Nanyang Technological University
Division of Physics and Applied Physics

Academic Year	2019/20	**Semester**	2
Course Coordinator	Dr. Chen Yu		
Course Code	PH4508		
Course Title	Introduction to General Relativity		
Pre-requisites	PH2102 and PH2104		
No of AUs	3 AU		
Contact Hours	2 hr – lecture; 1 hr – tutorial		
Proposal Date	21 Nov 2019		

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.

Intended Learning Outcomes (ILO)

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

Special Relativity (SR):

1. Explain the space-time structure of special relativity and show that the Minkowski metric is invariant under Lorentz transformations;

Manifolds and Tensors (MT):

2. Describe the Equivalence Principle and deduce its consequences such as the bending of light by a gravitational field and the gravitational redshift effect;
3. Recognise that gravity is formulated in terms of the geometry of spacetime pseudo-Riemannian manifold;
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;
5. Derive Christoffel symbols from space-time metric tensor by imposing the torsion-free and metric compatibility conditions;
6. Solve problems with covariant derivatives, geodesic equation, Riemann curvature tensor, Ricci and Einstein tensors;

Einstein's Field Equation (EFE):

7. Use the minimal-coupling principle to explain how gravity effects matter fields;
8. Interpret the components of the stress-energy tensor and express the stress-energy tensor for a perfect fluid source;
9. State Einstein's field equation, derive the number of independent equations it gives rise to and recover the Newtonian limit from it;
10. Derive the Schwarzschild metric as a solution to Einstein's field equation and examine its properties such as its geodesics;

Classical Tests of General Relativity (CTGR):

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

Assessment (includes both continuous and summative assessment)

Component	Course LO Tested	Related Programme LO or Graduate Attributes	Weighting	Team / Individual	Assessment Rubrics
1. Final Examination	All	Competence (1,3,4)	50%	Individual	Point-based marking (not rubric-based)
2. CA1: Quiz 1	Range (SR 1, MT 2-6)	Competence (1,3,4)	15%	Individual	Point-based marking (not rubric-based)
3. CA2: Quiz 2	Range (EFE 7-10, CTGR 11)	Competence (1,3,4)	15%	Individual	Point-based marking (not rubric-based)
4. CA3: Assignments	All	Competence (1,3,4) Creativity (1) Communication (3) Character (3)	20%	Individual	Point-based marking (not rubric-based) Please note that you can discuss with your group but you need to submit individually.
Total			100%		

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.

Learning and Teaching approach

Approach	How does this approach support students 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.

Reading and References

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

Course Policies and Student Responsibilities

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.

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. Consult your instructor(s) if you need any clarification about the requirements of academic integrity in the course.

Course Instructors

Instructor	Office Location	Phone	Email
Dr. Chen Yu	SPMS-PAP-02-08A	69083426	y.chen@ntu.edu.sg

Planned Weekly Schedule

Week	Topic	Course LO	Readings/ Activities
1	Lorentz Transformations; Minkowski Spacetime	SR 1	Textbook, Lecture notes
2	Four Vectors; Electromagnetic Field Tensor	SR 1	Textbook, Lecture notes
3	Equivalence Principle	MT 2, 3	Textbook, Lecture notes, Tutorial
4	Manifolds and Tensors	MT 3,4	Textbook, Lecture notes
5	Metric Tensor	MT 4,5	Textbook, Lecture notes, Tutorial
6	Covariant Derivative; Parallel-Transport; Geodesic Equation	MT 5,6	Textbook, Lecture notes
7	Curvature	MT 6	Textbook, Lecture notes, Tutorial

8	Minimal-Coupling Principle	EFE 7	Textbook, Lecture notes, Quiz 1
9	Stress-Energy Tensor; Einstein's Field Equation	EFE 8, 9	Textbook, Lecture notes
10	Newtonian Limit; Cosmological Constant	EFE 9	Textbook, Lecture notes, Tutorial
11	Schwarzschild solution and its properties	EFE 10	Textbook, Lecture notes
12	Classical Tests of General Relativity I	EFE 11	Textbook, Lecture notes, Tutorial
13	Classical Tests of General Relativity II	EFE 11	Textbook, Lecture notes, Quiz 2

Graduate Attributes

What we want our graduates from Physics and Applied Physics to be able to do:

Upon the successful completion of the PHY, APHY and PHMA programs, graduates should be able to:

Competency	1	demonstrate a rigorous understanding of the core theories and principles of physics involving (but not limited to) areas such as classical mechanics, electromagnetism, thermal physics and quantum mechanics;
		[PHMA only] demonstrate a rigorous understanding of the core theories and principles of mathematical sciences involving (but not limited to) areas such as analysis, algebra and statistical analysis;
	2	read and understand undergraduate level physics content independently;
	3	make educated guesses / estimations of physical quantities in general;
	4	apply fundamental physics knowledge, logical reasoning, mathematical and computational skills to analyse, model and solve problems;
	5	develop theoretical descriptions of physical phenomena with an understanding of the underlying assumptions and limitations;
	6	critically evaluate and distinguish sources of scientific/non-scientific information and to recommend appropriate decisions and choices when needed;
	7	demonstrate the ability to design and conduct experiments in a Physics laboratory, to make measurements, analyse and interpret data to draw valid conclusions.

Creativity	1	propose valid approaches to tackle open-ended problems in unexplored domains;

	2	offer valid alternative perspectives/approaches to a given situation or problem.

Communication	1	describe physical phenomena with scientifically sound principles;
	2	communicate (in writing and speaking) scientific and non-scientific ideas effectively to professional scientists and to the general public;
	3	communicate effectively with team members when working in a group.

Character	1	uphold absolute integrity when conducting scientific experiments, reporting and using the scientific results;
	2	readily pick up new skills, particularly technology related ones, to tackle new problems;
	3	contribute as a valued team member when working in a group.

Civic Mindedness	1	put together the skills and knowledge into their work in an effective, responsible and ethical manner for the benefits of society.