Recap I

- **Total Internal Reflection**: (for $n_2 < n_1$ only!)
  
  \[ \theta > \theta_c = \arcsin \left( \frac{n_2}{n_1} \right) \]

  Critical angle

- **Polarization by Reflection**:
  
  at **Brewster angle**: \( \theta_1 = \theta_B = \arctan \left( \frac{n_2}{n_1} \right) \)
  
  - \( \theta_1 + \theta_2 = 90^\circ \)
  
  - Reflected ray is plane polarized

- **Chromatic Dispersion**:
  
  Refractive index \( n \) depends on frequency \( f \) of EM wave. Generally, \( n \) is greater for higher frequency (shorter wavelength).
Recap II

- **Image:**
  - Real image: Location of image is actually a point of convergence of the light rays.
  - Virtual image: Rays only appear to diverge from a point on the image.

- **Plane Mirror:**
  - Object distance \( p = -\) image distance \( i \)
  - Lateral magnification \( m \):
    \[
    m = \frac{\text{image height}}{\text{object height}}
    \]
    
    Upright image: \( m > 0 \)
    
    Inverted image: \( m < 0 \)
Today:

- Mirrors and Lenses
Lunar Laser Ranging Experiment

- Measures the distance between the Earth and the Moon using laser ranging.
- Lasers on Earth are aimed at retroreflectors planted on the Moon during the Apollo program, and the time for the reflected light to return is determined.
- Round-trip time of about 2½ seconds
- Average distance of Earth to Moon: about 384,467 kilometers
- Measured with near mm precision!
- Finding: The Moon is spiraling away from Earth at a rate of 38 mm per year

Laser Ranging Facility at the Geophysical and Astronomical Observatory at NASA's Goddard Spaceflight Center in Greenbelt, Md.
Array of Corner Reflectors on the Moon
Corner reflector

Always reflects waves back directly towards the source!
**Spherical Mirrors:**

- **Concave Mirror:** $f > 0$
  - Incoming ray II to central axis
  - Real focal point $F$
  - Center of curvature
  - Radius of $f = r > 0$
  - For both cases:
    \[
    \frac{1}{f} = \frac{1}{2r}
    \]

- **Convex Mirror:**
  - Virtual focal point $F$
  - Central axis
  - $f < 0$
  - Center of curvature
  - Radius of curvature

\[
\boxed{f = \frac{1}{2} r}
\]
Mirrors: Locating Images by Drawing Rays

1. A ray that is initially parallel to the central axis reflects along the "focal point line".

2. A ray that reflects from the mirror after "passing" through the focal point emerges parallel to the central axis.

3. A ray that reflects from the mirror at point "s" is reflected symmetrically about the central axis.

4. A ray that reflects from the mirror after "passing" the center of curvature point returns along itself.
Image from Mirrors:

**Concave mirror:** $f > 0$

- Sign conventions:
  - $f > 0$ for concave mirror; $f < 0$ for convex mirror
  - $p > 0$
  - $i > 0$ for real image; $i < 0$ for virtual image

- For both cases: (for any mirror)
  \[
  \frac{1}{P} + \frac{1}{i} = \frac{1}{f}
  \]

Convex mirror: $f < 0$

- $f =$ focal length
- $P =$ object distance
- $i =$ image distance

Lateral magnification:

\[
m = -\frac{i}{P} = \frac{\text{image height}}{\text{object height}}
\]

$m > 0$: upright image
$m < 0$: inverted image
Thin lenses:

- Lens deflects the incoming light ray by angle $\alpha$ that is proportional to offset $h$ of the ray from the central axis.

\[ |\alpha| = |P| \frac{h}{f} \]

where $|P|$ is the "lens power" in diopters, $f$ is the focal length, and $h$ is the offset.
\[
\tan \alpha = \frac{h}{f} \implies \alpha = \tan^{-1} \left( \frac{h}{f} \right) \quad \text{for small angles:} \quad \tan \alpha \approx \alpha \\
\]

\[
\Rightarrow \text{ lens power } \quad P = \frac{1}{f} = \frac{1}{\text{focal length}} \\
\]

\[
\Rightarrow \text{ longer lens: larger lens power } \left( \frac{1}{f} \text{ shorter focal length } f \right) 
\]
Converging lens: $s > 0$

Diverging lens: $s < 0$

\[ \frac{1}{f} = (n-1) \left( \frac{1}{r_1} - \frac{1}{r_2} \right) \]

- $f$: focal length of lens (for thin lens in air)
- $n$: refractive index
- $r_1$, $r_2$: radii of curvature of lens surface
- $r_1$: surface near object
- $r_2$: other side