Fall 2007

General Relativity

Physics (PHY) 6938
5:00 – 6:20 (EDT) TR
Fleming Hall 424

http://physics.fau.edu/~cbeetle/PHY6938.07F/

This is an introductory course on general relativity. It has been designed primarily for Ph.D. students considering research in theoretical gravitation, astrophysics or particle physics.

Required Background

General relativity has a reputation for esoteric, abstract mathematics. This is not undeserved, but there are actually deep *physical* reasons that such methods are required. This course will emphasize these reasons throughout a self-contained survey of both the principles and the practice of modern relativity.

The most important pieces of mathematical background for this course are linear algebra and vector calculus. These are familiar from undergraduate work, but a little more sophistication—at the level of graduate quantum mechanics and electrodynamics—will be very useful. Familiarity with the variational formulations of classical mechanics will also help. On the physics side, general relativity is simply a classical field theory of gravitation, so classical mechanics and electrodynamics once again form the essential conceptual backdrop.

Course Structure

This course must motivate and introduce a new physical theory, general relativity, while simultaneously developing from scratch the unusual mathematical techniques, Riemannian geometry, needed to formulate it. In a sense, these are two separate courses, and the structure of this class will reflect this.

The lectures will focus on physics to the greatest extent possible. In parallel, students will develop mathematical skills in differential and Riemannian geometry working independently from the two required texts. Questions concerning the mathematics are certainly welcome during the lectures and, especially, office hours. But the formal presentation of pure mathematics will otherwise be confined to a short series of three lectures. The essential ideas will be explained mostly as they are encountered in practice, and then referring to students' independent study.

Instructor

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Required Texts

- R. d'Inverno. *Introducing Einstein's relativity*. Oxford, 1992. ISBN 0-19-859686-3
- B. Schutz. *Geometrical methods of mathematical physics*. Cambridge, 1980. ISBN 0-521-29887-3

Optional Texts

- W. Rindler. *Relativity: Special, general and cosmological,* Second Edition. Oxford, 2006. ISBN 0-19-856132-4 (Conceptual foundations)
- J. Stewart. *Advanced general relativity*. Cambridge, 1993. ISBN 0-521-44946-4 (Mathematical summary, spinors)
- R.M. Wald. *General relativity*. University of Chicago, 1984. ISBN 0-226-87033-2 (Definitive research reference)

This course will motivate and state the Einstein field equations as quickly as possible, thereby reserving more time to study important applications of those equations in contemporary physics. These applications include black holes, cosmology and gravitational radiation. The course schedule devotes some time to each. Additional topics, depending on student interest and time constraints, may also be discussed.

Course Outline and Schedule

This course comprises 28 eighty-minute lectures. The first day of class is **Tuesday, August 28**. The only scheduled deviation from the regular twice-weekly lecture schedule is for Thanksgiving, **Thursday, November 22**. All other classes will meet as planned—weather (i.e., hurricanes) permitting—on Tuesday and Thursday evenings at 5:00 Eastern Time. The last day of class is **Tuesday, December 4**. There is a final exam period scheduled for **Tuesday, December 11**, at the regular class time. The final exam will be due at this meeting.

The following outline gives a rough sense of the course as initially planned. The topics marked with an asterisk (*) are optional, and will be covered only if time permits.

I. Special Relativity (4 lectures)
   - A. Historical Origins, Postulates and Spacetime
   - B. Relativistic Kinematics and Dynamics
   - C. Non-Inertial Motion and the Equivalence Principle

II. Riemannian Geometry (3 lectures)
   - A. Manifolds, Connections and Symmetries

III. Foundations of General Relativity (6 lectures)
   - A. Principles of General Relativity
   - B. Gravitational Fields and Their Sources
   - C. Motion and Propagation in Curved Spacetime
   - D. *Action Principles for Gravity

IV. Isolated Gravitational Sources (6 lectures)
   - A. The Schwarzschild Solution
   - B. *Spherical Stars
   - C. *Black Holes

V. Gravitational Radiation (5 lectures)
   - A. Weak Gravitational Waves and Their Sources
   - B. Infinity and Radiation
   - C. *Local Characterization of Radiation
   - D. *Radiation Reaction

VI. Relativistic Cosmology (4 lectures)
   - A. Homogeneous and Isotropic Spacetimes
   - B. Simple Cosmological Models
   - C. *Global Structure of Cosmological Spacetimes
   - D. *Quantum Cosmology

Mathematical Self-Study

In parallel with the primarily physical discussion in lecture, students are expected to complete a set of exercises on mathematical techniques in differential and Riemannian geometry. These exercises are based on independent reading, and may be completed at each student's own pace. This parallel part of the course will span the first six weeks of class. The mathematical assignments are due before class on **Tuesday, October 9**. We may interrupt the planned lecture sequence to discuss particular mathematical topics during this period, subject to student demand, but this will affect the number of advanced topics we can cover.

VII. Mathematical Methods (6 weeks)
   A. Vectors and Tensors
   B. Manifolds and Tensor Calculus
   C. Connections and Curvature
   D. Integration on Manifolds

Grading Policy

Overall grades in this course are based, in the following proportions, on three factors:

- (35%) mathematical exercises based on parallel self-study,
- (45%) roughly ten graded homework assignments based on lectures and reading, and
- (20%) a graded, take-home final exam due Tuesday, December 11.

The mathematical assignments will *not* be graded, but only summarily checked to make sure all problems have been attempted with some seriousness of purpose. In fact, solutions for most exercises should be distributed before they are due. However, every student should plan to solve almost all exercises before checking the solutions, or suffer the collateral consequences of their mathematical inexperience later on in the course.

All course work must be completed subject to the following rules:

- Except by *prior* arrangement, all homework is due by the *beginning* of class on the date printed on the assignment. This is a graduate course, so permission to turn homework in late will generally be freely granted. But it must be obtained in advance.
- The final exam must be completed on time. No extensions will be granted.
- Students may form discussion groups and consult with one another on specific homework problems, but all written solutions must be independent. No copying is allowed.
- The previous rule applies also to the final exam.
- No extra credit will be offered.

Note that there is no class participation component to the grade. There are two reasons for this. First, graduate students at this level should have developed strong opinions about physics already, and therefore should eager to participate. Second, for technical reasons, it may be more difficult for some students at remote sites to participate as effectively as others. Students are, of course, encouraged to ask as many questions, or start as many debates, as they wish.

General Comments

The following comments address some of the questions students might have about this course.

Learning Objectives

This course is an introduction to general relativity. The goal is to provide students with the basic tools they need to tackle more advanced material in a subsequent course, or by studying textbooks on their own. While it provides the essential mathematical and physical backdrop for research, it should not be considered adequate preparation for reading current journals.

The basic goals of this course are as follows. Students should be able to: explain the physical content of the Einstein equation; use symmetry reductions to constrain and solve that equation;

compute the motion of bodies and gravitational radiation in weak fields; and explain what a black hole is, what the Big Bang is, and how to turn these concepts into calculations.

Mode of Instruction

The primary mode of instruction in this course will be old-fashioned lecturing. The purpose of these lectures is to highlight essential points in the textbooks, provide alternate points of view in some cases, and illustrate how to solve problems. These goals may not be so easily accomplished in other, more democratic, classroom approaches because of the technical nature of the course material. This being said, students are encouraged to interrupt with questions at any time. Bear in mind that any point that confuses one student is very likely to confuse others as well. Don't be shy.

Time Commitments

Students are not required to attend lectures, but must commit ten to fifteen hours per week of time outside of class to this course. This will include time spent reading both the textbook and other materials, in discussions with other students, and solving assigned problems.

There will be about one homework assignment per week, on average. Each assignment, graded or otherwise, should take between five and ten hours to complete. The final exam will likely take between ten and twenty hours to complete, and will be distributed one week before it is due. In all cases, students are asked to prepare a clear, final copy of their work to be graded.

Office Hours

Students can consult with me either during the regularly scheduled office hours listed on the front of this Syllabus, or by prior appointment. Students at remote campuses may use video, audio or text messaging through the AIM and Skype addresses listed on the front to take advantage of office hours. They may also prefer to consult with a professor at their own campus.

Special Needs

Any students with special needs or needing religious or other accommodations should contact me at their earliest convenience.

Academic Integrity

The guidelines in the section on grading policy above should be fairly clear. Please read the FAU Catalog's section on Student Responsibility and Discipline (p. 65), or simply ask me, if you have any questions.