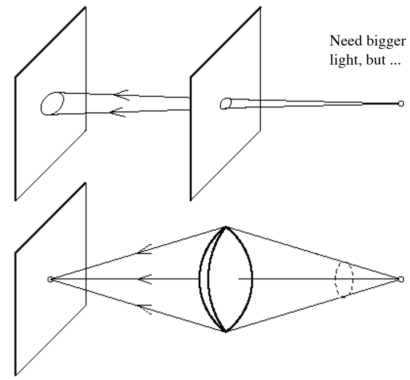
Real cameras

- Real cameras need lenses
  - Focus now depends on distance (unlike pinhole cameras)
  - Aberrations and distortions
- Brightness falls off towards edges
  - $\cos^4(\theta)$ falloff due to projection onto flat surface
  - Vignetting
- Chromatic aberration
  - Light at different wavelengths follows different paths; hence, some wavelengths are defocused (index of refraction is a function of wavelength).
- Scattering at optical surfaces (flare)
  - Light is reflected off each surface it encounters (a very difficult source of noise to purge or calibrate for)
- Capture process has many noise sources with different properties
  - Photon capture (Poisson statistics)
  - Thermal noise (Dark current)
  - Readout discretization noise
  - Noise in electronics

The reason for lenses



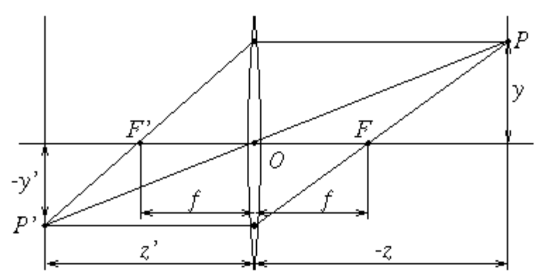
Need bigger hole to get more light, but ...

Depth of Field

Unlike a pinhole camera, a camera with a lenses has limited depth of field (only a limited range of depths are in focus at once)

The thin lens

Supplementary material



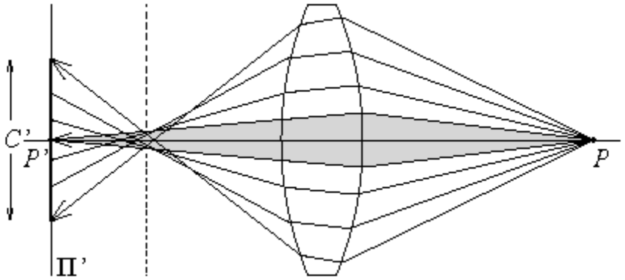
Focus depends on depth. When z=infinity, this is same equation as a pinhole.

$$\frac{1}{z'} - \frac{1}{z} = \frac{1}{f}$$

Supplementary material

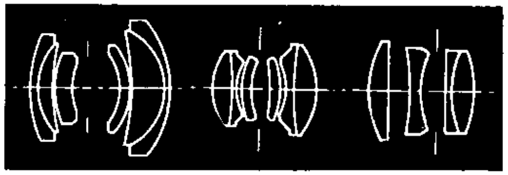
Spherical aberration

Aberrations occur because imaging equation is not exact



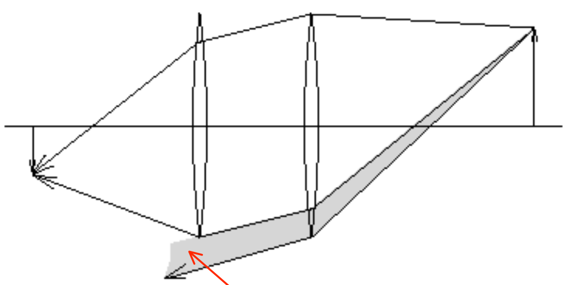
Supplementary material

Lens systems



Supplementary material

Vignetting: Fall-off in brightness is due to blockage of the optical path occurring more for off-axis light.



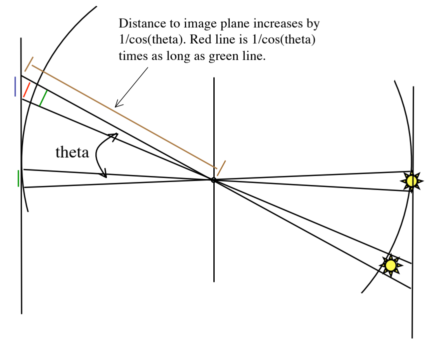
Would get to sensor if there only was only one lens element, or if it was less off axis.

Brightness falls off due to projection onto a plane

Supplementary material

Distance to image plane increases by 1/cos(theta). Red line is 1/cos(theta) times as long as green line.

Image is spread out by a factor of cos(theta) due to oblique angle--blue line is longer than red line by approximately a factor of 1/cos(theta)



What counts is the amount of light per direction. If the vertical line was a wall which was equally bright in all directions, then the amount of light going through the “sun” is the same in both cases. The area is bigger at the bottom, but the angle is oblique, meaning that angle for a patch as seen by camera is smaller. The two effects cancel each other.

Taking both effects into account, the blue line is longer than the green one by a factor of $1/\cos^2$(theta). Since images are 2D, expansion in one direction needs to be squared to give the change in area. So, the area receiving light from the “sun” increases by a factor of $1/\cos^4$(theta), and the brightness falls off by a factor of **$\cos^4$(theta)**.