Chapter 18: Ray Optics

Section 18.1: The Ray Model of Light

The Ray Model
- Light rays are straight lines
- Light rays can intersect
- Light rays propagate infinitely (unless interacting with matter)
- Objects are sources of light rays (emitting or reflecting)
- Eyes form images by focusing light rays

Sources of Light Rays
- Self-luminous objects emit light (stars, light bulbs, fireflies...)
- Most objects simply reflect the light that hits them

Ray Diagrams
- You can't observe individual rays
- You can model the behavior by tracing some of the rays

Section 18.2: Reflection

Law of Reflection
- $\theta_i = \theta_r$
- Angle of incidence = angle of reflection
- Always measure angle with respect to the normal to the surface (Why? Because surface may not be flat or smooth or regular)
- This law holds for any wave reflected off any surface: Sound waves, light waves, water waves, whatever waves

Specular Reflection
- Sharp, clear reflection that you see when you look in the bathroom mirror
- Parallel rays are reflected off a smooth surface: reflected rays are parallel as well
- Image formed is crisp, clear: in focus

Diffuse Reflection
- Blurry, low-resolution reflection seen when you look at yourself in the brushed steel refrigerator door
- Surface is not smooth or regular, so parallel incoming rays are not all reflected in the same direction
- Difficult to form a coherent image

Image Formation in a Plane Mirror
- Real rays remain on the same side of the mirror as the real object
- Virtual rays appear to originate from the other side of the mirror
- Where virtual rays intersect, image is formed: the image is virtual
- Object distance = image distance: $s = s'$
- Object height = image height: $h = h'$
- Magnification $M = h'/h = 1$

Section 18.6: Image Formation With Spherical Mirrors

Spherical Mirrors
- Shape is spherically curved
- Concave: Outside of spherical shell
- Convex: Inside of spherical shell
- Optical Axis: Normal through the geometric center of the mirror (central normal)
- Center of curvature $C$: Point where any two normals to the surface intersect
- C represents the center of the sphere from which mirror was taken
- Radius of curvature $R$: Distance from the mirror to the center of curvature along the optical axis
- This tells you about the geometry of the mirror
- Focal point: Point at which rays (real or virtual) appear to come together
Focal length $f$: Distance from the mirror to the focal point along the optical axis
- $f = \frac{R}{2}$

**Concave Mirror**
- Also called converging mirror
- Real rays that come in parallel to the optical axis are reflected and converge at the focal point
- Virtual rays extended back from the reflected rays appear to intersect at a focal point behind the mirror

**Convex Mirror**
- Also called a diverging mirror
- Real rays that come in parallel to the optical axis are reflected and diverge away from the focal point
- Virtual rays extended back from the reflected rays appear to intersect at a focal point behind the mirror

**Rules for Ray Diagrams**
- ① Parallel: Incoming ray parallel to optical axis reflect through focal point
- ② Radial: Incoming ray through center of curvature reflects right back through center of curvature
- ③ Focal: Incoming ray through the focal point reflects back parallel to the optical axis
- Parallel and focal are the same thing; just reverse the direction of the ray

**Real vs Virtual Images**
- Real image: Real rays really intersect
- Real images are always inverted
- Virtual rays intersect (or a real ray intersects a virtual ray)
- Virtual images are always upright
- Virtual images may appear magnified or minified

**Image Equation and Sign Conventions**
- $\frac{1}{s} + \frac{1}{s'} = \frac{1}{f}$

**Focal Length**
- Converging: $f > 0$: focal point is on the same side of the mirror as the real rays of light
- Diverging: $f < 0$: focal point is on the opposite side of mirror as the real light rays

**Object Distance**
- $s > 0$: object is on the same side (in front) of the mirror as the real rays of light (real object)
- $s < 0$: object is on the opposite side of (behind) the mirror as the real rays of light (virtual object)

**Image Distance**
- $s' > 0$: image is on the same side (in front) of the mirror as the real rays of light (real image)
- $s' < 0$: image is on the opposite side of (behind) the mirror as the real rays of light (virtual image)

**Image Height**
- $h' > 0$: image is upright
- $h' < 0$: image is inverted

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**Section 18.3: Refraction**

**Light Strikes A Boundary: Now What?**
- Transmission: light strikes a new medium, passes through
- Glass is transparent to visible light
- Absorption: light enters medium, but does not emerge out the other side
- Reflection: light strikes, cannot pass through; bounces off the surface
- Chrome is opaque to visible light, but highly reflective

**Light Slows Down**
- Vacuum is fastest medium for light transmission ($c = 3 \times 10^8 \text{m/s}$)
- Any medium that is not vacuum represents an obstacle to the transmission of light
- Light travels more slowly through air than vacuum (not so you’d notice, but a tiny bit)

**Index of Refraction**
- Compare speed of light through specific medium to speed through vacuum
- $n = \frac{c}{v}$

**Change in Medium = Change in Speed**
- Light travels more slowly through water than air: $v_w = \frac{(3/4)c}{n_w}$
  - $n_w = \frac{4}{3} = 1.33$
- Light travels more slowly through glass than water: $v_g = \frac{(2/3)c}{n_g}$
  - $n_g = \frac{3}{2} = 1.5$
- The larger the index of refraction, the slower the medium

**Wave front will bend if it strikes a boundary between media**
- This is because only a portion of the wave has to speed up or slow down
- If wavefront strikes parallel to surface, entire wave speeds up or slows down uniformly: no bending
- Fast to slow: beam bends toward normal
- Slow to fast: beam bends away from normal
Change in Speed = Change in Wavelength

- $v = \lambda f$
- If $v$ decreases, either $\lambda$ or $f$ also has to get smaller
- Frequency does not change: the rate of vibration does not change
- Wavelength gets smaller: the rate of propagation decreases, so less distance covered in the time it takes to complete one oscillation cycle

Snell's Law

- $n_1 \sin \theta_1 = n_2 \sin \theta_2$
- Where 1 and 2 represent two separate media (i.e., air and glass; water and air; etc.)
- As angle of incidence $\theta_1$ increases, so does angle of refraction $\theta_2$
- The bigger the difference in speeds between the two media, the greater the refraction

Total Internal Reflection

- As the angle of incidence increases, so does the angle of refraction
- When angle of refraction reaches 90°, light does not emerge
- Light is reflected back into incident medium, no light is transmitted through

Section 18.4: Image Formation By Refraction

Look! It's a Mirage!

- Why does the road look wet? It's a bright, sunny day.
- Layers of air with different temperatures: it's hotter near the surface of the road
- Warmer air is faster air: less dense means faster propagation of light
- Cooler air is slower air: more dense air means slower propagation
- Light bends near surface, creates image
- Your brain interprets the image as "wet"

Look! The Straw is Bent!

- You know the real straw does not bend when it is submerged

Wow! That Fish Is Huge!

- Probably not as big as you think
- Refraction makes the submerged object look larger (and closer) than it really is
- $s' = [\tan \theta_1/\tan \theta_2][n_2/n_1]$

And That Sunset! Huge, Gigantic Ball of Fire!

- Not really; you know the sun is not any bigger at sunset (or sunrise) than it is at noon
- Looks bigger near the horizon because the layer of atmosphere through which the light passes is thicker

Section 18.5 & 18.7: Thin Lenses: Ray Tracing and the Thin Lens Equation

Thin Lenses

- Assume that lens is thin enough that displacement due to refraction is negligible
- Optical Axis: Normal through the geometric center of the lens (central normal)
- Center of curvature $C$: Point where any two normals to the surface intersect
- Each side of the lens has a center of curvature

- Radius of curvature $R$: Distance from the lens to the center of curvature along the optical axis
- Radius of curvature not necessarily the same for both sides of lens
- Focal point: Point at which rays (real or virtual) appear to come together
- Focal length $f$: Distance from the lens to the focal point along the optical axis
• No fixed relationship between radius of curvature and focal length for lenses

Convex Lenses
• Convex: Tells you about the shape of the lens
• One or both sides is spherically curved outward
• Converging: Tells you what the lens does to light rays
• Incoming rays parallel to optical axis are converged to a focal point
• Positive: Tells you at which focal point light converges
• The positive focus is defined as the focal point on the side of the lens opposite the light source

Concave Lenses
• Concave: Tells you about the shape of the lens
• One or both sides is spherically curved inward
• Diverging: Tells you what the lens does to light rays
• Incoming rays parallel to optical axis are diverged away from a focal point
• Negative: Tells you at which focal point light converges
• The negative focus is defined as the focal point on the same side of the lens as the light source

Rules for Ray Diagrams
• ① Parallel: Incoming ray parallel to optical axis reflect through focal point
• ② Radial: Incoming ray through center of curvature reflects right back through center of curvature
• ③ Focal: Incoming ray through the focal point reflects back parallel to the optical axis
• Parallel and focal are the same thing; just reverse the direction of the ray

Image Equation and Sign Conventions
• $1/s + 1/s' = 1/f$

Focal Length
• Converging: $f > 0$: Focal point is on the opposite side of the lens as the light source
• Diverging: $f < 0$: Focal point is on the same side of mirror as the light source

Object Distance
• $s > 0$: Object is on the same side (in front) of the lens as the light source (real object)
• $s < 0$: Object is on the opposite side of (behind) the lens as the light source (virtual object)

Image Distance
• $s' > 0$: Image is on the opposite side (in front) of the lens as the light source (real image)
• $s' < 0$: Image is on the same side of (behind) the lens as the light source (virtual image)

Image Height
• $h' > 0$: Image is upright
• $h' < 0$: Image is inverted

Magnification
• Similar triangles: ratio $|h'/h| = |s'/s|
• Magnification: $M = h'/h = -s'/s$
• Sign Convention
  • $M > 0$: Image is upright (virtual)
  • $M < 0$: Image is inverted (real)

Real Image Formed By a Converging Lens
• Object distance must be greater than focal length: $s > f$
• $f < s < 2f$: Image is magnified
• $s = 2f$: image height = object height
• $s > 2f$: Image is minified

Virtual Image Formed By a Converging Lens
• Object distance $s$ must be less than focal length: $s < f$
• Image is magnified (this is a magnifying glass)

Virtual Images Formed By A Diverging Lens
• Diverging lens cannot form a real image for any object at any distance
• Image is always minified; $s$ does not matter

What Happens When Object is Exactly At the Focal Point?
• Converging lens: No image is formed; you can show this geometrically or algebraically
• Diverging lens: Virtual image at $s' = -f/2$, exactly half as tall as real object