PHY 251: Modern Physics

- Prof. Chris Jacobsen: office D-102, `Chris.Jacobsen@stonybrook.edu`. Office hours Tuesday 11:30-12:30 *or by appointment!!!*
- Course web page: `http://tinyurl.com/ltk8qr` which really points to `http://xray1.physics.sunysb.edu/~jacobsen/phy251f2009/index.html`
  - Schedule of lectures, with links to lecture notes.
  - Schedule of recitations, with links to homework assignments.
  - Schedule of PHY 252 labs, with links to lab writeups.
- Course grades will be posted on `blackboard.stonybrook.edu`, and I'll sometimes use Blackboard to send broadcast messages to the class.

What's PHY 251 about?

- This course gives you your first look at special relativity, quantum mechanics, nuclear physics, and a touch of quantum statistics and solid state physics.
- The breadth of the course comes at some cost of depth, but don't get the wrong idea: we will do good, solid physics, with derivations and homework problems.
- For those who go on in physics, you'll see some but not all of these subjects again, and in greater depth, in specific courses. But the fun of this course is that we get to put together a surprisingly complete picture of the world.

PHY 274

- You can also consider a course that will explore a subset of PHY 251's topics but in greater depth!
- PHY 274: Physical and Mechanical Foundations of Quantum Mechanics
  Physical and mathematical foundations of quantum mechanics. Maxwell waves and their properties: intensity, energy density, and momentum density. Planck-Einstein relation between energy and frequency for light quanta. De Broglie relation between momentum and wavelength. Number density and probability density of photons. One-photon quantum mechanics, with Maxwell field as the wave function. Diffraction phenomena. Uncertainty relation between wavelength and position, hence between momentum and position. Not for credit in addition to PHY 390 with similar topic.
- Tu-Th 17:20-18:40, recitation Tu 14:20-15:15. Prof. Alfred Scharff Goldhaber (`Alfred.Goldhaber@stonybrook.edu`)

The setting for Modern Physics

Physics in 1900: Newtonian mechanics, Maxwell's unified theory of electromagnetism, Thermodynamics. One could be smug!

- Attributed to Albert A. Michelson, 1894: "The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote. . . Our future discoveries must be looked for in the sixth place of decimals."
- Attributed to William Thomson, 1st Baron Kelvin, in an address to the British Association for the Advancement of Science, 1900: "There is nothing new to be discovered in physics now. All that remains is more and more precise measurement."

An aside: getting the quotes right!

- The usual report of Michelson's statement: "The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote. . . Our future discoveries must be looked for in the sixth place of decimals."
- The correct quote seems to be as follows: "It is never safe to affirm that the future of physical science has no marvels in store which may be even more astonishing than those of the past; but it seems probable that most of the grand underlying principles have now been firmly established and that further advances are to be sought chiefly in the rigorous application of these principles to all the phenomena which come under our notice."
  followed by a statement several hundred words later of
  "An eminent physicist has remarked that the future truths of physical science are to be looked for in the sixth place of decimals."

"I really didn't say everything I said"

- Yogi Berra, the great Yankees catcher from 1946–1963.

- Other Yogiisms: "Ninety percent of this game is half mental." "When you come to a fork in the road, take it." "It's like déjà vu all over again."
- The two versions of Michelson's words shown before are a bit different! The second [correct] one adds "It is never safe to affirm that the future of physical science has no marvels in store. . ."
- The first version of the quote is the one you'll commonly find if you do a Google search; one example states that Michelson said this in a speech at the dedication of the Ryerson Physics Lab at the University of Chicago in 1894.
- According to David Henige, "Mis/Adventures in Mis/Quoting," *Journal of Scholarly Publishing* **32** (3), 123–135 (2001), the second version of the quote is the earliest one he was able to find from original source material: Albert A. Michelson, "Some of the Objects and Methods of Physical Science," *University of Chicago Quarterly Calendar* **10**, 15 (August 1894).
- But if it's on the internet, it must be true, right?

Back to physics at the turn of the previous century

- The theme of this course is that the physics you have learned in your freshman courses, which is mainly “classical physics” that was largely worked out before 1900, is not fully correct.
- It’s not wrong; it works with remarkable accuracy in nearly all situations.
- It’s just incomplete, in that it does not fully describe the very small, the very fast, and the very energetic.
- As we explore the situations where classical physics breaks down, keep in mind that we will usually be able to apply a *correspondance principle* and show that the more correct modern physics theory reproduces the classical physics theory in less extreme circumstances.

Maxwell's equations

Maxwell unified some laws of electricity and magnetism in 1855; by 1873 he found that all of these laws could all be represented by four partial differential equations. A triumph of unification!

$$\begin{aligned}
\text{Faraday:} \quad \vec{\nabla} \times \vec{E} &= -\frac{\partial \vec{B}}{\partial t} \\
\text{Ampère:} \quad \vec{\nabla} \times \vec{B} &= \mu(\vec{J} + \epsilon \frac{\partial \vec{E}}{\partial t}) \\
\text{Gauss (electric):} \quad \vec{\nabla} \cdot \vec{E} &= \frac{\rho}{\epsilon} \\
\text{Gauss (magnetic):} \quad \vec{\nabla} \cdot \vec{B} &= 0.
\end{aligned}$$

$\vec{\nabla}\times$ is *curl*, and $\vec{\nabla}\cdot$ is *divergence*.

James Clerk Maxwell (1831–1879)

Ampère's law modified

Ampère's law is

$$\vec{\nabla} \times \vec{B} = \mu \left(\vec{J} + \epsilon \frac{\partial \vec{E}}{\partial t} \right)$$

Using Ohm's law $\vec{J} = \sigma \vec{E}$, Ampère's law becomes

$$\vec{\nabla} \times \vec{B} = \sigma \mu \vec{E} + \mu \epsilon \frac{\partial \vec{E}}{\partial t}.$$

Electromagnetic wave propagation

You'll see this in PHY 301: can manipulate Maxwell's equations to give

$$\nabla^2 \vec{E} = \mu\epsilon \frac{\partial^2 \vec{E}}{\partial t^2} \qquad \text{and} \qquad \nabla^2 \vec{B} = \mu\epsilon \frac{\partial^2 \vec{B}}{\partial t^2}$$

Wave solutions for electric field:

$$\text{Plane: } \vec{E} = \text{Re}\left[\vec{E_0} e^{-i(\vec{k}\cdot\vec{z}-\omega t)}\right] \qquad \text{Spherical: } E = \text{Re}\left[E_0 \frac{e^{-i(kr-\omega t)}}{r}\right].$$

Velocity of wave propagation:

$$c \equiv \frac{1}{\sqrt{\mu_0 \epsilon_0}} = 2.99792458 \times 10^8 \text{ m/sec}$$

or 30 cm per nanosecond. Can measure μ_0 from current in wires, and ϵ_0 from energy in capacitors!

Speed of light

- Inferred to be finite from astronomical measurements by Romer (1676)
- Huygens soon estimated 2.2×10^8 m/sec.
- Refined by Bradley (1728) to 2.98×10^8 m/sec.
- First terrestrial measurement by Fizeau (1849): 3.13×10^8 m/sec.

Maxwell on the similarity of $1/\sqrt{\mu_0 \epsilon_0}$ to the above, as quoted in Griffiths' *Introduction to Electrodynamics* (Prentice-Hall, 1981):

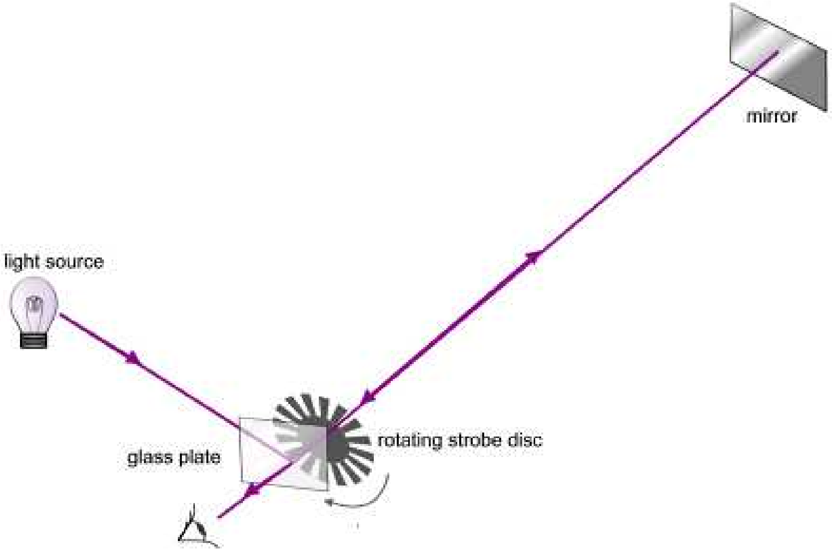
> *This velocity is so nearly that of light, that it seems we have strong reasons to conclude that light itself (including radiant heat, and other radiations if any) is an electromagnetic disturbance in the form of waves propagated through the electromagnetic field according to electromagnetic laws.*

Fizeau and Foucault

- Fizeau's 1849 measurement: use a "toothed" disc to see when light could still get through. *Very* distant mirror: about 5 miles away!
- Improved in 1850 by Léon Foucault: use a spinning mirror.
- More history is available here.

Armand Hippolyte Louis Fizeau, 1819–1896

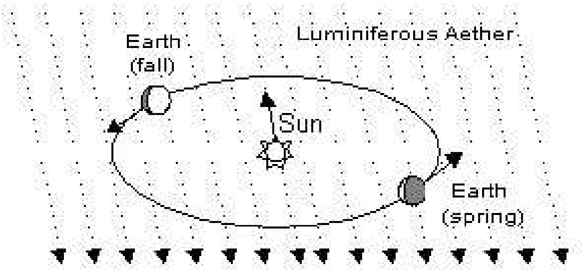
Fizeau’s experiment



As drawn on Wikipedia by Theresa Knott.

Speed of medium?

- Sound waves travel at speed of sound $v = \sqrt{(c_p/c_v)(P/\rho)}$ relative to speed of medium (wind speed).
- What's the medium for light? The æther. Speed of earth in its orbit: 3×10^4 m/sec (see homework).
- Differences in light speed?
- How does that fit into $c = 1/\sqrt{\mu_0 \epsilon_0}$?

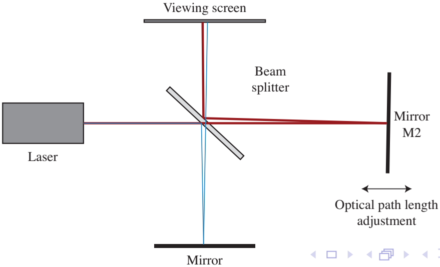


Course information
Modern Physics: the setting
Quotes
Maxwell and light
Waves in media
Einstein

Michelson and Morley

- Albert Michelson (Case-Western, 1881): interferometer. Fringe shift of 0.02; expected 0.04.
- Joined by Edward Morley in attempts to measure æther wind with 11 m long interferometer.
- Improved result (1887): fringe shift < 0.01 when 0.4 expected, so $v_{\text{æther}} < 8 \times 10^4$ m/sec. Later measurements on light from stars.
- Nobel Prize 1907 (Michelson)

Albert A. Michelson (1852–1931)



Enter Einstein

Before we look at how Einstein thought about this problem, let's start with learning who he was.
It is widely reported that Einstein was a learning disabled student. Here's a quote which claimed that Einstein was a learning disabled student:

> *Albert Einstein did not speak until the age of three. Even as an adult Einstein found that searching for words was laborious. He found school work, especially math, difficult and was unable to express himself in written language. He was thought to be simple minded (retarded), until it was realized that he was able to achieve by visualizing rather than by the use of language. His work on relativity, which revolutionized modern physics, was created in his spare time.*

Again, don't trust everything you read on the internet! A short response to this is given on another web page based on two complete biographies with citations to their source material and all that.

Einstein's early career

- Finished PhD 1901.
- Working in Swiss Patent Office in Bern while completing *privat-dozent* (called the Habilitation today in Germany; it's almost a sort of second PhD to prove that you're enough of a scholar to be a professor) so that he could seek a university professor position.
- 1905: what a year! Read Abraham Pais' book "Subtle is the Lord" to learn more.
- 1908: Received his *Privatdozent* at Bern
- 1911: Professor at the University of Prague
- 1914: Professor at the University of Berlin
- 1921: Nobel Prize for photoelectric effect.

Einstein's *annus mirablis*: 1905

Four papers to *Annalen der Physik*:

- "On the Motion - Required by the Molecular Kinetic Theory of Heat - of Small Particles Suspended in a Stationary Liquid." Direct evidence of the existence of atoms.
- "On a Heuristic Viewpoint Concerning the Production and Transformation of Light," interpreting observations of the photoelectric effect as indicating the existence of photons. Nobel Prize, 1921.
- "On the Electrodynamics of Moving Bodies," concerning what is now called special relativity.
- "Does the Inertia of a Body Depend Upon Its Energy Content?," containing $E = mc^2$.

Quite a year!

Albert Einstein (1879–1955) in 1905.
Photo source

Einstein's 3rd paper: motivation

First page of Einstein's 1905 paper "On the Electrodynamics of Moving Bodies" (translation from Griffiths, *Introduction to Electrodynamics*, Prentice-Hall, 1981, p. 392):

> *It is known that Maxwell's electrodynamics–as usually understood at the present time–when applied to moving bodies, leads to asymmetries which do not appear to be inherent in the phenomena. Take, for example, the reciprocal electrodynamic action of a magnet and a conductor. The observable phenomenon here depends only on the relative motion of the conductor and the magnet, whereas the customary view draws a sharp distinction between the two cases in which either the one or the other of these bodies is in motion. . .*
> *Examples of this sort, together with the unsuccessful attempts to discover any motion of the earth relative to the "light medium," suggest that the phenomena of electrodynamics as well as of mechanics possess no properties corresponding to the idea of absolute rest.*

Einstein's postulates

Special relativity: two frames with velocity difference (general relativity deals with large acceleration differences). Postulates:

1. The laws of physics are the same in all inertial reference frames.
2. The speed of light in free space has the same value $c = 1/\sqrt{\mu_0 \epsilon_0}$ in all inertial reference frames.

Postulate 2 explains Michelson-Morley. But what about the speed of light coming out from the headlights of a spaceship?