Indian Association for the Cultivation of Science

Department of Theoretical Physics

Integrated Phd in Physical Sciences

PH 516: General Relativity and Cosmology

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1 Main points to remember

- **Course Webpage**: I have created a webpage, where all the details regarding this course will be posted. You are encouraged to check the webpage in regular intervals. You can access it by clicking here. Or, copy paste the following url to your browser: *https://sumantachakraborty.weebly.com/general-relativity.html*. You are also encouraged to check the "announcements" section located here.
- **Assignments and Evaluation**: I will hand over one assignments for every **five** classes. These you have to work out of your own and you **do not** have to submit them to me. However if you are stuck at some problem, we can discuss them in the tutorials. The evaluation will be based on a mid-term with **twenty** marks and then a final examination with **eighty** marks. Both these examinations will be closed book, closed note examination.
- **Communications**: The main mode of communication outside class will be through emails. Thus I would request all of you to check emails at least once everyday. The assignments as well as other instructions will be handed over through emails only. The classes will be on **Tuesday** from **3:30** pm, **Wednesday** and **Friday** from **10:00** am.

2 Syllabus

- Diffeomorphism, Covariant and Contravariant tensors under general coordinate transformations, Parallel transport, Affine connection, Riemann curvature tensor.
- Einstein's equation, Principle of Equivalence, Energy momentum tensor, Spherically symmetric solution, Birkhoff's theorem, Schwarzschild geometry, Tests of Einstein's equation, Perihelion precession, Bending of light, gravitational redshift.
- Reissner Nordstrom geometry, Kerr Geometry, Black hole Physics, Kruskal-Szekers coordinate, Penrose diagram, Surface gravity, Hawking temperature, Hawking radiations, Elements of Black hole mechanics.
- Cosmological principle, Friedman-Robertson-Walker metric, equation of state, Hubble constant, Inflationary cosmology, Dark energy.

3 Books and Articles

- *Gravitation: Foundations and Frontiers* — T. Padmanabhan — Cambridge University Press.
- *Classical Theory of Fields* — L.D. Landau and E.M. Lifschitz — Pergamon Press.
- *A First Course in General Relativity* — B. Schutz — Cambridge University Press.
- *Relativity* — W. Rindler — Oxford University Press.
- *A Relativist's Toolkit* — E. Poisson — Cambridge University Press.
- *Exploring Black Holes: Introduction to General Relativity* — E. Taylor, J.A. Wheeler — Cambridge University Press.
- *Gravitation and Spacetime* — H.C. Ohanion and R. Ruffini — Cambridge University Press.
- *Introducing Einstein's Relativity* — Ray D' Inverno — Oxford University Press.

- *Cosmology* — S. Weinberg — Cambridge University Press.
- *Black Holes* — P.K. Townsend — arXiv:gr-qc/9707012.

4 Time Scale

The course will start from **8th January** and will continue till **20th April**. There will be one mid semester examination on **21st February** of **twenty** marks and the final exam will take place on **27th April** (tentative) carrying **eighty** marks. In total this course will continue for **13** weeks and possibly we will have around **30** classes. There will be tutorial, possibly once every two weeks in which the assignments will be discussed. Below a tentative course structure has been presented, I will try to stick to this schedule.

- **Class-01 (10.01.2018)** — Setting up the premise of the course; Surprises in Newtonian Gravity; Why one should look for modifications in Newtonian physics?; A brief overview of the current state of research in gravitational theories.
- **Class-02 (12.01.2018)** — Introduction to index notation; Definitions of vectors and tensors; Idea of coordinate transformation; Some basic examples and relevant applications.
- **Class-03 (16.01.2018)** — Notion of a metric tensor; Its properties; Illustration through examples; Idea of covariant derivative.
- **Assignment 1 has been handed over.**
- **Class-04 (17.01.2018)** — Brief Introduction to Lagrangian formulation; Conservation of energy, linear momentum and angular momentum; Interesting facts about Action principle and its implications.
- **Class-05 (19.01.2018)** — Introduction to Special Relativity; Lorentz Transformation; Notion of four vectors; Motion of a relativistic particle; Implications.
- **First feedback form has been circulated.**
- **Tutorial-01 (23.01.2018)** — Tutorial for the first assignment.
- **Class-06 (24.01.2018)** — Classical field theory; Example of a scalar field; Deriving field equations from action principle; Comments and Implications; Introduction to vector field theory and its connection to electrodynamics; Motion of a charged particle and Lorentz force law;
- **Class-07 (30.01.2018)** — Action for electromagnetic field; Derivation of Maxwell's equations; Comment on Gauge choices and some interesting examples.
- **Class-08 (31.01.2018)** — What about second rank symmetric tensor field?; Weak Equivalence Principle; Notion of an accelerated and rotating observer.
- **Assignment 2 has been handed over.**
- **Class-09 (02.02.2018)** — Another version of equivalence principle; Gravitational Redshift; Motion of a particle in a gravitational field.
- **Class-10 (06.02.2018)** — Notion of Christoffel connection; Geodesic equation.
- **Class-11 (07.02.2018)** — Parallel Transport will be introduced; Lie Transport will be discussed and Killing Vectors as a by product of the same.

- **Class-12 (09.02.2018)** — Broad overview of lessons learned; Notion of spacetime curvature will be discussed;
- **Tutorial-02 (13.02.2018)** — Tutorial for second assignment.
- **Assignment 3 has been handed over.**
- **Class-13 (14.02.2018)** — Commutator of covariant derivative as a measure of curvature; Properties and identities satisfied by the curvature tensor will be derived and discussed.
- **Class-14 (16.02.2018)** — Field Theory in Curved Spacetime, in particular modifications to scalar field theory and electrodynamics will be addressed.
- **Mid-term examination took place on 23rd February, Friday from 11:00 am. The duration was two hours.**
- **Class-15 (27.02.2018)** — Action principle for gravity, How to arrive at the Einstein-Hilbert action?
- **Class-16 (28.02.2018)** — Deriving Einstein's equations in vacuum. Varying the Matter Action and completing the derivation of Einstein's equation with matter.
- **Second feedback form has been circulated.**
- **Tutorial-03 (06.03.2018)** — Tutorial for third assignment.
- **Class-17 (14.03.2018)** — Basic Properties of field equation and weak field limit of gravity. Gravitational Waves.
- **Class-18 (16.03.2018)** — How to arrive at a spherically symmetric solution and writing down Einstein's equations for the same situation.
- **Class-19 (20.03.2018)** — Derivation of Schwarzschild, Schwarzschild de-Sitter and Reissner-Nordström solution. Related comments and manipulations in Mathematica.
- **Assignment 4 has been handed over.**
- **Class-20 (21.03.2018)** — A new way to look into Schwarzschild metric. Perihelion precession.
- **Class-21 (26.03.2018)** — Other Tests of General relativity, Bending of light. Comment on alternative theories of gravity. Writing down the Schwarzschild solution in various other coordinates and spacetime diagrams.
- **Class-22 (28.03.2018)** — Notion of Penrose diagram for flat spacetime and Schwarzschild spacetime. Unruh effect.
- **Tutorial-04 (03.04.2018)** — Tutorial for fourth assignment.
- **Class-23 (04.04.2018)** — Black Hole Thermodynamics and notion of black hole temperature. Connection to Hawking radiation and comment on information loss paradox. Penrose diagram for Reissner-Nordström black hole.
- **Class-24 (06.04.2018)** — Derivation of Kerr metric and the physics behind the same.
- **Assignment 5 has been handed over.**
- **Class-25 (10.04.2018)** — Introduction to Cosmology and the notion of homogeneity and isotropy; Kinematics in cosmological spacetime; Particle motion; redshift and all that.

- **Class-26 (11.04.2018)** — Derivation of Friedman equations; Consequences and the matter content of the universe.
- **Class-27 (13.04.2018)** — Accelerated expansion of the universe, Inflationary cosmology.
- **Final Examination will take place on 28th April, Saturday from 11:00 am to 2:00 pm.**
- **Final feedback form will be circulated.**

5 Students

Below the name of students either crediting or auditing the course are listed. The names which are striked through, stopped attending the course at some stage. In case any of you are missed please contact me as soon as possible.

- Bhaswati Mandal (PhD, Crediting)
- Swarup Ghosh (Int. PhD, Crediting)
- Subhadip Sau (PhD, Crediting)
- Akash Debnath (PhD, Crediting)
- Sougata Ganguly (PhD, Crediting)
- Ananya Tapadar (Int. PhD, Crediting)
- Isha Ali (Int. PhD, Crediting)
- ~~Manali Malakar (Int. PhD, Crediting)~~
- ~~Amitrajit Nag (Int. PhD, Crediting)~~
- Sauvik Roy (Int. PhD, Crediting)
- ~~Shameek Mukherjee (Int. PhD, Auditing)~~
- Raja Chakraborty (Int. PhD, Crediting)
- ~~Anudeepa Ghosh (PhD, Auditing)~~
- Suvajit Paul (Int. PhD, Crediting)
- Aritra Pal (Int. PhD, Crediting)
- Abhijit Mandal (PhD, Auditing)
- Dipanjana Das (PhD, Auditing)
- Chayan Patra (Int. PhD, Crediting)
- Pritikana Bhandari (PhD, Auditing)