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

Seeing Objects

- In order to see anything, the light has to hit you in the eye
- Compare a laser (effectively a single ray) to a light bulb (effectively a point source)

Shadows

- The obvious: a shadow is where the light doesn't reach
- Opaque object/material = does not let any light pass through
- Umbra: The sharp shadow where all the light gets blocked
- Penumbra: The fuzzy edges where some, but not all, light is blocked

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 my 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 = 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

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
  Real images may appear magnified or minified
- Virtual image: 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
- $1/s + 1/s' = 1/f$

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

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 ($c = 3\times10^8$ 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
- $n = c/v$
- Light travels more slowly through water than air: $v_w = (3/4)c$
  $n_w = 4/3 = 1.33$
- Light travels more slowly through glass than water: $v_g = (2/3)c$
  $n_g = (3/2) = 1.5$
- The larger the index of refraction, the slower the medium

Change in Medium = Change in Speed
- 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 λ 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 θ_1 increase, so does angle of refraction θ_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

The Medium Makes a Difference

- Use Snell's Law to show: $\sin\theta_c = (n_2/n_1)$
- Critical angle will depend on which media you use
- You only get TIR when the refractive medium is a faster medium than incident medium: $n_2 < n_1$
- No TIR if light transitions from fast to slow: $n_2 > n_1$ not possible ($\sin\theta \leq 1$!)

Fiber Optics

- Take a thin, transparent filament (maybe glass, maybe polymer)
- Using total internal reflection, light signal can be transmitted down the length of the fiber, even if the fiber is curved or curled or wound in a circle--whatever
- Signal transmission is remarkably lossless--if you have a high-quality fiber (minimize impurities)
- Data transmission is remarkably fast--sure you have millions of reflections, which makes the actual path longer than the fiber optic cable itself, but the signal is traveling at 3/4 the speed of light

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
- You are seeing the image of the straw: light bends at the water/air interface

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
- $s' = s[\tan\theta_1/\tan\theta_2] = [n_2/n_1]s$

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