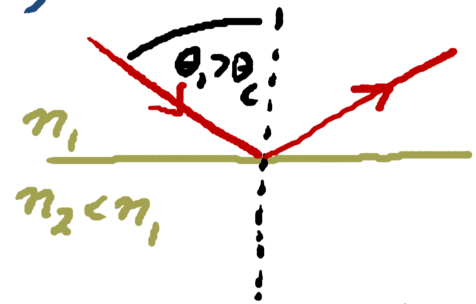
Recap I

- **Total Internal Reflection:** (for $n_2 < n_1$ only!)

  for $\theta_1 > \theta_c = \arcsin\left(\frac{n_2}{n_1}\right)$

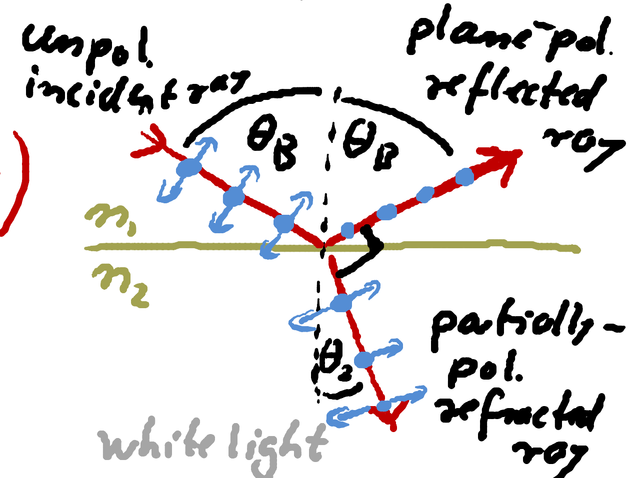
  ↑ critical angle



- **Polarization by Reflection:**

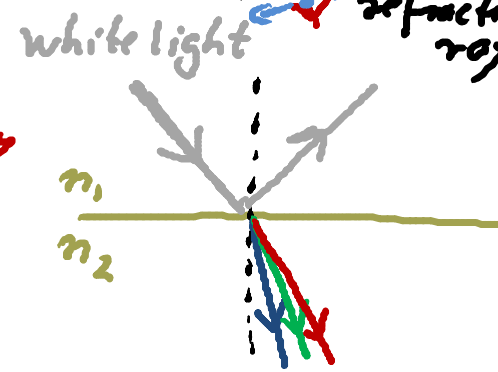
  at Brewster angle: $\theta_1 = \theta_B = \arctan\left(\frac{n_2}{n_1}\right)$

  - $\theta_1 + \theta_2 = 90°$
  - 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).



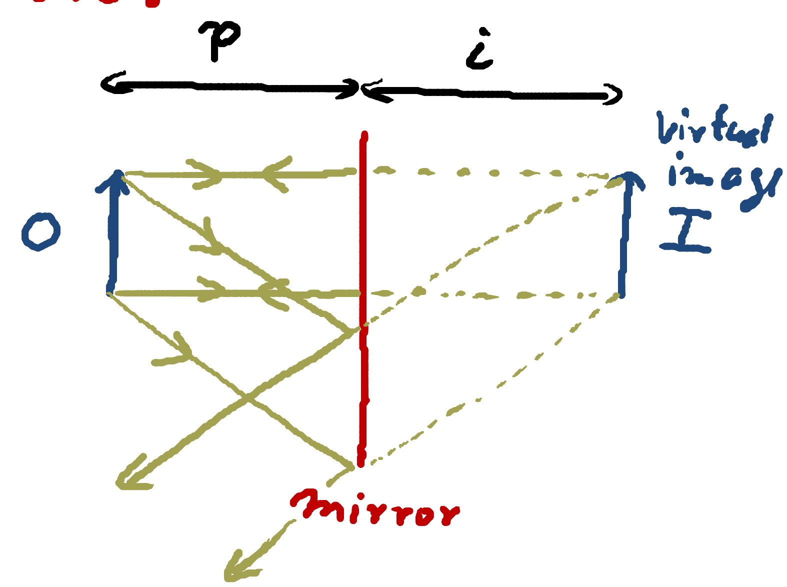
Recap II

- **Images:**
  - 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:

$$m = \frac{\text{image height}}{\text{object height}}$$

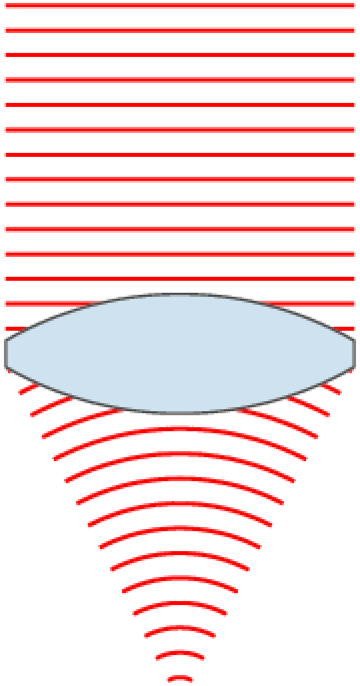
upright image : $m > 0$

inverted image : $m < 0$



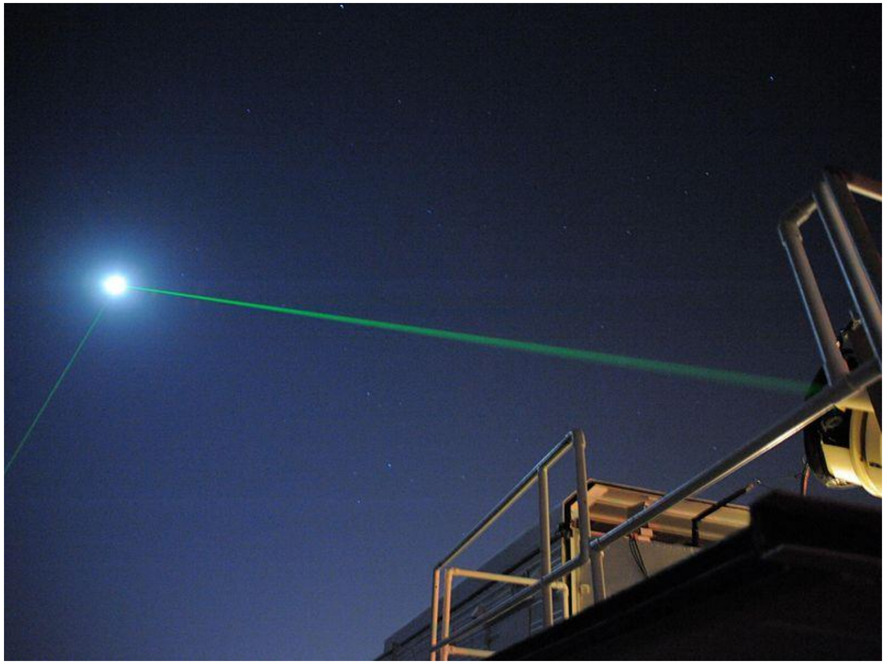
Today:

- **Mirrors and Lenses**



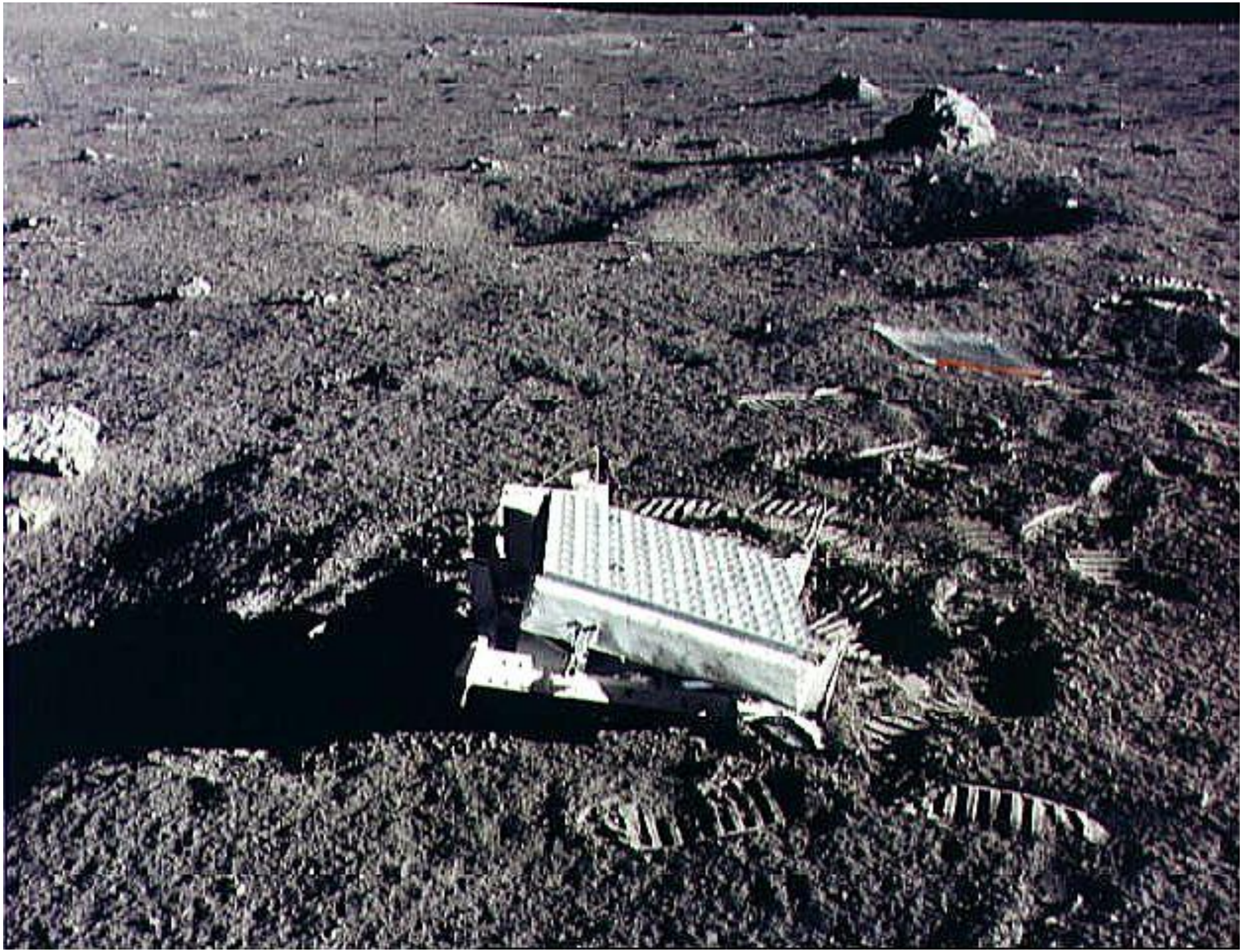
Lunar Laser Ranging Experiment

- **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**

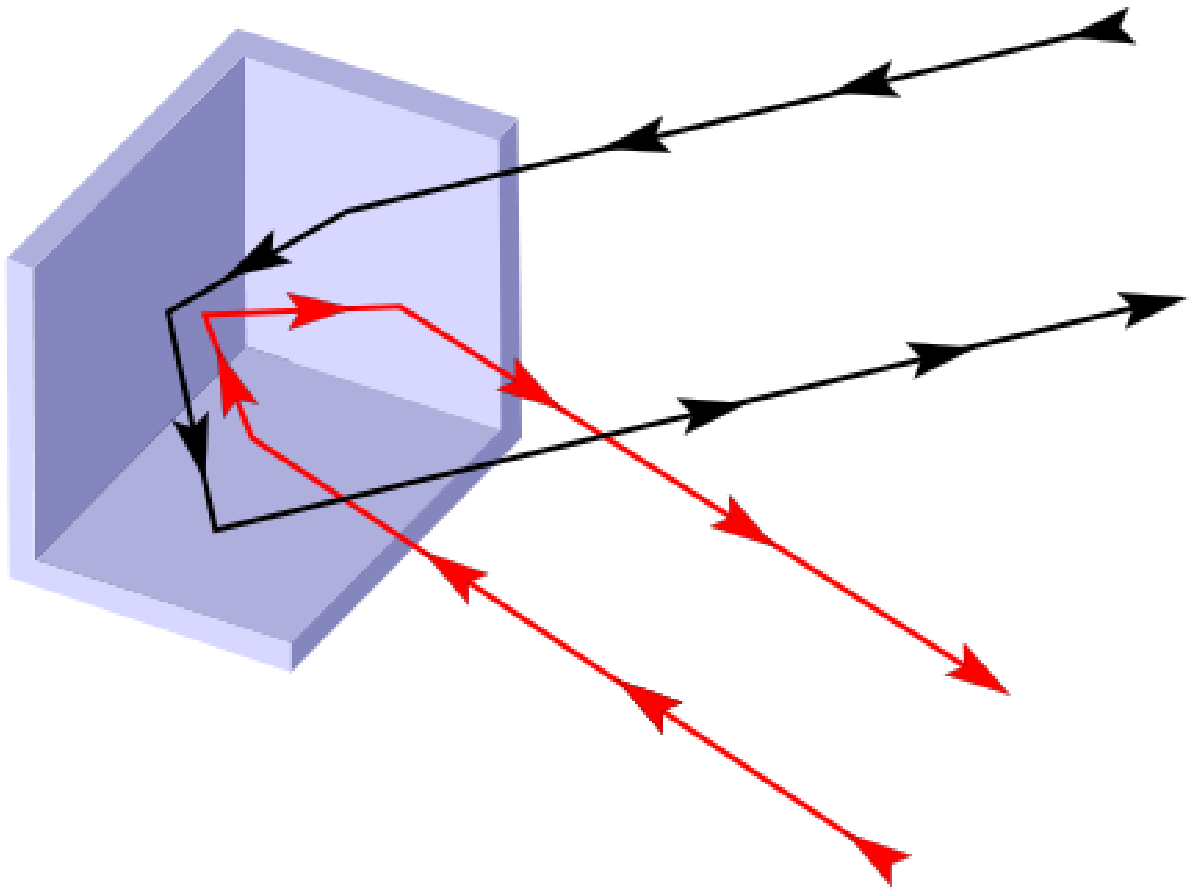


Laser Ranging Facility at the Geophysical and Astronomical Observatory at NASA's Goddard Spaceflight Center in Greenbelt, Md.

Array of Corner Reflectors on the Moon



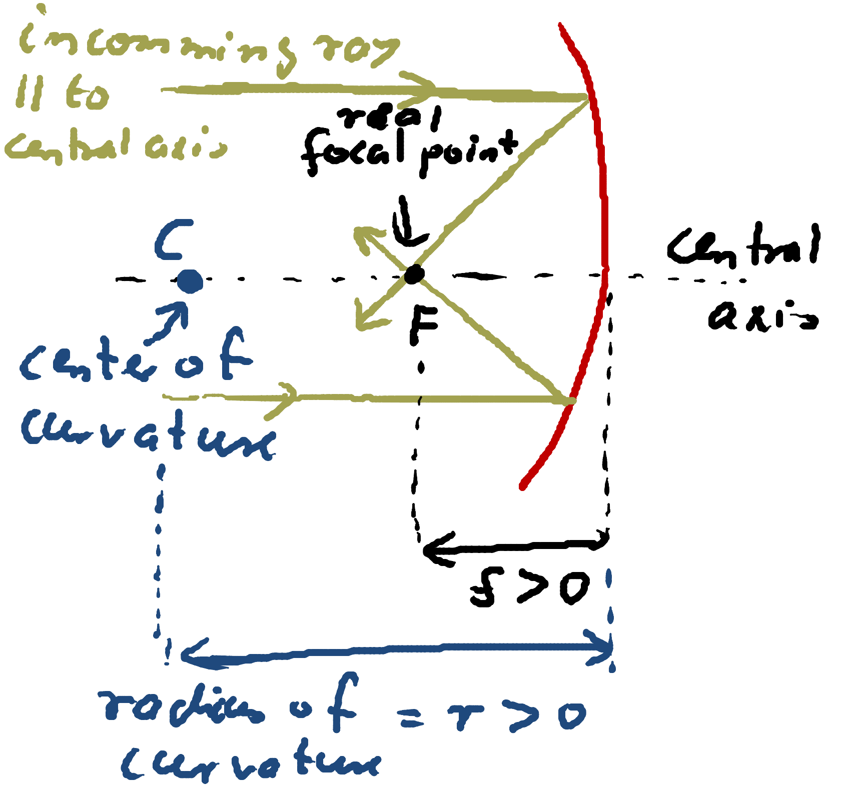
Corner reflector



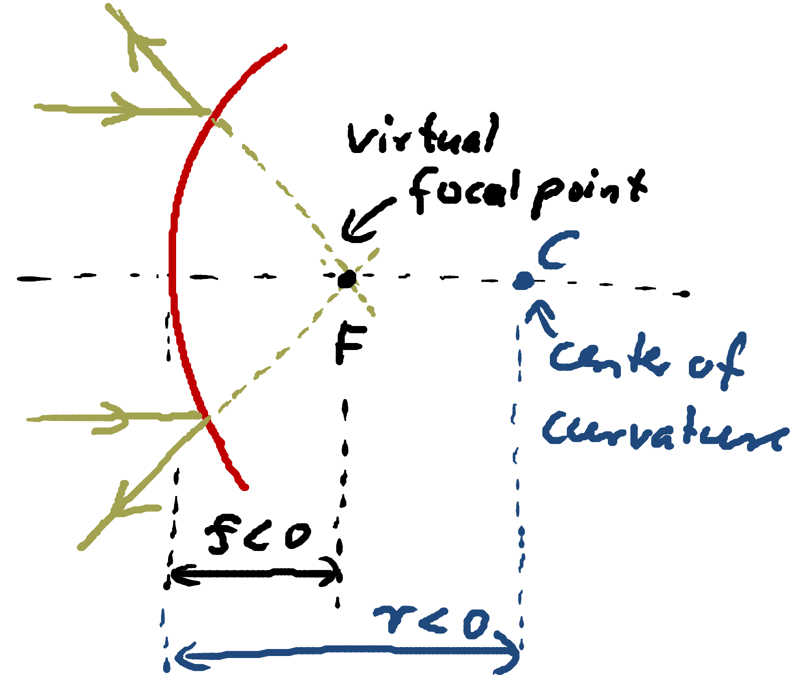
Always reflects waves back directly towards the source!

Spherical Mirrors:

Concave Mirror: $f>0$



Convex Mirror:



For both cases:

$$\begin{pmatrix}\text{focal length } f \\ \text{of mirror}\end{pmatrix} = \frac{1}{2}\begin{pmatrix}\text{radius of curvature} \\ r \text{ of mirror}\end{pmatrix}$$

$$\boxed{f = \frac{1}{2} r}$$

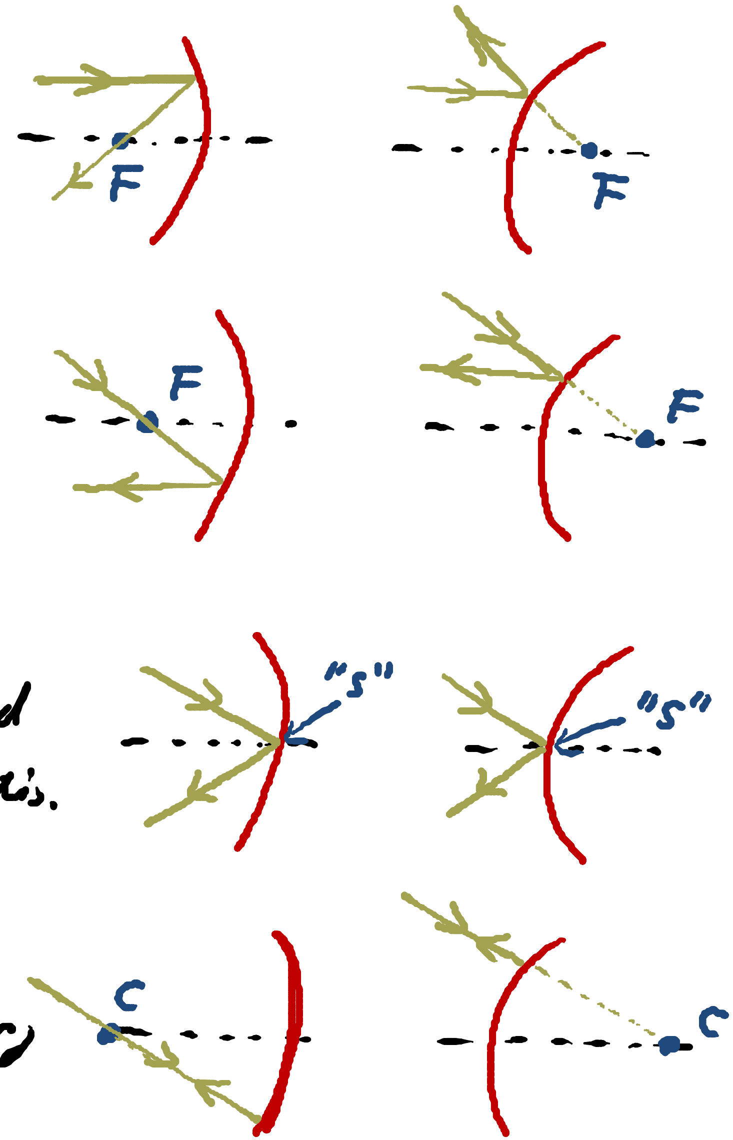
Mirrors: Locating Images by Drawing Rays

(1) 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.

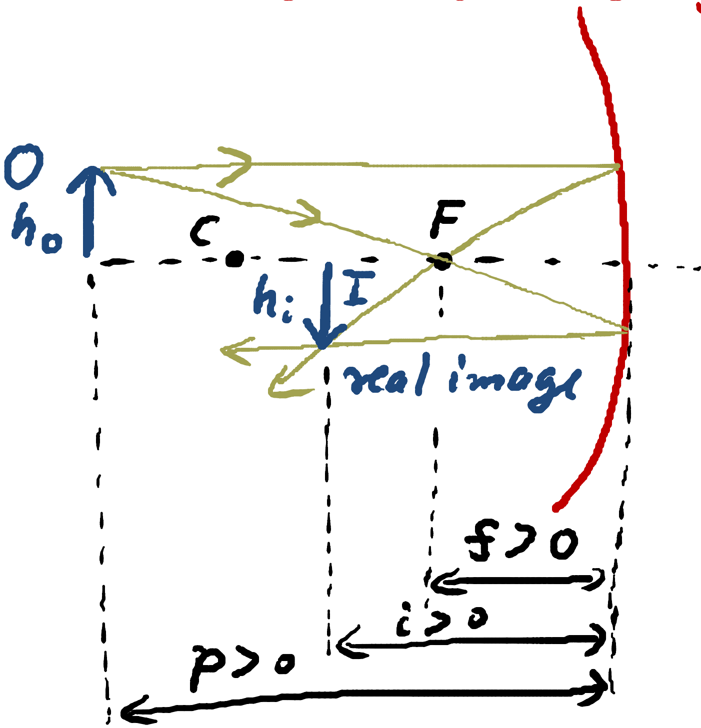
(3) A ray that reflects from the mirror at point "s" is reflected symmetrically about the center axis.

(4) A ray that reflects from the mirror after "passing" the center of curvature point returns along itself.

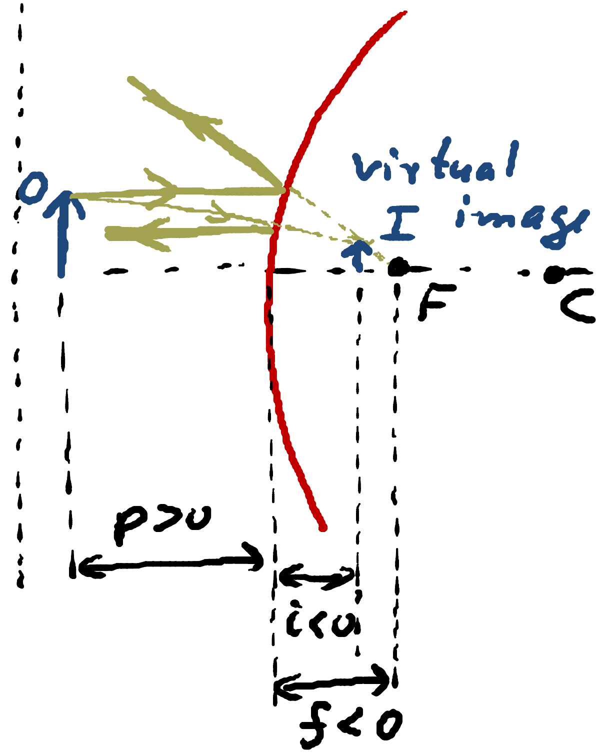


Images from Mirrors:

Concave mirror: $f > 0$



Convex mirror: $f < 0$



f = focal length

p = object distance

i = image distance

- 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)

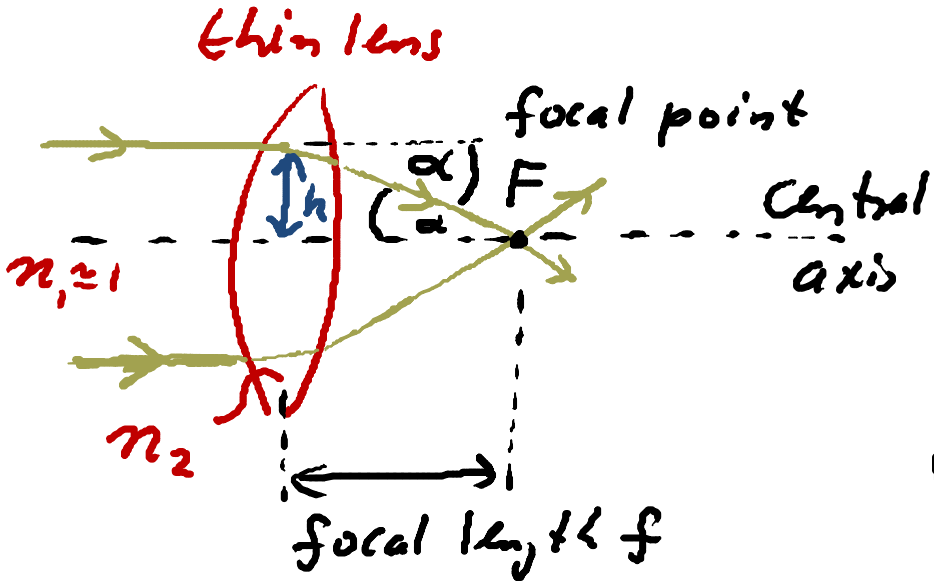
$$\frac{1}{p} + \frac{1}{i} = \frac{1}{f}$$

Lateral magnification $= m = -\frac{i}{p} = \frac{\text{image height}}{\text{object height}}$

$m > 0$: upright image

$m < 0$: inverted image

Thin lenses:



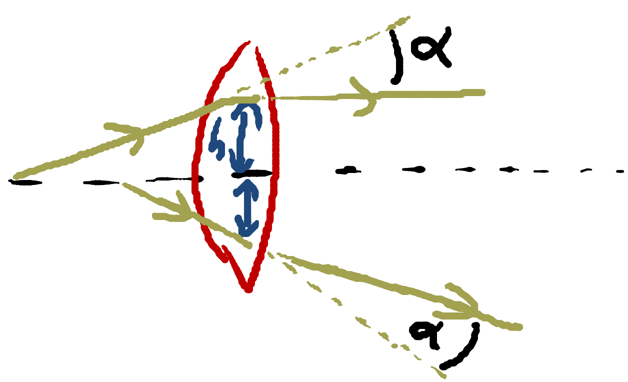
- Lens deflects the incomming light ray by angle α that is proportional to offset h of the ray from central axis

$$|\alpha| = |P|\, h$$

offset: h
deflecting angle in rads: α
"lens power" P

$$[P] = \frac{1}{m} = \text{diopter}$$

same offset h ⇒ same deflection angle α!



from top figure on previous page:

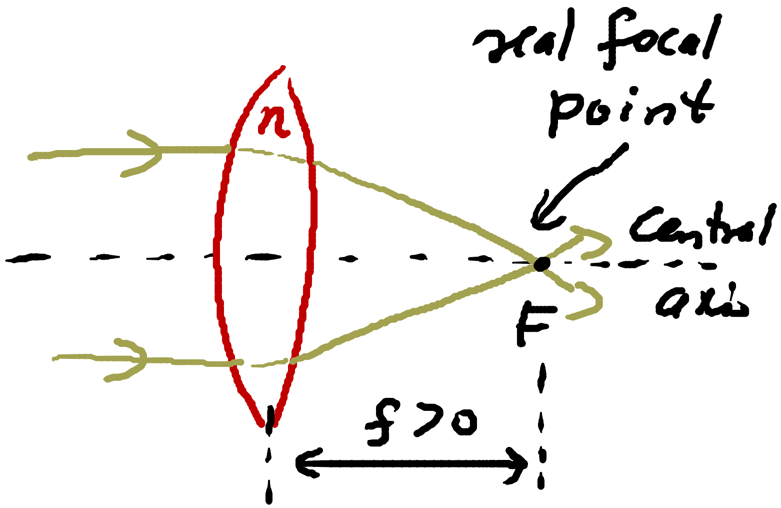
$$\tan\alpha = \frac{h}{f} \approx \alpha = P h$$

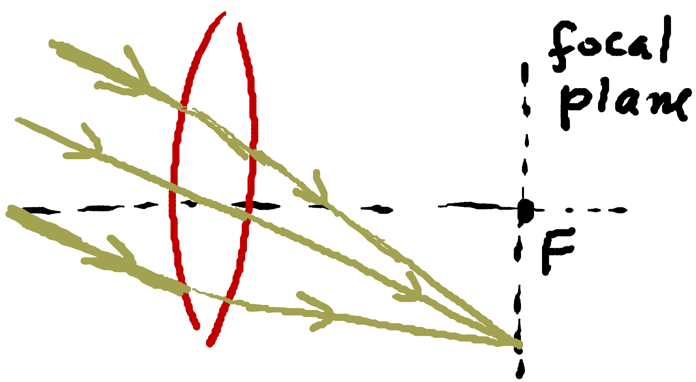
↑ for small angles: $\tan\alpha \approx \alpha$

⇒ lens power $\boxed{P = 1/f} = \frac{1}{\text{focal length}}$

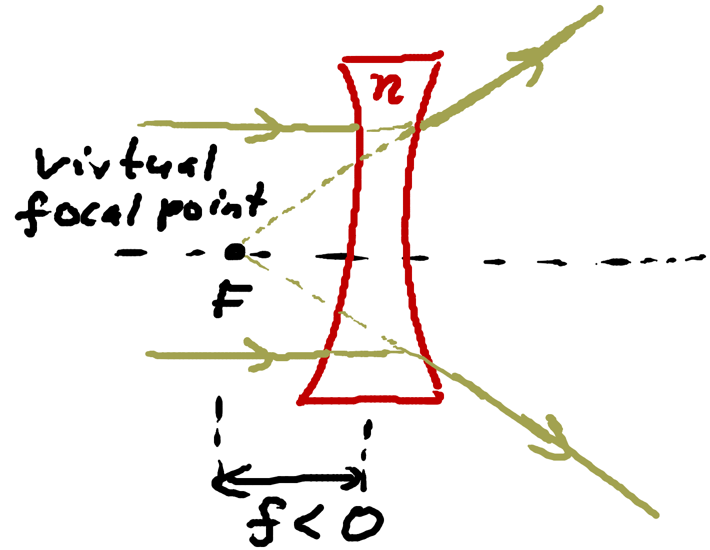
⇒ stronger lens: larger lens power $|P|$
shorter focal length f

Converging Lens: $f > 0$





Diverging Lens: $f < 0$



for both: focal length of lens (for thin lens in air)

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

radius of curvature of lens surface

r_1: surface near object

r_2: other side