SH2372 General Relativity, 6 credits – Period 2, Fall 2021, Academic Year 2021–2022

Examiner and course responsible

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Teachers

- Professor Tommy Ohlsson, lectures (12 x 2h.)
- Linda Tenhu, exercises (9 x 2h.)

Literature

The course literature consists of the following books:

Guidry	Mike Guidry, *Modern General Relativity – Black Holes, Gravitational Waves, and Cosmology*, Cambridge (2019)
Blennow (MB)	Mattias Blennow, *Mathematical Methods for Physics and Engineering*, CRC Press (2018)
Blennow & Ohlsson (B&O)	Mattias Blennow and Tommy Ohlsson, *300 Problems in Special and General Relativity – With Complete Solutions*, Cambridge (2021)

Guidry will be used as the main course book. MB and B&O will be used for the exercises. Note that it is not necessary to have your own copy of MB.

Additional literature

Further recommended reading:

Carroll	Sean M. Carroll, *Spacetime and Geometry – An Introduction to General Relativity*, Pearson (2004)
Cheng	Ta-Pei Cheng, *Relativity, Gravitation and Cosmology – A Basic Introduction*, 2nd ed., Oxford (2009)
Schutz	Bernard Schutz, *A First Course in General Relativity*, 2nd ed., Cambridge (2009)
Wald	Robert M. Wald, *General Relativity*, Chicago (1984)

Carroll, Cheng, Schutz, and Wald can be used as alternative books to Guidry or as complements.

Course contents

- Local coordinates on manifolds. Covariant and contravariant vector and tensor fields. (Pseudo-) Riemann metric.
- Covariant differentiation (Christoffel symbols, Levi-Civita connection). Parallel transport. Curved spaces. Lie derivatives and Killing vector fields.
- Basic concepts in general relativity.
- Schwarzschild space-time.
- Einstein's field equations.
- The energy-momentum tensor.
- Weak field limit.
- Experimental tests of general relativity.
- Gravitational lensing. Gravitational waves.
- Introductory cosmology (including the Friedmann–Lemaître–Robertson–Walker metric), including inflation and dark energy.

About the lectures, the exercises, the quizzes, and the final exam

The material presented in the lectures is based on similar material that is covered in the books by Guidry, Carroll, Cheng, Schutz, and Wald. Lecture notes will be posted on Canvas after each lecture. Note that the material for the first four lectures is extensive, and the lecturer will not be able to present all material at these lectures, but it will be included in the lecture notes.

The exercises are based on problem solving. The teaching assistant will present the problems and their solutions to some of the listed problems during the exercises (about four problems at each exercise). All listed problems are also given as PDF files with problem statements and solutions on Canvas. For the listed problems that are not solved during the exercises, you are encouraged to solve them on your own. For some exercises, there are also listed some additional problems that are not posted as PDF files on Canvas.

The course will be examined through continuous examination. During the course, there will be four scheduled one-hour quizzes with six conceptual questions and/or smaller problems each. Each quiz can give up to 10 % of the total examination score, which means that all four quizzes can give up to 40 % of the total examination score. At the end of the course, there will be a final written exam consisting of six full computational problems (similar to the problems that are solved during the exercises). The final written exam can give up to 60 % of the total examination score. In order to pass the course (and the examination TEN1), you need to achieve at least 50 % of the total examination score. This means that the quizzes are not mandatory, i.e. you can pass the course without the quizzes. However, you cannot pass the course without the final written exam, i.e. the final written exam is a requirement. Please see *Examination* and *Grades*.

Examination

			Examination score
Q1	Quiz 1	6 conceptual questions and smaller problems	10 %
Q2	Quiz 2	6 conceptual questions and smaller problems	10 %
Q3	Quiz 3	6 conceptual questions and smaller problems	10 %
Q4	Quiz 4	6 conceptual questions and smaller problems	10 %
FE	Final written exam	6 full computational problems	60 %
			100 %

Each quiz is given at a specific occasion for one hour on Canvas and only one time during the academic year. The results of the quizzes are valid during the whole academic year. The final written exam will be given twice during the academic year.

Grades

Grade	*Examination score*
A	≥ 90 %
B	≥ 80 %
C	≥ 70 %
D	≥ 60 %
E	≥ 50 %
F	< 50 %

If you do not have any results from the quizzes, then the highest grade that you can obtain in the course is D. Since the highest result on the quizzes corresponds to 40 %, you cannot pass the course without taking the final written exam.

Good luck with the course!

Lecture, exercise, quiz, and final exam plan

L = lecture, E = exercise, Q = quiz, FE = final exam

L1 [Mon. 1/11, 13-15] Local coordinates on manifolds. Covariant and contravariant vector and tensor fields.
Recommended reading: Guidry Chapter 2; Carroll 1.4–1.7, 2.3–2.5, 3.2; Cheng 5.2, 13.1; Schutz Chapter 5; Wald 2.2–2.4

L2 [Wed. 3/11, 10-12] (Pseudo-) Riemann metric. Covariant differentiation (Christoffel symbols, Levi-Civita connection).
Recommended reading: Guidry Chapter 3; Carroll 2.1–2.2, 2.6–2.10, Appendix A; Cheng 13.2–13.3; Schutz 6.1–6.3; Wald 2.1, Appendix A, C.1–C.2

E1 [Mon. 8/11, 13-15] MB 1.50, 2.10, 2.20, 2.21, 2.29, 9.1, 9.4, 9.7, 9.9, 9.10 (10 problems)
Additional problems: MB 2.1, 2.12, 2.26, 9.2, 9.3, 9.5, 9.11

L3 [Wed. 10/11, 10-12] Parallel transport. Curved spaces. Lie derivatives and Killing vector fields.
Recommended reading: Guidry 7.4–7.8, 8.4, 5.6; Carroll 3.3–3.10; Cheng 5.3; Schutz 6.4–6.7, 7.4; Wald Chapter 3, C.3

E2 [Mon. 15/11, 13-15] B&O Some differential geometry … & Christoffel symbols, … 2.5 [2.4], 2.9 [2.8+2.9], 2.33 [2.31+2.32+2.33], 2.35 [2.35], 2.15 [2.14], 2.39 [2.39+2.40], 2.16 [2.15], 2.41 [2.43], 2.45 [2.48], 2.50 [2.53] (10 problems)
Additional problems: MB 9.14, 9.15, 9.16, 9.17, 9.18, 9.24, 9.25, 9.19, 9.21, 9.26, 9.27, 9.29, 9.34, 9.35, 9.36

Q1 [Tue. 16/11, 16-17] Quiz 1 (based on lectures L1–L3 and exercises E1–E2)

L4 [Wed. 17/11, 10-12] Basic concepts in general relativity. Schwarzschild space-time.
Recommended reading: Guidry 7.1–7.2, 6.1–6.3, 9.1; Carroll 4.1, 4.7, 5.1–5.2; Cheng 6.1, 7.1; Schutz 7.1–7.3, 10.1; Wald 1.3–1.4, 4.1, 6.1

E3 [Wed. 17/11, 13-15] B&O Killing vector fields 2.63 [2.64], 2.65, 2.69 [2.70], Schwarzschild metric 2.72 [2.73], 2.73, Metrics, … 2.78 [2.81], 2.79 [2.82], 2.80 [2.83] (8 problems)

L5 [Thu. 18/11, 15-17] Schwarzschild space-time (continued).
Recommended reading: Guidry 9.3, 11.1–11.4; Carroll 5.3–5.4, 5.6–5.7, 6.1–6.3; Cheng 8.1–8.2, 14.1, 14.3, Schutz 10.2, 10.4–10.6, 11.2; Wald 6.2, 6.4, Chapter 9

L6 [Mon. 22/11, 13-15] Experimental tests of general relativity.
Recommended reading: Guidry 6.4–6.5, 9.2, 9.4–9.8; Carroll 5.5; Cheng 7.3.1, 8.3; Schutz 10.7, 11.1; Wald 6.3

E4 [Wed. 24/11, 10-12] B&O Frequency shifts 2.125 [2.132], 2.126 [2.133], Metrics, … 2.93 [2.94], 2.97 [2.98], 2.98 [2.100], Kruskal-Szekeres … 2.108 [2.109], Schwarzschild metric 2.76 [2.77] (7 problems)

Q2 [Wed. 24/11, 16-17] Quiz 2 (based on lectures L4–L6 and exercises E3–E4)

L7 [Thu. 25/11, 15-17] Einstein's field equations. The energy-momentum tensor.
Recommended reading: Guidry 8.5, 7.3; Carroll 4.2–4.6, 5.8; Cheng 14.2; Schutz 8.1–8.2, 10.3; Wald 4.3

L8 [Mon. 29/11, 13-15] Weak field limit.
Recommended reading: Guidry 8.1–8.3, 8.6–8.8, 22.2; Carroll 7.1–7.3; Cheng 6.2–6.3, 15.1–15.2; Schutz 8.3–8.4; Wald 4.4

E5 [Wed. 1/12, 10-12] B&O Maxwell's equations … 2.53 [2.57], 2.57 [2.61], 2.58 [2.62], 2.59 [2.106], Weak field … 2.114 [2.117], 2.116 [2.120], 2.118 [2.122] (7 problems)

L9 [Thu. 2/12, 15-17] Gravitational lensing. Gravitational waves.
Recommended reading: Guidry 17.7, 9.9, 22.1, 22.3–22.6; Carroll 8.6, 7.4–7.7; Cheng 7.2, 7.3.2, 15.3–15.4; Schutz Chapter 9; Wald 6.3, 4.4

E6 [Mon. 6/12, 13-15] B&O Gravitational lensing 2.119 [2.126], Metrics, … 2.82 [2.118], Gravitational waves 2.133, 2.135 (4 problems)

Q3 [Tue. 7/12, 16-17] Quiz 3 (based on lectures L7–L9 and exercises E5–E6)

L10 [Wed. 8/12, 10-12] Introductory cosmology (including the Friedmann–Lemaître–Robertson–Walker metric), including inflation and dark energy.
Recommended reading: Guidry Chapters 16.1, 18; Carroll 8.1–8.3; Cheng 9.1, 9.3–9.4, 10.1; Schutz 12.1–12.2; Wald 5.1–5.2

E7 [Thu. 9/12, 15-17] B&O Metrics, … 2.81 [2.84], 2.103 [2.103], Frequency shifts 2.131 [2.138], Cosmology … 2.146 [2.147] (4 problems)
Additional problems: Guidry 19.1, 19.2, 19.6

L11 [Fri. 10/12, 10-12] Introductory cosmology (including the Friedmann–Lemaître–Robertson–Walker metric), including inflation and dark energy (continued).
Recommended reading: Guidry Chapter 16.2, 17.1–17.5, 19, 17.11–17.13, 21.3; Carroll 8.4–8.5, 8.7–8.8; Cheng 10.2–10.3, 14.4, 11.1–11.5; Schutz 12.3–12.4; Wald 5.3–5.4

E8 [Mon. 13/12, 13-15] B&O Cosmology … 2.147 [2.148], 2.144 [2.146], 2.148 [2.149], 2.149 [2.150] (4 problems)
Additional problems: Guidry 21.2, 21.5

L12 [Wed. 15/12, 10-12] Extra

E9 [Wed. 15/12, 13-15] Old exams

Q4 [Thu. 16/12, 16-17] Quiz 4 (based on lectures L10–L11 and exercises E7–E8)

FE [Mon. 17/1, 8-13] Final written exam

All lectures and all exercises will take place in room FD41 in Albanova.
All quizzes will take place on Canvas.
The final written exam will take place in rooms FA31 and FA32 in Albanova.

Problems in […] refer to the old numbering of problems in the student's manual Mattias Blennow and Tommy Ohlsson, *Relativity Theory – A Collection of 300 Problems in Special and General Relativity Theory with Complete Solutions*, KTH (2020).
