DEPARTMENT OF MATHEMATICS

GUIDE TO OPTIONAL MODULES

THIRD/FINAL YEAR (BSc), THIRD YEAR (MSci)
2018-2019

Notes and syllabus details for modules available to students in their Third Year

For degree codings:

G100, G103 MATHEMATICS (BSc, MSci)
G104 MATHEMATICS WITH A YEAR ABROAD (MSci)
G102 MATHEMATICS WITH MATHEMATICAL COMPUTATION
G125 MATHEMATICS (PURE MATHEMATICS)
G1F3 MATHEMATICS WITH APPLIED MATHEMATICS/MATHEMATICAL PHYSICS
G1G3 MATHEMATICS WITH STATISTICS
G1GH MATHEMATICS WITH STATISTICS FOR FINANCE
GG31 MATHEMATICS, OPTIMISATION AND STATISTICS

NOTE that GG14, GG41, IG11 and GI43 MATHEMATICS AND COMPUTER SCIENCE are administered by the Department of Computing.

Professor David Evans
Director of Undergraduate Studies

4 June 2018.

TO BE READ IN CONJUNCTION WITH THE UNDERGRADUATE HANDBOOK.

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

The Third Year programme 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).

After the first two years, which consist predominantly of compulsory ‘core’ mathematics, the Third Year has been designed to permit much student choice.

Students must take EIGHT modules from a wide variety of selections from within the Department and from certain modules elsewhere. The modules specifically approved are listed below, but students may apply to the DUGS for permission to take any module offered in other departments, e.g. Physics or Computing. Each Mathematics module has up to 30 lectures or their equivalent. M2 option modules not taken in the Second Year are normally also available to Third Year students but only one of these may be taken in the Third Year and it counts for fewer ECTS (7 rather than 8).

Lecturing will take place during Term 1 and Term 2 with three hours per week, which usually includes some problems 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.

Some BSc students will prefer to remain broad in their interests in their Final Year of study, while others will specialise, either from personal preference, or in order to satisfy the requirements of their particular degree coding. Students registered for the MSci coding G103 Mathematics are advised not to specialise too narrowly at the Third Year stage and should retain some flexibility in their planning for the Fourth Year.

G103: The primary criterion for eligibility to remain on G103 is to achieve a year total of at least 60 percent in Second Year. Students who have a year-total of 60 percent in their Second Year, a year total of at least 58 percent on the College scale in their Third Year and pass all their Third Year modules, have the automatic right to continue on to the Fourth Year of the MSci degree. Anyone scoring less than 58 percent (on College scale) in their Third Year, or who fails a module, does not have this right and may be graduated with a BSc at the Department’s discretion.

Those who score less than 60 percent in their Second Year will be transferred to the BSc, but may be allowed to return to G103 at the end of the 3rd year. This is at the discretion of the Senior Tutor and will normally require a 3rd year total of 70 percent or more.

For further information on year totals, please see page 4.

G104: Students registered for G104 Mathematics with a Year Abroad spend their Third Year (of four) studying mathematics courses/project material at another institution. 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 and take M3 subjects in their Final Year. When this occurs, the weighting for each year is 1:3:0:5.

Selection of students wishing to spend their third year abroad at MIT will take place early in Spring term of the second year.

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 ‘Option Fair’ will take place after exams in the Summer Term, where staff will answer questions on all available options. Some staff from the Pure, Statistics and AMMP sections will hold ‘office hours’ towards the end of the 3rd term, during which they can be consulted about optional modules.

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 Tutors, the Senior Tutor and the Director of Undergraduate Studies.

You will not be committed to your choice of most optional modules until the completion of your examination entry at the beginning of Term 2. The exception to this is 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.

NON-MATHEMATICS MODULES

The Department offers a few options which are deemed to be 'less-Mathematical'.

For 2018-19, these options are:

M3C High Performance Computing
M3B Mathematics of Business
M3T Communicating Mathematics (only available to G104 students in year 4)

There is also an approved list of Centre for Co-Curricular Studies/Business School non-Mathematical options which may be taken by Mathematics students (see later in this guide).

Third year BSc students are permitted to take

either:

all three of the 'less-Mathematical' options M3C, M3T, M3B and no CCS/ Business School option,

or:

at most two from the combined list of 'less Mathematical' and CCS/ Business School options.

MSci students may take at most one option from the combined list of 'less Mathematical' and CCS/ Business School options in each of their Third and Fourth Years.

BSc students who are considering transfer to the MSci should ensure that they take no more than one module from the combined list of 'less Mathematical' and CCS/ Business School options during their third year. Otherwise they will not be able to satisfy the programme requirements of the MSci.

Subject to the Department’s approval, students may take a module given outside the Department, e.g. in the Departments of Physics or Computing. Students must obtain permission from the Director of Undergraduate Studies if they wish to consider such an option. The DUGS will determine whether the module can be substituted for a Mathematics option, or whether it will count as one of the less (or non-) Mathematical options.

PROGRESSION TO THE FOURTH YEAR AND GRADUATION

It is normally required that MSci students pass all course components in order to proceed into the Fourth Year.

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

The total of marks for examinations, assessed coursework, progress tests, assignments and projects, with the appropriate year weightings, is calculated and recommendations are made to the Examiners’ Meeting (normally held at the end of 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 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 online in the Scheme for the Award of Honours 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

**MARKS, YEAR TOTALS AND YEAR WEIGHTINGS**

What follows is a brief summary – more details of these topics can be found online at: https://www.imperial.ac.uk/natural-sciences/departments/mathematics/study/students/undergraduate/programme-information/ (information for 2018-2019 will be updated over the summer of 2018).

Within the Department each total module assessment is rescaled so that overall performances in different modules may be compared. From 2017-18 onwards, all marks will be computed on the College scale, rather than the Mathematics scale used in previous years. The rescaling onto the scale 0 – 100 marks is such that 40 (or 50 in the case of M4 modules) then corresponds to the lowest Pass mark and 70 corresponds to the lowest First Class performance.

Marks from the eight modules taken in the third year are combined with equal weightings into a year total expressed as a percentage.

Further information can found in the Scheme for the Award of Honours.

For three year BSc codings, the 1st : 2nd : 3rd year weightings are 1 : 3 : 5.

For the four year MSci codings G103, G104 the year weightings are 1 : 3 : 4 : 5.

(For G104 students who first enrol in the Department from 2017-18 onwards, the year weightings will be 1 : 3 : 3 : 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. In principle, 1 ECTS should equate to around 25 hours of study (including examinations and private study).

Each Third Year mathematics module has an ECTS value of 8. 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.

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.
MODULE ASSESSMENT AND EXAMINATIONS

Most M3 modules are examined by one written examination of 2 hours in length.

Some of the modules may have an assessed coursework/progress test element, limited in most cases to 10% of overall module assessment. Some modules have a more substantial coursework component (for example, 25 percent) and others are assessed entirely by coursework. Details can be found in the tables below. Precise details of the number and nature of coursework assignments will be provided at the start of each module.

Students should bear in mind that single-term modules assessed by projects usually require extra time-commitment during that term. Thus, the Department generally advises that students should not take more than one such module in a term. Students wishing to take more than one such module in a term will be required to discuss this with the Senior Tutor.

The module M3R is examined by a research project; an oral element forms part of the assessment.

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 will be expected to attend resit examinations where appropriate. Third Year students have resit opportunities the following May/June (NOT normally in September). Two resit attempts are normally available to students; however, MSci students who fail a module in their Third Year only have one resit opportunity to be able to progress to the Fourth Year.

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

Resit examinations are for Pass credit only – a maximum mark of 40 percent (College scale) will be credited. Once a Pass is achieved, no further attempts are permitted.

Students who have not achieved the required Passes by the beginning of the new academic year are required by College to spend a year out of attendance. During this time they are not considered College students. This may create a number of issues and hold visa implications.

THIRD 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 wishing to attend that module does not make it viable. Similarly, some modules are occasionally run as ‘Reading Modules’.

M2 optional modules not taken in the Second Year are normally also available to Third Year students but only one of these may be taken in the Third Year and it counts for fewer ECTS (7 rather than 8).

Modules marked * are also available in M4 form for Fourth Year MSci students (which typically involves taking a longer 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.
M3B 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. The module M3T may only be taken in year 4 by returning G104 students.

The following notes relate to the tables on optional modules for Year 3 as below:

All M3 modules are equally weighted and worth 8 ECTS points unless otherwise specified.

Column on % Exam – this indicates a standard closed-book written exam, unless otherwise indicated.

Column on % CW – this indicates any coursework that is completed for the module. This may include in-class tests, projects, or problem sets to be turned in.

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

**APPLIED MATHEMATICS/MATHEMATICAL PHYSICS/NUMERICAL ANALYSIS**

<table>
<thead>
<tr>
<th>Module Codes</th>
<th>Module Titles</th>
<th>Terms</th>
<th>Lecturer</th>
<th>% exam</th>
<th>% CW</th>
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</thead>
<tbody>
<tr>
<td>M2AM</td>
<td>Non-linear Waves</td>
<td>2</td>
<td>Professor J. Carrillo</td>
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<td>M3A2*</td>
<td>Fluid Dynamics 1</td>
<td>1</td>
<td>Professor A. Ruban</td>
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<td>M3A10*</td>
<td>Fluid Dynamics 2</td>
<td>2</td>
<td>Professor A. Ruban</td>
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<tr>
<td>M3A28*</td>
<td>Introduction to Geophysical Fluid Dynamics</td>
<td>2</td>
<td>Dr P. Berloff</td>
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<tr>
<td>M3M7*</td>
<td>Asymptotic Analysis</td>
<td>1</td>
<td>Professor X. Wu</td>
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**FLUIDS**

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<tr>
<td>M3PA48*</td>
<td>Dynamics of Games</td>
<td>1</td>
<td>Professor S. van Strien</td>
<td>40 (Oral)</td>
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<td>M3PA23*</td>
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<td>Professor D. Holm</td>
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<td>M3PA34*</td>
<td>Dynamics, Symmetry and Integrability</td>
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**DYNAMICS**

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<th>% CW</th>
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<tr>
<td>M3FA22*</td>
<td>Mathematical Finance: An Introduction to Option Pricing</td>
<td>1</td>
<td>Dr P. Siorpaes</td>
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<tr>
<td>M3A49*</td>
<td>Mathematical Biology</td>
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<td>Dr N. Jones</td>
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<tr>
<td>M3A50*</td>
<td>Methods for Data Science</td>
<td>1</td>
<td>Dr D. Oyarzun</td>
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**MATHEMATICAL PHYSICS**

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<td>M3A4*</td>
<td>Mathematical Physics 1: Quantum Mechanics</td>
<td>1</td>
<td>Dr E-M Graefe</td>
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<tr>
<td>M3A6*</td>
<td>Special Relativity and Electromagnetism</td>
<td>1</td>
<td>Dr G. Pruessner</td>
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<tr>
<td>M3A7*</td>
<td>Tensor Calculus and General Relativity</td>
<td>2</td>
<td>Dr C. Ford</td>
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<tr>
<td>M3A29*</td>
<td>Theory of Complex Systems</td>
<td>2</td>
<td>Professor H. Jensen</td>
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<tr>
<td>M3A52*</td>
<td>Quantum Mechanics II</td>
<td>2</td>
<td>Dr R. Barnett</td>
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<tr>
<td>M3M6*</td>
<td>Methods of Mathematical Physics</td>
<td>1</td>
<td>Dr S. Olver</td>
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**APPLIED PDEs, NUMERICAL ANALYSIS and COMPUTATION**

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<tr>
<td>M3M3*</td>
<td>Introduction to Partial Differential Equations</td>
<td>1</td>
<td>Dr M. Delgadino</td>
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<tr>
<td>M3M11*</td>
<td>Function Spaces and Applications</td>
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<td>Professor P. Degond</td>
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<td>Module Codes</td>
<td>Module Titles</td>
<td>Terms</td>
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<td>% exam</td>
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<tr>
<td>M3M12*</td>
<td>Advanced Topics in Partial Differential equations</td>
<td>2</td>
<td>Professor P. Degond</td>
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<tr>
<td>M3A47*</td>
<td>Finite Elements: Numerical Analysis and Implementation</td>
<td>2</td>
<td>Dr C. Cotter &amp; Dr D. Ham</td>
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<tr>
<td>M3N7*</td>
<td>Numerical Solution of Ordinary Differential Equations</td>
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<td>Dr I. Shevchenko</td>
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<td>M3N9*</td>
<td>Computational Linear Algebra</td>
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<td>Dr E. Keaveny</td>
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<td>M3N10*</td>
<td>Computational Partial Differential Equations</td>
<td>2</td>
<td>Professor J. Mestel</td>
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<tr>
<td>M3SC*</td>
<td>Scientific Computation</td>
<td>2</td>
<td>Dr P. Ray</td>
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### PURE MATHEMATICS

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<tr>
<td>M2PM5</td>
<td>Metric Spaces and Topology</td>
<td>2</td>
<td>Professor A. Skorobogatov</td>
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<td>Not for Credit</td>
<td>Pure Mathematics Study Group</td>
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### ANALYSIS

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<tr>
<td>M3P6*</td>
<td>Probability</td>
<td>2</td>
<td>Professor B. Zegarlinski</td>
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<td>M3P7*</td>
<td>Functional Analysis</td>
<td>2</td>
<td>Professor B. Zegarlinski</td>
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<td>M3P18*</td>
<td>Fourier Analysis and Theory of Distributions</td>
<td>2</td>
<td>Dr S. Boegli</td>
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<td>M3P19*</td>
<td>Measure and Integration</td>
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<td>Dr I. Krasovsky</td>
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<td>M3P60*</td>
<td>Geometric Complex Analysis</td>
<td>2</td>
<td>Dr A. De Zotti</td>
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<tr>
<td>M3P70*</td>
<td>Markov Processes</td>
<td>1</td>
<td>Professor X-M. Li</td>
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### GEOMETRY

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<td>M3P5*</td>
<td>Geometry of Curves and Surfaces</td>
<td>1</td>
<td>Professor T. Coates</td>
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<tr>
<td>M3P20*</td>
<td>Geometry 1: Algebraic Curves</td>
<td>1</td>
<td>Dr M. Talpo</td>
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<tr>
<td>M3P21*</td>
<td>Geometry 2: Algebraic Topology</td>
<td>2</td>
<td>Dr C. Urech</td>
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### ALGEBRA AND DISCRETE MATHEMATICS

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<th>Module Codes</th>
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<tr>
<td>M3P8*</td>
<td>Algebra 3</td>
<td>1</td>
<td>Dr D. Helm</td>
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<td>M3P10*</td>
<td>Group Theory</td>
<td>1</td>
<td>Professor A. Ivanov</td>
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<td>M3P11*</td>
<td>Galois Theory</td>
<td>2</td>
<td>Professor A Corti</td>
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<td>M3P12*</td>
<td>Group Representation Theory</td>
<td>2</td>
<td>Dr T. Schedler</td>
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<tr>
<td>M3P17*</td>
<td>Algebraic Combinatorics</td>
<td>1</td>
<td>Dr J. Fawcett</td>
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<td>M3P65*</td>
<td>Mathematical Logic</td>
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<td>Professor D. Evans</td>
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### NUMBER THEORY

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<th>Module Codes</th>
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<th>Terms</th>
<th>Lecturer</th>
<th>% exam</th>
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<td>M3P14*</td>
<td>Number Theory</td>
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<td>M3P15*</td>
<td>Algebraic Number Theory</td>
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<td>Dr A. Caraiani</td>
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### STATISTICS

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<td>M2S2</td>
<td>Statistical Modelling 1</td>
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<td>Dr B. Calderhead</td>
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<td>M3S1*</td>
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<td>M3S2*</td>
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<td>Dr C. Hallsworth</td>
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<td>Dr A. Abu-Khazneh</td>
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<td>M3S8*</td>
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<td>M3S9*</td>
<td>Stochastic Simulation</td>
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<td>Dr S. Virtanen</td>
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<td>M3S14*</td>
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PROJECT (Available Only to Final Year BSc Students)

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OTHER MATHEMATICAL OPTIONS

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<td>Professor E.J. McCoy, Dr L.V. White</td>
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<td>1</td>
<td>Dr T. Fissler</td>
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<td>M3C</td>
<td>High Performance Computing</td>
<td>1</td>
<td>Dr P. Ray</td>
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THIRD YEAR MATHEMATICS SYLLABUSES

Most modules running in 2018-2019 will also be available in 2019-2020, although there can be no absolute guarantees.

APPLIED MATHEMATICS/MATHEMATICAL PHYSICS/NUMERICAL ANALYSIS

M2AM  NON-LINEAR WAVES

This module considers the dynamics of a continuous medium or fluid. One dimensional flows and waves are considered in detail to model gas dynamics and water waves as well as models of traffic flow. Shock formation and propagation in single or two by two systems of conservation laws are developed and solutions constructed for different problems. The course concludes with the theory of water waves including progressing and standing waves.

The continuum hypothesis and fluid particles.
Eulerian and Lagrangian descriptions of 1D fluid motion.
Fluid acceleration, material derivative.
Simple problems in finding position, given velocity and vice versa.
Conservation of mass, equation of continuity.
Pressure and gravitational forces.
Conservation of momentum – Euler’s equation.
Non-linear solutions leading to kinematic wave equation and general implicit solution.
Wave steepening. The Burgers equation.
Method of characteristics.
Shocks and weak solutions: Rankine-Hugoniot conditions, shock evolution equation.
Ideal gas dynamics: linear and non-linear problems leading to same equations as above.
Application to traffic flow (or something similar).
Application to physiological flows, river flows and hydraulic jumps – all leading to similar equations to those already studied.
Shallow water waves, systems of hyperbolic PDEs, Riemann invariants.
Dam break problems. Advancing and receding piston problems.
The equations of water waves.
Gravity-capillary water waves.
Dispersion relations, wave-packets, group velocity.
Standing waves, travelling waves and particle paths.

**FLUIDS**

**M3A2* FLUID DYNAMICS 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.

**M3A10* FLUID DYNAMICS 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.
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).

M3A28* INTRODUCTION TO GEOPHYSICAL FLUID DYNAMICS

This is an advanced-level fluid-dynamics course with geophysical flavours. The lectures target upper-level undergraduate and graduate students interested in the mathematics of planet Earth, and in the variety of motions and phenomena occurring in planetary atmospheres and oceans. The lectures are a mix of theory and applications. Take a look at the lecture notes to get some idea of the material:
http://wwwf.imperial.ac.uk/~pberloff/gfd lectures.html

Main topics
- Introduction and basics;
- Governing equations (continuity of mass, material tracer, momentum equations, equation of state, thermodynamic equation, spherical coordinates, basic approximations);
- Geostrophic dynamics (shallow-water model, potential vorticity conservation law, Rossby number expansion, geostrophic and hydrostatic balances, ageostrophic continuity, vorticity equation);
- Quasigeostrophic theory (two-layer model, potential vorticity conservation, continuous stratification, planetary geostrophy);
- Ekman layers (boundary-layer analysis, Ekman pumping);
- Rossby waves (general properties of waves, physical mechanism, energetics, reflections, mean-flow effect, two layer and continuously stratified models);
- Hydrodynamic instabilities (barotropic and baroclinic instabilities, necessary conditions, physical mechanisms, energy conversions, Eady and Phillips models);
- Ageostrophic motions (linearized shallow-water model, Poincare and Kelvin waves, equatorial waves, ENSO "delayed oscillator", geostrophic adjustment, deep-water and stratified gravity waves);
- Transport phenomena (Stokes drift, turbulent diffusion);
- Nonlinear dynamics and wave-mean flow interactions (closure problem and eddy parameterization, triad interactions, Reynolds decomposition, integrals of motion, enstrophy equations, classical 3D turbulence, 2D turbulence, transformed Eulerian mean, Eliassen-Palm flux).

Suggested textbooks: Introduction to geophysical fluid dynamics (Cushman-Roisin); Atmospheric and oceanic
fluid dynamics (Vallis); Geophysical fluid dynamics (Pedlosky); Fundamentals of geophysical fluid dynamics (McWilliams).

Prerequisites: Introductory fluid mechanics.

M3M7* ASYMPTOTIC ANALYSIS

Term 1


DYNAMICS

M3PA48* DYNAMICS OF GAMES

Term 1

Recently there has been quite a lot of interest in modeling learning through studying the dynamics of games. The settings to which these models may be applied is wide-ranging, from ecology and sociology to business, as actively pursued by companies like Google. Examples include

(i) optimization of strategies of populations in ecology and biology
(ii) strategies of people in a competitive environment, like online auctions or (financial) markets.
(iii) learning models used by technology companies

This module is aimed at discussing a number of dynamical models in which learning evolves over time, and which have a game theoretic background. The module will take a dynamical systems perspective. Topics will include replicator dynamics and best response dynamics.

M3PA23* DYNAMICAL SYSTEMS

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

M3PA24* BIFURCATION THEORY

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.

M3PA16* GEOMETRIC MECHANICS

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.


M3PA34* DYNAMICS, SYMMETRY AND INTEGRABILITY

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.

FINANCE

M3F22* MATHEMATICAL FINANCE: AN INTRODUCTION TO OPTION PRICING

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 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, in a discrete-time setting. We will mostly focus on the no-arbitrage theory in market models described by trees; eventually we will take the continuous-time limit of a binomial tree to obtain the celebrated Black-Scholes model and pricing formula.

We will cover and apply mathematical concepts -such as conditional expectation, filtrations, Markov processes, martingales and martingale transforms, the separation theorem, and change of measure- and financial concepts such as self-financing portfolios, replication and delta hedging, risk-neutral probability, complete markets, non-anticipative strategies, and the fundamental theorem of asset pricing.

**BIOLOGY**

**M3A49* MATHEMATICAL BIOLOGY**

**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:

* Epidemiology - the spread of plagues.
* Reaction-Diffusion models: Turing mechanism for pattern formation. How the leopard got his spots (and sometimes stripes).
* Mass transport; Taylor dispersion.
* Biomechanics: Blood circulation, animal locomotion: swimming, flight. Effects of scale and size.
* Other particular problems from biology.

**M3A50* METHODS FOR DATA SCIENCE**

**Term 1**

This course is in two halves: machine learning and complex networks. We will begin with an introduction to the R language and to visualisation and exploratory data analysis. We will describe the mathematical challenges and ideas in learning from data. We will introduce unsupervised and supervised learning through theory and through application of commonly used methods (such as principle components analysis, k-nearest neighbours, support vector machines and others). Moving to complex networks, we will introduce key concepts of graph theory and discuss model graphs used to describe social and biological phenomena (including Erdos-Renyi graphs, small-world and scale-free networks). We will define basic metrics to characterise data-derived networks, and illustrate how networks can be a useful way to interpret data.

**MATHEMATICAL PHYSICS**
M3A4* MATHEMATICAL PHYSICS 1: QUANTUM MECHANICS

Term 1

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: Hamiltonian dynamics; Schrödinger equation and wave functions; stationary states of one-dimensional systems; mathematical foundations of quantum mechanics; quantum dynamics; angular momentum

Additional optional topics may include: Approximation techniques; explicitly time-dependent systems; geometric phases; numerical techniques; many-particle systems; cold atoms; entanglement and quantum information.

M3A6* SPECIAL RELATIVITY AND ELECTROMAGNETISM

Term 1

This module presents a beautiful mathematical description of a physical theory of great historical, theoretical and technological importance. It demonstrates how advances in modern theoretical physics are being made and gives a glimpse of how other theories (say quantum chromodynamics) proceed.

At the beginning of special relativity stands an experimental observation and thus the insight that all physical theories ought to be invariant under Lorentz transformations. Casting this in the language of Lagrangian mechanics induces a new description of the world around us. After some mathematical work, but also by interpreting the newly derived objects, Maxwell’s equations follow, which are truly fundamental to all our everyday interaction with the world. In particular, Maxwell’s equations can be used to characterise the behaviour of charges in electromagnetic fields, which is rich and beautiful.

This module does not follow the classical presentation of special relativity by following its historical development, but takes the field theoretic route of postulating an action and determining the consequences. The lectures follow closely the famous textbook on the classical theory of fields by Landau and Lifshitz.

Special relativity: Einstein’s postulates, Lorentz transformation and its consequences, four vectors, dynamics of a particle, mass-energy equivalence, collisions, conserved quantities.
Electromagnetism: Magnetic and electric fields, their transformations and invariants, Maxwell’s equations, conserved quantities, wave equation.

M3A7* TENSOR CALCULUS AND GENERAL RELATIVITY

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. Variational principles.
M3A29* THEORY OF COMPLEX SYSTEMS

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.

M3A52* QUANTUM MECHANICS II

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. 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.

This module is intended to be a second course in quantum mechanics and will build on topics covered in Quantum Mechanics I.

Core topics: Quantum mechanics in three spatial dimensions, the Heisenberg picture, perturbation theory, addition of spin, adiabatic processes and the geometric phase, Floquet-Bloch theory, second quantization and introduction to many-particle systems, Fermi and Bose statistics, quantum magnetism. Additional topics may include WKB theory and the Feynman path integral.

M3M6* METHODS OF MATHEMATICAL PHYSICS

Term 1

The aim of this module is to learn tools and techniques from complex analysis and orthogonal polynomials that are used in mathematical physics. The course will focus on mathematical techniques, though will discuss relevant physical applications, such as electrostatic potential theory. The course also incorporates computational techniques in the lectures.

Prerequisites: Complex analysis.

Topics:

1. Revision of complex analysis: Complex integration, Cauchy’s theorem and residue calculus [Revision]
2. Singular integrals: Cauchy, Hilbert, and log kernel transforms
3. Potential theory: Laplace’s equation, electrostatic potentials, distribution of charges in a well
4. Riemann–Hilbert problems: Plemeij formulae, additive and multiplicative Riemann–Hilbert problems
5. Orthogonal polynomials: recurrence relationships, solving differential equations, calculating singular integrals
6. Integral equations: integral equations on the whole and half line, Fourier transforms, Laplace transforms
8. Singularities of differential equations: analyticity of solutions, regular singular points, Hypergeometric functions

APPLIED PDEs, NUMERICAL METHODS and COMPUTATION

M3M3* INTRODUCTION TO PARTIAL DIFFERENTIAL EQUATIONS

Term 1

1. Basic concepts: PDEs, linearity, superposition principle. Boundary and Initial value problems.
3. Linear and Quasilinear 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.

M3M11* FUNCTION SPACES AND APPLICATIONS

Term 1

The purpose of this course is to introduce the basic function spaces and to train the student into the basic methodologies needed to undertake the analysis of Partial Differential Equations and to prepare them for the course ‘Advanced topics in Partial Differential Equations’ where this framework will be applied. The course is designed as a stand-alone course. No background in topology or measure theory is needed as these concepts will be reviewed at the beginning of the course.

The course will span the basic aspects of modern functional spaces: integration theory, Banach spaces, spaces of differentiable functions and of integrable functions, convolution and regularization, compactness and Hilbert spaces. The concepts of Distributions, compact operators and Sobolev spaces will be taught in the follow-up course “Advanced topics in Partial Differential Equations” as they are tightly connected to the resolution of elliptic PDE’s and the material taught in the present course is already significant.

The syllabus of the course is as follows:

1) Elements of metric topology

2) Elements of Lebesgue’s integration theory.

inequalities. Support of a function; Convolution. Young's inequality for the convolution. Mollifiers. Approximation of continuous or Lebesgue integrable functions by infinitely differentiable functions with compact support.


**M3M12* ADVANCED TOPICS IN PARTIAL DIFFERENTIAL EQUATIONS**

**Term 2**

This course develops the analysis of boundary value problems for elliptic and parabolic PDE's using the variational approach. It is a follow-up of 'Function spaces and applications' but is open to other students as well provided they have sufficient command of analysis. An introductory Partial Differential Equation course is not needed either, although certainly useful.

The course consists of three parts. The first part (divided in two chapters) develops further tools needed for the study of boundary value problem, namely distributions and Sobolev spaces. The following two parts are devoted to elliptic and parabolic equations on bounded domains. They present the variational approach and spectral theory of elliptic operators as well as their use in the existence theory for parabolic problems. The aim of the course is to expose the students some important aspects of Partial Differential Equation theory, aspects that will be most useful to those who will further work with Partial Differential Equations be it on the Theoretical side or on the Numerical one.

The syllabus of the course is as follows:


**M3N7* NUMERICAL SOLUTION OF ORDINARY DIFFERENTIAL EQUATIONS**

**Term 1**

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


**M3N10* COMPUTATIONAL PARTIAL DIFFERENTIAL EQUATIONS**

**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. Assessment will be by projects, probably 3 in total. The first project will only count for 10-20% and will be returned quickly with comments, before students become committed to completing the module. Typically, the projects will build upon each other, so that by the end of the module a research level problem may be tackled. Matlab codes will be provided to illustrate similar problems and techniques, but these will require modification before they can be applied to the projects. The use of any reasonable computer language is permitted.

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.

**M3SC**  **SCIENTIFIC COMPUTATION**

**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.

**M3N9**  **COMPUTATIONAL LINEAR ALGEBRA**

**Term 1**

Examined solely by project. Computational aspects of the projects will require programming in Matlab and/ or Python.

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.

Topics include:
1. Direct methods: Triangular and banded matrices, Gauss elimination, LU-decomposition, conditioning and finite-precision arithmetic, pivoting, Cholesky factorisation, QR factorisation.
2. Symmetric eigenvalue problem: power method and variants, Jacobi’s method, Householder reduction to tridiagonal form, eigenvalues of tridiagonal matrices, the QR method.
3. Iterative methods:
   (a) Classic iterative methods: Richardson, Jacobi, Gauss - Seidel, SOR.
   (b) Krylov subspace methods: Lanczos method and Arnoldi iteration, conjugate gradient method, GMRES, preconditioning.

M3A47* FINITE ELEMENTS: NUMERICAL ANALYSIS AND IMPLEMENTATION

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 element spaces, 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.
• Variational formulation of elliptic boundary value problems: Riesz representation theorem, symmetric and nonsymmetric variational problems, Lax-Milgram theorem, finite element approximation estimates.
• 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).

PURE MATHEMATICS
M2PM5  METRIC SPACES AND TOPOLOGY

Term 2

This module extends various concepts from analysis to more general spaces.


PURE MATHEMATICS STUDY GROUP

Various lecturers
Terms 1 and 2

This is a non-examined, not-for-credit optional module. It will consist of a mixture of independent study and discussion groups, together with lectures delivered by students or staff. The choice of topics will complement that available in taught modules and will be determined by students in discussion with and under the guidance of a member of staff.

ANALYSIS

M3P6*  PROBABILITY THEORY

Term 2

Prerequisites: Measure and Integration (M3P19, Term 1)

A rigorous approach to the fundamental properties of probability.


M3P7*  FUNCTIONAL ANALYSIS

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.


M3P18*  FOURIER ANALYSIS AND THEORY OF DISTRIBUTIONS

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.

**M3P19**  MEASURE AND INTEGRATION

**Term 1**


**M3P60**  GEOMETRIC COMPLEX ANALYSIS

**Term 2**

Complex analysis is the study of 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.

While you become familiar with basics of functions of a complex variable in the complex analysis module, 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 behaviour of conformal maps is highly dependent on the shape of their domain of definition.

The module will discuss the following topics: Schwarz lemma, automorphisms of the disk, the Riemann sphere and the rational maps, hyperbolic geometry on the disk, conformal mappings, normal families and Montel's theorem, Riemann mapping theorem, distortion theorems, quasiconformal mappings, Beltrami equation.

**M3P70**  MARKOV PROCESSES

**Term 1**

Markov processes are widely used to model random evolutions with the Markov property `given the present, the future is independent of the past'. The theory connects with many other subjects in mathematics and has vast applications. This course is an introduction to Markov processes. We aim to build intuitions and good foundations for further studies in stochastic analysis and in stochastic modelling.

The module is largely self-contained, but it would be useful for students to also take Measure and Integration (M345P19). A good knowledge of real analysis would be helpful (M2PM1).

It is related to:
Applied probability (M345S4), Random Dynamical Systems and Ergodic Theory (M4PA40), Probability theory (M345P6), Stochastic Calculus with Applications to non-Linear Filtering (M45P67), Stochastic Differential Equations (M45A51), Stochastic simulation (M4S9*), Ergodic Theory (M4PA36), Computational Stochastic Processes (M4A44), and many Mathematical Finance modules.


GEOMETRY

M3P5* GEOMETRY OF CURVES AND SURFACES

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.

M3P20* GEOMETRY 1: ALGEBRAIC CURVES

Term 1

Plane algebraic curves; Projective spaces; Projective curves; Smooth cubics and the group structure; Intersection of projective curves.

Genus of a curve (Riemann surfaces); Meromorphic differentials and Abel's theorem.

M3P21* GEOMETRY 2: ALGEBRAIC TOPOLOGY

Term 2

Homotopies of maps and spaces. Fundamental group. Covering spaces, Van Kampen (only sketch of proof).

Homology: singular and simplicial (following Hatcher's notion of Delta-complex). Mayer-Vietoris (sketch proof) and long exact sequence of a pair. Calculations on topological surfaces. Brouwer fixed point theorem.

ALGEBRA AND DISCRETE MATHEMATICS

M3P8* ALGEBRA 3

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.

**M3P10* GROUP THEORY**

**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.

**M3P11* GALOIS THEORY**

**Term 2**

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.


**M3P12* GROUP REPRESENTATION THEORY**

**Term 2**

Representations of groups: definitions and basic properties. Maschke's theorem, Schur's lemma.
Representations of abelian groups. Tensor products of representations.
The character of a group representation. Class functions. Character tables and orthogonality relations.

**M3P17* ALGEBRAIC COMBINATORICS**

**Term 1**

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.
Strongly regular graphs: examples, basic theory, and relationship with codes and designs.

**M3P65* MATHEMATICAL LOGIC**

**Term 1**

The module is concerned with some of the foundational issues of mathematics. In propositional and predicate logic, we analyse the way in which we reason formally about mathematical structures. In set theory, we will look at the ZFC axioms and use these to develop the notion of cardinality. These topics have applications to other areas of mathematics: formal logic has applications via model theory and ZFC provides an essential toolkit for handling infinite objects.
Propositional logic: Formulas and logical validity; a formal system; soundness and completeness.

Predicate logic: First-order languages and structures; satisfaction and truth of formulas; the formal system; Goedel's completeness theorem; the compactness theorem; the Loewenheim-Skolem theorem.

Set theory: The axioms of ZF set theory; ordinals; cardinality; the Axiom of Choice.

**NUMBER THEORY**

*M3P14*  **NUMBER THEORY**

**Term 1**

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


*M3P15*  **ALGEBRAIC NUMBER THEORY**

**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.

**STATISTICS**

*M2S2  **STATISTICAL MODELLING 1**

**Term 2**

Traditional concepts of statistical inference, including maximum likelihood, hypothesis testing and interval estimation are developed and then applied to the linear model, which arises in many practical situations.

Maximum likelihood estimation, likelihood ratio tests and their properties, confidence intervals. Linear models - including non-full rank models: estimation, confidence intervals and hypothesis testing. The analysis of variance.
M3S1* STATISTICAL THEORY

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.

M3S2* STATISTICAL MODELLING 2

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.


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

M3S4* APPLIED PROBABILITY

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.


M3S8* TIME SERIES

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.

M3S9* STOCHASTIC SIMULATION

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.


M3S14* SURVIVAL MODELS AND ACTUARIAL APPLICATIONS

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.

Explain concepts of survival models, right and left censored and randomly censored data. Introduce life table data and expectation of life.

Describe estimation procedures for lifetime distributions: empirical survival functions, Kaplan-Meier estimates, Cox model. Statistical models of transfers between multiple states, maximum likelihood estimators.


Graduation and testing crude and smoothed estimates for consistency.

M3S16* CREDIT SCORING

Term 1

Prerequisites: Statistical Modelling 1 (M2S2) with some dependency on Statistical Modelling 2 (M3S2).

This course introduces the fundamentals of credit scoring and predictive analytics. We cover the aims and objectives of scoring, along with legislative and commercial aspects. We consider issues regarding consumer credit data: characteristics, transformations, data quality and transaction types. The concept of a statistical scorecard is introduced and models developed using logistic regression, Naïve Bayes and decision tree methods. Application and behavioural model types and characteristics, including segmented models are explored. Basic methods of model selection, estimation and testing are considered, along with issues of selection bias and reject inference. Probability of default (PD) models are introduced, along with probability calibration and cost-basd measures for model assessment.

The R statistical package will be used to explore credit scoring models on example data.

M3S17* QUANTITATIVE METHODS IN RETAIL FINANCE

Term 2

Prerequisites: Essential - Credit Scoring 1 (M3/4S16). Useful – Statistical Modelling 2 (M3S2).
This course explores advanced and new methods in retail finance, dealing with statistical modelling and optimization problems. Core topics will be: behavioural models, profitability, fraud detection and regulatory requirements.

Specific topic areas are:-
Survival models for credit scoring to determine time to default and include time varying information. 
Roll-rate and Markov transition models to determine patterns of missed payments.
Mover-Stayer models of behaviour.
Profit estimation: concepts and use of behavioural models.
Setting optimal credit limits.
Fraud detection
Cost analysis of AUC and the H measure.
Expected Loss, PD, EAD and LGD models (using beta regression, Tobit and classification tree structures). 
Regulation and portfolio-level analysis. Capital requirements. One-factor Merton-type model.
Asset correlation and mixed effects panel models.
The R statistical package will be used to explore a topic from the course based on a retail finance data set.

PROJECT

M3R RESEARCH PROJECT IN MATHEMATICS
Available only to Final Year BSc students

Supervised by Various Academic Staff
(Terms 2 & 3)

The main aim of this module is to give a deep understanding of a mathematical area/topic by means of a supervised project in applied mathematics, mathematical physics, pure mathematics, numerical analysis or statistics. The project may be theoretical and/or computational and the area/topic for each student is chosen in consultation with the Department.

The module provides an excellent ‘apprenticeship in research’ and is therefore particularly strongly recommended for BSc students who are considering postgraduate study leading to MSc/MPhil/PhD.

There is an oral presentation as part of the module assessment.

There will be a meeting in mid-November for students interested in the M3R and a required Research Skills workshop at the start of Term 2.

OTHER “NON-MATHEMATICAL” MATHEMATICS MODULES

M3B The Mathematics of Business and Economics

Term 1

This module aims to:
Give a broad mathematical introduction to both microeconomics and macroeconomics with a particular emphasis on the former.
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.
Discuss the interplay of firms, households and the government on a microeconomic scale.

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**
Consumers' and Producers' surplus. Deadweight loss.

**Macroeconomic theory**

**Mathematical Methods:**
(Constraint) Optimisation. Quasi-concavity. Preferences relations and orders.

**M3C Introduction to High Performance Scientific Computing**

**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**

**(Terms 2 & 3)**

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.

<table>
<thead>
<tr>
<th>Module Codes</th>
<th>Module Titles</th>
<th>Terms</th>
<th>ECTS Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>HGC31</td>
<td>Lessons from History</td>
<td>1 + 2</td>
<td>6</td>
</tr>
<tr>
<td>HGC33</td>
<td>Creative Futures</td>
<td>1 + 2</td>
<td>6</td>
</tr>
<tr>
<td>HSCS3001</td>
<td>Advanced Creative Writing</td>
<td>1 + 2</td>
<td>6</td>
</tr>
<tr>
<td>HSCS3002</td>
<td>History of Science, Technology and Industry</td>
<td>1 + 2</td>
<td>6</td>
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<tr>
<td>HSCS3003</td>
<td>Philosophy of Mind</td>
<td>1 + 2</td>
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<tr>
<td>HSCS3004</td>
<td>Contemporary Philosophy</td>
<td>1 + 2</td>
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<tr>
<td>HSCS3006</td>
<td>Humanities Project</td>
<td>1 + 2</td>
<td>6</td>
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<tr>
<td>HSCS3007</td>
<td>Conflict, Crime and Justice</td>
<td>1 + 2</td>
<td>6</td>
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<tr>
<td>HSCS3008</td>
<td>Visual Culture, Knowledge and Power</td>
<td>1 + 2</td>
<td>6</td>
</tr>
<tr>
<td>HSCS3011</td>
<td>Psychology of Music</td>
<td>1 + 2</td>
<td>6</td>
</tr>
<tr>
<td>HSCS3012</td>
<td>How do you Know?</td>
<td>1 + 2</td>
<td>6</td>
</tr>
<tr>
<td>HSCS2007</td>
<td>Music Technology</td>
<td>1 + 2</td>
<td>6</td>
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<tr>
<td>BS0808</td>
<td>Finance and Financial Management</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>BS0820</td>
<td>Managing Innovation</td>
<td>1</td>
<td>6</td>
</tr>
</tbody>
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Syllabus and timetabling information can be viewed online at:
CLCC: [http://www.imperial.ac.uk/horizons](http://www.imperial.ac.uk/horizons)

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 CLCC/ BPES module being revoked, so you must contact the CLCC/ BPES programme if you are planning to make such a change. Save a screenshot of your registration to help in any dispute.

**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 3rd 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](http://www.imperial.ac.uk/horizons)

**BSC DEGREE COURSE CODING REQUIREMENTS**

All modules within the Department are registered for G100, G103 Mathematics. To qualify for any degree a student must satisfy the overall College requirements.

As well as the regular G100 degree, the department offers several specialist degree codings. To qualify for the BSc codings G102, G125, G1F3, G1G3, G1GH, GG31, a suitable number of modules must eventually be passed from subsets of the general list as follows:
It is generally possible to swap between the above BSc codings, subject to the stated requirements, at a fairly late stage.

As part of the continuing review of the undergraduate programme of study, amendments to this list can be expected, including changes in module numbering. **Not all of the individual modules listed are offered every session. The above are the normal requirements – the Department has the discretion to modify them.**

**FOUR YEAR (MSCI) DEGREES: G103/G104**

Students are normally required to maintain a good level of performance in Mathematics (at Upper Second Class level or better) in order to remain on this coding in their Third and Final Years – see page 3.

Note that the Third and Fourth Year syllabuses substantially overlap. If a module may be attended by both 3rd and 4th Year students then the 4th year students typically take an extended (2.5 hour) examination. (This replaces the Mastery Examination, which operated before 2015.)

**THE M4R PROJECT:**

A fundamental part of the G103/G104 MSc degree is a substantial compulsory project (M4R) 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.

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 abroad 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 MSc programme (with the additional option of M3T.) 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 and take M3 subjects in their Final Year.

For more complete details of the Fourth Year programme, the relevant documentation can be viewed online at: https://www.imperial.ac.uk/natural-sciences/departments/mathematics/study/students/undergraduate/programme-information/

**CHANGE OF PROGRAMME – Tier 4 visa holders.**

Holders of Tier 4 visas who are considering changing, or who are required to change between BSc and MSci programmes should consult the information available at:

http://www.imperial.ac.uk/study/international-students/visas-and-immigration/changes-to-course-of-study/

and contact the International Student Support Team if necessary.