

Examiners' Report: Final Honour School of Mathematical and Theoretical Physics Part C and MSc in Mathematical and Theoretical Physics Trinity Term 2025

20 November, 2025

Part I

A. STATISTICS

- **Numbers and percentages in each class.**

See Table 1.

NUMBERS							
Class	2025	2024	2023	2022	2021	2020	2019
D	45	53	37	38	42	42	40
M	17	13	7	13	10	9	6
P	17	14	9	11	12	3	6
F	4	6	4	1	3	1	1
Total	83	86	57	63	67	55	53
PERCENTAGES %							
Class	2025	2024	2023	2022	2021	2020	2019
D	54	62	65	60	63	76	76
M	20.5	15	12	21	15	16	11
P	20.5	16	16	17	18	6	11
F	5	7	7	2	4	2	2
Total	100	100	100	100	100	100	100

Table 1: Numbers and percentages in each class

- **Numbers of vivas and effects of vivas on classes of result.**

As in previous years there were no vivas conducted.

- **Marking of scripts.**

All dissertations and two mini-project subjects were double-marked. In cases of significant disagreement between marks, the two markers were consulted to agree a reconciled mark.

All written examinations and take-home exams were single-marked according to checked model solutions and a pre-defined marking scheme. A comprehensive independent checking procedure was followed.

B. New examining methods and procedures

None.

C. Changes in examining methods and procedures currently under discussion or contemplated for the future

The Examiners discussed having fewer mini-projects and replacing them with invigilated closed-book exams where possible.

D. Notice of examination conventions for candidates

Notices to candidates were sent on: 24th October 2024 (first notice), 4th November 2024 (second notice), 18th February 2025 (third notice), and 6th May 2025 (fourth notice).

The examination conventions for the 2024-2025 academic year were available to students online

Part II

A. General Comments on the Examination

B. Breakdown of the results by gender

Removed from public version

C. Detailed numbers on candidates' performance in each part of the examination

The number of candidates taking each paper is shown in Table 3 and in the Average USM per Formal Assessment graph below. In accordance with University guidelines, statistics are not given for papers where the number of candidates was five or fewer.

Paper	No. of Candidates	Average USM	StDev USM
Advanced Fluid Dynamics	9	71	11.4
Advanced Philosophy of Physics	3	83	-1.53
Advanced Quantum Field Theory	49	64	13.2
Advanced Quantum Theory (resit)	1	-	-
Algebraic Geometry	2	-	-
Algebraic Topology	5	-	-
An Introduction to Topological Phases of Matter	9	75	9.36
Anyons and Topological Quantum Field Theory	13	65	19.4
Applied Complex Variables	4	-	-
Classical Quantum Compositional Distributional Meaning	3	-	-
Collisionless Plasma Physics	5	-	-
Computational Complexity	1	-	-
Condensed Matter Physics	1	-	-
Cosmology	8	67	12.1
Differentiable Manifolds	8	42	31.3
Dissertation (single unit)	18	73	8.8
Dissertation (double unit)	36	76	8.2
Elasticity and Plasticity	1	-	-
Field Theories and Collective Phenomena in Condensed Matter	11	71	10.8
Galactic and Planetary Dynamics	5	-	-
General Relativity I	31	68	13.3
General Relativity II	19	67	15.9
Geometric Deep Learning	1	-	-
Geometric Group Theory	1	-	-
Geophysical Fluid Dynamics	5	-	-
Groups and Representations	54	72	14.6
Introduction to Quantum Information	32	70	15.2
Introduction to Schemes	2	-	-
Kinetic Theory	6	69	9.2
Lie Groups	5	58	11.8
Low-Dimensional Topology and Knot Theory	1	-	-
Mathematical Geoscience	3	-	-
Networks	9	70	6.3
Non-equilibrium Statistical Physics	11	89	4.6
Numerical Linear Algebra	4	-	-
Particle Physics	2	-	-
Perturbation Methods	11	67	16.6
Quantum Field Theory	70	69	15.4
Quantum Matter	12	65	18.8
Quantum Processes and Computation	4	-	-
Random Matrix Theory	4	-	-
Riemannian Geometry	5	-	-
String Theory I	33	66	5.8
Supersymmetry and Supergravity	24	60	11.8
Theories of Deep Learning	1	-	-
Topics in Fluid Mechanics	2	-	-

Table 3: Statistics for individual papers

The number of candidates taking each homework-completion course is shown in Table 4. In accordance with University guidelines, statistics are not given for papers where the number of candidates was five or fewer.

Paper	No. of candidates	% completing course
Advanced Fluid Dynamics	1	-
Advanced Philosophy of Physics	-	-
Advanced Topics in Plasma Physics	4	-
Algorithms and Computations in Theoretical Physics	14	100
Anyons and Topological Phases of Matter	20	100
Astroparticle Physics	15	100
Collisional Plasma Physics	3	-
Collisionless Plasma Physics	2	-
Conformal Field Theory	26	92.3
Disorder in Condensed Matter	14	100
Galactic and Planetary Dynamics	3	-
Group and Representations	53	100
High Energy Density Plasma Physics	3	-
Kinetic Theory	7	100
Machine Learning Fundamentals with Applications to Physics and Mathematics	23	100
Nonequilibrium Statistical Physics	6	100
Quantum Field Theory in Curved Space	16	100
Quantum Matter	4	-
Quantum Processes in Hot Plasma	3	-
Renormalisation Group	14	85.7
Statistical Mechanics and Computer Algorithms	23	100
String Theory II	7	100
The Standard Model and Beyond I	18	94.4
The Standard Model and Beyond II	7	100
Topics in Soft and Accretion Matter Physics	4	-

Table 4: Numbers taking each homework completion course

D. Assessors' comments on sections and on individual questions

Advanced Fluid Dynamics

Question 1.

The students generally did well on the Magnetohydrodynamics question. Some candidates lost marks for assuming, rather than proving, results discussed in the course. Other than this, book work parts were done well. Some students struggled to correctly interpret the physical implications of resistivity in the final part of the question.

Part (a) – Students generally answered this book work part of the question well. Common mistakes were sign errors in the Lorentz transform, and misidentifying different terms in the induction equation.

Part (b) – Nearly all students got this part in the end, although there were some very inefficient routes to the answer. Lost marks were typically for failing to interpret the results, as asked.

Part (c) – This question on Helicity was more poorly answered. Errors were typically technical mistakes, rather than a lack of understanding.

Part (d) – Some students answered this well, including one excellent answer. Many students derived the correct mathematical results, but then misinterpreted.

Question 2.

My question was a little easy. One candidate nevertheless obtained a very low mark. They could reproduce a lot of material about the resistance matrix formalism from my lectures, but it didn't help them to answer the question I set.

Advanced Quantum Field Theory

Question 1 was a question on scalar field theory. Some students had difficulty with part (c). In many cases it was to distinguish between renormalizable and non-renormalizable terms and the reasons to include or omit them from the Lagrangian. Some students also lost marks in part (d) due to not performing integration-by-parts correctly.

Question 2 was on quantum electrodynamics. In part (b) many students attempted to derive the form of $\Pi_{\mu\nu}$, which was not asked to be done in the question. Very few made use of the hint that would make the algebra much simpler; full points were awarded for any calculation scheme used. Most students did well to draw the Feynman diagrams and write the amplitudes. A very common calculation error was to declare that numerator terms like $\ell \cdot q$ integrate to zero, being odd in ℓ , without recognizing that the denominator was not symmetric in ℓ .

Question 3 was on non-Abelian gauge theory. Students generally did well on part (a). Some students did not correctly write down the propagator in Unitarity and R_ξ gauges, and did not correctly explain the connection of these expressions in relation to renormalizability of non-Abelian gauge theory.

Advanced Quantum Theory

Question 1.

This question concerns the transfer matrix treatment of the one-dimensional, nearest-neighbour Ising antiferromagnet. Some parts are very standard but it also includes challenging sections. These involve considering spin-spin correlation functions in a finite system with periodic boundary conditions and deriving differences in behaviour according to whether the number of sites is even or odd.

Question 2.

This question is concerned with fermionic Bogoliubov transformations for a two-orbital model that is a toy version of the BCS Hamiltonian. As expected, candidates found the final section the most difficult. It required them to find the transformation between the original vacuum for the problem and the ground state of the Hamiltonian, using methods they had seen in other contexts but probably not in this setting.

Anyons and Topological Quantum Field Theory

Question 1.

This question had a mean of 14/25 with standard deviation of 7. High score was 23. Overall the question seemed to work well. On part (a) either a student knew what gauge invariance was or they didn't. On part (b) many students did not bother to answer the last part of the question which cost a few marks. No students fully got the last part of the question (transparent can only be bosons or fermions!) although partial credit was generous if students said anything intelligent about transparent particles. Part (c) was done well by a fairly large fraction of students. Part (d) was a bit harder. One perfect answer was given and a few very close to perfect. However, here some students showed that they really didn't know how to manipulate diagrams even though the "useful information" page had everything needed on it.

Question 2.

This question had mean of 16/25 with standard deviation 7. High score was 24. Part (a) was identical to homework and most students remembered how to do it. The second part required only a bit of algebra and almost half of the students failed to get to the right answer. Part (c) was done well by almost everyone, although a mark was often lost by not using isotopy normalization (which would then cause problems in part (d)). Part (d) was the challenging piece, but it was a generalization of a homework problem and students should have known how to attack it. There were a few perfect or near perfect answers. However, a large number of students didn't get very far with this and lost a lot of marks.

Collisionless Plasma Physics

Q1 and Q2 examined the HT part of the course that deals with plasma waves. Students performed very well in this section on average and showed a good grasp of the material. Overall, the high average mark and students' actual work indicate that the main messages of the course seem to be being taken on board.

The standard of answers to Q1 was generally very high; this was not unexpected, since this question is a fairly minimal twist on material covered in lectures. Part (a) was bookwork, and all students scored full marks on this section. I was surprised (and somewhat disappointed) to see that so many students took a "kitchen sink" approach to this question, resulting in reams of algebra and attempting to repeat the lecture notes verbatim, rather than taking a cleaner line to the final result. Part (b) was a straightforward calculation, done well by the majority of candidates with the exception of a few algebra slips. Parts (c) and (d) didn't cause any major issues. Part (e) was done well, and all students managed to connect the idea that electrostatic waves propagating parallel to the magnetic field, $\epsilon_{\parallel} = 0$, are in resonance.

However, no one made the connection between electrostatic waves and the $k \rightarrow \infty$ limit of the cold plasma dispersion relation. Part (f) was done well, albeit again some candidates took a fairly circuitous route to get to the final result. Q2 was reasonably well done but caused more difficulties than Q1. Part (a) was fine; all candidates were able to write down the WKB approximation (albeit very few candidates were able to do this succinctly) and arrive at the correct equation for δE . Part (b) was answered correctly by all candidates. Part (c) caused some headaches, and some candidates struggled to write down the correct WKB solutions (and were confused about which waves were propagating in which regions). Surprisingly few candidates opted to introduce simplifying notation in this part of the question, instead preferring to write out complicated exponents many times over. Part (d) was well done. Parts (e) and (f) proved much more challenging. Many students struggled to argue (and apply) the correct boundary conditions. Without this, the algebra is quite involved, and this proved the undoing of several students. In Part (g), most students recognised that $R + T = 1$ was a statement of conservation of energy (though some tripped over this based on partially incorrect answers to previous parts of the question). No students struggled with the integration in Part (h), though the interpretation in terms of tunnelling was often somewhat lacking.

Q3. The standard of answers was quite high, which is consistent with past experience of a take-home exam to complete which the students are effectively given 5 days (if one includes the weekend). While good, performance was not off-scale and, as far as I can tell, the answers looked like a genuine effort, assisted by the course materials, but probably not by much else.

- (a) Checking that the proposed z -pinch equilibrium was indeed an equilibrium of KMHD caused to difficulties.
- (b) The linearisation of the momentum and induction equations around this equilibrium was also performed competently, with the approximations leading to the pressure balance correctly applied (the total perpendicular pressure gradient dominated the ξ_y equation); the dispersion relation was then obtained from the ξ_x equation.
- (c) In deriving the perturbed pressures via the kinetic equation, all students aimed at, and, as students tend to, ruthlessly achieved, the required result. However, not all correctly grasped why mathematically (or physically) no resonant denominators popped up in the expression for δf_α . In particular, not everyone realised that there would be a term $v_{||}\delta b_x \partial f_{0\alpha}/\partial x$ in the linearised kinetic equation, despite the transparent hint to that effect that appeared in part (d).
- (d) Most understood that the form of the perturbed distribution function was simply the result of locally displacing the equilibrium in the radial direction.
- (e) Not all students seemed to have a crystal clear idea about the 2D interchange instability, how it was replaced by Alfvén waves at sufficiently high $k_{||}$, or that a lower limit on $k_{||} = 0$ existed in a z pinch ($k_{||} > 1/R$). But by and large, they could see what roughly happened. Their “educated guesses” as to the effect of relaxing such assumptions as low β , and their idea of what was special about KMHD vs. MHD, mostly centred on pressure anisotropies. None mentioned the possibility of Barnes damping playing a role.
- (f) All knew the basic differences between the assumptions behind the ITG instability and KMHD, but there was not a lot of clarity about how the two regimes connected. In particular, the material in the notes regarding the electrostatic approximation obtaining at sufficiently large $k_{||}$ (with Alfvén waves propagating away magnetic perturbations) appears not to have been particularly firmly grasped.

Cosmology

Question 1.

Question 1 was attempted by all students. Conceptually, this was the simplest question in the exam, as it dealt mostly with background expansion and linear Newtonian growth. It required a bit more work in terms of algebra, however, and some students found it hard or perhaps more time-consuming than expected. Most students were able to get more than half of the marks, with an average of 15.1/25.

Question 2.

Question 2 was attempted by a majority of the students. It involved the derivation of the energy-momentum conservation equation for linear vector perturbations in Newtonian and relativistic theory. There was a moderate amount of index algebra and linear expansion to do, but most students were able to go through most parts of the question without much trouble.

Question 3.

Question 3 was only attempted by 2 students. Neither of them were able to complete part 3 correctly, even though most of the ingredients were already provided. A potential hurdle may have been the derivation of the growth prefactor for ϕ' in the ISW term, although this was done in the tutorials. Both students had the right physical intuition, though (ISW can only be relevant during Λ domination), and could complete most of the question (an average of 15.5/25).

Field Theories Collective Phenomena in Condensed Matter

Question 1.

Mean raw mark 16.8. This question concerns the imaginary time propagator for a free particle. It was done well or very well by most candidates (3 answers at 80% and above) and poorly by only a few. As expected, candidates found the final sections of the question most difficult. This part is about the relationship between contributions to the path integral for the propagator, and the paths followed by a Brownian particle. The relationship was discussed in the lectures but not covered in problem sets.

Question 2.

Mean raw mark 16.5. This question concerns the transfer matrix treatment of the one-dimensional, nearest-neighbour Ising antiferromagnet. Some parts are very standard but it also includes challenging sections. These involve considering spin-spin correlation functions in a finite system with periodic boundary conditions and deriving differences in behaviour according to whether the number of sites is even or odd. Most solutions were reasonably good, and a few were very good (3 answers at 80% and above).

Question 3.

Mean raw mark 17.9. This question is concerned with fermionic Bogoliubov transformations for a two-orbital model that is a toy version of the BCS Hamiltonian. It was done well or very well by nearly all candidates (4 answers at 80% and above). As expected, candidates found the final section the most difficult. It required them to find the transformation between the original vacuum for the problem and the ground state of the Hamiltonian, using methods they had seen in other contexts but probably not in this setting.

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Both students had the right physical intuition, though (ISW can only be relevant during Λ domination), and could complete most of the question.

Groups and Representations

With a raw average of 71, this paper was done well on the whole but this average hides uneven performance among the cohort as well as across the questions. In particular, questions 1 and 4 were done rather well, while performances on questions 2 and 3 were, on average, rather poor.

Question 1. With a raw average of 20 marks and tackled by all students, this question was done rather well. Most difficulties arose in part b) where some students performed random calculations (such as checking that P is a projector) rather than tackling the task at hand and in part e), where some students had conceptual problems applying the previous results within the given physics context, although a similar example had been discussed in the lectures. This may well be related to the growing trend of not attending lectures but rather claiming to listen to the recordings.

Question 2. This question was attempted by 48 students with an average raw mark of 12.6. Major conceptual problems arose in part b) where most students had no idea how to determine the unbroken sub-group although this had been discussed in the lectures and the exercise classes. Another, surprising issue was the inability of many students to carry out the relatively simple Casimir/index calculations in part c) numerically correctly.

Question 3. A very unpopular question attempted by only 14 students with an average raw mark of 7. Even though spinors were discussed at length in the lecture most who attempted the question struggled conceptually, despite the two-dimensional case being rather simple. I suspect patchy lecture attendance and the fact not many previous exams had a question on spinors plays a role.

Question 4. This question was tackled by all students with a very good average raw mark of 21. The only major difficulties arose in part d) where the results had to be applied in a physics context.

Kinetic Theory

Question 1. Almost all attempts were of a good standard.

Part (a) was mostly done well, though a few candidates forgot the scalings $f_1 = N\rho_1$ and $f_2 = N(N-1)\rho_2$. The interaction potential should appear in a sum over $i < j$ with a strict inequality to omit self-interactions. All the sums should have explicit upper and lower limits.

Part (b) was mostly done well. The main error was using $||^2$ instead of the peculiar velocity $|-|^2$ to express the temperature in terms of f . One needs to take the Boltzmann–Grad limit to justify expressing the f_2 contribution via the Boltzmann collision operator. The $f^{(0)}/\tau$ in the BGK collision operator is a model for the Boltzmann gain term with the right qualitative properties.

In part (c) several candidates left the contribution from U as an integral over $\cdot$. Integrating by parts gives $= -\rho\nabla U$ with a minus sign.

Part (d) caused most difficulty. Several candidates tried to take moments with respect to the peculiar velocity $= -(, t)$ directly. This operation does not commute with $\cdot$ and t derivatives, because $\cdot$ depends on $\cdot$ and t . It is easier to take moments with respect to $\cdot$ first, since $\cdot, \cdot, t$ are independent variables, then convert them into moments with respect to $\cdot$. The $\cdot$ moment of the ∇U term becomes $+$. This exactly cancels the $\cdot$ contributions from evaluating $\partial_t(\rho)$ using the momentum equation from part (c).

Question 2.

I did not expect this question to prove particularly challenging,

but the marks were fairly low, mostly due to candidates finding it difficult to perform some undergraduate-level manipulations, such as Taylor-expanding an expression or sketching a function knowing its asymptotics.

Part (a) — Most candidates realised that undamped waves would exist where $f'_0(u) = 0$, but some did not spot that, besides the plateau at $u \in [v_1, v_2]$, this also included $u < -v_0$ and $u > v_0 + v_2 - v_1$, where there were no particles.

Part (b) — This was a completely standard calculation and most got full marks, as I hoped they would.

Part (c) — Realising that all you had to do was find the zeros of the denominator inside the log (to get the log to go to infinity) proved surprisingly challenging.

Part (d) — This part required realising that solutions would exist at $u \gg v_0, v_1, v_2$ and at $u = v_1 + \delta u$, where $\delta u < v_2 - v_1 \ll v_0, v_1$, and then expanding the log in relevant small quantities. This task defeated most candidates. Many did understand though that the reason the EAW did not exist in a Maxwellian plasma was that, in the absence of a plateau, it would be heavily damped.

Part (e) — This proved hard for the same reason part (d) proved hard, but it was disappointing that few realised they could at least get points for showing how the desired expression asymptoted to the solutions already obtained in parts (d) and (c).

Part (f) — Sketching correctly functions with known asymptotics proved harder than I hoped it would.

Question 3.

The range of performances was very similar to last year, ranging from 16/25 to 23/25. Basic bookwork manipulations were done well but physical understanding was somewhat lacking.

Part (a) — almost all students got both marks.

Part (b) — this is a very standard bit of bookwork and was done well by everybody.

Part (c) — simple (rather mechanical) calculation, done well by all those who attempted it.

Part (d) — only one person got the mark for physical interpretation (the perturbation corresponds to a transient, m-armed, rotating bar or spiral pattern). Otherwise done well.

Part (e) — the physical reasoning was much better here than in parts (d) and (f), with most students giving plausible justifications for simplifying the integral. Once this was done, the rest of the question is straightforward algebra, although some students were clearly running out of time by this point.

Part (f) — perhaps a bit too hard, since nobody got either of the 2 marks on offer. The detailed answer is that R is a resonance function and that the contributions from (i) and (ii) correspond to stars located at corotation and Lindblad resonances of the rotating pattern, respectively. I'd have given at least one mark for any sensible words in this direction, but nobody provided any.

Quantum Field Theory

Overall the paper was well done. Most candidates were secure on the book-work aspects. The later parts of questions that required candidates to pull together different ideas caused more difficulties.

Question 1 Average mark 15.8. Some candidates did this question very well but a significant number of candidates failed to realise that there is a γ^5 factor in the Feynman rule for the fermion-scalar vertex. Some proofs that the one-loop contribution to one- and three- point functions vanishes were rather sketchy. In part d) many candidates failed to realise that for parity to be a good symmetry the scalar field must be parity odd – they assumed that it is even.

Question 2 Average mark 16.8. This question was mostly well-done. A small number of candidates failed to realise that the $U(1)$ transformations of ϕ and Φ are related, and in many answers the combinatoric factors in parts b) and c) were not consistently done. Strictly speaking (c)iii) should have asked for the decay mode $\Phi^\dagger \rightarrow \phi\phi$ (the dagger was missing); 8 candidates commented on this but then did the rest of the question assuming the matrix element was non-zero anyway. The most common error in the calculation of the width Γ_Φ was incorrect evaluation of the δ -function integral

$$\int \delta(f(x)) dx . \quad (1)$$

In the last part most candidates did not recall that for an unstable particle the pole of the two-point function is shifted off the real axis.

Question 3 Average mark 16.6. Some candidates seemed to be confused between commutators and anti-commutators in part a). In parts b) and c) some candidates tried to evaluate wave-functions rather than simply work with the states; this was not required and obscures the argument of a proof. A few candidates did not realise that the terms that vanish in part d) do so because of annihilation of the Fock vacuum, not because of spinor orthogonality.

Quantum Matter

Question 1

All students could define Hartree Fock (almost all perfectly). The second part of the question asked students to convert from first to second quantized notation. This kind of thing shows up every single year and it should not have been a surprise. Nonetheless only about half managed to do this without error. A surprisingly large number seemed to not have any idea how to do it. Parts (c) and (d) should have then been easy, but errors in writing the Hamiltonian in the first place sometimes caused even more confusion in getting any reasonable result later on. I was fairly generous in not deducting for minus signs or dropped constant factors (which in reality might have been important). The last part could have been done even without having done any of the earlier parts just by realizing that (i) spin up and spin down are completely decoupled and (ii) particles with the same spin don't want to be on adjacent sites.

Question 2

The first part of the question, BEC for particles in a 2d harmonic well, should have been very easy (particularly given that density of states $D(E)$ was given and the relevant integral was given). This is 2nd year stat mech material. Unfortunately, more than half the students either didn't know where to start, or regurgitated $\int d\mathbf{k}/(2\pi)^d$ without thinking. Fortunately, the rest of the problem didn't rely on getting this part right — although many of the students who ignored the harmonic well in this part continued to do so in later parts and then answered things incorrectly thereafter. For example in the second part of the problem almost half didn't pay attention to the harmonic well. The derivation of Gross-Pitaevski was done (mostly) correctly by most students. Errors in this part, though, caused trouble in later parts.

C3.1: Algebraic Topology

Question 1.

1.(a) was reasonably easy, and yet there was a surprising number of students that didn't manage to answer it. 1.(b) required familiarity with the universal coefficient theorem, and was a good test of the students understanding. Again, it was reasonably easy for those who understood that part of the course material. The first part of 1.(c) was unexpectedly easy, while the second part of 1.(c) was maybe a bit too hard.

Question 2. 2.(a) I was rather disappointed by the student's performance in that question, which was supposed to be really easy: many students completely failed to understand the notion of homotopy equivalence between spaces (confusing it with the notion of homotopy between maps). 2.(b) relied on geometric intuition, and might have disadvantaged those students whose visualisation capacity is not as strong. 2.(c) was as hard as I had intended it to be, meaning hard but yet doable by the strong students.

Question 3. 3.(a) was fun to mark, and worked really well for most. 3.(b) was generally ok, though sometimes led to messy/confused answers. 3.(c) required detailed understanding of how to justify the ring structure on cohomology. Most students fell short of what I would have liked to see, so I ended up being lenient in my way of marking that part of the question. A small number of students were able to provide perfect answers, which made me happy.

C3.2: Geometric Group Theory

Question 1. Almost all candidates attempted this question. A large majority forgot to mention, in the enumeration of the homomorphisms required in (a), (ii), that one should proceed by order of word length of the images of the generators.

In answer to question (c), (ii), many candidates attempted to prove first that the group satisfying the given assumption should be residually finite. This is not necessarily true, since, for instance, simple groups satisfy the given assumption as well.

Question 2. This question was attempted by about half of the candidates. Part (a) was well answered. In part (b), where the arguments required the use of the geometry of actions on simplicial trees, most answers were rather approximate and not well justified. A clear picture would have sufficed for (b), but even that was hard to find. Part (c) followed from a combination of (a) and (b), but only few candidates saw this.

Question 3.

Parts (a) and (c), (i) and (ii), were well answered and well explained. There were few attempts to answer part (b), even if it was a consequence of (a), (iii), and similar arguments have been seen both in lectures and in classes. The candidates attempting (c), (iii), noted, correctly, the obstruction to a quasi-isometry between the Euclidean plane and a hyperbolic space, but proceeded with a use of the Morse Lemma, instead of using the statement proved in (b), as suggested by the hint.

C3.3: Differentiable Manifolds

Question 1. This was the easiest question and attempted by all students, with many good answers. In 1(b), the ‘standard result’ the question intended was the Künneth Theorem. My preference was for people to give the full statement, not only the isomorphism $\bigoplus_{i+j=k} H^i(X) \otimes H^j(Y) \cong H^k(X \times Y)$, but also the map $\alpha \otimes \beta \mapsto \Pi_X^*(\alpha) \cup \Pi_Y^*(\beta)$, which many people omitted. If people did not state this, but used it in (c) without explanation, I deducted a mark.

Question 2. Students found the first part of (b), ‘Prove that . . .’, difficult, and no one answered this correctly. This was worth 6 marks, and I usually gave 3/6 for an attempt that showed some understanding. The rest of the question was easier. For example, in (d) you combine (b),(c) to get $\text{vol}(\mathcal{S}^{n+1}) = \frac{2\pi}{n} \text{vol}(\mathcal{S}^{n-1})$ and then give inductive formulae for $\text{vol}(\mathcal{S}^n)$ for n even or odd, which is 5 marks in the bag. Students should have been able to abandon the first part of 2(b), go on to answer the rest of the question, and score a high mark. But a significant proportion of students, after hitting a problem in 2(b), then went to pieces, and missed out on easy later marks. This happened more often for students on the MSc courses, who I guess are much less used to Oxford exam questions.

For the second part of 2(b), ‘Deduce . . .’, a point often missed was that the deletions in the domain and target of Φ have measure zero, so do not change the integrals. Most people did not notice the deletions.

For 2(c), the idea is to apply Stokes’ Theorem to the given form α , and note that $d\alpha$ is the volume form for $\mathcal{S}^1 \times B^n$, and the restriction of α to the boundary $\mathcal{S}^1 \times \mathcal{S}^{n-1}$ is $\frac{1}{n}$ times the volume form of $\mathcal{S}^1 \times \mathcal{S}^{n-1}$. I had thought that having to state Stokes’ Theorem earlier would be enough of a hint for this. However, many students instead tried to use the map Φ somehow, and got stuck.

Question 3. This was the least popular question. There was unfortunately a mistake in 3(b)(iii): the students were asked to prove that $\frac{d^2}{dt^2}(r^2 x_i(t)) = 0$, but in fact $\frac{d^2}{dt^2}(r^{-2} x_i(t)) = 0$. This also made it more difficult to answer 3(c) sensibly. This was dealt with in the marking by redistributing some of the marks for 3(b)(iii),(c) to earlier parts of the question, and giving the remaining marks as credit for a good attempt (for example, if the students assumed that $\frac{d^2}{dt^2}(r^2 x_i(t)) = 0$ and then correctly wrote down the general solution this implies in the second part of 3(b)(iii), I gave marks for this). Only 4 students answered 3(b)(ii) correctly, and so were in a position to attempt 3(b)(iii). None of them found the mistake.

C3.4 Algebraic Geometry

Q2 and Q3 were the most popular questions. Q1 was mostly solved correctly by the very few candidates who tackled it. Very few candidates managed to do Q2 (d). The point here is that the complement of U is the image of the set $S := \{(v_1, v_2) \in V \times V \mid f(v_1) = g(v_2)\} \cap \Delta_V$ in W . The set S is closed by (b), and its image in W is closed because $V \times V$ is complete. In Q3, many candidates were confused by (d) (i). The point here is that one can start with the graph of a representative of the rational map ρ ; this gives a subset of $V \times V$, and in order to obtain the variety V' , one should take the Zariski closure of this graph. Most candidates did not think of considering this Zariski closure.

C3.5 Lie Groups

Question 1. This was quite a popular question. Part (a) was standard bookwork and well done, with very few errors. Part (b) was usually done well, with only minor omissions in the argument on occasion. Part (c)(i) proved to be surprisingly challenging. Not all students spotted that it was a variation on the bookwork regarding covering maps, but those that did usually did well. Part (c)(ii), on the other hand, was done well by almost all students. Part (d), as expected, proved to be difficult for students. Several students spotted the links to covering maps as suggested by the question, but not all. Quite a few students spotted the idea for part (i), but failed to show the required condition on the differential. More students understood what was going on in part (ii), but often struggled to give a complete argument. The most common issue was not showing that the map needs to be surjective. Part (iii) proved to be the most difficult, with most students giving no or wrong answers, with only few seeing the correct answer. A common issue was that students did not know the centre of $SO(4)$ and that they again did not consider the condition on the differential.

Question 2. This was the most popular question, with almost all students attempting it. Part (a) was standard bookwork and was usually done well, but marks for lost for not saying whether objects were left-invariant vector fields or tangent vectors. Part (b)(i) provoked a mixed response. Many students did it well or had the idea, but there were a surprising number which, in particular, did not show that the resulting vector field was left-invariant (i.e. they did not use the hint) or further errors (such as that f takes the identity to the identity). Part (b)(ii) was usually done well using (b)(i). Part (c)(i) was standard bookwork and usually done well, but there were a number of errors in the definition. Part (c)(ii) was typically done well using (b)(ii), with the common error being that students did not say that conjugation was a Lie group homomorphism. Students took a variety of approaches to (d)(i). Those who chose to take the approach suggested by the hint usually did well, only failing to argue sufficiently why it is enough to restrict to the Jordan normal forms. Other students tried to use the lack of square root argument with mixed success, with the typical issue being errors in computation or incorrect choices of matrices. Students who attempted part (d)(ii) often did well, with the only error being not to argue sufficiently why one can use the exponential map on G by using (b)(ii) and the projection map.

Question 3. This was the least popular question, with relatively few attempts. Part (a) was standard bookwork but there were several common errors, including remembering the non-abelian condition and that the subgroups have to be connected in the definition of simple Lie group. As expected, part (b) provoked a mixed response. Most students had a fair attempt, but common errors included not saying that $\text{dexp}_0 = \text{id}$, and arguing why if $\sigma(X)$ preserves W then $\exp(\sigma(X))$ preserves W . Part (c)(i) was usually done well, with the only errors being not to say that $\text{dAd}_e = \text{ad}$. Part (c)(ii) was done less well, with the common error not being to consider the issue of abelian Lie groups and Lie algebra. Determining the roots in (d)(i) was usually done well. For the second half of (d)(i), the usual issue was again not considering the non-abelian condition or correctly

arguing why there are no non-trivial proper ideals in $\mathfrak{su}(2)$. Part (d)(ii) was typically not answered or not answered correctly. Several students spotted the link to quotients of products, but could not give a complete answer.

C3.11: Riemannian Geometry

Question 1. This question was about the Levi-Civita connection, and was the most popular, with almost all (13) candidates attempting it. Most candidates performed well and there were 8 marks in the 18-25 range. The bookwork was done well, and most candidates were able to see how parallel transport interacted with the covariant constant endomorphism. The final part also had many successful attempts.

Question 2. This question, on totally geodesic submanifolds received 8 attempts, of which 2 were in the 18-25 range. Showing that the fixed point locus of an involution was totally geodesic proved more tricky than expected, but there were some very good solutions. The example of an involution on complex projective space was generally well done. Some candidates mistakenly thought that a totally geodesic submanifold of an Einstein manifold was Einstein.

Question 3. This question was the most sophisticated, dealing with Myers's theorem and applications. It received 7 attempts of which 2 were in the 18-25 range. The bookwork, proving Myers's Theorem, was well done. Applying the theorem proved more challenging. Some candidates got confused about the behaviour of Ricci curvature under products and thought $S_1 \times S_2$ admitted a metric of positive Ricci because S_2 did and S_1 was flat. However other candidates answered this correctly using Myers and the fact that the fundamental group was infinite. The final part, using the idea of taking a product with a small sphere to get positive scalar curvature, proved quite difficult, but a couple of candidates did this very well, showing a good understanding of scalar curvature and fundamental group.

C3.12: Low-Dimensional Topology and Knot Theory

Question 1. This question tested knowledge of immersions, smooth manifolds, and Sard's theorem. The general level of solutions was mixed. Part (a) was generally fine. There was no complete solution for (b)(i) (even though describing an immersion of $T_2 \therefore \{x\}$ into $\mathbf{R}^2$ is not difficult) and only a few for (b)(ii). There were several essentially correct solutions for (b)(iii) and (b)(iv).

Question 2. This question tested knowledge of knot theory, the knot group, the Wirtinger presentation, and primeness of knots. The general level of solutions was mixed. There were no serious issues with part (a). There were a few correct solutions for (b)(i), and some candidates got the key ideas right for (b)(ii) (studying the intersection set between the torus and the hypothetical connected sum sphere).

Question 3. This question tested knowledge of 4-manifolds, Kirby diagrams, and the intersection form. The general level of solutions was mixed. Solutions for (a)(i) and (a)(ii) were typically correct. In (a)(iii), only a few candidates managed to show that the two forms are inequivalent, even though this was a Section A problem on Problem Sheet 4. There were several correct solutions for (b)(i), while a few for (b)(ii) and (b)(iii).

C5.2: Elasticity and Plasticity

Question 1. Unfortunately there was an error in the examination paper in Question 1 in which the Navier equation should have a factor of $\lambda + \mu$ rather than $\lambda + 2\mu$. While the extraneous factor of two does not change the methodology being examined, it made parts (a) and (b)(i) harder than intended because it affects one of the wavespeeds in part (a) and hence the coefficients in part (b)(i). To mitigate against the impact of the error, minor errors and partial progress in parts (a) and (b)(i) were marked generously using equitable marking schemes agreed in advance with the Chair. The bookwork in part (a) was well done overall, with nearly all of the candidates deriving the intended wavespeeds with only minor calculation errors or minor defects in the argument. Part (b)(i) caused more difficulties for those candidates that did not make effective use of the results of part (a) and the majority of candidates got bogged down in the algebra on the way to the dispersion relation. The tail in part (b)(ii) was unaffected by the error and received only a small number of attempts. The error in the question was corrected for the past paper archive.

Question 2. The bookwork in part (a) was reasonably well done overall though there was some confusion about the direction of the reaction force exerted by the obstacle on the string and many candidates did not justify the integration by parts nor exploit correctly the identity in part (a)(iii). Part (b)(i) was extremely well done, though only a few candidates spotted how to use it to write down the answer to part (b)(ii). There were a few good attempts at part (c), but the majority faltered in writing down the correct version of Newton's second law for the obstacle

Question 3. The book work in part (a) and the similar work in part (b) were well done by all candidates, with many of them scoring full marks. In part (c) the majority derived correctly the solution in the elastic region, but ran into difficulties applying the associated flow rule in the plastic region in the tail of the question. While the dilatation is spatially uniform in the elastic region, it is independent of time in the plastic region, and hence fixed at the value laid down by the advancing elastic/plastic free boundary. The tail was a bit too hard as set and with hindsight I should have given as a hint that the dilatation should be assumed to be continuous at the elastic/plastic free boundary as in the example in the online notes. This modification to the question was made for the past paper archive.

C5.5: Perturbation Methods

Question 1. Part (a) was well done, whereas most candidates struggled with (b) as higher order terms in the expansion needed to be taken.

Question 2. Part (a) was mostly answered well, though some candidates lost marks for not stating the distinguished limits. Part (b) was mostly answered relatively well. In part (c) many candidates lost marks by not spotting the conditions on the solutions at the various orders.

Question 3. Most candidates provided good solutions to part (a) and part (b) and many, sensibly used the results from (b) to make progress in the early parts of (c). The majority of marks were lost in computing the conditions on a in part (c).

C5.6: Applied Complex Variables

Question 1. This was the most popular question, attempted by 88% of candidates. Most answers were good. In part (a) some points were lost by not justifying the sketches of the regions. In particular a number of candidates did not state that $v = 0$ on AB and DE , or that $|w'| = 1$ on BC . There was some confusion over the labelling of the points. In part (d) the step some candidates found tricky was using double-angle formulae to convert $\cos \theta \tan \theta/2$ to $\sin \theta - \tan \theta/2$.

Question 2. This was the least popular question, attempted by 40% of candidates. Parts (a) and (b) were handled very well, with some good answers. Part (c) was also handled well, despite being less familiar. Surprisingly, there were no good answers to part (d). No candidate thought to use the results of part (b) to solve the singular integral equation, despite many casting it in that form using the hint.

Question 3. This was a popular question, attempted by 76% of candidates, and had the highest average mark. The material was challenging, but the format of the question was familiar, and there were some very good answers. The most common difficulty was candidates failing to realise that

$$\int_{-\infty}^{\infty} e^{-ikx} f(k) dk$$

is 2π times the inverse Fourier transform of f , so that taking the Fourier transform gives simply $2\pi f$.

C5.7: Topics in Fluid Mechanics

Question 1 was very popular, with all candidates starting the question and essentially all making a concerted attempt. It produced a wide spread of marks and, overall, the question was implemented well. While not in the markscheme, the possibility of a singularity near $\theta = 0$ escaped the attention of most candidates, though never to the detriment of progress in the question.

All candidates made a concerted attempt at Question 2 and the question was answered well on the whole. The final stage of the final part of the question was hindered by an incomplete specification of the physics required to simplify the boundary conditions. Consequently, the marking took this into account for those candidates that reached this stage of the question.

Question 3 was not popular, and only ever considered when Question 1 was attempted without much progress. This may explain the low marks achieved for this question in the very small number of attempts

C5.11: Mathematical Geoscience

Question 1. This question was reasonably popular and was done quite well, especially the physical interpretation. The last part was quite challenging, and a number of candidates drew various speculative curves based on things that had been seen in lectures without carefully working out the bifurcation diagram. But a few candidates gave almost complete answers. It was surprising how many candidates didn't seem to know what a graph of $\tanh(x)$ looks like, or seemed to have to go to great lengths to work this out, and this hampered progress from early on for some.

Question 2. This was the most popular question, but the construction of the characteristic diagrams proved to be quite challenging. The first part was done fine by most candidates. A common difficulty in part (b) was not being clear about which initial data were being used for the characteristics at which stage - the answers often became a sprawling assortment of characteristics that applied in overlapping regions. This was not helped by the fact that many people drew their characteristic diagram the wrong way round, or kept flipping their axes. Quite a few people made more progress with part (c), realising that the characteristics simply split into those on which $c = 0$ and those on which $c = 1$, but most candidates then had difficulty tracing those characteristics clear due to the incomplete or confused answers for h in part (b).

Question 3. This question was slightly less popular but was generally done quite well by those that attempted it. The first part was found fairly straightforward. Solving the quasi steady model in part (b) was also generally done well, and it was pleasing to see many candidates utilising the solution to correctly interpret the timing of ice thickness maxima/minima in terms of seasons (Spring/Autumn). Part (c) was also generally done well, with many candidates realising the utility of characteristics in a setting they hadn't previously seen. The last part about the net production was however harder, with many candidates thinking about the time-integral of h itself rather than the growth rate.

C6.1: Numerical Linear Algebra

Question 1. Q1 was quite popular. Some candidates worked out the least-squares solution via the QR factorisation. This is fine, but some then failed to note that $A = QR$ yields $A = Q$ and $R = I$. (iii) Many used insufficient arguments to justify the V factor in the SVD of A_1 and A_2 are the same. Q1(b) Stability appears to always be challenging for many. The key point here is to see that a small backward error would immediately imply small error in the singular values, by Weyl's theorem. This by contrast does not hold for eigenvalues of nonsymmetric matrices (b-iv).

Question 2. Q2 was the most popular question. The final question was essentially bookwork (given in lecture notes and lecture), but unsurprisingly not many got to the end. Part (b-iv) also seemed challenging to most. There was a typo in the definition of the Frobenius norm $\|A\|_F = \sqrt{\sum_{i,j} |A_{i,j}|^2}$ in Q2, where the square root was missing. Almost all candidates used the correct definition in their scripts. Where a few candidates used the incorrect/printed definition $\|A\|_F = \sum_{i,j} |A_{i,j}|^2$, full mark was awarded if the argument was otherwise correct.

Question 3. Q3 was somewhat less popular, but was still attempted by about half of the candidates, and had a slightly higher average mark. (iii) was done with a good success rate, which was a pleasant surprise. Perhaps (b-iv) was not difficult for a final problem, and the other problems are bookwork or a slight variant.

C7.4: Introduction to Quantum Information

Question 1. Was generally well answered by those who chose it, and the mistakes seemed to be very similar amongst most students. Quite a few students struggled with the very last part of part (b), and claimed that the rank was always 2. In part (c), many students only got 2 marks due to only showing one direction of the if and only if statement, and there were quite a lot of circular arguments. Part (d) was generally very well done. Parts (e) and (f) seemed to be the source of some confusion (perhaps the wording could have been improved), with many students not actually writing down what the constituent states $|\psi_1$ and $|\psi_2$ were but instead merely noting that the output states were indeed separable. However, quite a few students successfully gave the answer to part (f) in part (e) anyway. Finally, part (g) was surprisingly well answered by many students, with almost all who attempted it gaining at least 3 or 4 points.

Question 2. Contained a typo in the second equation defining decoherence, but it could at most have affected parts (b) and (c). The remainder of the question could still be answered using the expression given in part (c). Most students were able to self-correct the typo, as this part of the question was very similar to material covered in class. (The irony is that this question focuses on error correction.)

Out of the 20 students who attempted Question 2, six were, to varying degrees, affected by the typo, as reflected in their scripts. For these students, parts (b) and (c) were marked based on the method used, which is independent of the typo. This turned out to be a sufficient adjustment, counteracting the effect of the typo and enabling affected candidates to perform similarly on Q2 to those who were unaffected. Their performance on Q2 was also on par with that on the other questions.

Otherwise, almost all students answered part (a) correctly. Parts (d), (f), and (g) were also generally well done. However, many students struggled with part (e), failing even to complete the first step — namely, substituting the given expression for v into the probability of obtaining $(0, 0)$ — and consequently scored almost no marks.

A more explicit statement that t represents the interaction time might have helped. On the other hand, those students (around seven) who had a good physical understanding of the context were able to score nearly full marks on these questions.

Statistically, this question does not stand out; the average marks for Q2 are comparable to those of the other two questions.

Question 3. Was of medium difficulty. Most students had no problems with parts (a), (c), (d), and (f). Part (b), which required a geometric visualisation of the three elementary operations on a single qubit, was generally well answered, although describing the Hadamard gate in geometric terms proved surprisingly challenging for some. A significant number of students struggled with part (e). Those who answered correctly often did so in a rather pedestrian way, by exhaustively considering the four possible ways of encrypting and decrypting the state. The final two parts, (g) and (h), proved difficult for all who attempted them. In part (g), most students recognised that the T gate is not a Clifford gate, but only a few were able to explain the origin of the 50%

success rate. No one provided a fully satisfactory answer to part (h), which required the observation that in the first round, the T and $T^\dagger$ gates are equally likely to be implemented, and that the T gate can be recovered from the $T^\dagger$ gate by composing it with the S gate (a Clifford gate). The textbook-style parts of this question were, by and large, well done. However, the remaining parts, which required a more creative approach, proved challenging, with only a handful of students offering partial answers.

C7.5: General Relativity I

Question 1.

This question was attempted by every student and was the question most similar to previous exam questions.

In general people picked up full marks for parts a(i) and a(ii) being simple definitions. On the whole a(iii) was also very well done, with only a few students not getting maximum points for it. Part a(iv) was mostly well done too however a handful of students did not explain why they could strip off the vector field. Some also confused the transformation of a vector field here.

Part b was not as well done and weaker students lost their marks here generally. For b(i) number of students did not give the correct definition of normal coordinates, either writing only that the connection coefficients vanished or only that the metric looked like flat space. Some did not explain that the normal coordinates were valid at a point making it seem that they could be valid everywhere. b(ii) generally separated the stronger from the weaker students. If the students managed to correctly explain normal coordinates they typically picked up most marks for this part. However a large number of students did not state that they had worked in normal coordinates but because this is a tensorial equation it is valid in all coordinate systems and therefore holds in general, this lost them a mark. For the weaker students they did not realise that derivatives of the Christoffel symbols were non-zero and so ended up with the left-hand side vanishing. They typically justified this by saying that the right-hand side also vanishes, however neither of these statements is true. Most who attempted part b(iii) got most of the marks on offer. Some students used normal coordinates to erroneously argue that the Riemann tensor terms vanished and hence it was obvious.

Question 2.

The second most popular question and the one with the highest average mark. Most received all four marks for stating Birkhoff's theorem correctly and explaining that it means that the Schwarzschild solution is the solution outside any spherically symmetric distribution of matter (in a vacuum). Those that lost marks here left out one or more of the adjectives in Birkhoff's theorem.

Part b was almost universally well done. Almost everyone correctly obtained the three conserved quantities for part b(i). For b(ii) those that lost marks did not explain why one could choose the correct initial conditions or just stated $\theta = \pi/2$. Most did well here. The strictly illegal method of differentiating the Lagrangian was the most popular method and was accepted even without comment about issues at $\dot{r} = 0$. Some used this method but did not differentiate both sides with respect to τ and therefore ended up with $\dot{r}$ terms remaining.

In general most said $\ddot{r} = 0$ for a circular orbit. Surprisingly, having stated this, a large number of students then went back to looking at the Lagrangian, finding an expression for $\dot{r}^2 + V_{\text{eff}} = E^2$ and then finding the minima of V_{eff} . This is of course correct but meant

they spent extra time rather than using part b(iii). If the result for $h(r)$ was incorrect before propagated errors because of this were ignored and marks were awarded for correctly finding the roots for their $h(r)$. For c(ii) those that went back to computing $\dot{r}^2$ suffered a bit because it was not obvious how to simplify things as easily, though most did in the end. Students lost marks because they only looked at the stable orbit, neglecting to mention anything about the other orbit. Others instead correctly gave the conditions for when the orbits would be stable and unstable but then did not make contact with the location of the orbits computed in c(i).

This was the hardest part of the question. If c(iii) was done correctly then most did c(iv) correctly too. One common issue was trying to go from the period of the orbit to the proper time for the period by using the constrained Lagrangian, setting $\dot{\phi} = 0$ to get dt in terms of $d\tau$. This was wrong since $d\phi \neq 0$. Others gave a result still in terms of the Energy or Angular momentum when the question asked for it in terms of the root and the mass M .

Question 3.

The least popular question though still a healthy number of attempts. Parts a (i) and a(ii) were almost always done satisfactorily, though a few forgot the definition of an integral curve. a (iii) when attempted was done well. Some just stated that the Lie derivative measures the failure of the flow to commute rather than doing any computations.

Those that persevered through the part a typically did well with part b. b (i) was a free mark and part b (ii) though a bit fiddly was done well. For part b(iii) the use of integration by parts was done poorly. Given that there is a connection rather than a partial derivative a little more care is needed to use integration by parts and this was almost always ignored losing a mark.

C7.6: General Relativity II

Question 1. This was only attempted by one student who did very well in the question. Despite seeming intimidating the question is actually quite simple. Part a is bookwork which was given in class. Though part b looks like it gets nasty as you progress and the polarisation in the hint looks intimidating there is only one term that contributes and so it all truncates. Part c was well done with full marks obtained.

Question 2. Everyone but 1 student did this question. a (i) was correctly done by everyone, but interpreting the horizons was not as well done as expected. For a (iii) many got the idea behind the change of coordinates but could not do the integral. For the most part the Killing horizon was defined correctly though a few students did not say null. For part a (v) some students only showed it was null and did not discuss it being a Killing vector. Others did not use the change of coordinates they had found in a(iii) so they obtained a dual vector which was not Killing and ended up confused. b (i) was done well by almost everyone. b(ii) was on the whole correct however a small minority set $L = 1$ and then solved rather than $g_{\mu\nu} \mu^\nu = 1$. This led to an additional term in their result. b (iii) had been seen in a similar form in tutorials however it was rather polarising. Some students were able to get full marks, others got stuck in the logic of the question and scored only 1 mark.

Question 3. The most popular question. On the whole people picked up the most points from part a. For a (iii) you were guided in how to do it by your computations in a (ii) but some used another method which was fine but took longer. The metric is very similar to Schwarzschild with t and r interchanged. Despite this, it caused students quite a few problems. For b (i) a few students fell for making $r(0,)$ rather than the correct range $r(,)$. The bookwork part in b(ii) was well done. A few struggled to perform the change of coordinates in b (iii). Rather than defining a new time coordinate they tried to define a new radial coordinate like a tortoise coordinate. They ended up trying to solve an impossible equation. b(iv) was done well by stronger students and middle range students picked up a few marks. The Kruskal like coordinates are the same as the ones from Schwarzschild studied extensively in lectures one just needs to replace t and r . There were a large number of different Penrose diagrams produced. A few managed to get the correct answer, some even noted that it was a 90 degree rotation of Schwarzschild. If the students did the steps correctly, or outlined the correct steps, despite not drawing the correct diagram they still picked up 2 or 3 marks. If the diagram was wrong but labelled correctly students got 1 mark for this.

C7.7: Random Matrix Theory

Question 1 was well done in general and attempted by most students. Part (a) involved mostly bookwork on the GOE ensemble and Wick's theorem. For Part (b) most students got (i) right using the symmetry. For (ii), few saw that Wick's can be applied easily and that the dominant term come from the non-crossing partitions. For (c), many students were too brief in explaining that the matrix is non-negative definite. For the moments, few students were able to compute the third moments using Wick's and the fact that non-crossing partitions are dominant. Some used the general formula from the Marchenko-Pastur which is acceptable but not as straightforward. Question 2 was also attempted by most students. It involves the particular case of a 3×3 GUE matrix. Part (a) involves bookwork. To derive the orthogonal polynomials, some students relied on the general formula which was not necessary as they can be computed from scratch. This was acceptable. Part (b) was well done but few students mentioned that only the first two correlation functions are non-trivial as there are 3 eigenvalues. For part c, (i) was easy bookwork. Very few students were able to get full marks on part (ii) even though the function was given in Part (ii). Question 3 was attempted by few students (around 10). It involves Dyson Brownian which was covered in lectures and in revisions. From those who attempted, around half got the SDE right in (b). Only one student understood that the convergence in part c is related to the stationary uniform distribution discussed in (a). Only two students got full marks in (d) even though it was a question that appeared in problem sheets.

E. Comments on performance of identifiable individuals

Prizes

Prizes were awarded to the following candidates:

Aryaman Babbar (St Edmund Hall)

Yaprak Onder (Lincoln College)

Samuel Bates (Wadham College)

Mitigating Circumstances Notices to Examiners

The Examiners received 17 applications regarding mitigating circumstances.

The Examiners considered the applications carefully and agreed appropriate action.

F. Names of members of the Board of Examiners

Examiners:

Prof Christopher Beem (Chair, Mathematical Institute, University Of Oxford)
Prof John Magorrian (Department of Physics, University of Oxford)
Prof Mark Mezei (Mathematical Institute, University of Oxford)
Prof Steve Simon (Department of Physics, University of Oxford)
Prof Toby Wiseman (Blacklett Laboratory, Imperial College London)
Prof Steve Tobias (Department of Physics, University of Edinburgh)

Assessors:

Dr Adam Caulton
Dr Akshay Yellespur Srikant
Prof Aleks Kissinger
Prof Alexander Schekochihin
Prof Andre Lukas
Prof Andrei Starinets
Prof Andrew Daley
Prof Andrew Dancer
Dr Andrew Mummery
Prof Andrew Wells
Dr Anton Sokolov
Prof Ard Louis
Dr Aydin Deger
Dr Balint Koczor
Prof Bence Kocsis
Prof Caroline Terquem
Prof Chris Beem
Dr Chris Hamilton
Prof Chris Hays
Dr Christopher Couzens
Dr Christopher Timpson
DR Daniel Kennedy
Prof David Alonso
Dr Dominik Hahn
Dr Dumitru Calugaru
Prof Ed Hardy
Dr Erik Panzer
Prof Fabrizio Caola
Prof Fernando Alday
Dr Gabriel Wong

Prof Gavin Salam
Dr Giulio Gambuti
Prof Ian Hewitt
Prof J C Seamus Davis
Prof James Binney
Dr James Read
Prof James Sparks
Prof Jason Lotay
Prof John Chalker
Prof John Magorrian
Prof John March-Russell
Prof John Wheeler
Prof Joseph Conlon
Dr Katy Clough
Dr Linnea Grans-Samuelsson
Prof Lionel Mason
Dr Mario Reig
Prof Mark Mezei
Prof Michael Barnes
Prof Michele Levi
Prof Nayara Fonseca
Dr Nick Jones
Dr Oliver Lunt
Dr Paul Balduf
Prof Paul Dellar
Prof Pedro Ferreira
Prof Peter Grindrod
Prof Peter Norreys
Prof Pieter Bomans
Prof Prateek Agrawal
Prof Ramin Golestanian
Prof Renaud Lambiotte
Dr Romain Ruzziconi
Rusko Ruskov
Prof Sergii Strelchuk
Prof Seyed Faroogh Moosavian
Dr Sheng-jie Huang
Prof Shivaji Sondhi
Dr Silvia Zanolì
Prof Steve Simon
Tevz Lotric
Prof Thaddeus Komacek
Prof Tim Woollings

Dr Vijay Balasubramanian
Prof Xenia de la Ossa
Dr Zhenghao Zhong
Dr Zhenyu Cai