Physics 101: Foundations of Theoretical Physics

Spring 2019

Syllabus — Monday, January 28, 2019

Description

This course is a comprehensive, self-contained introduction to the conceptual and mathematical foundations of modern theoretical physics that starts from the very beginning of the subject, with an integrated, first-principles approach to its five main areas: analytical dynamics, statistical physics, relativity, fields, and quantum theory.

Purpose

Physics is a vast, highly developed subject, and it's easy for newcomers to feel overwhelmed. The purpose of this course is to present the conceptual and mathematical foundations of modern theoretical physics in a highly collaborative, cooperative setting for students from a variety of backgrounds, including those who are considering pursuing advanced study of physics in the concentration as well as those who are unsure. The course is also meant for undergraduate and graduate students in other fields of study—such as pure or applied math, astronomy, biology, chemistry, computer science, philosophy—who are interested in developing a better understanding of the modern foundations of theoretical physics either to serve the needs of their own academic work or as a first step toward switching their area of study to physics.

Goals

The course is intended to present a clear, quantitative picture of what theoretical physics really looks like. Primary goals include teaching the relevant concepts and problem-solving techniques, clarifying the necessary mathematical structures, elucidating the elegance and deep connections between the major areas of theoretical physics, probing the relationship between physics and our understanding of reality, and helping students develop a framework for integrating future learning. We will cover material in the course in as self-contained a manner as possible—with occasional exceptions for special cutting-edge examples—and we will introduce any necessary mathematics along the way. Cooperation and diversity strengthen our academic community, so the course prioritizes collaboration and will aim to provide a welcoming and inclusive environment for students with diverse identities and backgrounds. Students should bring plenty of curiosity, a high degree of self-motivation, an interest in active learning, the courage to ask questions and make mistakes, a willingness to share and collaborate with others, and a high comfort level with abstract ideas and mathematical thinking. The instructor will help students form study groups as needed.

Topics

Topics will include the general structure of physical systems, classical mechanics, orbital motion, classical fields, the Lagrangian formulation of classical physics and the principle of least action, symmetries and conservation laws, the Hamiltonian and Hamilton-Jacobi formulations of classical physics, statistical physics and thermodynamics, special relativity, probability and information theory, and an extensive introduction to quantum theory in its modern algebraic formulation. Examples will be drawn from many areas of physics, including Newtonian mechanics, electromagnetism, particle physics, general relativity, quantum information, quantum field theory, and string theory. In-class discussions will frequently address the history and philosophy of physics, as well as the important conceptual implications of our modern physical theories for making sense of the world around us.

Prerequisites

The course assumes a knowledge of single-variable differential and integral calculus, as well as a high comfort level with abstract concepts, but does not assume previous coursework in physics. The course is therefore appropriate both for students who have taken the Physics 15/16 sequence as well as those who have not. The course will cover relevant topics from undergraduate physics, vector calculus, linear algebra, complex analysis, and other areas of mathematics as needed, so a familiarity with these subjects, while helpful, is not required.

Teaching Staff

Dr. Jacob Barandes, Course Head

Director of Graduate Studies for the Science Division of the Faculty of Arts and Sciences
Co-Director of Graduate Studies for Physics
Lecturer on Physics
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Office Hours:

- Tuesdays, 2:30pm–4:30pm
- Fridays, 10:00am–noon

Houri Tarazi, Teaching Fellow

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Office Hours:

- Wednesdays, 10:00am–noon
- Thursdays, 6:00pm–8:00pm
- Fridays, 1:00pm–3:00pm

Course Website

https://canvas.harvard.edu/courses/50653

Please remember to fill out the preliminary survey on the course website by **5:00pm on Friday, February 1**. Filling out this preliminary survey will be one of the requirements for Homework #1!

Meeting Times and Location

Mondays, Wednesdays, Fridays, 3:00pm–4:15pm, in Science Center 302 (map: https://map.harvard.edu/).

Readings

There does not currently exist a textbook that would suit this course. Readings will therefore consist of the instructor's detailed, typed lecture notes, which will be posted online shortly after each class session.

Homework

Homework (70%) consisting of questions involving both concepts and calculations is assigned weekly on Fridays and is officially due at the beginning of class on the following Friday, but students have a three-day grace period and can hand in their homework at the beginning of class on the next Monday instead. (Students may freely take advantage of this three-day grace period as many times as needed, no questions asked.) Collaboration is encouraged and students who have difficulty finding a study group should contact the course head or teaching fellows. However, students must write or type up their own homework sets with their own answers and hand them in individually, as well as list all their collaborators on every homework assignment. Full simplification of results is necessary for full credit. Use of the Internet for general reference purposes is permitted provided that students cite all external resources they use, but students are not permitted to look up specific exercises or solutions on the Internet or elsewhere. In fairness to other students, late homework will not be accepted beyond the three-day grace period.

Final Projects

The course will conclude with final projects (30%), which students can either choose from a list of topics or select with the advance permission of the instructor. Student presentations will be scheduled after the end of classes, and full write-ups are due by 11:59pm on Monday, May 13.

Accommodations for Students with Disabilities

Students needing academic adjustments or accommodations because of a documented disability must present their faculty letter from the Accessible Education Office (AEO) and speak with the instructor of the course by the end of the second week of the term, Friday, February 2. Failure to do so may result in the instructor's inability to respond in a timely manner. All discussions will remain confidential, although faculty may contact AEO to discuss appropriate implementation.

Agenda (Tentative)

- General discussion of physics and physical systems
- Classical kinematics
- Differential and integral calculus, Taylor series
- Perturbation theory
- Classical dynamics
- Chaos
- Complex numbers, vectors
- Newtonian mechanics, work and energy, rotational motion
- Newtonian gravitation, central forces, celestial mechanics
- Reference frames
- Wave phenomena
- Vector calculus
- Classical fields, electromagnetism, Maxwell equations, Lorentz-force law

- Calculus of variations, Lagrangian formulation of classical physics, systems with constraints, Lagrange multipliers, path integrals in quantum theory
- Symmetries and conservation laws
- Introduction to the Standard Model of particle physics and to Einstein's theory of general relativity
- Breaking of dynamical symmetries
- Hamiltonian formulation of classical physics, Poisson brackets, generators
- Hamilton-Jacobi formulation of classical physics and action-angle variables
- Statistical physics, ergodicity, thermodynamics, entropy
- Linear algebra and matrix algebra
- Fourier analysis
- First look at quantum systems, blackbody radiation, Schrödinger's cat, entanglement
- Special relativity: time dilation, Lorentz transformations, hyperbolic geometry of spacetime, four-vectors, relativistic dynamics
- Equivalence principle, spacetime curvature, elementary general relativity, Einstein field equation, important solutions
- Black-hole thermodynamics
- Probability and information theory
- Quantum theory: Heisenberg matrix mechanics, Schrödinger wave mechanics, Dirac-von Neumann axioms, Hilbert spaces, bra-ket notation, operator algebras, Born rule, uncertainty principle, unitary evolution and the Schrödinger equation, Ehrenfest equations, quantum measurement problem