Astronomy 2142: Black Holes
Spring 2025

GE Theme: Number, Nature, Mind

Web page: `http://www.astronomy.ohio-state.edu/weinberg.21/A2142`

Midterm exam: Monday, Feb 24, in class

Final exam: Friday Apr 25, noon-1:45 pm, in regular classroom

Instructor: Professor David Weinberg, Dept. of Astronomy, `weinberg.21@osu.edu`, 292-1773
4019 McPherson Lab (4th floor), mailbox in 4055 McPherson Lab

In-person office hours: Thursday, 11:15-12:30, McPherson 4019

I will schedule additional, virtual office hours in weeks that homework assignments are due.

I will usually be available after class, 12:25-12:45.

I can schedule other one-on-one meetings on request.

Teaching Assistant: Wynne Turner, PhD Student, Dept. of Astronomy, turner.1839@osu.edu

Wynne is available for help on request and will hold office hours in the weeks that homework assignments are due.

Course Material

Black holes are among the strangest objects ever conceived by science, with gravity so strong that it traps light and warps space and time almost beyond recognition. But black holes are more than theoretical oddities — astronomical observations provide strong evidence that they exist, in at least two varieties. Stellar mass black holes are created in the explosive deaths of massive stars, and they can “light up” and become detectable by ingesting the outer layers of orbiting companions. Supermassive black holes, millions or even billions of times more massive than the sun, reside at the centers of galaxies and power quasars, the most luminous objects in the universe. Pairs of black holes can spiral together by emitting gravitational waves, ripples of spacetime that propagate through the cosmos at the speed of light.

This course will tell the story of black holes: how they were conceived as theoretical ideas, how they might form from dying stars, how they were discovered, what roles they play in cosmic history, how they distort space and time, how they produce tiny but detectable gravitational wave signals, and some of the remaining mysteries they present to contemporary physics. Along the way we will learn about Newton’s theory of gravity, Einstein’s theory of space and time, the life cycle of stars, and the nature of quasars. We will also see how astronomers use observations from telescopes and satellites together with basic physical principles to demonstrate the reality of black holes. The Nobel Prize in Physics from 2017 and the Nobel Prize in Physics from 2020 were both tightly connected to topics of this course, as were earlier Nobel Prizes from 1983, 1993, and 2002.

Course Topics

More specifically, the topics the course will cover are:

- Newton’s theory of gravity
- Special Relativity and spacetime
- General Relativity: Einstein’s theory of gravity
- Stellar death and black hole birth
- Stellar mass black holes
- Galaxies, quasars, and supermassive black holes

- Gravitational waves and black hole mergers
- The Milky Way's central black hole and the Event Horizon Telescope
- Black hole evaporation and other exotica

Prerequisites

If you are taking this course to satisfy the GEL (Legacy GE) requirement, then the only prerequisite is math at the level of Math 1050. If you are taking the course as part of the Number, Nature, Mind Theme of the new GE (GEN), then a previous Natural Science GEN course is also a prerequisite. If you have not previously taken a Natural Science course at OSU, please consult with me to check that you have adequate background to do well in the course.

The math in this course will not go beyond simple algebra, but there will be equations and geometrical or mathematical reasoning in the lectures and in the assignments. The math itself will not be difficult, but the concepts will be challenging, and *translating concepts into equations and back is one of the major things you will learn during the course.*

Readings

The primary reading for the course is *Black Holes and Time Warps: Einstein's Outrageous Legacy*, by Kip Thorne. It should be available from the campus bookstore. On Amazon it is $18.59 in paperback and $10 for Kindle.

This is not your typical science textbook. It was written as a popular book for a broad audience, and it covers both the science of black holes and the history of black hole discoveries. It does not perfectly match to our course material, covering some topics in less detail than we will treat them and other topics in more detail. On the whole, it is a great book, written by one of the world's most creative black hole researchers. The author, Kip Thorne, shared the 2017 Nobel Prize for Physics for his pivotal role in the first detection of gravitational waves; he was also the principal scientific advisor for the blockbuster movie *Interstellar*. The biggest shortcoming of the book is that it was published in 1995 and therefore does not extend through the experimental discovery of gravitational waves.

I will specify required and optional reading assignments with each new section of the course. Through the semester, we will read roughly two-thirds of this 600-page book.

There will be a few additional, short reading assignments specified during the course.

You may find it useful to supplement *Black Holes and Time Warps* with the on-line OpenStax astronomy text by Fraknoi, Morrison, and Wolff, especially for the discussions of Newtonian gravity (Chapter 3), electromagnetic radiation (Chapter 5), relativity and black holes (Chapter 24), and quasars (Chapter 27). You can download a free PDF from
`https://openstax.org/details/books/astronomy`
which also has links for other access options.

Lecture notes

I will provide lecture notes through the course web page as we get to each new section of the course. You can decide for yourself how best to use them, but you will probably find some hybrid between taking your own class notes and referring to my notes is the most effective.

Assignments, exams, and grading

Grades will be based on four take-home assignments (30% total), in-class questions (20% total), a take-home essay (10%), a midterm exam (15%), and a final exam (25%).

The take-home assignments will consist of questions from the lectures and reading and problems for you to work out, and they should typically take 4-8 hours apiece. I will accept assignments up to 3 days late but with a substantial penalty (see individual assignments for specifics).

There will be in-class questions on most class days. I will drop the five lowest scores from the in-class questions and average the rest. While there is no direct attendance grade, if your attendance is poor you will inevitably do poorly on the in-class question grade, and probably on everything else as well. The dropping of the five lowest scores already allows for absences due to illness, athletic events, etc., so there are no makeup assignments.

The essay assignment will connect the material of this course to the broader topics of the Number, Nature, Mind GE theme.

Submission details for the homework and essay assignments will be provided on the assignments themselves.

You will be allowed one page (both sides) of handwritten notes for the midterm and two pages (both sides) of handwritten notes for the final.

Makeup exams will be allowed only under exceptional circumstances and by prior arrangement. Makeup exams will be oral and/or essay exams that cover the same general topics as the original exam but in different form.

Grades will be assigned on the standard A-E scale. A (93%), A− (90-93), B− (87-90), B (83-87), B− (80-83), C+ (77-80), C (73-77) , C− (70-73), D+ (67-70) D (63-67), D− (60-63) and F (< 60).

How To Do Well In This Course

The most important advice is: come to class, start early on the take-home assignments, and get help on those assignments if you need it.

The take-home assignments are intended to be challenging. However, you are welcome to come to my in-person or virtual office hours to get help on them. You may also want to form study groups with others in the class to work on the assignments. You are welcome to do so, though the assignment you turn in at the end must be your own work. If you devote enough time to the assignments and get help on them as needed, you should be able to do well on this portion of the course grade. The work you put into the assignments will also improve your performance on the exams, but that is not the primary purpose of the assignments. They are an integral part of the course in their own right.

For doing well on the exams, my advice is to spend some time each week going over the lecture notes and the in-class questions, identify any things you don't understand, and ask me about them. There will also be question & answer review sessions before the midterm and the final, and attending these will likely improve your performance. I will give other advice in advance of the exams themselves.

Electronics

Calculators are allowed in class and exams. For exams, you may *not* use a cell phone, so you'll need a physical calculator if you want one. For the take-home assignments and some in-class questions, *you will need a calculator with scientific notation, and you will need to know how to use it.*

Except for in-class questions, I ask that you not use cell phones, iPads, or laptops in class. If you regularly use an iPad for taking notes that is OK, but please let me know and please use it in a way that doesn't distract others.

Course Calendar

An approximate week-by-week breakdown of the course is given below, with the caveat that topics do not neatly follow week boundaries and the pace for a given topic is not entirely predictable. The dates and times for the midterm and final are ironclad, and the due dates for the homework assignments are unlikely to change. I have not completely decided whether the essay assignment will be mid-way through the term, near the end, or split between the two.

Week 1 (Jan 6-10): Introduction to the Course

Week 2 (Jan 13-17): Newtonian gravity

Week 3 (Jan 22-24): Newtonian gravity
Jan 20 is MLK, no class
Homework 1 handed out on Friday 1/24

Week 4 (Jan 27-31): Transitions: Radiation, Momentum, Energy, Reference Frames
Homework 1 due on Friday 1/31

Week 5 (Feb 3-7): Special relativity
Homework 2 handed out on Friday 2/7

Week 6 (Feb 10-14): Special to general
Homework 2 due on Friday 2/14

Week 7 (Feb 17-21): General relativity as a theory of gravity

Week 8 (Feb 24-28): Stellar death and black hole birth
MIDTERM EXAM on Monday, 2/24

Week 9 (Mar 3-7): Astronomical observations: angles and spectra
Essay assignment handed out on Monday, 3/3

March 10-14: SPRING BREAK

Week 10 (Mar 17-21): Stellar mass black holes
Essay assignment due on Wednesday, 3/19
Homework 3 handed out on Friday, 3/21

Week 11 (Mar 24-28): Supermassive black holes
Homework 3 due on Friday, 3/28

Week 12 (Mar 31 - Apr 4): Gravitational waves
Homework 4 handed out on Friday, 4/4

Week 13 (Apr 7-11): Imaging BH event horizons
Homework 4 due on Friday, 4/11

Week 14 (Apr 14-18): Hawking radiation and black hole evaporation

Week 15 (Apr 21): Frontiers of black hole research

FINAL EXAM on Friday, 4/25, noon-1:45 pm

Syllabus Boilerplate

Boilerplate is, to quote Wikipedia, "written text that can be reused in new contexts or applications without significant changes to the original." OSU recommends including a large number of boilerplate statements in syllabi, about university policies and, for GE courses, about the GE learning objectives. I am skeptical of the value of including this boilerplate language in every course syllabus, even though I endorse the university policies and the GE learning objectives themselves.

For this syllabus, I have elected to include suggested language on academic integrity and accommodations for disability, as well as listing the relevant GE learning objectives.

You can find more of the university's suggestions at
`https://ugeducation.osu.edu/recommended-syllabus-statements-and-policies`
As a general rule, you can assume that I endorse the ideas and practices articulated in all of these suggested statements and that the course will comply with all university policies. If you have any questions about specifics, please feel free to ask me.

With regard to what's allowed for work on in-class questions, take-home assignments, and exams, I'll give specific instructions as we get to them.

Academic Integrity

Academic integrity is essential to maintaining an environment that fosters excellence in teaching, research, and other educational and scholarly activities. Thus, The Ohio State University and the Committee on Academic Misconduct (COAM) expect that all students have read and understand the University's Code of Student Conduct, and that all students will complete all academic and scholarly assignments with fairness and honesty. Students must recognize that failure to follow the rules and guidelines established in the University's Code of Student Conduct and this syllabus may constitute Academic Misconduct.

If I suspect that a student has committed academic misconduct in this course, I am obligated by University Rules to report my suspicions to the Committee on Academic Misconduct. If COAM determines that you have violated the University's Code of Student Conduct (i.e., committed academic misconduct), the sanctions for the misconduct could include a failing grade in this course and suspension or dismissal from the University.

Disability Statement

The university strives to maintain a healthy and accessible environment to support student learning in and out of the classroom. If you anticipate or experience academic barriers based on your disability (including mental health, chronic, or temporary medical conditions), please let me know immediately so that we can privately discuss options. To establish reasonable accommodations, I may request that you register with Student Life Disability Services. After registration, make arrangements with me as soon as possible to discuss your accommodations so that they may be implemented in a timely fashion.

If you are ill and need to miss class, including if you are staying home and away from others while experiencing symptoms of a viral infection or fever, please let me know immediately. In cases where illness interacts with an underlying medical condition, please consult with Student Life Disability Services to request reasonable accommodations. You can connect with them at slds@osu.edu; 614-292-3307; or slds.osu.edu.

Learning objectives

The Curriculum Committee of the College of Arts & Sciences requests that syllabi of all GE courses list the goals and learning objectives for the relevant category. At present, this request is complicated by the fact that Astronomy 2142 satisfies requirements for both the Number, Nature, Mind theme of the new GE (GEN) and the Natural Science-Physical Science category of the Legacy GE (GEL). I list these in turn.

GEN Goals

For all themes, the goals are that successful students will:

1. Analyze an important topic or idea at a more advanced and in-depth level than in the Foundations component. [Note: In this context, "advanced" refers to courses that are e.g., synthetic, reply on research or cutting-edge findings, or deeply engage with the subject matter, among other possibilities.]

2. Integrate approaches to the theme by making connections to out-of-classroom experiences with academic knowledge or across disciplines and/or to work they have done in previous classes and that they anticipate doing in future.

Goals of the GEN Number, Nature, and Mind Theme in particular:

1. Successful students will analyze the nature of mathematics and/or mathematical reasoning at a more advanced and in-depth level than in the Foundations component.

2. Successful students will integrate approaches to number, nature, and mind by making connections to their own experience of mathematical thinking and its application in the world, and by making connections to work they have done in previous classes and/or anticipate doing in the future.

3. Successful students will experience and examine mathematics as an abstract formal system accessible to mental manipulation and/or mathematics as a tool for describing and understanding the natural world.

For all GEN Themes, the expected learning outcomes tied to the goals are that successful students will be able to:

1.1. Engage in critical and logical thinking about the topic or idea of the theme.

1.2. Engage in an advanced, in-depth, scholarly exploration of the topic or idea of the theme.

2.1. Identify, describe, and synthesize approaches or experiences as they apply to the theme.

2.2. Demonstrate a developing sense of self as a learner through reflection, self-assessment, and creative work, building on prior experiences to respond to new and challenging contexts.

For the GEN Number, Nature, and Mind Theme, the Expected Learning Outcomes tied to the goals are that successful students are able to:

1.1 Engage in critical and logical thinking about the ideas embodied within "Number, Nature, Mind."

1.2 Engage in an advanced, in-depth, scholarly exploration of the ideas embodied by "Number, Nature, Mind."

2.1 Identify, describe, and synthesize approaches or experiences as they apply to "Number, Nature, Mind."

2.2 Demonstrate a developing sense of self as a learner through reflection, self-assessment, and creative work, building on prior experiences to respond to new and challenging contexts.

3.1 Analyze and describe how mathematics functions as an idealized system that enables logical proof and/or as a tool for describing and understanding the natural world or human cognition.

The specific learning objectives for Astronomy 2142 (Black Holes) are:

1. Students develop a physical understanding of Newtons and Einsteins theories of gravity, space, and time, the similarities and differences between them, and the senses in which Einstein's theory has superseded Newton's.

2. Students understand how Einstein's theory leads to the prediction of black holes and of the properties it predicts black hole to have.

3. Students understand the interplay between gravity, pressure, and nuclear energy generation in governing the life cycle of stars, and of how and why the deaths of massive stars are expected to lead to the formation of black holes.

4. Students understand how astronomers discovered the first empirical evidence for black holes and how they have set out to demonstrate the existence of black holes as conclusively as possible.

5. Students understand why supermassive black holes are thought to be the central engines of quasars, the most luminous objects in the cosmos, and the observational methods that are used to study quasars and the dormant black holes they have left behind in the centers of galaxies.

6. Students understand the ways that advanced space missions currently under development might lead to deeper understanding of black holes, by measuring X-rays from gas falling towards the event horizon and by measuring gravity waves propagating ripples in spacetime produced by colliding black holes at the far edge of the universe.

How this course meets the GEN ELOs:

The topics at the core of Astronomy 2142 the Newtonian revolution, special and general relativity, black holes and gravitational waves are among the most striking examples of mathematics as a tool for describing and understanding the natural world, making them an ideal subject for addressing these objectives.

You will experience these striking applications of mathematics to physics — Number to Nature — throughout the lectures, readings, and homework assignments. You will learn how mathematics functions as a tool for analyzing the natural world from lectures and readings and, above all, from solving multi-part problems on homework assignments which take you from initial assumptions to sometimes surprising conclusions. The synthesizing essay will invite you to reflect on the role of mathematical reasoning in the theory of gravity, spacetime, and black holes and on the empirical confirmation of mathematically derived consequences of that theory. This interplay goes to the heart of the Number, Nature, and Mind theme, illustrating that human application of the abstract language of mathematics can lead to startling predictions about the natural world that can then be tested and confirmed by observations and experiments.

Learning Objectives — GE Legacy (GEL) Course

Goals:

Successful students will:

Understand the principles, theories, and methods of modern science, the relationship between science and technology, the implications of scientific discoveries and the potential of science and technology to address problems of the contemporary world.

The expected learning objective tied to the GEL goals are that students

1. Understand the basic facts, principles, theories and methods of modern science.

2. Understand key events in the development of science and recognize that science is an evolving body of knowledge.

3. Describe the inter-dependence of scientific and technological developments.

4. Recognize social and philosophical implications of scientific discoveries and understand the potential of science and technology to address problems of the contemporary world.

How this course meets the GEL ELOs

We use the study of black holes, and more broadly the Special and General Theories of Relativity, as a worked example for the development of a modern scientific theory. This includes the development of the theory of gravity, from Galileo, Kepler, and Newton through to Einstein. The intellectual evolution of the subject is intimately linked with scientific and technical discoveries, such as the ability to detect gravitational wave signatures, and we tie it to broader philosophical implications.