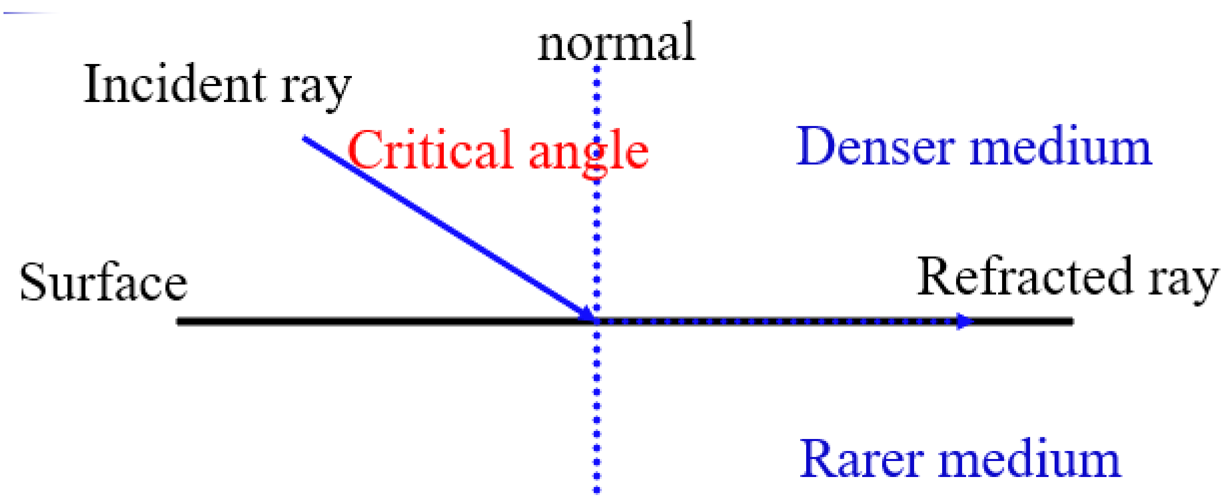
Engineering Optics

1.Basic laws of geometrical optics and imaging concepts

- The electromagnetic spectrum
  - wave length: short -> long
  - GammaRays | X-Rays | UltraViolet | VisibleLight(380nm-780nm) | InfraRed | MicroWaves | RadioWaves

1.1Basic laws

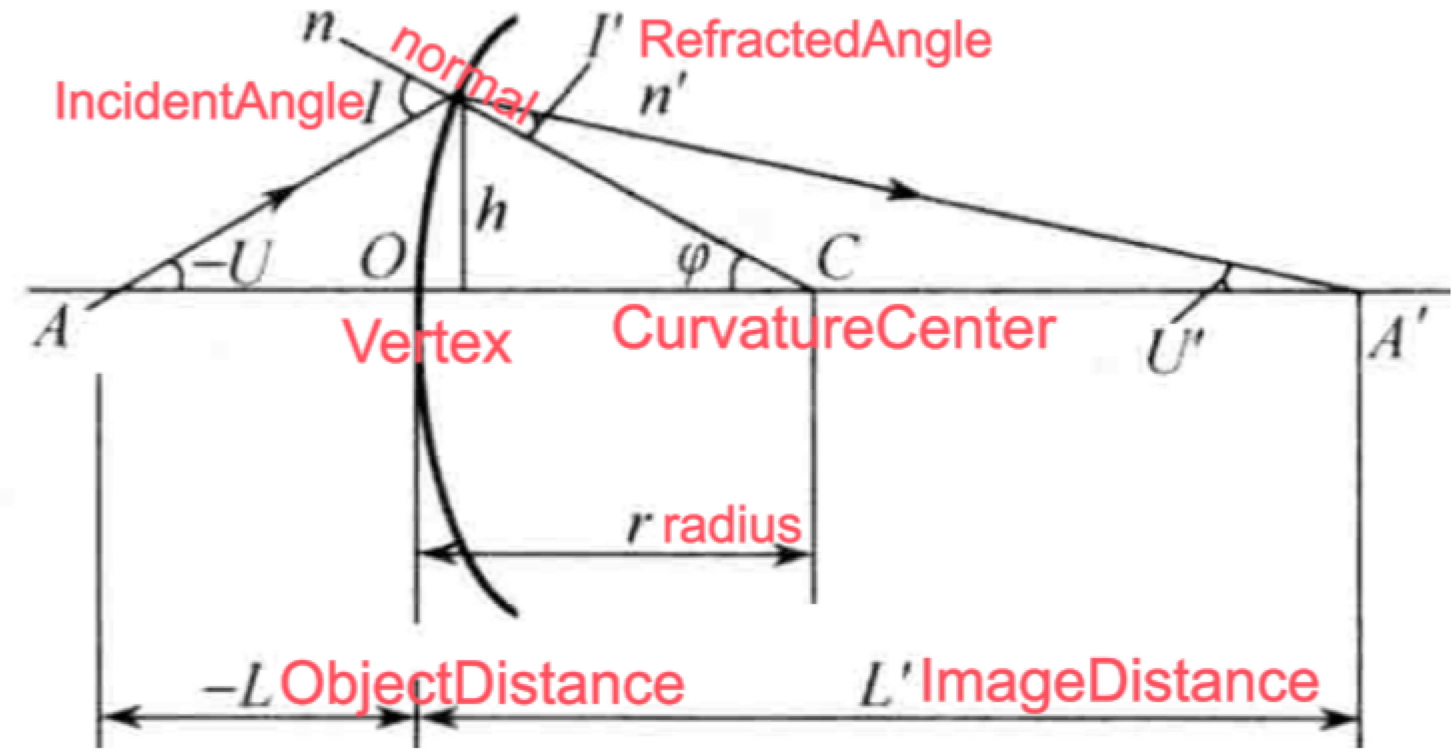
1. **Law of Rectilinear propagation**: Light -> free space / homogeneous, isotropic matter = beeline.
2. **Law of independent propagation**: different lights meet, not affect each other
3. **Law of Reflection**: Light -> reflecting surface and reflected make equal angles
   1. $I'' = -I$
   2. incoming, outgoing, normal $\in$ same plane
   3. **Total Internal Reflection**



4. **Law of Refraction**: incident angle ~ normal ~ refracted angle
   1. $n \sin I = n' \sin I'$
   2. incident, refracted, normal $\in$ same plane

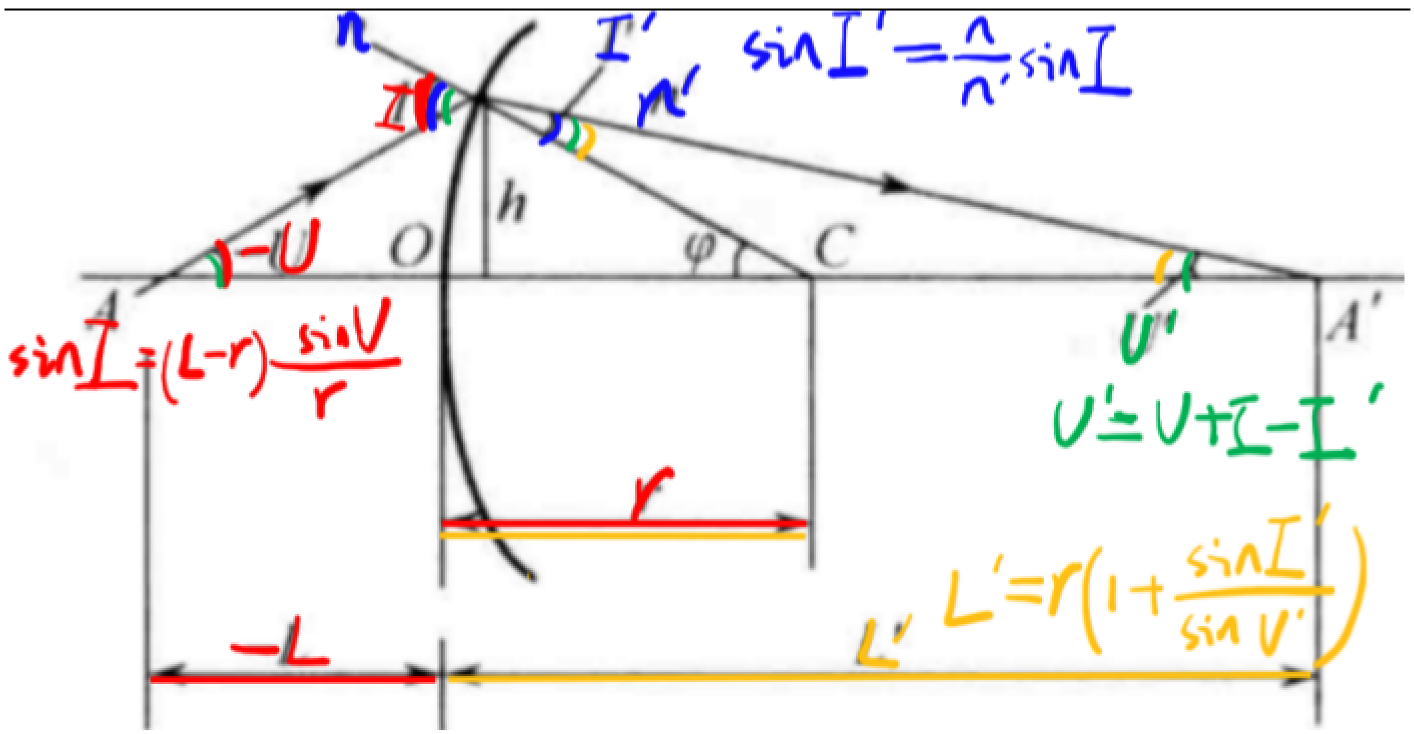
- **Fermat' principle**: light takes the path that requires the least time
- **Malus' principle**: In homogeneous&isotropic matter, Light $\perp$ WaveFront

1.2Light path calculation



Calculate light path

- $\frac{\sin I}{r - L} = \frac{\sin -U}{r}$
- $n' \sin I' = n \sin I$
- $U' + I' = U + I$
- $\frac{\sin I'}{L' - r} = \frac{\sin U'}{r}$



Paraxial rays

- $i = \frac{l-r}{r}u$
- $i' = \frac{n}{n'}i$
- $u' = u + i - i'$
- $l' = r(1 + \frac{i'}{u'})$
- $l'u' = lu = h$
- $\frac{n'}{l'} - \frac{n}{l} = \frac{n'-n}{r}$

1.3Imaging

Magnification

- Transverse magnification: $\beta = \frac{y'}{y} = \frac{n}{n'}\frac{l'}{l}$
- Axial magnification: $\alpha = \frac{dl'}{dl} = \frac{n'}{n}\beta^2$
- Angular magnification: $\gamma = \frac{\tan U'}{\tan U} = \frac{n}{n'}\frac{1}{\beta}$
- $\alpha\gamma = \beta$
- Lagrange's invariant: $J = n'u'y' = nuy$
- Reflection: $n = -n', \frac{1}{l'} + \frac{1}{l} = \frac{2}{r}$

Image characteristics

- larger | smaller
- upright | inverted
- real | virtual

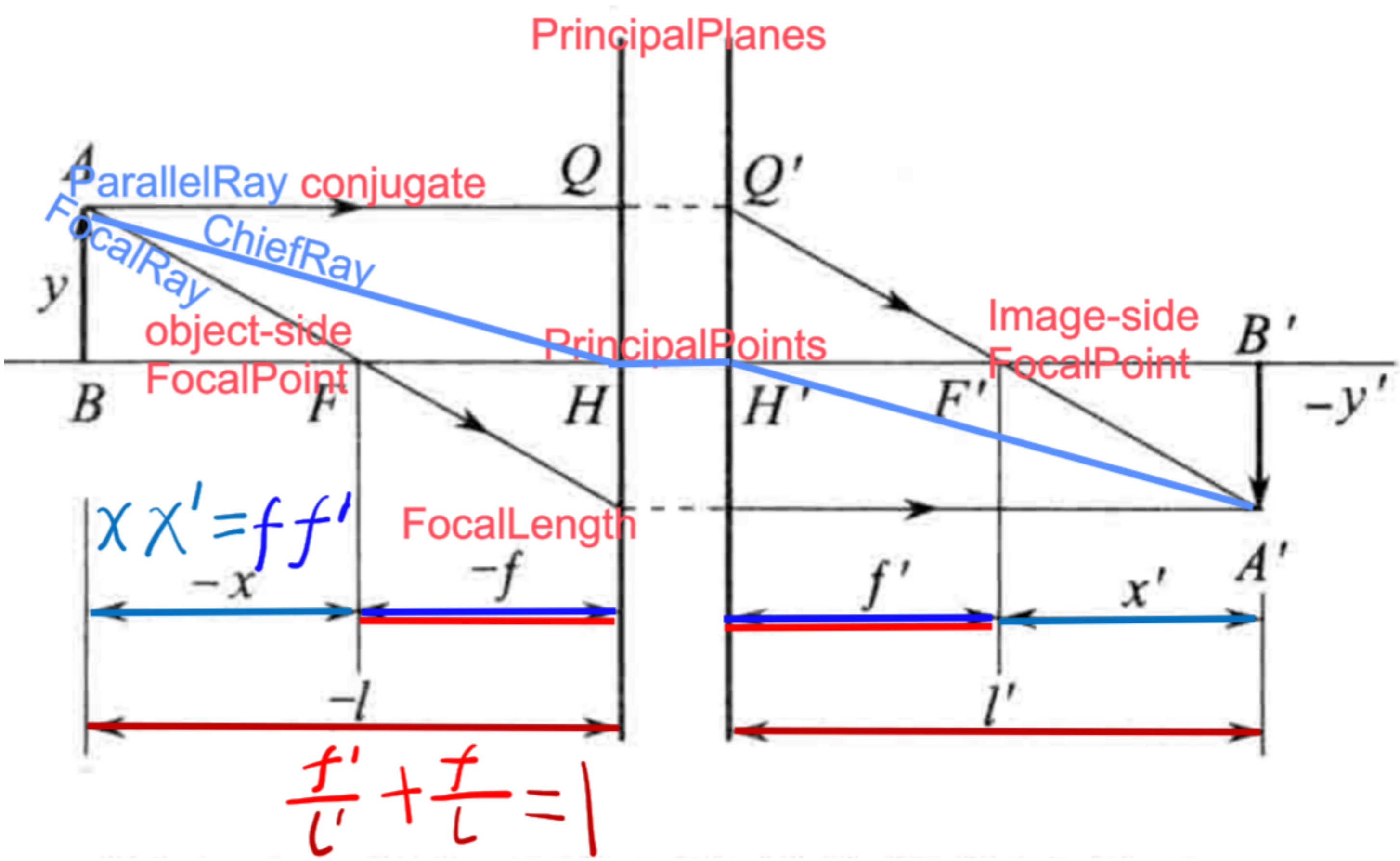
homework

1. A staff 2m long when held erect casts a shadow 3.4 m long, while a building’s shadow is 170 m long. How tall is the building?
   1. similar triangles: $\frac{x}{170} = \frac{2}{3.4}, x = 100m$
2. Light from a water medium with n=1.33 is incident upon a water-glass interface at an angle of 45° . The glass index is 1.50. What angle does the light make with the normal in the glass?
   1. Law of refraction: $1.33 \sin 45^\circ = 1.5 \sin\theta, \theta = 38.83^\circ$
3. A goldfish swims 10cm from the side of a spherical bowl of water of radius 20cm. Where does the fish appear to be? Does it appear larger or smaller?
   1. $\frac{n'}{l'} - \frac{n}{l} = \frac{n'-n}{r}, l' = -8.58cm$
   2. $\beta = \frac{n}{n'}\frac{l'}{l}, \beta = 1.14 > 1$,bigger
4. An object is located 2cm to the left of convex end of a glass rod which has a radius of curvature of 1cm. The index of refraction of the glass is n=1.5. Find the image distance.

1. $\frac{n'}{l'_1} - \frac{n}{l_1} = \frac{n'-n}{r_1}, l'_1 = -\infty$
2. $\frac{n}{l'_2} - \frac{n'}{l_2} = \frac{n-n'}{r_2}, l'_2 = 2cm$

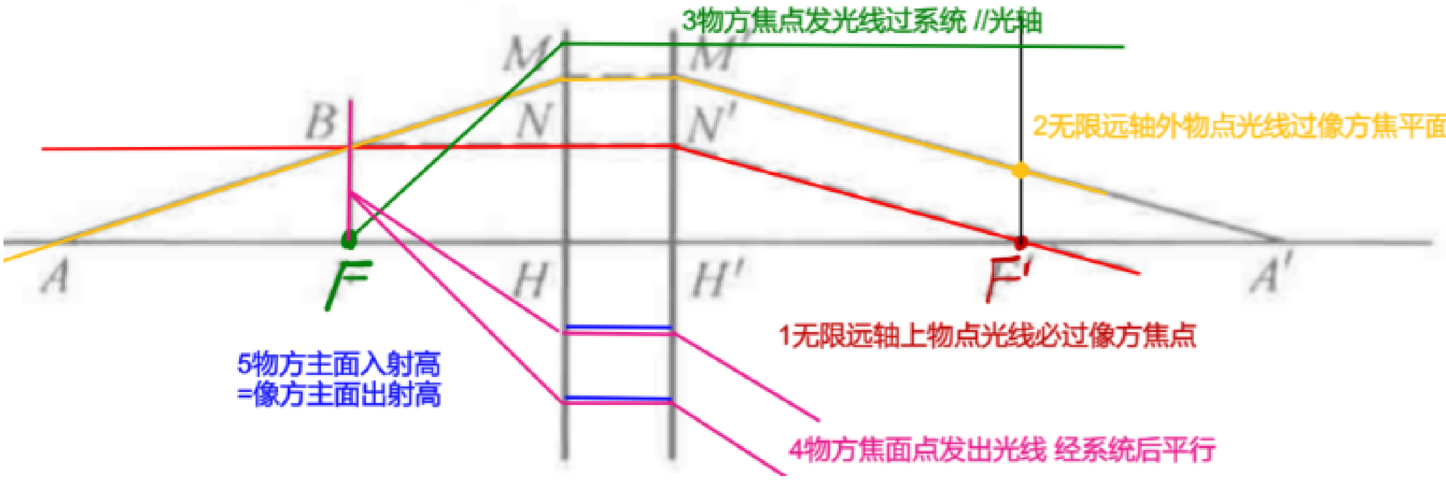
2.Perfect optical system

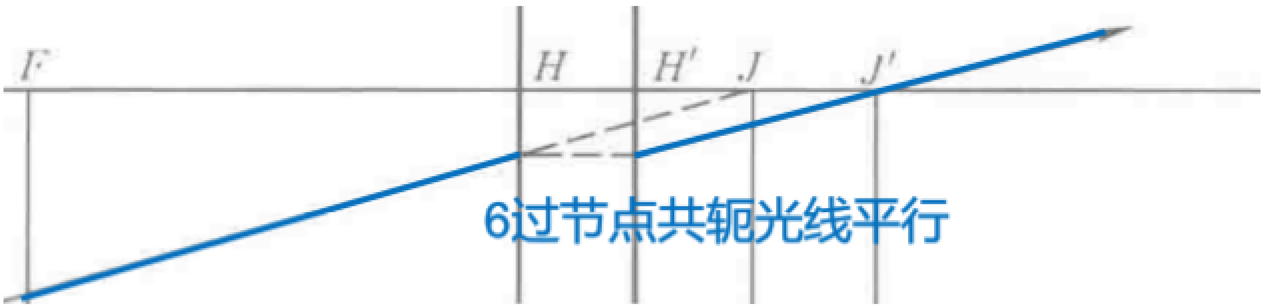
2.1Concept



- Principal plane: conjugate planes, $\beta = \pm 1$
- Focal plane
  $\frac{f'}{f} = -\frac{n'}{n}$
- Nodal plane: conjugate planes, $\gamma = \pm 1$
  $x_J = f', x'_J = f$
- Nodal points: no refraction occurs
  - n=n', NodalPoints=PrincipalPoints
  - n≠n', NodalPoints->bigger n side

2.2Grqphical construction





2.3Image position fomula

- Newton's equation: $xx' = ff'$
- Gauss' equation: $\frac{f'}{l'} + \frac{f}{l} = 1$,same matter$\frac{1}{l'} - \frac{1}{l} = \frac{1}{f'}$

2.4Magnificaation

- $\beta = -\frac{f}{x} = -\frac{x'}{f'}$
- $\alpha = -\frac{x'}{x} = -\frac{f'}{f}\beta^2$
- $\gamma = \frac{n}{n'}\frac{1}{\beta}$
- $\alpha\gamma = \beta$

2.5Combination

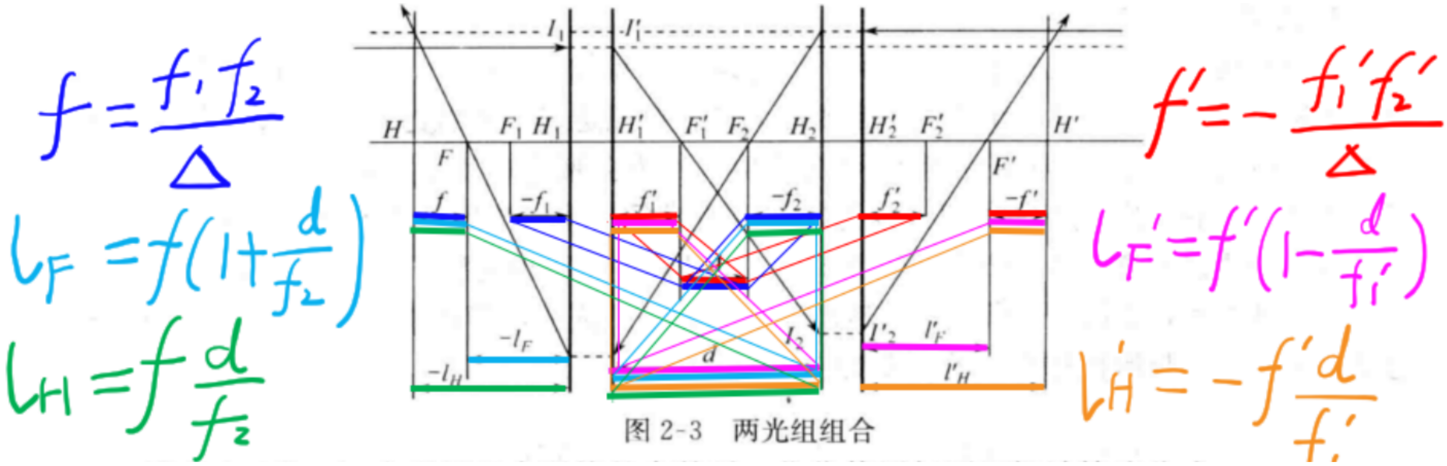
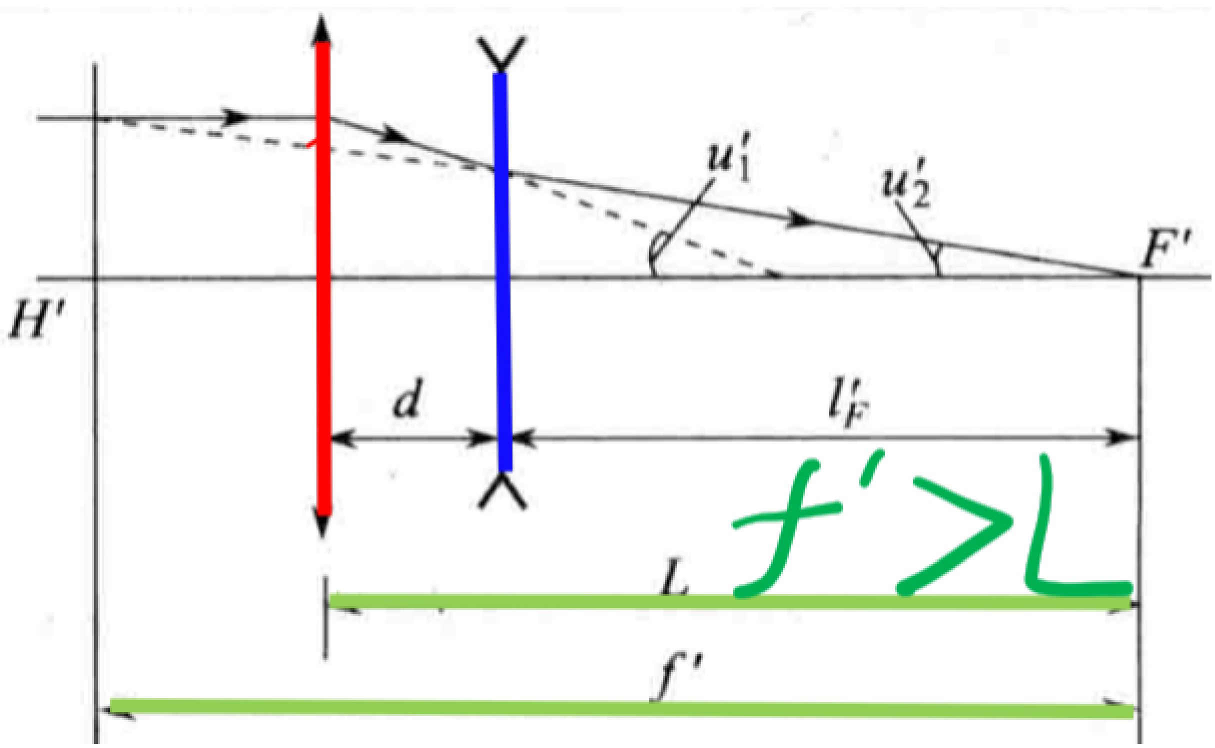


图 2-3 两光组组合

- $f' = -\frac{f_1' f_2'}{\Delta}$ ~ $f = \frac{f_1 f_2}{\Delta}$
- $l_F' = f'(1-\frac{d}{f_1'})$ ~ $l_F = f(1+\frac{d}{f_2})$
- $l_H' = -f'\frac{d}{f_1'}$ ~ $l_H = f\frac{d}{f_2}$
- focal power: $\Phi = \Phi_1 + \Phi_2 - d\Phi_1\Phi_2$

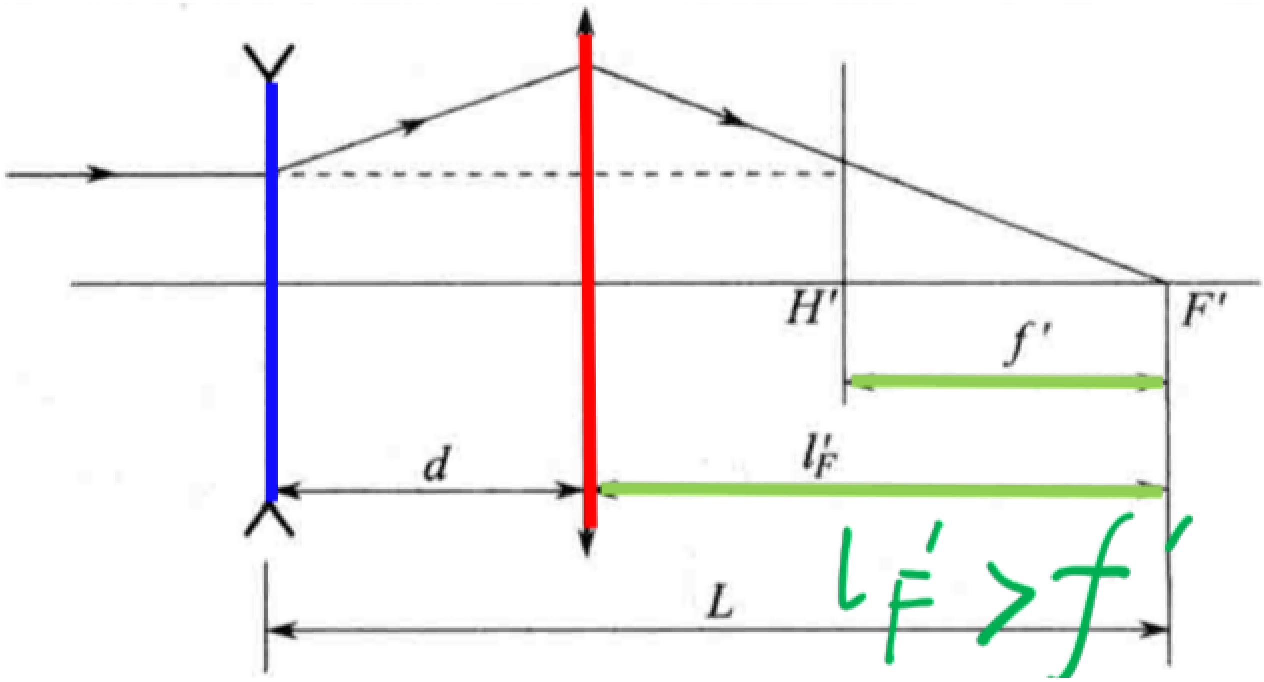
2.6examples

Telephoto group



- used for long focal length lenses to reduce mechanical dimensions

Inverse telephoto group



- used for short focal length & long work length(microscope objective)

2.7Lens

Convex lens not always are plus lens;
Concave lens not always are negative lens.
in air: $f' = \frac{nr_1r_2}{(n-1)[n(r_2-r_1)+(n-1)d]}$
thin lens d->0: $\Phi = (n-1)(\rho_1 - \rho_2)$

homework

1. An object 1cm high is 30cm in front of a thin lens with a focal length of 10cm. Where is the image? Verify your answer by graphical construction of the image.
    1. $\frac{1}{l'} - \frac{1}{l} = \frac{1}{f'}, l' = 15cm$
2. A lens is known to have a focal length of 30cm in air. An object is placed 50cm to the left of the lens. Locate the image.
    1. $\frac{1}{l'} - \frac{1}{l} = \frac{1}{f'}, l' = 75cm$
3. The object is a transparent cube, 4mm across, placed 60cm in front of a lens of 20cm focal length. Calculate the transverse and axial magnification and describe what the image looks like?
    1.

Solution. From Gauss's equation, we find for the rear surface of the cube (the face closer to the lens)

that, $l' = \frac{f' l_1}{f' + l_1} = \frac{20\times(-60)}{20+(-60)} = 30$ cm

For the front surface (the face farther away from the lens),

$l_2' = \frac{f' l_2}{f' + l_2} = \frac{20\times(-60.4)}{20+(-60.4)} \doteq 29.90099$ cm

The transverse magnification for the rear surface is $\beta = \frac{+30}{-60} = -0.5$

But the axial magnification is $\alpha = \frac{\Delta l'}{\Delta l} = \frac{30-29.90099}{-60-(-60.4)} \doteq 0.247525$

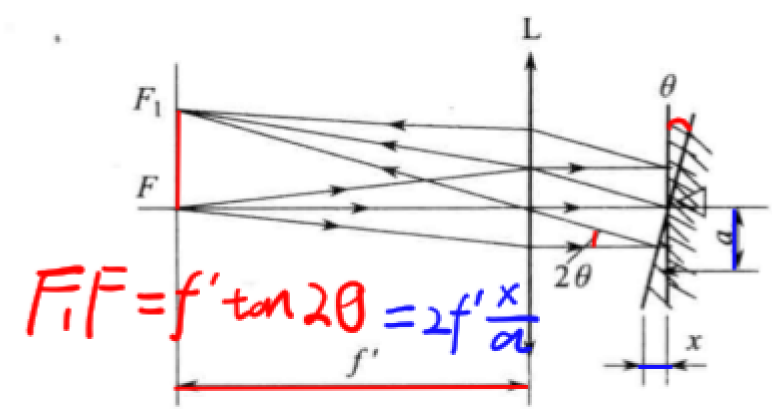
Since $\alpha \neq \beta$, so the cube doesn't look like a cube anymore.

4. A biconvex lens is made out of glass of n=1.52. If one surface has twice the radius of curvature of the other, and if the focal length is 5 cm, what are the two radius?
    1. $r_1 = -2r_2$, $\Phi = (n-1)(\rho_1 - \rho_2)$

3.Plane&Plane system

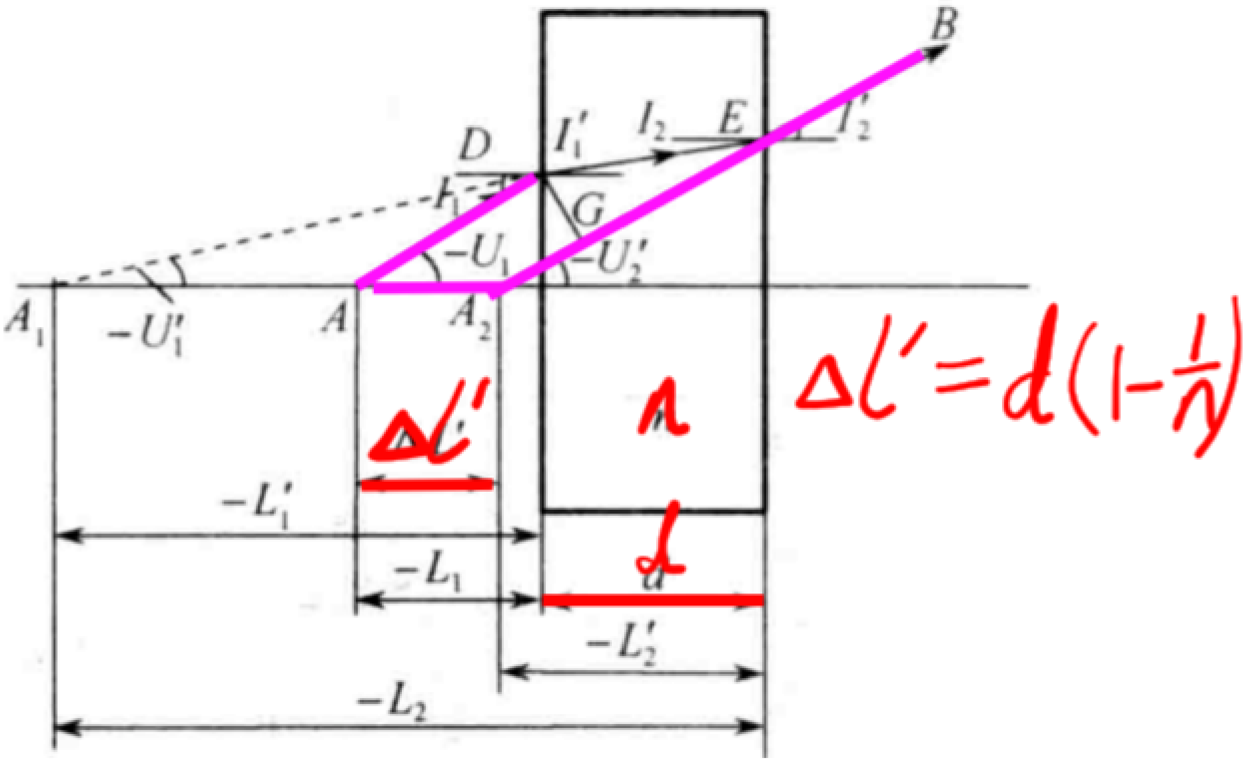
3.1Plane mirror

- the only simple optical element can produce a perfect image
- object distance = image distance, object size = image size, real-virtual in contrast, rotate in contrast
- mirror rotate α, reflected light rotate 2α



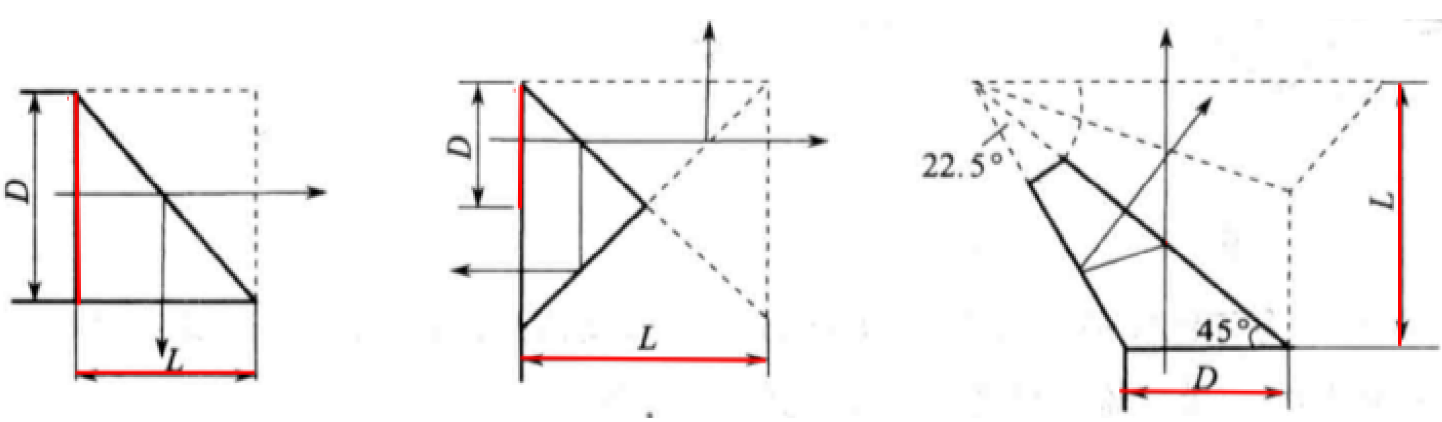
3.2Parallel plate

- direction, size is constant
- Axial displacement: $\Delta l' = d(1 - \frac{1}{n})$



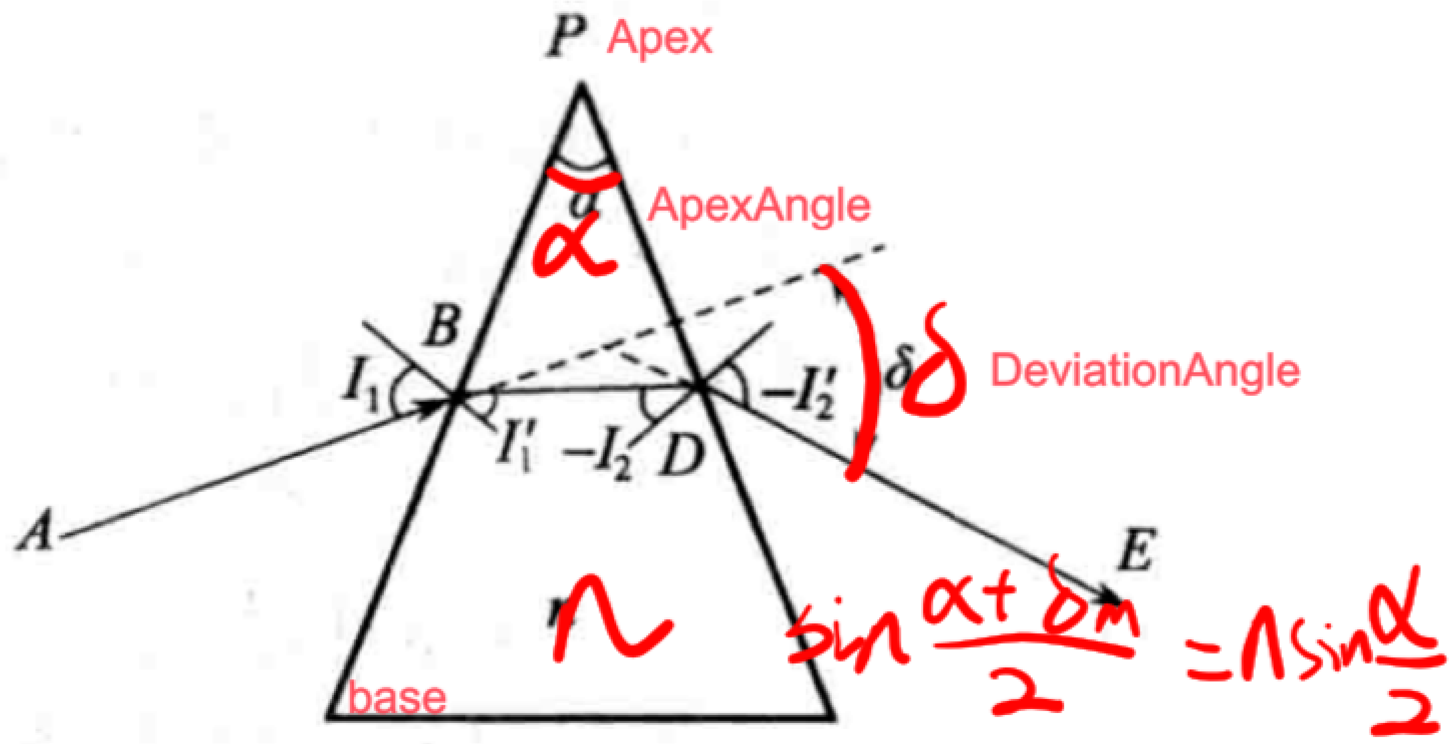
3.3Reflecting prism

- dispersing prisms
- reflecting prisms
  - right-angle prisms
  - roof(Porro) prisms
  - Dove(erecting) prisms
  - pentagonal prisms

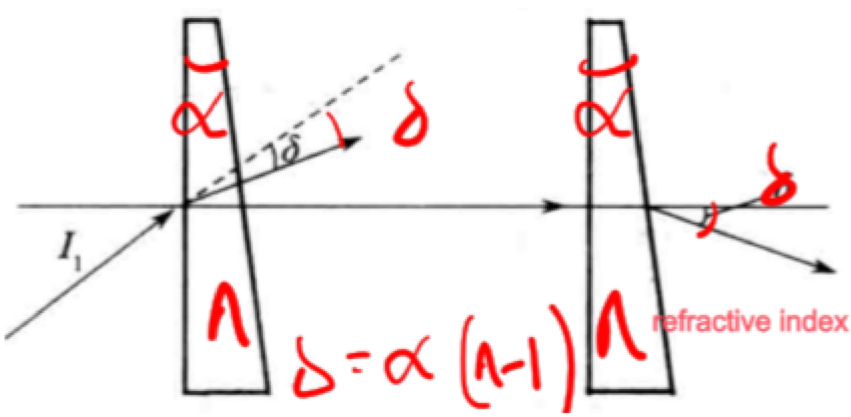


- $L = KD$ D:optical dia, L:plate thickness, K:structure constant
- Chromatic dispersion: $\lambda \uparrow n \downarrow$

3.4Dispersing prisms & optical wedge



- $\sin \frac{\alpha+\delta_m}{2} = n \sin \frac{\alpha}{2}$



- $\delta = \alpha(n-1)$
- measure angle: $\delta = 2\alpha(n-1)\cos\varphi$
- measure displacement: $\Delta y = \Delta z \dot{\delta}$

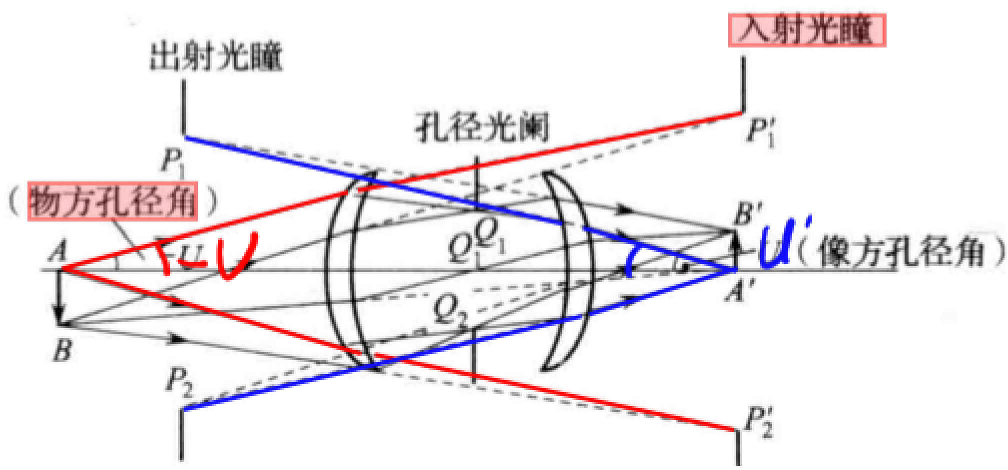
3.5Optical material

- transmission material
  - **optical glass, crytical, plastic**
  - Abbe constant↑ chronmatic dispersion↓
  - CrownGlass-low dispersion, FlintGlass-high dispersion
- reflecting material
  - no chronmatic dispersion

4.Beam limit

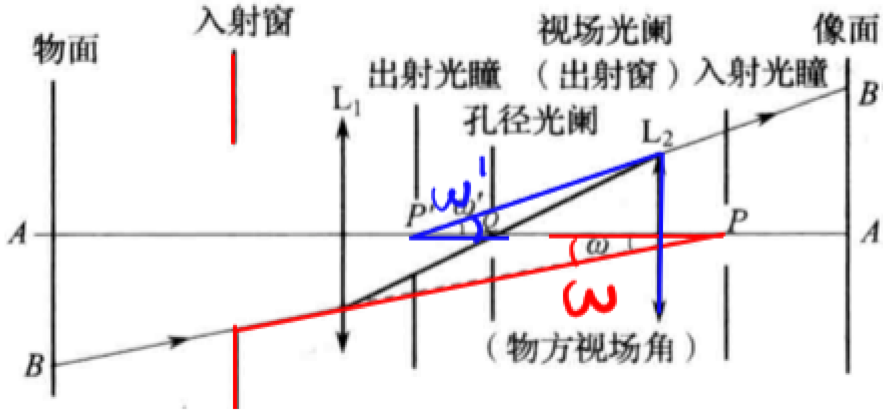
4.1Aperture stop

- Aperture stop: limit the aperture angle
  - Entrance pupil: Aperture stop image according to front optical group
  - Exit pupil: Aperture stop image according to behind optical group
  - Square aperture angle of object: Axis object point -- Entrance pupil ∠ optical axis
  - Square aperture angle of image: Axis image point -- Exit pupil ∠ optical axis



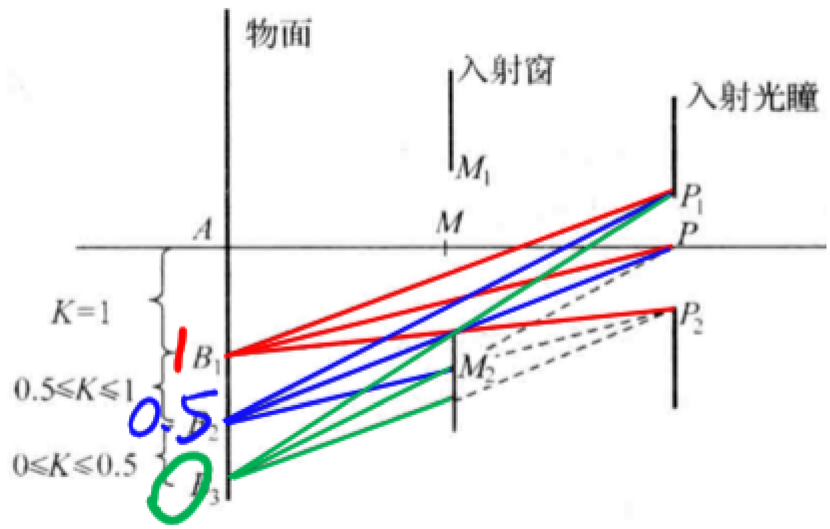
4.2Field stop

- Field stop: limit imaging range
  - Entrance window: Field stop image according to front optical group
  - Exit window: Field stop image according to behind optical group
  - Object square field angle: Entrance pupil center -- Entrance window ∠ optical axis
  - Image square field angle: Exit pupil center -- Exit window ∠ optical axis

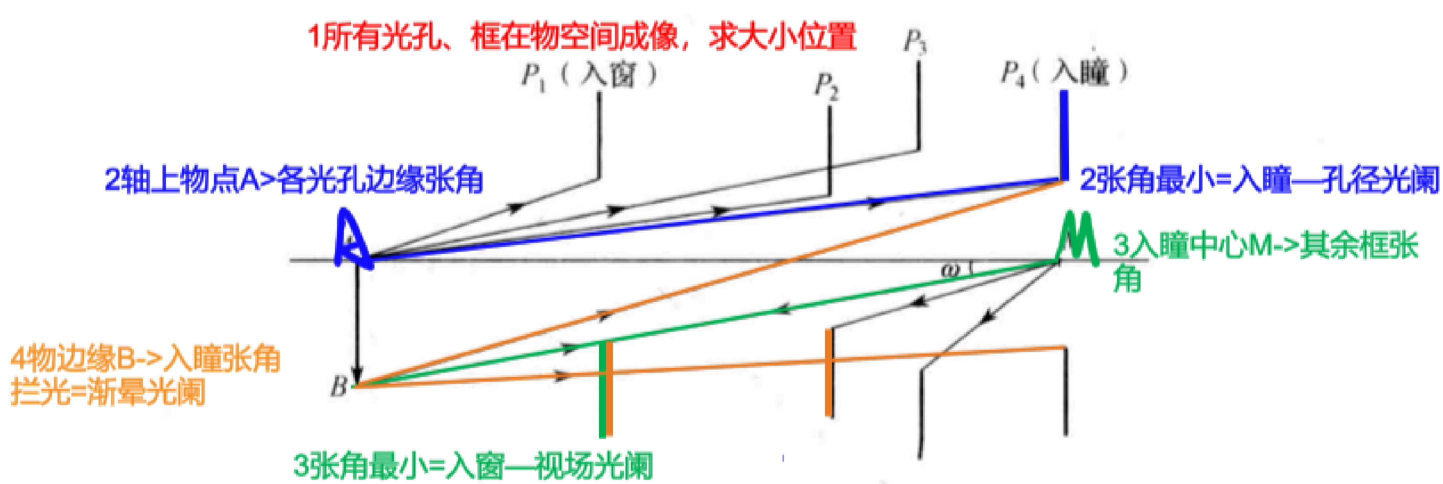


4.3Vignetting

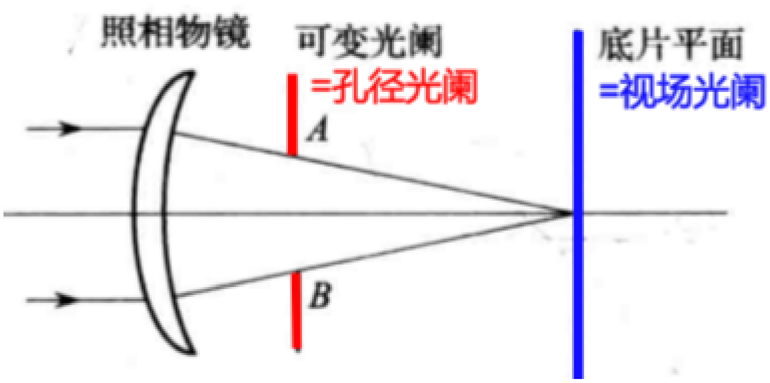
- Vignetting: light full of entrance pupil stopped by others aperture
- Vignetting factor: $K_\omega = \frac{D_\omega}{D}$



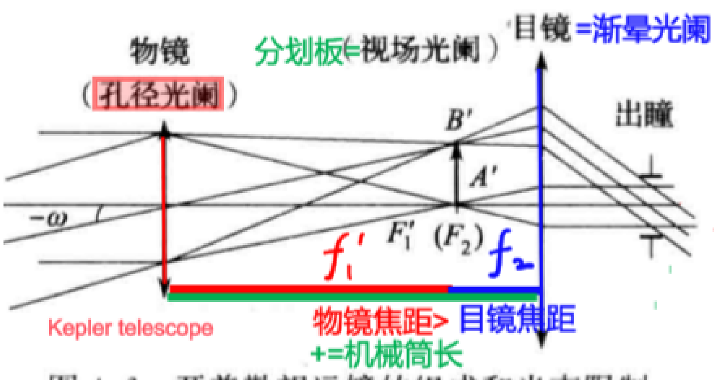
4.4distinguish

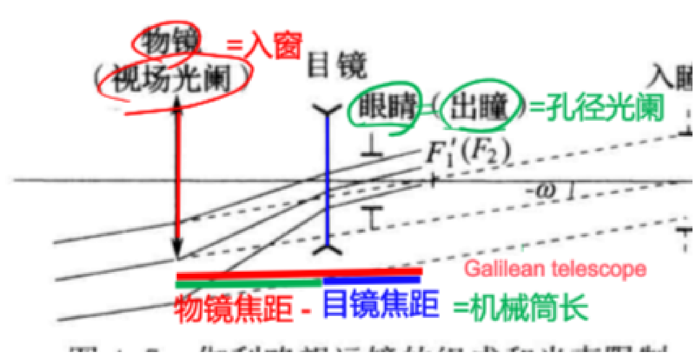


4.5Photographic system

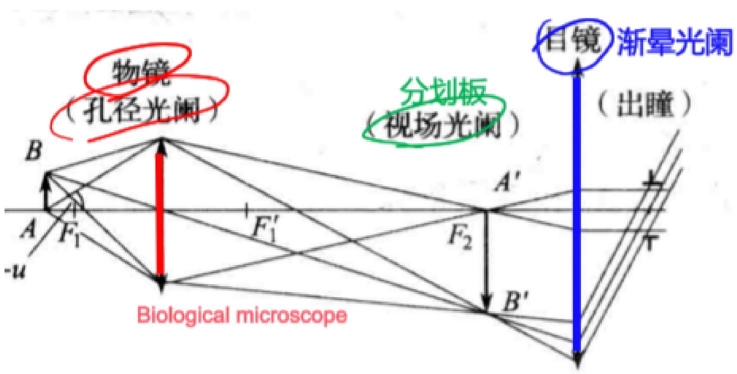


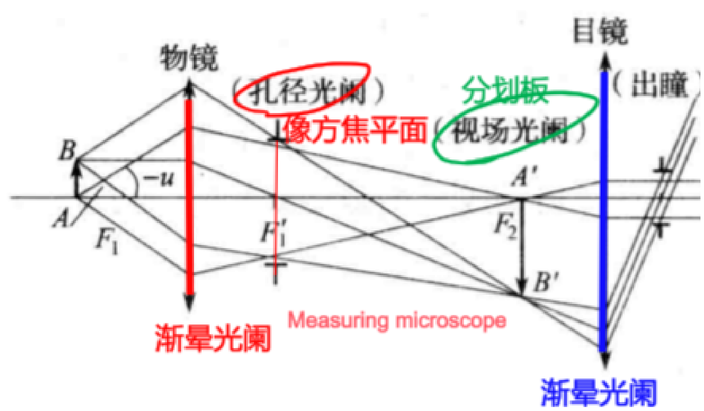
4.6Telescopic system





4.7Microscope system





Object side far center light path: avoid measurement error caused by inaccurate focusing

4.8Field lens

- compress h at which incoming ray is projected in the subsequent light set

- reduce optical aperture of subsequent optical groups
- no affect to image
- new pupil connection requirements

4.9Depth of field

- $\Delta = \Delta_1 + \Delta_2$
- Vision of the depth of field $\Delta_1 = \frac{pz}{2a-z}$
- Close shot the depth of field $\Delta_2 = \frac{pz}{2a+z}$
- disc of confusion z, z'

homework

1. A stop 8mm in diameter is placed halfway between an extended object and a large-diameter lens of 9cm focal length. The lens projects an image of the object onto a screen 14cm away. What is the diameter of the exit pupil?
   1. **Solution:**

      As shown in the figure.

      First, from the known focal length and the image distance, we can find the object distance:

      $$\because \frac{1}{l'} - \frac{1}{l} = \frac{1}{f'}\ ,\quad l' = 14\text{ cm, and } f'=9\text{cm},\ \Rightarrow l = -25.2\text{ cm}$$

      The stop is half of l, so $l_s = -12.6$ cm

      The exit pupil is the image of the stop, according to

      $\frac{1}{l_s'} - \frac{1}{l_s} = \frac{1}{f'}$, we can get $l_s' = 31.5$ cm

      $$\because \beta = \frac{D_{ex}}{D_{stop}} = \frac{l_s'}{l_s} = \frac{31.5}{-12.6} = -2.5$$

      $$\therefore |D_{ex}| = |\beta D_{stop}| = 2.5 \times 0.8 = 2\text{ cm}$$

      So, the exit pupil is located at 31.5 cm to the right side of the lens and its diameter is 2 cm.
2. Two lenses, a lens of 12.5cm focal length and a minus lens of unknown power, are mounted coaxially and 8 cm apart. The system is afocal, that is light entering the system parallel at one

side emerges parallel at the other. If a stop 15mm in diameter is placed halfway between the lenses:

1. Where is the entrance pupil?
2. Where is the exit pupil?
3. What are their diameters?

Solution. As shown in the figure. For the system to be afocal, the focal points of the two lenses must coincide. Since $f_1' = 12.5$ cm , and the two lenses are 8cm apart, so $f_2' = -4.5$ cm . The entrance pupil is the image of stop formed by the first lens.

According to Gauss's equation, $\frac{1}{l_1'} - \frac{1}{l_1} = \frac{1}{f_1'}$

and $l_1' = 4$ cm , $f_1' = 12.5$ cm . We get

$$l_1 = \frac{f_1' l_1'}{f_1' - l_1'} = \frac{12.5 \times 4}{8.5} = 5.88 \text{ cm}$$

So the entrance pupil is 5.88 cm behind the first lens.

$$D_{entrance} = \frac{D_{stop}}{\beta_1} = \frac{D_{stop}}{l_1'/l_1} = \frac{15}{4/5.88} = 22.05 \text{ cm}$$

So the diameter of the entrance pupil is 22.05 mm

Similarly, the exit pupil's location and diameter can be calculated as following

$$l_2' = \frac{f_2' l_2}{f_2' + l_2} = \frac{(-4.5) \times (-4)}{(-4.5) + (-4)} = -\frac{18}{8.5} = -2.12 \text{ cm}$$

$$D_{exit} = |\beta_2| D_{stop} = \frac{2.12}{4} \times 15 = 7.95 \text{ cm}$$

So the exit pupil is located 2.12 cm before the second lens and its diameter is 7.95 mm