Modern Introductory Physics, Part II: Quantum Mechanics & Nuclear Physics

Unofficial Course Title: Quantum Mechanics & Nuclear Physics

*Spring 2024, Deep Springs College, **Prof. Brian Hill***

Syllabus

A **PDF of the Syllabus** containing essentially the same information as is on these web pages.

Daily Schedules

Detailed daily schedules will be kept retrospectively:

- **Daily Schedule-Term 4**
- **Daily Schedule-Term 5**

Overview

In the fall semester, we laid the foundation for quantum mechanics and nuclear physics by taking a modern approach to classical mechanics. We covered the same material as is commonly covered in the first semester of college physics, but we did it with an emphasis on three principles that transcend Newtonian mechanics:

- Conservation of momentum
- Conservation of energy
- Conservation of angular momentum

For the spring semester, we will study quantum mechanics, including solutions of Shrödinger's equation, and then nuclear physics, following Volume Q of *Six Ideas that Shaped Physics.* Normally one does not get to study modern physics until the sophomore year as a physics major. To get to quantum mechanics so quickly, we are short-circuiting past electromagnetism. The cost of this is that we have not encountered electromagnetic waves! So to understand quantum-mechanical waves we will first immerse ourselves in other, simple examples of waves. By the end of our quantum mechanics studies, you will be able to do probabilistic calculations using the strange mixture of deterministic time evolution punctuated by non-deterministic measurement events. You will understand how particles behave like waves, including doing all the unexpected things that waves do, such as taking many routes to a destination and exhibiting interference patterns. We will then study nuclear physics, and thanks to our study of quantum mechanics, heuristic rules for nuclear stability will be made qualitatively compelling using fermion gas and Coulomb repulsion arguments.

As a bonus topic during the last week of the semester, we will finally tear ourselves away from quantum mechanics and nuclear physics, and get a brief introduction to Einstein's theory of Special Relativity. The three paradoxes in this theory will be forced upon us: (1) time dilation, (2) length contraction, and (3) the relativity of simultaneity.

In sum, in this course you will encounter behaviors and theories so strange and wonderful that no human could have thought them up. Instead, nature rubbed the behaviors in our faces, and eventually, almost miraculously, in the early 20th century, physicists were able to understand and articulate what nature was showing them. The goal of the modern introductory physics course is to share as much of these behaviors and theories as can be covered in a year-long, calculus-based physics sequence.

Prerequisite / Joining the Class

The prerequisite for the second semester in this sequence is one semester of college-level, calculus-based physics. If you had AP physics in high school and at the end they said you were ready for the second semester of college physics, then you are quite likely prepared. The best way of determining whether you are ready for the class is to self-assess by setting aside two hours to take fall semester's final exam. Copies of the final exam are on the **fall semester course website**.

Texts

- For quantum mechanics: ***Six Ideas that Shaped Physics*, 4th Edition, Volume Q** by Thomas Moore

Grading

- 40% assignments (last semester we alternated between assignments and presentations — this semester I would like to have assignments and presentations for *every* class)
- 20% (total) for two exams in Term 4 (10% each)
- 20% (total) for two exams in Term 5 (10% each)
- 20% thorough preparation for class and leadership of course

Problem Sets / Handouts / Being Neat and Organized

There will be around 20 problem sets and problem set solutions and 4 exams and exam solutions, and many handouts, and reviewing them will be valuable. To be organized, locate a three-ring binder and a three-ring hole punch, and file everything chronologically. Reverse-chronological is actually the most convenient, because you always open your binder to what you are currently working on. Problem sets should be on standard 8 1/2 x 11 paper. Multi-page problem sets should be stapled. Corrections should be erased (if done in pencil) or recopied (if done in pen). To make nice diagrams and graphs, you will very often need a ruler. The nicest technical work is facilitated by engineering pads, such as these **Roaring Spring Engineering Pads at Amazon**, and done with a mechanical pencil and with a ruler at hand. You are meant to only use one side of engineering paper. It might seem wasteful of trees and money, but it pays off in clarity and organization.

Absences (and late work)

The College's general policies on absences (and late work) are applicable. There was an email from Ryan on this on September 8, 2022 in response to a flagging Spring 2022 semester. Since that email predates half of you, the essential absence/late policies are reproduced from that email here:

Whereas missed coursework affects both your classmates and professors by lowering the thinking and understanding you bring to a given class, and interrupts the course schedule that has been set up and is adjusted on an ongoing basis with substantial care. The same is true for absences — whereas a handful of absences might be “normal” at colleges with large lectures or less serious academics, at Deep Springs we expect students to miss *no classes* save for legitimate health issues or emergencies requiring also missing labor and governance obligations. For a student wishing to submit a course assignment past its required deadline, the student may request an extension on the assignment directly from the professor 48 hours in advance. Within 48 hours of the due date, the student must request an extension directly from the Dean. Exceptions will be granted by the Dean only if the student faces unforeseen and unforeseeable circumstances. A student who misses the deadline will be penalized an amount that is roughly equivalent to a letter grade for each day the assignment is late. Assignments cannot be turned in after solutions and graded assignments have been handed back, which generally happens one to two classes after they were turned in.

Modern Introductory Physics Part II — Daily Schedule Term 4

Course **home page**

See also **Daily Schedule-Term 5**

Week 1 — Waves — Principle of Superposition

- Tuesday, Jan. 9 — Study *Six Ideas* Q1.1 to Q1.3 — Choose a problem to present from the end of Chapter Q1 and pair up with someone to discuss both problems and then present one of your two problems jointly — Study and complete the handout/worksheet on compression waves that I set out across from the copier
- Friday, Jan. 12 — Finish *Six Ideas* Q1 — Finish "The Bridge" handout — Look ahead to *Six Ideas* Q2 Section 1 — Problem Set 1 **Due Friday**

Week 2 — Standing Waves — Interference

- Tuesday, Jan. 16 — Theory and simulation presentations for the **weakly coupled harmonic oscillator** — Torsion wave theory, **torsion wave video**, and **torsion wave animation**
- Friday, Jan. 19 — Study Six Ideas Sections Q2.1 to Q2.3 — Discussion of Problem Set 2, especially harmonics on a guitar string and modes of an organ pipe — Presentation from Group 1 on **Single-Slit interference** — Presentation from Group 2 on **Double-Slit interference** — **Problem Set 2** for Friday

Week 3 — Interference — Light is a Particle

- Tuesday, Jan. 23 — Study Six Ideas Sections Q3.1 to Q3.5 (Q3.6 is advanced) — Advanced discussion of last problem on Problem Set 3 — Presentation from Ethan (with Hexi and Miles if out of quarantine): a Python program that does the in-class exercise from the last class — Presentation from Emma on applications of Section Q3.6 to laboratory class on cloning — Presentation from Brian (looking ahead to Q4.1): **Light is a wave** and the wave theory explains the entire electromagnetic spectrum — Presentation from Trey: the ultraviolet catastrophe vs. the actual black-body radiation spectrum — **Problem Set 3** for Tuesday
- Friday, Jan. 26 — Six Ideas Q4 — Presentation from Miles on the rare condition of tetrachromacy — Presentations from Rebecca and Hexi (who will coordinate and divide the historical material): Evidence for the wave nature of light such as the explanation of Snell's Law vs. evidence for its particle nature, especially Millikan's paper from 1913 — Presentation from Ren and Miles: Problem Q4R.1 on the visibility of stars — Presentation from Brian: Prelude to **"Particles Behave Like Waves,"** Chapter Q5 — **Problem Set 4**

Week 4 — Particles Behave Like Waves — Exam 1

- Tuesday, Jan. 30 — Six Ideas Q5 — Black-body radiation and the resulting appearance of **bluish stars, white and yellowish stars, and reddish stars** — Presentations on Q1 to Q4: Emma and Ethan, Q1R.1, a slightly tricky Doppler shift problem; Hexi and Miles, Q2R.2, pulsation frequency of variable stars; Rebecca and Ren, Q3R.1, passing by foghorns; Trey, the energy levels and photon spectrum of hydrogen — **Problem Set 5** for Tuesday — Discussion of interference patterns in the first problem of Problem Set 5 — A look ahead at Q6, spin, beginning with a comparison of the units of angular momentum with the units of h
- Friday, Feb. 2 — **Exam 1**

Week 5 — Complex Variables — The Stern-Gerlach Experiment

- Tuesday, Feb. 6 — We will start into both Q6 and complex variables — Study Sections Q6.1, Q6.2 and Q6.3 of Moore — Study Sections 1-4 of Churchill, Brown, and Verhey, *Complex Variables and Applications* — Presentation from Emma, how the Balmer, Lyman, and Paschen wavelengths from Hydrogen were observed and cataloged — **Problem Set 6** for Tuesday — Lecture and handout on

Electron Spin and Magnetic Moment — It is annoying just how many web sources there are with oversimplified versions of the Stern-Gerlach apparatus (so many that it is almost impossible to see how it is actually done) — Here is a description of an actual **MIT Stern-Gerlach lab**

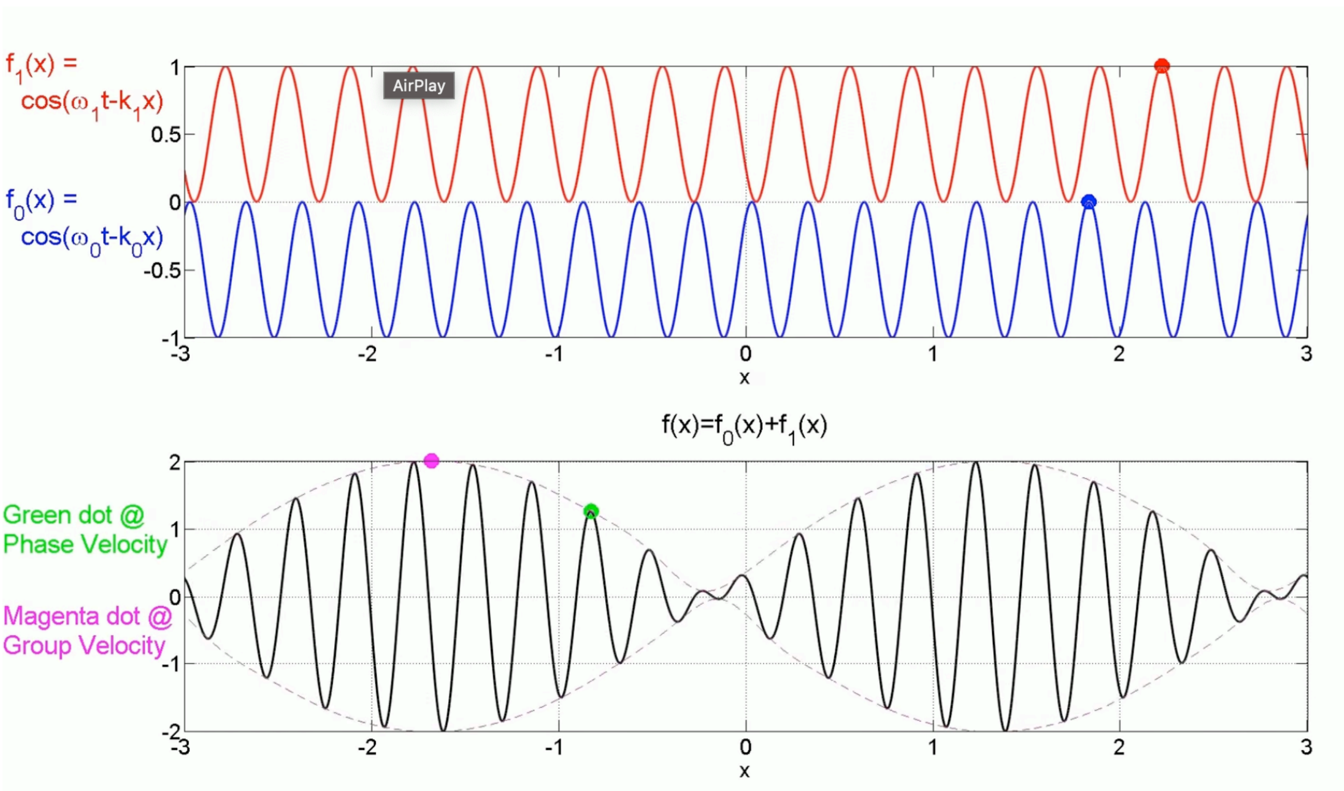
- Friday, Feb. 9 — Finish studying Chapter Q6 of Moore — Study Sections 5 and 6 of Churchill, Brown, and Verhey — **Problem Set 7** for Friday — Presentations: (1) Rebecca and Ren will cover angular momentum, torque, and precession, relying substantially on Volume C, Chapter C6 of *Six Ideas;* (2) Ethan and Hexi will flesh out your understanding of magnetism, electromagnets, and the magnetic field in the Stern-Gerlach apparatus using the relevant material from Section Q6.3, photos like **this one by Dana Mason**, **this diagram and photo of a C-shaped electromagnet**, and additional illustrations and examples from **this material from a Nanhua University course**; (3) Brian will say a more about magnetic moments and then do a look ahead to Chapter Q7, **Them's the Rules**

Week 6 — The Rules for Two-State Systems — The Wave Function

- Tuesday, Feb. 13 — Study Chapter Q7 of Moore — Presentations: (1) Ren and Hexi, Q7D.3 (2) Rebecca and Emma, Q7R.3 (3) Miles and Trey, Sections Q8.4 and Q8.5, Schrödinger's cat, the multiverse interpretation of quantum mechanics! — **Problem Set 8**
- Friday, Feb. 16 — Sections Q9.1 to Q9.3 — **Problem Set 9 for Friday** (includes defining and deriving the 2x2 matrix representations of S_x and S_z) — Defining and deriving the 2x2 matrix representation of S_y — Spin-1 systems — Symmetric and anti-symmetric combinations of two spin-1/2 systems — Group velocity vs. phase velocity of the electron — A **group velocity vs. phase velocity animation** — A **waves on a pond video** — A **boat wake in a canal video** — One more **group velocity vs. phase velocity animation** — Interpreting binned vs. continuous probability distributions — Interpreting and normalizing $|\psi(x)|^2$ — The complete wave function for one electron

Week 7 — Exam 2

- Tuesday, Feb. 20 — **Exam 2** covering Problem Sets 6, 7, 8, and 9, Moore, Chapters Q6, Q7, and Q9, and Churchill, Brown, and Verhey, Sections 1-6



Modern Introductory Physics Part II — Daily Schedule Term 5

Course **home page**

See also **Daily Schedule-Term 4**

Week 8 — Continue Wave Functions

- Tuesday, Mar. 12 — Finish Q9 and start Q10 — Study Moore through p. 154 — S_x , S_y , and S_z cannot be simultaneously specified — Position and momentum cannot be simultaneously specified! — The momentum operator in position space (one of the brilliant leaps of de Broglie and Schrödinger) — Review of a couple super-useful integral calculus techniques: changes of variables in integrals (nowadays, people are calling this "u-substitution") and integration by parts — The **Heisenberg Uncertainty Principle** (a long and important supplement that rigorously states what Moore only briefly states in Section Q9.4) — **Problem Set 10** for Tuesday
- Friday, Mar. 15 — Finish Q10 (except save Q10.4 until Tuesday, Mar. 19) — Presentations: Brian, The time-independent **Schrödinger Equation**; Hexi, Ethan, and Miles, Building a simple oscillator out of the **0th and 1st harmonic oscillator wave functions** introduced in Section Q10.5; Emma and Trey, The fundamental quantum mechanics behind **lasers** — Course **feedback** discussion — Debate and decision of what we will do in weeks 11-14 (it was decided that we will do more quantum mechanics and nuclear physics, rather than switching to special relativity) — **Problem Set 11** for Friday

Week 9 — Observed Properties of the Hydrogen Atom, Atomic Spectra, and the Schrödinger Equation

- Tuesday, Mar. 19 — Q10.4 and Q11.1 to Q11.5 — Presentations: Brian, The 3-D Schrödinger Equation; Ren and Rebecca, Using the Pauli Exclusion Principle to discover the energy of a **Fermion Gas** (ignoring Coulomb repulsion) — **Problem Set 12** for Tuesday
- Friday, Mar. 22 — Study Q11.6 and Q12.1 to Q12 — **Problem Set 13** for Friday — Presentations: Emma, Applying the ideas of Example 11.1 to other molecules (caffeine?!); Brian, Continuation of the quantum tunneling ideas started in Problem Set 13

Week 10 — Continue Schrödinger Equation Examples — Exam 3

- Tuesday, Mar. 26 — No new reading or problem set — In-class, we will analyze the **particle in a finitely-deep potential well**, and **the raising and lowering operators for the harmonic oscillator** (my writeup is a small taste of **operator methods** that are used a lot in quantum field theory because free field theories, including quantum electrodynamics (QED) in the absence of any charges, can be analyzed using the same raising and lowering operator methods as are used for the harmonic oscillator)
- Friday, Mar. 29 — **Exam 3** covering Problem Sets 10-13 and Moore Chapters Q10, Q11, and Q12 (through Q12.3)

Week 11 — Numerical Methods for Solving Schrödinger's Equation — Theory of the Hydrogen Atom — Spherical Harmonics — The Dawn of Nuclear Physics, 1896-1911

- Tuesday, Apr. 2 — Finish Q12 — **Problem Set 14** — Discussion of 12.6 and 12.7, qualitative graphical solutions of Schrödinger's equation and the application of qualitative methods to ramp and barrier wave functions — The **two-dimensional and three-dimensional rotationally-symmetric potential**, which is especially important for understanding hydrogen, and also a gateway to being able to converse with chemists who often think in terms of probability densities and electron clouds — **Another, possibly or even probably, better write-up of the what I wrote up**, see especially the state-naming conventions at the end which need to be second nature if you want to be able to converse with chemists — In a year-long, junior-level quantum mechanics course, you would spend lots more time studying these solutions — In our semester-long, sophomore-level course, we are being quite ambitious to have even discussed them at all

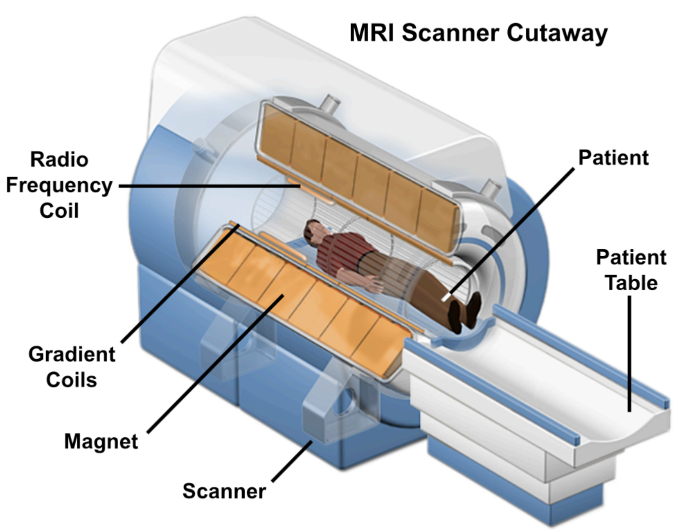
- Friday, Apr. 5 — **Nuclear Physics from 1896-1911**, the discovery of radioactivity, exponential decay and the nucleus following pp. 19-40 of Reed — Please jump on the historical reading because I would like three groups of two people to springboard from that into class presentations for Friday — Start Q13: Sections Q13.1, Q13.2 and Q13.6 — **Problem Set 15**

Week 12 — Continue Nuclear Physics

- Tuesday, Apr. 9 — Finish your study of Q13 — Presentations: (1) Brian will present the relativistic kinematics that forced the hypothesis of the neutron; (2) We had a five-part presentation on mass spectrometry! — We looked ahead to Section 14.1 and discussed how neutron decay is understood in terms of quarks — **Problem Set 16**
- Friday, Apr. 12 — Study Q14 — The reasoning behind the mass-deficit formulae — The traditional definition of the amu (atomic mass unit) — The traditional definitions of the meter and the kilogram (the distance from the north pole to the equator on a line passing through Paris as 10,000,000 meters was the first definition of the meter) — The modern definitions of **SI Units** and especially of the gram in terms of Avogadro's number and Carbon-12, which is now defined to have an amu of 12.0000 — Reading decay-chain diagrams (e.g. those in Moore in Fig. Q14.15, p. 237) — Why are β decays so slow — Why is an α-particle emission a decay mode? — How is fission induced? — **Problem Set 17**

Week 13 — Nuclear Physics Applications (Fission and Fusion) — Intro to Magnetic Resonance

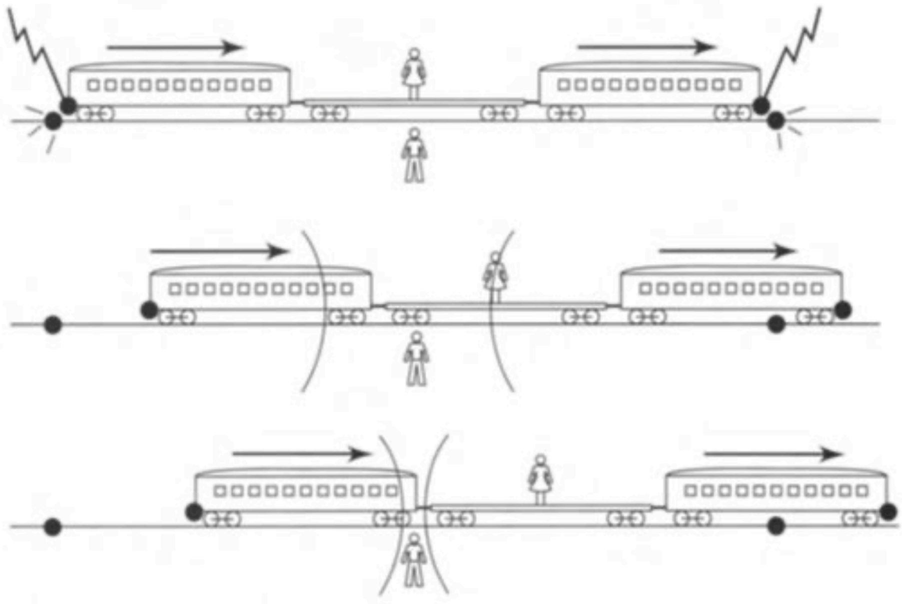
- Tuesday, Apr. 16 — Study Q15 — **Problem Set 18** — Some Q15 topics: (1) **Nuclear stability** (and in particular, why we plot binding energy per nucleon rather than just binding energy) (2) High-energy neutrons (mostly captured) vs. thermal neutrons (the ones that are likely to cause new fissions) in a reactor — Choose the remaining special topics (you will have homeworks on the special topics but not be tested on them) — We started our introduction to MRI by considering the behavior of a magnetic moment in the large constant axial magnetic field of an MRI machine
- Friday, Apr. 19 — Prepare by studying **Part I of the Introduction to MRI** — Presentation by Miles: How are atoms or electrons or ions counted so as to make 1 mole (abbreviated mol), *in practice*; and in particular, how is the gram which is now *defined* as 1/12 of the mass of an Avogadro's number (602,214,076,000,000,000,000,000) of Carbon-12 atoms counted *in practice* (or is it Silicon-29 that is now the definition!?) — Optional Exam Review Q&A scheduled for 11am Sunday (bring anything you want to ask about) — **Part II of the Introduction to MRI** — We did not get to the off-resonance response and the **Lorentzian function** — **Problem Set 19**



MRI Scanner Cutaway (from the National MagLab website)

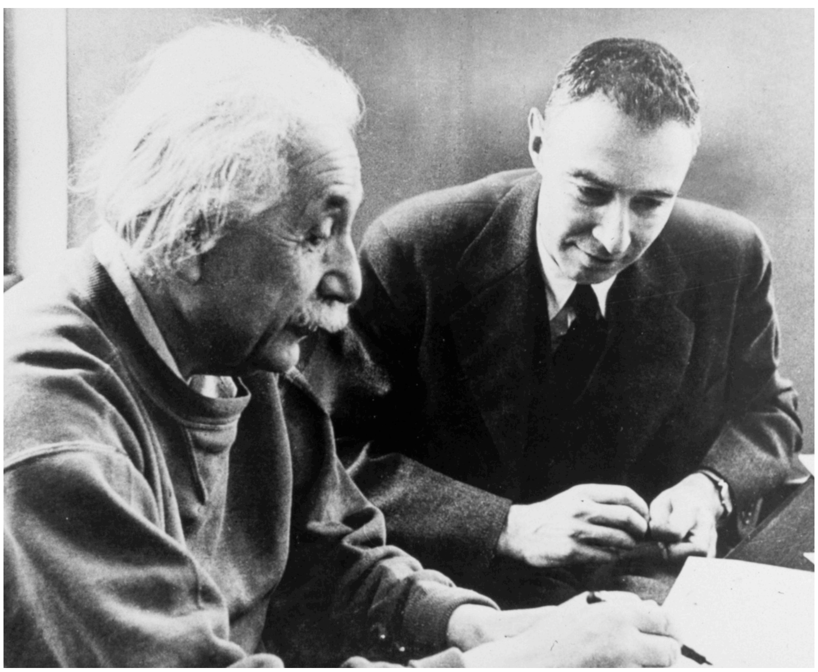
Week 14 — Exam 4 — Special Topic: Introduction to Special Relativity

- Tuesday, Apr. 23 — **Exam 4** Covering Problem Sets 14-18 — For your convenience when reviewing, here are **Problem Sets 14-18 combined** — You will need to use a calculator on this exam, unlike Exams 1-3 — I will bring some spare calculators



Einstein's thought experiment: lightning striking both ends of a train, "simultaneously"

- Friday, Apr. 26 — Length Contraction and Time Dilation in Special Relativity — **An animation of moving clocks** that Emma found — **Problem Set 20** — Reading: **The Relativity of Simultaneity**, a chapter from *Relativity* by Albert Einstein — An **Aging Paradox** presented by Brian — The Twin Paradox presented by Ethan



Einstein and Oppenheimer