DEPARTMENT OF MATHEMATICS

GUIDE TO OPTIONAL MODULES

FOURTH/FINAL YEAR (MSci)  
2016-2017

Notes and syllabus details on Fourth Year modules for students in their Fourth/Final Year

For degree codings:

G103 MATHEMATICS (BSc, MSci)  
G104 MATHEMATICS WITH A YEAR IN EUROPE (MSci)  
G1EM MATHEMATICS WITH EDUCATION (MSci)

NOTE that GG41, IG11 and GI43 MATHEMATICS AND COMPUTER SCIENCE are administered by the Department of Computing.

Professor David Evans  
Director of Undergraduate Studies

May 2016

TO BE READ IN CONJUNCTION WITH THE UNDERGRADUATE HANDBOOK.

This information WILL be subject to alteration. Updated programmes can be viewed online at: https://www.imperial.ac.uk/natural-sciences/departments/mathematics/study/students/undergraduate/programme-information/
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FOURTH YEAR OVERVIEW

The MSci Fourth Year is available to those on the G103, G104 and G1EM codings who perform to a satisfactory standard in their Third Year, here or elsewhere in Europe. There is considerable overlap with the taught postgraduate MSc programmes but the MSci is a separate degree.

The MSci programme is designed to provide a breadth and depth in mathematics to a level of attainment broadly equivalent to that of an MSc degree and takes place over three terms – Term 1 (also known as Autumn Term), Term 2 (also known as Spring Term) and Term 3 (also known as Summer Term).

Students choose six lectured modules from those made available to them in the Department and from certain modules elsewhere. Students also take the compulsory M4R project, which is equivalent to two lecture modules. Students on the Mathematics with Education G1EM coding take Education modules in the first term. They then take 3 Mathematics modules in the 2nd term, and produce a half-length M4R project.

Most, but not all, of the M4 modules are also available in M3 form. Fourth Year examinations normally consist of 5 questions and are 2.5 hours long, whereas the corresponding exam for 3rd year students (if any) contains 4 questions in 2 hours. Students may not take an M4 module if they have already taken the M3 version.

Lecturing will take place during Term 1 and Term 2 with three hours per week, which usually includes some classes. The normal expectation is that there should be a ‘lecture’/’class’ balance of about 5/1. The identification of particular class times within the timetabled periods is at the discretion of the lecturer, in consultation with the class and as appropriate for the module material.

ADVICE ON THE CHOICE OF OPTIONS

Students are advised to read these notes carefully and to discuss their option selections with their Personal Tutor. An `Options Fair` will take place after exams in the Summer Term, where staff will answer questions on all available options.

It is anticipated that lecturers will give advice on suitable books at the start of each module. Students should contact the proposed lecturers if they desire any further details about module content in order to make their choice of course options. Students should also feel free to seek advice from Year Level Tutors and the Senior Tutor, the Heads of Section and the Director of Undergraduate Studies.

Course option choices should be registered on the designated website between the 8th June and the 1st of July, 2016. This is predominantly to help us timetable the modules to minimise clashes between student selections. **Students will not be committed to taking those modules** for which they initially register until the completion of their examination entry at the beginning of Term 2. Note, however, that students do become committed to the completion of certain modules examined only by project at some stage during the module, as will be made clear by the lecturer.

M4R PROJECT

M4R ADVANCED RESEARCH PROJECT IN MATHEMATICS

Compulsory

**Supervised by Various Academic Staff**

Co-ordinator: Dr J. Britnell
(Terms 1, 2 & 3)

A fundamental part of the MSci degree is a substantial compulsory project equivalent to two lecture modules. The main aim of this module is to give a deep understanding of a particular area/topic by means of a supervised project in some area of mathematics. The project may be theoretical and/or computational and the area/topic for each student is chosen in consultation with the Department.
The project provides an excellent ‘apprenticeship in research’ and is therefore of particular value to students who are considering postgraduate study leading to a PhD.

Arrangements for this project will be set in motion after the Third Year examinations. **Students should approach potential supervisors in an area of interest before the end of their Third Year** and some preparatory work should be performed over the vacation between the Third and Fourth Years. Work on the project should continue throughout all three terms of the Fourth Year and submitted shortly after the Fourth Year examinations.

**G104:** For those on a Maths with a year in Europe coding, the third year is spent abroad at another university. G104 students should ideally negotiate with possible M4R supervisors by e-mail during their abroad, but this is not always possible. On return to Imperial, students take the regular Year 4 MSci programme (with the additional option of M4T.) On the rare occasion that a G104 student performs very poorly in their year away they may, at the discretion of the Senior Tutor, be transferred to the BSc G100 Mathematics degree or the BSc G101 Mathematics with a Year in Europe degree and take M3 subjects in their Final Year.

**G1EM:** For the Maths with Education MSci, the project is only half length the M4R length, and takes place only in the second term. During the first term students take Education modules rather than Mathematics ones.

**NON-MATHEMATICS MODULES**

MSci students may take one Centre for Co-Curricular Studies/Business School option in their Fourth Year from the approved list below.

No more than two of these ‘External’ options may be taken as part of a student’s degree.

In addition, the department offers a few options, which are deemed to be “non-Mathematical”. These may be taken as an alternative to a Centre for Co-Curricular Studies/Business School option. However, as they are Department of Mathematics modules, their ECTS value is 8 (rather than 6).

For 2016-17, these options are:

- M3E Econometric Theory and Methods
- M3C High Performance Computing
- M3H History of Mathematics
- M3B Mathematics of Business
- M3T Communicating Mathematics (only for G104 students)

Taking one of the modules listed above or a module outside the Department normally does not include an extended examination.

Subject to the Department’s approval, students may take a mathematical module given outside the Department, e.g. in the Department of Physics. Students must obtain permission from the Director of Undergraduate Studies if they wish to consider such an option.

**MODULE ASSESSMENT AND EXAMINATIONS**

Each of the following modules is examined by one written examination (usually 2.5 hours):

- M4A2, M4A4, M4A6, M4A7, M4A10, M4PA16, M4A21, M4PA22, M4A28, M4A30, M4A32, M4A34, M4A42, M4A44, M4A47, M4PA23, M4PA24, M4PA36, M4PA38, M4PA46, M4PA50, M4M3, M4M6, M4M7, M4M8, M4M9, M4P5, M4P6, M4P7, M4P8, M4P10, M4P11, M4P12, M4P14, M4P15, M4P16, M4P17, M4P18, M4P19, M4P20, M4P21, M4P32, M4P33, M4P34, M4P36, M4P41, M4P46, M4P47, M4P51, M4P54, M4P55, M4P57, M4P58, M4P59, M4P60, M4P61, M4P62, M4P63, M4S1, M4S2, M4S4, M4S7, M4S8, M4S9, M4S11, M4S14, M4S16, M4S17.
Some of the modules may have an assessed coursework/progress test element, limited in most cases to 10% of overall module assessment. This will be made clear at the commencement of each module, particularly for any exceptions that have a more substantial assignment element (e.g. M4A44, M4S2, M4S9, M4S16, M4S17 – each approximately 25%).

The modules M4A29, M4N7, M4N9, M4N10, M4S7, M3C and M4SC are examined solely by projects.

The module M4PA48 is examined by coursework, oral exam and an in-class test.

The module M4R is examined by a research project; an oral element forms part of the assessment.

The modules M3B, M3E, M3H, are examined by a 2 hour examination.

See module description for assessment of the M4S18++ modules.

The module M3T is examined by a journal of teaching activity, teacher’s assessment, oral presentation, and end of module report.

**Note:** Students who take modules which are wholly assessed by project will be deemed to be officially registered on the module through the submission of a specified number of pieces of assessed work for that module. Thus, once a certain point is reached in these modules, a student will be committed to completing it. In contrast, students only become committed to modules with summer examinations when they enter for the examinations in February.

Students who do not obtain Passes in examinations at the first attempt may be expected to attend resit examinations the following May/June (NOT normally in September) spending a year not in attendance. Two resit attempts are normally available to students. However, the Examinations Board has the power to condone not-too-serious fails in final year modules and permit graduation. Note that it is very rare for a 4th year student to fail any module, because of the high selection standards for the MSci.

**Note:** Results may not be offered for modules assessed solely by project.

Resit examinations are for Pass credit only – a maximum mark of 30 will be credited. Once a Pass is achieved, no further attempts are permitted.

### GRADUATION

Students graduating will receive an MSci degree that explicitly incorporates a BSc.

It is normally required that MSci students pass all course components in order to graduate. However, the College may condone a narrowly failed module in the Final Year of study. The Examination Board may also graduate students who have one or more badly failed module, provided the overall average mark is high enough.

The total of Honours marks for examinations, assessed coursework, tests and projects, with the appropriate year weightings, is calculated and recommendations are made to the Examiners’ Meeting (normally in late June) for consideration by the Academic Staff and External Examiners. Degrees are formally decided at this meeting.

Students at graduation may be awarded Honours degrees classified as follows: First, Second (upper and lower divisions) and Third, with a good Final Year and project being viewed favourably by the External Examiners for borderline cases.

Rarely, circumstances may require the Department to graduate an MSci student with a BSc.
Further information on degree classes can be found in the Scheme for the Award of Honours online at:
https://www.imperial.ac.uk/natural-sciences/departments/mathematics/study/students/undergraduate/programme-information/

In general, applications for postponement of consideration for Honours will NOT be granted by the Department except in special cases, such as absence through illness.

Information about Commemoration (Graduation) ceremonies can be found online at:
http://www3.imperial.ac.uk/graduation

HONOURS MARKS, YEAR TOTALS AND YEAR WEIGHTINGS

What follows is a brief summary – more details of these topics can be found in the Scheme for the Award of Honours online at:
https://www.imperial.ac.uk/natural-sciences/departments/mathematics/study/students/undergraduate/programme-information/

Within the Department each total module assessment is rescaled so that overall performances in different modules may be compared. The rescaling onto the scale 0 – 100 Honours marks is such that 30 then corresponds to the lowest Pass Honours mark and 75 corresponds to a clear First Class performance.

Note that Registry report individual module performances on transcripts using the College Scale. On this scale a Pass mark is reported as 40 and the lowest First Class mark is 70.

Information on the Mathematics and College scales can be found in the Scheme for the Award of Honours.

The total Fourth Year Honours mark available is 800 made up as 6x100 lecture modules together with 200 (M4R project).

**Note:** For uniformity, the total Honours marks for each year are scaled out of 1000 and are known as a year total.

For the four year MSci codings the year weightings are 1 : 3 : 4 : 5.

The differences in year weighting reflect the increasing level of mathematical complexity.

ECTS

To comply with the European ‘Bologna Process’, degree programmes are required to be rated via the ECTS (European Credit Transfer System) – which is based notionally on hour counts for elements within the degree.

As in Third Year, each Fourth Year mathematics module, including M3E and other mathematical optional modules, has an ECTS value of 8 except for M4R which has an ECTS value of 16. Centre for Co-Curricular Studies/Business School modules have an ECTS value of 6. Each Second Year mathematics module has an ECTS value of 7 with M2R having an ECTS value of 5. First Year mathematics modules have an ECTS value of 6.5 except for M1R which has an ECTS value of 4.5 and M1C which has an ECTS value of 4. Language modules, taken by G104 Mathematics with a Year in Europe students, have an ECTS value of 6.

**MSci students who wish to increase their ECTS counts from roughly 240 to 270 must undertake additional study over the summer vacations of their Second and Third Years. Contact the Director of Undergraduate Studies for further information.**

Details can be viewed online at:
http://www.imperial.ac.uk/natural-sciences/departments/mathematics/study/students/undergraduate/programme-information/
FOURTH YEAR MODULE LIST

Note that not all of the individual modules listed below are offered every session and the Department reserves the right to cancel a particular module if, for example, the number of students attending that module does not make it viable. Similarly, some modules are occasionally run as ‘Reading/Seminar Courses’.

Modules marked below with a * are also available in M3 form for Third Year undergraduates students (who typically take a shorter examination). When a module is offered it is usually, but not always, available in both forms. No student may take both the M3 and M4 forms of a module. In the rare event that the M4 version of a module is not available, the Department may permit one M3 module to be taken.

M3E, M3B, M3H and M3C are also available to Fourth Year students but function like a Centre for Co-Curricular Studies/Business School option, except that their ECTS value is 8. M3T may only be taken in year 4 by returning G104 students.

The groupings of modules below have been organised to indicate some natural affinities and connections.

APPLIED MATHEMATICS/MATHEMATICAL PHYSICS/NUMERICAL ANALYSIS

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<td>Representations of Symmetric Groups</td>
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<td>M4P46</td>
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<td><strong>NUMBER THEORY</strong></td>
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<td>M4N10*</td>
<td>Computational Partial Differential Equations 1</td>
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<td>M4SC*</td>
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<td>Finite Elements: Numerical Analysis and Implementation</td>
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- **Module Code**: M4S1*
- **Module Title**: Statistical Theory
- **Terms**: 2
- **Honours Marks**: 100
- **ECTS Values**: 8

### Statistical Modelling 2
- **Module Code**: M4S2*
- **Module Title**: Statistical Modelling 2
- **Terms**: 2
- **Honours Marks**: 100
- **ECTS Values**: 8

### Applied Probability
- **Module Code**: M4S4*
- **Module Title**: Applied Probability
- **Terms**: 1
- **Honours Marks**: 100
- **ECTS Values**: 8

### Time Series
- **Module Code**: M4S8*
- **Module Title**: Time Series
- **Terms**: 1
- **Honours Marks**: 100
- **ECTS Values**: 8

### Stochastic Simulation
- **Module Code**: M4S9*
- **Module Title**: Stochastic Simulation
- **Terms**: 1
- **Honours Marks**: 100
- **ECTS Values**: 8

### Games, Risks and Decisions
- **Module Code**: M4S11*
- **Module Title**: Games, Risks and Decisions
- **Terms**: 1
- **Honours Marks**: 100
- **ECTS Values**: 8

### Survival Models and Actuarial Applications
- **Module Code**: M4S14*
- **Module Title**: Survival Models and Actuarial Applications
- **Terms**: 2
- **Honours Marks**: 100
- **ECTS Values**: 8

### Credit Scoring
- **Module Code**: M4S16*
- **Module Title**: Credit Scoring
- **Terms**: 1
- **Honours Marks**: 100
- **ECTS Values**: 8

### Quantitative Methods in Retail Finance
- **Module Code**: M4S17*
- **Module Title**: Quantitative Methods in Retail Finance
- **Terms**: 2
- **Honours Marks**: 100
- **ECTS Values**: 8

### Topics in Advanced Statistics (choose one of each of the A/B options below) (M4S18++)
- **Module Code**: M4S18A1
  - **Module Title**: Multivariate Analysis
  - **Terms**: 2
  - **Honours Marks**: 50
  - **ECTS Values**: 4

- **Module Code**: M4S18A2
  - **Module Title**: Machine Learning
  - **Terms**: 2
  - **Honours Marks**: 50
  - **ECTS Values**: 4

- **Module Code**: M4S18B1
  - **Module Title**: Graphical Models
  - **Terms**: 2
  - **Honours Marks**: 50
  - **ECTS Values**: 4

- **Module Code**: M4S18B2
  - **Module Title**: Bayesian Data Analysis
  - **Terms**: 2
  - **Honours Marks**: 50
  - **ECTS Values**: 4

### PROJECT (Compulsory)
- **Module Codes**: M4R
- **Module Titles**: Research Project in Mathematics
- **Terms**: 1, 2 + 3
- **Honours Marks**: 200
- **ECTS Values**: 16

### OTHER MATHEMATICAL OPTIONS
- **Module Codes**: M3E
  - **Module Titles**: Econometric Theory and Methods
  - **Terms**: 1
  - **Honours Marks**: 100
  - **ECTS Values**: 8

- **Module Codes**: M3T
  - **Module Titles**: Communicating Mathematics
  - **Terms**: 2 + 3
  - **Honours Marks**: 100
  - **ECTS Values**: 8

- **Module Codes**: M3B
  - **Module Titles**: Mathematics of Business & Economics
  - **Terms**: 2
  - **Honours Marks**: 100
  - **ECTS Values**: 8

- **Module Codes**: M3C
  - **Module Titles**: Introduction to High Performance Computing
  - **Terms**: 1
  - **Honours Marks**: 100
  - **ECTS Values**: 8

- **Module Codes**: M3H
  - **Module Titles**: History of Mathematics
  - **Terms**: 2
  - **Honours Marks**: 100
  - **ECTS Values**: 8

### FOURTH YEAR MATHEMATICS SYLLABUSES
Most modules running in 2016-2017 will also be available in 2017-2018, although there can be no absolute guarantees.

### APPLIED MATHEMATICS/MATHEMATICAL PHYSICS/NUMERICAL ANALYSIS

#### FLUIDS

**M4A2**  FLUID DYNAMICS 1

**Professor A. Ruban**

**Term 1**

This module is an introduction to the Fluid Dynamics. It will be followed by Fluid Dynamics 2 in Term 2.

Fluid Dynamics deals with the motion of liquids and gases. Being a subdivision of Continuum Mechanics the fluid dynamics does not deal with individual molecules. Instead an ‘averaged’ motion of the medium is of interest. Fluid dynamics is aimed at predicting the velocity, pressure and temperature fields in flows past rigid bodies. A theoretician achieves this goal by solving the governing Navier-Stokes equations. In this module a derivation of the Navier-Stokes equations will be presented, followed by description of various techniques to simplify and solve the equation with the purpose of describing the motion of fluids at different conditions.
Aims of this module:
To introduce students to fundamental concepts and notions used in fluid dynamics. To demonstrate how the governing equations of fluid motion are deduced, paying attention to the restriction on their applicability to real flows. Then a class of exact solutions to the Navier-Stokes equations will be presented. This will follow by a discussion of possible simplifications of the Navier-Stokes equations. The main attention will be a wide class of flows that may be treated as inviscid. To this category belong, for example, aerodynamic flows. Students will be introduced to theoretical methods to calculate inviscid flows past aerofoils and other aerodynamic bodies. They will be shown how the lift force produced by an aircraft wing may be calculated.

Content:
Exact Solutions of the Navier-Stokes Equations: Couette and Poiseuille flows. The flow between two coaxial cylinders. The flow above an impulsively started plate. Diffusion of a potential vortex.

M4A10* FLUID DYNAMICS 2

Professor P. Hall
Term 2

Prerequisites: Fluid Dynamics 2 is a continuation of the module Fluid Dynamics 1 given in Term 1.

In Fluid Dynamics 1 the main attention was with exact solutions of the Navier-Stokes equations governing viscous fluid motion. The exact solutions are only possible in a limited number of situations when the shape of the body is rather simple. A traditional way of dealing with more realistic shapes (like aircraft wings) is to seek possible simplifications in the Navier-Stokes formulation. We shall start with the case when the internal viscosity of the fluid is very large, and the Navier-Stokes equations may be substituted by the Stokes equations. The latter are linear and allow for simple solutions in various situations. Then we shall consider the opposite limit of very small viscosity, which is characteristic, for example, of aerodynamic flows. In this cast the analysis of the flow past a rigid body (say, an aircraft wing) requires Prandtl’s boundary-layer equations to be solved. These equations are parabolic, and in many situations may be reduced to ordinary differential equations. Solving the Prandtl equations allows us to calculate the viscous drag experienced by the bodies. The final part of the module will be devoted to the theory of separation of the boundary layer, known as Triple-Deck theory.

Aims of the module:
To introduce the students to various aspects of Viscous Fluid Dynamics, and to demonstrate the power (and beauty) of modern mathematical methods employed when analysing fluid flows. This includes the Method of Matched Asymptotic Expansions, which was put forward by Prandtl for the purpose of mathematical description of flows with small viscosity. Now this method is used in all branches of applied mathematics.

Content:
Dynamic and Geometric Similarity of fluid flows. Reynolds Number and Strouhal Number.
Large Reynolds Number Flows: the notion of singular perturbations. Method of matched asymptotic expansions. Prandtl’s boundary-layer equations. Prandtl’s hierarchical concept. Displacement thickness of the boundary layer and its influence on the flow outside the boundary layer.
Triple-Deck Theory: The notion of boundary-layer separation. Formulation of the triple-deck equations for a flow past a corner. Solution of the linearised problem (small corner angle case).

M4A28* INTRODUCTION TO GEOPHYSICAL FLUID DYNAMICS

Dr P. Berloff
Term 2

Prerequisites: Students will be expected to have had grounding in classical and elementary fluid mechanics (inviscid and viscid), waves, vortices, vector calculus and partial differential equations. Studies in waves, vortices and hydrodynamic instabilities will be of use.

• Overview of physical phenomena
• Governing equations of motion
  — Rotation and sphericity
  — Geostrophic and hydrostatic balances
  — Boussinesq approximation
• Rotating shallow-water equations
  — Linear geostrophic and ageostrophic waves (including equatorial and Kelvin)
  — Geostrophic adjustment
  — Stokes drift
• Potential vorticity
• Quasigeostrophy
• Rossby waves
• Barotropic and baroclinic instabilities
  — Kelvin-Helmholtz instability
  — Eady and Phillips problems
• Turbulent baroclinic zonal jet
  — Eddy fluxes
  — Non-acceleration theorem
• Incompressible turbulence
  — The closure problem
  — Kolmogorov theory
  — Two-dimensional turbulence
  — Coherent vortices
• Ekman boundary layers
• Western boundary layers

M4A30 HYDRODYNAMIC STABILITY

Dr M.S. Mughal
Term 2


M4A32 VORTEX DYNAMICS

Professor D. Crowdy
Term 2

Prerequisites: A knowledge of basic applied mathematical methods is the only prerequisite. A basic knowledge of inviscid fluid dynamics (e.g. M4A2) is desirable but not required.
The module will focus on the mathematical study of the dynamics of vorticity in an ideal fluid in two and three dimensions. The module will be pitched in such a way that it will be of interest both to fluid dynamicists and as an application of various techniques in dynamical systems theory.

Fundamental properties of vorticity.
Helmholtz Laws and Kelvin's circulation theorem. Singular distributions of vorticity; Biot-Savart law.
Dynamics of line vortices in 2d and other geometries; dynamics of 2d vortex patches, contour dynamics.
Axisymmetric vortex rings. Dynamics of vortex filaments.
Stability problems.
Miscellaneous topics (effects of viscosity, applications to turbulence, applications in aerodynamics).

M4M7* ASYMPTOTIC ANALYSIS
Professor X. Wu
Term 1


M4PA48* DYNAMICS OF GAMES
Prof D. Turaev
Term 1

Contents of the module.
Recently there has been quite a lot of interest in modelling learning. The settings to which these models are applied is wide-ranging. Examples are
(i) how populations in biology optimise their strategies and
(ii) how people pick what actions to take in a competitive environment.

This module is aimed at discussing a number of such models in which learning evolves over time, and which have a game theoretic background. The module will use tools from the theory of dynamical systems, and will aim to be rigorous. Topics will include replicator dynamics and best response dynamics.

Prerequisites. M2AA1 (Differential Equations). A significant amount of the material will use dynamical systems tools. Related modules are M3PA46 (Chaos and Fractals) or M3PA23 (Dynamical Systems). However, it is not necessary to have taken these modules, nor is it necessary to have any background in game theory. In spite of its name, the module style will be rather Pure.

M4PA23* DYNAMICAL SYSTEMS
Dr M. Rasmussen
Term 1

The theory of Dynamical Systems is an important area of mathematics which aims at describing objects whose state changes over time. For instance, the solar system comprising the sun and all planets is a dynamical system, and dynamical systems can be found in many other areas such as finance, physics, biology and social sciences. This course provides a rigorous treatment of the foundations of discrete-time dynamical systems, which includes the following subjects:

- Periodic orbits
- Topological and symbolic dynamics
- Chaos theory
- Invariant manifolds
- Statistical properties of dynamical systems

**M4PA38 ADVANCED DYNAMICAL SYSTEMS**

**Lecturer to be confirmed**

**Term 1**

This reading course deals with topics in dynamical systems at an advanced level, touching upon current frontline research. Each year a selection will be made of material from the area of local bifurcation theory, global bifurcation theory, ergodic theory of dynamical systems or dynamical systems methods for PDEs/FDEs. The selection of reading material will be detailed at the beginning of the academic year.

**Assessment:** Students taking the course for credit are to prepare an essay (counting for 60%) and give an oral presentation about their work (counting for 40%).

**M4PA36 ERGODIC THEORY**

**Dr M Rasmussen**

**Term 2**

Ergodic theory has strong links to analysis, probability theory, (random and deterministic) dynamical systems, number theory, differential and difference equations and can be motivated from many different angles and applications. In contrast to topological dynamics, Ergodic theory focusses on a probabilistic description of dynamical systems, and hence, a proper background of probability and measure theory is required to understand even the basic material in ergodic theory. For this reason, the first part of the course will concentrate on a self-contained review of the required background; this can take up to three weeks and might be skipped if not necessary. The second part of the course will focus on selected topics in ergodic theory. The course will be organised as a reading course; there will weekly meetings, where selected material will be presented and discussed within the group; this will guide the independent study. The students will do a project in the second part of the course, which should be submitted by the end of the term, so that the project does not come into conflict with the exams. The project will count towards 60% of the mark. There will also be a thirty-minute regular oral exam, which consists of two parts, each of which will contribute 20% to the mark. The first part of the regular oral exam will concern a discussion about the project: the student will have five minutes time to explain the project, after which there will questions related to the project (up to ten minutes). The second half of the exam will consist of questions about the material of the course.

The core content of the course is given as follows:

2. Invariant measures and Krylov–Bogolubov Theorem,
3. Poincaré recurrence,
4. Ergodic theorems (such as Birkhoff Ergodic Theorem, Maximal Ergodic Theorem),
5. Decay of correlations,
6. Detailed discussion of examples (such as circle maps, maps with critical points, hyperbolic toral automorphisms, Bernoulli shifts),
7. Ergodicity via Fourier series
8. Mixing,
9. Markov chains and ergodicity/mixing of Markov measures,

**M4PA24* BIFURCATION THEORY**

**Dr D. Turaev**

**Term 2**

This module serves as an introduction to bifurcation theory, concerning the study of how the behaviour of dynamical systems (ODEs, maps) changes when parameters are varied.
The following topics will be covered:

1) Bifurcations on a line and on a plane.
2) Centre manifold theorem; local bifurcations of equilibrium states.
3) Local bifurcations of periodic orbits – folds and cusps.
4) Homoclinic loops: cases with simple dynamics, Shilnikov chaos, Lorenz attractor.
5) Saddle-node bifurcations: destruction of a torus, intermittency, blue-sky catastrophe.
6) Routes to chaos and homoclinic tangency.

M4PA16* GEOMETRIC MECHANICS

Professor D. Holm
Term 1

This module on geometric mechanics starts with Fermat's principle, that light rays follow geodesics determined from a least action variational principle. It then treats subsequent developments in mechanics by Newton, Euler, Lagrange, Hamilton, Lie, Poincaré, Noether, and Cartan, who all dealt with geometric optics.

The module will explicitly illustrate the following concepts of geometric mechanics:
* Configuration space, variational principles, Euler-Lagrange equations, geodesic curves,
* Legendre transformation, phase space, Hamilton's canonical equations,
* Poisson brackets, Hamiltonian vector fields, symplectic transformations,
* Lie group symmetries, conservation laws, Lie algebras and their dual spaces,
* Divergence free vector fields, momentum maps and coadjoint motion.

All of these concepts from geometric mechanics will be illustrated with examples, first for Fermat's principle and then again for three primary examples in classical mechanics: (1) motion on the sphere, (2) the rigid body and (3) pairs of n :m resonant oscillators.


M4PA34* DYNAMICS, SYMMETRY AND INTEGRABILITY

Professor D. Holm
Term 2

The following topics will be covered:
* Introduction to smooth manifolds as configuration spaces for dynamics.
* Transformations of smooth manifolds as flows of smooth vector fields.
* Introduction to differential forms, wedge products and Lie derivatives.
* Adjoint and coadjoint actions of matrix Lie groups and matrix Lie algebras
* Action principles on matrix Lie algebras, their corresponding Euler-Poincaré ordinary differential equations and the Lie-Poisson Hamiltonian formulations of these equations.
* EPDiff: the Euler-Poincaré partial differential equation for smooth vector fields acting on smooth manifolds
* The Hamiltonian formulation of EPDiff: Its momentum maps and soliton solutions
* Integrability of EPDiff: Its bi-Hamiltonian structure, Lax pair and isospectral problem, as well as the relationships of these features to the corresponding properties of KdV.

M4PA50* INTRODUCTION TO RIEMANN SURFACES AND CONFORMAL DYNAMICS

Dr F. Bianchi
Term 2
This elementary course starts with introducing surfaces that come from special group actions (Fuchsian / Kleinian groups). It turns out that on such surfaces one can develop a beautiful and powerful theory of iterations of conformal maps, related to the famous Julia and Mandelbrot sets. In this theory many parts of modern mathematics come together: geometry, analysis and combinatorics.


Syllabus:

Part 1: Discrete groups, complex Mobius transformations, Riemann surfaces, hyperbolic metrics, fundamental domains.

Recommended texts:

1) Kleinian Groups by Berbard Maskit,
2) The Geometry of Discrete Groups by Alan F. Beardon,
3) Dynamics in one complex variable by John Milnor,
4) Riemann surfaces, dynamics and geometry, lecture notes by Curtis McMullen.

FINANCE

M4F22* MATHEMATICAL FINANCE: AN INTRODUCTION TO OPTION PRICING

Professor N.H. Bingham
Term 1

Prerequisites: Differential Equations (M2AA1), Multivariable Calculus (M2AA2), Real Analysis (M2PM1) and Probability and Statistics 2 (M2S1).

The mathematical modeling of derivatives securities, initiated by the Louis Bachelier in 1900 and developed by Black, Scholes and Merton in the 1970s, focuses on the pricing and hedging of options, futures and other derivatives, using a probabilistic representation of market uncertainty. This module is a mathematical introduction to this theory, which uses a wide array of tools from stochastic analysis, which are covered in the module in a self-contained manner: Brownian motion, stochastic integration, Ito calculus and parabolic partial differential equations.

Outline:
Filtrations and information. Conditional expectation.
Brownian motion. Simulation of Brownian motion.
Gaussian properties Markov property, martingale property.
Relation with the heat equation. Feynman-Kac formula. Quadratic variation.
Bachelier's model. The Black-Scholes model.
The Ito stochastic integral: definition, properties. Ito processes.
Arbitrage strategies. Arbitrage-free markets.
The Ito formula. Applications of the Ito formula.
Stochastic exponentials. Lévy’s theorem.
Options and derivative securities. Call and put options.
Sensitivity analysis of an option: Delta, Gamma and Theta.
Arbitrage pricing of derivative securities: a one period example.
Dynamic hedging of options.
The Black-Scholes partial differential equation. Relation with heat equation.
The Black-Scholes formula.
Change of measure. The Cameron-Martin formula. 'Risk-neutral' probability.
Dynamic hedging in presence of uncertain volatility. Gamma exposure.

**BIOLOGY**

**M4A49** MATHEMATICAL BIOLOGY

Dr F. Tettamanti-Boshier
Term 1

The aim of the module is to describe the application of mathematical models to biological phenomena. A variety of contexts in human biology and diseases are considered, as well as problems typical of particular organisms and environments.

The syllabus includes topics from:

2. Epidemiology - the spread of plagues.
3. Reaction-Diffusion models: Turing mechanism for pattern formation. How the leopard got his spots (and sometimes stripes).
5. Mass transport; Taylor dispersion.
7. Other particular problems from biology.

**M4A43** INFECTION, CONTROL AND DRIVING IN NATURAL SYSTEMS

Dr N. Jones
Term 1

Prerequisites: Familiarity with introductory topics in dynamical systems, stochastic processes and statistical inference.

Topics in Bayesian inference and connections to implementations of samplers, chemical reactions and neural coding. Topics in optimal control including Markov decision processes, dynamic programming, HJB equations, linearly solvable stochastic optimal control and its path integral formulation. Links between control, inference and reinforcement learning. Theory for driving of (living) systems including (metabolic) control theory, polytopes and flux balance analysis, and ageing and error correction.

This is a theoretical module but some of the problem sets might require some computer programming.

**MATHEMATICAL PHYSICS**

**M4A4** MATHEMATICAL PHYSICS 1: QUANTUM MECHANICS

Dr S. Jevtic
Term 2

Quantum mechanics is one of the most successful theories in modern physics and has an exceptionally beautiful underlying mathematical structure. It provides the basis for many areas of contemporary physics, including atomic and molecular, condensed matter, high-energy particle physics, quantum information theory, and quantum cosmology, and has led to countless technological applications.

This module aims to provide an introduction to quantum phenomena and their mathematical description. Quantum theory combines tools and concepts from various areas of mathematics and physics, such as classical mechanics, linear algebra, probability theory, numerical methods, analysis and even geometry. However, most of the concepts are basic, and little background knowledge is required before we can put them to practical use.

Core topics: the mathematics and foundations of quantum mechanics; Schrödinger equation and wave functions; quantum dynamics; one-dimensional systems; harmonic oscillator; angular momentum; spin-1/2 systems; multiparticle systems; entanglement. Additional topics may include the hydrogen atom and approximation methods.

M4A6* SPECIAL RELATIVITY AND ELECTROMAGNETISM

Dr G. Pruessner
Term 1

Beautiful mathematical description of physical theory of great theoretical and technological importance. At every stage reference is made to experimental results and technological applications.

Special relativity: Einstein’s postulates, Lorentz transformation and its consequences, four vectors, dynamics of a particle, mass-energy equivalence, collisions.

Electromagnetism: Coulomb’s law and its consequences, the magnetic field, Biot-Savart law, field tensors, Lorentz force law, Faraday’s law, Maxwell’s equations, Poynting vector and energy-momentum conservation, radiation.

Specific examples of radiation from charged particles e.g. gyro-radiation, bremsstrahlung, Cerenkov radiation.

M4A7* TENSOR CALCULUS AND GENERAL RELATIVITY

Dr R. Barnett
Term 2

The mathematical description of a theory, which is fundamental to gravitation and to behaviour of systems at large scales.

Tensor calculus including Riemannian geometry; principle of equivalence for gravitational fields; Einstein’s field equations and the Newtonian approximation; Schwarzschild’s solution for static spherically symmetric systems; the observational tests; significance of the Schwarzschild radius; black holes; cosmological models and ‘big bang’ origin of the universe; the early universe.

Cosmology, gravitational waves.

M4A29* THEORY OF COMPLEX SYSTEMS

Professor H. Jensen
Term 2

Objective: To become familiar with the subject matter of Complexity Sciences, its methodology and mathematical tools.
Prerequisites: Curiosity and an interest in being able to understand the complex world surrounding us. Standard undergraduate mathematics (such as calculus, linear algebra). Some familiarity with computing (e.g. matlab or other programming language). A little familiarity with statistical mechanics may be helpful.

This module will provide the basic foundation in terms of concepts and mathematical methodology needed to analyse and model complex systems.

1) Simple functional integration: to discuss the emergent vortex solutions in terms extremal configurations for the partition integral of the 2D XY model.
2) Record statistics and record dynamics: to discuss the statistics of intermittent slowly decelerating dynamics as observed in models of evolution and many other complex systems. Relations to extreme value statistics.
3) Branching processes: to present a mean field discussion of avalanche dynamics in models of complex systems such as the sand pile, forest fires and more recent models of fusions of banks.
4) The Kuramoto transition to synchronisation as an example of collective cooperative dynamical behaviour of potential relevance to brain dynamics.
5) Intermittency in low (non-linear maps) and high dimensional systems (e.g. Tangled Nature model) and relation to renormalisation theory (low dim.) and mean field stability analysis (high dim).

Assessment: Two mini projects.

M4M3*  INTRODUCTION TO PARTIAL DIFFERENTIAL EQUATIONS

Dr E. Zatorska

Term 1

1. Basic concepts: PDEs, linearity, superposition principle. Boundary and Initial value problems.
3. Linear and Qasilinear first order PDEs in two independent variables. Well-posedness for the Cauchy problem. The linear transport equation. Upwinding scheme for the discretization of the advection equation.

M4M6*  METHODS OF MATHEMATICAL PHYSICS

Dr J. Marshall

Term 1

Complex integration [revision]
Wiener-Hopf technique continued [principal part integral – definition and examples, analytic properties of fns defined via a Cauchy-type integral on finite smooth contours, investigation of limits – Plemelj formulae, Hilbert problem (possibly limited to inversion formula possibly extended to the general case), log kernels].
Orthogonal polynomials [polynomials solutions to 2nd order differential equations, orthogonality, Gramm-Schmidt process, Rodrigues formula, generating functions, recurrence relations, numerous examples, but special care taken of Hermite, Lagrange and Laguerre polynomials all needed for quantum mechanics].
Hypergeometric series [Gamma function – integral representation and basic properties, Hypergeometric series – definition, convergence, special values of argument, differential equations, possibly extended series, Barnes integral and analytic continuations, special case needed for physics].
**M4M8  ADVANCED TOPICS IN PARTIAL DIFFERENTIAL EQUATIONS**

Professor P. Degond  
Term 2

Prerequisites: This module will provide an exposition of the most important methods of analysis of classical Partial Differential Equations. It will be best understood after taking Applied Functional Analysis (M345M9), but will be designed as a stand-alone course.

4. The heat equation in the whole space. Representation formula. Uniqueness by the duality method. Regularity and decay in time.

**M4M9*  APPLIED FUNCTIONAL ANALYSIS**

Professor P. Degond  
Term 1

Prerequisites: M4M9 provides a more comprehensive exposition of the basic functional analytic tools needed for Advanced Topics in Partial Differential Equations (M4M8). Elements of topology and integration theory will be provided so that students do not need to have previous training in these subjects.

1) Elements of metric topology  
2) Elements of Lebesgue's integration theory.  

**M4A42  APPLIED STOCHASTIC PROCESSES**

Professor G. Pavliotis  
Term 1
Prerequisites: Basics of probability theory and calculus; elements of functional analysis, of the theory of ODEs and PDEs.

1. Elements of Probability Theory
2. Stochastic processes and asymptotic behaviour: Law of Large numbers and (Functional) Central Limit Theorems.
3. Ergodic Theory.
5. Continuous time Markov processes: Markov diffusions, generator of a Markov process, Fokker-Planck equation, Brownian Motion, Langevin Equation.
7. Elements of non-equilibrium Statistical Mechanics.

NUMERICAL/COMPUTATION

(M3C HIGH PERFORMANCE COMPUTING – See later)

M4A44 COMPUTATIONAL STOCHASTIC PROCESSES

Professor G. Pavliotis
Term 2

Prerequisites: Some knowledge of stochastic processes, ODEs, PDEs, linear algebra, scientific computing, numerical analysis will be useful. Knowledge of Matlab or any other programming language.


Numerical methods for stochastic differential equations, weak and strong convergence, stability, numerical simulation of ergodic SDEs.


Statistical inference for diffusion processes, maximum likelihood, method moments. Markov Chain Monte Carlo, sampling from probability distributions

Applications: computational statistical mechanics, molecular dynamics

M4A47 FINITE ELEMENTS: NUMERICAL ANALYSIS AND IMPLEMENTATION.

Dr C Cotter and Dr D Ham
Term 2

Finite element methods form a flexible class of techniques for numerical solution of PDEs that are both accurate and efficient.

The finite element method is a core mathematical technique underpinning much of the development of simulation science. Applications are as diverse as the structural mechanics of buildings, the weather forecast, and pricing financial instruments. Finite element methods have a powerful mathematical abstraction based on the language of function spaces, inner products, norms and operators.

This module aims to develop a deep understanding of the finite element method by spanning both its analysis and implementation. In the analysis part of the module you will employ the mathematical abstractions of the finite element method to analyse the existence, stability, and accuracy of numerical solutions to PDEs. At the same time, in the implementation part of the module you will combine these abstractions with modern software engineering tools to create and understand a computer implementation of the finite element method.
Syllabus:

- Basic concepts: Weak formulation of boundary value problems, Ritz-Galerkin approximation, error estimates, piecewise polynomial spaces, local estimates.
- Efficient construction of finite element spaces in one dimension, 1D quadrature, global assembly of mass matrix and Laplace matrix.
- Construction of a finite element space: Ciarlet’s finite element, various element types, finite element interpolants.
- Construction of local bases for finite elements, efficient local assembly.
- Sobolev Spaces: generalised derivatives, Sobolev norms and spaces, Sobolev’s inequality.
- Numerical quadrature on simplices. Employing the pullback to integrate on a reference element.
- Computational meshes: meshes as graphs of topological entities. Discrete function spaces on meshes, local and global numbering.
- Global assembly for Poisson equation, implementation of boundary conditions. General approach for nonlinear elliptic PDEs.
- Variational problems: Poisson’s equation, variational approximation of Poisson’s equation, elliptic regularity estimates, general second-order elliptic operators and their variational approximation.
- Residual form, the Gâteaux derivative and techniques for nonlinear problems.

The course is assessed 50% by examination and 50% by coursework (implementation exercise in Python).

**M4N7**  NUMERICAL SOLUTION OF ORDINARY DIFFERENTIAL EQUATIONS

Dr I. Shevchenko
Term 1

An analysis of methods for solving ordinary differential equations. Totally examined by project.


**M4N10**  COMPUTATIONAL PARTIAL DIFFERENTIAL EQUATIONS 1

Professor J. Mestel
Term 2

The module will introduce a variety of computational approaches for solving partial differential equations, focusing mostly on finite difference methods, but also touching on finite volume and spectral methods. Students will gain experience implementing the methods and writing/modifying short programs in Matlab or other programming language of their choice. Applications will be drawn from problems arising in Mathematical Biology, Fluid Dynamics, etc. At the end of the module, students should be able to solve research-level problems by combining various techniques.

Topics (as time permits).

- Solvers for elliptic problems: direct and iterative solvers, Jacobi and Gauss-Seidel method and convergence analysis; geometric multigrid method.

- Methods for the heat equation: explicit versus implicit schemes; stiffness.

- Techniques for the wave equation: finite-difference solution, characteristic formulation, non-reflecting boundary conditions, one-way wave equations, perfectly matched layers. Lax-Friedrichs, Lax-Wendroff, upwind and semi-Lagrangian advection schemes.

- Domain decomposition for elliptic equations: overlapping alternating Schwarz method and convergence analysis, non-overlapping methods.

**M4SC* SCIENTIFIC COMPUTATION**

**Professor P. Schmid**

**Term 2**

Scientific computing is an important skill for any mathematician. It requires both knowledge of algorithms and proficiency in a scientific programming language. The aim of this module is to expose students from a varied mathematical background to efficient algorithms to solve mathematical problems using computation.

The objectives are that by the end of the module all students should have a good familiarity with the essential elements of the Python programming language, and be able to undertake programming tasks in a range of common areas (see below).

There will be four sub-modules: 1. A PDE-module covering elementary methods for the solution of time-dependent problems. 2. An optimization-module covering discrete and derivative-free algorithms. 3. A pattern-recognition-module covering searching and matching methods. 4. A statistics-module covering, e.g., Monte-Carlo techniques.

Each module will consist of a brief introduction to the underlying algorithm, its implementation in the python programming language, and an application to real-life situations.

**M4N9* COMPUTATIONAL LINEAR ALGEBRA**

**Dr E. Keaveny**

**Term 1**

Examined solely by project. Competence in MATLAB is a prerequisite.

Whether it be statistics, mathematical finance, or applied mathematics, the numerical implementation of many of the theories arising in these fields relies on solving a system of linear equations, and often doing so as quickly as possible to obtain a useful result in a reasonable time. This course explores the different methods used to solve linear systems (as well as perform other linear algebra computations) and has equal emphasis on mathematical analysis and practical applications. A portion of the course will also be devoted to optimisation and how linear algebra routines arise in this context.

Topics include:
1. Direct methods: Triangular equations, Gauss elimination, LU-decomposition, conditioning and finite-precision arithmetic, partial and complete pivoting, Cholesky factorisation, band matrices, QR-factorisation.
2. Iterative methods: Richardson, Jacobi, Gauss - Seidel, SOR; block variants; convergence criteria; Chebyshev acceleration.
3. Symmetric eigenvalue problem: power method and variants, Jacobi's method, Householder reduction to tridiagonal form, eigenvalues of tridiagonal matrices, the QR method
PURE MATHEMATICS

ANALYSIS

M4P6* PROBABILITY THEORY

Dr I. Krasovsky
Term 2

Prerequisites: Measure and Integration (M3/4P19, Term 1)

A rigorous approach to the fundamental properties of probability.


M4P7* FUNCTIONAL ANALYSIS

Dr D. Gajic
Term 2

This module brings together ideas of continuity and linear algebra. It concerns vector spaces with a distance, and involves linear maps; the vector spaces are often spaces of functions.


M4P18* FOURIER ANALYSIS AND THEORY OF DISTRIBUTIONS

Prof. M. Ruzhansky
Term 2

Spaces of test functions and distributions, Fourier Transform (discrete and continuous), Bessel’s, Parseval’s Theorems, Laplace transform of a distribution, Solution of classical PDE’s via Fourier transform, Basic Sobolev Inequalities, Sobolev spaces.

M4P19* MEASURE AND INTEGRATION

Dr G. Holzegel
Term 1


M4P60* GEOMETRIC COMPLEX ANALYSIS

Dr D. Cheraghi
Term 1

Complex analysis is the study of the functions of complex numbers. It is employed in a wide range of topics, including dynamical systems, algebraic geometry, number theory, and quantum field theory, to name a few. On the other hand, as the separate real and imaginary parts of any analytic function satisfy the Laplace equation, complex analysis is widely employed in the study of two-dimensional problems in physics such as hydrodynamics, thermodynamics, Ferromagnetism, and percolations.

While you become familiar with basics of functions of a complex variable in the complex analysis course, here we look at the subject from a more geometric viewpoint. We shall look at geometric notions associated with domains in the plane and their boundaries, and how they are transformed under holomorphic mappings. In turn, the behavior of conformal maps is highly dependent on the shape of their domain of definition. Below is a rough guide to the syllabus.

Part 1) Elements of holomorphic mappings: Poincaré metric, Schwarz-Pick lemma, Riemann mapping theorem, growth and distortion estimates, normal families, canonical mappings of multiply connected regions.


Part 3) Elements of quasi-conformal mappings and elliptic PDEs, Beltrami equation, singular integral operators, measurable Riemann mapping theorem.

M4P41 ANALYTIC METHODS IN PARTIAL DIFFERENTIAL EQUATIONS

Prof M. Ruzhansky
Term 1

The main object of this module is to introduce several fundamental techniques of analysis for the study of partial differential equations.

The topic will include Fourier analysis, distributions, differential operators, pseudo-differential operators. There will be a review of Sobolev spaces, embedding theorems, potentials. We will apply it to study L2 properties, almost orthogonality, and the regularity of wave (hyperbolic) equations as well as elliptic and parabolic equations.

M4P47 STOCHASTIC FILTERING

Professor D. Crisan
Term 2

Preliminaries: Conditional Expectation, Brownian motion, Itô integral, Solutions of SDEs, Girsanov's Theorem, Martingale Representation Theorem.


Finite Dimesional Filters. The Kalman Bucy Filter. The Benes Filter.


M4P62 RANDOM MATRICES

Dr I. Krasovsky
Term 2

Prerequisite: Measure and Integration; Corequisite: Probability.

Literature:

The course is an introduction to the theory of random matrices. Generally, a random matrix is a finite dimensional matrix whose elements are random variables. The theory aims to describe properties of the spectrum of such matrices in the limit when their dimension is large. Foundations of the theory were laid in 1950-60's, but it remains a very active research area. We will discuss the basics of the theory and some of the recent results.

Random matrices were invented as a model to describe large systems of particles whose precise law of interaction is unknown and can be considered random. They have therefore applications in several branches of physics. Random matrices also have intriguing conjectural connections to Riemann's zeta-function, these will be mentioned in the course.

GEOMETRY

M4P5* GEOMETRY OF CURVES AND SURFACES

Dr M-A Lawn
Term 1

The main object of this module is to understand what is the curvature of a surface in 3-dimensional space.

Topological surfaces: Definition of an atlas; the prototype definition of a surface; examples. The topology of a surface; the Hausdorff condition, the genuine definition of a surface. Orientability, compactness. Subdivisions and the Euler characteristic. Cut-and-paste technique, the classification of compact surfaces. Connected sums of surfaces. Smooth surfaces: Definition of a smooth atlas, a smooth surface and of smooth maps into and out of smooth surfaces. Surfaces in $\mathbb{R}^3$, tangents, normals and orientability. The first fundamental form, lengths and areas, isometries. The second fundamental form, principal curvatures and directions. The definition of a geodesic, existence and uniqueness, geodesics and co-ordinates. Gaussian curvature, definition and geometric interpretation, Gauss curvature is intrinsic, surfaces with constant Gauss curvature. The Gauss-Bonnet theorem. (Not examinable and in brief) Abstract Riemannian surfaces, metrics.

Mean curvature and minimal surfaces, including the definition of mean curvature, its geometric interpretation, the definition of minimal surfaces and some examples.

M4P20* GEOMETRY 1: ALGEBRAIC CURVES

Prof M. Haskins
Term 1

Plane algebraic curves including inflection points, singular and non-singular points, rational parametrisation, Weierstrass form and the Group Law on non-singular cubics. Abstract complex manifolds of dimension 1 (Riemann surfaces); elliptic curves as quotients of $\mathbb{C}$ by a lattice. Elliptic integrals and Abel's theorem.
M4P21* GEOMETRY 2: ALGEBRAIC TOPOLOGY

Prof M. Haskins
Term 2


M4P33 ALGEBRAIC GEOMETRY

Dr M. Orr
Term 2

Pre-requisites: M4P55 Commutative Algebra

Algebraic geometry is the study of the space of solutions to polynomial equations in several variables. In this course, you will learn to use algebraic and geometric ideas together, studying some of the basic concepts from both perspectives and applying them to numerous examples.


M4P51 RIEMANNIAN GEOMETRY

Dr Di Nezza
Term 2

Prerequisites: Geometry of Curves and Surfaces (M4/4P5) and Manifolds (M4P52).

The main aim of this module is to understand geodesics and curvature and the relationship between them. Using these ideas we will show how local geometric conditions can lead to global topological constraints.


M4P52 MANIFOLDS

Dr E. Segal
Term 1

Smooth manifolds, quotients, smooth maps, submanifolds, rank of a smooth map, tangent spaces, vector fields, vector bundles, differential forms, the exterior derivative, orientations, integration on manifolds (with boundary) and Stokes’ Theorem. This module focuses on foundations as well as examples.

M4P54 DIFFERENTIAL TOPOLOGY

Dr M-A Lawn
Term 2

Prerequisites: Fundamental group and covering spaces from Algebraic Topology (M4P21) and vector fields and differential forms, derivatives and pull-backs of smooth maps, exterior differentiation and integration from Manifolds (M4P52).

Differential topology is concerned with the topology of smooth manifolds.
The first part of the module deals with de Rham cohomology, a form of cohomology defined in terms of differential forms. We will prove the Mayer-Vietoris exact sequence, Künneth formula and Poincaré duality in this context, and discuss degrees of maps between manifolds.
The second part of the module introduces singular homology and cohomology, the relation to de Rham cohomology via de Rham's theorem, and the general form of Poincaré duality. Time permitting, there will also be a brief introduction to Morse theory.

ALGEBRA AND DISCRETE MATHEMATICS

M4P8* ALGEBRA 3
Dr T. Schedler
Term 1
Rings, integral domains, unique factorization domains.
Modules, ideals homomorphisms, quotient rings, submodules quotient modules.
Fields, maximal ideals, prime ideals, principal ideal domains.
Euclidean domains, rings of polynomials, Gauss's lemma, Eisenstein's criterion.
Field extensions.
Noetherian rings and Hilbert's basis theorem.
Dual vector space, tensor algebra and Hom.
Basics of homological algebra, complexes and exact sequences.

M4P10* GROUP THEORY
Prof A. Ivanov
Term 1
An introduction to some of the more advanced topics in the theory of groups.
Composition series, Jordan-Hölder theorem, Sylow's theorems, nilpotent and soluble groups.
Permutation groups. Types of simple groups.

M4P11* GALOIS THEORY
Professor A. Corti
Term 1
The formula for the solution to a quadratic equation is well-known. There are similar formulae for cubic and quartic equations, but no formula is possible for quintics. The module explains why this happens.
Irreducible polynomials. Field extensions, degrees and the tower law. Extending isomorphisms.
Normal field extensions, splitting fields, separable extensions. The theorem of the primitive Element.
Groups of automorphisms, fixed fields. The fundamental theorem of Galois theory.
The solubility of polynomials of degree at most 4. The insolubility of quintic equations.
M4P12*  GROUP REPRESENTATION THEORY

Dr R. Bellovin
Term 2


M4P17*  ALGEBRAIC COMBINATORICS

Professor M.W. Liebeck
Term 2

An introduction to a variety of combinatorial techniques that have wide applications to other areas of mathematics. Elementary coding theory. The Hamming metric, linear codes and Hamming codes. Combinatorial structures: block designs, affine and projective planes. Construction of examples using finite fields and vector spaces. Steiner systems from the Golay code. Basic theory of incidence matrices. Strongly regular graphs: examples, basic theory, and relationship with codes and designs. The Mathieu group and their relationship with codes and strongly regular graphs.

M4P36  REPRESENTATIONS OF SYMMETRIC GROUPS

Dr Schedler
Term 2

Background of the (ordinary) representation theory of finite groups: group algebra, irreducible modules, Maschke theorem, multiplicity of an irreducible module in a given module, the number of irreducible characters is equal to the number of conjugacy classes. The symmetric group: cyclic type, partitions and conjugacy classes, generation by transpositions. Action of the symmetric group on subsets of the basic set and irreducible decompositions of the corresponding permutation characters. Diagrams, tableaux and tabloids: definitions, examples and applications. Young diagram, Specht modules and their basic properties. Self-duality and absolute irreducibility of the Specht modules. The (ordinary) character table of the symmetric groups and its explicit calculations for small degrees. The standard basis of the Specht module. The branching rule and examples of its application.

M4P46  LIE ALGEBRAS

Professor A. Skorobogatov
Term 2


M4P55  COMMUTATIVE ALGEBRA
Dr A. Pal
Term 1


M4P61 INFINITE GROUPS

Dr J. Britnell
Term 2

Free groups. Group presentations, Tietze transformations, the word problem. Residually finite groups. Cayley graphs, actions on graphs, the Nielsen–Schreier Theorem. Free products, the Table-Tennis Lemma, amalgams. HNN extensions, the Higman Embedding Theorem, the Novikov–Boone Theorem. Geometry of groups, hyperbolic groups.

M4P63 ALGEBRA IV

Prof. A. Skorobogatov
Term 1

This course is a selection of topics in advanced algebra. It will be useful for the students who want to specialise in algebra, number theory, geometry or topology.

Co-requisites: Algebra 3 (M3P8) and Galois Theory (M3P11). Group Theory (M3P10) and Group Representations (M3P12) will be useful but are not obligatory.

Categories and functors, complexes, homological algebra.

Injective and projective modules, modules over Principal Ideal Domains.

Group cohomology.

Classical groups, symmetric and exterior algebra, quadratic forms, Witt's theorem, Clifford algebra.

Central simple algebras, Wedderburn's theorem, Brauer group, Hilbert's theorem 90.

NUMBER THEORY

M4P14* NUMBER THEORY

Dr D. Helm
Term 1

The module is concerned with properties of natural numbers, and in particular of prime numbers, which can be proved by elementary methods.


Arithmetic functions, multiplicative functions, perfect numbers, Möbius inversion, Dirichlet Convolution.

Primitive roots, Gauss's theorem, indices.

Quadratic residues, Euler's criterion, Gauss's lemma, law of quadratic reciprocity, Jacobi symbol.

Sums of squares. Distribution of quadratic residues and non-residues.

Irrationality, Liouville's theorem, construction of a transcendental number.

Diophantine equations. Pell's equation, Thue's Theorem, Mordell's equation.
M4P15*  ALGEBRAIC NUMBER THEORY

Dr A. Pal
Term 2

An introduction to algebraic number theory, with emphasis on quadratic fields. In such fields the familiar unique factorisation enjoyed by the integers may fail, but the extent of the failure is measured by the class group.

The following topics will be treated with an emphasis on quadratic fields $\mathbb{Q}(\sqrt{d})$.

Field extensions, minimum polynomial, algebraic numbers, conjugates and discriminants, Gaussian integers, algebraic integers, integral basis, quadratic fields, cyclotomic fields, norm of an algebraic number, existence of factorisation.

Factorisation in $\mathbb{Q}(\sqrt{d})$. Ideals, $\mathbb{Z}$-basis, maximal ideals, prime ideals, unique factorisation theorem of ideals and consequences, relationship between factorisation of numbers and of ideals, norm of an ideal. Ideal classes, finiteness of class number, computations of class number.

Fractional ideals, Minkowski’s theorem on linear forms, Ramification, characterisation of units of cyclotomic fields, a special case of Fermat’s last theorem.

M4P32  NUMBER THEORY: ELLIPTIC CURVES

Dr Bijakowski
Term 1


M4P58  MODULAR FORMS

Dr D. Helm
Term 1


STATISTICS

M4S1*  STATISTICAL THEORY (Previously Statistical Theory I)

Dr R. Drikvandi
Term 2

This module deals with the criteria and the theoretical results necessary to develop and evaluate optimum statistical procedures in hypothesis testing, point and interval estimation.

Theories of estimation and hypothesis testing, including sufficiency, completeness, exponential families, minimum variance unbiased estimators, Cramér-Rao lower bound, maximum likelihood estimation, Rao-Blackwell and Neyman-Pearson results, and likelihood ratio tests as well as elementary decision theory and Bayesian estimation.

M4S2*  STATISTICAL MODELLING 2
Dr D-H. Lau  
Term 2

Prerequisites: This module leads on from the linear models covered in M2S2 and Probability and Statistics 2 covered in M2S1.

The Generalised Linear Model is introduced from a theoretical and practical viewpoint and various aspects are explained. Generalised Linear Model, as a unifying statistical framework – linear models and quantitative responses. Generalised Additive Models, Kernel and non-parametric Regression. Fixed and random effect models.

The R statistical package will be used to expose how the different models can be applied on example data.

M4S4*  APPLIED PROBABILITY

Dr A. Veraart  
Term 1

This module aims to give students an understanding of the basics of stochastic processes. The theory of different kinds of processes will be described, and will be illustrated by applications in several areas. The groundwork will be laid for further deep work, especially in such areas as genetics, finance, industrial applications, and medicine.


M4S7*  STATISTICAL PATTERN RECOGNITION (Not running in 2016-17)

Dr E. Cohen  
Term 1

A fundamental aim in statistics is classifying things. For example, this occurs in medicine, where the aim is to assign people to diseases, speech recognition, where the aim is to assign words to meanings, banking, where the aim is to assign customers to risk classes, and in a vast number of other areas. This module provides a modern view of methods for performing such so-called pattern recognition tasks. Totally examined by projects.

Discriminant analysis, generalised linear models, nearest neighbour methods, recursive partitioning methods, trees, ensemble classifiers, and other tools. The areas of pre-processing, feature selection and classification performance assessment will also be explored, and an introduction to unsupervised pattern recognition methods will be given.

M4S8*  TIME SERIES

Professor A.T. Walden  
Term 1
An introduction to the analysis of time series (series of observations, usually evolving in time) is given, which gives weight to both the time domain and frequency domain viewpoints. Important structural features (e.g., reversibility) are discussed, and useful computational algorithms and approaches are introduced. The module is self-contained.


M4S9*  STOCHASTIC SIMULATION

Dr J.S. Martin
Term 1

Prerequisites: Material from M2S1 would form a firm foundation.

Computational techniques have become an important element of modern statistics (for example for testing new estimation methods and with notable applications in biology and finance). The aim of this module is to provide an up-to-date view of such simulation methods, covering areas from basic random variate generation to Monte Carlo methodology. The implementation of stochastic simulation algorithms will be carried out in R, a language that is widely used for statistical computing and well suited to scientific programming.


M4S11*  GAMES, RISKS AND DECISIONS

Dr L.V. White
Term 1

Simple probabilistic and mathematical tools are used to study the theory of games where two opponents are in conflict, including the celebrated Prisoners’ Dilemma problem. Utilities, based on (apparently) reasonable axioms are introduced, leading to a study of decision theory.


n-person cooperative games, coalitions and characteristic functions, imputations, the core of a game, Shapley values.

M4S14*  SURVIVAL MODELS AND ACTUARIAL APPLICATIONS

Prof A. Gandy
Term 2

Survival models are fundamental to actuarial work, as well as being a key concept in medical statistics. This module will introduce the ideas, placing particular emphasis on actuarial applications.

Graduation and testing crude and smoothed estimates for consistency.

**M4S16**  CREDIT SCORING

Dr A. Bellotti  
Term 1

*Prerequisites: Statistical Modelling 1 (M2S2) with some dependency on Statistical Modelling 2 (M3S2) and Applied Probability (M3S4).*

Introduction and background: Aims and objectives of scoring, legislative and commercial aspects. Consumer credit data: characteristics, transformations, data quality, transaction types, challenges. Notions of statistical scorecards. Basic models: Logistic regression and Naïve Bayes methods. Application and behavioural model types and characteristics, including segmented models Estimation and model fitting: basic principles and model selection. Issues of model search space and selectivity bias. Performance assessment and monitoring: measures and estimation, method comparison. Discrimination, probability calibration and cost-based measures. Testing and forecasting. The R statistical package will be used to explore credit scoring models on example data. Topics from fraud scoring, trigger and change analysis, reject inference.

**M4S17**  QUANTITATIVE METHODS IN RETAIL FINANCE

Dr A. Bellotti  
Term 2

*Prerequisites: Essential - Credit Scoring 1 (M3/4S16). Useful – Applied Probability (M3S4).*


**TOPICS IN ADVANCED STATISTICS (M4S18++)**

Dr E. Cohen, Prof D van Dyk, Prof A. Walden, Dr B. Calderhead  
Term 2

This is a demanding module comprising a choice of two from four already existing half-modules from the MSc in Statistics, one from pool A and one from pool B.

Note for example that the choice A1 & B1 will be assessed by 2 x 90 minute exams, and A2 & B1 by a 90 minute exam (B1) and continuous assessment (A2).

Pool A:
M4S18A1: Multivariate Analysis (Dr Cohen) [90 minute exam]  

M4S18A2: Machine Learning (Dr Calderhead) [Continuous assessment through coursework]  
Introduction to statistical pattern recognition and machine learning. Methods for feature extraction, dimensionality reduction, data clustering and pattern classification. State-of-art approaches such as support vector machines and ensemble learning methods. Real-world applications to real data sets.

Pool B:  
M4S18B1: Graphical Models (Prof Walden) [90 minute exam]  
Graphical modelling for both (a) a vector of random variables, and (b) vector-valued time series. Conditional independence. Dependence structure and graphical representation. Markov properties. Conditional independence graphs. Decomposable models. Graphical Gaussian models. Model selection. Directed acyclic graphs (DAGs), Bayesian networks. Graphical modelling of time series (model selection, Kullback-Leibler approach). *(Some prior knowledge of time series analysis would be helpful for part (b), the last section.)*

M4S18B2: Bayesian Data Analysis (Prof van Dyk) [90 minute exam]  

OTHER “NON-MATHEMATICAL” MATHEMATICS MODULES

*The modules M3E/M3H/M3B/M3C/M3T may each be taken as an alternative to a Centre for Co-Curricular Studies/Business School option. However, as Department of Mathematics modules, their ECTS value is 8.*

M3E  
ECONOMETRIC THEORY AND METHODS  
Dr H. Battey  
Term 1  
Econometric Theory and Methods aims to help students understand the econometric techniques that are widely employed in modern economic applications and research. It presents an advanced treatment of econometric principals for cross-sectional and panel (or longitudinal) data sets.


M3H  
HISTORY OF MATHEMATICS
The aim of this module is to give an overview of the development of mathematics from ancient to modern times.

The ancient world.
Prehistory. Egypt; Mesopotamia. The Greeks: from Pythagoras through Euclid and Archimedes to Apollonius.

The Middle Ages.
The Arabs. India and China. The beginnings of mathematics in Europe; the Renaissance; Copernicus and Galileo.

The modern world.
The Scientific Revolution; Newton, Leibniz and their followers.

The Enlightenment. Academies and universities.
The 18th C.; the Bernoullis, Euler, Lagrange. The Napoleonic period: Laplace, Gauss.
The 19th C.: Cauchy, Riemann, Cantor; Poincaré and Hilbert.
The 20th C., up to 1950: the development of modern algebra, analysis, probability, statistics, applied mathematics.

M3B THE MATHEMATICS OF BUSINESS AND ECONOMICS

Dr James Martin
Term 2

This module aims to:
Give a broad mathematical introduction to both microeconomics and macroeconomics
Consider the motivations and optimal behaviours of both firms and consumers in the marketplace, and show how this leads to the widely observed laws of supply and demand
Look at the interaction of firms and consumers in markets of varying levels of competition and further consider the roles of both, as well as the government, in a macroeconomic setting

Syllabus:
Theory of the firm
Profit maximisation for a competitive firm. Cost minimisation. Geometry of costs. Profit maximisation for a non-competitive firm.

Theory of the consumer
Consumer preferences and utility maximisation. The Slutsky equation.

Levels of competition in a market

Macroeconomic theory
Circular flow of income. Aggregate supply & demand. The multiplier effect.

M3C INTRODUCTION TO HIGH PERFORMANCE SCIENTIFIC COMPUTING

Dr P. Ray
Term 1

High-performance computing centres on the solution of large-scale problems that require substantial computational power. This will be a practical module that introduces a range of powerful tools that can be used to efficiently solve such problems. By the end of the module, which will be examined by projects, students will be prepared to tackle research problems using the tools of modern high-performance scientific computing in an informed, effective, and efficient manner.

Contents:
Getting started: working with UNIX at the command line
Software version control with git and Bitbucket
Programming and scientific computing with Python
Modular programming with modern Fortran, using scientific libraries, interfacing Python and Fortran
OpenMP (with Fortran) for parallel programming of shared-memory computers
MPI (with Fortran) for programming on distributed-memory machines such as clusters
Cloud computing
Good programming practice: planning, unit testing, debugging, validation (to be integrated with the above topics and the programming assignments.)

M3T  COMMUNICATING MATHEMATICS

Professor E.J. McCoy, Dr L.V. White
(Terms 2 & 3)

(Note: only G104 students who have already registered for it may take this module in their 4th year)

This module will give students the opportunity to observe and assist with teaching of Mathematics in local schools. Entry to the module is by interview in the preceding June and numbers will be limited. It is required for anyone on the Mathematics with Education degree coding.

For those selected there will follow a one day training course in presentation skills and other aspects of teaching. Students will be assigned to a school where they will spend ten half days in Term 2, under the supervision of a teacher. Assessment will be based on a portfolio of activities in the school, a special project, evaluation by the school teacher and an oral presentation.

CENTRE FOR LANGUAGE, CULTURE AND COMMUNICATION/BUSINESS SCHOOL

Students may consider broadening their study programme by taking advantage of the CLCC/Business School provision.

Note that Centre for Co-Curricular Studies modules extend throughout Terms 1 and 2 and some modules may be examined in January. Taking the HSCS3006 Humanities Project normally also requires explicit permission from the Centre for Co-Curricular Studies.

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<td>Lessons from History</td>
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<td>Global Challenges Independent Project</td>
<td>1 + 2</td>
<td>100</td>
<td>6</td>
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<tr>
<td>HSCS3001</td>
<td>Advanced Creative Writing</td>
<td>1 + 2</td>
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<td>HSCS3002</td>
<td>History of Science, Technology and Industry</td>
<td>1 + 2</td>
<td>100</td>
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<tr>
<td>HSCS3003</td>
<td>Philosophy of Mind</td>
<td>1 + 2</td>
<td>100</td>
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<td>Science, Politics and Human Identity</td>
<td>1 + 2</td>
<td>100</td>
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<td>Humanities Project</td>
<td>1 + 2</td>
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<td>Conflict, Crime and Justice</td>
<td>1 + 2</td>
<td>100</td>
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<td>HSCS3008</td>
<td>Visual Culture, Knowledge and Power</td>
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<tr>
<td>HSCS3009</td>
<td>Music and Western Civilization</td>
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<td>HSCS2007</td>
<td>Music Technology</td>
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<td>BS0808</td>
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<td>BS0820</td>
<td>Managing Innovation</td>
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</table>

MSci students may take at most one option from the collection of these modules and M3B/C/E/H/T in each of their Third and Fourth Years.

Syllabus and timetabling information can be viewed online at:
CLCC: http://www.imperial.ac.uk/horizons
Business School: http://wwwf.imperial.ac.uk/business-school/programmes/undergraduate-study/bpes-programme/

Note that places in CLCC and Business School modules are normally limited and registration should be done separately via the Centre for Co-Curricular Studies and Business School websites.

Note that a change in degree code registration can lead to your registration for a BPES code being revoked. This is an unfortunate side-effect of how the Business School runs things. Save a screenshot of your registration to help in any dispute.

Subject to the Department’s approval, in addition to the Centre for Co-Curricular Studies/Business School options, students may take a Mathematical module given outside the Department, e.g. in the Department of Physics. Students are advised to discuss this with the Director of Undergraduate Studies if they wish to consider such an option.

**IMPERIAL HORIZONS**

The College has created the ‘Imperial Horizons’ programme to broaden students’ education and enhance their career prospects. This programme is open to all undergraduate students.

The Department of Mathematics always endeavours to avoid timetabling Mathematics modules during the times allocated for Horizons modules.

**Note that modules on this programme (except for the ones listed separately above as approved modules for 4th year students) do not contribute to degree Honours marks but they do have an ECTS value of 6.**

Further information about the ‘Horizons’ programme can be found at: http://www.imperial.ac.uk/horizons