics and a project which are assessed in the Part C examination at the end of the fourth year. You take six specialist C papers and work on a project to produce a report. Please note that the availability of options may vary from year to year subject to staff availability.

Projects in the fourth year are normally undertaken by individual undergraduates, but sometimes a team of two or three may divide a larger exercise between them. Further information about fourth year projects can be found in the Course Handbook.

Accreditation: Principles of sustainability
The MEng degree in Engineering Science is accredited by the Professional Engineering Institutions; the first step towards full membership of one of the intuitions and Engineering Chartership. The course has been designed to achieve certain thresholds of knowledge and standards of learning across key areas that satisfy the criteria set out by the accrediting institutions; including acquiring the knowledge and ability to handle broader implications of work as a professional engineer. It is especially important that the principles of sustainability (environmental, social and economic) are embedded in the teaching and learning throughout the course in lectures, tutorials, laboratories and project work; in the fourth year, the individual research project (4YP) and the C-option papers include principles of sustainability.

Paper C2: Aerothermal Engineering

<u>c201: Viscous Flow and Turbulence; Matric 2023, Y4; Paper C2: 4 Lectures, 1 Tutorial Sheet</u>

Review of flow instabilities and transition to turbulence process. Characteristics and different regions in turbulent boundary layers. Coherent structures in turbulent boundary layers. Reynolds averaging of Navier-Stokes equations and turbulence closure problem. Characteristics of turbulence. Turbulent kinetic energy - production and dissipation, the different scales of turbulence from integral scale to Kolmogorov's microscale, energy cascade. Models of turbulence. Prandtl's Mixing Length model, One equation and two equation models. Direct Numerical Simulations (DNS) and Large Eddy Simulations (LES).

Learning Outcomes

1. Be able to discuss characteristics of different turbulent flows.
2. Understand kinetic energy transfer between mean flow and turbulent fluctuations (production of turbulent kinetic energy).
3. Understand dissipation process and energy transfer between different scales of turbulence.
4. Be able to derive the Prandtl's Mixing Length model.
5. To be familiar with different turbulence models used to model fluid flows.

6. To understand the concept of Large Eddy Simulations and requirements for DNS application in modelling real industrial flows.

c202: Wing Theory and Compressible Flow; Matric 2023, Y4; Paper C2: 4 Lectures, 1 Tutorial Sheet

Revision of potential flow and circulation. 2-D aerofoil camber line shape derived from circulation. Circulation distribution derived from general 2-D aerofoil shape. 2-D Pitch and lifting moments. Induced drag for finite wings; finite wing shape for required 3-D lift and pitching moment. Aerofoils in supersonic and transonic flow; characteristics from small perturbation theory. Critical Mach number for swept back wings in compressible flow.

Learning Outcomes:

1. Understand how circulation is generated around a thin aerofoil, and how this leads to lift.
2. Be able to describe the circulation around an aerofoil at arbitrary angle of attack using a general Fourier series.
3. Understand how lift and moment coefficients can be determined for an aerofoil, and how angle of attack may be used to linearly change the lift coefficient.
4. Be able to calculate the lift and drag of a finite wing in incompressible flow.
5. Understand the aircraft wing design equation.
6. Be able to calculate the lift on a simple supersonic aerofoil.
7. Be able to scale predictions of incompressible lift and moment to high-speed subsonic conditions.
8. Understand the existence of a Critical Mach number and how it may be calculated.

c203: Aircraft Flight and Propulsion; Matric 2023, Y4; Paper C2: 4 Lectures, 1 Tutorial Sheet

Review of wing drag, finite span wings and induced drag, downwash. Lift coefficient as independent variable. Aircraft lift-drag polar, parabolic drag model and forces in level flight. Level flight thrust and power, altitude, equivalent airspeed. Propeller and jet propulsion. Flight envelopes. Excess power for climbing flight, maximum climb rate, gliding flight. Range and Endurance, specific air range, Breguet range equations and optimisation for maximum range or endurance. Turning flight, load factor, manoeuvring. Distance required to take off and land over an obstacle and the length of runway required.

Learning Outcomes:

1. Understand influencing and limiting factors and associated mechanisms for wing performance.
2. Be able to use the lift-drag polar equation in selecting parameters for optimizing flight performance.
3. Understand characteristics of required power and thrust for level flight.
4. Understand altitude effects.
5. Understand jet and propeller engine characteristics.
6. Be able to calculate and maximize flight ranges in different modes.
7. Understand load balance and impacts on performance in non-level flight.
8. Understand landing and take-off procedures and be able to calculate corresponding runway lengths.

c204: Turbomachinery; Matric 2023, Y4; Paper C2: 4 Lectures, 1 Tutorial Sheet

Review of axial compressor and turbine stage characteristics and non-dimensional parameters. Dimensional analysis of compressible flows in turbomachines. Two-Dimensional cascade flow. Axial flow turbines – mean-line analysis and design. Axial flow compressors – mean-line analysis and design. Three-dimensional flows in axial turbomachines (radial equilibrium theory). Free-vortex turbine stage design. Three-dimensional design aspects (lean, sweep endwall profiling). Three-dimensional flow features in axial turbomachines (secondary flows, leakages).

Learning Outcomes:

1. To be able to calculate stage performance and different stage non-dimensional parameters for compressible axial flow turbine and compressor stages.
2. To perform mean-line analysis for compressible flow axial turbomachines.
3. To understands and be able to apply the principles of radial equilibrium theory.
4. To be able to apply free- vortex concept on turbine stage design
5. To understand physics of different three-dimensional flow features in axial turbomachines.
6. To understand three-dimensional design aspects in axial turbomachines.

Paper C3: Micromechanics and Materials Modelling

c301: Creep; Matric 2023, Y4; Paper C3: 4 Lectures, 1 Tutorial Sheet

Deformation mechanisms of slip, thermally activated climb and diffusion. Viscoplasticity vs creep. Dislocation multiplication, ageing, cavity nucleation, growth and coalescence as failure mechanisms. Creep fracture. Constitutive equations for creep deformation and failure; introduction to damage mechanics. FE Modelling techniques for creep, Examples and case studies.

Learning Outcomes:
1. Understand the principal mechanisms of creep and the related causes of failure.
2. Understand and apply relationships between microstructure and creep performance in alloys.
3. Apply simple creep calculations to predict component behaviour and lifetime.
4. Apply an understanding of creep to explain aspects of the practical use of metals and alloys in engineering applications.

c302: Fracture; Matric 2023, Y4; Paper C3: 4 Lectures, 1 Tutorial Sheet

Modes of loading. Linear fracture mechanics - K, G and J-integral. Griffiths' criterion under controlled load and displacement. Irwin K-G equivalence. Near crack tip fields- from finite crack in an infinite plane and Williams' asymptotic approach. Mechanisms of crack growth in brittle materials – crack path under mixed mode loading. Mechanisms of crack growth in semi-brittle and ductile materials. Dugdale plastic strip model, crack tip opening in yielding. R-curve behaviour, unstable crack growth. Crack bridging, toughening and damage. Case studies and practical problems.

Learning Outcomes:
1. Appreciate different modes of loading and failure.
2. Understand and be able to apply both the energetic and stress intensity-based concepts of fracture.

3. Understand and be able to apply crack tip fields to determine process zones, crack growth and crack growth direction.
4. Understand and be able to apply J-integral methods for linear and non-linear fracture problems.
5. Have a good fundamental understanding of fracture and toughening mechanisms in the presence of significant plasticity/inelastic deformation.

C303: Impact; Matric 2023, Y4; Paper C4: 4 Lectures, 1 Tutorial Sheet

Introduction to Impact: Elastic waves in continuous media: Longitudinal and shear waves in linear elastic isotropic solids; spherical waves; Rayleigh waves. Elastic Waves in Slender Rods: Wave equation and solutions. Formation of waves, $\sigma=\rho cv$, Interactions between waves and boundaries. The split-Hopkinson bar and general trends in mechanical properties of materials with strain rate. Torsional stress waves and Torsional Hopkonson Bar. Non-elastic behaviour: Plastic waves, the Taylor Impact experiment, spalling, scabbing.

Learning Outcomes:
1. Understand the Importance of Impact events, and the loading characteristics that distinguish these events.
2. Understand the derivation of the wave equation in continuous isotropic media.
3. Be able to solve the wave equation to produce pressure and shear waves.
4. Be able to derive and solve the wave equation in a longitudinal rod.
5. Be able to derive and understand the importance of $\sigma=\rho cv$, and calculate stresses and particle velocities resulting from single and overlapping waves.
6. Understand the operation of the Hopkinson bar and relevant trends in material properties with strain rate.
7. Understand the propagation of plastic deformation, and the dispersive nature of this propagation.
8. Understand the causes of spalling and scabbing.

c304: Shock; Matric 2023, Y4; Paper C3: 4 Lectures, 1 Tutorial Sheet

Thermodynamics of shock loading; Equations of state and the Hugoniot; Rankine-Hugoniot jump conditions; Shock waves; Shock propagation and interaction; Impedance matching and the P-up diagram; Role of strength and phase transitions on structured waves; Dislocation behaviour with increasing strain-rate; Microstructural evolution in materials; Spallation, Adiabatic shear bands, and ejecta.

Learning Outcomes:
1. Understand the effect of shock loading on both the thermodynamic state and stress state of a material.
2. Understand and be able to predict the evolution of pressure, temperature states produced during multiple shock wave interactions and release.
3. Understand the effect of strength in shock wave formation and interpretation of wave profiles.
4. Understand the underlying mechanisms responsible for different regimes of dislocation mobility.
5. Have a fundamental understanding of the failure mechanisms unique to shock loading and release.

Paper C4: Mechanical Performance and Integrity

c401: Finite Elements; Matric 2023, Y4; Paper C4: 8 Lectures, 2 Tutorial Sheets

Continuum mechanics: discrete vs. continuum, PDE solvers, continuum mechanics equations. Spatial discretization: element discretization, functional minimization, numerical integration. Time discretization: non-linear and linear dynamic systems, newmark algorithm (theory and implementation). Large deformation and finite elasticity. Materials failure in FEM. Application examples. The course will alternate between theory teaching and Matlab coding exercises.

Learning Outcomes:

1. The course aims at specializing the knowledge acquired in b103 to solid mechanics equations.
2. At the end of the course, the student will be able to use her/his knowledge of the FE theory so as to utilize commercial software AND understand their limitations, i.e., without considering them as "black boxes".
3. She/he should also be able to code on her/his own a simple FE model.

C402: Modelling of Alloys; Matric 2023, Y4; Paper C3: 4 Lectures, 1 Tutorial Sheet

Introduction to alloys. Large deformation theory. Stress measures. Common crystal systems of fcc, bcc and hcp and vector representation of slip systems. Dislocations as crystal lattice defects and relevance to plastic deformation. Twinning. Size effects in polycrystals. Schmid rule. Crystal plasticity and constitutive modelling: slip kinematics and relationship to strain, rate-independent and rate-dependent flow rules. Pole figures representations. A practical case study: Continuum modelling of Mg alloy AZ31 under uniaxial deformation. Nanomechanics of alloys: surface dominated metals, nanocrystalline metals, nanotwinned ultrafine crystals, ballistic loadings in nanocrystalline metals.

Learning Outcomes:

1. The course aims at providing a basic understanding of the role of alloys in engineering, their micromechanics and the modelling techniques currently used to simulate their deformation.
2. The student is expected to complement the knowledge acquired in b503 and understand when crystal plasticity is required instead of isotropic plasticity, and at what cost.

C403: Modelling of Polymers; Matric 2023, Y4; Paper C3: 4 Lectures, 1 Tutorial Sheet

Introduction: microstructural features of polymers determining mechanical properties. Elasticity of polymers: hyperelasticity; phenomenological and physics-based models. Viscoelasticity of polymers: linear viscoelasticity in 3D, relaxation spectra, Generalised Maxwell model, effect of temperature, time-temperature equivalence, deviation from linearity. Yield and plastic deformation of polymers: yield criterion, rate- and temperature-dependence.

Learning Outcomes:

1. Understanding of what microstructural features, at different length scales, influence the mechanical properties of polymers.

2. Understanding of the physical basis of elasticity and hyperelasticity in polymers, including factors governing elastic moduli and finite extensibility.

3. Ability to use empirical and physically based descriptions to model the 3D hyperelastic response of elastomeric polymers.

4. Understanding of the relation between molecular relaxation processes occurring on different time scales and the linear viscoelasticity of polymers.

5. Ability to use temperature-dependent relaxation spectra to model 3D linear viscoelastic deformation in polymers.

6. Understanding of the Eyring description of 3D plastic flow of solid polymers, leading to dependence on stress state, strain-rate, temperature, and structure.

7. Ability to use the Eyring approach to model the effects of strain-rate, temperature, and structure on yield in polymers.

Paper C5: Advanced Structures

<u>c501: Structural Steel Design; Matric 2023 Y4; Paper C5: 4 Lectures, 1 Tutorial Sheet</u>

Limit state design principles for steel structures. Design of elements for axial tension, bending, combined bending and axial compression. Analysis of simple welded and bolted connections.

Learning Outcomes:

1. Understand the significance of Euler buckling and lateral-torsional buckling in structural steel design.
2. Select appropriate steel sections to carry axial tension, compression, bending or combined compression and bending.
3. Analyse forces in bolted connections and determine required sizes of simple connecting elements.

c502: Advanced Structural Analysis; Matric 2023, Y4; Paper C5

The purpose of this course is for students to become familiar with the Principle of Virtual Work as a computational tool that allows for finding the displacements of statically determinate and over determinate trusses and beams. This year's topics covered are:

1. Understanding the energy method in general and the principle of virtual work in particular.

2. Applying the virtual work calculations for both statically determinate and indeterminate trusses to find deflections and reactions and forces.

3. Comprehending the principle of virtual work for beams.

4. Using the unit load method to determine deflections of statically determinate beams

5. Applying virtual work calculations for statically indeterminate beams to find reactions and moments

6. Apprehend the concept of influence lines for statically determinate beams.

c503: Plates and Shells; Matric 2023, Y4; Paper C5: 4 Lectures, 1 Tutorial Sheet

The course covers two unconventional engineering structures: tension structures and deployable structures. Tension structures: equilibrium equations, Kinematic relationships, identification of states of self-stresses, statical and kinematical indeterminacy. Deployable structures: mechanisms, assemblies of mechanisms, geometrical constraints, angulated elements, Closed-loop double chain linkages.

Learning Outcomes:

1. Understand the bending behaviour of plates under lateral loadings.
2. Able to conduct theoretical analysis of plates with various boundary conditions under bending.
3. Comprehend the interaction of bending and stretching in plates and plate buckling.
4. Able to analyse Circular cylinders under symmetric loading.
5. Comprehend axi-symmetric buckling for a cylindrical shell under end compression.

c504: Structural Dynamics; Matric 2023, Y4; Paper C5: 4 Lectures, 1 Tutorial Sheet

Dynamic loads: Earthquakes, wind, human-induced vibrations. Linear single-degree-of-freedom systems: equation of motion, free vibrations, response to time-varying base motions, and earthquake response spectrum. Linear multi-degree-of-freedom systems: natural frequencies and mode shapes, multi-modal response spectrum analysis, equivalent static analysis. Non-linear response: ductility and ductility-modified response spectra, non-linear time history analysis. Structural dynamics in seismic codes.

Learning Outcomes:

1. Evaluate the linear response of SDOF systems using Duhamel's integral.
2. Understand the derivation, meaning and use of response spectra.
3. Determine natural frequencies and mode shapes of beams with simple support conditions.
4. Determine equivalent SDOF systems based on the fundamental mode of continuous or MDOF systems.
5. Determine the response of MDOF systems to dynamic loads using mode superposition.
6. Understand the basic principles of calculation of non-linear dynamic response.

Paper C6: Geotechnics

c601: Mechanics of Soils; Matric 2023, Y4; Paper C6: 4 Lectures, 1 Tutorial Sheet

Revision of some essential topics in elasticity, plasticity, and soil mechanics. Compressive behaviour of soils. Shearing behaviour of soils: friction and dilation. Critical state soil mechanics as a means of unifying compressive and shear behaviour. Non-linearity in soil behaviour: appreciation of the variation of stiffness with strain amplitude. Theoretical models of soil behaviour: linear elasticity, elastic – perfectly plastic model based on the Mohr-Coulomb yield function, Cam Clay. Applications and limitations of theoretical soil models.

Learning Outcomes:

1. Have a thorough understanding of the oedometer test and the compression behaviour of soils.
2. Appreciate the role of friction and dilation in the shearing behaviour of soils.
3. Understand the concept of critical states.
4. Appreciate the non-linear behaviour of real soils and the implications for engineering problems.
5. Be familiar with the Mohr-Coulomb model and its limitations.
6. Be familiar with the principal elements of the Cam Clay model.
7. Be able to interpret triaxial tests using the triaxial variables, and be able to draw appropriate plots (based on an understanding of the critical state soil mechanics framework) for standard triaxial compression tests.
8. Be able to carry out simple calculations (e.g. on undrained shear strength of soils measured in the triaxial test) using the Cam Clay model.

c602: Offshore Foundations; Matric 2023, Y4; Paper C6: 4 Lectures, 1 Tutorial Sheet:

The course first will review the types of offshore structures and the loads that act upon them. Basic design methods for piled foundations for fixed offshore structures under vertical and lateral loading will be studied. Shallow foundations (gravity bases, mudmats and suction caissons) and anchoring systems will be discussed. The course will concentrate principally on failure calculations relevant to ultimate limit states, although some brief attention will be given to displacements. Much of the material presented in the course is applicable to foundations for wind turbine support structures.

Learning Outcomes:
At the end of this lecture course, and after working through the associated example sheet, you should:

1. Appreciate the different types of offshore structures in use and the foundation options that are available to a designer.
2. Appreciate the loading conditions on offshore structures, how these loads are transferred to the foundation, and the design cases that need to be considered.
3. Be aware of the role that site investigation plays in the design of offshore structures.
4. Understand and be able to apply basic design calculations for capacity of axially loaded piles foundations, of either closed or open ends, in clay or sand.
5. Be able to calculate the lateral/moment capacity of a single pile in either clay or sand.
6. Understand and be able to apply basic design calculations for shallow foundations under combined loadings, using Vesic's method and the yield surface approach.
7. Be aware of the load transfer method and be able to perform basic calculations of pile settlement.
8. Be able to calculate the penetration of suction caissons in clay under both self-weight and suction-assisted penetration and be aware of some of the risks to suction penetration in both clay and sand.
9. Be aware of the use of suction caissons as anchor foundations and be able to use appropriate design methods to calculate their capacity.

<u>c603: Slope Stability; Matric 2023, Y4; Paper C6: 4 Lectures, 1 Tutorial Sheet</u>

Introduction: types and causes of slope failure, design philosophy. Stability of infinite slopes: dry cohesionless slopes, saturated cohesionless slopes (with and without seepage), sands with pore water suction, purely cohesive slopes (exposed and submerged). Slip circle analysis: total stress analysis with $\varphi_u = 0$, Taylor's chart, effective stress analysis, methods of slices, Fellenius's method, Bishop's method, estimation of pore pressures, Bishop & Morgenstern's charts. Earth dams: construction, operation, rapid drawdown.

Learning Outcomes:

1. Understand the concept of 'limiting equilibrium'.
2. Be able to determine the factor of safety against sliding for infinite slopes, including the parallel seepage case.
3. Be able to conduct slip circle analyses to investigate the undrained stability of cuttings and embankments.
4. Understand the basis of the Taylor charts and their application in slope stability analysis.
5. Understand the basis and application of the Fellenius method.
6. Understand the basis and application of the Bishop Simplified method.
7. Understand the basis of the Bishop and Morgenstern charts and their application in slope stability analysis.
8. Appreciate the different numerical techniques for slope stability analysis.

<u>c604: Site Investigation; Matric 2023, Y4; Paper C6: 4 Lectures, 1 Tutorial Sheet</u>

Sources of information for a desk study (including geological maps, historical maps and photographs, aerial photographs and admiralty charts). Geophysical surveying. Methods for drilling or boring. Soil disturbance. Sampling using open-tube, coring and block samplers. Casagrande plasticity chart. The use of index properties to estimate engineering parameters. Brief review of the triaxial, shear box and oedometer tests. Introduction to the shear vane, SPT, CPT, pressuremeter, dilatometer and plate loading tests. Use of CPT for soil classification and to estimate undrained shear strength. Use of the pressure meter to measure G and s_u. Interpretation of the shear vane test in clay.

Learning Outcomes:

1. Be familiar with the concept of the desk study and ground investigation phases of a site investigation.
2. Be aware of the various sources of information that may be used to inform a desk study.
3. Have an awareness of the methods that are used in practice for drilling and sampling and appreciate issues relating to sample disturbance.
4. Be familiar with procedures used to produce grading curves for granular materials.
5. Be familiar with index testing and the relevance of the results.
6. Be familiar with procedures for the triaxial test, the direct shear test, the oedometer test, the SPT, the CPT, the shear vane test, the pressure meter test, the dilatometer test and the plate loading test.
7. Be able to use data from the CPT to suggest a likely profile of soil layering.
8. Be able to estimate the undrained shear strength for a clay from the results of a CPT, a pressure meter test and the shear vane test.
9. Be able to estimate the shear modulus from the results of a pressure meter test.

Paper C7: Hydraulics

c701: Offshore Engineering; Matric 2023, Y4; Paper C7: 4 Lectures, 1 Tutorial Sheet

Potential flow theory for waves in deep and intermediate water depth. Forces on cylinders in steady and oscillatory flow, including analytical solutions and Morison's equation. Short- and long-term wave statistics. Wave spectra.

Learning Outcomes:

1. Understand the hydrodynamic challenges in offshore engineering.
2. Understand linear potential flow theory for ocean waves and wave propagation.
3. Understand how to calculate the forces on drag-dominated and inertia-dominated structures in steady currents and waves.
4. Understand the concept of the wave spectra and use this to derive sea-state properties.
5. Understand how to calculate the probability of a wave with a given crest height being exceeded.

c702: Engineering Hydrology; Matric 2023, Y4; Paper C7: 4 Lectures, 1 Tutorial Sheet

The hydrologic cycle; hydrologic basins and water balance; precipitation and evapotranspiration; infiltration; surface water flow; groundwater flow; run-off and hydrograph analysis.

Learning Outcomes:

1. Understand the basic components of and physical mechanisms in the hydrologic cycle.
2. Understand the concept of a hydrologic basin.
3. Understand and be able to apply the idea of water balance.
4. Understand the concepts of precipitation and evapotranspiration, including their roles in the hydrologic cycle and the key strategies and challenges in measuring and modelling them.
5. Understand the subsurface as a porous medium.
6. Understand the basic concepts of infiltration, surface water flows, and groundwater flows, and be able to apply simple models for these processes.

7. Understand the coupling of surface water with groundwater, and the causes of drought and flooding.

c703: Coastal Engineering; Matric 2023, Y4; Paper C7: 4 Lectures, 1 Tutorial Sheet

Variations in water levels (tides, storm surge, wave-set up, seiches); wave transformation from deep to shallow water; wave mechanics in shallow water; waves propagating on currents; wave breaking; shallow water equations and application; vertical and rubble mound breakwaters.

Learning Outcomes**:**

1. Understand the challenges in designing coastal engineering structures.
2. Understand the processes that lead to changes in water level around the coasts.
3. Understand wave mechanics in shallow water and wave mechanics in the presence of steady currents.
4. Apply the shallow water equations to a range of practical problems.
5. Understand why waves break and be able to predict wave breaking.
6. Understand how to calculate the forces on vertical breakwaters.
7. Understand the basic ideas of how rubble mound breakwaters work and are designed.

c704: Fluid Structure Interactions; Matric 2023, Y4; Paper C7: 4 Lectures, 1 Tutorial Sheet

Fluid-structure interactions, including single and multi-degree of freedom steady and unsteady flow driven instabilities; vortex-induced vibrations, galloping, wake galloping, stall flutter, divergence, flutter. You will learn to set up simple models for these fluid excited motions and vibrations in order to derive conditions for the onset of each mechanism and develop estimates of vibration amplitudes and mechanisms of suppression.

Learning Outcomes:

1. Understand the unsteady mechanism of Vortex-Induced Vibrations and the phenomenon of lock-in.
2. Derive basic models for cross-flow vibration, and understand the role of phase angle, added mass and mass-damping in Vortex-Induced Vibrations.
3. Understand how such vibrations may be mitigated and / or suppressed.
4. Understand the steady flow excitation mechanism that leads to single degree of freedom galloping and be able to derive and use the Glauert-Den Hartog criterion for galloping instability to develop.
5. Understand the mechanisms of stall flutter and wake galloping.
6. Describe what is meant by added mass and identify its significance in flow-induced vibrations.
7. Derive the equations of fluid-structure interaction for divergence.
8. Derive the flutter equations, and the relationship for the flutter onset speed.
9. Derive and use the two degree of freedom equations for aeroelastic wing flutter.

Paper C8: Sustainable Energy

<u>c801: Wind Energy; Matric 2023, Y4; Paper C8: 4 Lectures, 1 Tutorial Sheet</u>

This course consists of four lectures and provides an introduction to wind energy. The first two lectures cover how the wind resource is evaluated, the fluid mechanics of energy extraction and Blade Element Momentum theory. The third and fourth lectures will cover turbine characteristics, design and modes of operation including pitch versus stall regulation. Turbine performance within large wind farms will also be discussed.

Learning Outcomes:

1. Understand the spatial and temporal variation of the wind resource.
2. Use a Weibull PDF to describe the wind resource.
3. Be able to describe the mechanics of operation of the principle device types.
4. Derive and use Blade Element Momentum theory to model the operation of an axial flow wind turbine.
5. Derive and use models for optimal blade design.
6. Understand how constant rpm devices operate and regulate power production.
7. Understand how pitch to feather or stall can be used to regulate power.

<u>c802: Solar and Photovoltaics; Matric 2023, Y4; Paper C8: 4 Lectures, 1 Tutorial Sheet</u>

Characteristics of solar energy and resource. Solar-thermal systems and applications. Types of photovoltaic cells and their characteristics, optical concentrators and other enhancements. Connecting cells and arrays: grid-connected and standalone systems. Solar building products. Energy storage issues.

Learning Outcomes:

1. Explain why location, orientation, date and time of day can affect the amount of solar radiation falling on a solar energy collector.
2. Describe the spectrum of daylight and the phenomena that affect this spectrum.
3. Explain the role of transparent covers and reflectors in solar collector systems.
4. Describe different types of solar energy concentrators and derive the theoretical limit of concentrators.
5. Describe at least one method of solar thermal power generation.
6. Explain the operation of a PV cell, including how the output is affected by material selection, the incident light and the origins of the maximum power point.
7. Describe how the maximum available output voltage from PV cells can be increased.

<u>c803: Marine Energy; Matric 2023, Y4; Paper C8: 4 Lectures, 1 Tutorial Sheet</u>

You will learn about renewable marine energy resources, tidal stream, tidal barrage and wave energy. For each you will consider the scale of the resource, how devices may interact with the resource to extract power, leading device types and operating modes. You will derive simple and complex models of interaction with the flow field to demonstrate the salient points of device-resource interaction, and thus understand the limits of power extraction for each marine energy resource.

Learning Outcomes:

1. Understand the nature and size of the tidal energy resource.
2. Derive the equations of Linear Momentum Acuator Disk Theory for devices operating under blocked flow conditions, with both deformable and rigid free surface conditions.
3. Describe how blockage and Froude number act to increase the power potential in tidal flows, including the limit of partial fence theory for globally unblocked flow conditions.
4. Calculate basin efficiency for devices and appreciate its role in limiting the extractable resource.
5. Derive and use simple one-dimensional channel dynamics models of tidal energy extraction.
6. Determine the gross energy potential and deliverable power of tidal barrage installations operating under single or dual mode operating strategies.
7. Classify wave energy devices as to their mechanism of interaction with the flow-field; attenuator, point absorber, terminator, and location of operation.
8. Describe the basic mechanisms of interaction with the wave field of leading device types.
9. Understand what is meant by capture width.

<u>c804: Carbon Capture and Storage; Matric 2023, Y4; Paper C8: 4 Lectures, 1 Tutorial Sheet</u>

Characteristics of different point sources of carbon dioxide. Carbon capture alternatives: pre-combustion vs. post-combustion. Carbon storage alternatives: geological storage, ocean storage, biomass production. Main features of geological storage. Economics, limitations and technical issues of the options.

Learning Outcomes:

1. To understand the basic principles of the biogeochemical carbon cycle.
2. To understand the nature of the carbon dioxide challenge – the quantitative effects of anthropomorphic carbon dioxide emissions on climate and ocean acidity.
3. To understand the consequences (technical and social) of mitigation strategies involving significant reduction in the use of fossil fuels.
4. To be able to draw up heat and mass balances for suggested schemes of carbon dioxide capture from stationary sources.
5. To understand the principles behind and the feasibility of various storage alternatives.
6. To understand the advantages and limitations of geological storage.

Paper C9: Environmental Engineering

<u>c901: Environmental Engineering 1; Matric 2023, Y4; Paper C9: 8 Lectures, 2 Tutorial Sheets</u>

This course of 8 lectures is to be taken in conjunction with Environmental Engineering part 2. The first 4 lectures introduce key aspects of environmental engineering, environmental media, contaminated land management and sustainability in relation to the management environmental pollution. The further 4 lectures are focused on public health engineering, water supply, wastewater treatment and the effects of polluting discharges to the environment. The lectures have an engineering focus and principally will be concerned with the water and land environments.

Learning Outcomes:

1. Recognise the three environmental media: air, water and land; understand the basics of environmental pollution and the importance of cross-media environmental protection agencies.
2. Understand the principal classes of contaminants of land, their properties and their behaviour in the ground, also methods for the investigation and management of potentially contaminated land.
3. Understand the fundamental requirements for potable water supply, quality and quantity and the basic processes by which water is treated for supply.
4. Understand the requirements for municipal wastewater treatment before it is returned to the environment and the engineering processes by which this treatment can be achieved.

c902: Environmental Engineering 2; Matric 2023, Y4; Paper C9: 8 Lectures, 2 Tutorial Sheets

Introduction to Environmental Biotechnology/Engineering biological means of dealing with environmental stress. Summary of key methods for the biological treatment: understanding the biological limitations and potential for remediation of contaminated environments and water clean-up. Monitoring biological and chemical response to remediation methods. Physical and engineered approaches for controlling and manipulating biological treatment of contaminated water and soil clean-up.

Sustainable low energy-focused treatment of high concentrate recalcitrant industrial waste waters/effluents and generation of clean- drinking water. Linking water treatment to energy reduction. Sustainable waste treatment, waste to energy and conservation of limiting resources such as phosphate.

Development of new technologies for environmental engineering. Nanomaterial-based methods for monitoring environmental contamination and the potential of nanomaterials for stimulating intrinsic environmental remediation, waste-minimisation and low-energy water treatment.

Learning Outcomes:

1. Introduction to environmental biotechnology and biological metabolism.

2. Understanding enzyme catalysis, introduction to bioenergetics and techniques for determining biomass cell detection in engineered systems.

3. Understanding remediation of environmental contamination, with case study review.

4. Introduction and understanding bioenergy, resource recovery and sustainability

5. Nanotechnology as novel environmental engineering solutions provider.

6. Develop the skill sets to design bespoke environment recovery approaches.

Paper C10: Bioprocess Engineering

c1001: Bioprocess Engineering; Matric 2023, Y4; Paper C10: 4 Lectures, 1 Tutorial Sheet

This part of the course consists of 4 lectures and provides an introduction to biotransformation and the biological processes, and principles leading to key chemical transformation such as production of food, antibiotics and enzymes. The first two lectures will provide background of the exploitation of biological systems for chemical transformations, including new technologies such as genetic and tissue engineering. The biochemical and bioenergetics principles underlying chemical processing will be detailed including highlighting key components such as the role of enzymes and electron transport. The third lecture will focus on the control and manipulation of cells for optimising biotransformations including cell immobilisation and the scale-up of production systems. The final lecture will focus on those areas such as food production, bioenergy and medicine where biotransformation processes are being increasingly exploited in the drive to make systems more sustainable.

Learning Outcomes:

1. Understand the biochemical and bioenergetic basis of biotransformation.
2. Understand how to harness and control biological processes.
3. Understand the central role biological processes play in food and medicine production and its potential for developing more sustainable procedures.
4. Understand the key routes where-by biotransformation process can to controlled and optimised.
5. Able to design engineered systems for exploiting biotransformation processes.

<u>c1002: Bioseparation; Matric 2023, Y4; Paper C10: 4 Lectures, 1 Tutorial Sheet</u>

The course outlines the main techniques employed for separation (whether of feed or intermediate/final products) in the biotechnology industry.

The following topics are covered:

Introduction, economic importance of bioseparation processes, RIPP scheme; properties of bioproducts; challenges to bioseparations; commonly used bioseparation processes.

Filtration-based separation: Operation cycle of cake filtration. Constant pressure and constant rate operations. Pressure drop through filter cake and filter medium.

Membrane-based separation processes: Introduction to membrane processes; Fundamentals of membrane separation; Mechanisms of ultrafiltration and microfiltration; Concentration polarisation and membrane fouling; Ultrafiltration, prediction of permeate flux and rejection; Microfiltration, fouling mechanisms and fouling control.; Protein separation and purification.

Introduction to chromatographic Separation: Principles of chromatography, ion exchange, gel filtration, affinity chromatography.

Learning Outcomes:

1. Understand the challenges and complexity of bioseparations.
2. Understand the different filtration operations (constant pressure vs constant rate) and be able to conduct filtration process analysis.
3. Understand the principles of membrane filtration and the difference between concentration polarisation and membrane fouling.
4. Be able to conduct process evaluation and prediction calculations for ultrafiltration using the concentration polarisation model and resistance/osmotic pressure models.
5. Understand the principles and practice of methods of fouling minimisation.
6. Understand the principles of gel filtration, ion exchange and affinity chromatography.

c1003: Engineering Principles for Synthetic Biology; Matric 2023, Y4; Paper C10: 8 Lectures, 2 Tutorial Sheets

Introduction to Biosystems and background material. Modelling and analysing population dynamic systems and biochemical reaction and metabolic networks. Examples from transcriptional regulation, enzymatic and signal transduction networks. Application of chemical engineering principles (e.g. unit operation, reaction engineering etc) to bioprocessing dynamics and control. Engineering design cycle for synthetic biology. Case studies of synthetic biology application to chemical and sustainable engineering on biorefinery and biofuels.

Learning Outcomes:

1. Understand challenges and opportunities in synthetic biology for chemical engineers.
2. Appreciate the complexity of biological systems and understand the hierarchical structure of biological organization.
3. Understand stochastic property in biological system.
4. Understand the process of translating biological phenomenon into mathematical equations.
5. Appreciate the meaning of the central dogma of molecular biology.
6. Develop mathematical models of simple biochemical reaction networks.
7. Develop mathematical models of transcriptional networks.
8. Understand the dynamics of regulation in transcriptional networks.

Paper C11: Chemical Engineering I - Advanced reaction engineering and separations

C11 advances on B6 Equilibrium Thermodynamics, B7 Fluid Flow, Heat and Mass Transfer, and B11 Chemical Processes. There are three core topics explored in this course: (1) advanced chemical reaction engineering (c1101), (2) surface chemistry and interfacial processes (c1102), and (3) advanced separation processes (c1103). This course is meant to be complementary to C12.

c1101: Advanced chemical reaction engineering: 4 Lectures, 1 Tutorial Sheets

This module advances on the B11 module on reaction engineering. It introduces the key concepts and methods of more advanced forms of chemical reactors – both conventional and emerging. It includes fluidised bed reactors (1 lecture), electrochemical reactors (1 lecture), homogeneous and heterogenous catalytic reactions/reactors (1 lecture), and emerging reactors – e.g., mixed-reactors, photochemical, bioreactors, etc. (1 lecture). Types of reactions covered include Haber-Bosch, polymerisation, methanol productions, etc.

Learning Outcomes:

1. Be able to apply first principle concepts (mass balances, design equations, kinetics, etc.) to more advanced types of reactors
2. Understand introductory concepts regarding electrochemistry and be able to design electrochemical reactors
3. Understand different types of catalytic reactions and grasp the principle of the corresponding reactor designs.
4. Understand the current state of emerging designs for reactors – e.g., catalytic electrochemical reactors, sonochemical reactors, photochemical reactors, etc.

c1102: Surface chemistry and interfacial processes: 4 lectures, 1 Tutorial Sheet

This module will focus on various interfacial phenomena relevant to the chemical and process industries. Lectures will include: (1) surface tension, contact angle, wetting, capillarity, roughness of different types of interfaces, e.g., solid-liquid, liquid-liquid, solid-gas and liquid-gas interfaces (1 lecture), (2) surface phenomena, surface energy, thermodynamic and kinetic effects (1 lecture), (3) surface active agents (i.e., surfactants) surfactant types, solubility, CMC and solubilisation phenomena (1 lecture), and (4) emulsions, colloids, flocculation, dispersion & aggregation (1 lecture).

Learning outcomes:

1. Understand surface tension in different situations and interfaces.
2. Understand surface interactions and phenomena.
3. Define surfactants and understand surfactant interactions at interfaces and their impact on solubility and critical micelle concentration.
4. Know the classifications of emulsions, colloids, etc. and understand their defining features and applications.

c1103: Advanced separation processes: 8 Lectures, 2 Tutorial Sheet

This module covers two key areas in separation. Part A (4 lectures) covers advanced distillation, a continuation of B7 Separation Processes. Revision of binary distillation, including calculation of vapour-liquid equilibria, operating line and equilibrium stage concepts. Extension to multicomponent systems with appropriate approximate design methods. Practical design consideration including distillation sequencing and tray sizing. Part B (4 lectures) covers new material regarding other separation processes, such as membrane separation, adsorption, crystallisation, chromatographic methods, etc.

Learning Outcomes:

1. Obtain a deep understanding on the internal components of a distillation column.
2. Be able to spec-out and size a distillation column to achieve defined separation.
3. Be able to define and categorise non-distillation separation processes.
4. Be able to predict separation achieved by non-distillation separation processes.

Paper C12: Chemical Engineering II - Systems and Sustainability

Complementary to C11 Chemical Engineering I, this paper introduces (1) methods for systematically approaching process engineering (c1201) and product design (c1203) and (2) assessment approaches and emerging chemical processes for environmental and resource sustainability (c1201, c1202).

c1201: Process modelling, optimisation and integration: 8 Lectures, 2 Tutorial Sheets

This module introduces the key concepts and methods of Process Systems Engineering and their applications. It includes (i) steady-state and dynamic (chemical/biochemical) process modelling and simulation (2 lectures); (ii) mathematical programming-based process optimisation (1 lecture); (iii) Pinch technology for energy integration (4 lectures) and (iv) Life-cycle analysis (LCA) of environmental impacts as targets for improving process systems and associated supply chains (1 lecture).

Learning Outcomes:

1. Formulate first-principle mathematical models for chemical processes.

2. Solve steady-state and dynamic process models using numerical (MATLAB or Python) and engineering (ASPEN) packages.
3. Formulate mathematical programming models for process optimisation.
4. Solve optimisation models using numerical (MATLAB or Python) packages.
5. Apply targeting approaches to determine minimum utility requirements.
6. Apply pinch principles to design energy efficient heat exchange networks.
7. Apply grand composite curves to support utility selection and process unit integration.
8. Apply Total Site Analysis to support energy integration across multiple process plants.
9. Apply lifecycle analysis (LCA) methods to assess the environmental performance of chemical processes and relevant supply chains.

c1202: Green chemical engineering: 4 lectures, 1 Tutorial Sheet

This module introduces emerging chemical, biochemical and electrochemical processes for reducing adverse environmental impacts, particularly in terms of the reduction of greenhouse gas emissions through using renewable energy and material resources. The key mechanisms of such processes will be explained, and their efficiencies, techno-economics and environmental impacts examined. The topics include clean hydrogen and CO_2 utilisation (2 lectures) and biomass conversion and biorefineries (2 lectures).

Learning outcomes:
1. Understand and be able to assess different options for hydrogen production.
2. Understand and be able to assess different options for CO_2 conversion.
3. Understand biomass compositions and potential products that can be derived from biomass.
4. Understand and be able to assess different biomass processing options, including integrated biorefining schemes.

c1203: Product Design: 4 Lectures, 1 Tutorial Sheet (same as in the original C12 syllabus, unchanged)

The course is about the design of chemical products, encompassing four categories:
1. Traditional commodity chemicals.
2. New speciality chemicals with a specific molecular structure, e.g. pharmaceuticals.
3. Products whose microstructure, rather than molecular structure, creates value e.g. paint, ice cream.
4. Devices that effect chemical change e.g. blood oxygenator.

The module will aim to introduce the basic principles and methodology of the four-step design template for conceptual design: Needs, Ideas, Selection and Manufacture. All four stages will be demonstrated with examples of recent/current product development examples in chemical process industries. The applications will consider examples from commodity products, chemical devices, molecular products, and microstructural design examples of novel products for advanced and targeted functionality. The importance of the application of systems design methodology to product design will be illustrated by considering sustainable development strategies, incorporating environmental impact analyses.

Learning Outcomes:
1. Understand the formal methodology of the four-step conceptual product design template.
2. Recognise differences between process and product design procedures.
3. Develop performance targets for product design systems including considerations of sustainable use of resources, recycle and re-use in developing product design selection and manufacture.

4. Understand the capabilities and shortcomings of individual technology applications with reference to future sustainable development.

Paper C13: Production Engineering

c1301: Production Processes; Matric 2023, Y4; Paper C13: 8 Lectures, 2 Tutorial Sheets

The overall aim of the course is to give an understanding of the processes involved in the manufacture of mechanical engineering products. Selection methods for choosing appropriate materials and processes are described. Simple models are used to give a quantitative understanding of manufacturing processes.

Learning Outcomes:

1. Describe and classify various processes.
2. Discuss the advantages/disadvantages of particular processes.
3. Give examples of manufactured products and explain the choice of processes used.
4. Define the material merit index associated with particular design problems.
5. Select materials using merit indices and performance charts.
6. Understand the interaction of shape with material selection.
7. Understand basic constraints on the choice of manufacturing process relating to size, shape, and material melting temperature.
8. Understand the need for process models.
9. Understand some issues in the casting process and their influence on component design.
10. Use simple models to explain issues in mould fill, solidification and microstructure of castings.
11. Understand design and material issues related to forging and rolling.
12. Estimate the forces involved in simple forging and rolling processes in plane strain.
13. Estimate the forces involved in simple drawing and extrusion processes in plane strain.
14. Understand design issues related to drawing and extrusion.
15. Estimate the forces and energy involved in machining processes.
16. Understand the key issues of tool wear in machining.
17. Use simple models to understand the sheet bending process.
18. Understand some issues relating to cold joining processes.
19. Use thermal analysis to understand the effects of welding on microstructure and the interaction between the welding process and various materials.
20. Estimate the heat generated in deformation processes, find the resulting temperature rises, and discuss their effects.

c1302: Additive Manufacturing; Matric 2020, Y4; Paper C13: 4 Lectures, 1 Tutorial Sheet

The course introduces the fundamentals of Additive Manufacturing, starting with the simple examples and principles, implementation, and classification (with reference to ISO/ASTM 52900), followed by discussion of practical procedures and inputs used to set up 3D prints, and post-processing techniques. The emphasis is then placed on understanding the significance of phase change for 3D printing, through overview of the basic facts and relationships, illustration of the mathematical description, and experimental characterisation using e.g., Differential Scanning Calorimetry (DSC) to determine temperature-dependent heat capacity. Kinetics of phase change is then considered through the Johnson-Mehl-Avrami-Kolmogorov formula and application, TTT and CCT diagrams. Analytical process models for the major additive manufacturing techniques (vat photopolymerisation, powder bed fusion, directed energy deposition, material jetting, binder jetting, material extrusion) are introduced and discussed. Characteristic metrics and dimensionless numbers are identified and discussed in the context of physical processes and time scales involved. Case studies are presented in the context of specific techniques.

Learning Outcomes:

1. Understanding of the difference between additive and subtractive manufacturing.

2. Understanding and classification of the different ways in which Additive Manufacturing (3D printing) can be implemented.

3. Understanding of the key stages of the additive manufacturing process, and ability to recognise them in different modalities of AM.

4. Understanding of the significance of phase change processes in AM.

5. Ability to describe the phase change thermodynamics and kinetics qualitatively and quantitatively.

6. Understanding of the Avrami equation assumptions, derivation and application.

7. Understanding of the key metrics and dimensionless parameters that govern AM processes and ability to use these to assess a manufacturing process.

8. Understanding process models for major AM techniques and ability to apply these to describe the manufacturing process.

<u>c1303: Modern Manufacturing Systems; Matric 2023, Y4; Paper C13: 4 Lectures, 1 Tutorial Sheet</u>

Trends shaping manufacturing: History of Quality Revolution and development of modern principles such as Just in Time (JIT), Continuous Improvement and Mass Customisation. Structure and factory layout of manufacturing systems: fixed build to flexible manufacturing to cell-based manufacturing. Principles of Lean Manufacturing: muda, optimisation using Group Technology, Structural Complexity. Scheduling: one and two machine examples, with and without precedence.

Learning Outcomes:

1. Provide an introduction into the historical development of industrial management, in order to understand how manufacturing has been forced to evolve.
2. Appreciate how manufacturing facilities should be operated, and what factors and laws can be applied in order to improve efficiency.
3. Recognise pitfalls in running a manufacturing operation and utilise tools to help deal with such practical issues.
4. Recognise the benefits and mathematics behind simple scheduling tools in the context of manufacturing scenarios.

Paper C14: Optoelectronics

<u>c1401: Applied Optics; Matric 2023, Y4: Paper C14: 8 Lectures, 2 Tutorial Sheets</u>

Lecture 1 provides an overview of the topics covered in these 8 lectures. We start by considering geometrical optics and derive the Laws of Reflection and Refraction from first principles using Fermat's principle of least time. We also introduce the concept of ray vectors and matrices and consider how these can be applied to describe simple lens systems.

In lecture 2 we review Maxwell's wave equation and consider the conditions that are required to generate standing waves and optical resonators. We also define the polarization of the wave and introduce the relevant parameters that are typically used to describe the polarization state e.g. the Jones and Stokes parameters.

In Lecture 3 we consider how the electromagnetic (EM) waves propagate through a crystal structure and re-derive the laws of reflection and refraction using the boundary conditions from EM theory. The Fresnel amplitude and reflection coefficients are also derived from first principles for the Transverse Electric and Transverse Magnetic cases. Finally, we discuss the Brewster angle as well as external and internal reflection.

Lecture 4 focuses on the phenomenon of interference and we discuss coherence, fringe visibility, interferometers, and thin films.

The first half of Lecture 5 considers multi-beam and multi-layer interference whereas the second half of the lecture introduces the phenomenon of diffraction. We describe the fundamental principles of the diffraction integral and derive the integrals for near and far-field diffraction.

In Lecture 6 we continue our discussion on Fraunhofer (far-field) diffraction and derive the expressions for the intensity of light in the far-field that has been diffracted by a simple geometric structure such as a square or circular aperture. In the second half of this lecture, we introduce the concept of Fourier Optics and show that the pattern generated in the far-field is equivalent to the 2-dimensional spatial Fourier transformation of the aperture structure.

Lecture 7 continues with Fourier Optics and shows how a thin lens can be used to as Fourier transforming element.

Lecture 8 concludes the lecture series by considering the formation of images in more detail for coherent and incoherent light. We also discuss how aberrations in an optical system can distort an image and how these might be corrected.

Learning Outcomes:

1. Understand the use of ray vectors and matrices and be able to apply these concepts so as to describe the propagation of light through basic lens systems.
2. To be able to derive from first principles the laws of reflection and refraction along with the Fresnel coefficients for transmission and reflection.
3. Understand the tools employed to describe the polarisation of an electromagnetic wave.
4. To be able to apply the Fresnel-Kirchhoff diffraction formula to certain scenarios such as the near and far-fields.
5. Understand the role Fourier transforms play in describing Fresnel and Fraunhofer diffraction.

c1402: Metamaterials and Plasmonics; Matric 2023; Y4; Paper C14: 8 Lectures, 2 Tutorial Sheets

Metamaterials is a new subject. The term 'metamaterial' means that it is something well beyond ordinary materials. So, what are metamaterials? A brief and quite good definition is 'artificial media with unusual electromagnetic properties' such as negative refraction. This lecture course serves as an introduction to this fascinating research field. This lecture course is aiming to provide an introduction into a new area of metamaterials and plasmonics. Fundamental concepts will be introduced with emphasis on physical principles and simple mathematical models; application will be illustrated with new devices and technologies.

The structure of the course is as follows:

- Lecture 1 provides a birds-eye view of the subject and a historic review. The concepts of negative refraction, negative permittivity, negative permeability, backward waves, left-handed media, subwavelength imaging are introduced.
- Lecture 2 reviews the basic concepts required to study metamaterials and plasmonics.
- These include Maxwell's equations, Poynting vector, wave equation, dispersion equation, propagating and evanescent waves, bulk plasma waves, Drude model, electromagnetic waves in metals, forward and backward waves, boundary conditions at an interface of □0 media.
- Lecture 3 considers the fundamental problem of light refraction at an interface air/metamaterial with arbitrary material parameters. Generalized Snell's law. The concept of surface waves. Surface plasmon-polaritons. Negative refraction.
- Lecture 4 treats the refraction problem for a metamaterial slab with arbitrary permittivity and permeability. Surface plasmon-polaritons for a slab. Negative refraction again.
- Lecture 5 discusses subwavelength imaging using metamaterials. Transfer function. Perfect lens with $n = -1$. Imaging with a silver slab (" < 0, $\mu = 1$). Multilayer systems. Cylindrical hyperlens.
- Lecture 6 describes magnetic metamaterials with negative permeability.
- Lecture 7 describes interactions between metaatoms. Magnetoinductive waves in magnetic metamaterials - analogy to plasma waves in electric metamaterials. Tailoring the dispersion properties.
- Lecture 8 provides an overview of applications of metamaterials and future research directions.

Learning Outcomes:

1. Understand the principles behind metamaterials including negative refractive index materials, their fabrication and applications.
2. Understand how permittivity and permeability in metamaterials can be calculated from the properties of individual resonators and interactions between them.
3. Understand how plasmonic excitations in metals can be described and employed for sub-wavelength imaging.
4. Understand the basic ideas behind applications of metamaterials including the perfect lens, invisibility, and manipulation of electromagnetic waves on a subwavelength scale.

Paper C15: Microelectronics

c1501: Digital Integrated Circuits; Matric 2023, Y4; Paper C15: 8 Lectures, 2 Tutorial Sheets

CMOS – Deep Sub Micron Technologies, structured logic design. Delay and Speed - Inverter Delay, RC delay model, Interconnects and related parasitics. Power - Static and dynamic power, low power designs, noise margins. Logic Design - Adders, counters, shifters, Multipliers, Latches and flip-flops. Memories - SRAM, DRAM, ROM, Addressing circuitry, Area, delay and power analysis. IC Design - Input/Output, Pads and ESD Protection, Clock systems, power distribution, charge pumps, packaging. Reliability and testing- Scaling, design economics, Design for Manufacturing, Logic verification, design for testability. Embedded System Design – Architectures, Multi and many-core systems, Real Time Operating Systems.

Learning Outcomes:

1. Have an appreciation of modern digital circuit design options.
2. Understand the key parameters of elementary logic and sequential elements and how they constrain the design and dictate the performance of digital design.
3. Understand the main types of digital architecture that are used and when each is appropriate.
4. Analyse the speed, power, area and scaling of simple combinatorial and sequential logic circuits.
5. Understand basic digital building blocks including adders, counters and multipliers.
6. Understand the power dissipation in integrated circuits and its effect on logic performance.
7. Describe the need and parasitics attached to the input and output schemes of an integrated circuit.
8. Describe random addressable and read only memories along with their addressing and sensing schemes.
9. Understand the importance of clock design and techniques to control clock skew.
10. Understand the importance and difficulties of testing modern electronic systems, and the importance of using a fault model and of getting good fault coverage.
11. Understand and avoid common CMOS circuit pitfalls and reliability problems including variability.
12. Describe building blocks of an embedded system.

c1502: Analogue Microelectronics; Matric 2023, Y4; Paper C15: 8 Lectures, 2 Tutorial Sheets

Overview of CMOS Processes: simple transistor models, short-channel effects, temperature effects, simulation models, small signal models, noise models, Pelgrom. Model of mismatch, layout for matching. MOS Switches: on-resistance, leakage current. Charge redistribution/Clock feedthrough: solutions to clock-feedthrough. Transmission Gates. Current Sources: cascode, robustness to threshold variations, matching. Current mirrors, including Improved Wilson current mirror. MOS diodes: Active Voltage Dividers, Gate-Source Voltage Reference Generators. boot strapped current source, including T dependence. High gain CMOS Inverters: gain, frequency response, noise. Cascode amplifiers: differential amplifier, common-mode input range, small signal gain. Two-Stage Comparator: design procedure, systematic offset error, inverter cascades to drive large C loads. Output amplifiers and source followers, two stage op-amp design, cascode design, low power op-amps.

Learning Outcomes:

1. Describe the stages of a CMOS process.
2. Describe the current-voltage characteristics of a MOSFET.
3. Derive the small signal model for a MOSFET.
4. Derive an analyse small signal equivalent circuits.
5. Explain the origins of mismatch between devices and their impact on circuits.
6. Design MOS Switches and Transmission gates.
7. Describe charge redistribution, clock feedthrough and solutions to clock-feedthrough.
8. Design current sources, mirrors and amplifiers.
9. Explain why cascode devices increase the impedance of circuits.
10. Explain gate-source voltage reference generators and boot a strapped Current Source.
11. Design high gain CMOS inverters.
12. Design cascode and differential amplifiers.
13. Design two-stage comparators and explain the origins of the systematic offset error.
14. Design output amplifiers and source followers.
15. Design two stage Op-Amp Design.
16. Design low power Op-amps.

Paper C16: Advanced Communications

<u>c1601: Introduction to Information Theory; Matric 2023, Y4; Paper C16: 8 Lectures, 2 Tutorial Sheets</u>

In 1948, Claude Shannon published a seminal piece of work outlining a mathematical theory of communication. This single paper gave birth to what is now known as information theory. Amazingly, although Shannon's original formulation seemed rather abstract at first, it almost immediately led to practical applications, and communications engineers continue to directly apply the theory to create new systems, including the 6G network that is currently under development. This course will provide an introduction to Shannon's theory and its consequences. The mathematical results will be reinforced with practical examples ranging from cellular applications to storage systems.

Syllabus:

- Measures of information: entropy, conditional entropy, joint entropy, relative entropy, mutual information, differential entropy, maximum entropy, properties of information measures, entropy rate
- Data compression: instantaneous codes, uniquely decodable codes, entropy bound on data compression, example codes and their optimality, penalty for incorrect code design, symbol grouping, compressing random processes
- Channel capacity: noisy channels, the channel coding theorem and its implications, binary symmetric channel capacity, binary erasure channel capacity, feedback capacity, source-channel separation theorem
- Error correcting codes: linear versus nonlinear codes, repetition codes, parity check operations, minimum distance, Hamming codes, iterative decoding
- Gaussian channels: additive Gaussian noise channel, band-limited additive white Gaussian noise channel, parallel Gaussian channels

Learning Outcomes:

1. Understand the interpretation of entropy and related concepts as measures of uncertainty and information.

2. Be able to recognise the importance of data compression in modern applications and have an appreciation for fundamental properties of data that facilitate compression.
3. Develop an understanding of basic noisy communication and storage channel models.
4. Understand the conditions that must be satisfied to communicate or store information reliably in different practical scenarios.
5. Gain an appreciation of modern error correcting codes, the importance in practice, and how they have contributed to modern communications and storage solutions.

c1602: Wireless Communications; Matric 2023, Y4; Paper C16: 8 Lectures, 2 Tutorial Sheets

Communicating data over wireless links is pervasive in modern society. Mobile phones contain multiple radio access technologies, which allow users to connect to the cellular network, Wi-Fi hotspots, and even directly to another user via Bluetooth file sharing apps. We also utilise wireless connectivity when we listen to or view digital content broadcast through the DAB and DVB (terrestrial and satellite)

systems. This course will study the basic physical layer theories and mechanisms that are employed in systems such as those described above. The focus will be on how engineers design systems to exploit the benefits offered by the wireless medium while coping with the inherent problems that arise when communicating wirelessly.

Syllabus:

- Wireless channels: propagation, path loss, shadowing, small-scale fading, narrowband fading, wideband fading, slow fading and fast fading
- Capacity and performance: SNR distribution and outage probability, outage capacity, ergodic capacity
- Diversity: time diversity, frequency diversity, spatial diversity, maximum ratio combining, selection combining, space-time coding
- Multiple-input multiple-output: capacity, SVD beamforming, spatial multiplexing
- OFDM: the DFT and FFT, digital implementation in additive noise channels, implementation in LTI channels
- Multiple access: orthogonal access, random access, spread spectrum, capacity-optimal schemes, multi-user (massive) MIMO

Learning Outcomes:

1. Understand the salient properties of wireless channels and be able to perform basic loss calculations for practical examples.
2. Be able to analyse the capacity of key wireless channels encountered in practical systems.
3. Have a clear understanding of the concept of diversity and how it can be exploited in practice.
4. Understand the information theoretic properties of multiple-input multiple-output channels as well as where and how these channels are encountered in practice.
5. Gain an appreciation for the digital implementation of OFDM and understand why it is so often used in modern practical systems.
6. Be able to describe how common multiple access strategies operate to enable multi-user communication in wireless networks.

Paper C17: Power Electronics

c1701: Overview of Power Converters; Matric 2023, Y4; Paper C17: 8 Lectures, 2 Tutorial Sheets

Power electronics is an important enabling technology in sustainable energy systems, linking a power source with a load in the most efficient and flexible way. This course will cover: The role of power electronics, overview of applications, recent advances and challenges; power semiconductor devices: requirements, ratings, junction features, stored charge effects, structure, design compromises; AC-DC converters/rectifiers: active and passive, front ends, distortion, power factor; switched mode power supplies; DC-DC converters: buck and boost, buck-boost, other converters; inductors, transformers and capacitors for power electronics applications; modulation schemes, filtering and electromagnetic compatibility for hard-switched DC-AC converters.

Learning Outcomes:

1. Appreciate the need for power electronics, the applications, and the main types of devices and converters used.
2. Appreciate the properties of semiconductor devices useful in power applications.
3. Be able to calculate power losses in devices.
4. Be familiar with the standard topologies for power converters and be able to describe their operating principles.
5. Know how to analyse standard power converters including DC-DC converters, DC-AC converters and AC-DC converters.
6. Be able to select and design appropriate converter topologies and specify semiconductors and passive components for particular applications.
7. Understand pulse width modulation schemes, filter design and electromagnetic compatibility in practical converters.

c1702: Power Converters for Electrical Machines; Matric 2023, Y4; Paper C17: 8 Lectures, 2 Tutorial Sheets

Power Converters for Electric Machines: Electrical motor drives are used to convert signals from the information world to the real world. This usually includes the control of torque, speed and position. Drives are important in many renewable energy systems, hybrid and electric vehicles and efficient industrial processes. This paper introduces this important topic, including electrical machine theory; DC motor drives; induction machine drives; vector control; brushless AC and DC machine drives, doubly fed induction machines.

Learning Outcomes:

1. Identify the key requirements for the control of drives.
2. Layout and size the active and passive components of a DC drive.
3. Analyse the drive waveforms.
4. Understand scalar control of induction machines.
5. Able to compare and contrast PWM schemes.
6. Understand principles of generalised machine theory and be able to develop the equations by inspection.
7. Able to derive vector control strategies for induction machines, DFIG and synchronous machines.

Paper C18: Machine Vision and Robotics

c1801: Computer Vision; Matric 2023, Y4; Paper C18: 8 Lectures, 2 Tutorial Sheets

Computer Vision I: Large scale image indexing and retrieval using quantized features. Fundamentals of deep neural networks and the backpropagation algorithm. Applications to image recognition, object detection and image segmentation.

Learning Outcomes:

1. Designing and evaluating large scale image retrieval systems: matching image pairs, bag of words, indexing.
2. Understanding deep neural networks and the backpropagation algorithm.
3. How to apply deep neural networks to image recognition, object detection and image segmentation.

Computer Vision II: The camera as a geometric device: homogeneous transformations, transformations from Euclidean to Projective, and back to Perspective; intrinsic and extrinsic contributions to camera calibration; lens distortion. The camera as a photometric device: traditional and neural network features. Two-view geometry: derivation of the fundamental matrix, estimation with RANSAC and eco-motion recovery, stereo 3D reconstruction.

Learning Outcomes:

1. The geometry of image formation in the perspective camera, and its description using homogeneous coordinates.
2. A hierarchy of transformations, from Euclidean to Projective.
3. Camera calibration including distortion correction.
4. Photometric modelling using features and neural networks.
5. The geometry of two views, including epipolar geometry.
6. Derivation of the fundamental matrix and its form for simple camera displacements.
7. Estimating the fundamental matrix from point correspondences and RANSAC.
8. Recovering the ego-motion from the fundamental matrix.
9. The reconstruction of depth from matches in two views, using traditional and neural neural based techniques.

c1802: Robotics; Matric 2023, Y4; Paper C18: 8 Lectures, 2 Tutorial Sheets

Introduction: motivates and introduces basic concepts in mobile robot navigation. It covers aspects of spatial estimation and motion estimation using common sensor modalities. We introduce fundamentals of planning (local and global methods). The syllabus couched and supported with a number of worked examples and real wold applications. A matlab toolbox is supplied to supplement the notes and to be used as an aid in the example sheets.

Learning Outcomes:

1. To be able to identify vehicle types (Holonomic, Non-Holonomic) and understand the impact of vehicle type on planning
2. To understand, implement and appraise concepts (e.g., configuration space, Minkowski Sum, Voronoi methods), local methods (e.g., bug methods and potential field methods) and global methods (A*, PRMs, RRTs) in path planning and obstacle avoidance.

3. To understand and relate fundamentals techniques of estimation : least squares (linear, weighted, non-linear), maximum likelihood, maximum a-posteriori estimation
4. To analyse, derive and appraise the Kalman Filter(linear) extended (non-linear) and its application to motion estimation and mapping under appropriately formulated motion models
5. To understand and critique sample-based methods for localisation
6. Running debugging and instrumenting software which demonstrates mobile robot localisation, mapping, simultaneous localisation and mapping

Paper C19: Machine Learning

c1901: Machine Learning: Generative; Matric 2023, Y4; Paper C19: 8 Lectures, 2 Tutorial Sheets

Introduction: applications; supervised vs unsupervised learning; nearest neighbour methods; regularisation; the challenge of generalisation.

Graphical models: simple graph theory; directed graphical models; factor graphs; prediction; canonical examples from machine learning

Approximate Inference: Laplace's method; variational methods; Monte Carlo integration; rejection sampling; Markov chain Monte Carlo; Metropolis Hastings; Gibbs Sampling; detailed balance; stationary distributions, a Gibbs sampler for Gaussian mixture models.

Learning Outcomes:

1. Learn to formulate various applications into regression, classification or clustering problems.
2. Become familiar with the definition and strengths of nearest neighbour algorithms.
3. Appreciate the challenge of generalisation.
4. Understand the role of regularisation, and its emergence from the use of priors in Bayesian inference.
5. Understand the use of graphical models as a parsimonious representation of a joint distribution.
6. Appreciate that the challenge of inference is integration and recognise the family of approaches to the challenge: Laplace's method, variational inference, Monte Carlo and Markov chain Monte Carlo.
7. Learn how to apply Laplace's method and understand when it might be appropriate to use.
8. Learn how to apply variational inference and understand when it might be appropriate to use.
9. Learn how to use Jensen's inequality to bound intractable integrals.
10. Learn how to apply Monte Carlo sampling and understand when it might be appropriate to use.
11. Gain an overview of different Markov chain Monte Carlo methods, particularly Gibbs Sampling and Metropolis Hastings.
12. Understand the meaning of detailed balance and stationary distribution.

c1902: Machine Learning: Discriminative; Matric 2023, Y4; Paper C19: 8 Lectures, 2 Tutorial Sheets

This course presents key topics in discriminative machine learning, providing the necessary mathematical background and motivating synthetic and real-world examples.

Topic 1: Regression

Given an input (more precisely, a feature vector extracted from an input), regression requires us to predict a real scalar output. In order to learn the parameters of a regression function, we will derive an objective function that consists of two terms: (i) the loss function, which encourages high accuracy on the training data; and (ii) the regularizer, which prevents overfitting. Specific regression frameworks that will be presented include ridge regression (which admits a closed form solution) and Lasso (which requires solving a convex optimization problem).

Topic 2: Support vector machines for classification

Given an input (more precisely, a feature vector exacted from an input), classification requires us to predict a class from a finite discrete set. We will review the popular support vector machine (SVM) classifier, which provides a linear classification rule. The parameters of the classifier are estimated using a learning objective that consists of two terms: (i) a convex upper bound on the empirical risk, which is measured by a user-specified loss function; and (ii) the regularizer, which prevents overfitting. Optimization algorithms for parameter estimation of an SVM will be discussed.

Topic 3: SVM duality

In order to overcome the limitation of an SVM to only provide a linear prediction rule, we will derive the dual of the SVM problem. The dual will allow us to use the kernel trick, that is, project the input to a high-dimensional space by only providing a function to compute the dot product. The dual problem will also be shown to be convex under certain conditions of the kernel.

Topic 4: Weak supervision

Many real-world applications do not provide a full annotation of the training samples, which prohibits the use of supervised classifiers such as SVM. We describe a latent variable extension of the SVM, where the latent variables (unknown during training) represent the missing part of the annotations. The parameters of a latent SVM are learned by minimizing a regularized difference-of-convex upper bound on the empirical risk.

Topic 5: Neural networks

Neural networks can be thought of as compositions of non-linear functions. The argument of the function is the input to an AI system, while the value of the function represents the desired output. The composite nature of the function enables us to compute the gradients of a learning objective using the chain rule - a fact that is cleverly exploited by the backpropagation algorithm.

Learning Outcomes:

1. Understand the effects of different loss functions and regularizers in machine learning.
2. Become familiar with the standard classification and regression frameworks in machine learning.
3. Understand how to use high-dimensional mappings of feature vectors to enable better classification.
4. Become familiar with the basic optimization techniques used in machine learning.

Paper C20: Robust and Distributed Control

c2001: Convex Optimisation; Matric 2023, Y4; Paper C20: 4 Lectures, 1 Tutorial Sheet

Introduction to convex optimisation, including convex sets and convex functions. Classes of convex problems including linear and quadratic programs, general conic problems and semidefinite programming. Lagrangian functions and dual problems for convex programs. KKT conditions for convex problems. Introduction to modelling tools and software for convex optimisation.

Learning Outcomes:

1. Understand basic notions of convex sets, functions and optimisation problems.
2. Be able to formulate convex optimisation problems into standard-form linear, quadratic or semidefinite programs.
3. Understand Lagrangian duality and the dual of a convex program.
4. Understand the KKT conditions for optimality.

c2002: Robust Control; Matric 2023, Y4; paper C20: 4 Lectures, 1 Tutorial Sheet

Analysis of dynamical systems using Lyapunov functions, Stability analysis by Linear Matrix Inequalities (LMIs), Performance measures for systems with disturbances, Performance analysis by LMIs, Controller synthesis by semi-definite programming (SDP), Schur Complement, H2 Optimal Control, Linear Quadratic Regulator (LQR) and the Riccati equation, Stability of systems with uncertain dynamics by LMIs, Stability of systems with non-linearities using the S-procedure.

Learning Outcomes:

1. Understand basic notions of stability, performance, and robustness of dynamical systems
2. Formulate guarantees of robustness through Lyapunov functions
3. Pose robustness guarantees for linear systems using convex optimization (Linear Matrix Inequalities)
4. Pose controller synthesis problems using convex optimization (Semi Definite Programs)
5. Analyse complex dynamical systems with uncertainties and systems with non-linearities using convex optimization

c2003: Distributed Systems; Matric 2023; Y4 paper C20: 4 Lectures, 1 Tutorial Sheets

Introduction to parallel and distributed computation; Primal and dual algorithms for multi-agent networked systems; The Jacobi and the Gauss-Seidel algorithms in optimization; Proximal minimization and the augmented Lagrangian algorithm; The alternating direction method of multipliers (ADMM); Distributed dual decomposition.

Learning Outcomes:

1. Familiarity with a variety of cutting-edge distributed optimization algorithms; applicable to a wide class of application domains ranging from energy systems and robotics to machine learning.
2. Application of duality and convex optimization to parallelize computation.
3. Introduction to network systems and optimization over time-varying communication graphs.

4. Introduction to fixed-point theoretic results and convergence analysis tools.

C2004: Robust Optimisation; Matric 2023; Y4 paper C20: 4 Lectures, 1 Tutorial Sheets

Decision making under uncertainty; Introduction to probabilistic robustness; Learning and generalization; Probably approximately correct (PAC) learning.
Probabilistically robust control design and the “scenario approach"; Connections with randomized optimization algorithms; The notion of support and connections with active constraints; Tightness of confidence bounds on the probability of constraint violation; Bounds on the expected probabilistic feasibility.

Learning Outcomes:

1. Introduction to decision making in the presence of uncertainty.
2. Familiarity with the notion of probably approximately correct (PAC) learning, and different notions of learnability.
3. Connections between learning and data driven optimization.
4. Introduction to the “scenario approach” for chance constrained optimization; applicable to a wide class of application domains ranging from geometric problems to robust stability and controller synthesis applications.
5. Tightness of confidence bounds on the probability of constraint violation.
6. Expected value bounds on the probability of constraint violation.

Paper C21: Nonlinear and Optimal Control

c2101: Nonlinear Systems; Matric 2023, Y4; Paper C2: 4 Lectures, 1 Tutorial Sheet

Concepts of stability; equilibrium points, limit cycles, regions of attraction. Stability analysis based on linearization. Positive definite functions, Lyapunov’s direct method and asymptotic stability.

Convergence analysis: Barbalat’s Lemma, the use of invariant sets to determine regions of attraction. Stability of linear and passive systems.

Learning Outcomes:

1. Understand the basic Lyapunov stability definitions.
2. Analyse stability using the linearization method.
3. Analyse stability by Lyapunov’s direct method.
4. Determine convergence using Barbalat’s Lemma.
5. Use invariant sets to determine regions of attraction.
6. Construct Lyapunov functions for linear systems and passive systems.
7. Use the circle criterion to design controllers for systems with static nonlinearities.

c2102: Model Predictive Control; Matric 2023, Y4; Paper C21: 4 Lectures, 1 Tutorial Sheet

Constraints on system inputs and states; PID anti-windup, receding horizon control. Prediction and optimization: infinite horizon cost, quadratic programming. Closed-loop properties: recursive feasibility and Lyapunov analysis. Dual mode predictions; terminal cost and constraints. Disturbances: integral action, robust constraints, pre-stabilized predictions.

Learning Outcomes:

1. Understand the advantages of receding horizon control, its limitations and areas of application.
2. Know how to formulate receding horizon control as:
   a. Fixed-term feedback controller (for unconstrained linear systems).
   b. A quadratic program (for linearly constrained linear systems).
   c. A nonlinear program (general case).
3. Understand and know how to determine the stability properties of a predictive controller in terms of:
   a. Recursive feasibility guarantees.
   b. Monotonic cost decrease through optimization.
4. Know how to design terminal constraints through a constraint checking horizon.
5. Know how to incorporate integral action.
6. Know how to ensure robustness to bounded disturbances.

<u>c2103: Systems Identification; Matric 2023, Y4; Paper C21: 4 Lectures, 1 Tutorial Sheets</u>

Uses of system identification; review of discrete time systems, stability and frequency response; stochastic signals.

Parametric identification; prediction error methods; model structures; extension to state space models and relationship to recursive neural networks; properties of prediction error; finding optimal parameter estimates; accuracy of estimates; model validation; model order selection

Learning Outcomes:

Lecture 1.

- Understand the need for system identification
- Understand difference between physical modelling and data based modelling
- Know how to obtain the frequency response of a discrete time system
- Appreciate why the presence of disturbances makes system identification difficult
- Understand how to obtain the statistics of signals that combine stochastic and deterministic components

Lecture 2

- Appreciate that system identification estimates the parameters within a model
- Understand the model structures used in (linear) system identification
- Recognise the link between identifying state space models and learning Recurrent Neural Networks
- Appreciate the importance of the predictor in system identification
- Understand how to obtain the predictor and the prediction error

Lecture 3

- Understand that the parameters of the model can be estimated by minimising the power of prediction error
- Appreciate that the estimate obtained from a single experiment is a random variable
- Understand how to obtain the estimate for models that are linear in the parameters and appreciate that this is a least squares problem
- Understand iterative methods for finding the parameters of models that are non-linear in the parameters

Lecture 4

- Understand that the accuracy of the estimated parameters can be expressed in terms of the covariance matrix
- Understand that the covariance matrix depends upon the input signal and the number of data points
- Understand how confidence intervals for parameter estimates can be obtained from the estimated covariance matrix
- Understand the importance of model validation
- Understand model validation methods based on analysing estimated correlations
- Understand how to compare model structures using the final prediction error criterion
- Know why it is important to carry out cross-validation

<u>c2104: Dynamic Programming and Reinforcement Learning; Matric 2023, Y4; Paper C20: 4 Lectures, 1 Tutorial Sheet</u>

The dynamic programming framework: states, actions, transitions, costs. Modeling dynamic decision-making problems under uncertainty, such as shortest path problems. Definition of a policy and the value/cost-to-go function of a policy. Bellman's principle of optimality and the dynamic programming algorithm. Infinite horizon problems, stationary policies, and the Bellman equation. Algorithms for solving infinite horizon problems: policy iteration and value iteration. Solving dynamic programming problems from data: introduction to reinforcement learning approaches. Learning value functions and learning policies.

Learning outcomes:

1. Pose dynamic decision-making problems in the dynamic programming framework
2. Modelling problems with a finite horizon and an infinite horizon
3. Analyse policies using the concept of value functions
4. Understand Bellman's principle of optimality
5. Design optimal policies using Bellman's principle of optimality and the Bellman equation
6. Tackle problems with large state spaces and/or unknown models using data
7. Understand basic reinforcement learning approaches

Paper C22: Medical Imaging and Informatics

<u>c2201: Medical Image Analysis; Matric 2023, Y4; Paper C22: 8 Lectures, 2 Tutorial Sheets</u>

Revision of 2D linear filtering/convolution. Feature detection: derivative-based feature detection, edge detection. Filtering: Linear filters (Gaussian), anisotropic diffusion, nonlocal filters. Segmentation: edge-vs.region-based segmentation, clustering-based segmentation, discrete methods (graph-based methods), active contours, introduction to deep learning for image segmentation. Registration: Basic principles. Components of a registration system: geometric transformations, similarity measures, optimisation. Examples of state-of-the-art rigid and non-rigid registration methods and applications. Motion estimation: methodologies and applications.

Validation: The importance of validation in medical image analysis. Basic concepts. Methods for qualitative and quantitative validation. Examples of applications. Image characterisation: Methods for image classification. Applications: diagnosis, image localisation, detection of important structures.

Learning Outcomes:

1. Be familiar with the importance of imaging in biomedicine, its main concepts and terminology.
2. Have a good understanding of the importance of feature detection in biomedical imaging, and the main methods to detect features with their advantages and limitations.
3. Understand the use of filtering methods to improve image quality and detect important structures, as well as the main methods used in the field.
4. Understand the importance of segmentation and be familiar with the main techniques used for segmenting medical images.
5. Have gained a good understanding of the fundamental principles of image registration, including geometric transformation models, feature- and voxel-based registration methods
6. Have developed an insight into advanced non-rigid registration methods and clinical applications
7. Understand the concept and applications of motion estimation in biomedical imaging. Be familiar with the main motion estimation methods.
8. Understand the relevance and importance of validation for medical image analysis methods, and be familiar with the most common techniques used for validating medical image segmentation and registration techniques
9. Understand the use of image classification in different medical applications and be familiar with traditional and advanced classification methods.

<u>c2202: Medical Informatics; Matric 2023, Y4; Paper C22: 8 Lectures, 2 Tutorial Sheets</u>

The course consists of 8 lectures that will provide an overview of major trends and technical state of the art in health and clinical informatics illustrated with recent digital health examples. Ways of extracting important bio-signals are reviewed and algorithms to estimate important vital signs are explored. Students will explore how clinical knowledge is structured using medical standards and how these help the health informatics world. This course extends the topics covered in previous years and extends them to application in the medical informatics domain. The course will provide practical examples of techniques discussed with applications in the medical informatics and digital health domains. Additionally, the course will provide interesting pointers to relevant data sources (e.g. open source databases) and examples of successfully translated medical research into clinical practice to supporting evidence-based medicine.

Learning Outcomes:

1. Learn what health informatics is and how to structure a medical informatics project for the acquisition and analysis of signals.
2. Understand what standards are used in the medical informatics domain and how to enable interoperability of medical informatics systems.
3. Learn how to extract relevant features and vital signs from bio-signals (e.g. respiratory rate and blood pressure estimation advanced algorithms).
4. Familiarise with advanced signal processing topics and learn how to extract vital signs from non-conventional bio-signals.
5. Explore uses of quantitative methods in the medical domain.

Paper C23: Cellular Engineering and Therapy

c2301: Non-invasive Therapy; Matric 2021, Y4; Paper C23: 8 Lectures, 2 Tutorial Sheets

Lecture 1: Introduction to non-invasive therapies; principles and motivation; classes of non-invasive therapy.

Lecture 2: Ionising radiation therapies; introduction to different types (alpha, beta, gamma, proton beam, including radiopharmaceuticals); mechanisms of biological interaction; instrumentation; dosimetry; applications.

Lecture 3: Non-ionising radiation therapies; introduction to different types (microwave, RF, laser, cryogenic and electroporation methods); mechanisms of biological interaction; instrumentation; applications.

Lectures 4-5: Ultrasound and shock waves; definitions of sound, ultrasound and shockwaves; physics of the propagation of sound in tissue; mechanisms of biological interaction including mechanical and thermal effects; instrumentation; applications.

Lecture 6-7: Drug based therapies; classes of pharmaceutical products; mechanisms of action. Small molecules, antibodies, viruses, cell therapies, CRISPR/Cas gene modification.

Lecture 8: Combination therapies; principles and motivation; examples.

Learning Outcomes

1. Understand the principles and motivation for non-invasive therapy.
2. Understand the definition of ionising radiation, how it is produced, how it interacts with tissue, how this can be used therapeutically and the concept and need for radiation dosimetry.
3. Understand how non-ionising radiation can be used therapeutically and the corresponding mechanisms and methods of production.
4. Understand how sound waves interact with tissue, the definitions of ultrasound and shockwaves, how these are generated and the different mechanisms that can produce therapeutic effects.
5. Understand the basic principles of the main classes of drugs currently in use and their mechanisms of action.
6. Appreciate the advantages and disadvantages of different types of non-invasive therapy and how improved efficacy can be achieved through combinations of different approaches.

c2302: Neurotechnology for therapies and prostheses; Matric 2021, Y4; Paper C23 4 Lectures, 1 Tutorial Sheet

This course explores how the bioelectrical properties of cells and tissues may be harnessed to deliver therapeutic effects. The multi-scale behaviour of cells, networks and systems will be introduced together with current theories and computational modelling of neural circuits in both typical operation and disease processes. Throughout, relevant clinical examples and biomimetic (prosthestic) applications will be highlighted.
Lecture 1: Developing a framework for thinking about bioelectronic medicines– the core technology stack of a bioelectronic system will be developed including key design constraints for closed-loop

design. Multiple clinical applications will be discussed: deep brain stimulation, cardiac pacemakers and artificial pancreas.
Lecture 2: Basic Principles of Neural Actuation – electrical stimulation principles, safety limits, and design principles; emerging areas in optogenetics and temporal interference. Comparing and contrasting actuation methods. Clinical applications: deep brain stimulation (first generation), and cochlear prosthesis.
Lecture 2: Basic Principles of Neural Sensing – bioelectrical interfacing, signal properties, conditioning and considerations with a detailed review of circuit and safety considerations. Clinical application: brain-computer-interfaces.
Lecture 3: Bi-directional therapy systems and Risk Mitigations. An overview of medical device risk considerations and mitigations will be discussed, particularly for physiologic closed-loop systems. Clinical application: smart cardiac pacemakers and the artificial pancreas, and a deep-dive into a bidirectional brain-computer-interface in clinical trials for tremor control.

Learning Outcomes:

1. Knowledge of role of bioelectrical systems in neurotypical and disease physiology.
2. Knowledge of models of cell and network bioelectrical behaviour.
3. Appreciation of tissue interface challenges and their impact on stimulating and sensing from neural circuits.
4. Appreciation of complexity of interdisciplinary communication with engineers and clinicians required to formulate new therapies for neurological disease.
5. Knowledge of experimental tools used for electrical and biological characterisation in neurological disorders.
6. Knowledge of safety considerations for neural interfacing and closed-loop designs.
7. Knowledge of clinical applications most closely associated with neuromodulation and neuroprosthesis.

<u>c2303: Tissue Engineering; Matric 2021, Y4; Paper C23: 4 Lectures, 1 Tutorial Sheet</u>

Lecture 1: Introduction; history and principle of tissue engineering; key issues in tissue engineering; cell sources; potentials of stem cells.

Lecture 2: Introduction to extracellular matrix; scaffold materials for tissue engineering; fabrication techniques; scaffold design.

Lecture 3: Introduction to bioreactors; classification and configuration of bioreactors; advantages and disadvantages of different types of bioreactors; bioreactor design; monitoring technologies.

Lecture 4: Cryopreservation of cells and engineered tissues; mass transfer limitation; diffusional and convective mass transfer; cell metabolic rates; transport through cell membranes; mathematical modelling of mass transport in growing tissues.

Learning Outcomes:

1. To understand the principle of tissue engineering and stem cell therapy.
2. To appreciate the contributions of engineering and technology towards the regenerative medicine.
3. To understand the importance of mass transfer to the success of tissue engineering and to be able to evaluate relevant mass transfer processes.
4. To be informed the cutting-edge research and development in tissue engineering.

Paper C24: Probability, Systems and Perturbation Methods

c2401: Dynamical Systems; Matric 2023, Y4; Paper C24: 8 Lectures, 2 Tutorial Sheets

Introduction to Dynamical Systems. Examples from different fields. Maps, flows and questions of interest. Existence and uniqueness of solutions. A geometric way of thinking about differential equations. Phase space, equilibria. Stability and linearized stability. Saddles, nodes, foci and centres. Hartman-Grobman theorem. Lyapunov functions. Gradient and Hamiltonian Systems. Vector fields possessing an integral. Invariance. La Salle's theorem. Domain of attraction. Limit sets, attractors, periodic orbits, limit cycles. Poincaré maps. Poincaré-Bendixson theorem. Index theory. Saddle-node, transcritical, pitchfork and Hopf bifurcations. Logistic map. Fractals. Chaos. Lorenz equations.

Learning Outcomes:

1. To understand how the solutions of non-linear differential equations, used to model engineering systems, can be understood by studying the shape of solution trajectories in state space.
2. To understand when a linearized state space model will determine the local stability properties of a non-linear dynamical system and when such a determination fails.
3. To learn to use a number of simple tools to reason about the geometry and topology of simple 1-D and 2-D dynamical system state-space flows.
4. To understand how discrete maps differ from dynamical systems and how dynamical system orbital properties can be studied using such maps.
5. To understand the classification of simple equilibrium points and limit-cycles; to then develop a qualitative understanding of why some systems can exhibit more exotic behaviour such as chaos.

c2402: Perturbation Methods; Matric 2023, Y4; Paper C24: 4 Lectures, 1 Tutorial Sheet

Perturbation series; Asymptotic matching; Boundary layers; Multiple scales; WKB and related methods; homogenization.

Learning Outcomes:

1. Understand the role of perturbation methods in providing approximate solutions to differential equations.
2. Be able to apply perturbation series, asymptotic matching and multiple scales techniques to simple differential equations.
3. Understand the nature and behaviour of boundary layers and be able to analyse them in simple cases.
4. Understand the nature of multiple scales and the role of homogenisation.

c2403: Advanced Probability; Matric 2023, Y4; Paper C24: 4 Lectures, 1 Tutorial Sheet

The course will cover model comparison, the value of information and Gaussian processes. Inference, hypothesis testing and model selection: introduction to Bayesian inference, model hypothesis & evidence testing. Information theory: Entropy and mutual information. Gaussian processes; kernels/covariance functions.

Learning Outcomes:

1. Understand Bayesian model evidence ratios for model selection.
2. Understand the connections between and uses of entropy, conditional entropy and mutual information.
3. Appreciate the value of Gaussian processes for regression.
4. A basic understanding of the role of kernels/covariance functions and their influence on Gaussian process inference.

Paper C25: Mathematical Techniques

c2501: Optimization; Matric 2023, Y4; Paper C25: 8 Lectures, 2 Tutorial Sheets

Overview of the scope of optimisation from the perspectives of optimisation problems and the techniques for solving optimisation problems. Revision of optimality conditions for unconstrained and constrained problems. Introduction of mathematical concepts that underpin the subject of optimisation (including Lagrangian duality, KKT optimality conditions, and algorithmic complexity). Introduction of a collection of techniques for solving optimisation problems (including analytical solutions, simplex method, local descent, and genetic algorithm). Case studies (including the shortest path problem).

Learning Outcomes:

1. Confidence and competence in specifying an optimisation problem mathematically for a given real-world problem.
2. Knowledge of classes of optimisation problems (e.g., LP, QP, CP, IP, NLP) and categories of optimisation techniques (e.g., analytical solutions, problem conversion, divide and conquer, local descent, direct methods, stochastic methods, and population method).
3. Awareness of benchmark solutions (e.g., brute-force enumeration and NP algorithm) and their algorithmic complexity.
4. Understanding of the first and second order optimality conditions for unconstrained problems.
5. Understanding of the duality theory for constrained optimization.
6. Knowledge of the KKT conditions.
7. Knowledge of several optimisation techniques (including local descent and genetic algorithm)
8. Experience of using the simplex method to solve linear programs.
9. Experience of solving the shortest path problem using a direct algorithmic method, an integer linear program, and its dual program.

c2502: Advanced Transforms; Matric 2023, Y4; Paper C25: 8 Lectures, 2 Tutorial Sheets

The Fourier Transform and its extensions: Windowed FT; 2-D FT; FFT. The Hilbert Transform. The analytic signal and the monogenic signal. Wavelets: properties; Haar, Morlet, Debauchies wavelets. Discrete Wavelet Transform: Multi Resolution Analysis; Two-dimensional wavelets: applications in image compression and de-noising. Data reduction: PCA and ICA.

Learning Outcomes:

1. Understand the limitations and applications of the Fourier transform and be able to apply the Gabor transform
2. Understand the mapping of time-frequency space and the fundamental limitation of transforms
3. Be able to apply the Hilbert transform and interpret the analytic signal

4. Understand the fundamentals of wavelet transforms and their properties and be able to apply these to example transforms
5. Understand the theory of multi-resolution analysis and discrete wavelets
6. Understand the limitations of wavelets and their applications to image compression
7. Be able to apply data reduction techniques, such as Principal Component Analysis, and understand the role of visualisation.
8. Understand Independent Component Analysis and the cocktail party problem

Paper C26: Electrochemical Energy Technology

c2601: Electrochemical principles; Matric 2023, Y4; Paper C26: 8 lectures, 2 Tutorial Sheets

Introduction to electrochemistry; electrodynamics, charge balances, and the electric potential; electrochemical thermodynamics; Poisson-Boltzmann theory (double layers and ion activity); transport phenomena; reaction kinetics; characterization techniques (voltammetry, impedance spectroscopy); porous-electrode theory.

At the end of this lecture course students should be able to:

1. Describe reaction thermodynamics and kinetics, electrolyte transport, and interfacial adsorption or charging processes,
2. Analyse experimental characterization data pertinent to energy-storage materials,
3. Apply charge, energy, and material balances in the analysis of energy devices,
4. Model electrochemical devices using equivalent circuit representations.

c2602: Energy storage and conversion devices; Matric 2023, Y4; Paper C26: 8 lectures, 2 Tutorial Sheets

Overview of devices; battery selection and design; fuel cells; flow batteries; supercapacitors; lithium-ion batteries; battery management systems and control; thermal modelling and management.

At the end of this lecture course students should be able to:

1. Appreciate the role of energy storage and conversion devices in transport and on the power grid,
2. Demonstrate mechanistic knowledge about electrochemical energy systems, including batteries, capacitors, and fuel cells,
3. Model the processes that lead to energy losses or power inefficiency in storage and conversion devices,
4. Understand the need for estimation and control of electrochemical devices and be able to analyse the main approaches that are used,
5. Estimate temperatures in devices using thermal models.

Paper C28 Multiphysics of Biological Materials

c2801: Mechanics and Biomineralisation; Matric 2023, Y4; Paper C28: 4 Lectures, 1 Tutorial Sheet

Mineralised tissues found within the human body serve the purposes of supporting weight and transmitting contact loads. They possess special hierarchical macro- to micro- to ultra-structure that allows delivering the required properties, i.e. the combination of hardness (strength), stiffness and fracture toughness. The structure and function of hydroxyapatite nanocrystals will be presented. The formation of mineralised tissues involves the activity of special cells (osteoblasts in bones, odontoblasts in teeth) that give rise to specific structures: Haversian canals in bone, tubules in dentine, rods in enamel. The methods for 2D and 3D characterisation of these tissues across the scales will be described, including in the context of osteoporosis and dental caries. The mechanostat and osteodyne hypotheses will be presented that describe the reciprocal relationship between internal stresses and tissue growth.

At the end of this part of the module the student will be able to:

1. Describe the structure, properties and arrangement of hydroxyapatite in mineralised tissues
2. Apply composite models to predict mineralised tissue hardness
3. Understand the mechanisms of main diseases that affect mineralised tissues
4. Understand the role of computed tomography and related methods

<u>c2802: Mechanics and Elastic, Fibrous and Cartilage Connective Tissue; Matric 2020, Y4; Paper C28: 4 Lectures, 1 Tutorial Sheet</u>

This course will be devoted to the materials science of collagen. Structure of procollagen, tropocollagen, collagen fibril and fibres, and their arrangement into fibrous tissues will be presented in the context of appropriate modelling and characterisation tools. Deformation properties of tendons will be considered, along with damage and repair mechanisms.

1. Describe the hierarchical structure and properties of collagen
2. Understand different arrangement of collagen in tissues ranging from cornea to skin
3. Be aware of the significance of small angle scattering (SAXS and SANS) as methods for collagen characterisation

<u>c2803: Mechanics and fluids: haemodynamics; Matric 2023, Y4; Paper C28: 4 Lectures, 1 Tutorial Sheet</u>

In this course, the interaction between the solid mechanics of tissue and fluid mechanics of blood will be explored. The primary focus will be on the brain, but other organs will be briefly mentioned. The governing equations will be presented. The multiscale nature of this problem will be highlighted, and the use of homogenisation techniques explained (although it will not be necessary to use them). The resulting whole-organ models will be shown and their behaviour in different pathological conditions considered (both in very simple cases with analytical solutions and more complex geometries). Links between model parameters and medical imaging will be briefly explored.

1. Understand the multiscale nature of both tissue and the vasculature
2. Appreciate the mathematical techniques used to scale up to whole-organ models
3. Understand simple pathological cases and the link with medical imaging

<u>c2804: Mechanics and electrophysiology: nervous system; Matric 2023; Y4; Paper C28: 4 Lectures, 1 Tutorial Sheet</u>

In this module, the physical basis of electrophysiology in the central nervous system and peripheral nervous system will be discussed. In particular, both the biochemical foundation of ion channel activity and the phenomenological formulations of electrophysiology in axons will be presented in the context of mechanical deformation. Other less established concepts aimed at linking electrophysiology to mechanics will also be discussed. Finally, the module will provide insights on how external mechanical loading (either traumatic or “controlled”) affect the nervous system.

At the end of the module the student will be able to:

1. Understand the macroscopic and microstructure of the nervous system, the role of myelin and glial cells both in CNS and PNS
2. Make use of the Hodgkin-Huxley model (and its derivatives) and enrich it with additional physical considerations (e.g., Nernst equation, morphological deformation) for electrophysiological prediction
3. Proposed other multiphysics phenomena known to link mechanics and electrophysiology (e.g., piezoelectricity, flexoelectricity, membrane capacitance alteration, etc.)
4. Apply those concepts in illustrative applications, with in particular, traumatic brain injury and ultrasound neuromodulation

Paper C29 Computing Technology

<u>c2901: Advanced Computer Architecture; Matric 2023, Y4; Paper C29: 4 Lectures, 1 Tutorial Sheet</u>

Revision of basic computer architecture, pipelines and ISA; advanced pipelines and instruction parallelism, ILP and branch prediction, OOO and superscalar; multi-thread and multi-core architectures; Modern computer architectures, RISC-V; Interconnect, PCIe and DMA.

At the end of this lecture course students should be able to:

1. Understand what determines processor design goals
2. Appreciate what constrains the design process and how architectural trade-offs are made within these constraints
3. Be able to describe the architecture and operation of pipelined and superscalar processors, including techniques such as branch prediction, and out-of-order execution
4. Have an understanding of multithreaded and multi-core processor architectures
5. For the architectures discussed, understand what ultimately limits their performance and application domain

<u>c2902: Memory and Storage; Matric 2023, Y4; Paper C29: 4 Lectures, 1 Tutorial Sheet</u>

Revision of caching and memory hierarchies; block replacement policies, write policies, cache performance; Memory technologies, SRAM and DRAM operation, memory performance and the memory wall, emerging memory technologies; types of storage devices, storage interconnect, RAID, storage systems.

At the end of this lecture course students should be able to:

1. Understand memory hierarchy including different policies
2. Appreciate what constrains the memory technologies and how architectural solutions address these constraints;
3. Understand how DRAM and SRAM operate on a logical level
4. Understand how different types of storage devices operate
5. Appreciate the need for redundancy in storage systems and understand how RAID operates.

c2903: Computer Networks; Matric 2023, Y4; Paper C29: 4 Lectures, 1 Tutorial Sheet

Overview of networking; OSI reference model, TCP/IP Protocol Stack; LANs and WANs, Internet structure; Circuit-switching, packet-switching; routing and forwarding, switch architecture; Principles of reliable data transfer, congestion control.

At the end of this lecture course students should be able to:

1. Have an informed view of computer networks and the internal workings of the Internet;
2. Understand the general principles behind multiplexing, addressing, routing
3. Be able to describe the architecture and operation of network switches
4. Appreciate the need for network protocols and understand principles in reliable data transfer and congestion control.

c2904: Cloud computing and accelerators; Matric 2023, Y4; Paper C29: 4 Lectures, 1 Tutorial Sheet

Overview of cloud computing and operating model; Cloud availability, performance, scalability and cost; data centre infrastructure, virtualization, resource management; Cloud workloads and acceleration; GPU, FPGA and Programmable network devices; Accelerator architectures.

At the end of this lecture course students should be able to:

1. Understand how modern clouds operate and provide computing on demand
2. Understand principles in cloud availability, performance, scalability and cost
3. Have an informed view of cloud infrastructure technologies
4. Appreciate the types of workloads running in the cloud and the need for acceleration
5. Be able to describe the architecture and operation of different types of accelerators