Oxford Master Course
in
Mathematical and Theoretical Physics

Master of Mathematics and Physics (MMathPhys) and MSc in Mathematical and Theoretical Physics

Course Handbook

2015–2016

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1 Introduction

The Oxford Master's Course in Mathematical and Theoretical Physics fills a need to offer students a high-level education in mathematical and theoretical physics. As the name suggests, the course concentrates on the main areas of modern mathematical and theoretical physics: elementary-particle theory, including string theory, condensed matter theory (both quantum and soft matter), theoretical astrophysics, plasma physics and the physics of continuous media (including fluid dynamics and related areas usually associated with Applied Mathematics programmes in the UK system). If you are a physics (or physics & philosophy) student with a strong interest in theoretical physics or a mathematics student keen to apply high-level mathematics to physical systems, this is a course for you.

The Master's Course in Mathematical and Theoretical Physics is offered in two modes, the MMathPhys for Oxford students and the MSc for students from outside Oxford. The academic content is identical for both modes. If you are an Oxford MPhys, MMath or MPhysPhil student, you are eligible to apply for transfer to the MMathPhys programme for the fourth year of your study. If accepted, you will spend your fourth year studying within the MMathPhys programme, rather than following the fourth year of your original degree programme. You will graduate as a "Master of Mathematical and Theoretical Physics" with a double classification consisting of the BA degree class in your original subject and an MMathPhys degree class. If you are a student from outside Oxford with a Bachelor or masters degree in physics or mathematics you can apply for the MSc mode, which leads to an "MSc in Mathematical and Theoretical Physics."

Admission to the course is based on aptitude, potential and motivation to study mathematical and theoretical physics. Evaluation criteria include the BA degree class (or equivalent), letters of reference, personal statements and prior performance on mathematical and theoretical physics courses. A necessary condition for admission to the course is a 2.i or higher degree class at BA level for MMathPhys applicants or an equivalent qualification for MSc applicants. While this represents a minimum requirement it is not, by itself, a sufficient condition for acceptance, since the degree class will be considered together with the other indicators. It is anticipated that, in most cases, the students accepted into the course will have a 1st class BA degree or equivalent.

The programme offers considerable choice. You will be able to study focusing on a specific subject area or aim for a broader education across two or several fields, concentrate on "mathematical" or "physical" aspects. Your aim may be to prepare yourself for doctoral-level research in a chosen area or to explore theoretical physics broadly before deciding what to do. While the degree allows flexibility of choice, its salient feature is the coherent structure of its main themes. This handbook contains a section on possible pathways through the course, which can be found in Appendix B.

You will be required to take 10 units within the programme, with each unit corresponding to a 16-hour lecture course. At least 4 of these units must be assessed by invigilated written examinations and have to be covered by courses offering a written exam (typically the "foundational courses," see below). This is, in fact, the only formal constraint on course choices and you are otherwise free to design your own pathway, although attention to the guidance offered to you is strongly encouraged. The remaining units will be assessed on the basis of written course work, take home papers or mini-projects. In addition, you will give an oral presentation towards the end of the course. Both the MMathPhys and MSc students will receive a graduate-style distinction/pass/fail classification. Note that, for Oxford students on the MMathPhys stream, this will be different from the 1st/2.1/2.2... degree classification they would have received had they continued with their original degree.

MPhys and MMath courses in the UK both provide good undergraduate degrees with a broad overview of physics and mathematics. It is widely felt, however, that neither provides an adequate foundation that allows a student to proceed directly to research in modern mathematical and theoretical physics. Namely, on the one hand, it is felt that, MPhys degrees no longer provide adequate theoretical and mathematical training, while, on the other hand, MMath degrees provide the mathematical training but are weak in their provision of quantum theory and classical field theory, which are the mainstays of a theoretical physicist's intuition. Yet other core subjects, such as quantum field theory, the standard model of particle physics, cosmology, or kinetic theory of gases and plasmas are not taught at all or not at sufficient depth to prepare for research in these, and related, areas. As a result, MPhys and MMath graduates have found the transition to postgraduate research in mathematical and theoretical physics increasingly difficult. The present programme is designed to resolve those problems. It provides a high-level, internationally competitive training in mathematical and theoretical physics, right up to the level of modern research in the area. As a graduate of this programme you should be well-prepared for PhD studies in an area of mathematical and theoretical physics and in a prime position to secure a relevant PhD place.

The course will be offered for the first time in the academic year 2015/16. Oxford MMath, MPhys or MPhysPhil students who are in their second year in the academic year 2013/14 are the first cohort eligible to apply in the round of graduate applications in January 2015, to start the course in October 2015.

We hope that most of your questions are answered in the remainder of this handbook. If anything remains unclear, please contact Mrs. Charlotte Turner-Smith at academic.administrator@maths.ox.ac.uk.

2 Structure of the course

The programme consists of a large array of lecture courses covering the main areas of modern Theoretical/Mathematical Physics and Applied Mathematics. The courses are subdivided into three *strands:*

- Theoretical Particle Physics,
- Theoretical Condensed Matter Physics,
- Theoretical Astrophysics, Plasma Physics and Physics of Continuous Media.

As various areas of Theoretical Physics are in fact, interconnected, routed in universal principles and thrive on ideas that cross any sub-field boundaries, the programme offers a number of courses that are shared between the three strands and emphasise the unity of Theoretical Physics. This applies especially to the *foundational courses* offered in Michaelmas Term. These are followed by increasingly specialised courses in Hilary and Trinity Terms, although those too will strive to make connections between subject areas. Besides these Theoretical Physics courses, the programme offers, in Michaelmas and Hilary Terms, a range of lecture courses teaching the underlying mathematical methods, as well as further mathematics courses for the more mathematically oriented students. Lecture courses will normally be accompanied by problem sets and problem classes. Note that, in any given year, the more specialised courses will be taught only if a sufficient number of students attend.

An overview of the courses can be found in the table accompanying this section; their syllabi can be found in Appendix A. You will have to attend at least 10 units worth of courses, with 1 unit corresponding to 16 hours of lectures. In addition to the courses listed in the table, which are offered explicitly as part of the MMathPhys/MSc programme, you will also be allowed to choose a maximum of three-units worth of MMath Part B or C or MPhys Part C lecture courses that are not listed here, subject to approval by the Director of Studies.

The programme offers considerable flexibility and choice. There are no courses that all or any students are obliged to follow, and you will thus be able to choose a path reflecting your intellectual tastes or career choices. This arrangement caters both to students who prefer a broad theoretical education across subject areas and to those who have already firmly set their sights on one of the three subject areas (although they too are encouraged to explore across sub-field boundaries). Studies can be pursued with stronger emphasis on mathematical or on physical aspects.

Appendix B gives examples of different pathways through the course along with suggested prior courses you might take during your BA degree. You will be offered detailed academic guidance from the Director of Studies or an Academic Adviser designated by the Director of Studies on choosing an individual path suitable for you (the choice is not restricted to the examples in Appendix B!). Course lecturers will also advise on the recommended background for their courses or possible follow-up courses you might wish to choose.

The programme does not offer a research project as its emphasis is on offering its students an opportunity to receive an intensive and thorough academic training, which is an indispensable pre-requisite for a modern theoretical physicist or applied mathematician wishing to work on a level appropriate for PhD research or a similar occupation. Indeed, most past and current PhD students in Theoretical/Mathematical Physics or Applied Mathematics at the world's leading research institutions have been educated in this way (sometimes via Master-level programmes similar to this one and sometimes via coursework during the first year of their doctoral degree). The present programme does, however, offer a substantial opportunity for independent study and research in the form of an optional *dissertation* (worth 1 unit). The dissertation is undertaken under the guidance of a member of staff and will typically involve investigating and then presenting in writing a particular area of Theoretical Physics or Mathematics, without the requirement (while not excluding the possibility) of obtaining original results.

Legend for fonts, colours and superscripts in the Table:

Bold: a foundational course;

Plain: an interdisciplinary course shared between strands;

Italic: a course special to a particular strand;

Red$^{(PU:NN)}$: a course also taught (in some cases in part) as a Part C course in Physics, NN is its number;

Blue$^{(MU:NNN)}$: a course also taught as a Part B or C course in Mathematics, NNN is its number;

Purple$^{(MG)}$: a course also taught as a PG course in Mathematics;

Black: an MMathPhys/MSc course, also taught as a PG course in Physics;

$^{(*)}$ a course that may not be available every year.

Overview of Lecture Courses			
	Theoretical Particle Physics	*Theoretical Condensed Matter Physics*	*Theor. Astrophysics, Plasma Physics & Physics of Continuous Media*
MT	**Quantum Field Theory** (24)		
		Statistical Mechanics$^{(MU:C6.2a)}$ (16)	
		Intro. Quant. CMP$^{(PU:C6)}$ (16)	
		Nonequilibrium Statistical Physics$^{(PU:C6)}$ (8)	
		Kinetic Theory (24)	
		Viscous Flow$^{(MU:B6a)}$ (16)	
	Gen. Relativity I$^{(MU:C7.2a)}$ (16)	⇐ ⇒	**Gen. Relativity I**$^{(MU:C7.2a)}$ (16)
	Perturbation Methods$^{(MU:C6.3a)}$ **(16)**		
	Scientific Computing I$^{(MG)}$ (12)		
	Numerical Solutions to Differential Equations I$^{(MU:B21a)}$ (16)		
	Numerical Linear Algebra$^{(MU:C12.1a)}$ (16)		
	Groups and Representations (24)		
	Algebraic Topology$^{(MU:C3.1a)}$ *(16)*		
	Algebraic Geometry$^{(MU:C3.4a)}$ *(16)*		
HT		Advanced Fluid Dynamics (16)	
		Soft Matter Physics (16)	
		Nonlinear Systems$^{(MU:B8b)}$ (16)	
	Advanced QFT (24)	*Quant. CMP II*$^{(PU:C6)}$ *(24)*	*Waves & Comp. Flow*$^{(MU:B6b)}$ *(16)*
	String Theory I$^{(MG)}$ *(16)*	*Networks*$^{(MU:C6.2b)}$ *(16)*	*Plasma Physics (16)*
	Supersymmetry & Sugra (24)		*Galactic & Planetary Dyn. (16)*
			Stellar Astrophysics$^{(PU:C1)}$ *(16)*
	Gen. Relativity II$^{(MU:C7.2b)}$ (16)	⇐ ⇒	Gen. Relativity II$^{(MU:C7.2b)}$ (16)
	Cosmology (16)	⇐ ⇒	Cosmology (16)
	Applied Complex Variables$^{(MU:C6.3b)}$ (16)		
	Scientific Computing II$^{(MG)}$ (12)		
	Numerical Solutions to Differential Equations II$^{(MU:B21b)}$ (16)		
	Differential Geometry (16)	⇐ ⇒	Differential Geometry (16)
	Geom. Group Th.$^{(MU:C3.2b)}$ *(16)*		
TT	Conformal Field Theory (16)		
	Introduction to Gauge-String Duality (16)		
		Topics in Soft & Active Matter Physics (8)	
		Complex Systems$^{(MG,*)}$ (16)	
	String Theory II$^{(MG,*)}$ *(16)*	*Advanced Quant. CMP (8)*	*Turbulence*$^{(*)}$ *(16)*
	The Standard Model (16)	*Topics in Quant. CMP (8)*	*Geophys. Fluid Dynamics (16)*
	Beyond the St. Model (16)	*Critical Phenomena*$^{(*)}$ *(16)*	*Advanced Plasma Physics (16)*
	Nonpert. Meth. in QFT (16)		*Astrophys. Fluid Dynamics (16)*
			High-Energy Astrophysics$^{(*)}$ *(16)*
	Astroparticle Phys.$^{(*)}$ (16)	⇐ ⇒	Astroparticle Phys.$^{(*)}$ (16)
	QFT in Curved Space$^{(*)}$ (16)	⇐ ⇒	QFT in Curved Space$^{(*)}$ (16)
	Dissertation, replacing one 16-hour lecture course		

3 Admissions

Oxford students are eligible to apply for transfer to the MMathPhys in their fourth year, if they are enrolled in the third year of either the MPhys, MMath or MPhysPhil courses. Students from outside the University of Oxford wishing to enter the MSc mode can apply if they either hold a BA or a masters degree (or equivalent) in mathematics, physics or a related subject, or are enrolled in such a degree programme and are set to complete it by the time they intend to start the MSc.

3.1 Admission criteria

The aim of the admission procedure is to select applicants with the potential and preparedness to successfully complete the programme. Subject to equal opportunities principles and legislation, applications will be considered in light of a candidate's ability to meet the following criteria:

- proven and potential academic excellence in mathematical and theoretical physics;
- motivation for studying mathematical and theoretical physics.

These will be assessed using indicators including

- the compatibility of the candidate's previous programme of study with the prerequisites of the MMathPhys course;
- the candidate's performance in her/his previous programme of study and in particular in courses related to theoretical and mathematical physics. Candidates will normally be required to have completed at least a 2.i-class honours degree (or an equivalent qualification) in mathematics, physics, or a related discipline at the time their MMathPhys course starts;
- two reference letters;
- a short personal statement detailing the candidate's motivation.

No interviews will be conducted.

3.2 Application procedure

At the time of application you may not yet have completed your first undergraduate degree. In this case your application will be assessed on the basis of your performance in your course thus far (for MMathPhys applicants, this means performance in Part A). If admitted, you will be given a conditional offer. A standard condition is completion of your BA degree at 2.i level or better (or equivalent).

Applying to enter the MMathPhys course does not entail a risk for Oxford students: should you miss your offer conditions, you can continue with your original programme (MMath, MPhys, or MPhysPhil) as long as you satisfy the necessary requirements to proceed according to the regulations for those degrees. If you are an Oxford student admitted to the MMathPhys part of the programme, you will be able to return to your original degree programme (MMath, MPhys, or MPhysPhil) during the first four weeks of the Michaelmas Term of your fourth year. This will allow you to continue with your original course if you find that the MMathPhys course is not to your liking. A return later than four weeks into Michaelmas Term is not possible, because catching up with the original course becomes too difficult. If you are an Oxford student and are considering the MMathPhys option, you are encouraged to consult your tutors prior to submitting an application.

For deadlines and practical details on how to apply, see Appendix C.

3.3 Other admissions requirements (for MSc applicants only)

- **English language requirement:** applicants whose first language is not English are usually required to provide evidence of proficiency in English at the higher level required by the University. See http://www.ox.ac.uk/admissions/postgraduate_courses/apply/internat_students.html.
- **Whether or not an applicant has secured funding** is not taken into consideration in the decision to make an initial offer of a place, but this offer will not be confirmed until the College to which you applied or are assigned is satisfied that you have sufficient funding to cover the fees and living costs for the standard period of fee liability for your course.

3.4 Disability, health conditions, and specific learning difficulties

Students are selected for admission without regard to gender, marital or civil partnership status, disability, race, nationality, ethnic origin, religion or belief, sexual orientation, age, or social background. Decisions on admissions are based solely on the individual academic merits of each candidate and the application of the selection criteria appropriate to the programme of study. Further information on how these matters are handled during the admissions process is available at the following websites:
http://www.ox.ac.uk/admissions/postgraduate_courses/apply/disabilities.html,
http://www.ox.ac.uk/admissions/undergraduate_courses/why_oxford/support_wellbeing/disabled_students.html.

4 Suggested academic background

While there are no formal pre-requisites beyond the admissions criteria listed above, those applicants whose undergraduate degree programmes have optional components may wish to receive some guidance as to how best to prepare themselves for the MMathPhys/MSc programme. Below we give some suggestions for the Oxford students intending to apply to the MMathPhys. These suggestions might inform your choice of optional courses during the first three years of your undergraduate course. Equivalents might be available to MSc applicants at their own universities.

Note that in some cases, it might be useful to take a course early instead of waiting for the MMathPhys year (for example, some Part B Mathematics courses that are relevant for certain paths or general interests). If an overlap occurs between courses you have taken previously and some of the courses in this programme, you will have the flexibility and opportunity to explore another area, which you otherwise might not have had time for.

4.1 Suggestions for physics students (MPhys)

Parts A and B of the MPhys only have a small optional component consisting of Short Options. We consider the first three years of the MPhys to be adequate preparation for the MMathPhys. This said, if you are thinking of taking up the MMathPhys option in your 4th year, you may wish to consider the following Short Options:

- *All students:* S01 Functions of Complex Variables, S07 Classical Mechanics
- *Students interested in specialisations involving Quantum Field Theory and related topics (e.g., Teorica Universalis, Geometra, Particulata, Supercordula, Condensata, and Duracella example pathways in Appendix B):* S18 Advanced Quantum Mechanics
- It is possible within the MPhys to take Mathematics courses en lieu of Short Options. If you decide to do this, some of the suggestions for the Mathematics students in Section 4.3 may prove useful to you (we particularly recommend Part B Numerical Solutions to Differential Equations I, II).

4.2 Suggestions for Physics & Philosophy Students (MPhysPhil)

Part B of the MPhysPhil has an optional physics component. We recommend that you consider the following Part B papers:

- *All students:* B7 Classical Mechanics
- *Students interested in specialisations involving relativistic Quantum Field Theory, General Relativity, Cosmology, etc. (e.g., Teorica Universalis, Geometra, Particulata, Supercordula, Condensata, Duracella, Astra-Stella, and Cosmicosmica example pathways in Appendix B):* B2 Symmetry and Relativity, B3 General Relativity and Cosmology
- *Students interested in specialisations involving physics of continuous media of various kinds (e.g., Applicata, Continua, Condensata, Mollis, Complicata, Astra-Stella, Cosmicosmica, Gaia, and Plasma example pathways in Appendix B):* B1 Fluctuations, Flows and Complexity

4.3 Suggestions for Mathematics Students (MMath)

Both Parts A and B of the MMath have a large number of options. Here are some general recommendations to help the students interested in the MMathPhys make an informed choice.

- *All students:* We recommend the following courses that will teach you the basic mathematical and numerical techniques common to most areas of Theoretical/Mathematical Physics and Applied Mathematics: Part A: Numerical Analysis; Part B: Techniques of Applied Mathematics, Applied Partial Differential Equations, Numerical Solutions to Differential Equations I, II.

  We also recommend recommend that you consider some of the suite of courses that cover the foundations of modern physics: Part A: Quantum Theory, Special Relativity, Fluids and Waves; Part B: Classical Mechanics, Quantum Mechanics, Electromagnetism (<u>note</u>: these three courses are in the process of being approved).

  Some of these will be more important than others depending on the specialisation that you might choose in the MMathPhys (see example pathways in Appendix B and consult your tutor in the first instance if in doubt as to what courses might be relevant).
- *Students interested in specialisations involving physics of continuous media of various kinds (e.g., Applicata, Continua, Condensata, Mollis, Complicata, Astra-Stella, Cosmicosmica, Gaia, and Plasma example pathways in Appendix B):* Part B Viscous Flow, Waves and Compressible Flow, Nonlinear Systems are cross-listed as part of the MMathPhys programme, but if you take them early, this will allow you the time to explore more advanced topics. The same consideration applies to Numerical Solutions to Differential Equations I, II, which are especially important for these specialisations.
- *Students interested in mathematical physics specialisations that involve a substantial amount of modern geometry and algebra (e.g., Geometra, Particulata and Supercordula example pathways in Appendix B):* There are a number of pure mathematics options that may prove useful, e.g., Part A Group Theory, Projective Geometry, Topology; Part B Geometry of Surfaces, Algebraic Curves, Introduction to Representation Theory, Group Theory and an Introduction to Character Theory, Topology and Groups. Consult your tutor for further advice.

5 Assessment and exams

5.1 Requirements

You will be required to attend at least 10 units (with one unit defined as a 16 hour lecture course or a dissertation) from the programme of lectures courses described in Section 2. You can opt to replace one 16-hour lecture course by a dissertation. Your performance will be assessed by one or several of the following means: (i) Invigilated written exams. (ii) Course work marked on a pass/fail basis. (iii) Take-home papers. (iv) Mini-projects due shortly after the end of the lecture course. The modes of assessment for a given course are decided by the course lecturer and will be published at the beginning of each academic year. As a general rule, foundational courses will be offered with an invigilated exam while some of the more advanced courses will typically be relying on the other assessment methods mentioned above. In addition, you will be required to give an oral presentation towards the end of the academic year which will cover a more specialized and advanced topic related to one of the subject areas of the course.

At least four of the 10 units must be assessed by an invigilated exam and, therefore, have to be taken from lecture courses which provide this type of assessment. Apart from this restriction, you are free to choose from the available programme of lecture courses. However, it is strongly recommended that you consider the discussion on sensible pathways through the course given in Section 2 and Appendix B and, in case of doubt, seek advice from the Director of Studies or other designated academic advisors for the course.

5.2 Arrangements

Each setter, normally the course lecturer, will assess your exam papers, mini-projects and course work as appropriate, and produce a raw mark for the course. Assessment and scaling of mini-projects and take home exams will follow the conventions established in Mathematics and laid out in the MMath handbook. Invigilated written exams will be conducted according to the existing guidelines for mathematics and physics fourth year students. Lecture courses assessed with a take-home paper or by a mini-project will be marked by the course lecturer, and the final USMs will be awarded by the Examiners Panel based on the recommendation of the course lecturers. Dissertations will be assessed following the guidelines and procedures of part C of the mathematics course (see the guidelines at
`http://www.maths.ox.ac.uk/current-students/undergraduates/projects/`).
We emphasize that there is no expectation that a dissertation includes original research.

Some courses in the MMathPhys programme are managed by one of the departments and are part of the MMath or MPhys courses. In all these cases you will be examined following the instructions of the corresponding department. Typically these courses are assessed by an invigilated exam at the end of TT. For other lecture courses taught in Michaelmas Term, exams are timetabled in week 0 of Hilary Term, for other courses taught in Hilary Term exams take place in week 1 of Trinity Term.

All students, both on the MMathPhys and MSc course, will attend a compulsory oral presentation (typically in TT), based on a somewhat more specialized and advanced topic which relates to a subject area in the course. A list of such topics will be published in this handbook. The oral presentation will be marked on a pass/fail basis and has to be passed. One re-take (in the same academic year) in case of a fail will be allowed.

A panel of examiners will be moderating the raw marks and produce a class list at the end of the academic year. Moderation of the marks by examiners will involve a suitable re-scaling algorithm. As a general principle, this algorithm will be the same for MSc and MMathPhys students and will, in particular, not be based on prior performance in the first three years of student's degrees.

The Mathematical Institute and Physics Department have guidance on plagiarism and cheating in exams and these guidelines will be followed in the assessment procedures. Reasonable adjustments for disabled students will be made following the current practices in physics and mathematics, including, whenever it is necessary, the provision of alternative methods of assessment.

5.3 Classification

Degrees for both the MMathPhys and the MSc mode will have a distinction/pass/fail classification but with detailed transcripts provided. Note that this is different from the current MPhys and MMath classifications which follow the 1/2.1/2.2/3 scheme. As an MMathPhys student you will, therefore, be classified differently from your peers who have stayed on the MPhys or MMath programmes.

More precisely, as an MMathPhys student you will receive a double-classification, with the first part given by your BA degree class and the second part by your MMathPhys degree class as above. This means that as an MMathPhys student coming, for example, through Physics you would receive a classification as follows:

Parts A and B: first class honours in Physics
Part C: distinction in Mathematical and Theoretical Physics

A Syllabi

Below you will find syllabi for all courses in the programme, as listed in the table in Section 2. Note that the designated *pre-requisites* are only recommendations — they are not required as a conditions of enrolment in each course as some students may have already had adequate equivalent training during their Bachelor's degree or may choose to catch up via an independent autodidactic effort.

A.1 Michaelmas Term

Quantum Field Theory [24 hours] *FOUNDATIONAL COURSE.*

Syllabus *(written by J. Cardy, F. Essler, A. Lukas, A. Starinets).* Classical field theory, Noether's theorem, canonical quantization, path integral formulation of quantum mechanics, path integrals in field theory: generating functionals, finite temperature field theory, Feynman diagrams, Feynman rules, divergences and regularisation, renormalisation and renormalisation group, scattering and S-matrices, response functions, path integrals for fermions.

Sequel: Advanced Quantum Field Theory for Particle Physics (HT), Conformal Field Theory (TT), Quantum Field Theory in Curved Space-Time (TT)

Statistical Mechanics [16 hours] *(Maths C6.2a). This course can be taken by students who have not studied this subject before (e.g., as Physics A1) but would like to be able to follow the more specialised courses offered in Hilary and Trinity that require familiarity with Statistical Mechanics.*

Syllabus *(from the 2012–13 Mathematics Handbook).* Thermodynamics and Probability: microscopic versus macroscopic viewpoints, the laws of thermodynamics, temperature, entropy, free energy, etc. Classical Statistical Mechanics: ideal gas, Gibbs paradox, canonical and grand canonical ensembles, Liouville's theorem and ergodicity, Maxwell relations. Nonequilibrium Statistical Mechanics: Boltzmann equation, Boltzmann-Grad limit. Phase Transitions: order parameters, phase transitions, critical phenomena, Ising model, Potts model, renormalization, symmetry breaking. Other Topics and Applications: This could vary from year to year, but a good example would be Bose-Einstein condensates or statistical mechanics of random graphs.

Introduction to Quantum Condensed Matter Physics [16 hours] *FOUNDATIONAL COURSE. Part of this course is also offered as part of Physics C6.*

Syllabus *(written by J. Chalker and F. Essler).* Second quantisation. Ideal Fermi and Bose gases in second quantization. Weakly interacting Bose gas: Bogoliubov theory; superfluidity. Weakly interacting fermions: mean-field theory; Hartree-Fock approximation. Linear response theory.

Sequel: Quantum Condensed Matter Physics II (HT)

Nonequilibrium Statistical Physics [8 hours] *FOUNDATIONAL COURSE. Part of this course is also offered as part of Physics C6.*

Syllabus *(written by R. Golestanian).* Stochastic Processes. Brownian motion; Langevin and Fokker-Planck equations. Normal and anomalous diffusion. Brownian ratchets. Molecular motors.

Sequel: Soft Matter Physics (HT)

Kinetic Theory [24 hours] *FOUNDATIONAL COURSE.*

Syllabus *(written by J. Binney, P. Dellar, R. Golestanian, J. Magorrian, A. Schekochihin).* Part I: Basic Kinetic Theory of Gases. Liouville Theorem. BBGKY hierarchy and derivation of Boltzmann's equation. H-theorem, Maxwell's distribution. Derivation of fluid equations. Transport: viscosity and thermal diffusvity. Onsager symmetries. Part II: Plasma Kinetics (Charged Particles in Electromagnetic Fields). Kinetics in an external field. Plasma: charged particles and self-consistent electromagnetic fields. Debye screening. Landau collision integral. Outline of the derivation of two-fluid equations and magneto-hydrodynamics. Collisionless plasma in electrostatic field. Dielectric permittivity, Landau damping, kinetic instabilities, waves. Outline of the quasilinear theory and nonlinear approximations. Part III: Kinetics of Gravitating Objects. Self-gravitating kinetics and the resultant fluid equations. Invariants of motion and the Jeans theorem. Non-Maxwellian (collisionless) equilibria. Anisotropic distributions. Part IV: Kinetics of Quasiparticles. Phonons. UV catastrophe.

Sequels: Advanced Fluid Dynamics (HT), Plasma Physics (HT), Galactic and Planetary Dynamics (HT)

Viscous Flow [16 hours] *(Maths B6a). This course is particularly recommended to the students who have not studied basic Fluid Dynamics (e.g., as Physics B1) and would like to be able to follow the more specialised courses offered in Hilary and Trinity and requiring familiarity with this subject.*

Syllabus *(from the 2012–13 Mathematics Handbook).* Euler's identity and Reynolds' transport theorem. The continuity equation and incompressibility condition. Cauchy's stress theorem and properties of the stress tensor. Cauchy's momentum equation. The incompressible Navier-Stokes equations. Vorticity. Energy. Exact solutions for unidirectional flows; Couette flow, Poiseuille flow, Rayleigh layer, Stokes layer. Dimensional analysis, Reynolds number. Derivation of equations for high and low Reynolds number flows. Thermal boundary layer on a semi-infinite flat plate. Derivation of Prandtl's boundary-layer equations and similarity solutions for flow past a semi-infinite flat plate. Discussion of separation and application to the theory of flight. Slow flow past a circular cylinder and a sphere. Non-uniformity of the two dimensional approximation; Oseen's equation. Lubrication theory: bearings, squeeze films, thin films; Hele-Shaw cell and the Saffman-Taylor instability.

Sequels: Advanced Fluid Dynamics (HT), Waves and Compressible Flow (HT)

General Relativity I [16 hours] *(Maths C7.2a). FOUNDATIONAL COURSE. Some students may have studied this subject before (for example, as Physics B5).*

Syllabus *(from the 2012–13 Mathematics Handbook).* Review of Newtonian gravitation theory and problems of constructing a relativistic generalisation. Review of Special Relativity. The equivalence principle. Tensor formulation of special relativity (including general particle motion, tensor form of Maxwell's equations and the energy momentum-tensor of dust). Curved space time. Local inertial coordinates. General coordinate transformations, elements of Riemannian geometry (including connections, curvature and geodesic deviation). Mathematical formulation of General Relativity, Einstein's equations (properties of the energy-momentum tensor will be needed in the case of dust only). The Schwarzschild solution; planetary motion, the bending of light, and black holes.

Sequels: General Relativity II (HT), Cosmology (HT), Quantum Field Theory in Curved Space-Time (TT)

Perturbation Methods [16 hours] *(Maths C6.3a). FOUNDATIONAL COURSE.*

Syllabus *(from the 2012–13 Mathematics Handbook).* Asymptotic expansions. Asymptotic evaluation of integrals (including Laplace's method, method of stationary phase, method of steepest descent). Regular and singular perturbation theory. Multiple-scale perturbation theory. WKB theory and semiclassics. Boundary layers and related topics. Applications to nonlinear oscillators. Applications to partial differential equations and nonlinear waves.

Sequel: Applied Complex Variables (HT)

Scientific Computing I [12 hours] *Part of a 2-term 24-hour course, designed as an introduction to computing for doctoral students.*

Syllabus. See Maths Graduate Handbook. URL: `http://www.maths.ox.ac.uk/courses/course/19944`

Sequel: Scientific Computing II (HT)

Numerical Solutions to Differential Equations I [16 hours] *(Maths B21a).*

Syllabus *(from the 2012–13 Mathematics Handbook).* Development and analysis of numerical methods for initial value problems. Classical techniques for the numerical solution of ordinary differential equations. The problem of stiffness in tandem with the associated questions of step-size control and adaptivity: Initial value problems for ordinary differential equations: Euler, multistep and Runge-Kutta; stiffness; error control and adaptive algorithms. Numerical solution of initial value problems for partial differential equations, including parabolic and hyperbolic problems: Initial value problems for partial differential equations: parabolic equations, hyperbolic equations; explicit and implicit methods; accuracy, stability and convergence, Fourier analysis, CFL condition.

Sequel: Numerical Solutions to Differential Equations II (HT)

Numerical Linear Algebra [16 hours] *(Maths C12.1a).*

Syllabus *(from the 2012–13 Mathematics Handbook).* Common problems in linear algebra. Matrix structure, singular value decomposition. QR factorization, the QR algorithm for eigenvalues. Direct solution methods for linear systems, Gaussian elimination and its variants. Iterative solution methods for linear systems. Chebyshev polynomials and Chebyshev semi-iterative methods, conjugate gradients, convergence analysis, preconditioning.

Groups and Representations [24 hours]

Syllabus *(written by A. Lukas).* Basics on groups, representations, Schur's Lemma, representations of finite groups, Lie groups, Lie algebras, Lorentz and Poincare groups, SU(n), SO(n), spinor representations, roots, classification of simple Lie algebras, weights, representations and Dynkin formalism.

Algebraic Topology [16 hours] *(Maths C3.1a).*

Syllabus *(from the 2012–13 Mathematics Handbook).* Chain complexes of free Abelian groups and their homology. Short exact sequences. Delta (and simplicial) complexes and their homology. Euler characteristic. Singular homology of topological spaces. Relative homology and the Five Lemma. Homotopy invariance and excision (details of proofs not examinable). Mayer-Vietoris Sequence. Equivalence of simplicial and singular homology. Degree of a self-map of a sphere. Cell complexes and cellular homology. Application: the hairy ball theorem. Cohomology of spaces and the Universal Coefficient Theorem (proof not examinable). Cup products. Knneth Theorem (without proof). Topological manifolds and orientability. The fundamental class of an orientable, closed manifold and the degree of a map between manifolds of the same dimension. Poincar Duality (without proof).

Algebraic Geometry [16 hours] *(Maths C3.4a).*

Syllabus *(from the 2012–13 Mathematics Handbook).* Affine algebraic varieties, the Zariski topology, morphisms of affine varieties. Irreducible varieties. Projective space and general position points. Projective varieties, affine cones over projective varieties. The Zariski topology on projective varieties. The projective closure of affine variety. Morphisms of projective varieties. Projective equivalence. Veronese morphism: definition, examples. Veronese morphisms are isomorphisms onto their image; statement, and proof in simple cases. Subvarieties of Veronese varieties. Segre maps and products of varieties, Categorical products: the image of Segre map gives the categorical product. Coordinate rings. Hilbert's Nullstellensatz. Correspondence between affine varieties (and morphisms between them) and finitely generate reduced k-algebras (and morphisms between them). Graded rings and homogeneous ideals. Homogeneous coordinate rings. Categorical quotients of affine varieties by certain group actions. The maximal spectrum. Discrete invariants projective varieties: degree dimension, Hilbert function. Statement of theorem defining Hilbert polynomial. Quasi-projective varieties, and morphisms of them. The Zariski topology has a basis of affine open subsets. Rings of regular functions on open subsets and points of quasi-projective varieties. The ring of regular functions on an affine variety in the coordinate ring. Localisation and relationship with rings of regular functions. Tangent space and smooth points. The singular locus is a closed subvariety. Algebraic reformulation of the tangent space. Differentiable maps between tangent spaces. Function fields of irreducible quasi-projective varieties. Rational maps between irreducible varieties, and composition of rational maps. Birational equivalence. Correspondence between dominant rational maps and homomorphisms of function fields. Blow-ups: of affine space at appoint, of subvarieties of affine space, and general quasi-projective varieties along general subvarieties. Statement of Hironaka's Desingularisation Theorem. Every irreducible variety is birational to hypersurface. Re-formulation of dimension. Smooth points are a dense open subset.

A.2 Hilary Term

Advanced Quantum Field Theory for Particle Physics [24 hours]

Prequel/pre-requisite: Quantum Field Theory (MT)

Syllabus *(written by X. de la Ossa, G. Ross).* Quantum Electrodynamics: Introduction, photon propagator, scalar electrodynamics (Feynman rules, radiative corrections), canonical quantization, fermions (fermions propagator, path integral and Feynman rules), spinor electrodynamics, sample calculations (scattering in spinor electrodynamics), beta function in QED. Non-Abelian Quantum Field Theory: SU(N) local gauge theory, path integral, gauge fixing, BRST, spontaneous symmetry breaking, anomalies, introduction to the standard model.

Sequels: The Standard Model (TT), Beyond the Standard Model (TT), Non-perturbative Methods in Quantum Field Theory (TT)

String Theory I [16 hours]

Pre-requisite: Quantum Field Theory (MT)

Syllabus *(written by P. Candelas).* String actions, equations of motion and constraints, open and closed strings — boundary conditions, Virasoro algebra, ghosts and BRS, physical spectrum, elementary consideration of D branes, Veneziano amplitude.

Sequels: String Theory II (TT), Introduction to Gauge-String Duality (TT)

Supersymmetry and Supergravity [24 hours]

Pre-requisite: Quantum Field Theory (MT)

Syllabus *(written by J. Conlon).* Motivations for supersymmetry, spinor algebras and representations, supersymmetry algebra and representations, extended supersymmetry and BPS states, superfields, SUSY field theories, non-renormalisation theorems, SUSY breaking, the MSSM and its phenomenology, rescaling anomalies, NSVZ beta function, basic properties of supergravity.

Advanced Fluid Dynamics [16 hours]

Prequels: Kinetic Theory (MT), Viscous Flow (MT)

Pre-requisites: basic familiarity with fluid equations and stress tensors as provided, e.g., by Kinetic Theory (MT).

Syllabus *(written by P. Dellar, A. Schekochihin, J. Yeomans).* Introduction to the dynamics of fluids with stress tensors more complex than the viscous and Euler momentum fluxes. Part I: Magnetohydrodynamics. MHD equations: Maxwell stress, magnetic pressure and tension, flux freezing, magnetic diffusion, magnetic reconnection, Zeldovich rope dynamo. Conservation laws. Helicity, Taylor relaxation, force-free solutions. Simple MHD equilibria. MHD waves, Elsasser variables and Elsasser solutions. Lagrangian MHD, Cauchy solution, action principle. Energy principle, instabilities: sausage, kink, interchange (overview). Braginskii stress tensor. Part II: Non-Newtonian fluids. Stokes flow, reciprocity and minimal dissipation, forces and torques on rigid bodies. Stokeslets, the Oseen tensor, multipole expansions. Microscopic bead-spring models of polymers, derivation of upper convected Maxwell model. Properties of viscoelastic fluids: normal stress differences, rheological flows, die swell, rod climbing, elastic waves, elastic instabilities, analogies with MHD. Liquid crystals and active suspensions.

Sequels: Astrophysical Fluid Dynamics (TT), Advanced Plasma Physics (TT), Topics in Soft and Active Matter Physics (TT), Turbulence (TT)

Soft Matter Physics [16 hours]

Prequel/pre-requisite: Nonequilibrium Statistical Physics (MT)

Syllabus *(written by R. Golestanian, A. Louis, J. Yeomans).* Polymers: statics and dynamics. Membranes. Liquid Crystals and topological defects. Colloids: dispersion interactions and transport. Diffusion-reaction processes and pattern formation. Self-assembly.

Sequel: Topics in Soft and Active Matter Physics (TT)

Nonlinear Systems [16 hours] *(Maths B8b).*

Syllabus *(from the 2012–13 Mathematics Handbook).* Part I: Bifurcations and Nonlinear Oscillators. Bifurcation theory: standard codimension one examples (saddle-node, Hopf, etc.), normal forms and codimension two examples (briefly). Non-conservative oscillators: Van der Pol's equation, limit cycles. Conservative oscillators (introduction to Hamiltonian systems): Duffing's equation, forced pendulum. Synchronization: synchronization in non-conservative oscillators, phase-only oscillators (e.g., Kuramoto model). Part II: Maps. Stability and periodic orbits, bifurcations of one-dimensional maps. Poincaré sections and first-return maps. Part III: Chaos in Maps and Differential Equations. Maps: logistic map, Bernoulli shift map, symbolic dynamics, two-dimensional maps (examples could include Henon map, Chirikov-Taylor ["standard"] map, billiard systems). Differential equations: Lyapunov exponents, chaos in conservative systems (e.g., forced pendulum, Henon-Heiles), chaos in non-conservative systems (e.g., Lorenz equations). Part IV: Other topics. Topics will vary from year to year and could include: dynamics on networks, solitary waves, spatio-temporal chaos, quantum chaos.

Quantum Condensed Matter Physics II [24 hours]

Prequel/pre-requisite: Introduction to Quantum Condensed Matter Physics (MT)

Syllabus *(written by J. Chalker and F. Essler).* Phase transitions: transfer matrix methods, spontaneous symmetry breaking in the Ising model, Landau theory of phase transitions. Fermi liquid theory. BCS theory of superconductivity. Strong interactions: Mott insulators. Ferromagnetism and antiferromagnetism, Holstein-Primakoff transformation. Quantum Hall effect: integer and fractional QHE; fractional statistics. Disorderd systems: random potential and localization.

Sequels: Advanced Quantum Condensed Matter Physics (TT), Topics in Quantum Condensed Matter Physics (TT)

Networks [16 hours] *(Maths C6.2b, to start in 2013-14)*

Pre-requisite: Maths C6.2a or another undergraduate course in Statistical Mechanics.

Syllabus *(written by M. Porter).* Introduction and basic concepts. Small worlds. Toy models of network formation. Additional summary statistics and other useful concepts. Random graphs. Community structure and mesoscopic structure. Dynamics on (and of) networks. Additional topics.

Sequel: Complex Systems (TT)

Waves and Compressible Flow [16 hours] *(Maths B6b).*

Prequels: Viscous Flow (MT), Kinetic Theory (MT)

Syllabus *(from the 2012–13 Mathematics Handbook).* Equations of inviscid compressible flow including flow relative to rotating axes. Models for linear wave propagation including Stokes waves, internal gravity waves, inertial waves in a rotating fluid, and simple solutions. Theories for Linear Waves: Fourier Series, Fourier integrals, method of stationary phase, dispersion and group velocity. Flow past thin wings. Nonlinear Waves: method of characteristics, simple wave flows applied to one-dimensional unsteady gas flow and shallow water theory. Shock Waves: weak solutions, Rankine–Hugoniot relations, oblique shocks, bores and hydraulic jumps.

Sequels: Geophysical Fluid Dynamics (TT), Astrophysical Fluid Dynamics (TT), Turbulence (TT)

Plasma Physics [16 hours]

Prequel: Kinetic Theory (MT)

Pre-requisite: Kinetic Theory (MT) or a basic introductory course in Plasma Physics.

Syllabus *(written by F. Parra).* Part I: Magnetised plasmas. Particle motion in magnetic field, adiabatic invariants. Drift kinetics, drift waves and instabilities. Kinetic MHD and CGL (double-adiabatic) equations. Two-fluid (Braginskii) equations, MHD. Part II: Plasma waves. Cold plasma dispersion relation. Hot-plasma dispersion relation for electrostatic waves. Hot-plasma dispersion relation for electromagnetic waves. Landau, Barnes (transit-time) and cyclotron damping. Quasilinear theory.

Sequel: Advanced Plasma Physics (TT)

Galactic and Planetary Dynamics — Celestial Mechanics for the 21st Century [16 hours]

Prequel/pre-requisite: Kinetic Theory (MT)

Syllabus *(written by J. Magorrian).* Introduction to prototypical systems: Galactic disk, globular clusters, protoplanetary disks. Characteristic length and time scales. Collisionless approximation. Derivation of Jeans and virial equations. Simple applications: need for closure relations. Orbits: integrals of motion, orbit families. Introduction to action-angle variables: tori. Jeans' theorem. Simple equilibrium models. Disc dynamics: winding problem; wave mechanics of discs; bars. Interactions between stellar systems. Dynamical friction. Tidal shocks. Disk heating mechanisms. Collisional systems. Negative specific heat and gravothermal catastrophe. Fokker–Planck equation. Application to globular clusters.

Stellar Astrophysics [16 hours] *Part of this course is also offered as part of Physics C1.*

Syllabus *(written by P. Podsiadlowski).* Part I: Modern Topics in Stellar Astrophysics. Late stages of stellar evolution; massive stars; supernovae, millisecond pulsars, hypernovae, gamma-ray bursts; compact binaries; the origin of elements, chemical evolution of the Universe. Part II: Accretion discs, Theory and Applications. Accretion disc theory, thin and thick discs; disc instabilities (thermal instability, gravitational instabilities [Toomre criterion]); optically thin advection-dominated flows, super-Eddington accretion.

Sequels: Astrophysical Fluid Dynamics (TT), High-Energy Astrophysics (TT), Astroparticle Physics (TT)

General Relativity II [16 hours] *(Maths C7.2b, revised)*

Prequel: General Relativity I (MT)

Pre-requisite: General Relativity I (MT) or equivalent.

Syllabus *(written by X. de la Ossa).* Lie derivative and isometries, linearised GR and the metric of an isolated body, Schwarzschild solution and extensions, Eddington-Finkelstein coordinates and Kruskal extension, Penrose diagrams, area theorem, stationarity, axisymmetric metrics and orthogonal transitivity, the Kerr solution and its properties, interpretation as rotating black hole, gravitational waves, the Einstein field equations with matter, energy momentum tensor for a perfect fluid, equations of motion from the conservation law, cosmological principle, homogeneity and isotropy, cosmological models, Friedman-Robertson Walker metric and solutions, observational consequences.

Cosmology [16 hours]

Pre-requisite: General Relativity I (MT) or equivalent.

Syllabus *(written by P. Candelas, P. Ferreira).* Einstein field equations and the Friedman equations, universe models, statistics of expanding background, relativistic cosmological perturbations, observations, from the Hubble flow to the CMB.

Applied Complex Variables [16 hours] *(Maths C6.3b).*

Prequel: Perturbation Methods (MT)

Syllabus *(from the 2012–13 Mathematics Handbook).* Review of core complex analysis, especially continuation, multifunctions, contour integration, conformal mapping and Fourier transforms. Riemann mapping theorem. Schwarz-Christoffel formula. Solution of Laplace's equation by conformal mapping onto a canonical domain. Applications to inviscid hydrodynamics: flow past an aerofoil and other obstacles by conformal mapping; free streamline flows of hodograph plane. Unsteady flow with free boundaries in porous media. Application of Cauchy integrals and Plemelj formulae. Solution of mixed boundary value problems motivated by thin aerofoil theory and the theory of cracks in elastic solids. Reimann-Hilbert problems. Cauchy singular integral equations. Transform methods, complex Fourier transform. Contour integral solutions of ODE's. Wiener-Hopf method.

Scientific Computing II [12 hours] *Part of a 2-term 24-hour course, designed as an introduction to computing for doctoral students.*

Prequel/pre-requisite: Scientific Computing I (MT)

Syllabus. See Maths Graduate Handbook. URL: `http://www.maths.ox.ac.uk/courses/course/19944`

Numerical Solutions to Differential Equations II [16 hours] *(Maths B21b).*

Prequel: Numerical Solutions to Differential Equations I (MT)

Syllabus *(from the 2012–13 Mathematics Handbook).* Numerical methods for boundary value problems. Numerical techniques for the approximation of boundary value problems for second-order ordinary differential equations. Boundary value problems for ordinary differential equations: shooting and finite difference methods. Finite difference schemes for elliptic boundary value problems. Introduction to the theory of direct and iterative algorithms for the solution of large systems of linear algebraic equations which arise from the discretisation of elliptic boundary value problems. Boundary value problems for PDEs: finite difference discretisation; Poisson equation. Associated methods of sparse numerical algebra: sparse Gaussian elimination, iterative methods.

Differential Geometry [16 hours]

Syllabus *(written by X. de la Ossa, P. Candelas, A. Dancer, J. Sparks).* Manifolds, tangent and cotanget spaces, differential forms and co-homology, Riemannian manifolds, fibre bundles (also principal bundles and vector bundles), connections on fiber bundles, characteristic classes, index theorems.

Geometric Group Theory [16 hours] *(Maths C3.2b).*

Syllabus *(from the 2012–13 Mathematics Handbook).* Free groups. Group presentations. Dehn's problems. Residually finite groups. Group actions on trees. Amalgams, HNN-extensions, graphs of groups, subgroup theorems for groups acting on trees. Quasi-isometries. Hyperbolic groups. Solution of the word and conjugacy problem for hyperbolic groups. If time allows: Small Cancellation Groups, Stallings Theorem, Boundaries.

A.3 Trinity term

Conformal Field Theory [16 hours]

Prequel/pre-requisite: Quantum Field Theory (MT)

Syllabus *(written by J. Cardy).* Scale invariance and conformal invariance in critical behaviour, the role of the stress tensor, radial quantisation and the Virasoro algebra, CFT on the cylinder and torus, height models, loop models and Coulomb gas methods, boundary CFT and Schramm-Loewner evolution, perturbed conformal field theories: Zamolodchikov's c-theorem, integrable perturbed CFTs: S-matrices and form factors.

Introduction to Gauge-String Duality [16 hours]

Prequel: String Theory I (HT)

Pre-requisite: Quantum Field Theory (MT)

Syllabus *(written by A. Starinets).* Duality in lattice statistical mechanics and quantum filed theory (an overview), black hole thermodynamics and black hole entropy, D-branes, the AdS-CFT correspondence, main recipes of gauge-string duality, gauge-string duality at finite temperature and density, fluid mechanics, black holes and holography, transport in strongly correlated systems from dual gravity, gauge-string duality and condensed matter physics, modern developments.

String Theory II [16 hours

Prequel/pre-requisite: String Theory I (HT)

Syllabus *(written by P. Candelas).* Superstring action, super-Virasoro algebra, RNS model and GSO projection, physical spectrum, type I, IIA, IIB and heterotic strings, D-branes, string dualities.

The Standard Model [16 hours]

Prequel/pre-requisite: Advanced Quantum Field Theory for Particle Physics (HT)

Syllabus *(written by X. de la Ossa, G. Zanderighi).* Part I. Weak interactions, weak decays, non-renormalizable Fermi four-point interactions (violation of unitarity), $SU(2)\times U_Y(1)$ gauge symmetry, spontaneous symmetry breaking (masses of gauge bosons), custodial symmetry and Yukawa masses, axial anomaly cancellation, accidental symmetries, renormalizability and power counting, neutrino masses (see-saw mechanism), Higgs phenomenology, Part II. Strong interaction, $SU(3)$ symmetry, Lagrangian, color identities, beta-function and asymptotic freedom, infrared divergences and infrared safety, $e^+e^- \to$ hadrons, R-ratio, parton model (failure with radiative corrections), parton distribution functions, dimensional regularisation, subtraction procedures for calculations of cross-sections, hadron collider phenomenology: event shapes, jets, benchmark processes (Drell-Yan, heavy quarks etc.).

Beyond the Standard Model (16 lectures, TT)

Prequel/pre-requisite: Advanced Quantum Field Theory for Particle Physics (HT)

Syllabus *(written by J. March-Russell).* SM precision tests, flavour physics, neutrino physics, strong CP and axions, hierarchy problem, motivations for susy/technicolour/warped extra dimensions and their basic phenomenology, introduction to grand unified theories.

Non-perturbative Methods in Quantum Field Theory [16 hours]

Prequel/pre-requisite: Advanced Quantum Field Theory for Particle Physics (HT)

Syllabus *(written by M. Teper).* Lattice Field Theory: Motivation and applications, gauge fields on a lattice and continuum limit(s), strong coupling calculations: confinement and mass gap, fermions on a lattice. Markovian Monte Carlo: Metropolis, heat bath, hybrid Monte Carlo, lightest glueball masses and their continuum limit, calculating the hadron spectrum, the running coupling. Solitons: kinks in D=1+1 scalar QFT, a no-go theorem and its limitations, vortices in D=2+1 scalar QFT (KT phase transition), vortices in D=2+1 gauge+scalar QFT, solitonic 'strings' in D=3+1 gauge+scalar QFT (Meissner effect and magnetic confinement), textures, domain walls, homotopy groups, monopoles in the D=3+1 Georgi-Glashow model. Instantons: tunnelling in D=1+1 Quantum Mechanics, Abelian-Higgs model in D=1+1: the dilute gas approximation, n-vacua and theta-vacua, Wilson loops and linear confinement, SU(2) gauge fields in D=3+1: the dilute gas calculations, n-vacua (Chern-Simons) and theta-vacua, SU(N) and intertwined theta-vacua, fermions and index theorems, anomalies and chiral symmetry breaking (Banks-Casher) in QCD, anomalies, sphalerons and the baryon asymmetry in SM.

Advanced Quantum Condensed Matter Physics [8 hours]

Prequel/pre-requisite: Introduction to Quantum Condensed Matter Physics (MT), Quantum Condensed Matter Physics II (HT)

Syllabus *(written by F. Essler).* From particles to fields: phonons and self-interacting scalar field theory. Weakly interacting electron gas: perturbation theory, Dyson equation, Hartree-Fock and random-phase approximations.

Topics in Quantum Condensed Matter Physics [8 hours]

Prequel/pre-requisite: Quantum Condensed Matter Physics II (HT)

Syllabus *(written by F. Essler).* This is a reading course. Under the guidance of the course organiser, students will give presentations based on key papers in quantum condensed matter theory. Some examples of the topics for these presentations are: Kramers-Wannier duality for the Ising model. Feynman's wavefunction approach to superfluid helium. The Haldane conjecture for integer quantum spin chains. Quantum friction. Homotopy and defects. Renormalisation group for Fermi liquids. The Kondo effect and scaling. Fractional statistics.

Complex Systems [16 hours]

Prequel: Networks (HT)

Pre-requisite: Maths C6.2a or another undergraduate course in Statistical Mechanics.

Syllabus *(written by M. Porter).* Percolation, fractals, self-organised criticality, and power laws. Stochastics and generative models: random walks, preferential attachment, master equations. Dynamical systems on networks: includes models of epidemics, social influence, voter models, etc. and how they are affected by network architecture. Agent-based models. Numerical methods: Monte Carlo, simulated annealing, etc.

Critical Phenomena [16 hours]

Pre-requisites: Quantum Field Theory (MT), Statistical Mechanics (MT) or equivalent.

Syllabus *(written by J. Cardy).* Phase transitions in simple systems. Mean field theory and its limitations (Landau theory). Basic theory of the RG. Scaling and crossover behaviour. Perturbative RG and the epsilon-expansion. Relation to the field-theoretic RG. Some applications: low-dimensional systems, random magnets, polymer statistics, critical dynamics.

Topics in Soft and Active Matter Physics [8 hours]

Prequels: Soft Matter Physics (HT), Advanced Fluid Dynamics (HT)

Pre-requisites: Soft Matter Physics (HT)

Syllabus *(written by R. Golestanian, A. Louis, J. Yeomans).* This is a reading course. Under the guidance of the course organiser, students will give presentations based on key papers in soft condensed matter theory. Some examples of the topics for these presentations are: Active nematics and active gels. Wetting, spreading and contact line dynamics. Hydrodynamics of microswimmers: Stokes equation, scallop theorem, multipole expansion, active suspensions. Fluctuations and response.

Turbulence [16 hours]

Prequels: Kinetic Theory (MT), Viscous Flow (MT), Advanced Fluiod Dynamics (HT), Waves and Compressible Flow (HT)

Pre-requisite: basic familiarity with fluid equations as provided, e.g., by Kinetic Theory (MT), Maths B6a or an equivalent undergraduate course (e.g., Physics B1).

Syllabus *(written by A. Schekochihin).* Kolmgorov 1941 theory and general philosophy of turbulent cascades (Obukhov). Turbulent diffusion, mixing of a scalar. General framework of mean-field theory, closures (basic idea, not detailed exposition). Kinematics of turbulence: correlation functions. Exact laws (Kolmogorov's 4/5 and Yaglom's 4/3). Intermittency: basic ideas; refined similarity (Kolmogorov 1962); She-Leveque theory. Turbulence in systems with waves: introduction to weak turbulence theory. Critically balanced turbulence in wave-supporting systems: general idea and the example of rotating turbulence. Restoration of Kolmogorov symmetries. Time-permitting: MHD turbulence, turbulent dynamo.

Geophysical Fluid Dynamics [16 hours]

Prequel: Waves and Compressible Flow (HT)

Pre-requisite: basic familiarity with fluid equations as provided, e.g., by Kinetic Theory (MT), Maths B6a or an equivalent undergraduate course (e.g., Physics B1).

Syllabus *(written by D. Marshall).* Rotating frames of reference, Rossby number, geostrophic and hydrostatic balance, thermal wind relation, pressure coordinates. Shallow water and reduced gravity models, f and beta-planes, conservation laws for energy and potential vorticity (relation to particle relabelling symmetry?), inertia-gravity waves, equations for nearly geostrophic motion, Rossby waves, Kelvin waves. Linearised equations for a stratified, incompressible fluid, internal gravity waves, vertical modes. Quasigeostrophic approximation: quasigeostrophic potential vorticity equation and Rossby waves solutions, vertical propagation and trapping. Barotropic and baroclinic instability, necessary conditions for instability of zonal flow, Eady model of baroclinic instability, qualitative discussion of frontogenesis. Wave-mean flow interaction, transformed Eulerian mean, Eliassen-Palm flux, non-acceleration theorem. Angular momentum and Held-Hou model of Hadley circulations. Applications to Mars and slowly-rotating planets. Giant planets: Multiple jets, stable eddies and free modes. Ekman layers, spin-down and upwelling. Sverdrup balance and ocean gyres, western intensification, simple models for the vertical structure of ocean circulation. Energetics and simples models of the meridional overturning circulation.

Advanced Plasma Physics [16 hours]

Prequel: Plasma Physics (HT)

Pre-requisites: Plasma Physics (HT), Advanced Fluid Dynamics (HT)

Syllabus *(written by F. Parra).* Part I: Resistive MHD. Tearing modes. Magnetic Reconnection. Part II: Drift kinetics in curved magnetic fields: neoclassical transport. Part III: Drift-wave modes in curved magnetic fields: ion-temperature-gradient (ITG) instabilities, trapped electron modes (TEM), etc.

Astrophysical Fluid Dynamics [16 hours]

Prequels: Advanced Fluid Dynamics (HT), Waves and Compressible Flow (HT)

Pre-requisite: Advanced Fluid Dynamics (HT) and/or a standard course in Fluid Dynamics.

Syllabus *(written by S. Balbus).* Part I: Basic Equations. Review of Euler and Navier-Stokes equations. Effects of radiation. Heating and cooling processes. MHD. Ion-electron fluid equations. Part II: Basic

Dynamics. Rotating Frames Gravitational tides and indirect potentials. Vorticity and field freezing. Taylor-Proudman theorem. Local Equations for discs and spheres. Part III: Waves and Instabilities. Eulerian and Langrangian perturbations. Classic waves: sound, density (in discs), gravity/inertial, MHD (slow, Alfvn, fast). Classic instabilities: gravitational, Rayleigh-Taylor, Schwarzschild-Parker, Kelvin-Helmholtz, Rayleigh and magnetorotational, thermal. Transport by correlated fluctuations. Part IV: Astrophysical Flows. Shock Waves, Taylor-Sedov blast-wave solution. Bondi accretion, Parker winds. Classical accretion disc theory. Solar rotation. Growth of cosmological perturbations. Part V: Elementary Turbulence Theory. Scaling and Kolmogorov arguments. Kinematic and MHD Dynamos.

High-Energy Astrophysics [16 hours]

Prequel: Stellar and Atomic Astrophysics (HT)

Syllabus *(written by G. Cotter).* Physics of interactions between high-energy particles and radiation (synchrotron, inverse-Compton, thermal Bremsstrahlung). Relativistic jets.

Astroparticle Physics [16 hours]

Pre-requisites: Quantum Field Theory (MT), General Relativity I (MT)

Syllabus *(written by S. Sarkar).* The Universe observed, constructing world models, reconstructing our thermal history, decoupling of the cosmic microwave background, primordial nucleosynthesis. Dark matter: astrophysical phenomenology, relic particles, direct and indirect detection. Cosmic particle accelerators, cosmic ray propagation in the Galaxy. The energy frontier: ultrahigh energy cosmic rays and neutrinos. The early Universe: constraints on new physics, baryo/leptogenesis, inflation, the formation of large-scale structure, dark energy.

Quantum Field Theory in Curved Space-Time [16 hours]

Prequels/pre-requisites: Quantum Field Theory (MT), General Relativity I (MT)

Syllabus *(written by A. Starinets).* Non-interacting quantum fields in curved space-time (Lagrangians, coupling to gravity, spinors in curved space-time, global hyperbolicity, Green's functions, canonical quantization, choice of vacuum) Quantum fields in Anti de Sitter space. Quantum fields in an expanding universe. Unruh effect. Casimir effect. Black hole thermodynamics. Hawking radiation. Interacting quantum fields in curved space-time. Effective action, heat kernel and renormalization. Holographic principle.

B Case Studies

The following table details some examples of possible pathways through the Programme. These case studies are for illustrative purposes only and show the breadth and diversity of the programme. Many other paths through the course are possible — and in fact much more eclectic or more generalist selections of courses may be appropriate for students who have not settled on a specialisation they intend to pursue eventually.

Indispensable courses ("core") for each given case study are indicated in bold. 1 unit=16 lectures; at least 10 units have to be taken over three terms. Note that some of the Case Studies below are sufficiently broad to allow multiple pathways within them.

Pathway	*MT*	*HT*	*TT*
"TEORICA UNIVERSALIS" (Generalist Theoretical Physicist) **Core 4–5 units** Total 10-12 units	**1. QFT 24** **2-4. *Three of*** **Intro. Quant. CMP 16** **Noneq. Stat. Phys. 8** **Kinetic Theory 24** **GR I 16** **Pert. Methods 16**	1-3. *Three of* Advanced QFT 24 Quantum CMP II 24 Adv. Fluid Dyn. 16 Soft Matter 16 Nonlinear Systems 16 Plasma Physics 16 Cosmology 16	1-3. *Three of* Gauge-String Duality 16 Standard Model 16 Critical Phenomena 16 Turbulence 16 AFD 16 QFT in Curved Space 16
"APPLICATA" (Applied Mathematician) **Core 4–4.5 units** Total 10–10.5 units	**1-2. *Two of*** **Noneq. Stat. Phys. 8** **Kinetic Theory 24** **Visc. Flow 16** **GR I 16** **3. Pert. Methods 16** 4. *One of* Sci. Comp. I 12 Num. Slns Diff. Eqns I 16 Num. Lin. Algebra 16	**1. Adv. Fluid Dyn. 24** 2. *One of* Nonlinear Systems 16 Networks 16 Waves/Comp. Flow 16 Plasma Physics 16 Galactic Dyn. 16 GR II 16 **3. *One of*** **Complex Variables 16** **Diff. Geometry 16** 4. *One of* Sci. Comp. II 12 Num. Slns Diff. Eqs II 16	1-2. *Two of* Complex Systems 16 Turbulence 16 GFD 16 AFD 16 Dissertation
"CONTINUA" (Fluid Dynamicist) **Core 8.5-9 units** Total 10–10.5 units	**1. Kinetic Theory 24** **2. Visc. Flow 16** **3. Pert. Methods 16** **4. *One of*** **Sci. Comp. I 12** **Num. Slns Diff. Eqs I 16**	**1. Adv. Fluid Dyn. 24** **2. Waves/Comp. Flow 16** 3. *One of* Nonlinear Systems 16 Soft Matter Phys. 16 Plasma Physics 16 Complex Variables 16 **4. *One of*** **Sci. Comp. II 12** **Num. Slns Diff. Eqs II 16**	**1. Turbulence 16** 2. *One of* Topics Soft Matter 8 GFD 16 AFD 16 Dissertation

"GEOMETRA" (Mathematician with a physics streak) **Core 5.5 units** Total 10 units	**1. QFT 24** **2. GR I 16** 3. *One of* Groups & Repr. 24 Algebraic Topology 16 Algebraic Geometry 16	**1. String Theory I 16** **2. Diff. Geometry 16** 3. *One of* Advanced QFT 24 SUSY & SUGRA 24 GR II 16 Geom. Group Theory 16	**1. String Theory II 16** 2. *Two of* CFT 16 Standard Model 16 Beyond the SM 16 QFT in Curved Space 16
"PARTICULATA" (Particle Phenomenologist) **Core 8 units** Total 10.5–11 units	**1. QFT 24** **2. Groups & Repr. 24** 3. *One of* Stat. Mech. 16 GR I 16 Pert. Methods 16 Sci. Comp. I 12 Num. Slns Diff. Eqs I 16	**1. Advanced QFT 24** **2. SUSY & SUGRA 24** 3. *One of* String Theory I 16 GR II 16 Cosmology 16 Sci. Comp. II 12 Num. Slns Diff. Eqs II 16	**1. Standard Model 16** **2. Nonpert. QFT 16** 2. *One of* String Theory II 16 Beyond the SM 16 QFT in Curved Space 16 Astroparticle Phys. 16
"SUPERCORDULA" (Hard-core String Theorist) **Core 7.5 units** Total 10–10.5 units	**1. QFT 24** **2. Groups & Repr. 24** 3. *One of* Stat. Mech. 16 GR I 16 Pert. Methods 16 Sci. Comp. I 12 Num. Slns Diff. Eqs I 16 Algebraic Geometry 16	**1. Advanced QFT 24** **2. String Theory I 16** 3. *One of* SUSY & SUGRA 24 GR II 16 Cosmology 16 Sci. Comp. II 12 Num. Slns Diff. Eqs II 16 Diff. Geometry 16	**1. String Theory II 16** **2. CFT 16** 3. *One of* Gauge-String Duality 16 Standard Model 16 Beyond the SM 16 QFT in Curved Space 16 Nonpert. QFT 16
"CONDENSATA" (Condensed Matter Theorist) **Core 7 units** Total 10.5–11.5 units	**1. QFT 24** **2. Intro Quant. CMP 16** **3. Noneq. Stat. Phys. 8** **4. Sci. Comp. I 12**	**1. Quant. CMP II 24** **2. Soft Matter 16** 3. *One of* Advanced QFT 24 Adv. Fluid Dyn. 16 Nonlinear Systems 16 **4. Sci. Comp. II 12**	1. Topics Quant. CMP 8 2. Topics Soft Matter 8 3. *Two of* Adv. Quant. CMP 8 Critical Phenomena 16 CFT 16
"DURACELLA" (Hard-core Hard Condensed Matter Theorist) **Core 6.5 units** Total 10–11.5 units	**1. QFT 24** **2. Intro Quant. CMP 16** 3. *One of* Noneq. Stat. Phys. 8 Kinetic Theory 24 Pert. Methods 16 **4. Sci. Comp. I 12**	**1. Quant. CMP II 24** 2. *One of* Advanced QFT 24 String Theory I 16 Adv. Fluid Dyn. 16 **3. Sci. Comp. II 12**	**1. Adv. Quant. CMP 8** **2. Topics Quant. CMP 8** 3-4. *Two of* Critical Phenomena 16 CFT 16 Gauge-String Duality 16 Nonpert. QFT 16
"MOLLIS" (Soft Condensed Matter Physicist/Biophysicist) **Core 7 units** Total 11.5 units	1. QFT 24 **2. Noneq. Stat. Phys. 8** **3. Kinetic Theory 24** 4. Pert. Methods 16 **5. Sci. Comp. I 12**	**1. Adv. Fluid Dyn. 16** **2. Soft Matter 16** 3. *One of* Nonlinear Systems 16 Networks 16 4. **Sci. Comp. II 12**	**1. Topics Soft Matter 8** 2. Critical Phenomena 16 3. Complex Systems 16

"COMPLICATA" (Complexity Scientist) **Core 5–5.5 units** Total 10–11 units	**1. Noneq. Stat. Phys. 8** 2. Kinetic Theory 24 3. Pert. Methods 16 **4. *One of*** **Sci. Comp. I 12** **Num. Slns Diff. Eqs I 16**	1. Soft Matter 16 **2. Nonlinear Systems 16** **3. Networks 16** **4. *One of*** **Sci. Comp. II 12** **Num. Slns D. Eqs II 16**	**1. Complex Systems 16** 2-3. *Two of* Topics Soft Matter 8 Critical Phenomena 16 Turbulence 16
"ASTRA-STELLA" (All-round Astrophysicist) **Core 6.5 units** Total 11–12 units	**1. Kinetic Theory 24** **2. GR I 16** 3. *One of* QFT 24 Pert. Methods 16 4. *One of* Sci. Comp. I 12 Num. Slns Diff. Eqs I 16	**1-2. *Two of*** **Galactic Dyn. 16** **Stellar Astrophys. 16** **Cosmology 16** 3. *One of* Waves/Comp. Flow 16 Adv. Fluid Dyn. 16 Plasma Physics 16 4. *One of* Sci. Comp. II 12 Num. Slns Diff. Eqs II 16	**1. AFD 16** **2. High-Energy Astro 16** 3. *One of* Turbulence 16 GFD 16 Astroparticle Phys. 16 QFT in Curved Space 16
"COSMICOSMICA" (Dedicated Cosmologist) **Core 4 units** Total 10–11 units	**1. GR I 16** 2-3. *Two of* QFT 24 Kinetic Theory 24 Pert. Methods 16 4. *One of* Sci. Comp. I 12 Num. Slns Diff. Eqs I 16	**1. Cosmology 16** **2. GR II 16** 3. *One of* Waves/Comp. Flow 16 Galactic Dyn. 16 Stellar Astrophys. 16 4. *One of* Sci. Comp. II 12 Num. Slns Diff. Eqs II 16	1. *One of* AFD 16 High-Energy Astro 16 QFT in Curved Space 16 **2. Astroparticle Phys. 16**
"GAIA" (Geophysicist/ Climate Physicist) **Core 4.5–5 units** Total 10–10.5 units	1-2. *Two of* Kinetic Theory 24 Viscous Flow 16 Noneq. Stat. Phys. 8 **3. Pert. Methods 16** **4. *One of*** **Sci. Comp. I 12** **Num. Slns Diff. Eqs I 16**	**1. Nonlinear Systems 16** 2. *One of* Networks 16 Waves/Comp. Flow 16 **3. *One of*** **Sci. Comp. II 12** **Num. Slns D. Eqs II 16**	**1. GFD 16** 2. Turbulence 16 3. Complex Systems 16
"PLASMA" (Plasma Theorist) **Core 7–7.5 units** Total 10.5-11 units	**1. Kinetic Theory 24** 2. Noneq. Stat. Phys. 8 **3. Pert. Methods 16** **4. *One of*** **Sci. Comp. I 12** **Num. Slns Diff. Eqs I 16**	**1. Adv. Fluid Dyn. 16** **2. Plasma Physics 16** 3. *One of* Nonlinear Systems 16 Stellar Astrophys. 16 Complex Variables 16 **4. *One of*** **Sci. Comp. II 12** **Num. Slns D. Eqs II 16**	**1. Adv. Plasma Phys. 16** 2. AFD 16 3. Turbulence 16

C Application procedure

MSc applicants should follow the usual Oxford University postgraduate admission procedure explained at

http://www.ox.ac.uk/admissions/postgraduate_courses/apply/application_guide.html.

MMathPhys applicant should submit their application by the end of the first week of Hilary term, in January. Application documents should be sent, preferably in electronic form by email, to

address, TBA
email, TBA

The following documents are required.

- A transcript for the first two years of your study.
- A concise personal statement (maximal one page) in English, providing the reasons for applying, evidence of motivation for and understanding of the proposed area of study, commitment to the subject beyond the requirements of the degree course, capacity for sustained and intense work, reasoning ability, the ability to absorb abstract ideas and at a rapid pace and an indication of your intended pathway through the MMathPhys programme.
- Two academic references, typically written by your college tutors. In particular, these should include information about you intellectual ability, academic achievement, academic potential, and motivation, particularly with regard to mathematical and theoretical physics and your likely BA degree class. They should be sent directly, preferably by email, to the above address.