Geometrical Optics Notation & Sign Conventions

Physics textbook convention (e.g. Hecht's *Optics*) … not used in this class

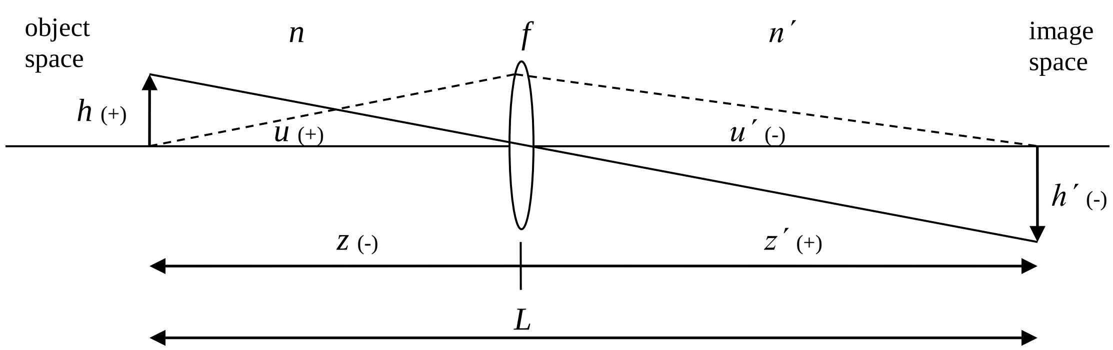
- Object distances are positive to the left, negative to the right
- Image distances are negative to the left, positive to the right

Optical engineering convention …what we will use

- Directed distances are positive to the right, negative to the left
- Angles are positive when they have positive slope relative to the local optical axis and negative when they have negative slope relative to the local optical axis.
- Curvature is positive when the center of curvature lies to the right
- Curvature is negative when the center of curvature lies to the left
- Index of refraction changes sign on reflection (e.g., air index = -1 after reflection)
- Effective focal length is positive if initially parallel rays are caused to converge; effective focal length is negative if initially parallel rays are caused to diverge

Greivenkamp (*Field Guide to Geometrical Optics*)

<u>Thin lenses</u>



Transverse magnification in air $$m = \frac{h'}{h} = \frac{z'}{z} = \frac{u}{u'}$$

Longitudinal magnification $$\bar{m} = \left(\frac{n'}{n}\right) m^2$$

Image & object locations $$\frac{1}{z'} = \frac{1}{z} + \frac{1}{f}$$

Effective focal length $$f = f_E = \text{EFL} = \frac{1}{\phi}$$ (ϕ = optical power)

(*sign denotes converging/diverging*)

Front focal length (*directed distance*) $f_F = -\frac{n}{\phi} = -nf_E$

Rear focal length (*directed distance*) $f_R' = \frac{n'}{\phi} = n' f_E$

Effective focal length from front or rear focal lengths $f_E = -\frac{f_F}{n} = \frac{f_R'}{n'}$

☼ Note: the front and rear focal lengths are directed distances (signs determined by direction), but the effective focal length is not (its sign is determined by whether the surface or element causes incoming parallel rays to converge or diverge).

Ray 'optical angle' $\omega = nu$ (in appropriate space)

<u>Refractive and reflective surfaces</u>

Radius of curvature of surface = R = distance from surface vertex to center of curvature

Curvature of surface $C = \frac{1}{R}$

Optical power of a surface $\phi = (n'-n)C = \frac{(n'-n)}{R}$

Power of reflective surface (n'=-n) $\phi = -2nC = \frac{-2n}{R}$

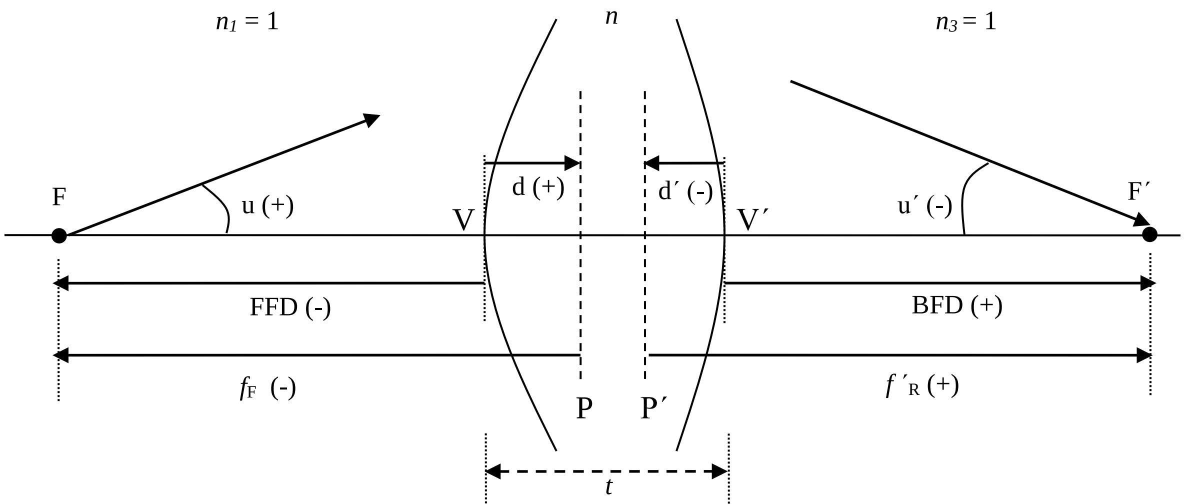
Focal lengths of reflective surface $f_F = f_R' = -\frac{n}{\phi} = -nf_E = \frac{R}{2} = \frac{1}{2C}$

Reduced distance (for distance t in index n) $\tau = \frac{t}{n}$

Power of two surfaces (or elements) separated by distance t in medium of index n

$$\phi = \phi_1 + \phi_2 - \tau\, \phi_1 \phi_2$$

Thick lenses (Greivenkamp notation)



Optical power of first surface $\phi_1 = (n-1)C_1$

Optical power of second surface $\phi_2 = -(n-1)C_2$

Optical power of lens $\phi = \phi_1 + \phi_2 - \tau\phi_1\phi_2 = (n-1)\left[C_1 - C_2 + (n-1)\tau C_1 C_2\right]$

Distance from vertex to principal planes $d = \dfrac{\phi_2}{\phi}\tau$ $\quad d' = -\dfrac{\phi_1}{\phi}\tau$

Focal distances & principal plane distances BFD = $f_R' + d'$ FFD = $f_F + d$

Paraxial optics

Considers rays propagating close to the optical axis at small angles

- Replace actual ray angle U with ray slope $u = \tan(U)$
- Curved surfaces become planes (but still have optical power)
- Entire surface is located at surface vertex

Cardinal points (planes)

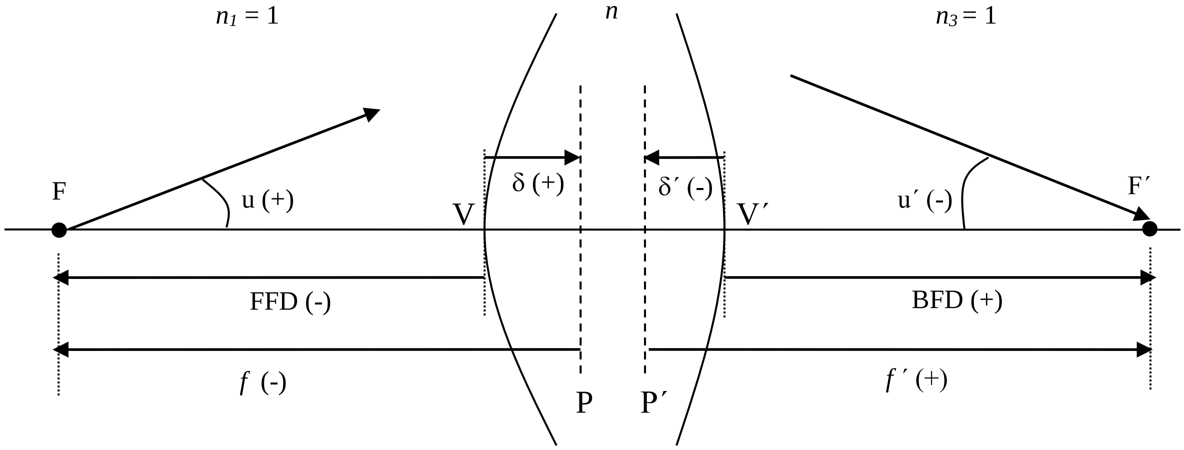
- Focal points (planes)
  Front focal point is located at convergence of initially parallel rays from ∞
  Rear focal point is located at convergence of initially parallel rays from - ∞
- Principal points (planes) … $m = 1$
  (rays can be modeled as bending only at the principal planes)
- Nodal points (planes) … N, N' … angular magnification = 1
  (a ray passing through N at some angle leaves N' at the same angle)

For object and image spaces both in air, nodal points are located at principal points.

For object or image space indices different from air, the distance of the nodal points from the principal planes are:

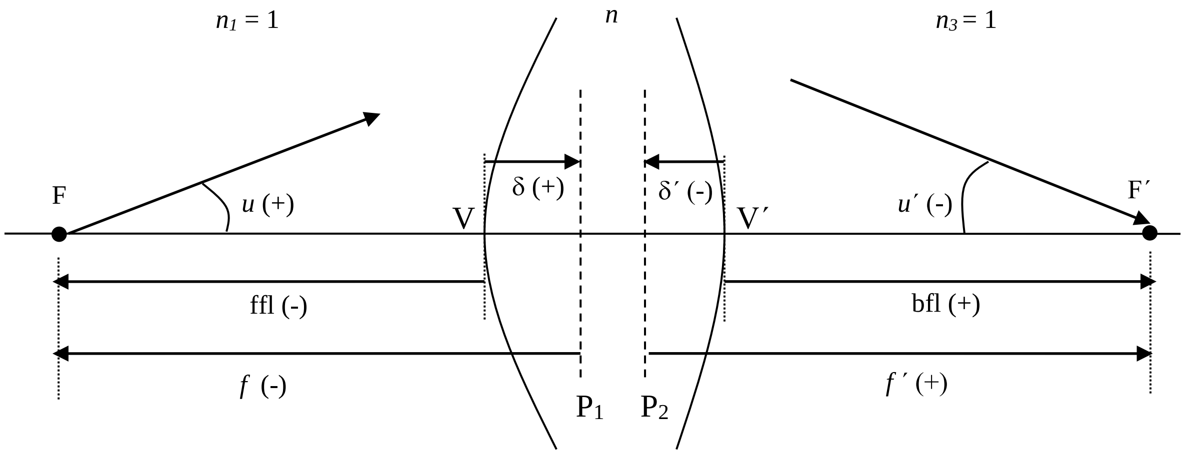
$$z_{PN} = z'_{PN} = f_F + f'_R = (n' - n) f_E$$

Joseph Geary (*Introduction to Lens Design*)



Geary uses notation very similar to the Greivenkamp and Zemax conventions.

Warren Smith (*Modern Optical Engineering* and *Practical Optical System Layout*)



Smith uses front focal length (ffl) in place of FFD and back focal length (bfl) in place of BFD and focal lengths f and f' in place of the front and rear focal lengths. He represents the effective focal length as efl = f_E.

<u>F-numbers</u>

Image-space F/# = $\dfrac{\text{EFL}}{\text{EPD}} = \dfrac{f_e}{D_{ep}}$ used primarily at infinite conjugates

Paraxial working F/# = $\dfrac{1}{2n'\tan(U')}$ (U'= marginal ray angle in image space)

Working F/# = $\dfrac{1}{2n'\sin(U')}$ (applies to real, aberrated systems, where U' departs from the ideal unaberrated path) … used at finite conjugates

<u>Numerical aperture</u>

NA = $n\sin(U)$ (U = marginal ray angle in space under consideration)

NA = $\dfrac{1}{2(\text{working F/\#})}$