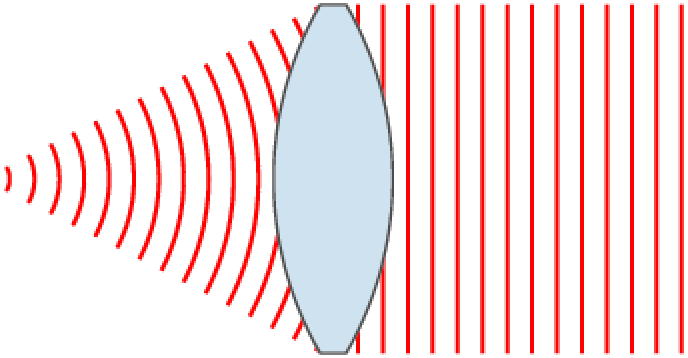
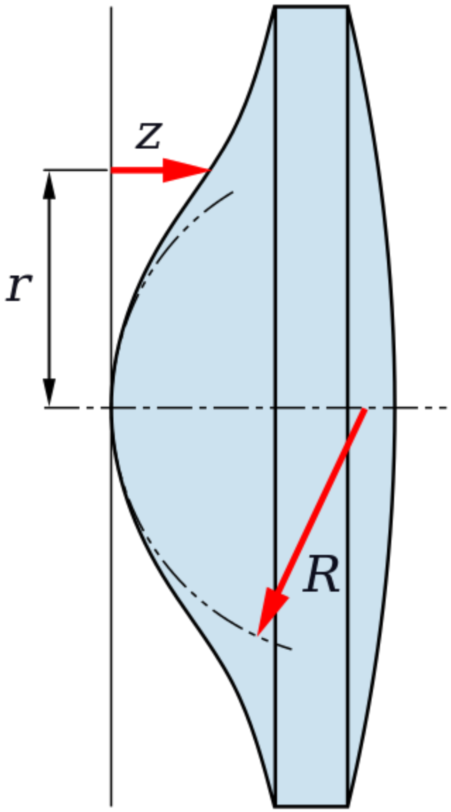
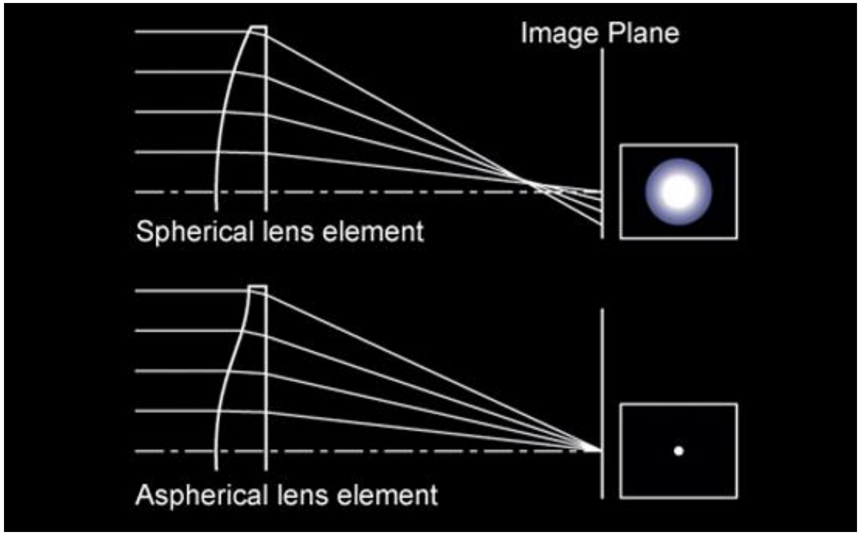
RAY OPTICS

P47 – Optics: Unit 3

Ideal vs Spherical Lenses

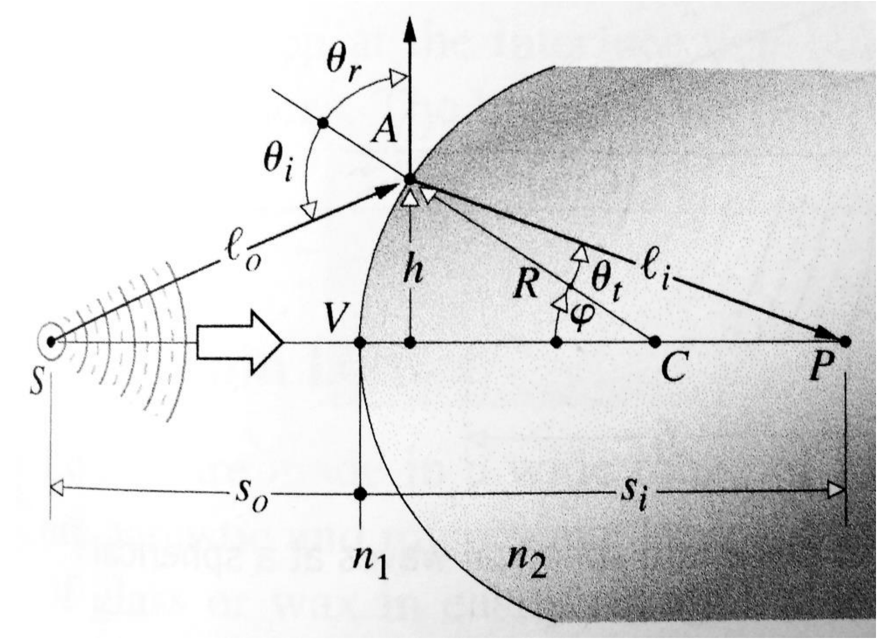




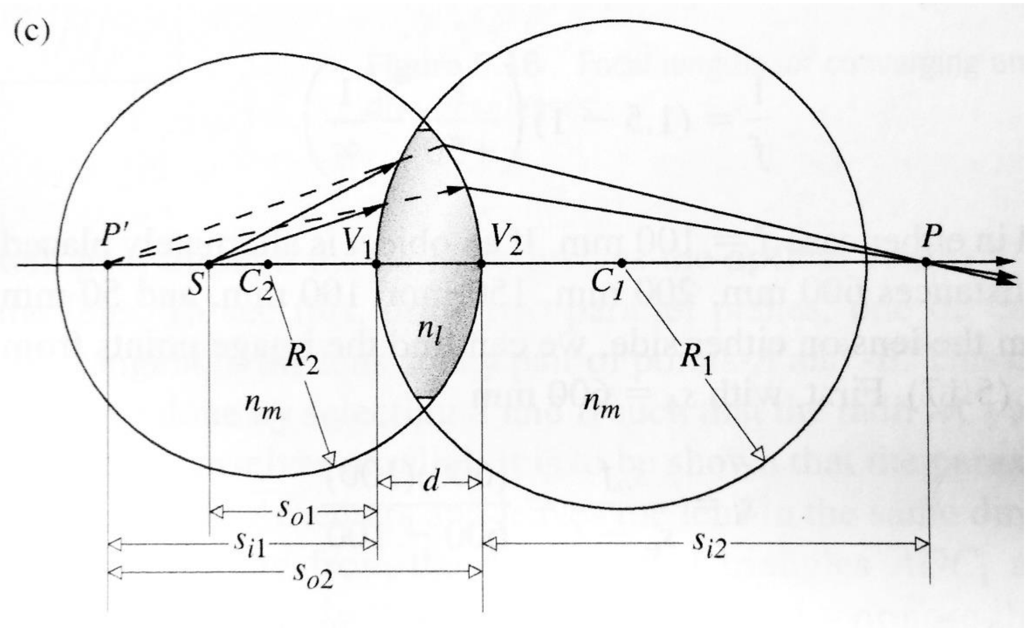


Spherical Lenses

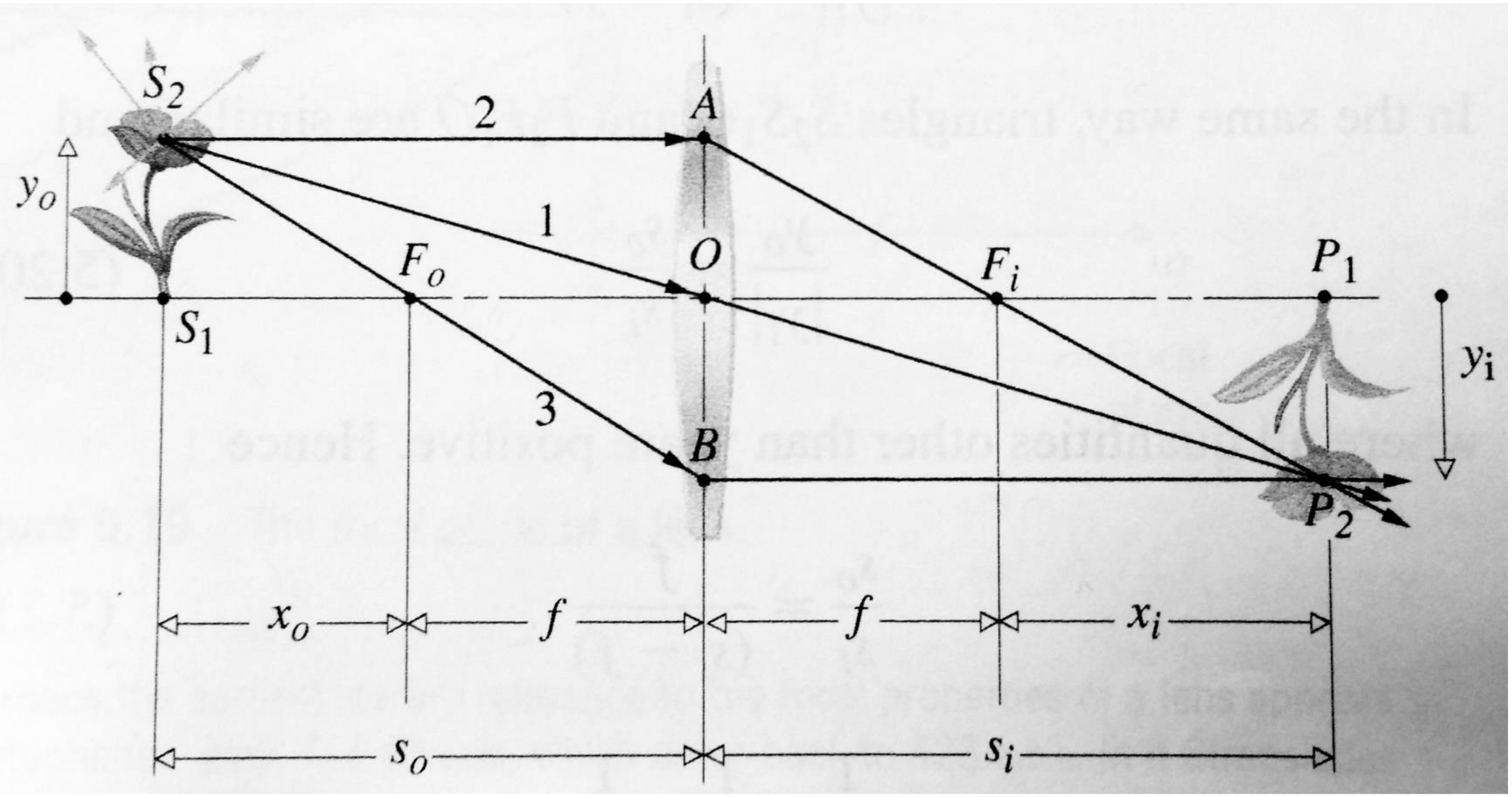
single interface



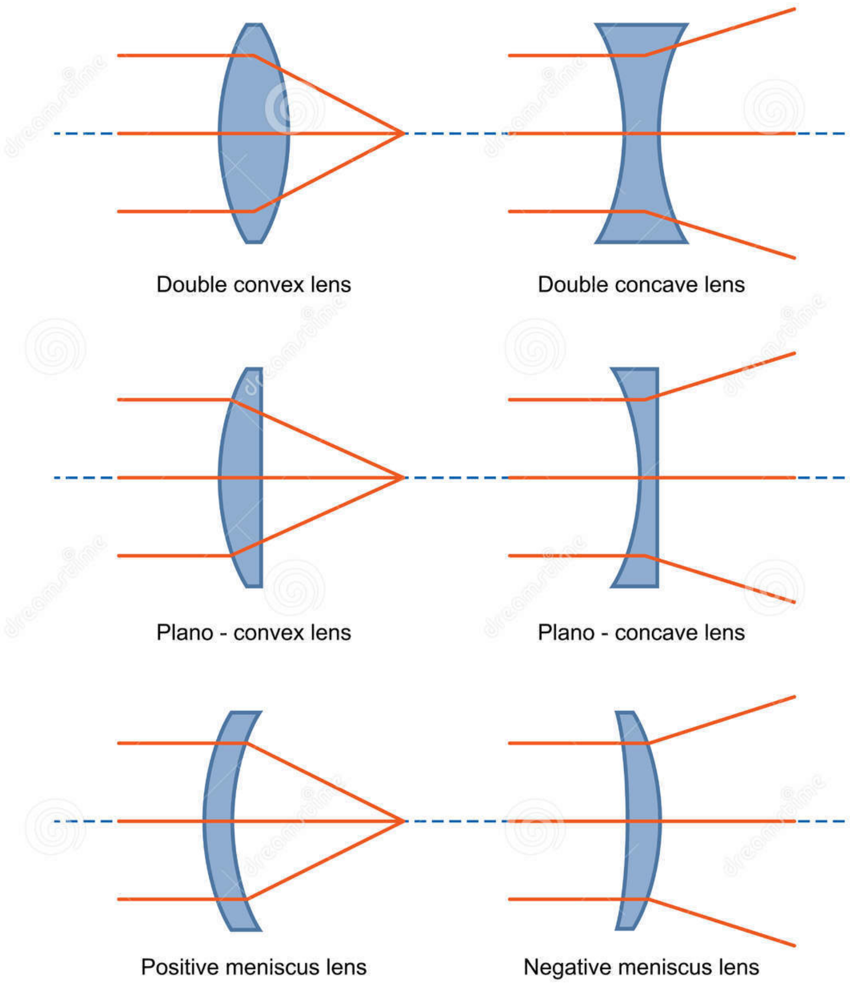
dual interface



Thin Spherical Lenses



Sign Conventions (lens)



CONVEX	CONCAVE
$R_1 > 0$ $R_2 < 0$ Bi-convex	$R_1 < 0$ $R_2 > 0$ Bi-concave
$R_1 = \infty$ $R_2 < 0$ Planar convex	$R_1 = \infty$ $R_2 > 0$ Planar concave
$R_1 > 0$ $R_2 > 0$ Meniscus convex	$R_1 > 0$ $R_2 > 0$ Meniscus concave

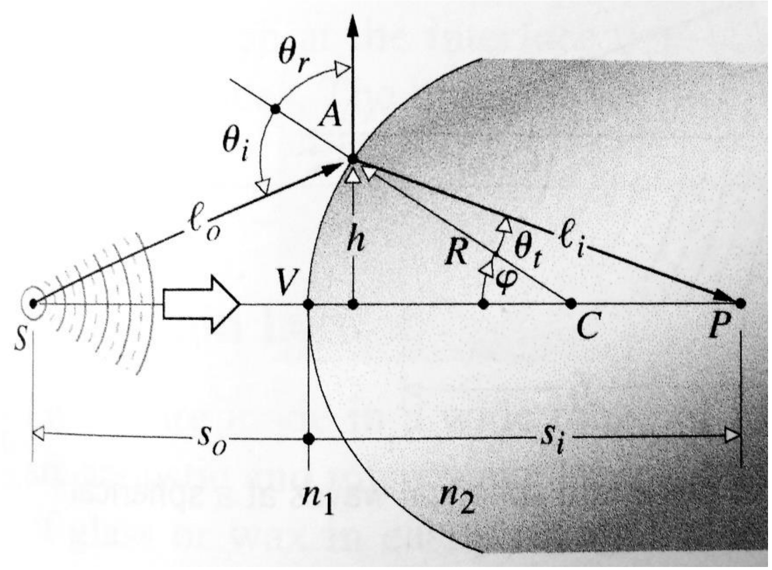
Mirrors:

Concave (R < 0) ; Convex (R > 0)

Sign Conventions (lens)

TABLE 5.1 Sign Convention for Spherical Refracting Surfaces and Thin Lenses* (Light Entering from the Left)

s_o, f_o	+ left of V
x_o	+ left of F_o
s_i, f_i	+ right of V
x_i	+ right of F_i
R	+ if C is right of V
y_o, y_i	+ above optical axis



Sign Conventions (real vs virtual)

Lenses

TABLE 5.2 Meanings Associated with the Signs of Various Thin Lens and Spherical Interface Parameters

Quantity	Sign +	Sign −
s_o	Real object	Virtual object
s_i	Real image	Virtual image
f	Converging lens	Diverging lens
y_o	Erect object	Inverted object
y_i	Erect image	Inverted image
M_T	Erect image	Inverted image

Mirrors

TABLE 5.4 Sign Convention for Spherical Mirrors

Quantity	Sign +	Sign −
s_o	Left of V, real object	Right of V, virtual object
s_i	Left of V, real image	Right of V, virtual image
f	Concave mirror	Convex mirror
R	C right of V, convex	C left of V, concave
y_o	Above axis, erect object	Below axis, inverted object
y_i	Above axis, erect image	Below axis, inverted image

Real vs Virtual & Magnification

Lenses

TABLE 5.3 Images of Real Objects Formed by Thin Lenses

Convex

Object Location	Image Type	Image Location	Image Orientation	Image Relative Size
$\infty > s_o > 2f$	Real	$f < s_i < 2f$	Inverted	Minified
$s_o = 2f$	Real	$s_i = 2f$	Inverted	Same size
$f < s_o < 2f$	Real	$\infty > s_i > 2f$	Inverted	Magnified
$s_o = f$		$\pm\infty$		
$s_o < f$	Virtual	$\lvert s_i \rvert > s_o$	Erect	Magnified

Concave

Object Location	Image Type	Image Location	Image Orientation	Image Relative Size
Anywhere	Virtual	$\lvert s_i \rvert < \lvert f \rvert$, $s_o > \lvert s_i \rvert$	Erect	Minified

Mirrors

Table 5.5 Images of Real Objects Formed by Spherical Mirrors

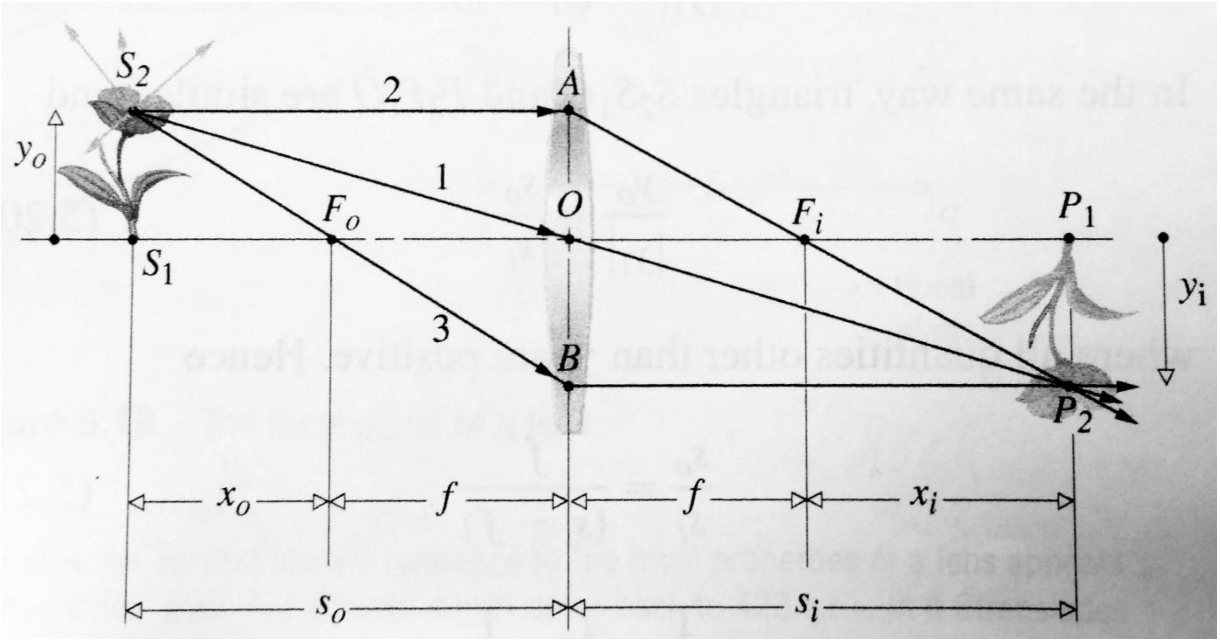
Concave

Object Location	Image Type	Image Location	Image Orientation	Image Relative Size
$\infty > s_o > 2f$	Real	$f < s_i < 2f$	Inverted	Minified
$s_o = 2f$	Real	$s_i = 2f$	Inverted	Same size
$f < s_o < 2f$	Real	$\infty > s_i > 2f$	Inverted	Magnified
$s_o = f$		$\pm\infty$		
$s_o < f$	Virtual	$\lvert s_i \rvert > s_o$	Erect	Magnified

Convex

Object Location	Image Type	Image Location	Image Orientation	Image Relative Size
Anywhere	Virtual	$\lvert s_i \rvert < \lvert f \rvert$, $s_o > \lvert s_i \rvert$	Erect	Minified

Magnification



$\updownarrow$ Transverse Magnification: $M_T = \boxed{\frac{y_i}{y_o} = \frac{-s_i}{s_o}} = \frac{-x_i}{f} = \frac{-f}{x_o}$

$\longleftrightarrow$ Longitudinal Magnification: $M_L = \frac{dx_i}{dx_o} = \frac{-f^2}{x_o^2} = -M_T^2$

Lens Characteristics

1) Focal Length
2) Shape (Aberration)
3) Diameter (Aperture)
4) Material (Dispersion)

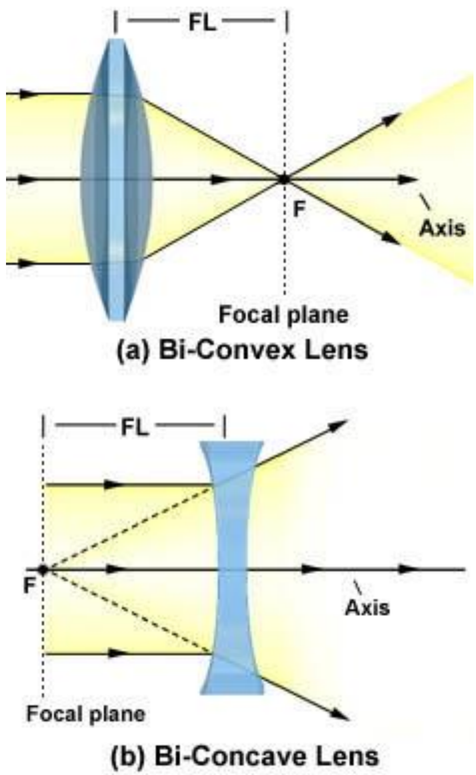
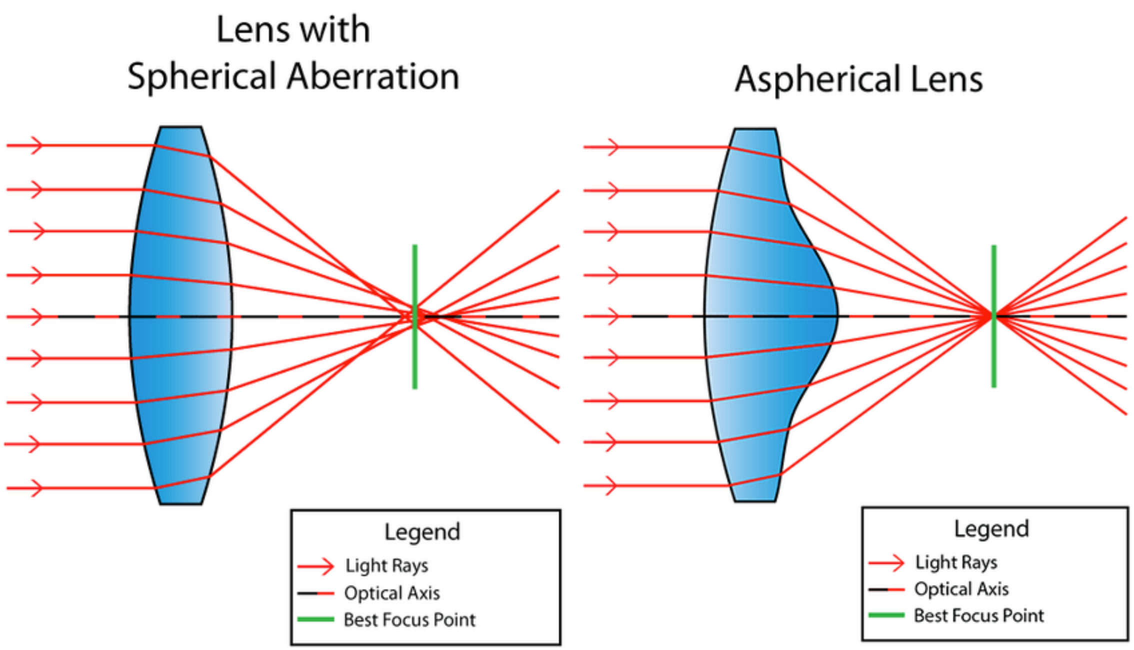
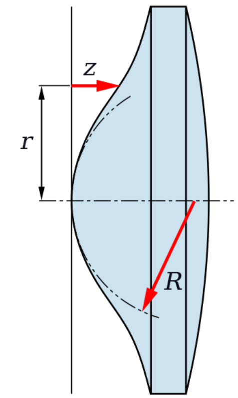
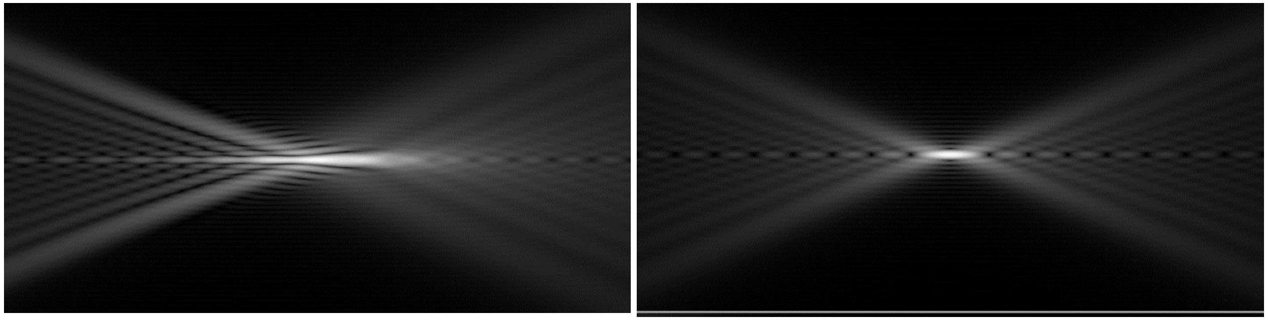


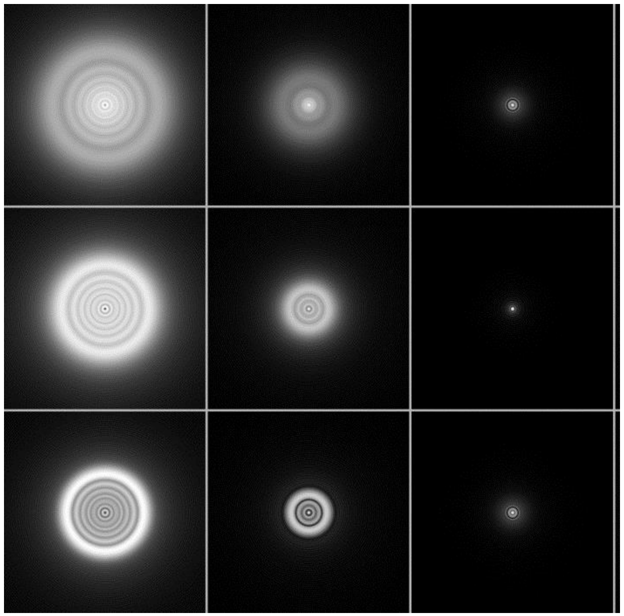
Figure 1

Lens Characteristics: Spherical Aberration



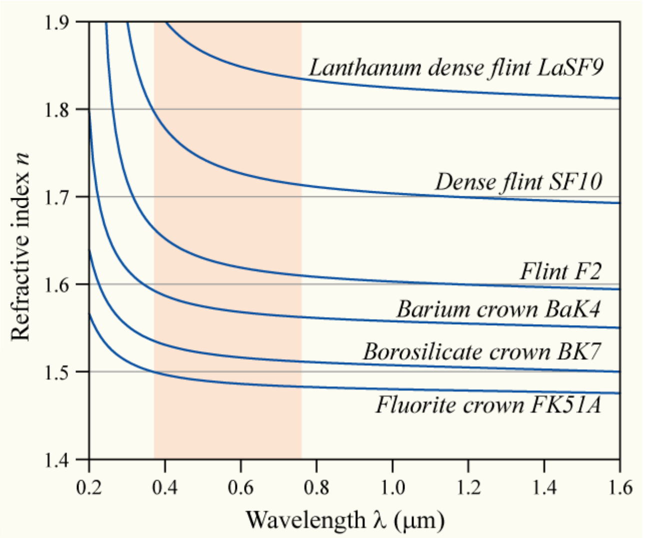


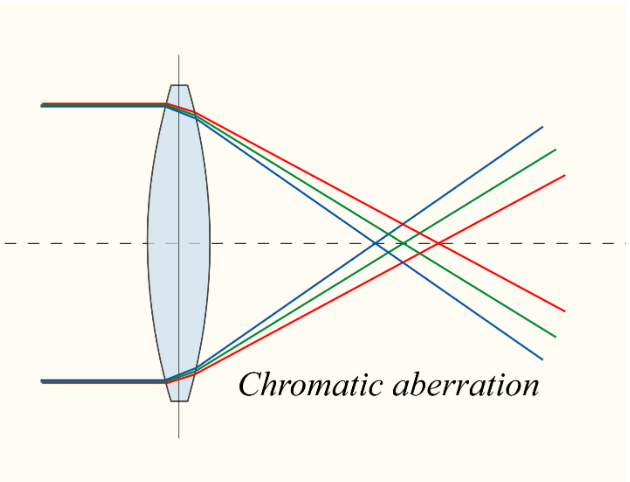


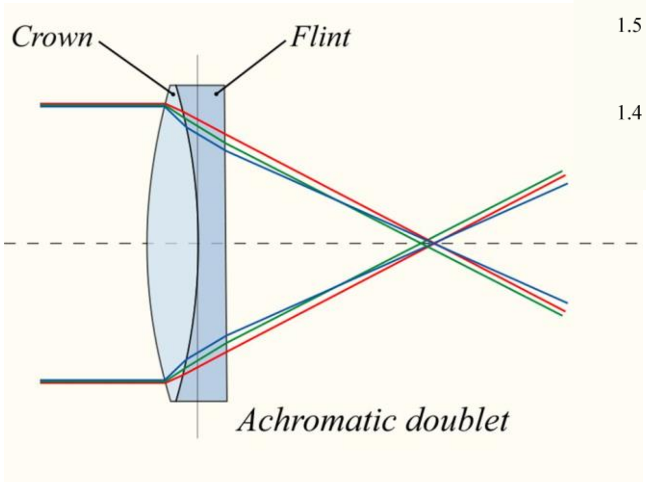


Lens Characteristics: Chromatic Aberration

$$n^2(\omega) = 1 + \frac{Nq_e^2}{\epsilon_0 m_e}\left(\frac{1}{\omega_0^2 - \omega^2}\right)$$

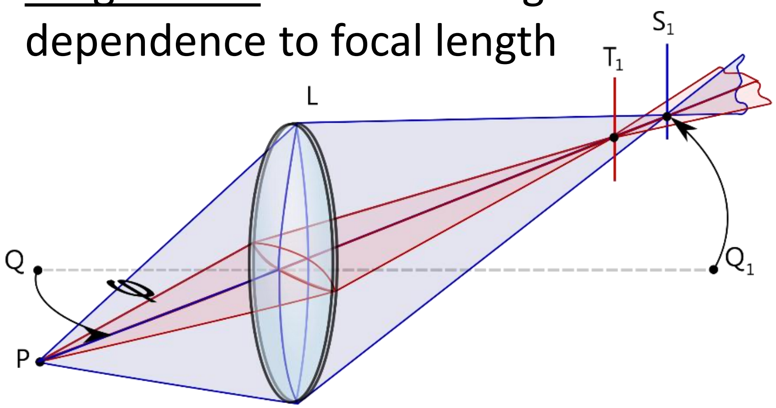


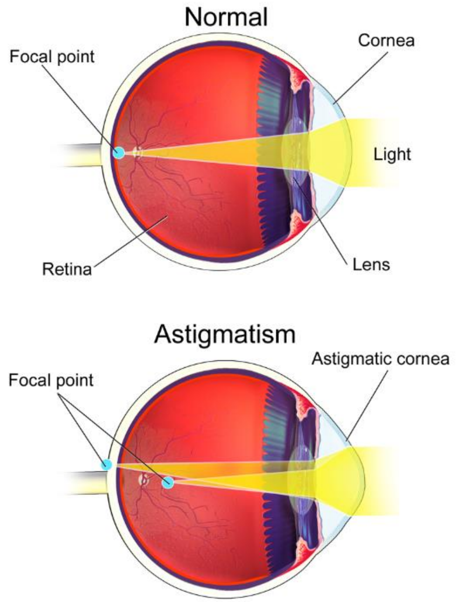


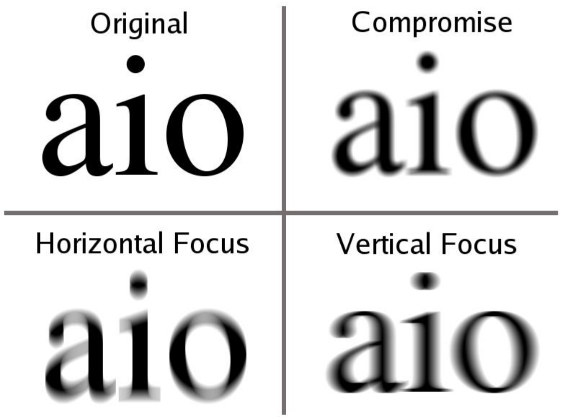


Lens Characteristics: Other Aberrations

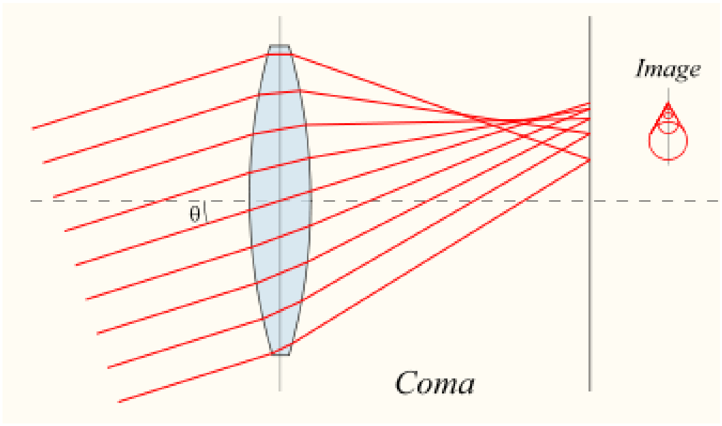
astigmatism – lens has angular dependence to focal length

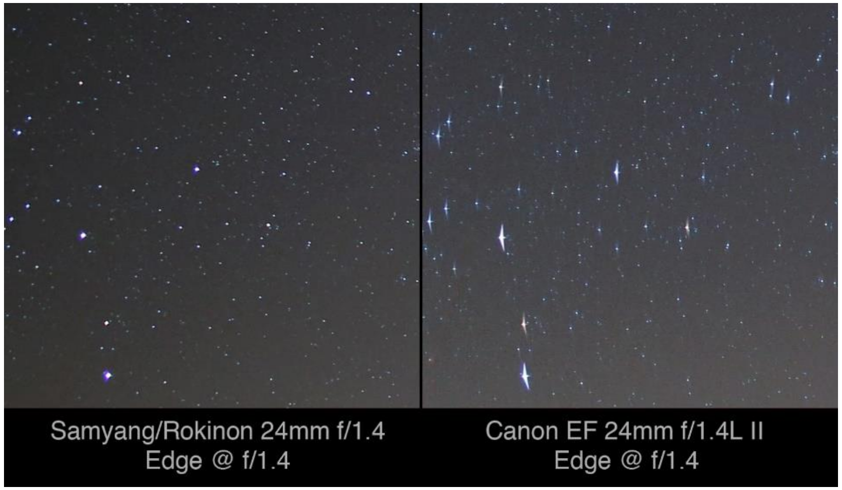






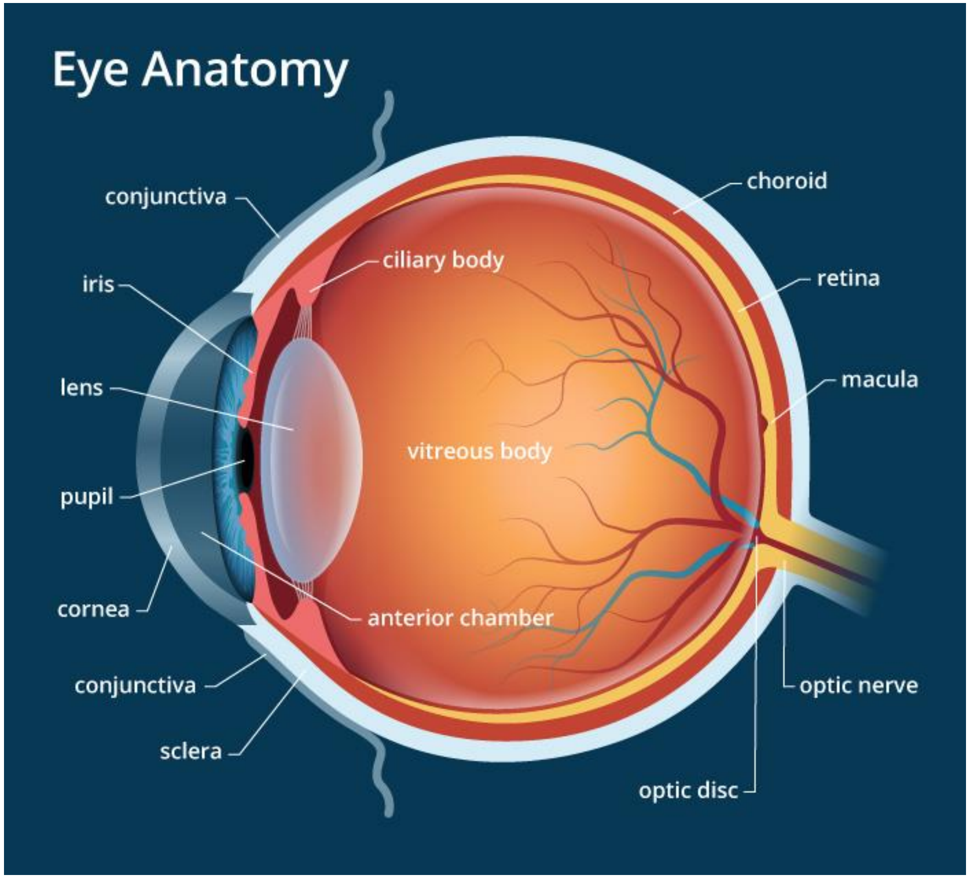
coma – lens has radial dependence to magnification

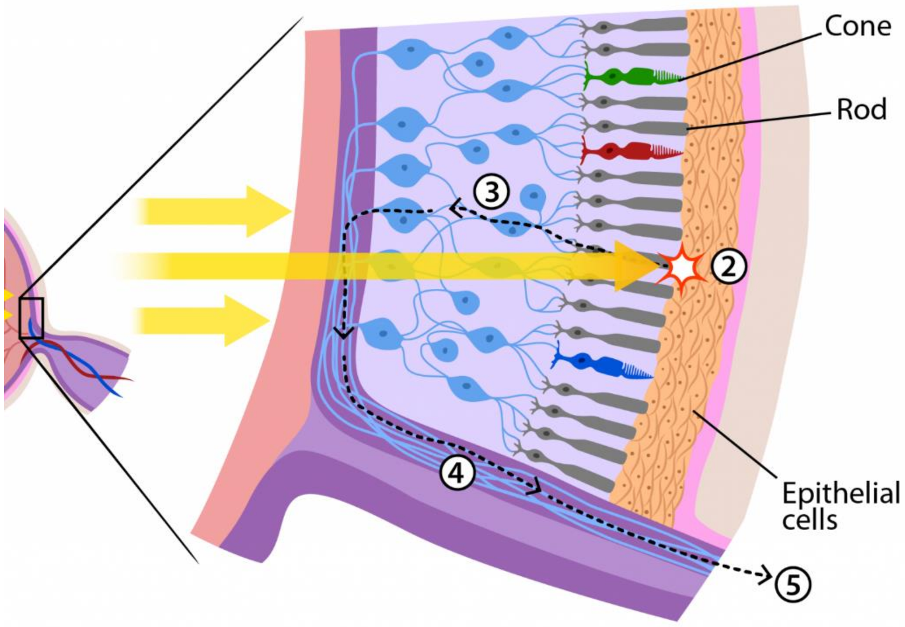




credit: Royce Bair

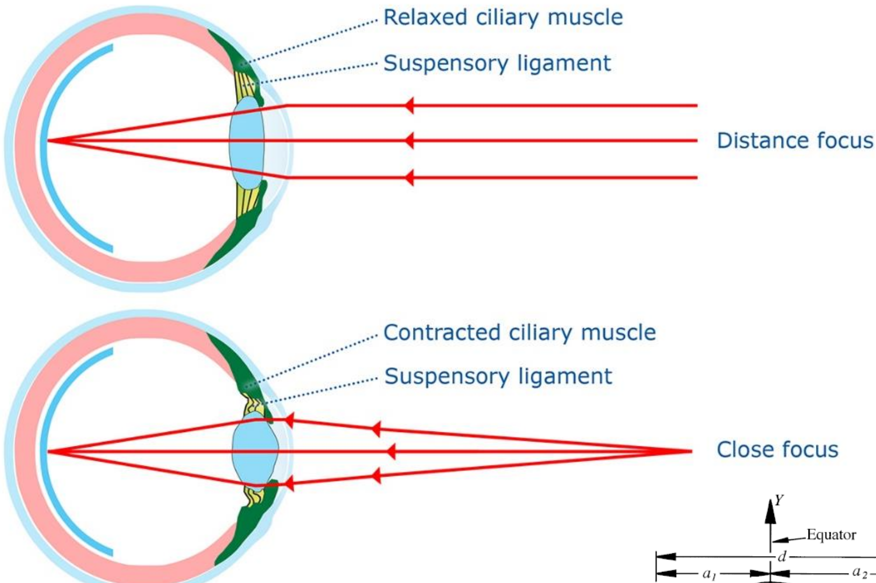
Human Eye

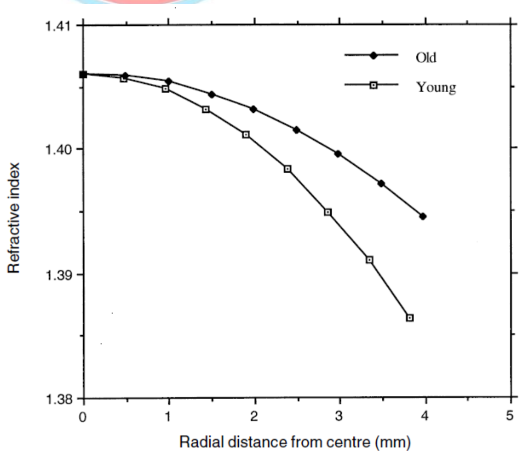

Eye Anatomy
conjunctiva
iris
lens
pupil
cornea
conjunctiva
sclera
ciliary body
vitreous body
anterior chamber
choroid
retina
macula
optic nerve
optic disc

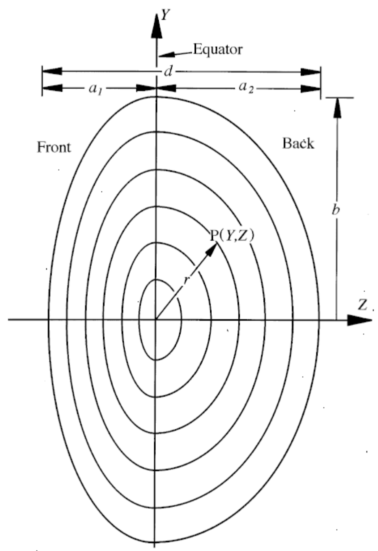

Cone
Rod
Epithelial cells
3
2
4
5

Human Eye – Accommodation

Normal Lens

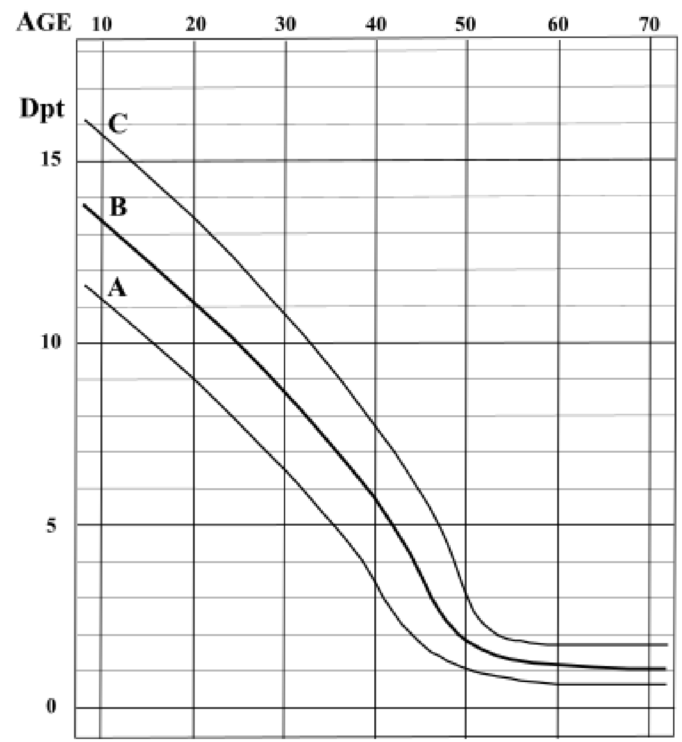






Aging Lens (presbyopia)

Accommodation Amplitude (Dpt) vs. Age



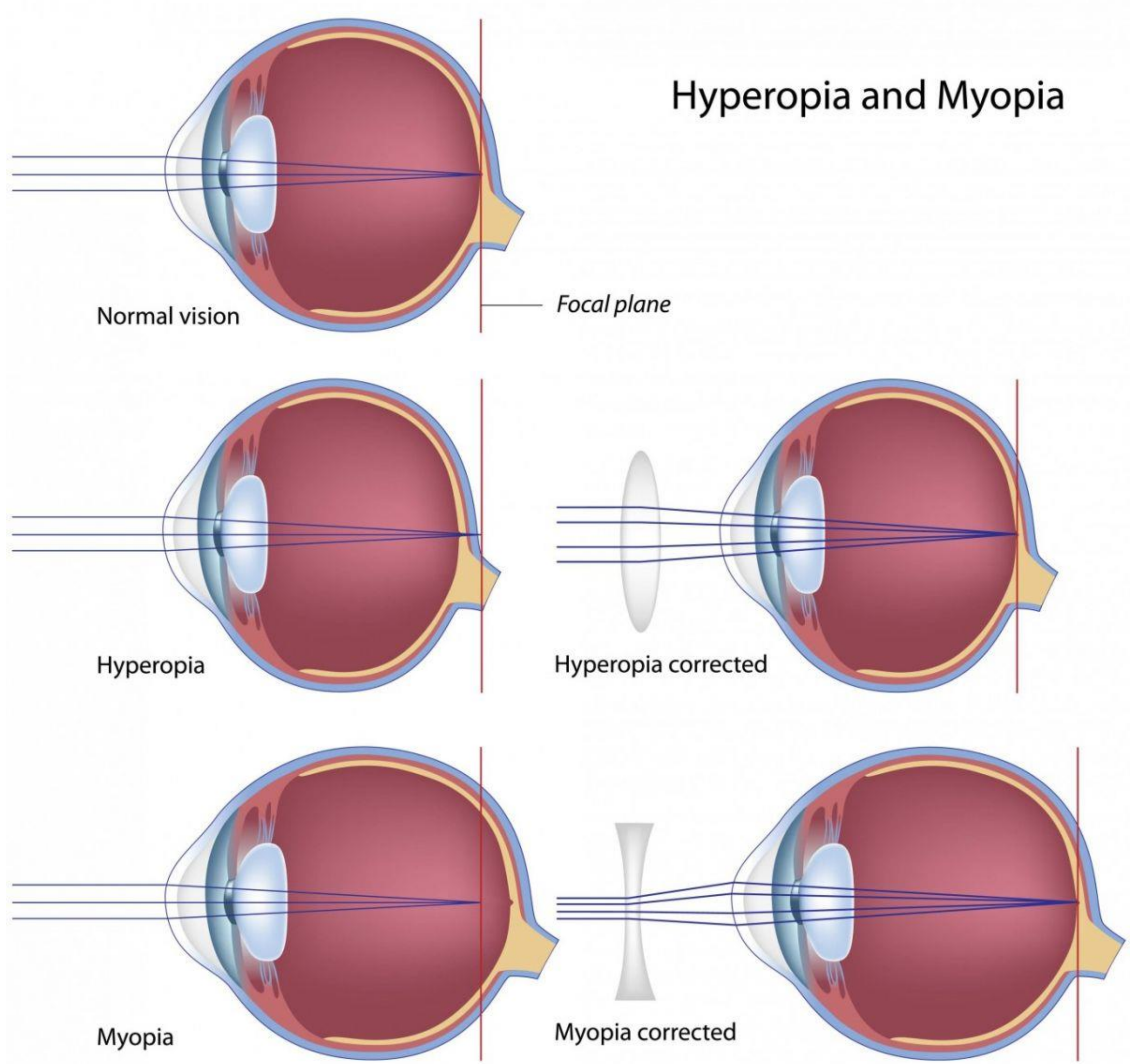
Garner et.al. Clinical and Experimental Optometry **81.4** 1998

Duane A, Am J Ophthalmol 5:865, 1922

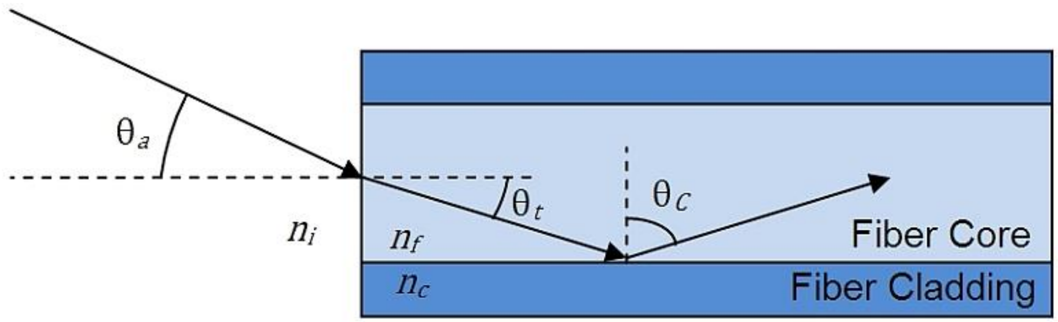
Human Eye – Near vs Far Sighted

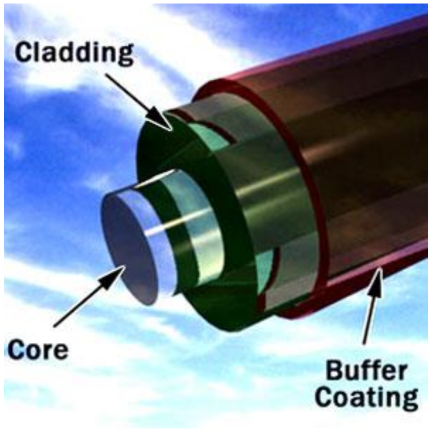
(nearsighted)

(farsighted)



Fiber Optics





$$\sin\,\theta_c = n_c/n_f = \sin\,(90° - \theta_t)$$

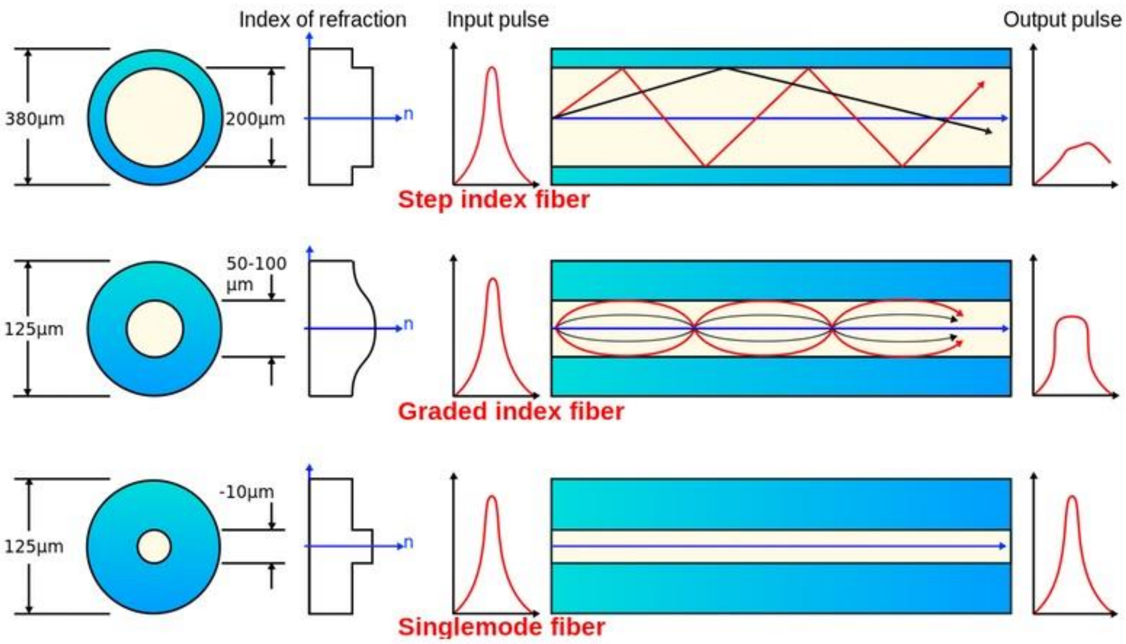
$$n_c/n_f = \cos\,\theta_t$$

$$n_c/n_f = (1 - \sin^2\,\theta_t)^{1/2}$$

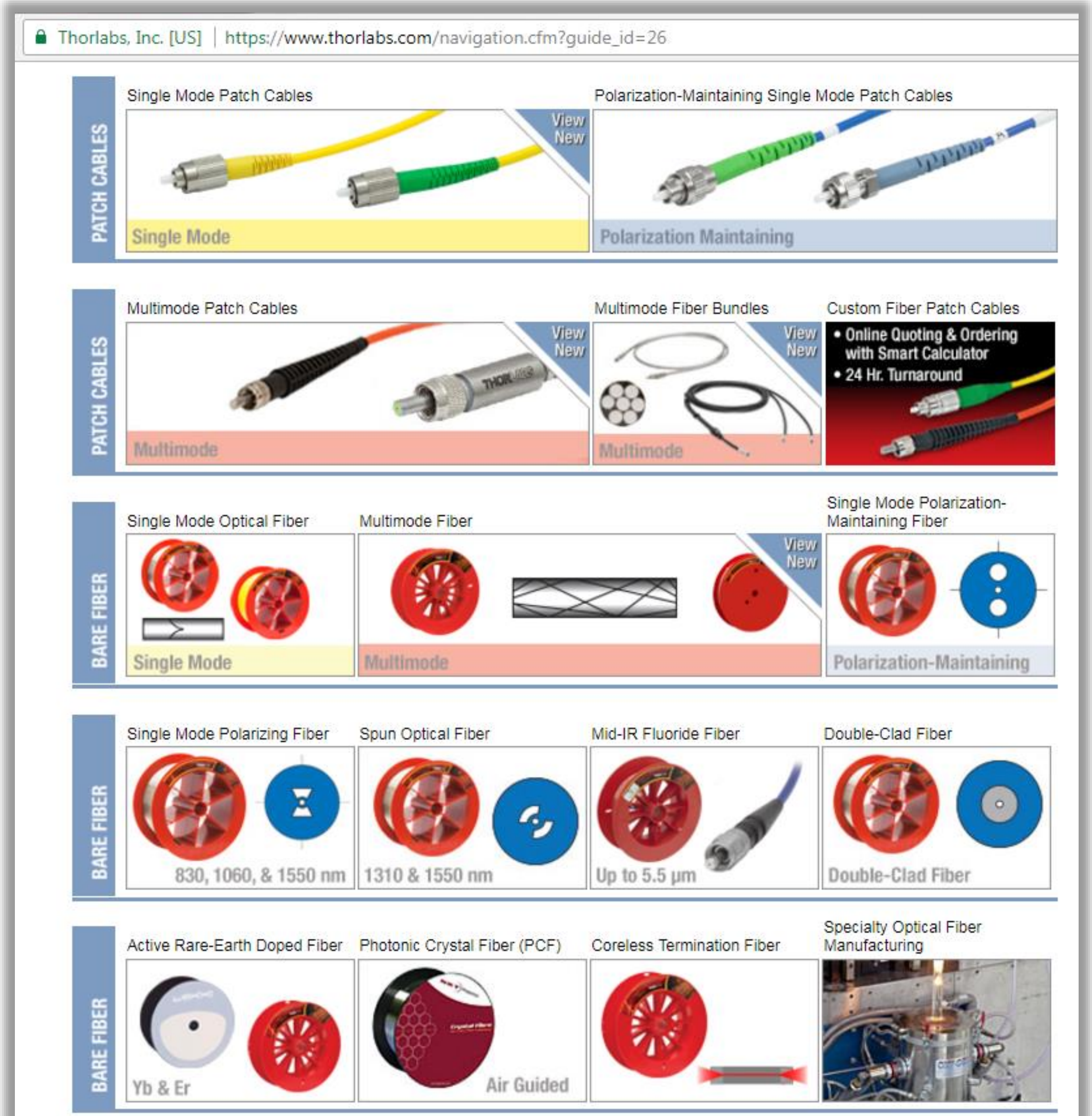
$$\sin\,\theta_{\max} = \frac{1}{n_i}(n_f^2 - n_c^2)^{1/2}$$

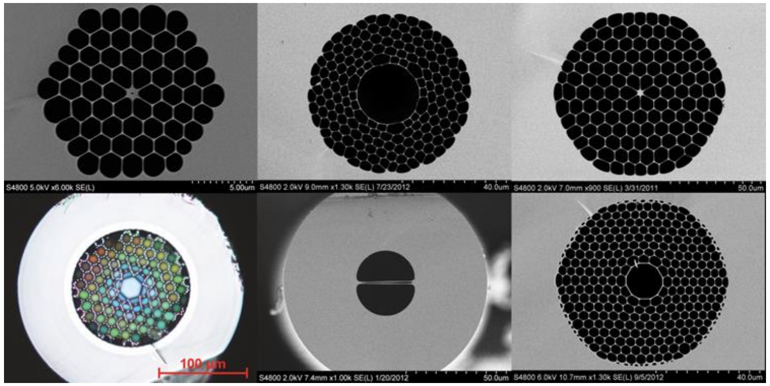
$$\mathrm{NA} = n_i \sin\,\theta_{\max}$$

$$\mathrm{NA} = (n_f^2 - n_c^2)^{1/2}$$

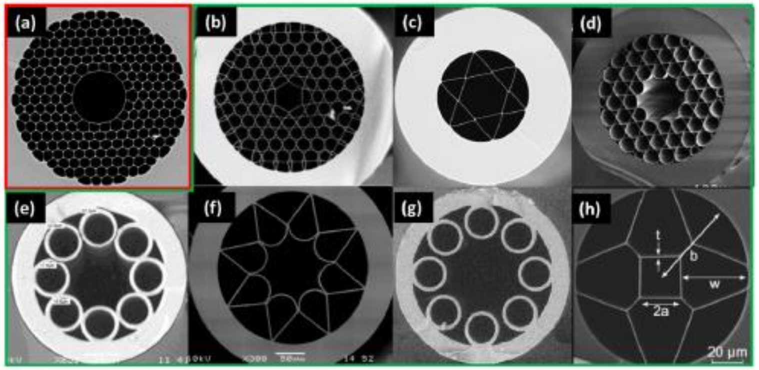


Fiber Optics





credit: Michael Frosz group, Max Planck Institute



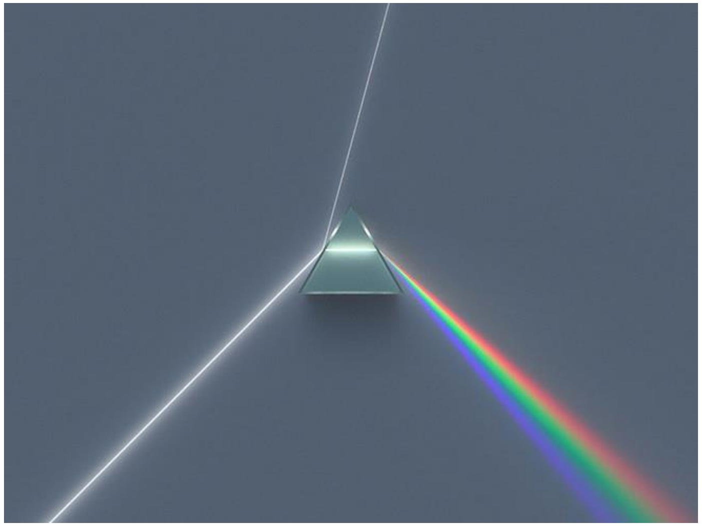
F. Poletti, Optics Express, **22**, 20, 23807 (2014)

Prisms

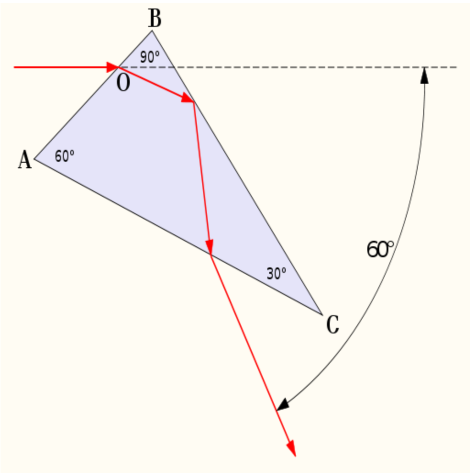
- Before Newton, was thought that light was colorless and presumed the colored light was generated by the prism

- Showed this was not true in two ways:
  1. use a second prism to disperse the red rays → only red transmitted
  2. use a second prism to recollect the dispersed output of the first → white light recovered

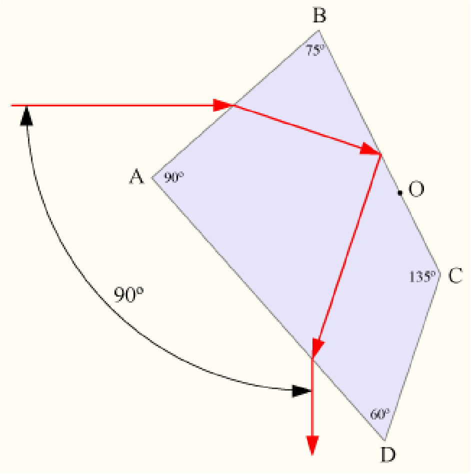
- Three main types of prisms:
  1. Dispersive
  2. Reflecting / Deflecting
  3. Polarizing



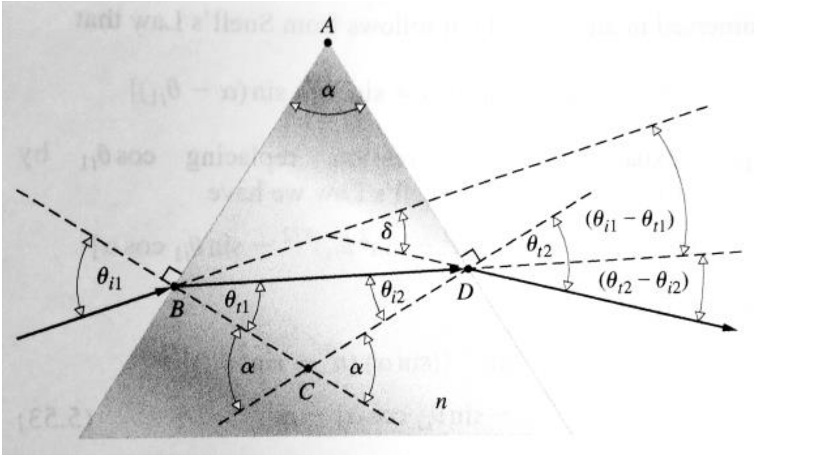
Prisms – Dispersive



Abbe Prism: wavelength selective, only one frequency transmitted at 60° deviation



Pellin-Broca Prism: same as Abbe prism, but transmitted at 90° deviation

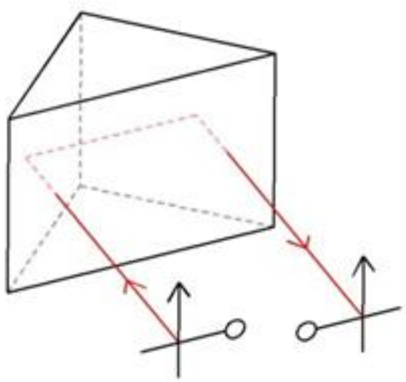


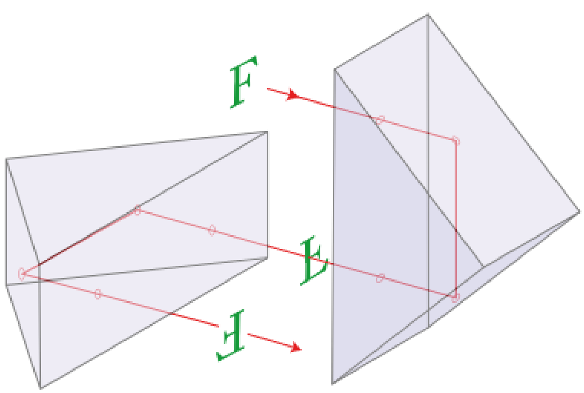
Triangular Prism: Easily used to determine index of refraction for new materials – just make a prism out of the material!

$$n = \frac{\sin[(\delta_m + \alpha)/2]}{\sin \alpha/2}$$

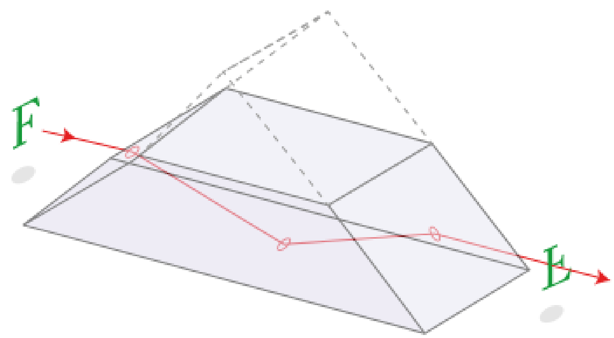
Prisms – Reflective/Deflective

Porro Prism: Uses TIR to rotate image by 180°. Double Porro elements used to completely invert image (in telescopes, binoculars).

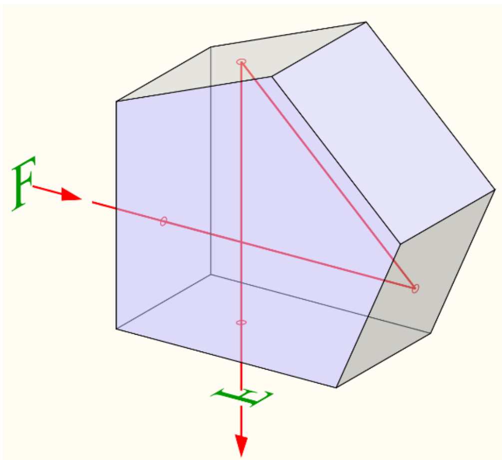




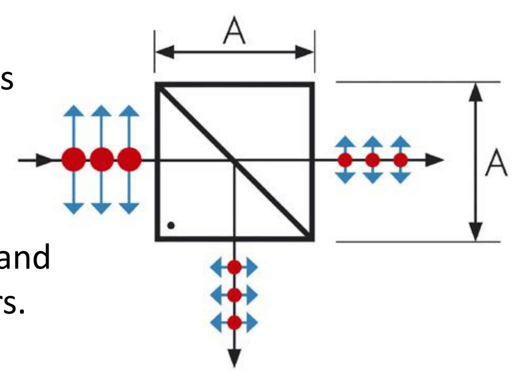
Dove Prism: Flips image without beam deviation. Rotating crystal around beam axis rotates output twice as fast – used as a beam rotator.



Penta Prism: Deviates beam by 90° no matter entrance angle. Does NOT use TIR – reflecting faces silvered!



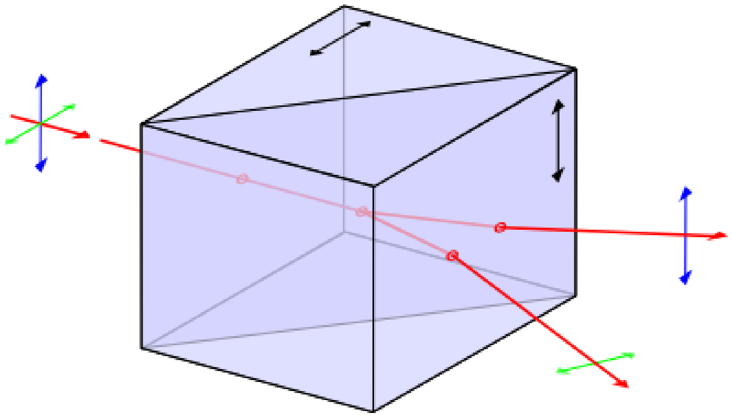
Beam Splitter Cubes: Uses 'frustrated' TIR to split incoming beams into two components. Also have "dichroic" beam splitters and "polarizing" beam splitters.



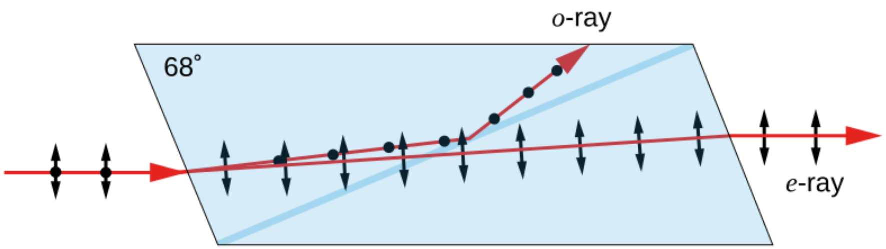
Prisms – Polarizing

- can use Brewster's angle to separate E-field polarization states
- more common to use birefringent crystal
    - different refractive index, *n*, for p- and s-polarizations
- ➢ We'll come back to these when discussing polarization optics!

Wollaston Prism

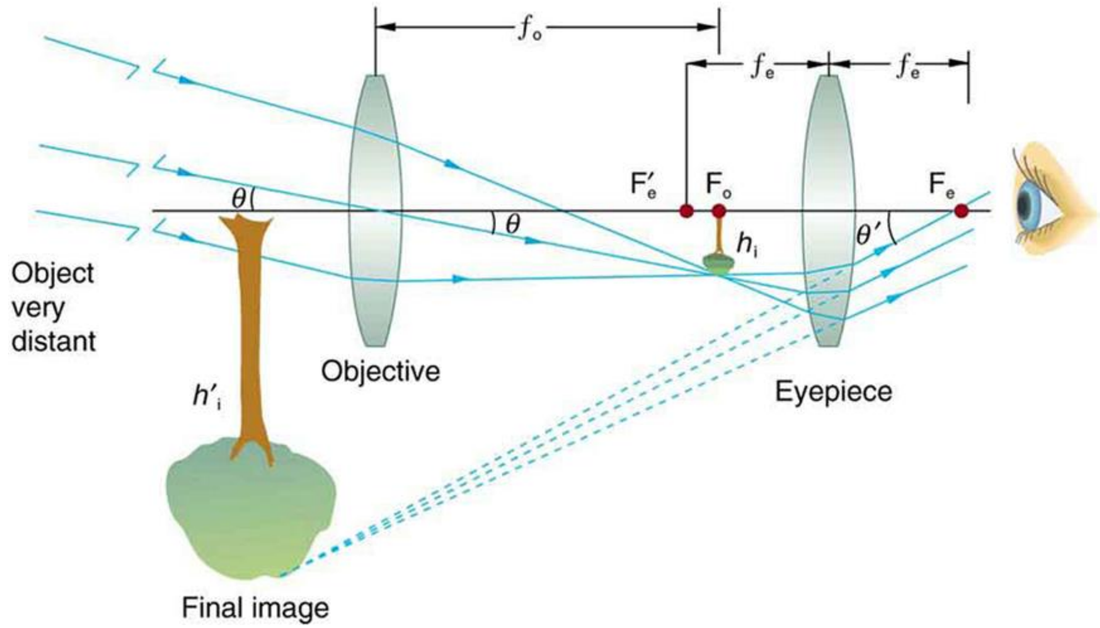


Nicol Prism



Telescopes

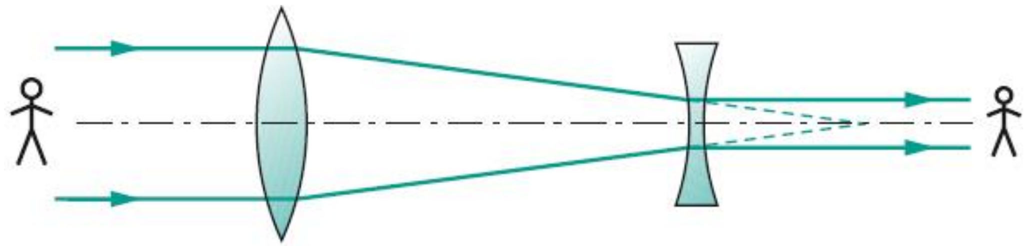
- Object at infinity, first image at f_o
- Increases *angular* magnification $M = \dfrac{\theta'}{\theta} = -\dfrac{f_o}{f_e}$
- Increases apparent brightness of objects (essentially increases diameter of eye)
- Three main types of telescopes:
  1. Refracting (lenses)
  2. Reflecting (mirrors)
  3. Catadioptric (combination lenses/mirrors)



Telescopes – Refracting

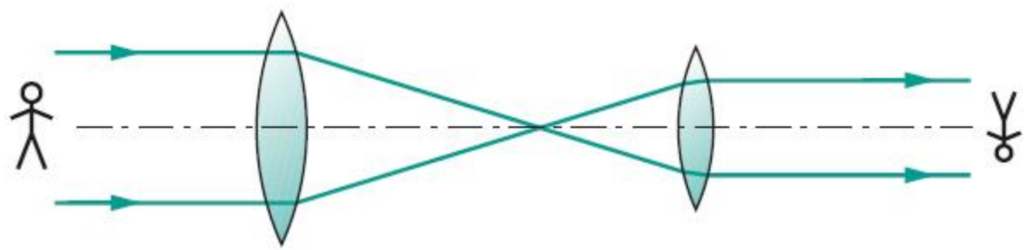
credit: Don Bruns

Galilean Telescope



A

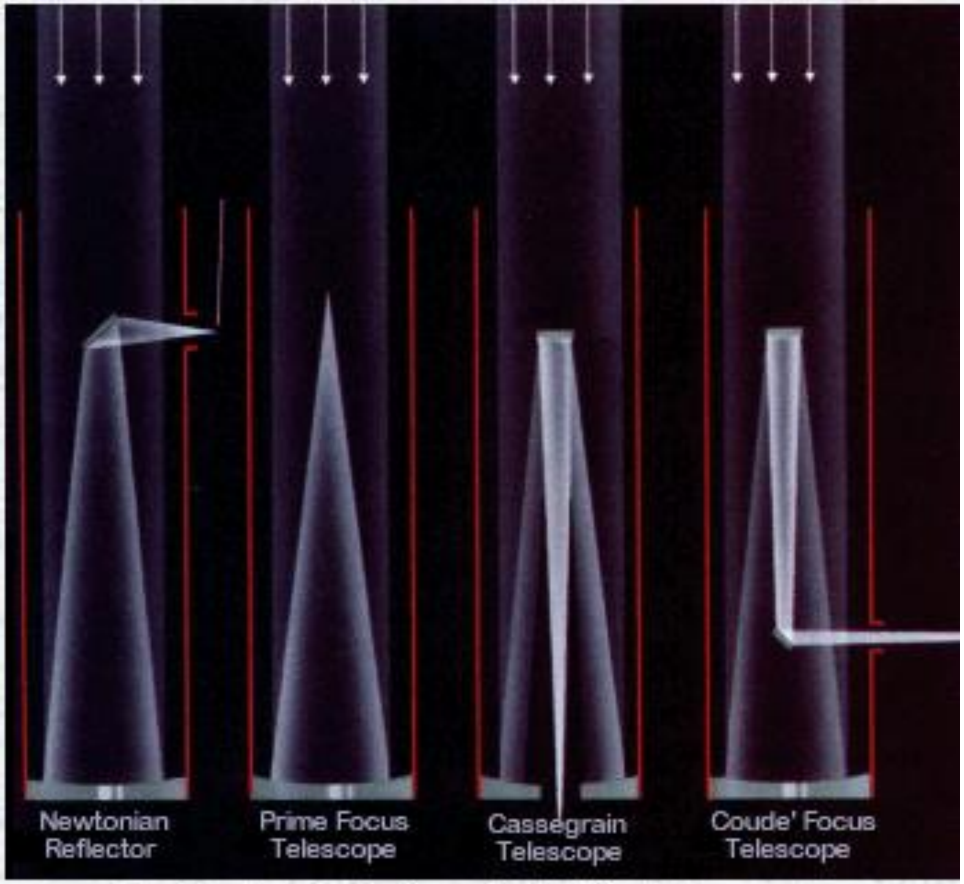
Keplerian Telescope



B

Telescopes – Reflecting

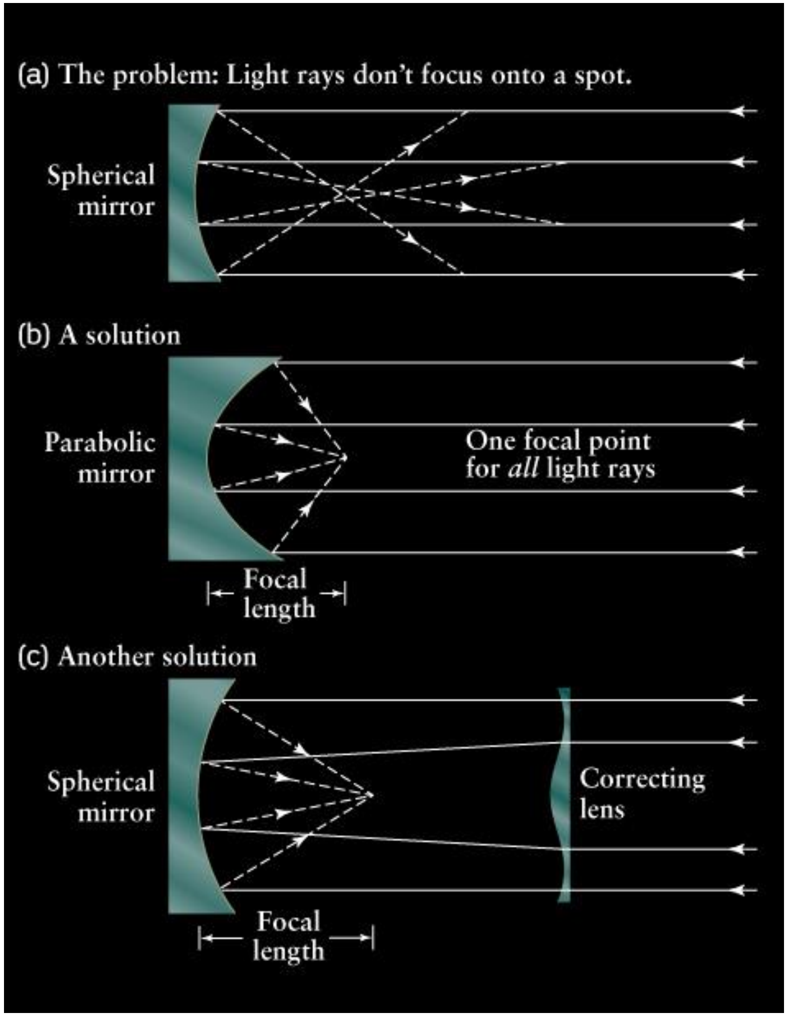
- Much longer focal length gives more angular magnification
- Are *much* more compact than refracting telescope of similar power
- Easier to manufacture large diameter mirrors than lenses
- Mirrors are free of chromatic aberration (Newton's motivation for invention!)



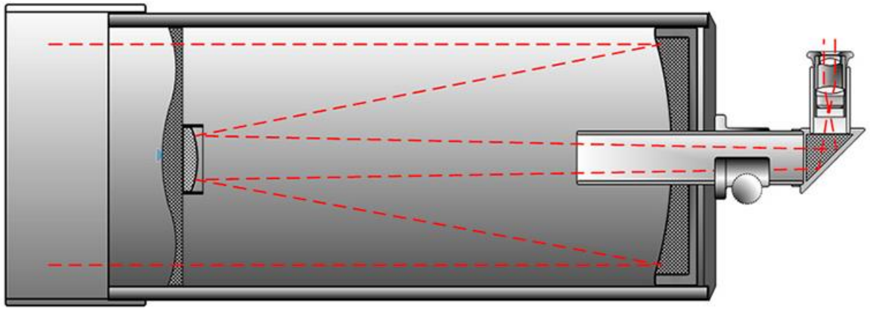
The four basic designs of reflecting telescopes.

Newton's First Reflecting Telescope

Telescopes – Catadioptric



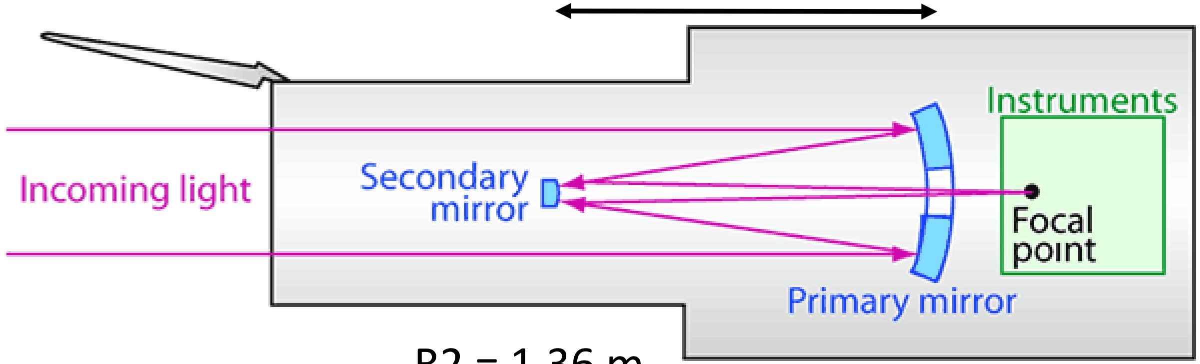
Schmidt-Cassegrain Telescope



credit: Glenn @ sfastro.net

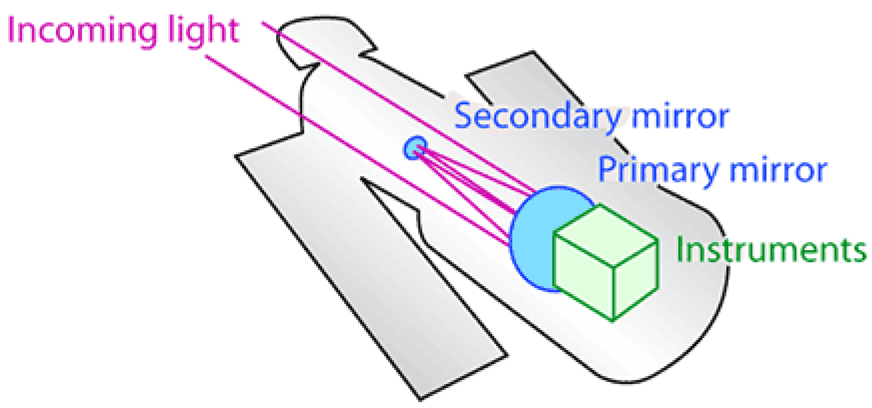
Telescopes – The Hubble

D = 4.9 m

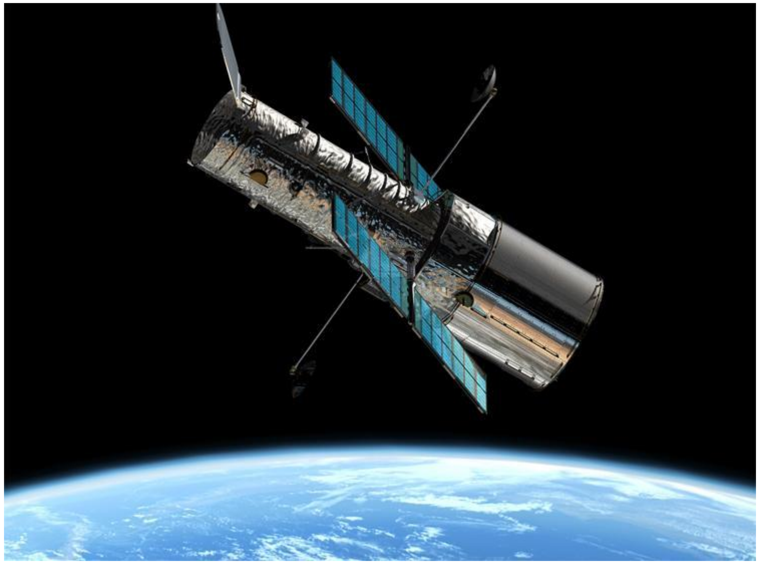


R2 = 1.36 m

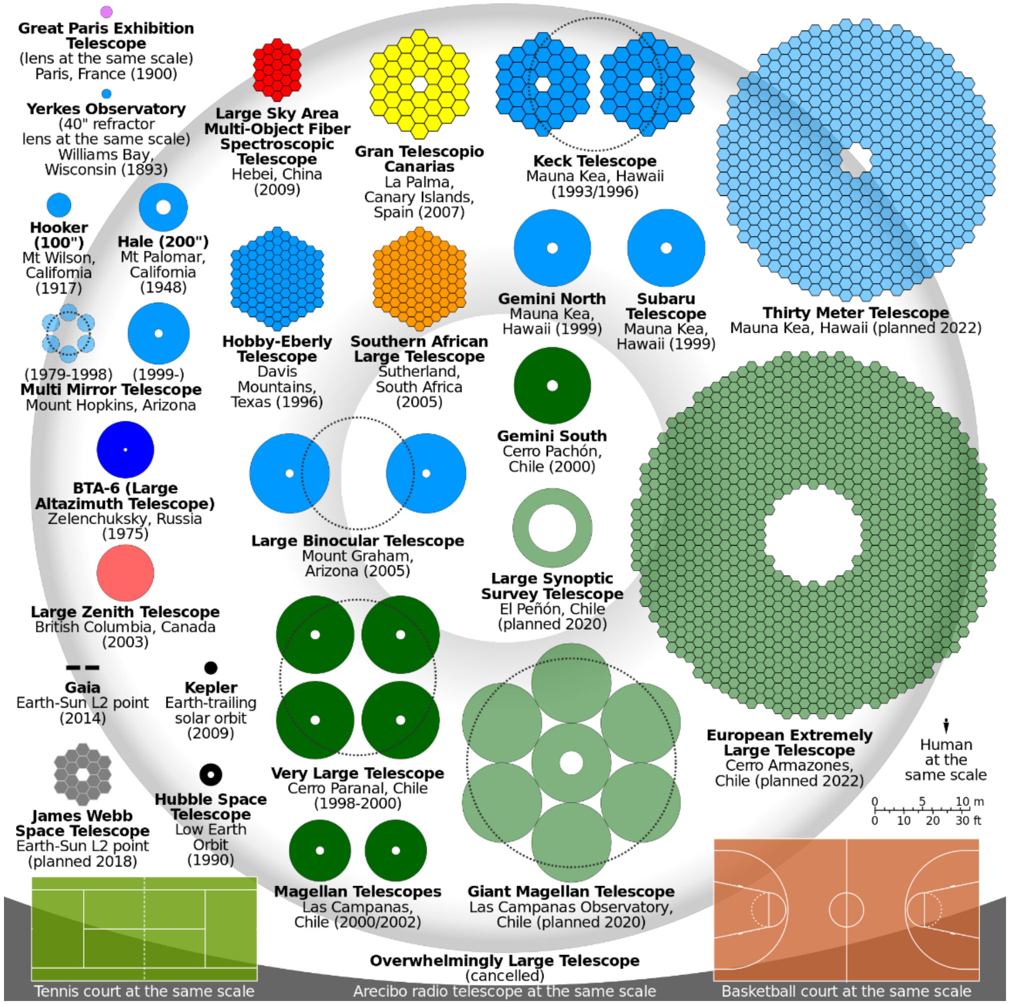
R1 = 11.04 m



Ritchey-Chretien Cassegrain

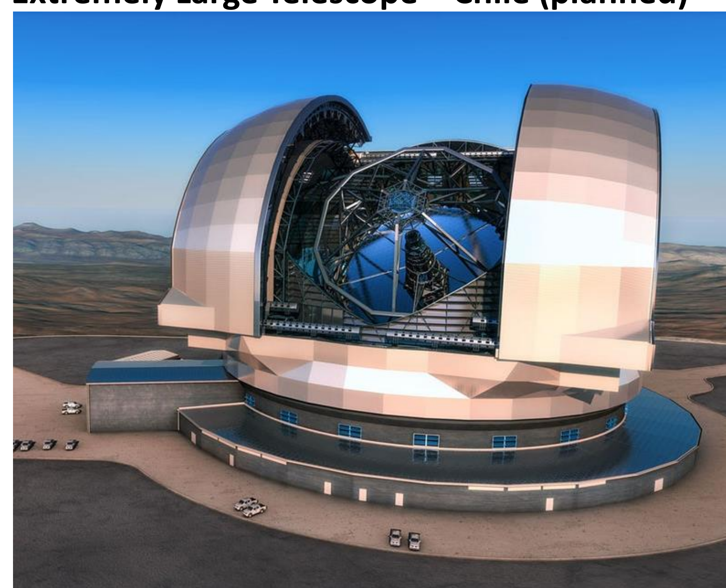


Telescopes – Diameter Comparison



Keck Observatory – Hawaii

Extremely Large Telescope – Chile (planned)



Thick Lenses

- Distance measurements now with respect to **Principal Planes** and **Points** (P_1, P_2 and H_1, H_2)
- Angles measurements now found using **Nodal Points**
- By knowing **Focal Points, Principle Points, and Nodal Points**, can calculate rays for any thick lens system
- These 6 pts are the **Cardinal Points**