Department of Physics

Department of Physics
Carnegie Mellon University

33-650 General Relativity

"Any intelligent student can grasp it without too much trouble" -- Albert Einstein

Fall Semester 2020

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Overview

Albert Einstein published his theory of relativity 105 years ago! The last year marks an important milestone in the history of physics. The Laser Interferometer Gravitational-Wave Observatory (LIGO) has detected gravitational waves from inspiraling black holes! This discovery is an important confirmation of general relativity in its own right; moreover, the gravitational waves provide a new means to view the universe and reveal relativistic events in regions shielded from electromagnetic observation.

General Relativity is the classical theory of gravity. Unlike Special Relativity, which evolved through the work of many, the genesis of GR was essentially the work of Einstein alone. GR is widely recognized as a beautiful theory-equating gravity and the geometry of spacetime leads to a profound conceptual change in the way we regard the Universe. The predictions of the theory are relevant to systems as varied as high precision measurements of the Earth's gravitational field to the strongly curved spacetimes around black holes. In this course, we will gradually develop an understanding of the geometries which are the solutions of the Einstein equation, with an emphasis on their relevance to physical situations. We will motivate the theory step by step and eventually fully introduce (and solve) the Einstein equation itself.

General relativity lies at the heart of a wide variety of exciting astrophysical and cosmological discoveries made during the past decade or so. Perhaps the most compelling of the new results is the 1998 discovery that not only is the universe expanding, but the expansion
is accelerating. The **2011 Nobel Prize** in Physics was awarded for observations of high-redshift supernovae whose distance and brightness revealed the accelerated expansion and therefore showed that the cosmos is filled with "dark energy" (see PHYSICS TODAY, December 2011). Observations of the cosmic microwave background have also provided evidence for dark energy—and for non luminous dark matter.

Astronomers observe supermassive black holes in the centers of galaxies, including our own Milky Way. We now recognize that neutron stars are abundant in our galaxy and that they provide the basis for extreme and intriguing astrophysical phenomena. LIGO has detected gravitational from inspiraling black holes: **2017 Nobel Prize in Physics**. Gravity Probe B, which had been orbiting Earth, recently observed frame-dragging and geodetic effects predicted by general relativity. The global positioning system (GPS), which we all regularly use, requires general relativity to ensure its meter-scale accuracy (see the article by Neil Ashby in PHYSICS TODAY, May 2002). In a way that was not true even two decades ago, general relativity has become an issue of practical concern to mainstream physicists and even engineers.

What you'll learn/ Outcomes:

By the end of the course, **students will be proficient in the tensor calculus and other techniques required to solve the full Einstein equation.** They will be able to apply these to such problems as the nature of spacetime close to black hole, spaceship warp drives and the evolution of the Universe as a whole. They will have an understanding of the topics outlined above in the syllabus, including the ability to solve the geodesic equation or the paths of test particles in curved spacetime.

About this course:

Lectures: MWF 1:20-2:10pm in GHC 4401

Our class is in the Gates Hillman Center - a bit unusual for a physics classroom - here it is:


You can enter the building from Forbes Avenue


looking back at the Forbes entrance door. GHC 4401 is the Rashid Auditorium on the the far right (in the picture above)


This is what it looks like inside.

It is extremely large (no issue for social distancing for our class size) and easily accessible from Forbes, there is no elevator. I will be teaching from there - it is a 600 level class so I will start in person instruction from the first day of class.

Prerequisites

- Physical Mechanics including variational principle.
- Special Relativity.
- E&M

This said, the course will be as self contained as possible - we will review the above topics.

Textbook

Required: ``Gravity, An Introduction to Einstein's General Relativity'',
James Hartle (Addison Wesley).

ISBN 0-8053-8662-9

We will follow the textbook closely, picking one path through the possible courses on page 561. This will involve the following chapters:

Week 1

Gravitational Physics - **Chapter 1**
Geometry as Physics - **Chapter 2**

Week 2

Space, Time and Gravity in Newtonian Physics - **Chapter 3**

Week 3

Principles of Special Relativity - **Chapter 4**

Week 4

Special Relativistic Mechanics - **Chapter 5**

Week 5

Gravity as Geometry - **Chapter 6**

Week 6

The Description of Curved Spacetime - **Chapter 7**

Week 7

Geodesics - **Chapter 8**

Week 8

The Geometry Outside a Spherical Star - **Chapter 9**

Week 9

Gravitational Collapse and Black Holes- **Chapter 12**

Week 10

A Little More Math - **Chapter 20**

Week 11

Curvature and the Einstein Equation - **Chapter 21**

Week 12

The Source of Curvature - **Chapter 22**

Week 13-14

Solving Einstein Equation - We will go in more depth than Chapter 22

I will also introduce/add on some ideas of differential geometry beyond what Hartle does. For this I will be using mostly ``Spacetime and Geometry'' from Carroll (not required).

Note though: **The mastery of the index notation and the chain rule almost suffices**. **Riemannian Geometry, the language to describe curvature, is of course totally logical and algorithmic.** Any physics student at this level will be continually puzzled by the physics and not at all by the math.

Assessment:

All comprehension checks/quizzes, homeworks, midterm exam and the final project/take home exam are graded.

Homework Assignments:

There will be approximately 10 homeworks during the course (30% of your grade). Homework assignments will be given a week before they are due to be handed in (due on Wednesdays?)

Quizzes:

There will be a few comprehension checks/quizzes which, together with attendance will account for 10% of the total grade.

Exams:

There will be two exams: one midterm and the final (likely take-home). The **Midterm** is tentatively scheduled for **October 14.**
All exams will be on everything in the course up to that point, including lectures and homework

Office hours:

I am happy to schedule zoom meetings at your request, feel free to email me to set up a meeting. Even if you are on campus, for now, we are not expected to meet in person in my office. I am happy to Discussion on Canvas or Piazza or start a Slack channel for the class.

Discussion Forum

As you know, this is the first time at CMU we embark in this Hybrid teaching. I welcome your feedback, so if something is confusing or doesn't work the way you expect, let me know and I'll

do our best to address it. We will make use a discussion board (via zoom, piazza, discussion and conferences on Canvas). We will have a zoom session every class to introduce ourselves to each other and let me know how you're doing. I want to encourage everyone to actively use any of the canvas forums, to ask questions, give feedback, and even help your fellow learners. However, please do not post answers.

I will also be available to, provide guidance, and moderate the discussion forum.

Academic Integrity

Academic Integrity is a core CMU value, and as a member of the CMU community, it is important that the work you turn in for this class is wholly your own. As your instructor, I will strive to ensure that you develop the necessary knowledge and skills to meet the learning objectives for this class, just as it is your task to put in the effort to complete the work and ask for help if you need it. In this hybrid/remote environment for Fall 2020, you might have questions about what is and is not acceptable.

You can discuss and work on homework and quizzes together but you should each write out your own solutions. You should work on exams completely on your own and not discuss those with others.

For each exam, you will be asked to sign a statement affirming that you will not cheat, plagiarize, or receive unpermitted assistance on the work that you turn in. As a reminder all students should follow CMU's Academic Integrity Policy.

Zoom in this class:

In this class, we will be using Zoom for synchronous (same time) sessions. The link is available on the Canvas

https://cmu.zoom.us/j/96705790409?pwd=QUFmL0J1VitFT3NFbDFpYzcyZnlsdz09

Please make sure that your Internet connection and equipment are set up to use Zoom and able to share audio and video during class meetings.

Sharing video: In this course, being able to see one another helps to facilitate a better learning environment and promote more engaging discussions. Therefore, our default will be to expect students to have their cameras on during lectures and discussions.

Support for students' learning and well-being

Take care of yourself! Do your best to maintain a healthy lifestyle this semester by eating well, exercising, avoiding drugs and alcohol, getting enough sleep and taking some time to relax. This will help you achieve your goals and cope with stress.

All of us benefit from support during times of struggle. You are not alone. There are many helpful resources available on campus and an important part of the college experience is learning how to ask for help. Asking for support sooner rather than later is often helpful.

If you or anyone you know experiences any academic stress, difficult life events, or feelings like anxiety or depression, we strongly encourage you to seek support. Counseling and Psychological Services (CaPS) is here to help: call 412-268-2922 and visit their website at

http://www.cmu.edu/counseling/. Consider reaching out to a friend, faculty (such as myself) or family member you trust for help getting connected to the support that can help.

Use of technology during class:

This semester involves regular use of technology during class – both for in-person and remote students. Research has shown that divided attention is detrimental to learning, so I encourage you to close any windows not directly related to what we are doing while you are in class. Please turn off your phone notifications and limit other likely sources of technology disruption, so you can fully engage with the material, each other, and me. This will create a better learning environment for everyone.