Annexe A: New/Revised Course Content in OBTL+ Format

Course Overview

Expected Implementation in Academic Year	AY2022-2023
Semester/Trimester/Others (specify approx. Start/End date)	Semester 2
Course Author * Faculty proposing/revising the course	Chen Yu
Course Author Email	y.chen@ntu.edu.sg
Course Title	Introduction to General Relativity
Course Code	PH4508
Academic Units	3
Contact Hours	39
Research Experience Components	Not Applicable

Course Requisites (if applicable)

Pre-requisites	PH2102 and PH2104
Co-requisites	
Pre-requisite to	
Mutually exclusive to	
Replacement course to	
Remarks (if any)	

Course Aims

Einstein's general theory of relativity is the accepted classical theory of gravity. This course aims to introduce to you the essentials of general relativity: its basics concepts, mathematical formulation and observational consequences. Upon completing the course, you will be able to develop an understanding of the geometrical structure and physical implications of this theory. The geometrical framework of general relativity and analytical tools that you will learn in this course will be of wide use across subjects in theoretical physics and some branches of mathematics as well.

Course's Intended Learning Outcomes (ILOs)

Upon the successful completion of this course, you (student) would be able to:

ILO 1	Explain the space-time structure of special relativity and show that the Minkowski metric is invariant under Lorentz transformations
ILO 2	Describe the Equivalence Principle and deduce its consequences such as the bending of light by a gravitational field and the gravitational redshift effect
ILO 3	Recognise that gravity is formulated in terms of the geometry of spacetime pseudo-Riemannian manifold
ILO 4	Operate with covariant vectors, contravariant vectors and tensors in general, and perform basic operations on tensors, such as tensor addition, tensor product, tensor contraction and raising and lowering indices of a tensor
ILO 5	Derive Christoffel symbols from space-time metric tensor by imposing the torsion-free and metric compatibility conditions
ILO 6	Solve problems with covariant derivatives, geodesic equation, Riemann curvature tensor, Ricci and Einstein tensors
ILO 7	Use the minimal-coupling principle to explain how gravity effects matter fields
ILO 8	Interpret the components of the stress-energy tensor and express the stress-energy tensor for a perfect fluid source
ILO 9	State Einstein's field equation, derive the number of independent equations it gives rise to and recover the Newtonian limit from it
ILO 10	Derive the Schwarzschild metric as a solution to Einstein's field equation and examine its properties such as its geodesics
ILO 11	Apply Einstein's field equation to analyse the three classical tests of general relativity: the gravitational redshift of light , bending of light by the Sun and precession of the perihelion of the orbits of Mercury

Course Content

Special Relativity (SR)

Lorentz Transformations

Minkowski Metric

4-Vectors in Minkowski Spacetime

Relativistic Dynamics

Electromagnetic Field Tensor

Manifolds and Tensors (MT)

Equivalence Principle

Spacetime Manifold

Contravariant and Covariant Vectors

Tensors

Metric Tensor

Covariant Derivative

Chirstoffel Symbols

Parallel Transport

Geodesic Equation

Riemann Curvature Tensor

Ricci Tensor

Einstein Tensor

Einstein's Field Equation (EFE)

Minimal-Coupling Principle

Stress-Energy Tensor

Perfect Fluid

Einstein's Field Equation

Cosmological Constant

Schwarzschild Solution

Geodesics of the Schwarzschild Solution

Classical Tests of General Relativity (CTGR)

Gravitational Redshift Effect

Bending of Light by the Sun

Procession of the Perihelion of the Orbits of Mercury

Reading and References (if applicable)

Primary

1. B. Schutz, A first course in general relativity. W. H. Freeman and Company (2009). ISBN-13: 978-0521887052
2. S. M. Carroll, Spacetime and geometry: An introduction to general relativity. San Francisco, USA: Addison-Wesley (2004). ISBN-13: 978-1108488396

Supplementary

3. J. Hartle, Gravity: An Introduction to Einstein's General Relativity. Addison-Wesley (2003). ISBN-13: 978-0805386622
4. C. W. Misner, K. S. Thorne, and J. A. Wheeler, Gravitation. W. H. Freeman, San Francisco (1973). ISBN-13: 978-0691177793
5. S. Weinberg, Gravitation and cosmology: principles and applications of the general theory of relativity. John Wiley (1972). ISBN-13: 978-8126517558
6. R. M. Wald, General relativity. Chicago University Press (1984). ISBN-13: 978-0226870335

Planned Schedule

Week or Session	Topics or Themes	ILO	Readings	Delivery Mode	Activities
1	Lorentz Transformations; Minkowski Spacetime	SR 1	Textbook, Lecture notes	In-person	
2	Four Vectors; Electromagnetic Field Tensor	SR 1	Textbook, Lecture notes	In-person	
3	Equivalence Principle	MT 2,3	Textbook, Lecture notes	In-person	Tutorial
4	Manifolds and Tensors	MT 3,4	Textbook, Lecture notes	In-person	
5	Metric Tensor	MT 4,5	Textbook, Lecture notes	In-person	Tutorial
6	Covariant Derivative; Parallel-Transport; Geodesic Equation	MT 5,6	Textbook, Lecture notes	In-person	
7	Curvature	MT 6	Textbook, Lecture notes	In-person	Tutorial
8	Minimal-Coupling Principle	EFE 7	Textbook, Lecture notes	In-person	Midterm Test
9	Stress-Energy Tensor; Einstein's Field Equation	EFE 8,9	Textbook, Lecture notes	In-person	
10	Newtonian Limit; Cosmological Constant	EFE 9	Textbook, Lecture notes	In-person	Tutorial
11	Schwarzschild solution and its properties	EFE 10	Textbook, Lecture notes	In-person	

Week or Session	Topics or Themes	ILO	Readings	Delivery Mode	Activities
12	Classical Tests of General Relativity I	EFE 11	Textbook, Lecture notes	In-person	Tutorial
13	Classical Tests of General Relativity II	EFE 11	Textbook, Lecture notes	In-person	

Learning and Teaching Approach

Approach	How does this approach support you in achieving the learning outcomes?
Lectures	Reviews of previous materials will be done first. The emphasis is on laying out the logic and the present material will follow on with the logical flow. Some conceptual questions will be interspersed during the lectures.
Tutorial	You take turns to do individual presentations during tutorials, explaining your solutions step by step. The instructor gives comments and helps to clarify any doubts.
Homework	Working out homework problems independently is an essential part of the learning process for the course. Discussions with peers and seeking help online are allowed only after you have attempted hard but failed. You can have a refined understanding of the basic ideas and also sharpen your calculation skills in the learning process.

Assessment Structure

Assessment Components (includes both continuous and summative assessment)

No.	Component	ILO	Related PLO or Accreditation	Weightage	Description of Assessment Component	Team/Individual	Rubrics	Level of Understanding
1	Summative Assessment (EXAM): Final exam(Final Examination)	All	Competence (1,3,4)	50		Individual	Analytic	Extended Abstract
2	Continuous Assessment (CA): Test/Quiz(CA1: Midterm Test)	Range (SR 1, MT 2-6)	Competence (1,3,4)	30		Individual	Analytic	Extended Abstract
3	Continuous Assessment (CA): Assignment(CA2: Assignments)	All	Competence (1,3,4) Creativity (1) Communication (3) Character (3)	20		Individual	Analytic	Extended Abstract

Description of Assessment Components (if applicable)

Formative Feedback

Quick questions are to be expected from the instructor during tutorial lesson discussions and formative feedback is given. Homework will be graded and feedback will be given, with an emphasis on key concepts involved, common mistakes made and alternative methods. Feedback is also given after each quiz on the common mistakes and level of difficulty of the problems. Past exam questions and examiner's report are made available for students.

NTU Graduate Attributes/Competency Mapping

This course intends to develop the following graduate attributes and competencies (maximum 5 most relevant)

Attributes/Competency	Level
Creative Thinking	Intermediate
Curiosity	Intermediate
Problem Solving	Intermediate

Course Policy

Policy (Academic Integrity)

Good academic work depends on honesty and ethical behaviour. The quality of your work as a student relies on adhering to the principles of academic integrity and to the NTU Honour Code, a set of values shared by the whole university community. Truth, Trust and Justice are at the core of NTU's shared values. As a student, it is important that you recognize your responsibilities in understanding and applying the principles of academic integrity in all the work you do at NTU. Not knowing what is involved in maintaining academic integrity does not excuse academic dishonesty. You need to actively equip yourself with strategies to avoid all forms of academic dishonesty, including plagiarism, academic fraud, collusion and cheating. If you are uncertain of the definitions of any of these terms, you should go to the academic integrity website for more information. On the use of technological tools (such as Generative AI tools), different courses / assignments have different intended learning outcomes. Students should refer to the specific assignment instructions on their use and requirements and/or consult your instructors on how you can use these tools to help your learning. Consult your instructor(s) if you need any clarification about the requirements of academic integrity in the course.

Policy (General)

Policy (Absenteeism)

Absence Due to Medical or Other Reasons
If you are sick and unable to attend your class / Mid-term quizzes, you have to:

1. Send an email to the instructor regarding the absence and request for a replacement class and make-up mid-term quizzes.
2. Submit the original Medical Certificate* or official letter of excuse to administrator.
3. Attend the assigned replacement class (subject to availability) and make-up mid-term quizzes.

* The medical certificate mentioned above should be issued in Singapore by a medical practitioner registered with the Singapore Medical Association.

Policy (Others, if applicable)

Diversity and inclusion policy

Integrating a diverse set of experiences is important for a more comprehensive understanding of science.

It is our goal to create an inclusive and collaborative learning environment that supports a diversity of perspectives and learning experiences, and that honours your identities; including ethnicity, gender, socioeconomic status, sexual orientation, religion or ability.

To help accomplish this:

- If you are neuroatypical or neurodiverse, have dyslexia or ADHD (for example), or have a social anxiety disorder or social phobia;
- If you feel like your performance in the class is being impacted by your experiences outside of class;
- If something was said in class (by anyone, including the instructor) that made you feel uncomfortable;

Please speak to your teaching team, our school pastoral officer or a peer or senior (either in-person or via email) about how we can help facilitate your learning experience.

As a participant in course discussions, you should also strive to honour the diversity of your classmates. You can do this by: using preferred pronouns and names; being respectful of others opinions and actively making sure all voices are being heard; and refraining from the use of derogatory or demeaning speech or actions.

All members of the class are expected to adhere to the NTU anti-harassment policy. if you witness something that goes against this or have any other concerns, please speak to your instructors or a faculty member.