Lecture 2

Telescopes

Part 1

- Optics
  - Revision
- Characteristics of a telescope
  - Focal length
  - Plate scale
  - Focal ratio

Refraction

- As a light ray travels from one transparent medium to another, its path is bent at the interface.

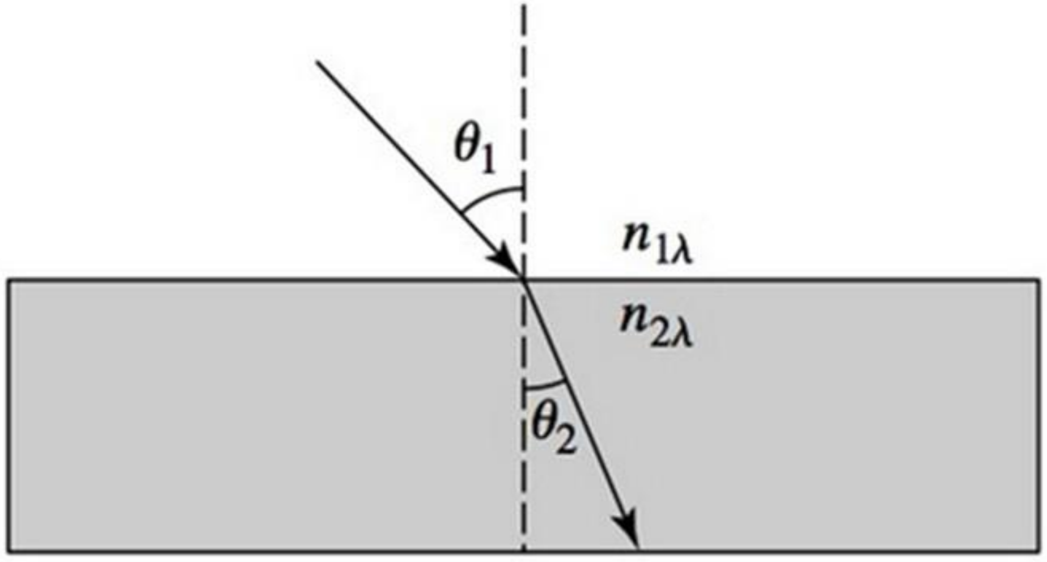


FIGURE 1 Snell's law of refraction.

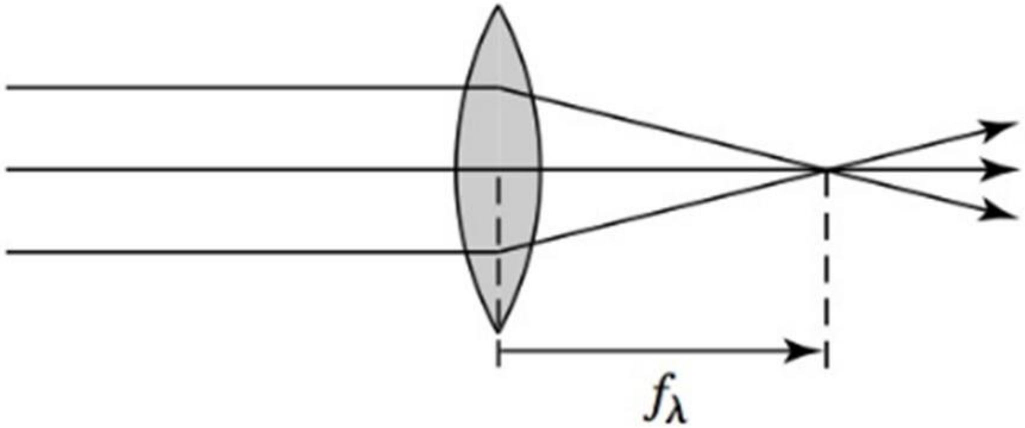
Snell's law

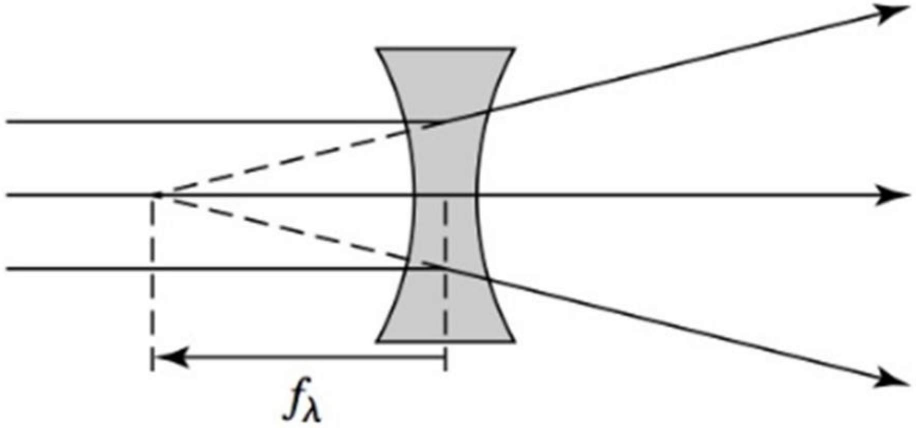
- The amount that the ray is bent depends on the ratio of the wavelength-dependent indices of refraction $n_\lambda \equiv c/v_\lambda$ of each material, where v_λ represents the speed of light within the specific medium.
- Snell's law is given by

$$n_{1\lambda} \sin\theta_1 = n_{2\lambda} \sin\theta_2$$

Converging lens & diverging lens

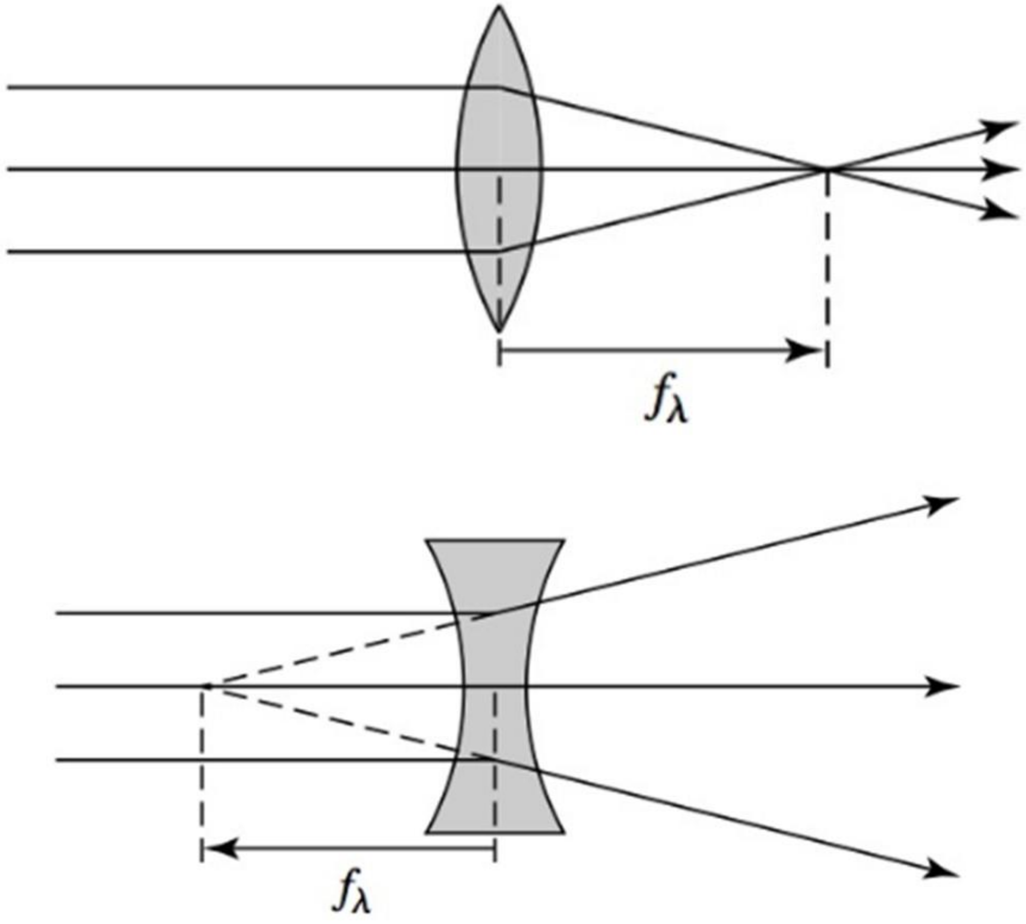
- A beam of light rays of a given wavelength originally traveling parallel to the optical axis of a converging lens can be brought to the focal point of the lens.
- Alternatively, the light can be made to diverge by a diverging lens and the light rays will appear to originate from the focal point of the lens.





Paraxial approximation

- Paraxial approximation is an approximation.
- Rays that are at sufficiently large angles to the optic axis of a spherical lens will not be brought to the same focus as paraxial rays.



Focal length

- The distance to the focal point from the center of the lens is known as the focal length, f_λ.
- For a converging lens f_λ is taken to be positive, and for a diverging lens f_λ is negative.

Measure of optical power

- The focal length of an optical system is a measure of how strongly the system converges or diverges light.
- A system with a shorter focal length has greater optical power than one with a long focal length; that is, it bends the rays more strongly, bringing them to a focus in a shorter distance.

Lensmaker’s formula

- The focal length of a given thin lens can be calculated directly from its index of refraction and geometry.
- If we assume that both surfaces of the lens are spheroidal, then it can be shown that the focal length f_λ is given by:

$$\frac{1}{f_\lambda} = (n_\lambda - 1)\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

Radii of curvature

- R_1 and R_2 are the radii of curvature of each surface, taken to be positive if the specific surface is convex and negative if it is concave.

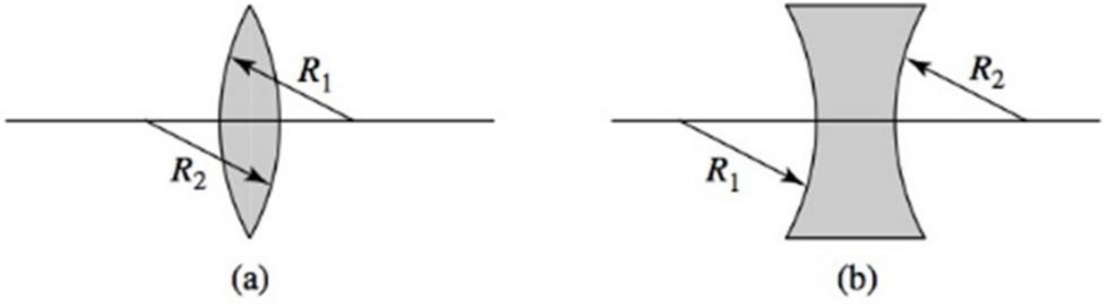


FIGURE 3 The sign convention for the radii of curvature of a lens in the lensmaker's formula. (a) $R_1 > 0$, $R_2 > 0$. (b) $R_1 < 0$, $R_2 < 0$.

Reflection

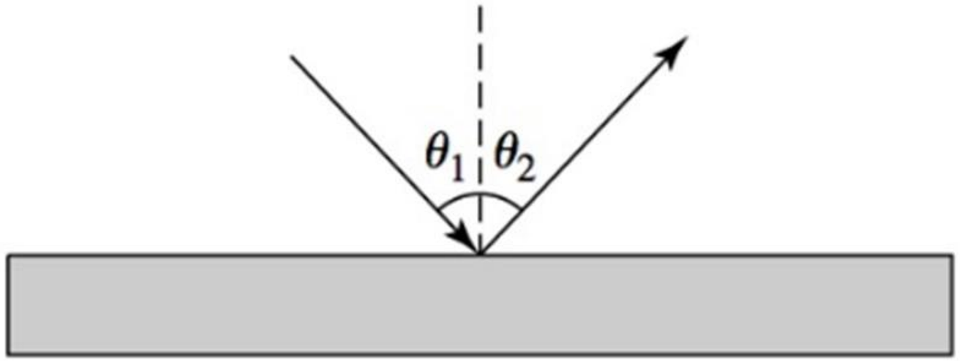


FIGURE 4 The law of reflection, $\theta_1 = \theta_2$.

- For mirrors, the angle of incidence always equals the angle of reflection ($\theta_1 = \theta_2$).

Converging & diverging mirrors

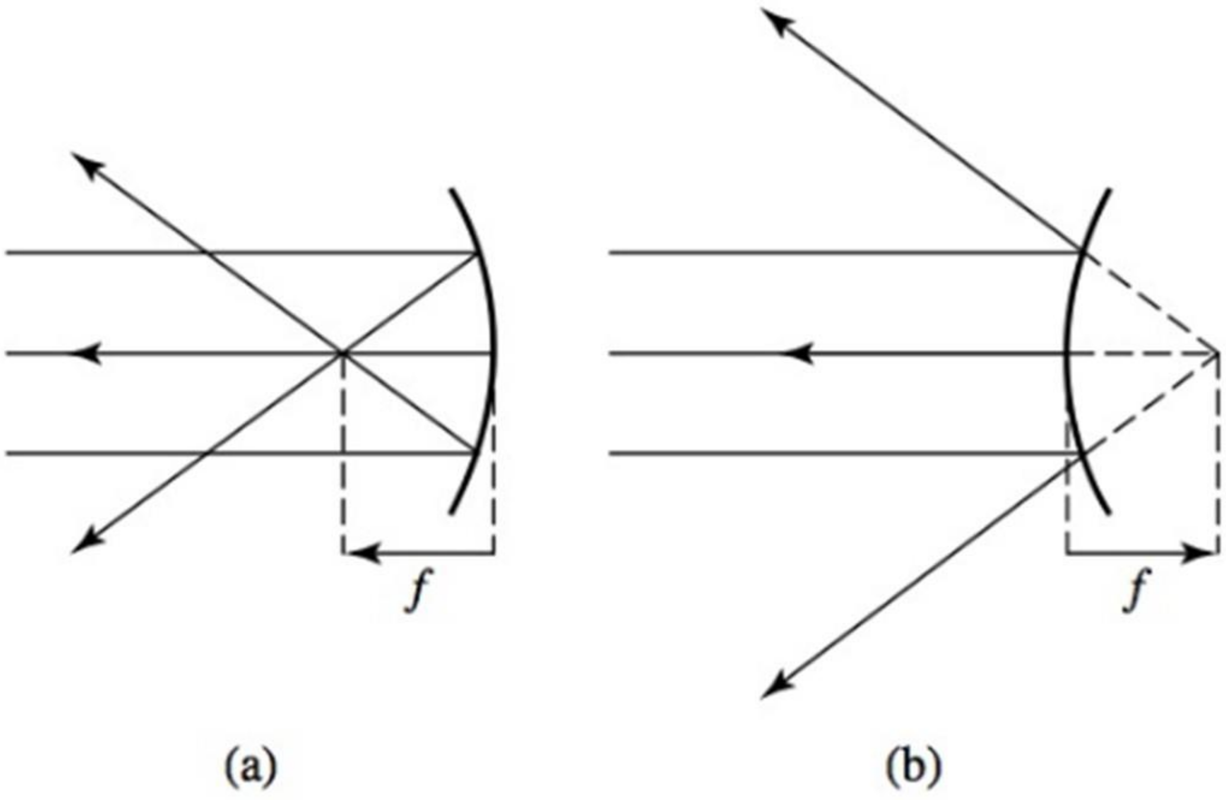


FIGURE 5 (a) A converging mirror, $f > 0$. (b) A diverging mirror, $f < 0$.

Focal length

- For mirrors, f is wavelength-independent.
- In the case of a spheroidal mirror, the focal length becomes $f = R/2$, where R is the radius of curvature of the mirror, either positive (converging) or negative (diverging).

Summary

- Focal length
  - Lens

$$\frac{1}{f_\lambda} = (n_\lambda - 1)\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

  - Mirrors

$$f = R/2$$

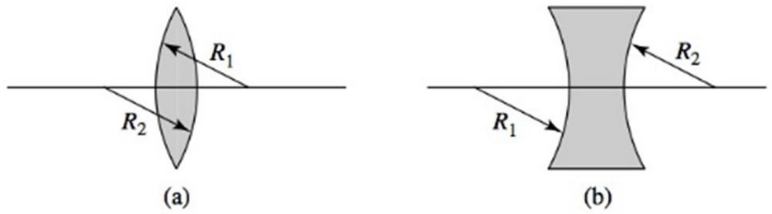


FIGURE 3 The sign convention for the radii of curvature of a lens in the lensmaker's formula. (a) $R_1 > 0$, $R_2 > 0$. (b) $R_1 < 0$, $R_2 < 0$.

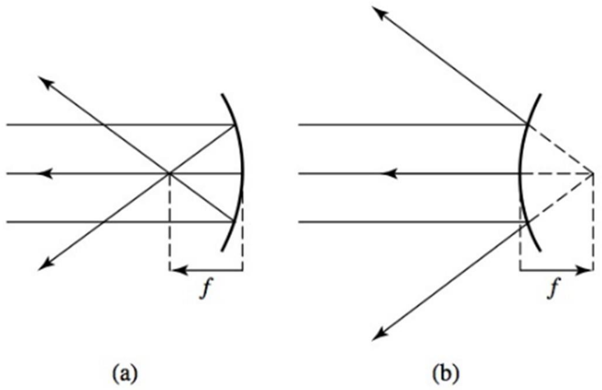


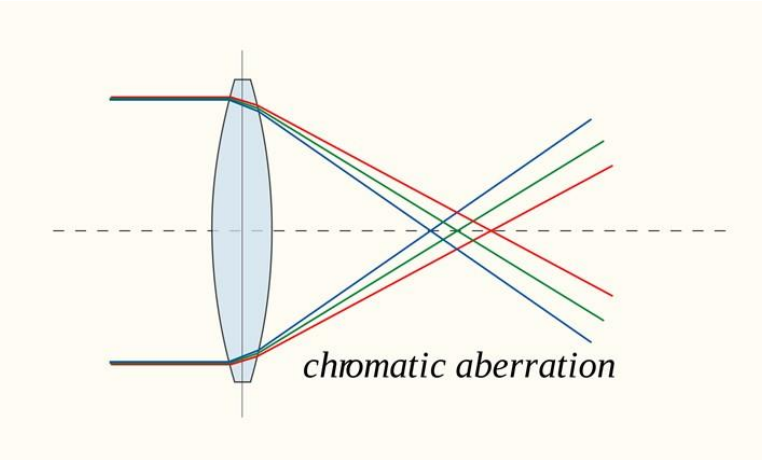
FIGURE 5 (a) A converging mirror, $f > 0$. (b) A diverging mirror, $f < 0$.

Aberrations

- Both lens and mirror systems suffer from inherent image distortions known as aberrations.
- Often these aberrations are common to both types of systems, but chromatic aberration is unique to refracting telescopes.

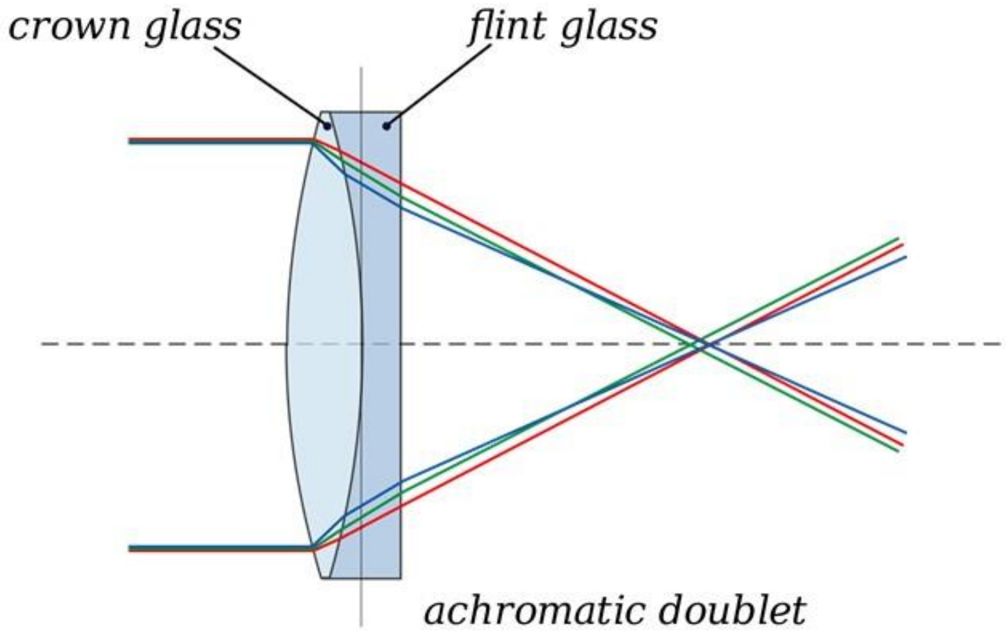
Chromatic aberration

- Chromatic aberration stems from the fact that the focal length of a lens is wavelength-dependent.
- As a result, a focal point for blue light differs from that for red light.



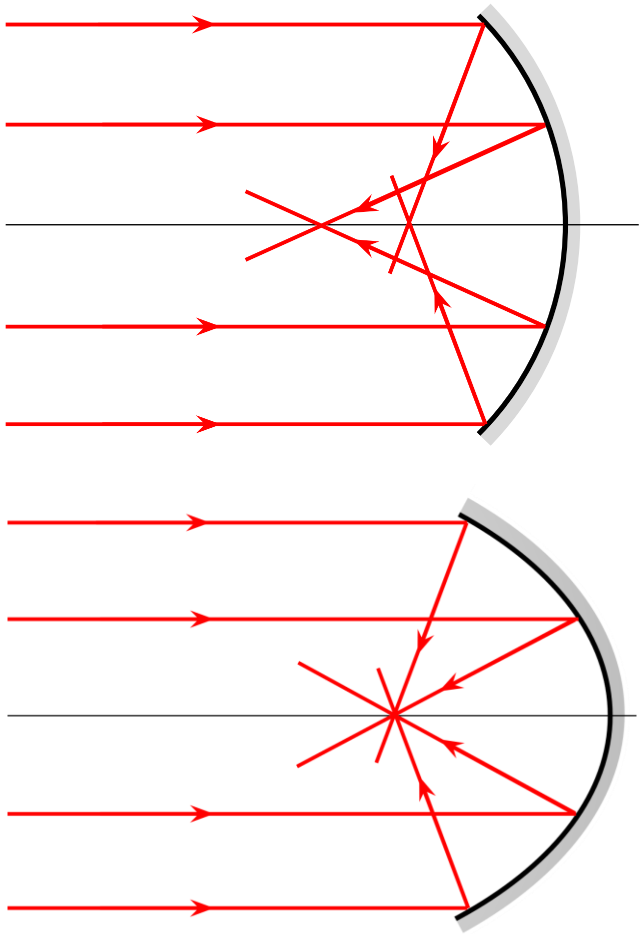
Correcting lenses

- The problem can be diminished somewhat by the addition of correcting lenses.
  - Crown glass has relatively low refractive index and low dispersion.
  - Flint glass has relatively high refractive index and high dispersion.



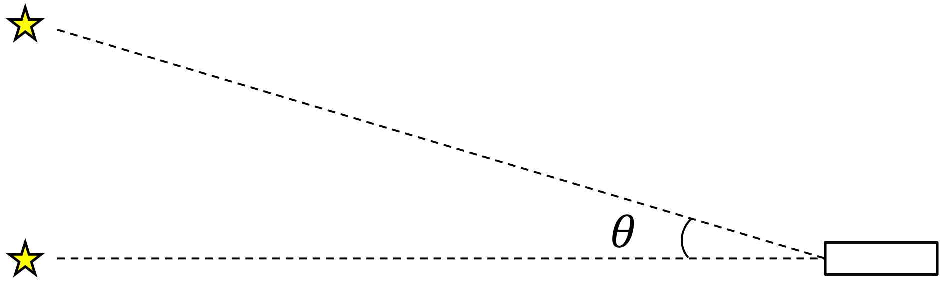
Spherical aberration

- Although it is easier, and therefore cheaper, to grind lenses and mirrors into spheroids, not all areas of these surfaces will focus a parallel set of light rays to a single point.
- This effect, known as spherical aberration, can be overcome by producing carefully designed optical surfaces (paraboloids).



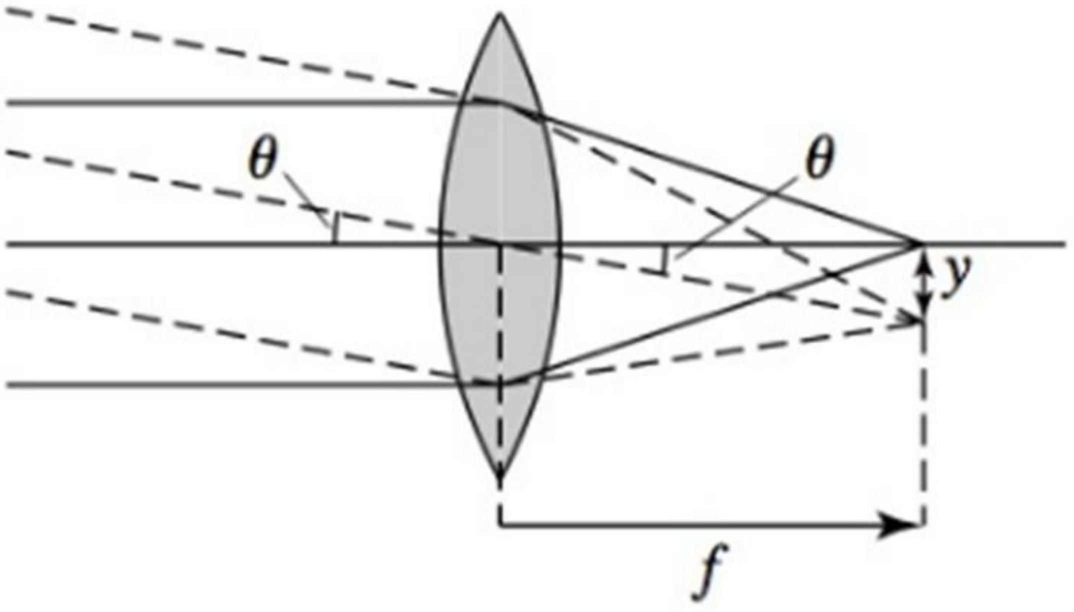
Two point sources

- Consider two point sources.
- Their angular separation is θ.



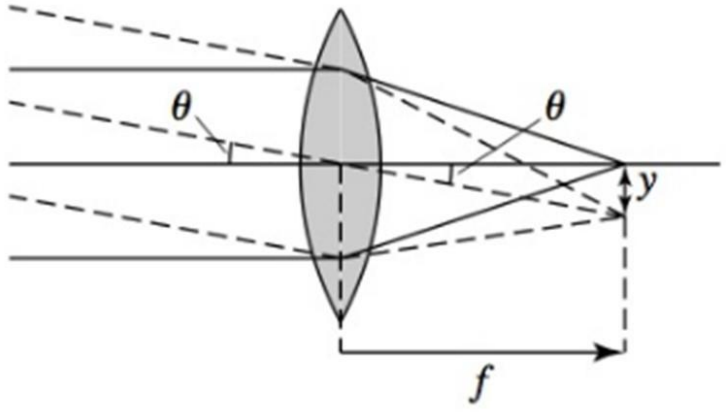
Parallel rays

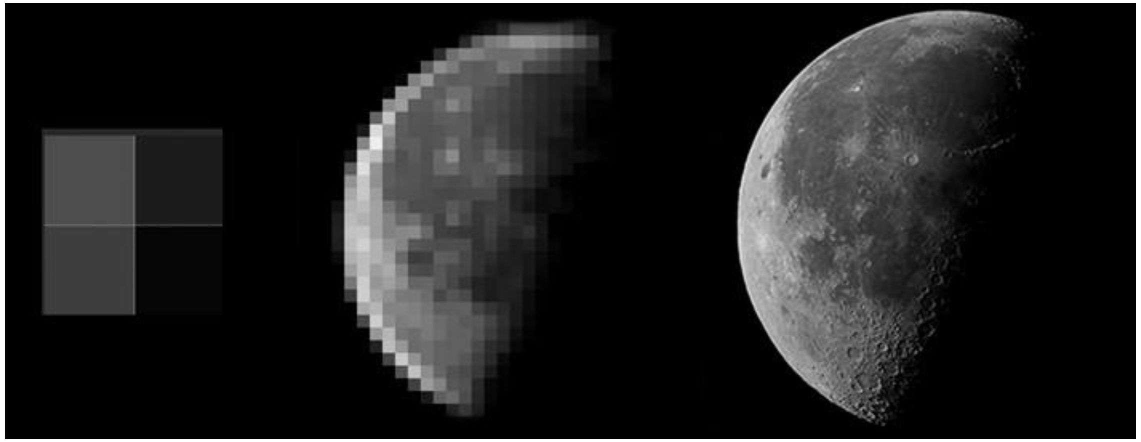
- Since, for all practical purposes, any astronomical object can reasonably be assumed to be located infinitely far from the telescope, all of the rays coming from that object are essentially parallel to one another, although not necessarily parallel to the optical axis.



Focal plane

- If a photographic plate or some other detector is to record the images of two point sources, the detector must be placed in the focal plane of the telescope.
- The focal plane is defined as the plane passing through the focal point and oriented perpendicular to the optical axis of the system.





https://skyandtelescope.org/astronomy-blogs/imaging-foundations-richard-wright/astrophotography-pick-your-pixels/

Image separation

- If it is assumed that the field of view of the telescope is small, then θ must also be small.
- Using the small-angle approximation, for θ expressed in radians, the image separation, y, of two point sources on the focal plane is given by

$$y = f\theta$$

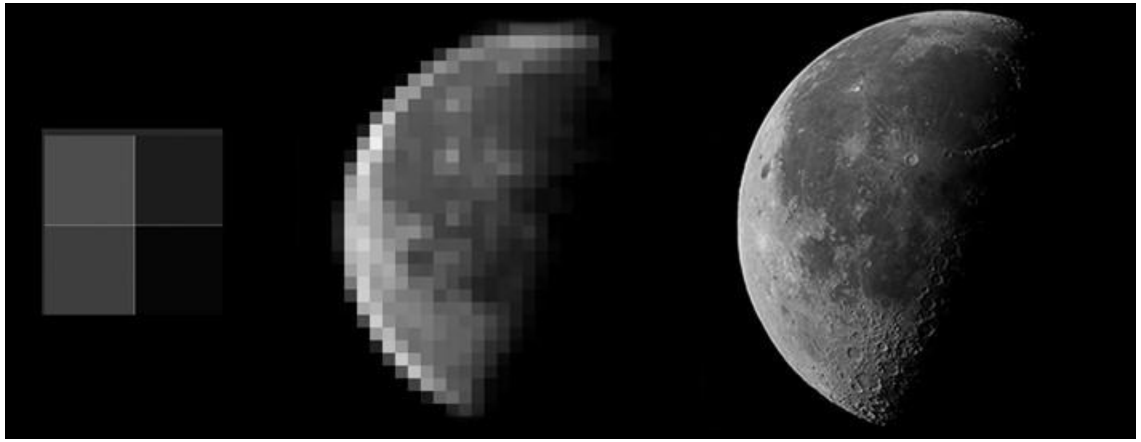
- The focal length controls the separation of two images that is presented at the focal plane.

Plate scale

- The plate scale, p, connects angular separation of the objects with the linear separation of their images at the focal plane.
- It is given by simply the focal length:

$$p = \frac{\theta}{y} = \frac{1}{f}$$

- Plate scale is usually expressed in arcseconds per mm or in arcseconds per pixel after further division through the pixel scale.

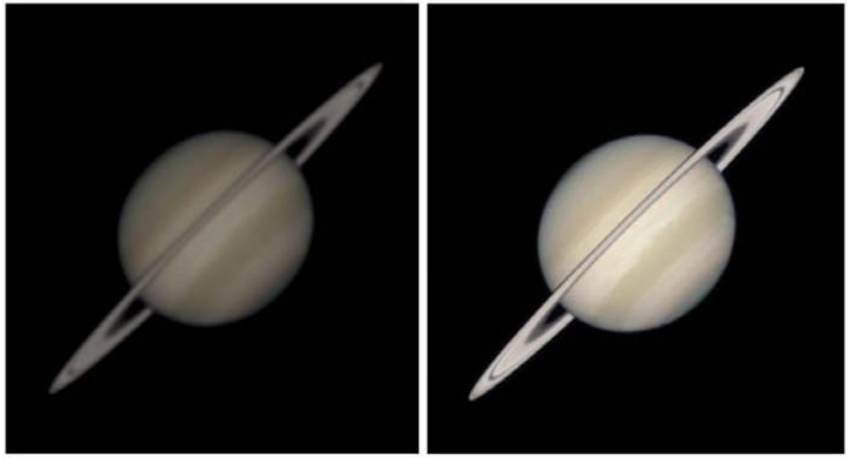


https://skyandtelescope.org/astronomy-blogs/imaging-foundations-richard-wright/astrophotography-pick-your-pixels/

Image brightness

- The brightness of an extended (resolved) image increases with the area of the telescope lens, since more photons are collected as the aperture size increases.
- The amount of light collected from a source is proportional to D^2, where D is the diameter of the aperture.

https://skyandtelescope.org/astronomy-equipment/how-to-choose-a-telescope/



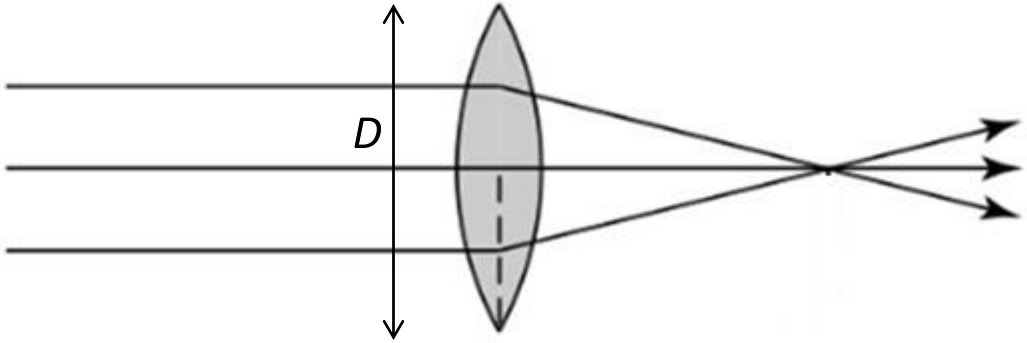
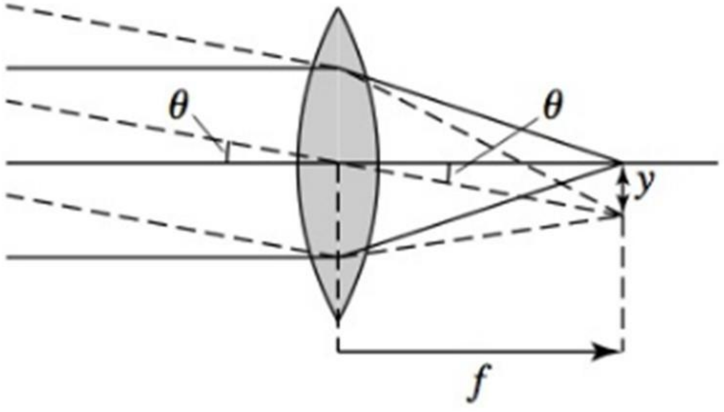


Image area

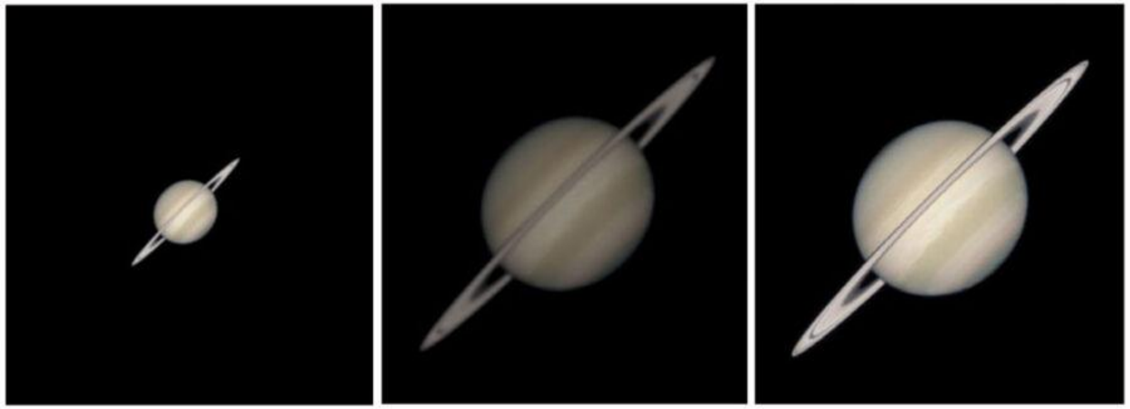
- The linear size of an image is proportional to the focal length of the lens; therefore, the image area is proportional to f^2.



Illuminance

- The illuminance J is the amount of light energy per second focused onto a unit area of a resolved image:

$$J \propto \left(\frac{D}{f}\right)^2$$



Focal ratio

- The inverse of $\frac{D}{f}$ is often referred to as the focal ratio,

$$N = \frac{f}{D}$$

- The focal ratio is usually expressed with the format f/N.
  - E.g. the New Technology Telescope has a focal ratio of $f/2.2$

Amount of time needed to form a bright image

- The focal ratio indicates the amount of time required to collect the photons needed to form a sufficiently bright image for analysis.
- Numerically large focal ratios are said to be long or slow.
- Small numbers are short or fast.

Summary

- Optics
  - Revision
- Characteristics of a telescope
  - Focal length
  - Plate scale
  - Focal ratio