Waves and Light
History of Light

- 5th Century B.C.
  - Philosophers thought light was made up of streamers emitted by the eye making contact with an object
  - Others thought that light was made of particles that traveled from the eye
  - Even others thought that light traveled as waves
17th Century

- Newton supports the particle theory because there was no evidence of wave characteristics
- Huygens states that light is a wave
- Both men noticed that light was a form of energy and that energy can only be transferred as a wave or particle
So who was right?
History Cont.

- During the 1800’s evidence was gathered supporting the wave theory
- Early 1900’s brought us Hertz who discovered the Photoelectric Effect which couldn’t be described by waves – only if light exists as particles
Today

- We believe that light has a dual nature – it exists as both a wave and a particle.
  - Wave/Particle Duality
- We will look at the properties Light and see if these properties can determine if light is a particle or a wave.
Wave Characteristics
10 Characteristics of Waves

1. Propagation
2. Reflection
3. Polarization
4. Refraction
5. Diffraction
6. Interference
7. Diffusion
8. Color
9. Dispersion
10. Scattering
Propagation

- How light will travel from one place to another
- There were 2 ideas that were common to both those scientists who saw light as a particle and those who saw it as a wave:
  1. Light travels in a straight line
  2. Light travels at a high speed
Light In A Straight Line

- To prove that light travels in a straight line, 2 experiments were performed.
- The use of shadows proved that light would travel in a straight line.
- The use of images projected through a pin hole also proved that light travels in a straight line.
Light At High Speed

There were 3 experiments done to determine the speed of light by:

1. Galileo
2. Roemer
3. Michelson
Light At High Speed

- Before the 1500’s, light was considered to travel at infinite speed or to be instantaneous in nature.
- During the 1500’s, 2 experiments were performed, one by Galileo and one by Roemer, to determine the speed of light.
- A 3rd experiment was conducted in the 1800’s by Michelson.
Light Speed Today

- It was through Michelson’s experiment that we have our current standard for the speed of light.

\[ c = 3.00 \times 10^8 \text{ m/s} \]
Geometric Optics
Reflection

- How did reflection work in the previous unit on sound?
- Reflection works the same in regards to light.
- “The angle of reflection equals the angle of incidence.”
Reflection Cont.

- What happens when a light wave is reflected off of 2 surfaces?
- In this case you need to remember the Law of Similar Triangles
- All you need to do is subtract the original incidence angle from $90^\circ$ and you have the new angle of incidence on the second surface
Reflection in Curved Mirrors

- There are 2 types of mirrors
  - Concave
  - Convex
- What is the difference between the 2 types?
Terminology

- **Center of Curvature** – center of the hollow glass sphere that the curved mirror was originally part of
- **Radius of Curvature** – radius of the hollow glass sphere that the curved mirror was originally part of
- **Principal Axis** – an imaginary line that passes through its pole and the center of curvature
Terminology Cont.

- **Pole** – the geometric center of the curved mirror
- **Focal Length** – the distance between the pole and the principal focus of the mirror
- **Principal Focus** – the point on the principle axis where light rays traveling parallel to the axis after reflection actually meet or appear to meet. This is ½ the distance from the center of curvature to the mirror
Reflection in Mirrors Cont.

- The Principal Focus is also called the Focal Point
- There are 2 types of focal points
  - Real focal points – found using Concave mirrors and the rays DO converge at this point
  - Virtual focal points – found using Convex mirrors and the rays only APPEAR to diverge from this point
These 2 types of mirrors create 2 types of images

- Real Images – these can be projected onto a screen
- Virtual Images – these appear to be behind the mirror
Ray Diagrams

- The position, size, and nature of an image produced by a curved mirror can be found using a scale ray diagram
- Use the following steps to create the ray diagrams for mirrors
Ray Diagrams Cont.

1. Draw the mirror showing the principal axis, center of curvature, and the principal focal point
2. Place a vertical arrow on the principal axis to illustrate the position and size of the object
3. Draw 2 rays from the tip of the arrow to the mirror. Draw the reflected rays from the mirror. The point where they meet will or tend to diverge from is the position of the image.
Concave Mirrors

- Center of Curvature
- Focal Point
- Object
- Vertex
- Image
Ray Diagrams Cont.

- Always answer the following 4 Questions:
  1. Is the image Real or Virtual
  2. Is the image enlarged, diminished, or the same size
  3. Is the image erect or inverted
  4. Measure the $H_i$ and $d_i$
Ray Diagrams Cont.

- An image is:
  - **Real** – if the object is formed where the REAL light rays converge
  - **Virtual** – if the object is formed where the APPARENT light rays converge
Formula Method

- To find the location use the following
- \( d_o = \) object distance
- \( d_i = \) image distance
- \( f = \) focal length

\[
\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}
\]

- +’ve \( f \) if using a Concave Mirror
- -’ve \( f \) if using a Convex Mirror
- If \( d_i \) is negative, the image is virtual
The size of the object is found using the following:

- \( H_i = \) height of the image
- \( H_o = \) height of the object

If the Height of the image is negative, it is inverted.

\[
H_i = -d_i \\
H_o = d_o
\]
Ray Diagram Examples

- Locate an object (↑) that is 10.0 cm high and placed 5, 10, 15, 20, and 25 cm in front of a convex mirror whose $C = 20.0$ cm. Find using a scale drawing method and a formula method

- Locate an object (↑) that is 10.0 cm high and placed 5, 10, 15, 20, and 25 cm in front of a concave mirror whose $C = 20.0$ cm. Find using a scale drawing method and a formula method
Spherical Mirrors

- Spherical mirrors have a defect in them where rays traveling parallel to the principal axis near the edges of the mirror are not reflected through the focal point.
- This is called Spherical Aberration.
- It can be fixed by using a more parabolic shaped mirror.
Refraction

- Occurs when a wave changes direction that it is moving
- Caused when the wave travels into different mediums

\[ \lambda_1 = \frac{\sin \Theta_1}{v_1} = n_2 \]
\[ \lambda_2 = \frac{\sin \Theta_2}{v_2} = n_1 \]
Refraction Through Different Medias

- Refraction occurs when a light ray passes from one medium into another.
- When light passes from air into another medium, it has to slow down and the light ray will bend toward the normal.
- The wavelength, velocity, and angle will change depending on the type of medium the ray started in and passed through.
Example

- Light waves with a frequency of $3.00 \times 10^{13}$ Hz and traveling at $3.00 \times 10^8$ m/s in air, strike a surface of water at $35^\circ$ to the normal.

- Air: $n = 1.00$

- Water: $n = 1.33$

1. Sketch the refracted wave
2. Determine the:
   a. Speed in water
   b. Wavelength in water
   c. Angle in water
Optical Density

- When we talk about light, we typically use the OPTICAL Density – how easily light will pass through the medium
- Do not confuse this with the objects actual density
- When we discuss refraction, Diamond has the highest optical density of any object at 2.42
Calculating $v$, $\lambda$, and $\Theta$

This is called Snell’s Law

- To calculate angles:
  - $n_i \sin \Theta_i = n_r \sin \Theta_r$

- To calculate velocities:
  - $n_i v_i = n_r v_r$

- To calculate wavelengths:
  - $n_i \lambda_i = n_r \lambda_r$
Total Internal Reflection

- When a ray passes from a high density medium into a low density medium, it bends away from the normal.
- As $\Theta_i$ increases, $\Theta_r$ gets closer to 90° or along the boundary.
- The angle that this occurs is called the CRITICAL ANGLE.
Total Internal Reflection Cont.

- If $\Theta_i < \text{critical angle}$ then the ray is refracted
- If $\Theta_i$ gives a refracted angle of $90^\circ$, then $\Theta_i$ is called the critical angle
- If $\Theta_i > \text{the critical angle}$ then you get Total Internal Reflection

\[ n_i \sin \Theta_c = n_r \sin 90^\circ \]
Images and Refraction

- There are 2 types of refracting surfaces (lenses):
  - Spherical
  - Parabolic

- Each type of lens come in concave and convex form
Locating Refracted Images

- When dealing with lenses, you will have 2 focal points and 2 centers of curvature.
- When you are going to locate an image formed using a lens the following rules must be followed:
  1. Draw the center of axis
  2. Locate C, f, v, C₂, and f₂
  3. Place the object on the side of f₂
Locating Images Using Lenses

4. Draw a line parallel to the center of curvature from the point of the object. This line will go through the vertex to f (convex lens) or through f (concave lens)

5. Draw a line from the point through the vertex

6. Where the lines intersect is where the object is located
Convex Lenses

- C2
- f2
- Image
- Object
- Vertex
- f
Concave Lenses
Locating Images in Lenses Cont.

- Always answer the following 4 Questions:
  1. Is the image Real or Virtual
  2. Is the image enlarged, diminished, or the same size
  3. Is the image erect or inverted
  4. Measure the $H_i$ and $d_i$
Ray Diagram Examples

- Locate an image (↑) that is 10.0 cm high and placed 5, 10, 15, 20, and 25 cm in front of a convex lens whose C = 20.0 cm. Find using a scale drawing method and a formula method.

- Locate an image (↑) that is 10.0 cm high and placed 5, 10, 15, 20, and 25 cm in front of a concave lens whose C = 20.0 cm. Find using a scale drawing method and a formula method.
The only thing you can see is light.

In order to see light, the light must enter your eyes.

If no light enters your eyes, you will see nothing --- only darkness.
What can you see in a dark room?

Nothing!
Shadows
Shadows are black because the body is blocking all the light. Seeing a shadow is seeing the absence of light.
The eye adapts to varying light conditions.

This is similar to the shutter of a camera.
The Eye

- Tendon of lateral rectus muscle
- Ciliary body and ciliary muscle
- Canal of Schlemm
- Suspensory ligament of lens
- Iris
- Lens
- Cornea
- Anterior chamber
- Posterior chamber
- Anterior chamber angle
- Conjunctiva
- Tendon of medial rectus muscle
- Retina
- Choroid
- Sclera
- Fovea centralis
- Central artery and vein of retina
- Optic nerve
The eye “sees” an object when bundles of diverging rays from each point on the object enter the pupil and are focused to an image on the retina.
Two types of “sightedness”

Farsighted
Nearsighted
FARSIGHTED
Farsightedness

• Easier to see far away things.
• The eye’s lens is too weak.
• The image would focus past the retina (back of the eye).
Correction (Farsighted)

• A convergent lens helps the eye out by focusing the light a bit before it enters the eye.
NEARSIGHTED
Nearsightedness

- Easier to see close up
- Lens is too strong.
- The image focuses before the retina (back of the eye).
Correction (nearsighted)

• A divergent lens is used to spread the light out a bit before it enters the eye.
A person who sees more clearly under water than in air without eyeglasses is...

1) Nearsighted  2) farsighted  3) neither
Nearsighted! The speed of light in water is less than in air, so the change in speed is less as light goes from water to your eye. Less refraction occurs.

This makes all people more farsighted under water, which is advantageous if you’re nearsighted. If you’re very nearsighted, the image may fall on your retina and you’ll see as clearly under water as a person with normal vision who wears an air-enclosed mask.
Optical Illusions???

- Why does the road appear wet far off in the distance?
- Why can we see the sun a few minutes before it rises and after it sets?
- How do fiber optic wires work?
- Why does an object appear closer in water than it actually is?
Color Blindness - What number do you see?
Blind Spot

Stare at the O with only your right eye.
Count the black dots! :o)
Are the horizontal lines parallel or do they slope?
How many legs does this elephant have?
Man Playing Horn... Or Woman Silhouette?
(hint: woman's right eye is the black speck in front of horn handle)
A Rabbit.... Or A Duck?
hint: the duck is looking left, the rabbit is looking right
Look at the chart and say the COLOUR not the word

YELLOW  BLUE  ORANGE
BLACK   RED   GREEN
PURPLE  YELLOW RED
ORANGE  GREEN BLACK
BLUE    RED   PURPLE
GREEN   BLUE  ORANGE

Left – Right Conflict
Your right brain tries to say the colour but your left brain insists on reading the word.
Woman In Vanity... Or Skull?
hint: move farther a bit from the screen and
blink to see the skull or the woman (looking at
the mirror)
A Face Of A Native American... Or An Eskimo?
Old Woman...Or Young Girl?
hint: The old woman's nose is the young girl's chin.
Two Faces... Or One?

(hint: two faces side profile...or one face front view)
HOW CAN THIS BE TRUE?

Below the four parts are moved around.

The partitions are exactly the same, as those used above.

From where comes this "hole"?
Square A and B are the same shade of grey
Becky Lorenz in the walk-in box.
Stare at the black dot....
Color and Dispersion

History

• Early Greeks saw light as “Pure Light” and the color was found by adding impurities to the light.
• Newton, 1672, found color rings as he was making his telescope. He began studying this phenomenon, and published Optiks in 1702.
Newton

- Said white light was made up of many colors
- Proved this by:
  1. Using a prism he was able to separate light into its various colors
  2. Showing colors could not be broken down any further
  3. Said different colors caused by different shaped particles
  4. Explaining that object are of a particular color because of the way that the object absorbs and reflects light
Hooke

- Totally apposed Newton during the 1700’s
- He said that light had to be a wave
- Each color of light was produced by a different wave travelling in different planes
Modern Theory of Light

- Today we know that each color of light is found in a different “f and λ” range within white light
- **Red** → $7.00 \times 10^{-7}$m
- **Orange** → $6.00 \times 10^{-7}$m
- **Yellow** → $5.50 \times 10^{-7}$m
- **Green** → $5.00 \times 10^{-7}$m
- **Blue** → $4.00 \times 10^{-7}$m
- **Indigo** → $3.80 \times 10^{-7}$m
- **violet** → $3.50 \times 10^{-7}$m

All of these colors still travel at the speed of light
Modern Theory of Light Cont.

- Why does white light dispersed in a prism?
- As white light enters a prism, the different colors will slow down at different rates – using $v = f\lambda$, larger the $\lambda$, the larger the $v$
- Ex: Red and Violet
  - Red light will travel faster in a prism than violet will and therefore will refract less than violet
Additive Theory of Light

- When you bring light of 2 different colors together, you can form a light ray of a 3\textsuperscript{rd} color
- This is called the Additive Theory of Light
Subtractive Theory of Light

- This is used to explain why objects are the color that they appear to be.
- Whatever color you see is the color of light that is reflected back to your eye. All other colors of light are absorbed by the material.
- If all colors are absorbed, the object will appear black.
- If all colors are reflected, the object will appear white.
Additive Theory of Light Cont.

- Absorption depends on the type of PIGMENT that is used:
  - A primary pigment will absorb 1 color and reflect 2
    - Ex. Yellow is a primary pigment because it absorbs blue and reflects back green and red to make yellow
  - A secondary pigment will absorb 2 colors and reflect 1
    - Ex. Red is a secondary pigment because it absorbs blue and green and reflects back red
Diffusion and Scattering

- **Diffusion** – the spreading of a wave
- **Scattering** – the amount of scattering depends on the size of the scattering particle
  - If the size of the scattering particle is > the size of the wavelength of the light – Total Internal Reflection
  - If the size of the scattering particle is < the size of the wavelength of the light – wave passes through
Scattering Cont.

- If the size of the scattering particle = the size of the wavelength of the light – you get scattering
  - Amount of scattering is $\alpha \frac{1}{\lambda^4}$
  - Therefore if you have red light and violet light, $\lambda$ for red light is 2 times that of violet
    - Red scatters $\frac{1}{2^4} = \frac{1}{16}$ as much as violet.
    - Therefore we can say that violet light will scatter more than red light will
Polarization

- A light wave that is vibrating in only 1 plane
- A wave that is travelling in more than one plane is called an Unpolarized wave
- If an unpolarized wave is passed through a filter, only wave travelling in the same plane as the filter will pass
Polarization Cont.

- Light from the sun is always unpolarized
- The only way to polarize light is to pass it through a filter or have the light ray reflect off a surface
- Only transverse waves can be polarized, longitudinal waves cannot
Diffraction

- The bending of a wave as it passes through an opening
- The wavelength, frequency, velocity, and period DO NOT change
- The amount of diffraction depends
  1. Size of the opening
  2. Size of the wavelength

Diffraction effects get less obvious as the gap gets larger.
Interference

- There are 2 types of Interference
  - Constructive – when 2 or more waves meet in phase. They create ANTINODES or larger waves
  - Destructive – when 2 or more waves meet out of phase. They create NODES or smaller waves or nothing
Interference

- To determine what the resulting wave will look like when 2 or more waves interfere with each other, use the Law of Superposition.
Young’s 2-Slit Experiment

- Until Young came along with his experiment, the sides of the light/particle argument were evenly split.
- Through his experiment, Young was able to show that light acted as a wave.
- He did this by showing that light diffracts and is affected by interference.
Young Cont.

- What he did was to view light through a barrier that had 2 slits in it.
- What he noticed was the creation of 2 separate images on either side of the original light beam.
- This was caused by diffraction and interference.
The Explanation

Proof that light diffracts

Proof that light interferes

Original Light

Images
The Explanation Cont.

- When 2 rays travel the same distance from the source, through the slits to the screen, the rays will meet and interfere.
- This will produce constructive interference.
The Explanation Cont.

- When one light ray has to travel a slightly farther distance before they come together, you get interference
- This produces a 1st Order Image
Rules For Young’s 2 Slit

- If the extra distance travelled by one ray is $1\lambda$, $2\lambda$, $3\lambda$..., then you get constructive interference and produce $1^{st}$, $2^{nd}$, $3^{rd}$... order images.

- If the extra distance travelled by one ray is $1/2\lambda$, $3/2\lambda$, then you get destructive interference which produces dark regions on the screen between the images.
Proof of Particles or Waves

1. Propagation
2. Reflection
3. Refraction
4. Color
5. Dispersion
6. Diffusion
7. Scattering
8. Polarization
9. Diffraction
10. Interference
Properties

1. Propagation
   - Does not prove if light is a wave or particle

2. Reflection
   - Does not prove if light is a wave or particle

3. Refraction
   - Does prove that light is a wave

4. Color
   - Does not prove if light is a wave or particle

5. Dispersion
   - Does not prove if light is a wave or particle
Properties

6. Diffusion
   • Does not prove if light is a wave or particle

7. Scattering
   • Does not prove if light is a wave or particle

8. Polarization
   • Does not prove if light is a wave or particle

9. Diffraction
   • Does prove that light is a wave

10. Interference
    • Does prove that light is a wave
So is light a wave or a particle???
Conclusion

- At this point, we can conclude that there are certain properties of light do prove that light is a wave.
- BUT there are more properties that do not give proof one way or another
- There are properties that you will see in future courses that will also prove that light is a particle, which gives rise to the Wave/Particle Duality of Light