Ray Optics

- Ray model
- Reflection
- Refraction, total internal reflection
- Color dispersion
- Lenses
- Image formation
- Magnification
- Spherical mirrors
Ray optics

Optical imaging and color in medicine
Integral part of diagnosis
Ray model

- Ray model is composed of **light rays** – abstract idea to show the direction along which light energy flows
- Works for systems where the objects are much larger than the wavelength of light
Ray model rules

Light travels in straight lines
Light rays can cross
Ray model rules

Light rays travel through materials with a speed \( c/n \), where \( n \) is the refractive index.

At a boundary, light can be reflected or refracted (or both)

Within a material, light can be scattered, or absorbed.
Ray model rules

Light rays originate from **objects**.

The object radiates in all directions.

The light may be from the object (self-luminous objects – light bulbs), or the light may be reflected.
Ray model rules

Light rays are detected by the eye if they pass through the pupil, and can be focused onto the retina at the back of the eye.
Seeing Objects

Objects are seen when light (scattered or transmitted) from an object enters the eye.

A point source

Everyone can see a point source.

An extended source

All points of an extended source are visible.
Shadows

- Light rays can be absorbed by an opaque object.
- For an extended source, shadows can be fuzzy.
Pin hole camera

The pin hole camera selects rays which will create an inverted image.
Pin hole camera

Advantages – no focusing required, (infinite field of depth), no color dispersion

Disadvantage – requires long exposure time
specular reflection is the reflection from a flat surface.
Reflection

**diffuse reflection** is the reflection from a flat surface.

Each ray obeys the law of reflection at that point, but the irregular surface causes the reflected rays to leave in many random directions.

(b) **Normal**

- Angle of incidence
- Angle of reflection

Incident ray \( \theta_i \)  \( \theta_r \) Reflected ray

Reflective surface
Plane Mirror Images

The reflected image in a mirror is **virtual**. A screen placed there would not show an image.

The reflected rays *all* diverge from $P'$, which appears to be the source of the reflected rays. Your eye collects the bundle of diverging rays and “sees” the light coming from $P'$. 
Plane Mirror Images

The reflected image in a mirror is **not inverted**.

- The correct terminology for a reflected image is to say it **reverses front and back**.

- Or say the image is **reflected**.
Refraction

Light rays get bent going through a medium boundary:

The ray has a kink at the boundary.
Snell’s law

Snell’s law relates the angle of refraction to the index of refraction.

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]
Snell’s Law

• The frequency of the light must be a constant.
• The length of the wave-front at the boundary must be a constant

\[ l = \frac{\lambda_1}{\sin \theta_1} = \frac{\lambda_2}{\sin \theta_2} \]

\[ \lambda = \frac{v}{f} = \frac{c}{nf} \]

\[ l = \frac{c}{n_1 f \sin \theta_1} = \frac{c}{n_2 f \sin \theta_2} \]
Snell’s law

- Snell’s law is a consequence of light slowing down in a medium.
- Works in either direction
- Independent of reflections

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]
Total Internal Reflection

When light is leaving a denser medium to go into a lighter medium, above a certain angle, Snell’s law predicts unreal angles ($\sin \theta > 1$)

- This angle is the **critical angle**
- Above this angle, light will not be refracted, it undergoes **total internal reflection** (TIR)
Total Internal Reflection

The critical angle for the boundary between two media can be calculated as

\[ n_1 \sin \theta_c = n_2 \sin 90^\circ \]

\[ \theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) \]

\[ n_2 < n_1 \]
TIR application

Used in fiber optics

The fiber has a core (8μm, or 50/62.5μm) surrounded by cladding (125μm).

\[ n_{\text{core}} > n_{\text{cladding}} \]
Color

• Color is a property of the human eye. The eye detects different wavelengths as different photo-chemical reactions.

• White light is a mixture of all colors.

• The refractive index of materials changes slightly with color.

A prism disperses white light into colors.

A second prism can combine the colors back into white light.
Color Dispersion

- The refractive index of materials changes slightly with color, and a prism can be used to split up and recombine the different colors in white light.

![Graph showing refractive index vs. wavelength for Flint glass and Crown glass.](image)

A second prism can combine the colors back into white light.

A prism disperses white light into colors.
Color Dispersion

Rainbows are created by color dispersion in water droplets in the sky.

1. The sun is behind your back when you see a rainbow.

2. Dispersion causes different colors to refract at different angles.

3. Most of the light refracts into the air at this point, but a little reflects back into the drop.

4. Dispersion separates the colors even more as the rays refract back into the air.
Color Dispersion

Rainbows are created by color dispersion in water droplets in the sky.

You see a rainbow with red on the top, violet on the bottom.

Red light is refracted predominantly at 42.5°. The red light reaching your eye comes from drops higher in the sky.

Violet light is refracted predominantly at 40.8°. The violet light reaching your eye comes from drops lower in the sky.
Colored Objects

• Objects have a color because they either transmit light (e.g. colored glass), or reflect light (e.g. leaves).

• An object which transmits red light is absorbing all colors other than red

• An object which reflects green light is absorbing all colors other than green.
Questions

Q. What colors are absorbed by blue glass?
A.

Q. What color is absorbed by black paper?
A.

Q. What color is absorbed by white paper?
A.

Q. What color will a green apple seen through red glass be?
A.
Questions

Q. What colors are absorbed by blue glass?
A. All except blue.

Q. What color is absorbed by black paper?
A. All colors

Q. What color is absorbed by white paper?
A. No colors

Q. What color will a green apple seen through red glass be?
A. black
Images from Refraction

Images in water (either a tank, or viewed through an underwater face mask) appear larger and closer:

(a) A fish out of water

The eye sees the object at distance $d$.

(b) A fish in the aquarium

The eye sees the image at distance $d'$. Diverging rays appear to come from this point. This is a virtual image.
Images from Refraction

• Rays from the object are refracted when they meet the water-air boundary.

• We can calculate the apparent distance, $s'$, from the edge of the tank or face mask.
Images from Refraction

- The ratio of the actual and apparent distances from the boundary is related to the ratio of the tangents

\[ l = s \tan \theta_1 = s' \tan \theta_2 \]

\[ s' = s \frac{\tan \theta_1}{\tan \theta_2} \]
Images from Refraction

- Using the small angle approximation, and Snell’s Law we find the position of the image.

\[ s' = s \frac{\tan \theta_1}{\tan \theta_2} \approx s \frac{\sin \theta_1}{\sin \theta_2} \]

\[ s' = s \frac{n_2}{n_1} \]

(\( \theta \ll 1 \))
Lenses

• A lens focuses light rays by refraction.
• In a converging lens, parallel rays converge to a single point, called the focal point.
• The surfaces are ground to be spherical
Converging and Diverging Lenses

Two types of lenses.

- Converging lens – thicker in the middle, light rays refract towards the optical axis
- Diverging lens – thinner in the middle, light rays refract away from the optical axis

The focal point is the point from which paraxial rays converge or diverge.
Converging Lenses

The focal length is the distance from the lens at which rays parallel to the optical axis converge. These rays are known as **paraxial rays**.

![Diagram of a converging lens showing parallel rays converging at the focal point.](image)

Any ray initially parallel to the optical axis will refract through the focal point on the far side of the lens.
Converging Lenses

Similarly, the focal length is the distance from the lens at which rays will refract out of the lens parallel to the optical axis.
Converging Lenses

Light through the center of the lens pass through without changing angle. These rays are known as **principal rays**.

Any ray directed at the center of the lens passes through in a straight line.
Real Images

- A real image can be seen in focus on a screen.
- Note they are always **inverted** with a simple converging lens when \( s > f \).
Another definition for a real image is that the rays converge at a point at the **image plane**.
Virtual Images

For a virtual image – the rays diverge from a point in the object plane.
Pin-hole Images

Rays for pin-hole images neither diverge nor converge (although they do project onto a screen).

Sometimes called a *projected image*
In focus images

- The image will only be in focus at the particular plane where rays from the same point on the object converge.
- The image will appear blurry if the screen is not at the image plane.
Finding images

The image properties can be found by ray tracing on scale drawings, or from calculations with similar triangles.
Magnification

Magnification is the ratio of the size of the image to the object and depends on the focal length and object distance. For a thin-lens, we have:

\[ m = \frac{h'}{h} = \frac{s'}{s} \]
Converging lenses and Virtual Images

When an object is placed between the focal point and a lens (s<f), the image is virtual and upright.
Converging lenses and Virtual Images

The virtual image is enlarged and not inverted, but upright.
Diverging lenses

Thinner in the middle. Usually used with other lenses for magnification and focusing.
Diverging lenses

Use the same rules to find the image –

- Trace the principle ray through the center of the lens
- Trace the two paraxial rays through the focal points
- Images are **virtual** and **upright**
Spherical Mirrors

- Concave spherical mirrors.
- Convex spherical mirrors.
- Note that a perfectly spherical mirror will not focus exactly, but we ignore this for now.
Concave Mirrors

- The focal point is the point where paraxial rays converge or diverge.
- Principle ray is reflected at an equal angle at the center of the lens.
Concave Mirrors

• Draw the principle ray, and the two paraxial rays to find the image.

• Applications – telescopes.

• If \( s > f \) image is inverted and real

• If \( s < f \) image is upright and virtual
Convex Mirrors

- The focal point is the point where paraxial rays converge or diverge.
- Principle ray is reflected at an equal angle at the center of the lens.

(a) Any ray initially parallel to the optical axis will reflect as though it came from the focal point.

(b) Any ray initially directed toward the focal point will reflect parallel to the optical axis.

(c) Any ray directed at the center of the mirror will reflect at an equal angle on the opposite side of the optical axis.
Convex Mirrors

- Draw the principle ray, and the two paraxial rays to find the image.
- Image is always upright and virtual, but “images are closer than they appear”
- Applications – wide angle mirrors,
Summary

- Ray model
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- Refraction, total internal reflection
- Color dispersion
- Lenses
- Image formation
- Magnification
- Spherical mirrors
Homework problems

Chapter 18 Problems
41, 49, 53, 59, 65, 66.