Welcome to ENGN1560

OPTICS

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Office hours:
Thursdays, 1:00-2:30pm

All assignments and important class information:

https://www.brown.edu/research/labs/mittleman/engn-1560-spring-2018

NOTE: there will be no printed handouts.
Logistics

• Syllabus: [online]
• Lectures: MWF@noon
• Problem sets: weekly (mostly)
• Office Hours: Thursdays 1:00-2:30pm
  (or by appointment)
• Exams: two oral midterms, one written final
• Text book: *Optics*, by Eugene Hecht (5th ed.)
• Handouts / Announcements: online only
• Lecture attendance: strongly recommended
1. Optics: An Introduction

A few of the key questions that have motivated optics research throughout history

A short, arbitrary, condensed history of optics

Maxwell's Equations

Cool things that involve light
- Total internal reflection
- Interference
- Diffraction
- The Laser
- Nonlinear Optics
- Ultrafast Optics
Optics: A few key motivating questions

1. What is the speed of light? Is it infinitely fast? If not, then how do we measure its speed?

2. What is light? Is it a wave, or is it a stream of particles?

There is a big difference in the behavior of particles vs. waves.
What do we mean by “particle” and “wave”?

When speaking of a flow of particles, it is clear that something with a mass (greater than zero) is moving:

$$\vec{P} = m \vec{V}$$

Bullets carry momentum.

Also, they can’t be subdivided:
Half a bullet doesn’t work.

For waves, it is clear that energy moves along one direction.

But there is no net flow of mass.

Also, a wave can be shrunk arbitrarily and it’s still a wave - there is no “smallest size”.

Can you have a wave in empty space?

Waves and particles are very different things.
Optics in Ancient History

**Ancient Egypt:**
Mirrors have been discovered in many tombs, some going back as far as 1500 BCE.
Usually created by polishing a thin bronze or copper sheet.

**Ancient Greeks (500-300 BCE):**
Brought us the word “optics”, from πτική meaning “appearance”.
Burning glass mentioned in a play by Aristophanes (424 BCE).
Law of Reflection: “Catoptrics” by Euclid (300 BCE).
Refraction in water mentioned in Plato’s “The Republic” (380 BCE).

**Ancient Chinese (468-376 BCE):**
First mention of the ‘camera obscura’ (pinhole camera) phenomenon.
Law of Reflection; focusing effect of curved mirrors.
Optics in Ancient History

Ancient Greeks:
“Burning glass”: supposedly used as a weapon against the Roman fleet by Archimedes (212 BCE)

Mythbusters:
Demonstrated that this almost certainly would not have worked (2006)

But the story of Archimedes and the burning glass was well known throughout history, and inspired many subsequent efforts.
Optics in Ancient History

Ancient Rome:
- **Seneca** (3 BCE–65 AD) discussed globes of water as lenses
- **Lucretius** (55 BCE) proposed a theory of light involving a “flow of minute atoms” streaming forth from the sun.

Ancient Islamic science:
- **Alhazen** (965–1040 AD) studied spherical and parabolic mirrors, and was the first to establish that sight results from light entering the eye, not from a beam emerging from the eye.
- **Ibn Sahl** (940–1000 AD) derived the Law of Refraction.
- **Abu Rayhan al-Biruni** (973–1048 AD) determined that the speed of light was finite, but greater than the speed of sound.
Hans Lippershey (1570–1619) applied for a patent on the Galilean telescope in 1608.

A year later, Galileo Galilei (1564–1642) used one to look at Jupiter and its moons.

Francesco Fontana of Naples (1580–1656) replaced the concave eyepiece of the Galilean telescope with a convex lens, yielding a Keplerian telescope.

Johannes Kepler (1571–1630) discovered total internal reflection; showed why telescopes work; developed a first-order theory of geometric optics; used a Keplerian telescope to discover the laws of planetary motion.
More 17th-century Optics

Rene Descartes modeled light as pressure variations in a medium, and re-discovered the Law of Refraction.

Pierre de Fermat developed the "Principle of Least Time" to describe the propagation of light.

Francesco Maria Grimaldi of Bologna (1618-1663) discovered diffraction.

Robert Hooke (1635-1703) studied colored interference between thin films and developed the first wave theory of light.

Willibrord Snel van Royen (1591-1626) of Leyden was the third person to discover the Law of Refraction, now named after him (Snell’s Law, not Willibrord’s Law).
Christiaan Huygens
(1629-1695)

Huygens extended the wave theory of optics.

He realized that light slowed down on entering dense media.

He explained polarization and double refraction.

Huygens' principle says that a wave propagates as if the wave-front were composed of an array of point sources each emitting a spherical wave.
Isaac Newton (1642-1727)

"I procured me a triangular glass prism to try therewith the celebrated phenomena of colours." (Newton, 1665)

Newton introduced a new level of rigor to optics. At age 23, he did his famous experiments dispersing light into its spectral components. After remaining ambivalent for many years, he eventually concluded that it was evidence for a particle theory of light.
Opticks (1704)

One of the most important scientific publications of all time

Along with *Principia*, established Newton as the greatest physicist since Aristotle

Unlike *Principia*, it was written in English, not Latin.

Price in 1704: £1

Price today: $60,000
(www.abebooks.com)
Leonhard Euler (1707–1783) further developed the wave theory and designed achromatic lenses by combining lenses of different materials.

Thomas Young (1773–1829) explained interference and colored fringes and showed that light was a transverse wave.

Augustin Fresnel (1788–1827) did experiments to establish the wave theory and derived expressions for reflected and transmitted waves.

Joseph von Fraunhofer (1787–1826) perfected techniques for fabricating high-quality optics, and invented the spectroscope.
James Clerk Maxwell

Maxwell unified electricity and magnetism with his now famous equations (1864).

This was one of the most important events in the history of physics. It was one of the first examples of the unification of two seemingly unrelated phenomena into a single theoretical framework.

Maxwell’s equations showed that light is an electromagnetic wave.

Maxwell assumed that, like all waves, it must require some medium in which to propagate. His equations did not rule out the existence of this unknown medium, which was known as “the aether.”
Albert Michelson & Edward Morley

A series of careful measurements were made by Michelson and Morley, to attempt to measure the earth's velocity with respect to the aether (1890’s).

They found it to be zero.

This proved that either
(a) the aether doesn’t exist or
(b) the earth is the center of the universe, around which all things move

Nobody liked option (b).
Albert Einstein

Einstein showed that light:

- is a phenomenon of **empty space**; (i.e., the ‘aether’ isn’t necessary)
- has a velocity that is **constant**, independent of the velocity of the observer
- is **both** a wave and a particle.
The “miracle year” (1905)

"On a Heuristic Viewpoint Concerning the Production and Transformation of Light"

proposed the idea that light is composed of energy quanta

"On the motion required by the molecular kinetic theory of heat of small particles suspended in a stationary liquid"

provided the first empirical evidence for the existence of atoms

"On the electrodynamics of moving bodies"

proposed that the speed of light is a fundamental constant of the universe, which implies that space and time are not two different things, but two aspects of the same thing (Special Theory of Relativity).

“Does the inertia of a body depend upon its energy content?”

\[ E = mc^2 \]
The equations of optics are Maxwell’s equations.

\[ \vec{\nabla} \cdot \vec{E} = \rho / \varepsilon_0 \quad \vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \]

\[ \vec{\nabla} \cdot \vec{B} = 0 \quad \vec{\nabla} \times \vec{B} = \mu_0 \vec{J} + \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t} \]

where \( \vec{E} \) is the electric field, \( \vec{B} \) is the magnetic field, \( \rho \) is the charge density, \( \vec{J} \) is the current density, \( \varepsilon \) is the dielectric permittivity, \( \mu \) is the magnetic permeability…

…and \( \vec{\nabla} \) is “del”, the vector differential operator.
You may be more familiar with the integral forms.

Gauss’ Law for magnetic fields
\[ \oint \mathbf{B} \cdot d\mathbf{a} = 0 \]
Faraday’s Law of Induction
\[ \oint \mathbf{E} \cdot d\mathbf{l} = -\frac{\partial}{\partial t} \int \mathbf{B} \cdot d\mathbf{a} \]
Gauss’ Law for electric fields
\[ \iint \mathbf{E} \cdot d\mathbf{a} = \frac{q}{\varepsilon_0} \]
Ampere’s Law with Maxwell’s correction
\[ \oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 \mathbf{I} + \mu_0 \varepsilon_0 \frac{\partial}{\partial t} \iint \mathbf{E} \cdot d\mathbf{a} \]

If any of this stuff is unfamiliar to you, then you need to review.
“Electromagnetic Waves” are solutions to Maxwell’s equations

Electric (E) and magnetic (B) fields that oscillate as a function of both position and time.

The electric field, the magnetic field, and the propagation direction are all perpendicular.
Some of the optical effects we will discuss this semester.

Many materials absorb light strongly. This absorption can vary dramatically with the wavelength of the light.

Water is transparent to visible light, but not to most other light waves.

Notice that the penetration depth varies by over ten orders of magnitude!
Scattering of light waves

Rainbows result from the reflection and refraction of light from water droplets in the air.

Note that there can be two rainbows, and the top one is inverted.
An interesting question is what happens to light when it encounters a surface.

At an oblique angle, light can be completely transmitted or completely reflected.

"Total internal reflection" is the basis of optical fibers, a multi-billion dollar industry.
Light beams can interfere with each other.

Light waves are coherent. This means that two light waves can interfere with each other.

For example, using a partially reflecting mirror, we can split a beam into two. If we then recombine the two beams, their relative phase matters.
Coherence and interference

We can exploit the coherence properties of light by making artificial structures that control the propagation of light in amazing ways. These are known as “photonic crystals”.

Opals and butterfly wings are naturally occurring photonic crystals. They are colorful because of the interference of scattered light waves.
Often, interference is not intentional
**Diffraction**

Light bends around corners. This is called diffraction.

Light patterns after passing through rectangular slit(s):

A “diffraction grating” can be used to separate different colors of light.
Diffraction

This also often happens unintentionally, and gives rise to familiar sights.
Modern optics started with the Laser

A laser is a device that stores energy and emits it in the form of coherent light.

The invention of the laser (1960) completely revolutionized the field of optics. And many other fields too.

Ted Maiman (1927-2007), holding his invention
Lasers are extremely photogenic
Lasers are the basis for global communications

Lasers

Frequency-registered transmitters

WDM Max

Optical Fiber

Amp

40 - 120 km

Amp

WDM DeMux

Up to 10,000 km

Δλ = 25 - 100 GHz

(0.4 or 0.8 nm @ 1500 nm)

worldwide installed undersea fiber optic network

(more than 100 million km of fiber)
Nonlinear Optics produces many exotic effects.

Sending infrared light into a crystal yielded this display of green light:

This is an example of non-linear optics, because the output beam is not simply a linear multiple of the input beam. It’s a different color.

Such effects are almost never encountered in nature, but can be extremely useful in engineered applications.
Ultrashort laser pulses are the shortest events ever created.

The pulse intensity vs. time and the spectrum of one of the shortest events ever created, a pulse only $4.5 \times 10^{-15}$ seconds long, that is, 4.5 femtoseconds (0.0000000000000045 seconds).

This is about 10,000 times faster than the fastest electrical switch.

Generating such a short event is impossible without nonlinear optics. So is measuring it.
“Light is, in short, the most refined form of matter.”

Louis de Broglie

Problem set 1 will be posted on the web site on Friday.