PHYS 8240: Advanced General Relativity

Fall 2021 Semester

University of Virginia

Department of Physics

Course Basics (When, Where, Who, and How)

Course meeting time:	T,Th: 12:30–1:45p.m., Aug. 24–Dec. 7
	No Class: Oct. 12 (T), Nov. 25 (Th)
	Final Exam Period: Th, Dec. 16, 2:00–5:00p.m.
Course meeting location:	Physics Building/JBL 218
Office hours:	T,W,Th: 5:00–6:00p.m., or by appointment
	T/Th are in person, W is over Zoom
Course website:	UVA Collab site
Instructor:	David A. Nichols
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Phone:	+1 (434) 924-0501
Prerequisites:	PHYS 5240 (or equivalent) or instructor permission

Course Description (What)

The Big Bang and the collisions of black holes and neutron stars are some of the most luminous astrophysical events that have occurred in our Universe. These very different phenomena can be described using a common underlying framework: Einstein's theory of general relativity. This course will build upon PHYS 5240: Introduction to the Theory of General Relativity and will explore topics in relativity that are frequently used in current research in gravitation theory. The anticipated course topics are elements of differential geometry, the Lagrangian, Hamiltonian, tetrad, and Landau-Lifshitz formulations of relativity; the dynamics of hypersurfaces and congruences of geodesics; and perturbations of flat spacetime and black holes. The course will not cover cosmology, as these is now a separate course on this topic (PHYS 5170).

Learning Objectives (Why)

For the students interested in research in relativity, gravitational waves, relativistic astrophysics, or cosmology, the intent of this course is to introduce you to a set of techniques and concepts that will appear throughout your future research. For students interested in other aspects of theoretical astrophysics and physics, the goal of this course is to increase the breadth of your knowledge and to introduce you to geometric methods that could be useful for providing a different viewpoint on your area of research.

Course Format and COVID Policies

Lectures will be delivered in person, and you are encouraged to ask questions at any time. If there are not many questions, I will try to implement more discussion through posing questions to the class or through in-class exercises.
COVID contingencies: For the first two weeks of the course, you must wear a mask in the lecture and in office hours. The University will revisit the mask policy after these two weeks. However, you are always welcome to wear a mask! If you do not feel well or are required to quarantine, then do not come to class. Instead, please contact me, and we can set up an alternate way for you to obtain the material you will miss (for example, obtaining notes from a classmate, setting up a zoom connection for the class, or recording the lecture). If I am required to quarantine or do not feel well, then I will inform the class of any changes in the course format. This may require a temporary switch to a different format, such as a synchronous Zoom format, recorded lecture, or guest lecturer until I am able to return to teaching in person.

Course Resources and Texts

There is not a single text that covers all the topics planned for this course. Between the following books, there is a relatively comprehensive coverage for what I plan to cover:

- Robert Wald. *General Relativity.* U. of Chicago Press (Chicago) 1984.
- Eric Poisson. *A Relativist's Toolkit: The Mathematics of Black-Hole Mechanics.* Cambridge University Press (Cambridge, UK) 2007.
- Michele Maggiore. *Gravitational Waves: Volume 1: Theory and Experiments.* Oxford University Press (Oxford, UK) 2007; and *Volume 2: Astrophysics and Cosmology.* Oxford University Press (Oxford, UK) 2018.

The UVA library has a subscription to the books by Maggiore the book by Poisson, so you should be able to access them for free when you are on the UVA network (or using a VPN). You are encouraged to look at other resources that you find helpful, both primary and secondary sources. I list a few more commonly used texts below:

- Sean Carroll. *Spacetime and Geometry: An Introduction to General Relativity.* Cambridge University Press (Cambridge, UK) 2019.
- Bernard Schutz. *A First Course in General Relativity* Cambridge University Press (Cambridge, UK) 2009.
- Charles W. Misner, Kip S. Thorne, and John Archibald Wheeler. *Gravitation.* W. H. Freeman and Co. (New York) 1973.
- Steven Weinberg. *Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity.* John Wiley & Sons (New York) 1972.
- Eric Poisson and Clifford Will. *Gravity: Newtonian, Post-Newtonian, Relativistic.* Cambridge University Press (Cambridge, UK) 2014.

- Thomas W. Baumgarte and Stuart L. Shapiro. *Numerical Relativity: Solving Einstein's equations on the Computer*. Cambridge University Press (Cambrdige, UK) 2010.

The last two books are also freely available from UVA library when on the UVA network. I will sometimes suggest optional further reading with homework assignments for the course.
Piazza: To help facilitate discussion, I have set up a Piazza forum for this course (which you can also access through Collab).

Assignments and Evaluation

Your grade in this course will be determined by your performance on weekly homework assignments (most weeks), a midterm exam, a midterm project, and a final project. The relevant weights of these factors are as follows:

Homework:	50%
Midterm Exam:	15%
Midterm Project:	15%
Final Project:	20%

All assignments should be uploaded through Gradescope, which you can access through the UVA Collab site.
Homework assignments: Unless otherwise specified, homework assignments will be posted on Thursdays on the UVA Collab website for this course, and they will be due at the end of the day (11:59p.m.) on Thursday.
Midterm exam: The midterm exam will be a take-home exam, which will be due Wed., Sept. 29, 2021 at the end of the day (11:59p.m.). The topics, exam length, and amount of time for the exam will be determined at a later point.
Midterm project: The midterm project will be assigned after the midterm exam. You will be assigned a spacetime metric randomly, and you will use some of the formalisms and techniques in the course to identify the physical properties of the metric. The project will be assigned after the midterm and will be due Wed., Nov. 10, 2021 at the end of the day (11:59p.m.).
Final project: The final-exam period for this course is 2:00–5:00 p.m. on Th., Dec. 16, 2021. Instead of an exam, you will research an area of relativity that interests you, which was not covered in the class, and give a mini-lecture on the topic during the final-exam period. The details of the assignment will be given out after the midterm project is due. The main elements will be (i) to give a one-paragraph proposal of the topic you plan to cover due Wed., Nov. 23, 2021 at the end of the day (11:59p.m.), (ii) give a detailed outline of the lecture notes (or presentation slides) due Tues., Dec. 7, 2021 at the end of the day (11:59p.m.), and (iii) deliver your chalkboard talk or powerpoint/beamer presentation during the final-exam period. I will provide feedback on all three parts of the project.
Participation: There is no component of the grade that comes from participation, but it is expected that you will attend lectures, perform the required reading, and ask questions. Reading assignments will be listed on the homework and on the Collab website.

Grading Scale

The default grading scheme is a letter grade, with the following scale as the anticipated grading scale.

A+	A	A-	B+	B	B-	C+	C	C-
100–95	95–90	90–85	85–80	80–75	75–70	70–65	65–60	60–55

D+	D	D-	F
55–50	50–45	45–40	40–0

I reserve the right to curve the grades if the assignments are much more challenging or much easier than anticipated.

Policies for Graded Assignments

I expect all students in this course to abide by the UVA Honor Code. In addition, there are the following policies for assignments in this course: (i) You may discuss homework questions with other students in the class, but you must individually write your own solutions for the homework assignments. (ii) Extensions on homework assignments will not generally be granted, although exceptions could be made for certain serious and unforeseen situations (e.g., an illness of you or a close family member). Late homework will be penalized by reducing the amount of points obtained by the fraction of the week by which it is late. After 7 days (168 hours) late, you will no longer receive credit for the homework assignment (although your understanding will still benefit from completing the homework!). (iii) The midterm exam and the projects must be completed by the deadlines given in the syllabus. (iv) The exam must be completed individually, without consulting others, and must be completed using only the resources specified on the exam. (v) The homework assignments, exams, and the solutions should not be distributed to or used by others not registered in this class.

Inclusivity and Accommodations

UVA is committed to creating a learning environment that meets the needs of its diverse student body. If you anticipate or experience any barriers to learning in this course, please discuss your concerns with me. If you have a disability, or think you may have a disability, you may also want to meet with the Student Disability Access Center (SDAC) to request an official accommodation. You can find more information about SDAC through their website at https://www.studenthealth.virginia.edu/sdac. If you have already been approved for accommodations through SDAC, then please send me your accommodation letter and meet with me as soon as possible.

Anticipated Course Schedule (Subject to Change)

Week of	Topics Covered	Assignments Due
08/23	Manifolds, vectors, and tensors	—
08/30	Derivatives and curvature	HW 1
09/06	Geodesics and normal coordinates	HW 2
09/13	Geodesic congruences	HW 3
09/20	Diffeomorphisms and Lie derivatives	HW 4
09/27	Hypersurfaces	Midterm
10/04	Lagrangian formulation	HW 5
10/11*	Hamiltonian formulation	HW 6
10/18	Hamiltonian continued	HW 7
10/25	Tetrad formulation	HW 8
11/01	Null tetrads	HW 9
11/08	Linear perturbations	Midterm Project
11/15	Post-Minkowski/Newtonian	HW 10
11/22*	Black holes	Final Project Proposal
11/29	Black-hole perturbations	HW 11
12/06*	Wrap up/review	Final Project Draft
12/13*	Th., Dec. 16, 2:00–5:00pm	Final Presentation

*Only one class meeting that week