DEPARTMENT OF
ENGINEERING SCIENCE

Third Year Syllabus

In the third year you will be required to take five optional written B papers from a list published annually and, in addition, Paper B2 Engineering in Society or B2E Entrepreneurship & Innovation.

You will also be required to take three coursework subjects, as follows:

- B1 Engineering Computation
- B3 Group Design Project
- B4 Engineering Practical Work

Paper B1 will consist of a report on a mini-project. The project task will be the solution of an engineering problem requiring the use of advanced numerical techniques and require a significant amount of serious program coding.

Paper B3 will consist of a report on your contribution to a design project carried out as part of a small team of undergraduates in the third year. Further information about third 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 third year, paper B2, design project (B3), laboratory exercises (B4) and the B-option papers, include principles of sustainability.

Paper B1: Engineering Computation

<u>b101: Numerical Algorithms; Matric 2020, Y3; Paper B1: 4 Lectures; 1 Tutorial Sheet</u>

Sources of error: round-off, order of algorithm; Function fitting and approximation: polynomial & trigonometric bases, Gram-Schmidt orthogonalisation. Convergence: Richardson's method; Numerical quadrature: trapezium & Simpson's rule, sampling methods; Numerical integration of ODEs, predictor-corrector methods, modified Euler, Runge-Kutta, adaptive step-size control, stiff systems; Discretization in both space and time; Linear PDE solution by finite differences.

Learning Outcomes:

1. Appreciate the importance of error analysis in engineering computation (numerical analysis) and understand the meaning of terms such as truncation and round-off error, convergence rate and order of convergence.
2. To develop experience in deriving convergence rates based on a Taylor series analysis.
3. Understand the importance of conditioning as a way to measure the stability of a method and how to compute it numerically.
4. To develop experience in solving simple engineering problems by numerical analysis.
5. Be familiar with established numerical analysis methods that are used to solve a large class of engineering problems that can be modelled mathematically by: $Ax=b$, $Ax=\lambda x$, integration, differentiation, curve fitting, ODEs, and PDEs.
6. Be able to fit an approximating curve to data by polynomial regression and least-squares and discuss the stability of polynomial fitting.
7. Be able to approximate a function using a polynomial basis and appreciate the importance of an orthogonal basis for function and data fitting and approximation.
8. Be able to compute integral estimates (numerical quadrature and derive the governing equations and error terms.
9. Be able to derive finite difference approximations to first and second differentials and their error terms and estimate them from numerical data.
10. Be able to solve first order differential equations using the Euler and Modified Euler methods, derive the governing equations and orders of convergence, and have an awareness of higher-order (Runge-Kutta) methods.
11. Be able to solve second and higher order differential equations using the Euler and Modified Euler method.
12. Be able to solve linear second order partial differential equations using finite differences, derive the governing equations and discuss conditions of convergence in general terms.

<u>b102: Optimisation; Matric 2021, Y3; Paper B1: 4 Lectures;1 Tutorial Sheet</u>

Root finding: bisection, Newton; Gradient methods: steepest descent, Newton, quasi-Newton, Gauss-Newton; Direct methods: Monte-Carlo, simulated annealing; Constrained optimisation: Linear programming with equality and inequality constraints, Simplex method.

Learning Outcomes:

1. To understand the properties, origins, suitable domains and limitations of common optimisation techniques.
2. To be able to reason mathematically about the convergence and computational cost (including memory) of optimisation procedures especially steepest descent and Newton’s method.
3. To understand the implications of numerical round off in optimisation (tie into numerical methods).
4. To be able to explain (where appropriate) the approach of an optimisation technique using both geometric and analytical arguments.
5. To be able to formulate a suitable cost function (and constraints) to be minimised given a verbal (written) problem description. This done, to be able to reason about a suitable choice of optimisation procedure.
6. To understand the role of iteration in optimisation and how this manifests itself in the structure of algorithm implementations.

7. To understand the role and application of direct search (Monte Carlo methods) have in optimisation especially in analytically intractable problems. To understand the role of computing in realisation of these methods.
8. To understand how constraint satisfaction can be folded into the optimisation task, e.g. in linear programming and barrier methods.
9. To have experience and understanding of how and in what form optimisation techniques are used in engineering disciplines: e.g. PCB layout, fiscal profit maximisation, shape optimisation.
10. To understand the relationship between numerical methods (solving Ax=b) and optimisation techniques.

<u>b103: Finite Elements; Matric 2021, Y3; Paper B1: 4 Lectures;1 Tutorial Sheet</u>

Finite Elements as a general technique for solving partial differential equations. Derivation of the weak and discrete forms of boundary value problems for one unknown scalar field. Linear and quadratic shape functions in triangular and quadrangular elements. Numerical integration techniques on triangles and quadrangles. Construction of the stiffness matrix and nodal force vector. Numerical illustration for the Poisson problem. Application to steady-state heat transfer and 1D elasticity problems. Introduction to 2D elasticity problems.

Learning Outcomes:

1. Obtain the weak and discrete form equivalent to a partial differential equation for one unknown scalar function (Laplace or Poisson problem).
2. Interpolate an unknown function using shape functions on triangular or quadrangular elements based on its nodal values.
3. Numerically integrate a function on triangular or quadrangular elements.
4. Construct and solve the algebraic system of equations to find nodal values for a given boundary-value problem.
5. Appreciate the broader use of the Finite Element method to solve a variety of problems in engineering.

Paper B2: Engineering in Society

<u>b201: Technical Communication Skills; Matric 2021, Y3; Paper B2: 2 Lectures</u>

Overview of basic writing and presentation skills, including those needed to produce a technical report (as in B1 and the 4YP) and to report on and present a group design project (as in the 3YP). Use and types of reporting in engineering. Record-keeping and audit trails. Writing skills: aims and objectives; structure and layout; use of equations, figures, and tables; figure design; referencing and how to avoid plagiarism; the importance of clarity, consistency, and accuracy, including syntax, grammar, spelling, and formatting. Presentation skills: aims and objectives; structure and layout;

slide design; use of animations and videos; presentation styles and effective storytelling; use of props.

Learning Outcomes:

1. Understand the context within which communication skills are used in engineering.

2. Be familiar with the basic types of reporting used in engineering.

3. Be familiar with the typical layout and structure of a technical report, including the use of equations, figures, and tables.

4. Have revised basic concepts in writing, including syntax and grammar.

5. Understand the effective design and use of figures and tables.

6. Understand the need for text review, the role of the review process, and the use of drafts.

7. Understand the importance of clarity, consistency, and accuracy in reporting.

8. Understand how to plan your write-up and submit on time.

9. Understand the importance of referencing and be aware of what constitutes plagiarism.

10. Understand how to structure, prepare, and deliver an effective presentation.

11. Understand the importance of slide design, including effective use of text and media.

12. Understand the need to practise your presentation.

13. Understand the need to work as a team in order to produce a successful project, to write a report, and to prepare a presentation.
14. Be aware of how individual team members earn appropriate credit for their work.

<u>b202: Engineering Ethics: Matric 2021: Y2, Paper B2: 4 Lectures, 1 Tutorial Sheet</u>

Introduction to ethics, professionalism and public trust, engineering codes of ethics. Potential ethical dilemmas: engineering decision-taking and problem-solving techniques. Responsibilities: ethical and legal obligations, whistleblowing, barriers to ethical decision making. Engineering ethics case studies.

Learning Outcomes:

1. Understand why engineering ethics is being taught.
2. Become aware of the responsibilities, both societal and legal, of a professional engineer.
3. Learn how to apply problem-solving techniques to ethical dilemmas, how to utilise case studies to demonstrate ethical or unethical practice, and to see the need to include ethical principles in engineering projects.

4. Determine when a conflict of interest might arise and when it is appropriate to act as a whistleblower.
5. Be able to incorporate the above into an effective discussion.

b203: Safety and Risk: Matric 2021, Y3; Paper B2: 8 Lectures, 2 Tutorial Sheets

Introduction and case studies. Risk: presentation of information and its perception; tolerability and acceptability. Qualitative methods of risk analysis (e.g. checklists, HAZAN, HAZOP). Reliability and equipment failure; failure in series and parallel components; revealed and unrevealed failures. Quantitative methods of risk analysis (e.g. fault trees, event trees, FMEA/FMECA). Human factors; human failure and error; human information processing; display and workplace design.

Learning Outcomes:

1. Understand the importance of safety and risk
2. Understand that risk is a function of hazard and frequency
3. Understand zero-risk and 100% safe and why these statements are problematic
4. Learn both quantitative and qualitative approaches to assessing risk
5. Understand the role of human beings in safety
6. Develop writing skills in the context of technical safety matters, including writing risk assessments

b204: Engineering Sustainability and the Environment; Matric 2021, Y2; Paper B2: 4 Lectures, 1 Tutorial Sheet

The need for sustainability in engineering. Principles of sustainability (economics, society, and environment). Sustainable development. Sustainability tools and metrics. Environmental legislation frameworks. Environmental impact assessments, Life cycle analyses, multi-criteria analysis, scenario planning.

Learning Outcomes:

1. The concept and consequences of sustainable development: social, environmental and economic.
2. The changing role of engineering in sustainable development.
3. The tools used to implement sustainable design.

b205: Teamwork and Project Management; Matric 2020, Y3; Paper B2: 4 Lectures, 1 Tutorial Sheet

Introduction to teamwork and project management: How do you work well in a team? How can team dynamics be managed? What is a project? Different types of project; stages of a project from initiation to close-down; formal methodologies (e.g. Agile). Project organisation; project definition; identification of resources; project teams – defining and identifying skills; teamwork skills. Project planning: work structure breakdown; critical path analysis; Gantt and Pert charts. Project monitoring and control: risk identification and management; measuring progress; earned value analysis. Project evaluation and review.

Learning Outcomes:

1. Understand what is meant by a project and why projects are often more difficult to manage than regular ‘day to day’ work.

2. Understand the different phases of projects.
3. Be able to define a project and produce a specification.
4. Be able to identify and estimate resources for a project.
5. Understand the importance of the project team and the effects of different organisational structures for the team.
6. Be aware of attributes and skills required by the project manager, including motivation and conflict resolution.
7. Be able to produce a work breakdown structure for a project.
8. Be able to produce a network diagram for a project and identify the critical path.
9. Be able to produce a Gantt chart for a project, taking account of resource limitations.
10. Understand how to identify and control risk in a project.
11. Understand how to monitor and control project progress.
12. Appreciate the advantages and disadvantages of formal project management approaches such as PRINCE2.

<u>b206: Project Financing; Matric 2021 Y3; Paper B2: 4 Lectures, 1 Tutorial Sheet</u>

Importance of finance for engineering. Money: the value of money; inflation; interest rates and relationship with lending risk. Financial statements; requirements for capital. Sources of capital. Financial status; accounts. Financing projects and investment appraisal: net present value; internal rate of return. Pricing of contracts and products: assigning costs within the development; product costs; overheads.

Learning Outcomes:

1. Understand the importance of financial considerations in engineering projects.
2. Understand the sources of finance available to organisations and the implications of different financing routes.
3. Be familiar with the basic elements of a business plan.
4. Understand the importance of cash flow.
5. Understand basic means of reporting financial information, including the depreciation of assets.
6. Be able to appraise the financial implications of projects using net present value and internal rate of return approaches.
7. Understand the importance of the discount rate used in project financial appraisal and its implications.
8. Understand how to cost a project, including both direct and indirect costs.

<u>b207: Technology Strategy; Matric 2021, Y3; Paper B2: 4 Lectures, 1 Tutorial Sheet</u>

Identification of the needs of customers – early adopters, main product maturity, feature creep. Predicting technical trends and obsolescence; interact with sales and marketing; product life-cycle. IP strategy: patents; trademarks; design; copyright; know how; knowledge capture. How do we make what we have designed, design for manufacture, customisation, end of life. People and roles: What is the job (technical research, technical development, customer interface); who is best to do the job; identification of internal capability – what do we do best; don't reinvent the wheel; need for key technical partnerships.

Learning Outcomes:

1. Know what a Business Idea is: (a) Be able to identify key competencies within an organisation and how these lead to a competitive advantage.
2. Know about reinforcing loops: (a) To be able to articulate how an entrepreneurial insight can lead to a competitive advantage, allowing strategic investment and the development of distinctive competences, these then re-enforcing the competitive advantage.
3. Know about scenarios: (a) To be able to describe how a company interacts with its environment; (b) Be able to use drive space ranking with a scenario matrix to enumerate potential future external drivers; (c) Be able to use the scenario matrix to map out potential future environmental conditions affecting a company's distinctive competencies.
4. Be able to develop an IP strategy: (a) Be aware of the legal framework surrounding IP and how to choose between various options to protect a company's distinctive competencies.
5. Be aware of how House of Quality can be used to connect the needs of the customer to engineering specifications.
6. Be able to develop a technology roadmap: (a) Be aware of the Innovation Matrix can be used with roadmaps to synchronise Technology Push with Market Pull.
7. Be able to put together a business plan: (a) Know the purpose of a business plan and the key components of the Context, Opportunity, Risk and People for the Business Idea.

Paper B2E2: EEM pathway replacement to B2 (Saïd Business School)

<u>b2E201: Personal, People, Project, Performance Management; Matric 2021, Y3; Paper B2E2; 8 lectures</u>

Project Management Strategies; Introducing Scrum and Agile project management; Managing People and Performance; Develop knowledge of key areas of human resource management and development; Regulatory and key skills for managing development projects; Personal Development Planning (PDP) with a focus on goal setting; Influencing professional identity, values and ethics; Communicating and networking; Human Capital Work-based experiential activities and reflection.

Learning Outcomes:

1. Understand different cooperate organisational structures
2. Understand the value and overlap of different project management strategies
3. To be able to apply performance management methodologies for building capacity and skills
4. To be able to apply specific project management strategies
5. Analyse factors for success in project management
6. Understand basic legislation, regulations and standards relevant for management
7. To be able to discuss different human resources strategies that are applied in industry
8. To be able to reflect, record, plan, execute and evaluate a PDP
9. Understand Value-Based Management within the engineering context
10. Understand how human capital can be created
11. Develop and understand the essential skills and abilities that are necessary to manage and lead people effectively for the benefit of the individual and teams.
12. Develop your leadership skills and style, assisted by leadership tools
13. Understand how to critically apply management tools

b2E202: Financial, Operation, Global, Supply Management; Matric 2021, Y3; Paper B2E2; 8 lectures

Problem-based innovation; Operations and Supply Management; Procurement of materials and services processing and distribution to the customer either directly or through a network of distributors; Management from a network perspective; Financial management; Statistics in management; Queuing in supply chains; Scheduling in global context, Impact of culture, regulations and locations on management, International relations, Virtual management and communication, Assignment optimisation for management.

Learning Outcomes:

1. Understand the concept and the scope of operations and supply management in an industry
2. Able to take a system engineering approach to supply and operation management
3. Able to apply and analyse queuing in operations and supply management
4. Understand the different types of distribution and how to manage them
5. Understand key information required to make financial decisions
6. To be able to read financial statements
7. Able to apply schedule management to deliver stakeholders requirements
8. Understand the role of culture, government policy and history on identifying an appropriate international management approach.
9. Able to solve an assignment problem in management
10. Understand value of network analysis in problem-based innovation
11. Understand how foreign knowledge and language skills can be applied in managing international business opportunities
12. Understand global supply chains.
13. Understand how teams can work in a virtual context
14. Understand the constrains of effective team work in a virtual environment
15. To be able to apply statistics in management

b2e03: Entrepreneurship and Innovation; Matric 2021, Y3; Paper B2E: 8 Lectures

Introduction to entrepreneurship and innovation, entrepreneurial thinking & process. Opportunities: Where do opportunities come from, how to identify them, and how to evaluate them? Business models: Market analysis, revenue models, firm boundaries, strategy, competition. Innovation: Disruptive vs. incremental innovation, entrants vs. start-ups, competition or cooperation, strategic partnerships. Managing IP: Patents, trade secrets, commercializing university technology. Financials: Financial projections, alternative valuation methods. Deal structures: Term sheets, deal negotiation, alternative types of investors. Teams and Ecosystems: Founders, managers, corporate governance, ecosystems.

Learning Outcomes:

1. Students will be able to understand key parameters of the process of commercializing innovations and starting new ventures.
2. They will have frameworks for evaluating business opportunities and structuring new ventures.
3. Students will also understand principles of entrepreneurial thinking that can be applied across a much broader range of technological, economic and social problems.

Paper B5: Solid Mechanics

b501: Theory of Elasticity; Matric 2021, Y3; Paper B5: 6 Lectures, 1 Tutorial Sheet

Boundary-value problems in elasticity: kinematics, equilibrium, constitutive equations and boundary conditions. Plane strain and plane stress conditions. Solution methods based on stress functions (Airy and Prandtl) in Cartesian and Polar coordinates. Michell's solution and William's solution. Applications: line loading of half planes and cylinders, spinning discs, holed plates, cracks and wedges, and non-uniform temperature distributions. St Venant's theory of Torsion.

Learning Outcomes:

1. Formulate a boundary-value problem corresponding to a real-world situation.
2. Obtain analytical solutions of 2D elasticity problems using Airy's stress functions in Cartesian or Polar coordinates.
3. Calculate stress distributions near holes, inclusions, wedges or cracks using the Michell solution or William solution. Calculate corresponding strain and displacement fields.
4. Use superposition to build up solutions to complex problems.
5. Use stress functions to solve 2D thermo-elastic problems with non-uniform temperature distributions or 2D problems with body forces.
6. Use Prandtl stress functions to calculate stresses, strains and displacements in thin-walled tubes and shafts under torsional loading.
7. Appreciate the benefits and limitations of stress functions for stress analysis.

b502: Engineering Applications and Methods; Matric 2021, Y3; Paper B5: 6 Lectures, 1 Tutorial Sheet

Curved beams, approximate solutions and their solution by Airy stress function. Shear stress distribution in beams deduced from elementary bending theory, and also via Airy stress function. Applications of Williams' solution. Plane stress and plane strain. Introduction to plate bending theory for axi-symmetric plates. Principle of minimum total potential energy. The Rayleigh Ritz method applied to one dimensional stress problems, beams, and plates. Piecewise Rayleigh-Ritz problems.

Learning Outcomes:

1. Be able to solve the state of stress in beam-like components with small or large curvature subject to bending.
2. Be able to find the shear stress distribution in beams sustaining a shearing force.
3. Understand the limitations of linear elasticity and, in particular, the approximate nature of plane stress solutions.
4. To be able to solve for the state of stress in a circular plate subject to axi-symmetric transverse loading.
5. To understand the use of Williams' solution for finding stresses near cracks and notches or in wedges.
6. To have a basic understanding of the stress state in cylindrical plates.
7. To understand the energy basis of elasticity, and be able to apply the Rayleigh-Ritz method to 1-D stress, beam and plate bending problems.

b503: Non-linear Material Behaviour and Plasticity; Matric 2021, Y3; Paper B5: 4 Lectures, 1 Tutorial Sheet

Von Mises and Tresca yield criteria, Mohr-Coulomb. Stability, normality and flow rules. Material hardening. Upper bound and lower bound methods. Applications: plane strain and axi-symmetric problems, metal forming and processing, collapse of structures and foundations.

Learning Outcomes:

1. Be aware of and understand the differences between Tresca, Mises and Mohr-Coulomb yield.
2. Be able to apply normality and consistency for post-yield plastic flow and understand stability.
3. Have knowledge of flow rules for plasticity, isotropic and kinematic hardening and an awareness of the differences and when each has applicability.
4. Be able to apply upper and lower bound methods to plasticity problems to determine loading estimates for plane strain and axi-symmetric problems such as thick-walled tubes, and to collapse of structures.
5. Be able to apply upper and lower bound methods to metal forming and processing.

b504: Solid Mechanics Laboratory; Matric 2021, Y3; Paper B5

This practical laboratory is concerned with enabling students to demonstrate their knowledge of governing equations used to describe deformation and response of solid bodies to mechanical loading. Moreover, the students are expected demonstrate their ability to obtain correct and comparable results using experimental, analytical and numerical approaches to assessing the deformation and consequent stress exerted in solid bodies of simple geometric shape subjected to simple mechanical loading. The practical knowledge of Matlab and SolidWorks software is the prerequisite, as much as the sound understanding of the topics covered in models of B1 and B5 papers.

Learning Outcomes:

1. To be able to appreciate issues related to stress analysis and corresponding design criteria in product engineering.
2. To be able to interpret the strain measurements obtained by means of discrete strain gauges on the surface of a solid body, using linear elastic assumptions about the material's constitutive response to given simple load.
3. To be able to solve analytically the equivalent problem of finding the distribution of stress using the stress function within the geometrically simple domain of interest arising from simple load.
4. To be able to solve numerically the same problem by performing simple finite element method based stress analysis.
5. To be able to compare three different techniques for the determination of the stresses and to assess their relative merits.

Paper B6: Equilibrium Thermodyamics

b601: Chemical Thermodynamics; Matric 2021, Y3; Paper B6: 8 Lectures, 2 Tutorial Sheets

General Thermodynamic principles (2 lectures). The principle of corresponding states, and equations of state. Maxwell's relations. Gibbs energy, chemical potential and fugacity. Equilibrium under constant temperature and pressure. Gibbs phase rule.

Liquid-vapour equilibrium (6 lectures). PVT data for vapour and liquid phases. Vapour-liquid equilibrium and the treatment of non-ideality in the liquid phase. Activity coefficients. Air/water-vapour mixtures. Degree of saturation: percentage saturation, specific humidity, relative humidity and dew point. Calculation methods using steam tables or perfect gas properties. Cooling towers and air-conditioning.

Learning Outcomes:

1. Understand and use Principle of Corresponding States for pure components and mixtures.
2. Understand and use Equations of State.
3. Understand Gibbs energy, chemical potential and fugacity in order to analyse systems at equilibrium under constant temperature and pressure.
4. Understand activity coefficients, handle models for activity coefficients and be able to produce vapour-liquid equilibrium curves.
5. Understand the various term appertaining to air/water-vapour mixtures including degree of saturation, specific humidity, relative humidity and dew point.
6. Undertake calculations for cooling towers and air conditioning systems.

b602: Chemical Reaction Equilibrium and fuel cells; Matric 2021, Y3; Paper B6: 4 Lectures, 1 Tutorial Sheet

Equilibrium in systems with chemical reaction. The equilibrium constant and its variation with temperature. Combustion. Application to fuel cells.

Learning Outcomes:

1. Analyse equilibrium in systems with chemical reactions.
2. Analyse combustion and similar processes where there are multiple species and multiple equilibria.
3. Understand the different types of fuel cell and their half-cell reactions, and have an appreciation of their construction and associated systems.
4. Undertake thermodynamic calculations for fuel cells, fuel reforming and carbon monoxide removal, and analysis of fuel cell systems.

b603: Engineering Alloys; Matric 2021, Y3; Paper B6: 4 Lectures, 1 Tutorial Sheet

Introduction to engineering alloys and reasons for alloying. Binary solutions – configurational entropy, Gibbs energy for ideal and regular solutions. Phase diagrams, the lever rule. Solutions with a miscibility gap – eutectics. Heterogeneous systems, intermediate phases –phase diagrams, eutectoids, peritectics and peritectoids. Phase diagrams for selected metallic and ceramic alloys - the iron-carbon, aluminium-copper and zirconia-yttria systems. Microstructures produced under slow cooling. Experimental and computational methods for determination of Gibbs free energy and phase diagrams.

Learning Outcomes:

1. Understand the concepts of intrinsic and extrinsic thermodynamic variables.
2. Understand Gibbs statistics for the free energy of ideal solution based on the energy and entropy of an ensemble of atoms, and the use of Lagrange multiplier in the derivation.
3. Appreciate the differences between ideal and real solutions, and the effect of interchange term and temperature on the energy landscape.
4. Understand the phenomenon of phase separation, and the derivation of the common tangent construction.
5. Understand the relationship between Gibbs energy landscape and the equilibrium phase diagram, and how one can be derived from the other.
6. Appreciate the background of the computation approach to Gibbs free energy determination.
7. Have an appreciation of the thermodynamics of phase transformation, and the difference between spinodal decomposition, and nucleation and growth.
8. Understand the relationship between equilibrium phase diagrams, cooling curves, and microstructures.

<u>b604: Thermodynamics Laboratory; Matric 2021, Y3; Paper B6</u>

Thermodynamics of alloys: In this lab the equilibrium phase diagram of the Pb-Sn system is studied. Cooling curves for three different Pb-Sn compositions will be recorded. These will be supplemented with several further cooling curves for other compositions. Using these as well as plots of Gibbs free energy at a number of different temperatures, students will construct the Pb-Sn phase diagram. This will then be compared to a Pb-Sn equilibrium phase diagram from the literature.

Learning Outcomes:

1. Ability to experimentally record cooling curves and interpret them.
2. Ability to analyse system energetics using Gibbs free energy.
3. Ability to construct an equilibrium phase diagram given a number of experimental observations.
4. An appreciation of the limitations and conditions of validity of equilibrium phase diagrams.

The B6 Chemical Equilibrium Lab is an experiment using a desktop forced draught cooling tower. The experiment reinforces concepts developed in the b601 Chemical Equilibrium course. The cooling tower's operation is flexible and students will design experiments to vary the water and air flow rates through the cooling tower along with the cooling requirement. The cooling tower is instrumented with thermocouples such that the air inlet and exit wet and dry bulb temperatures can be constantly monitored along with the water inlet and exit temperatures. The air flow and water loss through evaporation can be measured during the experiment as can the heating power. The object of the experiment is to run the cooling tower at several equilibrium conditions systematically varying the power, air and water flow rates to investigate their effects on the efficiency with which heat is rejected from the system and provide practical demonstration of the choices facing the engineer in deciding on the operating point of a practical system.

Learning Outcomes:

1. Understand the operation of a forced draught cooling tower.
2. Be able to use the pyschrometric chart to determine the relative and specific humidities specific volume, and specific enthalpy of moist air based on wet and dry bulb measurements throughout the system.
3. Be able to conduct an energy balance around a cooling tower.
4. Understand the effect of heat load, water flow rate and air flow rate through the tower on the water consumption of the cooling tower.
5. Be able to make a comparison of the cooling performance of the cooling tower relative to a dry heat exchanger working over the same range of driving temperatures.

Paper B7: Fluid Flow, Heat & Mass Transfer

b701: Applied Thermodynamics; Matric 2021, Y3; Paper B7: 4 Lectures, 1 Tutorial Sheet

Air Compressors (2 lectures): Classification of compressor types, their flow range and pressure ratio range. Analysis of compressors with internal compression using linked-process and steady-flow analysis. Analysis of volumetric efficiency and multi-staging. Analysis of compressors with no internal compression (such as Roots blowers).

Learning Outcomes:

1. Have a good understanding of the different types of air compressor and their applications – be able to identify non-positive and positive displacement compressors and those with, with some or with no internal compression.
2. Be able to analyse compressors with positive displacement on a basis of both individual processes and the Steady Flow Energy Equation.
3. Be able to analyse compressors without positive displacement such as the Roots blower, and compressors with some positive displacement, such as vane compressors.
4. Understand the advantage of isothermal compression and how to optimise multi-stage compression with intercooling.
5. Be able to calculate the volumetric efficiency of reciprocating compressors.

Availability and Exergy (2 lectures): Revision of the 2nd Law of thermodynamics and its extension to the concepts of availability and exergy, so that thermodynamic performance of systems can be compared with that predicted by the 2nd Law. This also enables irreversibilities to be identified and quantified. Applications will be to material encountered already (such as steam cycles and refrigeration), and more complex processes such as gas liquefaction. This will require use of real gas thermodynamic data.

Learning Outcomes:

1. Have a good understanding of the concepts of availability and exergy.
2. Be able to analyse thermodynamic systems using availability and exergy so at quantify the thermodynamic performance in terms of the 2nd Law of Thermodynamics.
3. Understand the differences between perfect, semi-perfect and real gases, and know when it is appropriate to use the perfect and semi-perfect gas approximations.
4. Be able to analyse simple gas liquefaction systems.

b702: Multiphase Flow and Heat Transfer; Matric 2021, Y3; Paper B7: 4 Lectures, 1 Tutorial Sheet

Heat Transfer with Phase Change (2 lectures): Lectures develop the principles of heat transfer with phase changes, nucleate and film boiling, and condensation.

Learning Outcomes:

1. Understand the different regimes, and associated heat transfer coefficients, of a typical boiling curve.
2. Understand the difference between pool and flow boiling and be able to sketch the resultant flow patterns.
3. Be able to apply correlations to predict the heat transfer coefficient for different boiling regimes and understand the importance of the critical heat flux.
4. Be able to use basic theoretical analysis to predict the heat transfer coefficient distribution for condensation on vertical plates and be able to extend the analysis to non-plate geometries
5. Be able to select, and apply, the correct correlations to predict the heat flux in boiling heat transfer problems.

Multi Phase Flows (2 lectures): This is an introductory discussion of basic multiphase phenomenology, flow models, and flow regimes, including cavitation, rising bubbles, bubble dynamics, coalescence & breakup, and two phase pipe flow.

Learning Outcomes:

1. Understand the concepts of multiphase flows with gas-liquid-solid interface combinations.
2. Understand the flow patterns that can form within flowing immiscible fluids.
3. Understand how to measure and calculate the Laplace pressure, interfacial tension and contact angles of drops on surfaces.
4. Calculate the dynamics of bubbles in a liquid filled reservoir and understand the condition for break-up or coalescence.
5. Understand basic design parameters relevant to multi-phase flow: phase fraction, heat transfer coefficient, mass transfer coefficient, and pressure drop.
6. Understand the basics of heat pipes and their limitations.

b703: Separation Processes; Matric 2021, Y3; Paper B7: 8 Lectures, 2 Tutorial Sheets

Mass transfer, diffusivity and mass transfer coefficients, film, penetration and surface renewal models. Absorption of gases into liquids, column designs, mass balances, equilibrium stage concept and idea of a transfer unit, operating lines, equilibrium line. Distillation in binary systems, McCabe-Thiele diagram, operating line, effect of reflux ratio, tray efficiency. Maxwell-Stefan approach to multicomponent mass transfer.

Learning Outcomes:

1. Understand the principles of diffusion in gases and liquids, and be able to calculate diffusive fluxes in simple case, including use of Stefan’s law.
2. Be able to calculate gas/liquid equilibrium using solubility values, or Henry’s law.
3. Be able to calculate overall gas and liquid phase mass transfer coefficients from gas and liquid film mass transfer coefficients using film theory.

4. Appreciate the role played in mass transfer calculations by unsteady state theories of diffusion.
5. Be able to calculate the operating line for a counter-current absorber, and understand the concept of minimum solvent flow-rate.
6. Be able to define an equilibrium (theoretical) stage.
7. Be able to calculate the number of absorption equilibrium stages from a McCabe-Thiele plot.
8. Understand the use of mass transfer units in calculating absorption column height.
9. Be able to calculate the number of equilibrium stages or mass transfer units in an absorber for the special case of straight equilibrium and operating lines.
10. Understand the use of Dalton's and Raoult's laws in calculating vapour/liquid equilibrium.
11. Be able to calculate vapour/liquid equilibrium data for binary systems (a) with constant relative volatility, and (b) with known activity coefficients.
12. Be able to plot a single stage equilibrium flash on a y-x diagram.
13. Be able to draw and explain the layout of a continuous distillation column with partial reboiler and total condenser, and calculate its q-line and top and bottom operating lines.
14. Be able to find the number of equilibrium stages required for a binary distillation from a McCabe-Thiele plot.
15. Be able to derive and use Fenske's method for the number of equilibrium distillation stages at total reflux.
16. Be able to calculate the number of actual trays required in a column using (a) Overall tray efficiency, or (b) Murphree vapour efficiency.

<u>b704: Fluid Flow & Heat and Mass Transfer Laboratory; Matric 2021, Y3; Paper B7</u>

The B704 Fluid Flow and Heat and Mass Transfer Laboratory experiments have been developed to provide students with first-hand, practical experience of typical engineering transport processes, and will enhance the learning experience when studying the B7 courses. There are several different experiments available in the laboratory, which all involve the study of different types of transport process: momentum (fluid mechanics), heat transfer and mass transfer. As the practical requirement of the B7 paper, you will be expected to attend two sessions. The laboratory will be organised into two session, one session on Two-phase flow and the other on Distillation. The experiments are undertaken in teams of two or three. Each laboratory session will last two and a half hours, after which the report must be completed by the student and signed off by a laboratory demonstrator on the same day. Both sessions will take place in the chemical engineering laboratory (3rd floor, Thom laboratory).

Learning Outcomes:

By the end of the laboratory session, students should in general:

1. Gain experience in the safe operation of large-scale momentum, heat and mass transfer equipment.

2. Be able to apply methods to analyse the characteristics and performance of a range of equipment used for mixing, separation, and related processing steps for fluids and multi-phase flow.

3. Be able to undertake well-planned experimental work and to interpret, analyse and report on experimental data.

4. Recognise the importance of working effectively with others.

5. Appreciate the inter-dependence of elements of a complex system and be able to synthesise such systems by integrating process steps into a sequence and applying analysis techniques such as balances of mass and energy.

6. Understand the principles of risk assessment and of safety management, and be able to apply techniques for the assessment and abatement of process and product laboratory hazards.

b704b Distillation Tray Simulator: Distillation columns, absorbers and strippers are usually equipped either with trays or packing. The type of tray demonstrated in this experiment is the simplest: the cross-flow sieve tray. The purpose of the tray is to cause an intimate contacting of liquid and gas, to allow mass transfer to occur (or, occasionally, heat transfer). In this experiment, you will investigate the hydrodynamics of tray operation, and in particular the maximum and minimum vapour handling capacity.

Learning Outcomes:

1. Gain an understanding of how tray hydrodynamics affects overall equipment performance.

2 Be able to calculate how maximum load factor varies as a function of the flow parameter

3 Be able to calculate and plot the load factor at weeping conditions.

4 Estimate the magnitude of the sources of error in this experiment.

b704c Distillation Column: When designing a distillation column for a mixture that has not been distilled before, we often use a small test column like the one in this experiment. This will be run under total reflux in order to determine the tray efficiency. Scale-up rules are then needed to estimate the efficiency at commercial scale operation. The purpose of this experiment is to observe the behaviour of a distillation column under total reflux, and to measure the tray efficiency as a function of column load factor.

Learning Outcomes:

1. Be able to qualitatively interpret phase diagrams for binary mixtures.

2. Understand that mass transfer operations require the combined use of equilibrium and mass balances.

3. Calculate and produce graphical plots of the overall efficiency and Murphree vapour efficiency as a function of load factor.

4. Be able to calculate a heat balance.

5. Be able to create a McCabe-Thiele plot showing the reboiler and trays.

6. Estimate the magnitude of the sources of error in this experiment.

b704d Liquid and Gas Flow in a Bubble Column: Bubble columns are commonly used as chemical reactors for gas-liquid systems. They are also used for gas absorption. The column consists of a column of liquid (in this case, tap water) through which the case (in this case, air) is bubbled. The advantage of a bubble column is that a large amount of interfacial area is created because the gas in mostly present as small gas bubbles. Note that there is one task to be done in advance.

b704e Boiling Heat Transfer: This experiment demonstrates boiling heat transfer. It can also provide insights into the effects of pressure and non-condensable gases on heat transfer.

Paper B8: Materials

<u>b801: Metals; Matric 2021, Y3; Paper B8: 6 Lectures, 1 Tutorial Sheet</u>

The need for alloying; the alloy selection problem; the big picture: uses of metals and alloys. Crystallography and crystal structures; basic concepts in dislocation theory; mechanisms of alloy strengthening. Phase diagrams, Lever rule; brittleness and its causes; applications, existing and possible. Phase transformations: diffusional and shear; ferrite/pearlite and martensitic microstructures; properties: strength and toughness. Extraction/Recycling; influence of alloying for phase change; manufacturing: SPF and friction welding. Strengthening for high temperature operation; processing: casting vs. forging; applications: the jet engine.

Learning Outcomes:

1. An appreciation of the different metallic alloys used for engineering applications, particularly those based upon Al, Fe, Mg, Ni and Ti.
2. Their properties, particularly strength, toughness, density; the rationale for their specification for different applications.
3. The underlying metallurgical theory which explains why Al, Fe, Mg, Ni and Ti are rarely used in their pure metallic form; the role of alloying.
4. An understanding of the manufacturing processes used for metallic components, *e.g*. casting, rolling, forging and the role of heat treatment.

5. Knowledge of the extraction processes used to produce metals and alloys, *e.g*. pyrometallurgical techniques and electrochemical means.
6. An appreciation of the physical processes responsible for the failure of metallic components, particularly the onset of plasticity, fast fracture and fatigue.
7. Learning of the role of microstructural engineering *via* heat treatment and control of chemistry, to engineer superior properties in these materials.

<u>b802: Polymers and Ceramics; Matric 2021, Y3; Paper B8: 6 Lectures, 2 Tutorial Sheets</u>

Polymers (3 lectures): The structure of polymers: monomers, molecular length, branching and crosslinking; crystallinity and spherulites. Molecular mobility and reptation in polymer melts, and free volume. Crystallisation of polymers: thermodynamics and kinetics. The glass transition in polymers. Solid-state mechanical properties of polymers: viscoelasticity and the role of temperature, rubber-like entropic elasticity, crazing, yield and fracture. Introduction to processing of polymers, and consequences for polymer microstructure and properties.

Learning Outcomes:

1. Knowledge of the key features of structure of polymer solids, at different length scales.
2. Awareness of factors determining molecular mobility in polymer melts: molecular architecture, entanglements, free volume.
3. Understanding of polymer crystallisation by secondary nucleation, leading to lamella crystals; and the role of temperature.
4. Knowledge of how the glass transition is manifest in physical properties of polymers (volume, mechanical response) and the free volume explanation.
5. Knowledge of viscoelastic effects seen in polymers and their explanation via spring-dashpot models, including their dependences on temperature and structure.
6. Understanding of rubber-like elasticity seen in polymers, and its dependence on crosslink density, in terms of entropic elasticity.
7. Knowledge of how polymers fail: crazing, yield and fracture of polymers, and dependence on molecular length and crystallinity.
8. Awareness of the principles of polymer processing.

Ceramics (3 lectures): Phase transformations in ceramics. Alloying in ceramics – yttria stabilised zirconia, the alumina/silica system. Processing of ceramics, solid and liquid phase sintering. Mechanical properties of ceramics, fracture toughness. Mechanically induced transformations – transformation toughening. Weibull statistics for strength. Strength of fibres and fibre bundles.

Learning Outcomes:

1. Knowledge of key engineering ceramic materials, their structure, properties and applications.
2. Understanding of the key processing routs for ceramics, including powder based methods and coating technologies.
3. Understanding of the processes involved in fracture of polycrystalline ceramics.
4. Ability to use Weibull statistics as a tool in ceramic design.
5. Understanding the processes that lead to failure of ceramics in compression.
6. Knowledge and understanding of toughening mechanisms – transformation toughening, ductile particle and fibre reinforced composites.

b803: Composites; Matric 2021, Y3; Paper B8: 4 Lectures, 1 Tutorial Sheet

Introduction to the materials used as fibres and matrices in fibre reinforced composite materials, especially high performance fibres and thermoset polymer matrices. Micromechanical interactions between fibres and matrices, leading to combining rules for calculating physical properties of unidirectional continuous fibre composites, including anisotropic elasticity, thermal expansion and strength. Introduction to laminated composites: nomenclature and symmetry (hence the importance of symmetric and balanced laminates). Laminate stiffness calculations for in-plane and out-of-plane deformations. Failure of laminates.

Learning Outcomes:

1. Understanding of the principles of mechanical property enhancement by combining materials to create composite materials.
2. Knowledge of the distinctive features of the main materials used as fibres and matrices in polymer matrix fibre-reinforced composite materials.
3. Ability to use simplified micromechanics models to predict elastic constants and thermal expansion coefficients of uni-directional (UD), continuous fibre, composites, and understanding of the approximations involved.
4. Ability to apply anisotropic linear thermo-elasticity to UD fibre composites.
5. Understanding of the principal mechanisms of failure in continuous fibre composites, and ability to apply the maximum stress failure criterion.
6. Ability to apply symmetry restrictions to the response of a laminated composite.
7. Ability to calculate the linear elastic and thermal expansion response of a symmetric laminated composite of given stacking sequence and lamina properties.
8. Ability to predict first failure in a symmetric laminated composite, under in-plane or out-of-plane loading, using the maximum stress failure criterion.

b804: Materials Laboratory; Matric 2020, Y3; Paper B8

Tutor has not provided syllabus material for this laboratory.

Paper B9: Structures and Hydraulics

b901: Reinforced Concrete Structures; Matric 2020, Y3; Paper B9: 8 Lectures, 2 Tutorial Sheets

Concrete - constituents, mix design and properties; limit state design - load, element capacity and safety factors; reinforced concrete design – singly and doubly reinforced beams in bending and shear, columns under axial load and bending, yield line analysis of slabs.

Learning Outcomes:

1. Understand the basics of cement production and chemistry.
2. Appreciate the key properties of concrete and how to test for them.
3. Understand the underlying principles of limit state design codes.
4. Understand why concrete is often reinforced by embedded steel bars, and how this affects its performance.
5. Know the key differences between plain, reinforced and prest ressed concrete.
6. Analyse reinforced concrete beams in bending and shear at the point of collapse.
7. Understand how serviceability requirements are dealt with by codes of practice.
8. Design reinforced concrete beams to the current European code.

9. Analyse reinforced concrete columns under axial load and bending at the point of collapse.
10. Design reinforced concrete columns to the current European code.
11. Predict likely collapse mechanisms for reinforced concrete slabs.
12. Make upper bound estimates of collapse loads for slabs using the yield line method.

<u>b902: Civil Engineering Hydraulics; Matric 2020, Y3; Paper B9: 8 Lectures, 2 Tutorial Sheets</u>

Steady flow in open channels. Analysis of frictionless flow using continuity, energy, and momentum principles. Critical depth and specific energy. Subcritical and supercritical flow conditions. The hydraulic Jump. Flow over a hump. Flow through channels of varying section. Uniform flow. Effect of bed friction: Chézy and Manning formulae. Gradually varied flow and surface profiles. Unsteady flow in open channels. Solitary waves, surges and bores. Pipe hydraulic transients; water hammer in elastic and rigid pipes, surge tanks.

Learning Outcomes:

1. Understand the key concepts in open channel flows.
2. Be able to analyse steady, frictionless, uniform flows in open channels.
3. Understand the concept of criticality in an open channel flow, and be able to assess whether a given flow is subcritical, critical, or supercritical.
4. Be able to derive the equations for gradually varied flow in an open channel.
5. Be able to classify surface profiles according to the channel slope and the flow depth.
6. Be able to predict surface profiles in open channels using analytical and semi-analytical methods.
7. Be able to predict the propagation of solitary waves, surges, and bores in open channels.
8. Understand the origins of, and be able to analyse, hydraulic transients in pipes (*e.g.*, waterhammer)
9. Be able to analyse and hence design a surge tank.

<u>b903: Reinforced Concrete and Civil Engineering Hydraulics Laboratory; Matric 2021, Y3; Paper B9</u>

Reinforced Concrete Laboratory: Cast and test reinforced concrete beams.

Learning Outcomes:

1. Be able to design concrete mixes.
2. Understand the construction of a steel reinforcement cage and the work of a steel fixer.
3. Experience the construction of a steel reinforcement cage.
4. Batch, mix concrete and cast reinforced concrete beams.
5. Experience the testing to destruction of reinforced concrete beams.
6. To be able to assess the mix proportions on the properties of concrete.
7. To compare the performance of beams having significantly different amounts of reinforcement.
8. To assess the accuracy of strength prediction methods.
9. Analyse the collected test data and evaluate the accuracy of the design mix and beam design strength.

Civil Engineering Hydraulics Laboratory: Observe, investigate, and analyse the various flow conditions of a hydraulic jump.

Learning Outcomes:

1. Observe and appreciate subcritical, critical, and supercritical flows.
2. Be able to apply and assess the theory related to a hydraulic jump.
3. Be able to collect, analyse, and interpret data using appropriate equations and graphs in order to determine specific energy.
4. Be able to calculate the energy head and power loss across a hydraulic jump.
5. Be able to determine the force on a sluice gate.
6. Compare results with other researchers.
7. Comment on the types and stability of the jumps observed, with reference to their Froude numbers.

Paper B10: Soil Mechanics

<u>b1001: Basic Soil Mechanics; Matric 2021, Y3; Paper B10: 8 Lectures, 2 Tutorial Sheets</u>

Introduction to soil as a granular material. Grains, grain size distribution and contrasting characteristics of clays and sands/gravels. Definitions of void ratio, specific volume, porosity, degree of saturation. Unit weight and density relationships. Basic concept of effective stress.

Seepage through soils. Darcy’s equation for steady state seepage. Measurement of permeability in the laboratory and the field. Approximate solution of confined and unconfined 2D steady-state seepage problems using flow nets. Introduction to the use of finite element analysis for steady state seepage.

Compression and consolidation. Oedometer test and compression/swelling relationships. Overconsolidation. Transient pore pressures in the oedometer, leading to Terzaghi’s 1D consolidation theory. Elementary applications of 1D consolidation theory.

Strength of soils. Shear box and triaxial tests. Friction, dilation and density (illustrated by shear box test). Drained and undrained shear strength for clays (illustrated by triaxial test).

Learning Outcomes:

1. Appreciate that saturated soil is a two-phase material (water and solids).
2. Appreciate how measures of packing (e.g. void ratio) are a useful aid to the understanding of soil behaviour.
3. Understand the significance of the concepts of relative density and liquidity index.
4. Able to apply the concept of effective stress to the analysis of simple cases of stresses in the ground and to the analysis of the triaxial and shear box tests.
5. Understand the concepts of undrained and drained loading.
6. Understand the basis of the 1D Terzaghi consolidation equation and its solution.
7. Able to solve simple 1D consolidation problems using graphical solutions of the Terzaghi consolidation equation.
8. Able to determine *c*v using data from the oedometer test.
9. Understand the concept of dilation and to appreciate the contribution that dilation makes to the strength of soil.
10. To appreciate the concept of the critical state.
11. To appreciate that the strength of course grained (e.g. sands) and fine-grained (i.e. clays) can be expressed within a unified framework.

12. To understand the concepts of undrained shear strength and critical state angle of friction.

b1002: Soil Mechanics Applications; Matric 2021, Y3; Paper B10: 8 Lectures, 2 Tutorial Sheets

Foundations: Elastic solutions for settlement. Theoretical basis of bearing capacity (lower and upper bound approaches). Use of Terzaghi bearing capacity formula.

Learning Outcomes:

1. Have an appreciation of the use of shallow foundations and the considerations required for design of a foundation.
2. Understand the lower bound theorem of plasticity and its application to foundation design, including simple examples.
3. Understand the upper bound theorem of plasticity and its application to foundation design, including simple examples.
4. Know about Terzaghi's bearing capacity theory and how it can be used for foundation design.
5. Know about elasticity solutions for the stress distribution under the foundations.
6. Be able to estimate foundation settlements using elasticity theory and other simple methods.

Retaining Walls: Types of retaining wall, design philosophy, active and passive failure. Rankine earth pressure and Coulomb wedge theories. Effective stress and total stress analysis. Tension cracks. Design of gravity and embedded walls (cantilevered and anchored/propped), diaphragm walls. Design of reinforced soil walls: external stability, internal stability.

Learning Outcomes:

1. Be familiar with the common types of retaining wall, and the circumstances in which their use might be appropriate.
2. Understand typical failure modes for retaining walls and why the provision of drainage is important.
3. Know what is meant by 'active failure' and 'passive failure' of the soil adjacent to a wall.
4. Understand the basis of Rankine's theory of earth pressure and be able to derive Rankine's equations for both the active and passive case.
5. Understand the basis of Coulomb's trial wedge method and know how to set up Coulomb force polygons for both the active and passive case.
6. Know how the Rankine and Coulomb methods specialise for (i) total stress analysis of a purely cohesive soil (ii) effective stress analysis of a purely frictional soil.
7. Know how to design mass gravity and cantilever gravity walls against sliding and overturning and be able to estimate the variation of bearing pressure across the base of the wall.
8. Know how Rankine's theory is applied to the design of embedded sheet pile walls, both cantilevered and anchored.
9. Understand the principle behind reinforced earth structures, and be able to perform simple design checks for the case of a sandy backfill.

b1003: Soil Mechanics Laboratory; Matric 2021, Y3; Paper B10

Shear box test with sand. Undrained triaxial test with clay. Sample preparation, data collection, analysis and interpretation of results.

Learning Outcomes:

1. To learn how to conduct a basic shear-box test and a basic undrained triaxial test, and how to interpret the results.
2. To understand the role of pore pressure in a triaxial test.
3. To understand the roles of friction, dilation, and density in a shear box test.
4. To understand the fundamental differences between sands and clays.

Paper B11: Chemical Processes

b1101: Process Design Fundamentals; Paper B11: 8 Lectures, 2 Tutorial Sheets

The first half of the course covers the fundamentals of chemical process design, and will include an introduction to process design and its methodology, flow-sheeting, process calculations, heat and mass balances, and examples of flow sheets. It will also introduce the key unit operations in chemical processes. The second half of the course introduces hazards and safety, also known as loss prevention, in chemical processes. It starts with some examples of previous disasters in the chemical industry, and discusses risks, hazard and safety management and relevant legislation. It then outlines the main hazards in the chemical process industry, and examines in detail two particular hazards: fires and explosions. Finally, it covers the 'HAZOP' procedure in detail

Learning Outcomes

1) Be proficient in process calculations using the concepts of mass, volume, moles, density, concentration, mole fraction, mass fraction and flow-rate.
2) Understand common terminology used in process design, such as continuous and batch operations, turn-down, purge, recycle, pinch and yield.
3) Recognise the role played in manufacturing processes by important unit operations, such as distillation, absorption and heat exchange.
4) Understand the use of block diagrams and Process Flow Diagrams (PFDs) and its associated stream table.
5) Be able to draw up heat and mass balances and to calculate a mass balance for a simple process which includes a recycle and purge.
6) Be able to explain the concept of "loss prevention" and evaluate acceptable risks and safety priorities in process design.
7) Understand the principal hazards arising in the process industries and their significance.
8) Understand fire and explosive properties of materials. Estimate fire and explosion events and associated damage. Apply procedures to reduce fire and explosion hazards, e.g. inerting.
9) Understand the HAZOP procedure and be able to conduct a HAZOP study to evaluate the safety design and devise modifications.

Introduction to process design; Units and dimensions; Graphic representation of process streams, equipment and unit operations; Mass balance in mixing, splitting, separation and with reactions; Heat balance at steady state; Recycle stream and calculations.

Process design methodology; Product specification; Raw material selection; Process selection, batch, semi-batch, and continuous; PBD (Process block diagram); Recycle; Purge; Heat integration; Utilities; Case study – ethylene oxide production.

Hazards and safety; introduction to Loss Prevention in the chemical industry. Hazards in the chemical industry, including toxicity, flammability, explosions, ignition, radiation, pressure and temperature deviations, and noise. Fires and Explosions. Pressure relief systems. HAZOP and HAZOP procedure. HAZAN, Inherent safety.

b1102: Chemical Reactors; Matric 2021, Y3; Paper B11: 8 Lectures, 2 Tutorial Sheets

Introduction to chemical kinetics. Types of reactor: batch reactors, continuous stirred tank reactors (CSTR), and plug flow reactors (PFR). Comparison of CSTR vs PFR. Design of reactor systems, e.g. CSTRs in series. Design equations for single-reaction, isothermal batch, CSTR, PFR, and semi-batch. Multiple reactions in series, parallel and combinations. Adiabatic and non-isothermal operation of CSTR and PFR; multiple steady states in CSTR. Catalytic reaction; rate limiting steps. The effects of heat and mass transfer in heterogeneous catalysis. Langmuir-Hinshelwood kinetics. Non-ideal reactors and the Residence Time Distribution (RTD).

Learning Outcomes:

1. Understand the concepts of stoichiometry, reaction rate, conversion and residence time.
2. Use the Rate Law and the Arrhenius equation to estimate the rate of a reaction.
3. Construct a Stoichiometric Table and estimate the concentration of species in terms of the conversion.
4. Develop the Design Equations for the main types of reactor (batch, CSTR, PFR and semi-batch) in terms of different variables, e.g. concentration, conversion, reaction time.
5. Estimate the volume and/or residence time for the main types of reactor under isothermal operation conditions.
6. Design systems of reactors in series.
7. Calculate the Selectivity and Yield of multiple reaction systems (series, parallel and combinations) in CSTR and PFR reactors.
8. Understand the concepts of Instantaneous Selectivity and Yield.
9. Develop and solve the energy balance equations for non-isothermal operation of CSTR and PFR.
10. Calculate the adiabatic temperature of operation and conversion of CSTR and PFR reactors.
11. Understand and explain the presence of multiple steady states in a non-isothermal CSTR.
12. Describe catalyst types and components, catalytic mechanisms, rate limiting steps and catalyst deactivation.
13. List and describe the steps in a generic heterogeneous catalytic reaction, and derive the reaction rate applicable when the limiting step is external mass transfer, pore diffusion or surface reaction.
14. Develop expressions for the reaction rate using the Langmuir-Hinshelwood kinetic theory.
15. Apply a Residence Time Distribution to calculate the concentration and conversion in a non-ideal reactor.

16. Select and justify the type of reactor to be used based on the characteristics of the reaction system and the operation conditions.

<u>b1103: Chemical Processes Laboratory; Matric 2021, Y3; Paper B11</u>

The B11 Chemical Engineering Laboratory experiments have been developed to provide students with first-hand, practical experience of typical chemical engineering processes, and will enhance the learning experience when studying the B11 chemical engineering courses. There are several different experiments available in the laboratory, which all involve the study of different types of chemical reactor. As the practical requirement of the B11 paper, you will be expected to perform one (or two shorter) experiments chosen by the laboratory supervisors. This will be performed in teams of two or three. The laboratory session will last two and a half hours, after which the report must be completed by the student and signed off by a laboratory demonstrator. You will also carry out an exercise using the ASPEN process simulator; this exercise will be carried out in a separate location, and during a time to be arranged with the supervisor of that activity.

Learning Outcomes:

1. Gain experience in the safe operation of large-scale chemical engineering equipment.

2. Be able to undertake well-planned experimental work and to interpret, analyse and report on experimental data.

3. Recognise the importance of working effectively with others.

4. Be able to apply methods to analyse the characteristics and performance of a range of typical mixing, separation, reactor and similar processing steps for fluids, particulates and multi-phases.

5. Appreciate the inter-dependence of elements of a complex system and be able to synthesise such systems by integrating process steps into a sequence and applying analysis techniques such as balances (mass, energy) and pinch.

6. Understand the principles of risk assessment and of safety management, and be able to apply techniques for the assessment and abatement of process and product laboratory hazards.

7. Understand and be able to adapt and modify Aspen Plus models of a simplified chemical process with recycle and purge, and of a more detailed reaction section of a process.

Paper B12: Electronic Devices

<u>b1201: Semiconductor Devices; Matric 2021, Y3; Paper B12: 12 Lectures, 3 Tutorial Sheets</u>

Schrödinger's equation, effective mass, density of states and Fermi-Dirac statistics, doping and carrier concentrations.

Charge carriers in semiconductors: Drift and diffusion currents, generation and recombination of charge carriers, continuity equation, effect of light on generation and recombination – direct and indirect semiconductors.

Properties of p-n junctions: Built-in potential, depletion region, forward and reverse bias, capacitance.

Photodiodes, Light Emitting Diodes. Carrier confinement in heterostructures. Quantum well structures: optical confinement, Homojunction lasers, Quantum well lasers

Bipolar Junction Transistor: Theory of operation and different operational modes, Ebers-Moll model, common emitter configuration, the Early effect.

High-frequency performance of BJT - small-signal equivalent circuits, optimisation of BJT for high frequency performance

MOS (MIS) structure; MOS capacitor.

MOSFETS: Theory of operation and static I-V characteristics, MOSFET effect of substrate bias and non-ideal behaviour.

JFETs: Operation, non-ideal characteristics, frequency response, MESFET and HEMT structures

CMOS implementation of complex gates, Schmitt trigger inputs, tri-state outputs, transmission gates flip-flops and memory cells. Electrical behaviour: speed – propagation times, fan-out, set-up and hold times clock skew; power consumption mechanisms – capacitance charging, leakage, short circuit currents.

Learning Outcomes:

1. Understand how the effective mass and band structure of a semiconductors arise from a combination of quantum mechanics and the periodic structure of a solid.

2. Understand the relationship between the density of states, Fermi level and the doping of a semiconductor

3. Explain the structure of p-n junction diodes and bipolar transistors and the impact of the different Fermi levels within these devices on the alignment of the conduction and valence bands in different parts of these devices.

4. Understand the continuity equation and the role of drift, diffusion, recombination and generation in p-n junction diodes, photodiodes, light emitting diodes and bipolar transistors

5. Explain the origins of non-ideal and high frequency effects in bipolar transistors

6. Understand how quantum wells are created and how they are used to improve the performance of LEDs.

7. Understand how heterostructure are created and how they improve the performance of HBJTs and HEMTs.

8. Explain the differences between the structure and operation of light emitting diodes and semiconductor lasers.

9. Understand the structure of JFETs, MESFET, HEMT and MOSFET.

10. Understand the high frequency of field effect transistors.

11. Explain the relationship between physical parameters of a MOSFET and its electrical characteristics.

12. Understand the non-ideal behaviour of MOSFET.

13. Understand the principles of CMOS design, and implementation of standard integrated circuit building blocks.

14. Appreciate the real electrical behaviour of integrated circuits and the methods used to compete against non-ideal performance, synchronisation and power consumption.

b1202: Power Electronics; Matric 2021, Y3; Paper B12; 4 Lectures, 1 Tutorial Sheet

Power electronics (PE) circuits control and convert electrical energy. PE is a key enabling technology that is present in almost all consumer and industrial electronic systems, for example PE circuits charge the battery in your mobile phone (at a few watts), drive electric vehicle motors (at a few hundred kilowatts) and connect wind turbines to the national grid (at a few megawatts). This course will pick up where A4 left off; it will introduce DC-DC converter circuits that contain a high-frequency transformer and so provide galvanic isolation between input and output (1.5 lectures), and it will show how closed-loop control can be applied to DC-DC converters (1 lecture) and to three-phase inverters (1.5 lectures).

Learning outcomes:

1. Recall and revise (from A4): Basic DC-DC converter types, three-phase inverters.
2. Understand the need for galvanic isolation in many applications.
3. Be able to draw, analyse and select component values for the flyback, forward and dual active bridge circuits.
4. Examine how high-frequency transformers and inductors may be designed and constructed.
5. Be able to apply the state-space averaging technique for the analysis of pulse-width modulated converters.
6. Design control systems for DC-DC converters using state-space averaging to obtain output voltage or current regulation.
7. Use the Park and Clarke transforms to control three-phase inverters in the stationary reference frame (dq-control).
8. See how dq-control is used to operate power electronic grid interfaces and synchronous machine drives.
9. Understand the need for phase-locked loops in many practical inverter applications.

b1203: Semiconductors Laboratory; Matric 2021, Y3; Paper B12

In this laboratory the voltage and currents are measured for semiconductor diodes made from different semiconductor materials. Measurements are recorded at room temperature and when the diodes are raised to higher temperatures. From the recorded data it is possible to determine the diode characteristic properties using the equations given in the lecture notes. The second stage of the experiment considers bipolar transistors. Measurements of terminal currents and voltages are used to explore transistor performance and estimate the doping densities.

Learning Outcomes:

1. Appreciate the role the band gap of the semiconductor material has on the electronic properties.
2. Understand how to make semiconductor device measurements using a range of equipment.
3. Interpret and analyse collected data using appropriate equations and graphs in order to determine key material properties.
4. Have a better understanding of the characteristics of transistor devices.

Paper B13: Circuits and Communications

b1301: Analogue and Digital Circuits; Matric 2021, Y3; Paper B13: 8 Lectures, 2 Tutorial Sheets

One-transistor circuits: common emitter amplifier and emitter follower, small signal equivalent circuit for npn and pnp BJTs. Two-transistor circuits: long-tailed pair, current mirror, power stages, a real op-amp. Analogue filters; types of low-pass transfer function: Butterworth, Chebyshev, and Bessel-Thomson filters; transformation to high-pass and band-pass. Design of analogue filters using active circuits. (4 lectures)

Digital design: discrete implementation, ASICs, gate arrays, field-programmable logic. PLDs, CPLDs, FPGAs. CAD tools for field-programmable logic. VHSIC Hardware Description Language (VHDL). CAT and design for testability. (3 lectures)

Combining analogue and digital circuits: switched-capacitor filters; phase-locked loops, clock & data recovery. (1 lecture)

Learning outcomes

To investigate various two transistor circuits and examine their performance and applications. To learn more about the limitations of op-amps. Development of tools for filter design and investigation of techniques to establish network stability and synthesis. To understand the various architectures for programmable logic devices and design issues. To appreciate the effort that goes into the testing of integrated circuits and to have exposure to some of the simpler techniques. To have some rudimentary introduction to hardware design by computer codes, such as VHDL. To explore various circuits that exploit both digital and analogue characteristics, such as the PLL.

b1302: Communications; Matric 2021, Y3; Paper B13: 8 Lectures, 2 Tutorial Sheets

- Baseband Signal Representation: Sampling and Nyquist's theorem, quantisation, sample-bit-symbol mapping, forward-error correction, signal space constellations, digital baseband transmission (line codes) and digital pulse amplitude modulation (PAM), pulse sequence spectrum
- Spectral Analysis: Stationary and cyclostationary random processes, power spectral density, random pulse sequence spectrum, spectral analysis of digital baseband modulation schemes
- Passband Modulation: Baseband versus passband signals, Hilbert transform, analytic signals, digital passband modulation and spectral analysis, multidimensional signals and orthogonal basis expansions, frequency shift keying (FSK), orthogonal frequencydivision multiplexing (OFDM)
- Coherent Demodulation and Detection: Phase-locked loop, additive white Gaussian

noise (AWGN) channel, signal-to-noise ratio, correlation and matched-filter demodulation, maximum a posteriori probability detection, maximum likelihood detection

- Noncoherent Demodulation and Detection: Optimum demodulator for binary signals, optimum detector for binary orthogonal signals, performance comparisons (coherent versus noncoherent)
- Dispersive Channels: Linear time-invariant (LTI) systems, Nyquist's condition for zero intersymbol interference, eye diagrams, maximum likelihood sequence detection and the Viterbi algorithm, linear equalisation
- Multi-user and Mobile Communications: Telecommunications traffic and the Erlang distribution, hexagonal cell geometry, frequency reuse, the wireless channel, path loss, channel fading, co-channel interference, channel protection ratio, CDMA and OFDMA

Learning Outcomes:

1. Be able to describe the key steps in creating digital data that can be used to modulate a physical waveform.
2. Have an appreciation for the need to use forward-error correction in digital communication systems.
3. Be able to determine the bandwidth of a random data pulse sequence and apply this to quantify the spectrum of baseband and passband digital modulation techniques.
4. Gain knowledge of signal space representations of digital signals and use this to compare and contrast different digital modulation schemes.
5. Understand the similarities and differences between single- and multi-dimensional digital modulation techniques.
6. Understand the construction and spectral properties of OFDM signals and have an appreciation of the importance of OFDM in modern systems.
7. Understand the properties of the AWGN channel and how to optimally, coherently demodulate a signal at the receiver in such channels.
8. Be able to explain the process of noncoherent demodulation and detection for binary orthogonal signals.
9. Have an appreciation of how intersymbol interference is caused in LTI channels.
10. Be able to describe how the Viterbi algorithm can be used to recover the most likely transmitted data sequence in an LTI channel.
11. Learn how to derive the Erlang distribution from first principles and apply this to analyse traffic in a communication system.
12. Be able to analyse the path loss in a wireless system and understand the origin and effects of channel fading.
13. Understand the hexagonal cell model and its limitations as applied to mobile network analysis.
14. Gain knowledge of how interference can be mitigated in mobile systems through modulation design and frequency allocation.

<u>b1303: Circuits and Communications Laboratory; Matric 2021, Y3; Paper B13</u>

The experiments are intended to give experience in designing, simulating, building and testing electronic circuits. Students will be expected to undertake simulation work on a circuit prior to the practical session, and then during the session to build and test their circuit and then complete a short report to be uploaded to canvas.

The lab investigates the Phase-Locked Loop which was covered in the lecture course. It is expected that at the end of the laboratory the students will have completed their simulation, built their design and investigated/assessed its performance.

Learning Outcomes:

1. Gain experience in the design of the Phase-Locked Loop circuit and component selection

2. Gain experience in using a simulator to model the performance of the Phase-Locked Loop

3. Gain experience in the construction and testing of the circuit

4. Gan understanding of typical sources of error between simulation and actual circuit performance

Paper B14: Information Engineering Systems

<u>b1401: Signal Analysis; Matric 2021, Y3; Paper B14: 4 Lectures, 1 Tutorial Sheet</u>

Understanding of the Fourier transform and the discrete Fourier transform, principles and design of analogue and digital filters, stochastic models and spectral estimation.

Learning Outcomes:

1. Basics of signals and simple filter theory, frequency response, transfer functions, design of simple analogue filters, the Butterworth filter.

2. Convolution, sampling and aliasing and their relationships to digital filtering, principles of digital filtering, recursive and non-recursive filters, the z-transform, pulse transfer function, frequency response of digital filters.

3. Design of simple digital filters, z-domain design, window functions, the bilinear transformation.

4. Discrete Fourier transform, stochastic (in particular AR) models, methods for spectral estimation

<u>b1402: Image Processing; Matric 2021, Y3; Paper B14: 4 Lectures, 1 Tutorial Sheet</u>

The paper is organized to cover the following four main topics:

Image enhancement. General review of image basics and terminology: Point operations, spatial filters, matched filters.

2D Fourier transforms and applications: Spatial frequencies, convolution theorem, aliasing.

Image restoration: Inverse and Wiener filters, applications to defocus and motion deblurring, MAP estimation.

Non-linear filters & Image compression: Bilateral filter, nonlocal means, median filter, JPEG, inpainting application.

Learning Outcomes:

1. Basics of images, and image enhancement using linear filters, e.g. to remove noise, or enhance edges.
2. The Fourier transform, convolution, sampling and aliasing in 2D, and applications to linear filtering.
3. Restoration of 2D signals: inverse and Wiener filters, applications to defocus and motion deblur.
4. Non-linear filters: order statistic filters, bilateral filter, non-local means.
5. Compression of 2D signals, the discrete cosine transform, JPEG.
6. Applications of image processing.

<u>b1403: Estimation; Matric 2021, Y3; Paper B14: 4 Lectures, 1 Tutorial Sheet</u>

Basics of pdfs: properties, joints, conditional and marginalisation, combining pdfs (convolutions, multiplications). Parametric representation of pdfs: multi-variate Normal distribution and its properties, moments, correlation. Central limit theorem. Modelling sensors probabilistically; Bayes rule. Estimators: ML, MAP and Bayes, bias and variance, applications to model fitting.

Learning Outcomes:

1. Basic properties of distributions: independence, joint and conditional distributions, marginals. Bayes' theorem. The extension from univariate to multivariate distributions.
2. How to represent distributions parametrically, how to transform into new sets of random variables, and how to combine density functions.
3. How to devise generative models and the optimization of their parameters using Maximum Likelihood Estimation.
4. The relationship between MLE and Least Squares optimization.

<u>b1404: Inference; Matric 2021, Y3; Paper B14: 4 Lectures, 1 Tutorial Sheets</u>

We are implicit in an increasingly dense web of data: the rise of big data presents unprecedented research opportunities across science and engineering. Modelling such data presents acute challenges; its complexity demands principled management of uncertainty. As such, this course will provide an introduction to probabilistic inference and modern computational statistics.

- Modelling sensors probabilistically.
- Estimators: ML, MAP and Bayes, with applications to model fitting.
- Recursive estimation.
- Decision theory.
- Classification, particularly linear classification.

Learning Outcomes:

1. How to devise generative models and the optimization of their parameters using Maximum Likelihood Estimation.
2. The relationship between MLE and Least Squares optimization.
3. The use of priors and Bayes' rule in Maximum A Posteriori estimation.
4. Sequential inference, in particular, Kalman filtering.
5. Bayesian Decision Theory: the specification of appropriate loss functions, and the minimisation of expected loss to select actions.
6. Classifiers and Decision Surfaces, particularly the discriminant function derived from Normal distributions.
7. Linear Classifiers - decision hyperplanes and their appearance in Logistic Regression.
8. Shortcomings of linear methods, and possibilities for non-linear classification.

b1405: Information Engineering Laboratory; Matric 2021, Y3; Paper B14

In this laboratory the students will learn to implement some of the techniques presented during the lectures in MATLAB. The topics covered are: Basic image manipulation, image filtering in the spatial (convolution) and frequency domains (FFT), image denoising and deblurring, how to generate random samples from a distribution, manipulate Normal distributions and apply statistical inference to infer their parameters, how to combine information from different sensors to obtain more accurate estimations (sensor fusion), compute panoramic mosaics using planar homographies, train a classifier to learn facial expressions.

Learning Outcomes:

1. Understand how to implement Weiner filters and FFT's and use them for image denoising
2. Understand how to combine iid multivariate normal measurements
3. Understand how to implement feature extraction and classification
4. Understand how to fuse multi-view imagery

Paper B15: Control Systems

b1501: Linear Dynamic Systems; Matric 2021, Y3; Paper B15: 4 Lectures, 1 Tutorial Sheet

Transforming continuous time linear systems (linear differential equations) to state space form. Existence and uniqueness of solutions to linear systems. Time-domain solution of state space equations and connections with stability. Controllability and observability properties and their interpretation. Connections between state space and transfer functions.

Learning outcomes:

1. Familiarization with state space representation as a modelling formalism of linear differential equations.
2. Linearization of nonlinear differential equations to obtain state space equations.
3. Derive the zero-input and zero-state solution of linear systems; learn to compute the transition matrix.
4. Understand the implications of the solution to the response and stability of the system.
5. Determine and analyze structural linear system properties: controllability and observability.

6. Understand connections between state space equations and transfer functions.

b1502: Optimal Control; Matric 2021, Y3; Paper B15: 8 Lectures, 2 Tutorial Sheet

Minimum energy control. Kalman decomposition. State feedback control design via pole placement. Observer design. Separation principle. Output feedback control design. Linear Quadratic Regulator (LQR) and its interpretation. Derivation of the Riccati equations.

Learning outcomes:

1. Derive of minimum energy control laws.
2. Learn how to design state feedback controllers via pole placement.
3. Learn how to design linear observers.
4. Understand the separation principle and exploit to perform output feedback control.
5. Become familiar with the Linear Quadratic Regulator (LQR) control design, its interpretation and its mathematical analysis.

Transforming linear dynamic equations to state space. Modelling exogenous variables. Time-domain solution of state space equations. Normal coordinates, modes and eigenvalues. Controllability, observability (matrix tests and physical interpretation). State space realisations and their transfer functions. Full state feedback: pole placement; LQP derived for linear systems. Feedback controllers where the full state feedback law is driven by an observer. LQR results and effects of modelling errors; integral action; reference and disturbance signals with known dynamics. Derivation of Linear Kalman filter and its applications; Extended Kalman Filter; LQG control laws; Frequency domain interpretations, Loop Transfer Recovery and robustness.

Learning Outcomes:

1. Be able to linearise nonlinear models to get a state space description.
2. Derive the free and force response of linear systems.
3. Determine the structural properties (stability, controllability, observability) of state space models.
4. Use state feedback to place system poles
5. Derive the Riccati equation and the associated LQR optimal feedback gains.
6. Know how to select weights by appropriate use of the Hamiltonian matrix.
7. Derive observer models and use them for optimal feedback configurations.
8. Use of optimal control theory to get optimal PID controllers.
9. Be able to derive Kalman filter.
10. Understand the meaning of Kalman filter tuning parameters.
11. Application of Kalman filter to estimation and fault detection problems.
12. Use the LQG design to derive optimal control laws.
13. Understand and apply Loop transfer Recovery to recover robustness of LQG control laws.

b1503: Limits on Controller Performance; Matric 2021, Y3; Paper B15: 4 Lectures, 1 Tutorial Sheet

The aim of this topic is to build on the control theory that you learn in the 2nd and 3rd years of the course, providing an introduction to the more advanced topics in the 4th year courses. The lectures cover a review of different representations of dynamic systems and stability; stability of closed loop systems including internal stability; controller design using loop shaping; limitations on achievable controllers; introduction to robustness for single-input, single-output systems. The aim is to emphasise the relationships between the different approaches to the design of control systems.

Course Outline:

1. Comparing different representations of dynamic systems
2. A review of closed loop stability
3. Controller design using loop shaping
4. Limitations on achievable controllers
5. A introduction to robustness for single-input, single-output systems

Learning Outcomes:

1. Be able to describe a system using an ordinary differential equation (ODE), transfer function, impulse response and state space model and be able to switch between these representations.
2. Have a deeper understanding of closed loop stability including internal stability.
3. Know how to use loop shaping to design feedback controllers.
4. Appreciate the limitations on performance that can be achieved using feedback.
5. Understand how to use induced norms for systems.
6. Understand the importance of designing controllers that make the feedback system robust to uncertainties in the response of the system.
7. Appreciate how to use weighting functions and the small-gain theorem to design controllers that provide robustness for single-input, single-output systems.

b1504: Control Laboratory; Matric 2021, Y3; Paper B15

The lab explores the control of water levels in a pair of connected tanks using a pump and level sensors. A linearised state space model of the process is first constructed, model parameters are identified, and the model validated by experiment. A linear-quadratic optimal controller is designed using this model assuming that measurements of both tank levels can be used to provide feedback. The effects of including an integral term in the controller are investigated. A state estimator is then designed for the case that only one of the tank levels can be measured. The state estimator is incorporated in the controller and performance is evaluated experimentally. The lab uses material from the B15 Linear Dynamic Systems course (linearisation, controllability, observability) and B15 Optimal Control (linear-quadratic regulation, integral action, state estimation).

Learning Outcomes:

1. Know how to create a linearised state space model of a nonlinear system.

2. Identify the parameters of the model and validate these using the response of the experimental equipment.

3. Design and implement a linear-quadratic optimal controller.

4. Understand controller limitations and the significance of cost weights.

5. Design and implement a linear-quadratic optimal controller with integral action to eliminate steady state error.

6. Design and implement a linear-quadratic optimal output feedback controller using a state estimator.

Paper B16: Software Engineering

b1601: Software Design in C/C++: 8 Lectures, 2 Tutorial Sheets

Software engineering and the complexity of software. Software system design: modularity and abstraction; test-driven development. Introduction to compiled languages and C/C++; The heap: global variables and dynamic memory. The stack: local variables, parameter passing, recursive function calls. Data types: primitive and compound, including arrays and structures. Object-oriented design. Classes: data, methods, constructors. Data hiding: public vs private data, accessor methods, encapsulation. Inheritance, polymorphism. Templates. Standard Template Library.

Learning Outcomes:

1. Understand the concepts of modularity and abstraction.
2. Understand the concept and use of flow, scope, variables, stack and heap.
3. Understand concepts of and advantages of object-oriented design, including: data hiding (encapsulation); inheritance and polymorphism; templates.
4. Understand how specific object-oriented constructs are implemented using C++.
5. Be able to understand C++ programs.
6. Be able to write small C++ programs.

b1602: Algorithms and Data Structures: 8 Lectures, 2 Tutorial Sheets

Algorithms: Refresher: algorithms, complexity, and correctness. Divide & conquer, merge sort, quick sort, bisection, introduction to greedy, backtracking, dynamic programming. Trees, recursive visit, binary search tree, balanced trees. Lower bound on linear sort complexity, radix sort. Heaps & heap sort. Hashing, chaining, hash functions, universal hashing. Locality sensitive hashing. Graphs, breadth-first search, depth-first search & topological sorting. Shortest paths, Dijkstra, Bellman-Ford, Floyd-Warshall. Basics of software architecture; Class diagrams and UML; creational, structural, behavioural patterns.

Learning Outcomes:

1. Understand data structures and associated algorithms: arrays, linked lists, trees, heaps, graphs, hash tables; binary search, heap sort.
2. Understand the lower bound on linear sort complexity.
3. Understand shortest paths algorithms.
4. Understand concepts of and advantages of reusable software design.
5. Understand strategies for structuring software design.
6. Understand approaches to object creation.
7. Understand models of software behaviour.

b1603: Programming Laboratory

The purpose of this laboratory is to familiarise the student with the practical aspects of computer programming in C++, as well as to consolidate through practice the material taught in the other parts of B16: object-oriented programming, data structures, and algorithms. Throughout this practical, the student will: learn to use an integrated development environment to compile C++ programs; design a program structure; then implement and debug the program.

Learning Outcomes:

1. Learn to use modern software development tools and integrated development environments.
2. Understand through practice fundamental structured programming notions: types, variables, control flow, functions.
3. Consolidate object-oriented programming skills: classes, constructors and destructors, and class hierarchies.
4. Learn to debug code using an integrated debugger.
5. Learn to use third-party libraries in your development.

Paper B17: Biomechanics

<u>b1701: Biomechanics; Matric 2021; Y3; Paper B17: 8 Lectures, 2 Tutorial Sheets</u>

Structure, function, and mechanical properties of bone, muscle, articular cartilage, tendon and ligament, along with measurement methods, clinical applications, and mathematical models (bone: mixture model, foam model; articular cartilage, tendon, and ligament: viscoelastic and poroelastic models; muscles: models of contraction, force-length, and force-velocity behaviour).

Description, measurement, and quantification of the kinematics and kinetics of human motion. Translations, rotations, and the general (Newton-Euler) equations of motion in three dimensions. The inertia tensor and principal moments and axes of inertia. Anthropometric data and inertial properties of the human body. Use of inverse dynamics and link-segment models to find inter-segmental forces and moments. The indeterminate (distribution) problem and its solution by reduction, addition, and optimization methods. Basic spatial and temporal parameters of the gait cycle for walking and running. Force measurement and the ground reaction force. Determinants of walking gait and simple models of walking. Clinical applications.

Learning Outcomes:
1. An appreciation of the complexities of the human musculoskeletal system and of the strengths and limitations of a mechanical engineering approach to the study of biological systems.

2. Knowledge of the multi-scale structure and function of bone, muscle, articular cartilage, tendon and ligament.
3. Understanding of and ability to use simple mathematical models to describe soft tissue mechanical function, including muscle contraction.
4. Knowledge of methods for mechanical property estimation and their clinical application in musculoskeletal and other tissues.
5. Understanding of clinical terminology for human three-dimensional position and orientation and its relation to mathematical descriptions of rotation.
6. Use of 3D Newton-Euler equations of motion to describe human movement and methods to calculate the anthropometric and inertial properties of the body.
7. Understanding of inverse dynamics and its use to calculate resultant forces and moments within the human body.
8. The ability to describe the main spatial and temporal parameters of the gait cycle and the characteristics of the ground reaction forces for walking and running, along with the key determinants and basic models of walking gait.

<u>b1702: Biomedical Fluid Mechanics; Matric 2021, Y3; Paper B17: 8 Lectures, 2 Tutorial Sheets</u>

Introduction to the fluid mechanics in the human body. For each fluid system covered the lectures will cover the relevant human physiology, the underlying fluid mechanics, measurements that can be used to assess function, a selection of pathological conditions that affect the flow and engineering approaches to addressing these pathologies.

The first four lectures focus on the cardiovascular system:

- The systemic and pulmonary circulation systems and the presence of the lymphatics.
- The anatomy of the heart, the cardiac cycle, and the variation in pressure and flow in the heart. Measurement of blood pressure.
- The flow profiles in major vessels accounting for pipe curvature and flow pulsatility.
- Flow in the capillaries and gas exchange in the capillary bed including the role of red blood cells.
- Various pathologies of the cardiovascular system are described including: aneurysms, atherosclerosis, thrombi and stenoses, as well as approaches to address them such as stents and shunts.

The second four lectures focus on some of the other fluid systems in the body:

- Cerebrospinal fluid. Its physiological role and fluid path ways. Pathologies, such as hydrocephalus, and engineering approaches to address it.
- The pulmonary system. The pressure and flow characteristics in a respiratory cycle. The branching structure of the lung and fluid and gas transport in the aveoli. Measuring lung function. The effect of pathologies on the function of the lungs.
- The renal system. Flow of blood through the kidney. The double capillary bed of the nephron. Mass and fluid exchange in the glomerulus and tubules. Urine production and urine excretion.
- The engineering of devices for replicating organ performance, e.g., the heart-lung by-pass machine and kidney dialysis.

Learning Outcomes:

1. Understand the role and function of the cardiovascular system from a fluid mechanics perspective.
2. Understand the role of fluid mechanics in other selected systems in the body: cerebrospinal fluid, lungs, and renal system.
3. Be able to carry out calculations of the fluid flow in various systems in the body.
4. Understand what measurements can be made for the various fluid systems in the body.
5. Appreciate the range of pathologies that exist and engineering approaches to addressing them through an understanding of the fluid mechanics.

b1703: Biomechanics Laboratory; Matric 2021, Y3; Paper B17

The Biomechanics Laboratory has two parts: one 1.5-hour 1.5-hour Mobile Gait Lab session; and one 3-hour data analysis session in the Department of Engineering Science. In the first session, students are shown the equipment used to collect motion, force, and muscle activity data on patients who have trouble walking. Demonstrators will explain how this data is collected and processed for clinical interpretation. Sample data will be collected on volunteers. In the second session, students use Matlab to calculate a number of temporal and spatial parameters used in gait analysis.

Learning Outcomes:

1. Understanding of technologies used for motion capture including optical marker, accelerometer / gyroscope / magnetometer, video and relevant applications.
2. Knowledge of clinical applications and research use of motion capture
3. Knowledge of gait characterisation parameters used clinically (such as velocity of progression, step length, stride length, cadence).
4. Understanding of limitations of optical marker-based motion capture systems and wearable sensors including skin motion artefact.
5. Familiarity with methods for artefact and noise reduction
6. Ability to analyse and extract clinically relevant information from 3D datasets.

Paper B18: Biomedical Modelling and Monitoring

b1801: Cellular Physiology; Matric 2021, Y3; Paper B18, 4 Lectures, 1 Tutorial Sheet

The course consists of 4 lectures and will provide an introduction for using mathematical models for modelling certain physiological parameters of cellular systems. The structure of mammalian cells and a set of basic biochemical reactions will be introduced. The concept on cellular homeostasis and the membrane potential will be discussed. Key concepts of cellular signalling mechanisms will be presented. The aim of the course is to demonstrate what type phenomena and processes can be modelled with the help of mathematical models. Student will learn how their engineering or mathematical modelling skills can be applied to study cellular physiology.

Learning Outcomes:

1. Be familiar the elementary structures of cells
2. Ability to model basic biochemical reactions using mass action kinetics and enzyme kinetics
3. Understand the concept of cellular homeostasis
4. Develop a simple cell model that incorporates the free principles: concentration of balance, electric neutrality and the Gibbs-Donnan equilibrium
5. Apply the Hodgkin-Huxley model for modelling basic action potentials

6. Apply reaction-diffusion equations for modelling carrier-mediated transport (example: glucose transport)

b1802: Systems Physiology; Matric 2021, Y3; Paper B18, 4 Lectures, 1 Tutorial Sheet

This course introduces the basic concepts and applications of pharmacokinetic modelling, the structure of the cardiovascular system, electrical activity of the heart as well as the structure and function of the respiratory and nervous systems. This course also considers how these process give rise to changes that can be measured externally from the body.

Learning Outcomes:

1. Have a good basic understanding about the anatomy and physiology of the human body.
2. Have knowledge of compartmental models describing compound or drug concentration in the human body.
3. Understand the physiological absorption, distribution, metabolism and elimination of foreign substances in the body and be able to calculate the concentration-time curves of these compounds using pharmacokinetic modelling techniques.
4. Understand the heart and cardiovascular system, the basics of electrocardiography as well as how to read a simple electrocardiogram and to measure blood pressure.
5. Be able to model the vasculature using an electrical equivalent circuit model and to calculate the relevant model parameters.
6. Be able to describe the function of the lung and to calculate lung volumes, respiratory capacity, gas exchange, blood pH and other relevant parameters.
7. Be able to describe the function of the nervous system, including afferent and efferent nerves, and the sympathetic and parasympathetic nerves.

b1803: Wearable Technology Matric 2021, Y3; Paper B18: 4 Lectures, 1 Tutorial Sheet

The course consists of 4 lectures and will provide an introduction to the acquisition methods for important biosignals. The physiological processes that manifest themselves in these biosignals are discussed, and estimation of physiological parameters (such as the vital signs) is studied. This course extends the electrical engineering covered in previous years to the application of biosignal acquisition and conditioning, via biomedical instrumentation. Applications of the methods to the monitoring of patients within hospital and home settings are described, including the understanding of basic pathologies for which the vital-sign monitoring methods are used in practice.

Learning Outcomes:

1. Have a good understanding of biopotentials, including electrodes and the conversion of ionic currents to electrical currents.
2. Understand ECG instrumentation amplifiers and noise reduction using driven right-leg circuitry.
3. Have an understanding of the estimation of respiratory rate from biosignals, including electrical impedance changes of the chest due to breathing and blood flow.
4. Be able to describe 2 and 4-electrode measurement of electrical impedance, and the derivation of respiration rate from the amplitude and frequency-modulation of the ECG and photoplethysmogram.
5. Understand the basic principles of oximetry, including the measurement of arterial oxygen saturation using visible and infra-red light.

6. Be able to describe the separation of a.c. and d.c. components of light absorption in pulse oximetry, and understand standard circuitry used within pulse oximeters.
7. Have an understanding of the estimation of systolic and diastolic blood pressure, using non-invasive measurements from inflatable cuffs, via oscillometry, and Korotkoff sounds.

b1804: Medical Imaging ; Matric 2021, Y3; Paper B18, 4 Lectures, 1 Tutorial Sheet

This course introduces methods by which images from within the human body can be reconstructed from signals measured externally. It covers a number of widely used medical imaging modalities, briefly introducing the underlying principles and methods for image construction. The concept of imaging metabolic processes using specifically labelled molecules and imaging apparatus is also introduced.

1. Transmission, reflection and emission.
2. Tomographic reconstruction.
3. Resonance and frequency reconstruction.
4. Metabolic imaging with contrast agents.

Learning Outcomes:

1. Understand how electromagnetic and sound waves can be used to identify structure within the body based on attenuation and reflection.
2. Describe the process of tomographic reconstruction, including simple reconstruction methods such as filtered back projection.
3. Understand the concept of a point spread function and sources of error the limit the resolution of tomographic techniques.
4. Describe how magnetic resonance can be used to selectively image body tissues.
5. Understand why magnetic resonance imaging gives rise to signals in the frequency domain and be able to describe the resulting relationships between frequency sampling and image resolution.
6. Appreciate how molecules can be labelled such that they can be detected by imaging apparatus so that physiological processes can be monitored.
7. Quantify uptake and binding of contrast agents through the use of kinetic models.

b1805: Wearable Technology Laboratory; Matric 2021, Y3; Paper B18

This lab session aims to provide practical experience of acquiring biosignals such as the EEG and the ECG. We relate the signals to the various physiological processes from which the observed data arise, and investigate the role of conditioning (such as filtering and amplification) as would typically be required to acquire and use these signals in practice. The main sources of error in the acquisition of these signals will be investigated, including gaining an understanding of appropriate sensors and their placement on the patient.

Learning Outcomes:

1. Gain practical experience in the acquisition of ECG waveforms using two different sensor systems.
2. Investigate the typical difficulties involved in instrumenting a patient with non-invasive sensors.
3. Investigate the acquisition of EEG waveforms using scalp-mounted sensors.

4. Be able to relate the acquired signals to the physiological processes from which the waveforms arise.
5. Gain an understanding of signal conditioning methods, based on electrical engineering principles that have been learned in previous years.
6. Be able to select suitable parameters for data acquisition systems, making appropriate design decisions concerning sampling rate, filter characteristics, etc.
7. Be able to describe the main sources of error and potential for artefact in the resulting signals.

B19 Fluid Mechanics: Turbulence, Compressible Flow and Turbomachinery

b1901: Turbulence and Boundary Layers; Matric 2021; Y3; Paper B19: 6 Lectures, 2 Tutorial Sheets

These lectures revisit the fundamental equations of fluid mechanics: fluid deformation and derivation of the Navier-Stokes equations. Stokes first and second problem are solved and analysed. The Prandtl boundary layer is developed in which flow is separated into a viscous region (near a boundary) and an inviscid flow elsewhere. The von Karman integral is introduced from which qualitative behaviour of boundary layers is considered in various flows, and Thwaite's method will be used for flows with pressure gradient. A physical description of the features of turbulence in flow will be discussed and an introduction into how turbulence manifests itself as an effective viscosity in the Navier-Stokes equations. The effect of turbulence on the details of boundary layers is described and in particular the "law of the wall." The generation of vorticity in flow will then be developed and a combination of models derived and used to represent real life flows such as tornados. Finally models to represent the decay of vortices will be described

Learning Outcomes:

1. To understand the physical basis of the Navier-Stokes equations.
2. Be able to solve time varying problems using NS equations.
3. To be familiar with the Prandtl boundary layer concept.
4. Be able to use semi-analytical methods for pressure gradient flows.
5. Understand the concept of scale analysis as applied to boundary layers.
6. To describe the characteristics of a turbulent flow
7. Develop time averaged Navier-Stokes equations.
8. To describe details of the "law of the wall" in a turbulent boundary layer.
9. Understand the concept of transitional boundary layers and how to model them.
10. To be familiar with vorticity in a flow and be able to represent real problems involving vorticity.

b1902: Compressible Flow; Matric 2021; Y3; Paper B19: 6 Lectures, 1 Tutorial Sheet

Introduction to high speed flows. Dimensionless formulation in terms of Mach number. The steady flow energy equation applied to adiabatic flow of a perfect gas. Continuity equation for compressible flow. One-dimensional analysis of flow in a duct of variable area. Throat conditions and choking. Use of tabulated data. Speed of sound in a compressible fluid. Physical description of the development of shock waves from large compressive disturbances. Conservation laws applied to analysis of shock wave. Analytical relationship between flow conditions upstream and downstream of a normal shock wave. Extension to oblique shock waves and the use of shock charts. Prandtl-Meyer expansion.

Learning Outcomes:

1. Be able to derive the adiabatic energy equation for compressible flow, and the equation for the speed of sound in a gas.
2. Be familiar with the concept of Mach number.
3. Be familiar with the isentropic relations for pressure, temperature and density in compressible flow.
4. Be able to derive the governing equations for Rayleigh flow, in which there is heat addition at constant area, and be able to perform simple Rayleigh flow calculations.
5. Be able to derive the governing equations for Fanno flow, adiabatic flow with friction, and be able to perform simple Fanno flow calculations.
6. Understand the differences between finite compression waves, finite expansion waves and normal shock waves.
7. Be able to derive and use the area velocity relation.
8. Understand the possible flow regimes in convergent divergent nozzles and the concept of over-expanded and under-expanded flow.
9. Understand the Mach cone and the characteristics of oblique shock waves.
10. Be able to perform simple calculations of flow through oblique shock waves.
11. Understand fundamentals of Prandtl-Meyer expansions and be able to perform simple calculations of flow through such expansions.

b1903: Turbomachinery; Matric 2021; Y3; Paper B19: 4 Lectures, 1 Tutorial Sheet

This course aims to provide a general understanding of the principles which govern the design of axial flow and radial flow turbomachines. Review of different types of turbomachines. Efficiency definitions. Euler's equation. Characteristics of axial compressor and turbine stage design. Stage non-dimensional parameters. Dimensional analysis of incompressible and compressible flow turbomachines. Theory of radial flow turbomachines. Design aspects of centrifugal and mixed flow compressors and radial inflow turbines.

Learning Outcomes:

1. To be able to select a turbomachine for a given duty.
2. To be able to draw velocity triangles for all types of turbomachines.
3. To be able to calculate stage performance and different stage non-dimensional parameters.
4. To understand factors which influence the overall design of turbomachine stages.

b1904: Fluid Mechanics Laboratory; Y3; Paper B19

The theme of this lab is flow in a transonic nozzle with a shock wave. The material part of the B19 paper (compressible flow & turbulence & boundary layer) and the lab is designed to last 5 hours, consisting of two parts,: a) a transonic nozzle experiment (2.5 hours), b) computational analysis of the tested case (2.5 hours). This exercise is designed to demonstrate the fundamental difference between subsonic and supersonic flows, how a shock wave can form in a nozzle duct, its impact on the flow distribution, and how the transonic flow can be influenced by and interaction with frictional viscous effects. The students will perform measurements of total and static pressures at several points along a nozzle with variable cross section area, carry out the theoretical analysis with the aid of HLT tables and understand the flow pattern and the influence of shock wave. Computational simulations and analyses of the tested configurations will be conducted by means of computational fluid dynamics (CFD) and the results will be compared with the test data.

Learning Outcomes:

1. Understand pressure distribution and associated flow conditions in a convergent-divergent nozzle.
2. Use HLT for compressible flow calculations.
3. Use Pitot probe for Mach number measurement in a transonic flow.
4. Set up and apply CFD for a transonic nozzle flow.
5. Use of CFD to help understand/interpret the related fluid dynamic phenomena.