Finalities

- Final: Thursday May 19, 2:15 to 4:45 pm
  - ESS 079 (this room)
Chapters on Exam

• Introductory Chapters
  - 1 (What is light), 2 (Geometric Optics)

• Geometric Optics Applications
  - 3 (Lenses), 4 (Cameras)

• Vision
  - 5 (Eye as a Camera), 7 (Visual Processing), 8 (Binocular Vision), 9 (Color)

• Physical Optics
  - 12 (Wave Optics), 13 (Polarization and Scattering), 15 (Quantum Optics)
Light is a Electromagnetic Wave

• Properties of Light
  - Velocity: 300,000,000 m/s (i.e. $3 \times 10^8$ m/s) in vacuum
    • Constant speed in vacuum
    • But can slow down in materials
  - Light moves
    • Energy
    • Momentum

• Described by
  - Wavelength, frequency, period, polarization, amplitude, intensity
Symbols for Light

- Symbols to represent ideas:
  - Wavelength: $\lambda$
    - This is the Greek letter Lambda
      - Because "l" is easily confused with "1" and "I"
  - Velocity: $v$
    - The velocity of light (in vacuum) gets a special symbol: $c$
  - Period: $T$
  - Frequency: $f$
    - The book gets clever and uses the Greek letter Nu ($\nu$)
Important Equation

- Relate the velocity of light to its frequency and wavelength

\[ v = f \lambda \]
The Electromagnetic Spectrum

Visible Light

~400 nm to 700 nm
Reflection and Transmission

- Waves change velocity at a boundary
  - The frequency is the same on both sides of the boundary
    - That means the wavelength changes \( (v = f \lambda) \)

- Vocabulary:
  - **Reflected**: Part of the energy “reverses” direction
  - **Transmitted**: Part of the energy “crosses” the boundary
    - Only if the new material is also *transparent*
    - For metal, wave is reflected, but not transmitted
Relating Wave Properties to Perception

- Light is describe by
  - Wavelength, Intensity
- We perceive
  - Color: Related to wavelength
  - Brightness: Related to intensity
- These are related, but are not the same thing
  - For instance, our perception of brightness depends on both the wavelength and intensity
Light Rays

- Give the direction of light
- Rays are straight
  - Only change direction when they hit something (i.e. scatter)
- Light Rays are an *approximation*
  - Useful, but not quite accurate
  - We can use light rays when
    - When sizes and distances are much greater than the wavelength
When Do Rays Work

- As long as stuff is a lot bigger than the wave length
  - Red is 650 nm → Stuff bigger than 65000 nm
    - That is about a 1/15\textsuperscript{th} of a millimeter
  - Blue is 475 nm → Stuff bigger than 47500 nm
    - That is about 1/20\textsuperscript{th} of a millimeter
- How big is that
  - A hair is about 1/10\textsuperscript{th} of a millimeter thick
  - A piece of paper is about 1/10\textsuperscript{th} of a millimeter thick
Light Wave Fronts

- Specify the position of the wave crests
  - Tell us the direction, and phase of a wave
  - Wave fronts have to be continuous, but can bend at a surface (e.g. refraction)
Rays and Wave fronts

Wave fronts and rays are perpendicular
Ray Tracing

Light Source

Light Rays

Screen

Tells us where the light will hit
We only need to draw the *principal rays* which are the ones where something changes.

For lenses and mirrors we concentrated on the principal rays.
Names for Shadows

Penumbra

Umbra

Penumbra
Law of Reflections

- The normal is perpendicular

- The angle of incidence...

- Is equal to the angle of reflection
Specular and Diffuse Reflection

Specular Reflection

\[ \theta_i, \theta_r, \text{ normal} \]

Diffuse Reflection

light rays shining on a surface

Reflected rays in all directions

scatter
Index of Refraction

- **Light Speeds**
  - Speed of light in vacuum is a universal constant, \( c \)
  - Speed of light in a material is a property of the material (e.g. \( c_{\text{glass}} \))

- **Index of refraction**

\[
 n_{\text{material}} = \frac{\text{speed of light in vacuum}}{\text{speed of light in material}}
\]
# Index of Refraction

<table>
<thead>
<tr>
<th>Material</th>
<th>Index of Refraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum</td>
<td>1</td>
</tr>
<tr>
<td>Air</td>
<td>Just more than 1</td>
</tr>
<tr>
<td>Water</td>
<td>1.33</td>
</tr>
<tr>
<td>Glass</td>
<td>1.3 to 1.5</td>
</tr>
</tbody>
</table>

\[
\text{speed of light in material} = \frac{\text{speed of light in vacuum}}{n_{\text{material}}}
\]
Example

Light is traveling in a material with an index of refraction, $n = 1.2$. What is the velocity of the light in the material?

$$\text{speed of light in material} = \frac{\text{speed of light in vacuum}}{n_{\text{material}}}$$

The speed of light in vacuum is $3 \times 10^8$ m/s, so

$$\text{speed in material} = \frac{3 \times 10^8 \text{ m/s}}{1.2} = 2.5 \times 10^8 \text{ m/s}$$
Refraction

- Incident Ray
- Refracted Ray
- Normal
- $n_I$
- $n_R$
- $\theta_I$
- $\theta_R$
Snell's Law

\[ n_{\text{incident}} \times \sin \theta_{\text{incident}} = n_{\text{refracted}} \times \sin \theta_{\text{refracted}} \]

\[ \sin \theta_{\text{refracted}} = \frac{n_{\text{incident}}}{n_{\text{refracted}}} \times \sin \theta_{\text{incident}} \]

\[ \sin \theta_{\text{incident}} = \frac{n_{\text{refracted}}}{n_{\text{incident}}} \times \sin \theta_{\text{refracted}} \]
Example

Light travels from air into water \((n = 1.33)\) with a 30 degree angle of incidence. What is the angle of refraction?

\[
\sin \theta_{\text{refracted}} = \frac{n_{\text{incident}}}{n_{\text{refracted}}} \times \sin \theta_{\text{incident}}
\]

The index of refraction for air is \(n = 1\), so

\[
\sin \theta_{\text{refracted}} = \frac{1}{1.33} \times \sin 30 = 0.376
\]

\[\theta_{\text{refracted}} = \arcsin 0.376 = 22 \text{ degrees}\]
SOH-CAH-TOA

- Sine is Opposite over Hypotenuse
  - \( \sin \theta = \frac{O}{H} \)
- Cosine is Adjacent over Hypotenuse
  - \( \cos \theta = \frac{A}{H} \)
- Tangent is Opposite over Adjacent
  - \( \tan \theta = \frac{O}{A} \)
What does Snell's Law Tell Us?

- Light going from a small index of refraction (air) to a large index of refraction (glass) is bent toward the normal.

- Light going from a large index of refraction (glass) to a small index of refraction (air) is bent away from the normal.
Describing a Spherical Mirror

- **Optical Axis**
- **Focal Point**
- **Center**
- **Radius (twice Focal Length)**
- **Focal Length**

If center is in front of mirror (concave), the focal length is positive.
If center is in back of mirror (convex), the focal length is negative.
Example

A spherical mirror has a 1 meter radius of curvature. What is its focal length?

\[ f = \frac{R}{2} \]

so

\[ f = 50 \text{ cm} \]
Convex Mirror Ray Tracing Rules

- All incident rays parallel to the axis appear to come from the focal point.
- All incident rays that (when extended) pass through the focal point are reflected back parallel to the axis.
- A virtual image is formed where the previous two rays cross.
A Convex Mirror

Image Distance  ---  Object Distance

The image is behind the mirror, so the image distance is negative!

Virtual Image

Virtual image is closer to mirror than the object.
Concave Mirror Ray Tracing Rules

Object closer than focal point

- Draw a line from the focal point passing through the tip of the object to the mirror.
  - Draw a ray along this line from the object to the mirror. It will be reflected parallel to the axis

- Draw a ray from the tip of the object parallel to the axis. It will be reflected through the focal point.

- Extend the rays behind the mirror. There will be a virtual image where they cross.
A Concave Mirror
(object close to mirror)

Object Distance ---- Image Distance

Object

Image is further from mirror than object

Virtual Image

Image is behind the mirror, so the image distance is negative!

Light doesn't actually come from virtual image...

The image is behind the mirror, so the image distance is negative!
Ray Tracing a Concave Mirror
Object further than focal point

- A ray going parallel to the axis are reflected through the focal point.
- A ray going through the focal point is reflected parallel to the axis
- A real image is formed where the rays cross.
A Concave Mirror
(object far from mirror)

Object Distance

Object

Real Image

Object and image are further from focal point

Image Distance
Mirror Equations

- We can also rearrange to get the magnification

  - The Mirror Equation: \( \frac{1}{f} = \frac{1}{X_O} + \frac{1}{X_I} \)

  - The magnification: \( m = \frac{S_I}{S_O} = \frac{-X_I}{X_O} \)

- Notice the magnification is negative for a concave mirror with a real image!
Example

A mirror has a focal length of 50 cm. If the object distance is 80 cm, what is the image distance?

\[ \frac{1}{f} = \frac{1}{X_o} + \frac{1}{X_i} \]

so

\[ X_i = \frac{1}{(\frac{1}{f} - \frac{1}{X_o})} \rightarrow \]

\[ \frac{1}{(\frac{1}{(50 \text{ cm})} - \frac{1}{(80 \text{ cm})})} = 133 \text{ cm} \]

The magnification is \[ m = - \frac{X_i}{X_o} = - 1.66 \]

This is a real image.
Ray Tracing a Convex Lens
Object further than focal point

- A ray going parallel to the axis is refracted through the “opposite” focal point.
- A ray going through the “near” focal point is refracted parallel to the axis.
- A real image is formed where the rays cross.
Ray Trace a Convex Lens

Object further than focus

Object Distance

Focal Length

Opposite Focal Point

Near Focal Point

Object
Convex Lens Ray Tracing Rules
Object closer than focal point

- Draw a line from the focal point passing through the tip of the object to the lens.
  - Draw a ray along this line from the object to the lens. It will be refracted parallel to the axis.

- Draw a ray from the tip of the object to the lens parallel to the axis. It will be refracted through the focal point.

- Extend the rays back to the other side of the mirror
  - There will be a virtual image where they cross.
Ray Trace a Convex Lens

Object closer than focus

- Image Distance
- Object Distance
- Focal Length
- Focal Point
- Optical Axis
- Virtual Image
- Object
Concave Lens Ray Tracing Rules

- Draw a line from the object passing through the opposite focal point of the lens.
  - Draw a ray along this line from the object to the lens. It will be refracted parallel to the axis.

- Draw a ray from the tip of the object to the lens parallel to the axis.
  - It will be refracted along a line passing through the near focal point.

- Extend the rays back to the other side of the lens
  - There will be a virtual image where they cross.
Image and Object Distances

Object Dist.  Image Dist.

Focal Length

Object

Virtual Image

Image Dist.  Negative!

Object Dist.  Positive

Focal Length

Object

Virtual Image
Lens Equations

- Same as Mirror Equations
  - The Lens Equation: \( \frac{1}{f} = \frac{1}{X_O} + \frac{1}{X_I} \)
  - The Lens Magnification: \( m = \frac{S_I}{S_O} = -\frac{X_I}{X_O} \)

- The important things to remember are
  - When \( f \) is positive or negative
  - When \( X_O \) is positive or negative
  - When \( X_I \) is positive or negative
Chapter 4: Cameras

- Basic Components of the Camera
  - Lens, Film, Shutter, Focus

- Types of Lens
  - Focal Length
  - Telephoto, Wide Angle,
  - Depth of Field

- Basics of Film (Image Capture)
  - Black and White Film
  - Digital Sensors
“Modern” Film Cameras (e.g. 35mm)
Lenses

Telephoto
210 mm

Normal
50 mm

Wide angle
28 mm
Depth of Field

If film spot is smaller than resolution of film, the image appears in focus.
f-number

- We can find the relative intensity of images focused on film by comparing the f-numbers of lenses
  - \( f\text{-number} = \frac{\text{focal length of lens}}{\text{diameter of lens}} \)

- Lens stops:
  - You can't change the actual size of a lens, but you can “stop” it to an size
    - show demo
    - Change f-number for stops
  - \( f\text{-number} = \frac{\text{focal length of lens}}{\text{diameter of stop}} \)
Recording the Image

- Control how much light strikes the film
  - How long the film is exposed
    - Shutters
  - Intensity of light striking the film
    - f-stops
    - aperture

- Correct range of light intensity determined by film
How does film work

• Expose to Light
  – When light strikes a chemical called silver halide it breaks a bond
    • Yields a metallic silver + other stuff

• Develop Film
  – Use other chemical processes to increase size of metallic grains to develop film

• Print Image
  – Film records a negative image
Film Response

• Record the intensity of the light striking it
  - For color, record the light intensity for several different wavelengths (approximate color)

• Want a logarithmic response...

![Graph 1: Log of amount of light vs. Recorded Value](image1)

![Graph 2: Amount of light vs. Recorded Value](image2)
Steps to a Digital Image

• Light is focused on a sensor
  – Same as film or any other optical system
• Light is turned into electricity (electrons)
• Amount of electricity is amplified
• Amount of electricity is digitized
• Digitized values are recorded
  – Compressed for later use
• Digitized values are displayed
Pixels vs Grains

Grains (Film)

Pixels (Digital)

35mm film $\rightarrow \sim 20$ mega pixels
Features of Digital Photography

- Light intensity is recorded as discrete levels
- Light intensity is recorded in a regular pattern (checkerboard)
- Requires digital post processing to display
  - LCD, Printer, etc.
- Digital images can be transferred by “wire”
  - Email, internet, anything that can transfer a computer file
  - Doesn't work for film (have to digitize)
Human Vision

• Parts of the eye
  – Cornea, Lens, Retina
  – Accomodation

• Structure of the Retina
  – Rods: Sensitive to intensity
  – Cones: Sensitive to Color

• Properties of Retina
  – Latency, Persistence of Response...
The Eye

- Cornea
- Iris
- Lens
- Retina
- Fovea
- Blind Spot
Human Visual Processing

- How the image is processed:
  - Weber's Law
  - Retinal Stability
    - Edge Detection, Lateral Inhibition, Lightness, Lightness Constancy
  - Persistence
    - Afterimages
  - Other Cells in Retina
    - Bipolar, Anacrine, Horizontal, Ganglion
- Visual Channels (in brain)
The Retina

Light

Ganglion and Amacrine Cells

Bipolar and Horizontal Cells

Rods

Cone
Processing in the Retina

- Need to compress data before going to brain
  - Almost 100 times more photo-receptors than Ganglion
  - Both rods and cones stop sending signal if light intensity stays constant.
- Structures in the Retina
  - On-Center
  - Off-Center
- Made by interconnects between bipolar, horizontal, amacrine, and ganglion
Eye Movements

- Rods and Cones only respond when light level changes
  - If the light levels didn't change, then our vision would fade to gray (*Retinal Stabilization*)
  - Some animals (e.g. some frogs) use this to detect movement (e.g. prey/predators)

- Eye movements keep our view from fading
  - Drifts: Slow scanning
  - Tremors: Tiny, very fast movements (~50 Hz)
  - Saccades: Bigger movements (~4Hz)
Binocular vs Monocular Vision

• Everything so far has been about one image
  - One view of the object
• We have two eyes
  - Brain receives two images of an object
• Effects of binocular vision
  - Increased field of view
  - Depth preception
Depth Perception

- This lets us see in 3 dimensions
  - Think Avatar...

- Several Effects at work
  - Accommodation (e.g. the eye's depth field)
  - Convergence
  - Parallax/Binocular Disparity
  - Distance Cues
    - Size, perspective, shadows, overlay, patterns
Photo Receptors

- Cone Cells
  - ~ 100 times less sensitive to light than Rod Cells
  - Three Types
    - S – type : Peak sensitivity is 420 – 440 nm
      - Blue/Violet
    - M – type : Peak sensitivity is 535 – 545 nm
      - Green
    - L – type : Peak sensitivity is 565 – 580 nm
      - Red
  - About 5 million in each eye
    - Concentrated in center.
Response of Cones
Description of Color

- Practical, but limited
  - Hue – Saturation – Value
  - Red - Green – Blue
- Any color (visible to humans)
  - Chromaticity
Wave Optics: Interference

- Interference is a consequence of wave superposition
  - Generally called
    - Constructive Interference
    - Destructive Interference
- Applies to waves with the same wavelength
- Diffraction is the interference of a wave with itself.
  - Multi-slit diffraction
  - Single slit diffraction
Huygen's Principle

- Any wavefront can be replaced by a lot of sources located uniformly over the wave front radiating in phase.

When viewed from here, a wave front and a bunch of sources look the same.
Particles and Waves

• Light acts like a wave
  – Diffraction
  – Refraction
  – Phase

• Light also acts like a particle
  – Carries discreet bits of energy

• Intensity is either (and both)
  – Amplitude squared (times frequency)
  – Number of photons (times energy of photon)
What is Physics?

- A (reductionist) philosophy for looking at the world
  - Observational:
    - First look at the world around and see what happens
    - Make measurements
      - How long, how far, how fast, how big
  - Empirical:
    - Describe the results “mathematically”
    - Develop theories to predict results of future observations
  - Reductionist:
    - Assumes complexity can be explained in terms of its component parts
The End