CS348C – Winter 1997

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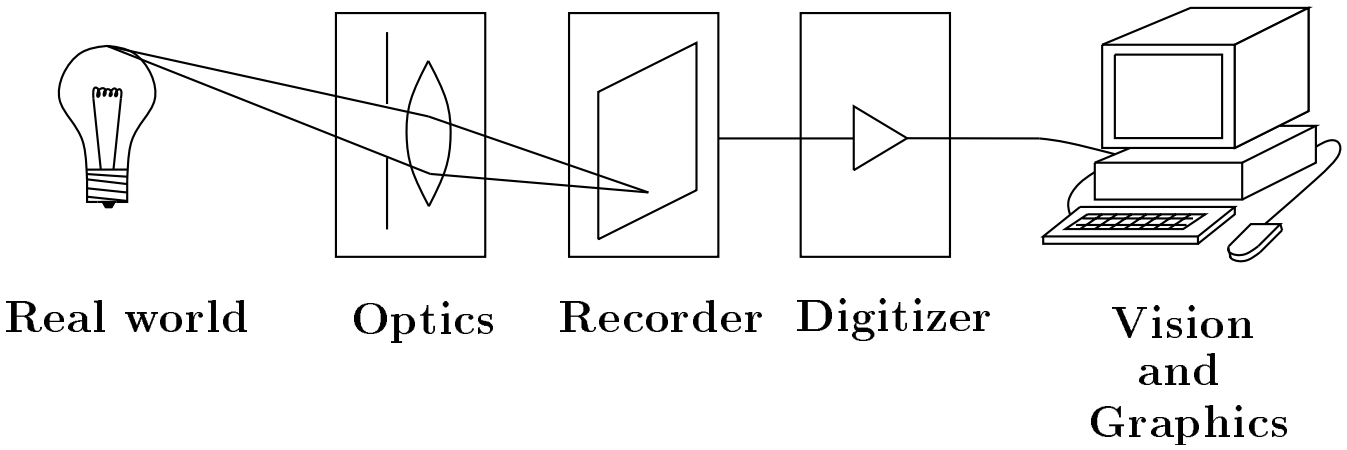
Stanford University

Imaging



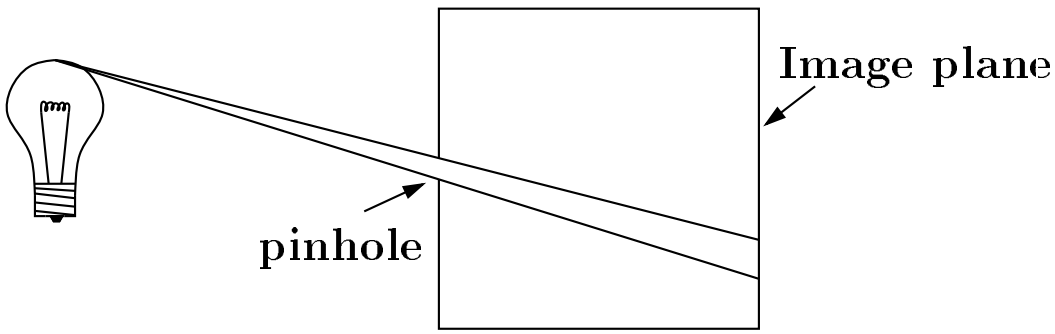
Optics

1. Pinhole camera
    a. Principle of operation
    b. Limitations
2. Lenses
    a. Principle of operation
    b. Limitations
        – Monochromatic aberrations
        – Chromatic aberrations
        – Flare
        – Vignetting
        – Depth of field

The pinhole camera

First camera – "camera obscura" – known to Aristotle.

First recording in 1826 by Joseph Nicephore Niepce.
Recorded onto a pewter plate over the course of 8 hours.



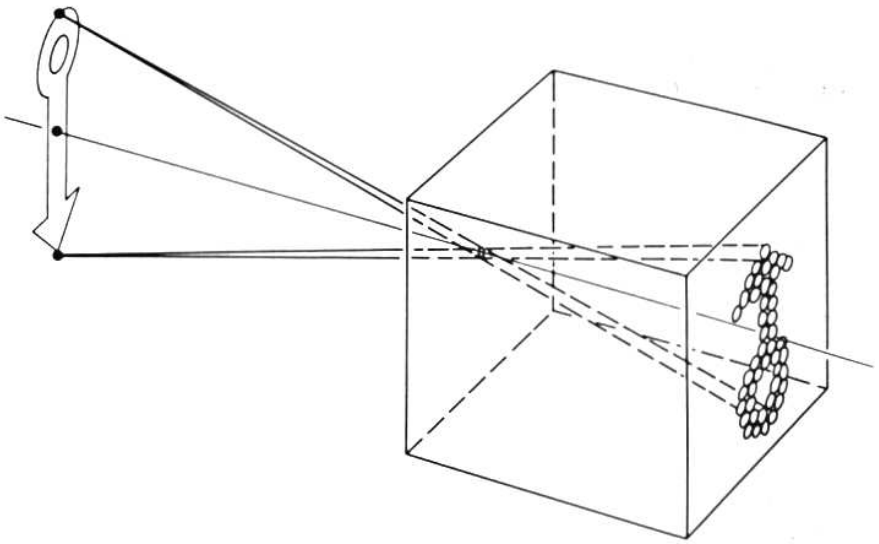
Pinhole camera

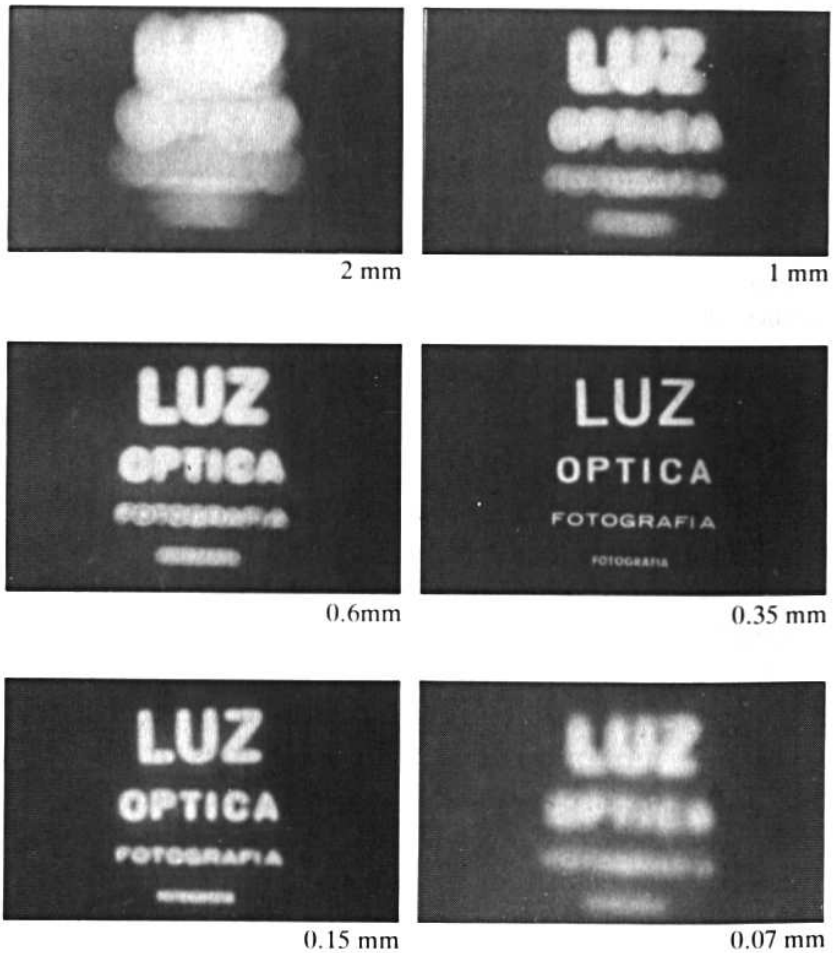
Limitations:

Fidelity varies widely with aperture size

- Small aperture => high fidelity, but
  small aperture => long exposure or very bright illumination
- Cannot make the aperture arbitrarily small

Image fidelity vs. aperture size for a pinhole camera

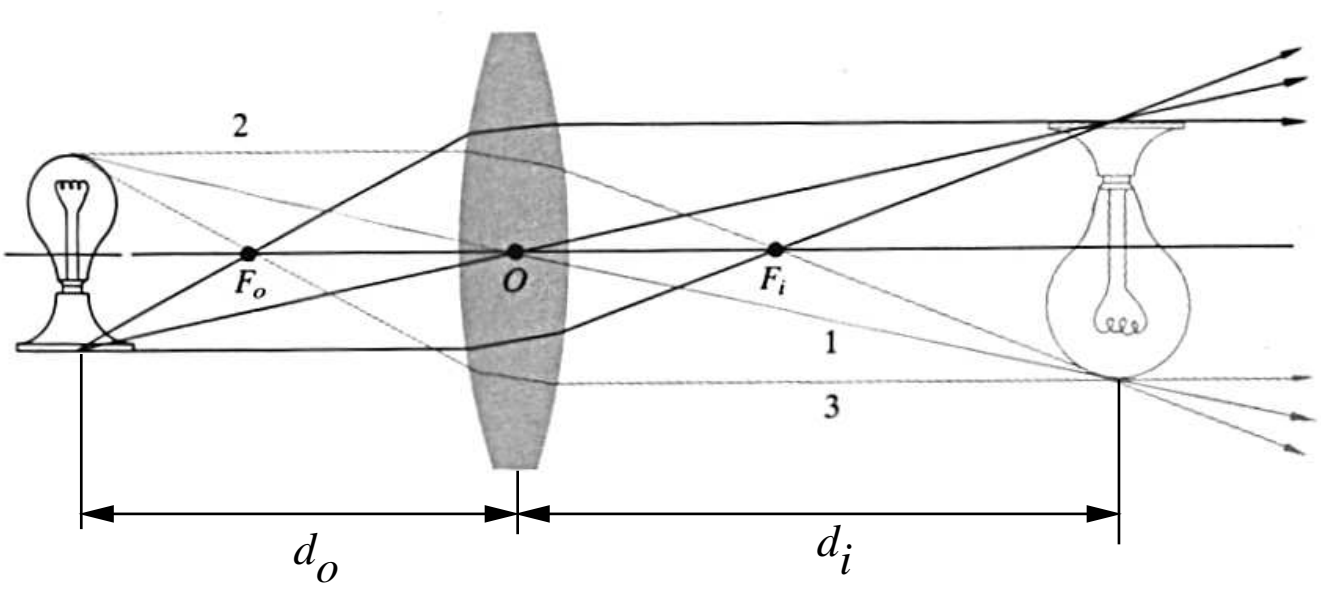




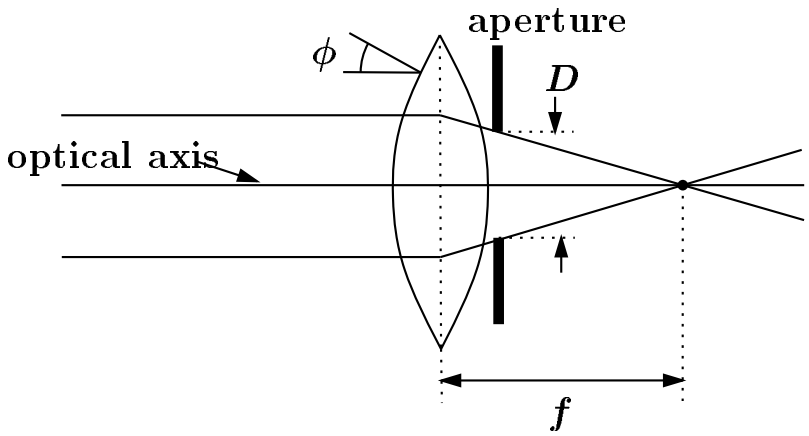
[Figure from Hecht 1987]

Lenses

Lenses overcome the need to make the aperture very small by focusing a bundle of rays onto one point.



[Figure from Hecht 1987]



The lens images a bundle of a parallel rays to a point at distance *f* beyond the plane of the lens. *f* is the focal length.

An aperture of diameter, *D*, is used to restrict the extent of the rays being refracted.

For economical manufacture, lens surfaces are usually spherical.

A spherical lens behaves like an ideal lens if we can restrict the angle ϕ to permit the approximation:

$$\sin\phi = \phi - \frac{\phi^3}{3!} + \frac{\phi^5}{5!} - \ldots \approx \phi$$

This angle restriction means that we consider only rays that are near the optical axis. Such rays are called *paraxial* rays.

For a thin lens, we neglect the lens thickness and the paraxial approximation leads to the thin lens or Gaussian lens law:

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$$

Monochromatic aberrations

If we allow for the next higher order term in the sinϕ approximation:

$$\sin\phi = \phi - \frac{\phi^3}{3!} + \frac{\phi^5}{5!} - \ldots \approx \phi - \frac{\phi^3}{3!}$$

we arrive at the third order theory. The deviations from ideal optics in this theory are called the *primary* or *Seidel aberrations*. These (monochromatic) aberrations are:

- Spherical aberration
- Coma
- Astigmatism
- Petzval field curvature
- Distortion

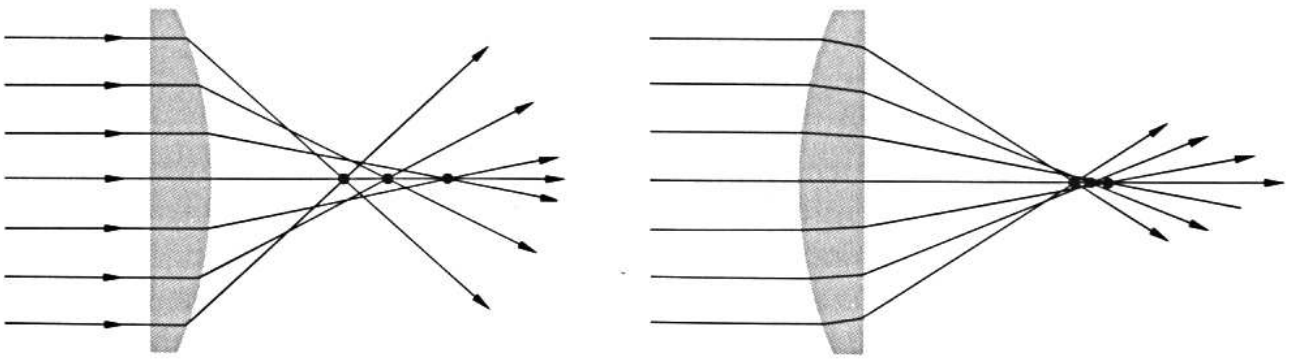
Spherical aberration

Cause:
Spherical glass surfaces

Effect:
Unsharpness, focus shifts when stopped down

Where common:
Cheaper lenses, large aperture lenses

Ways of improving:
aspherical surfaces or multiple elements, stop down the aperture



[Figure from Hecht 1987]

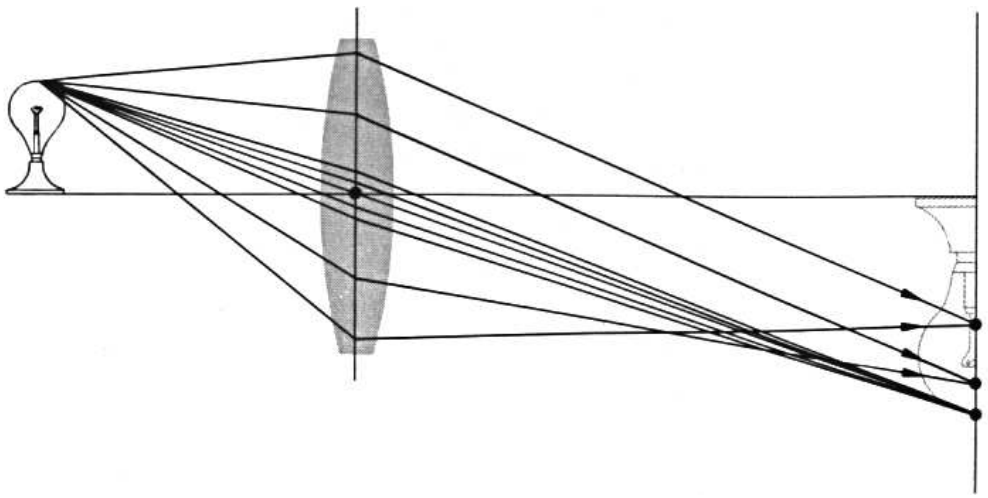
Coma

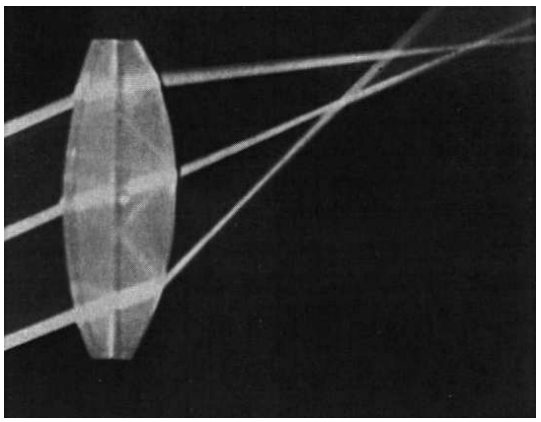
Cause:
Variations in magnification with aperture

Effect:
Tear−drop (comet) shaped images of off−axis points of light

Where common:
Off−center highlights

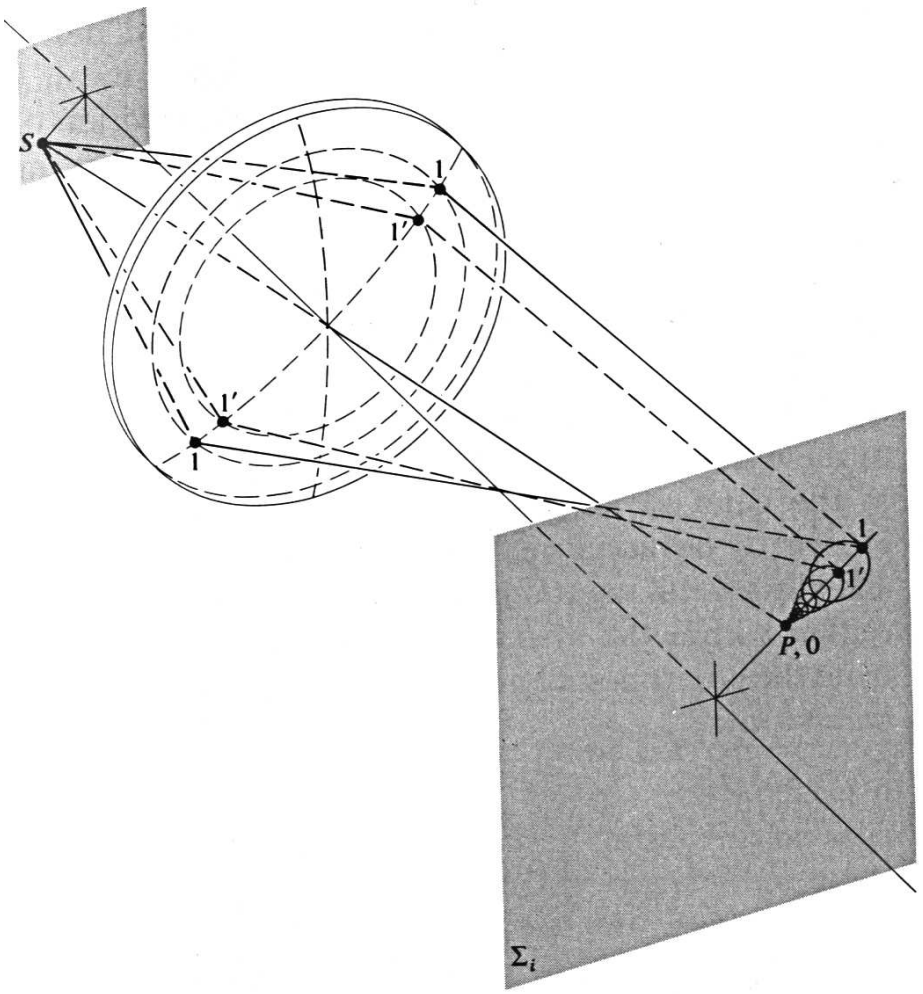
Ways of improving:
Symmetrical design, stop down aperture

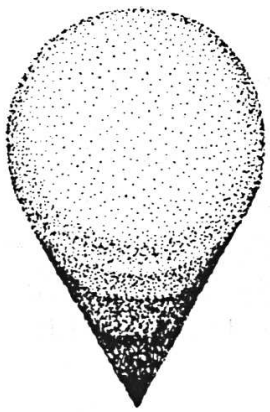




[Figures from Hecht 1987]

Coma (cont'd)





[Figures from Hecht 1987 and Smith 1990]

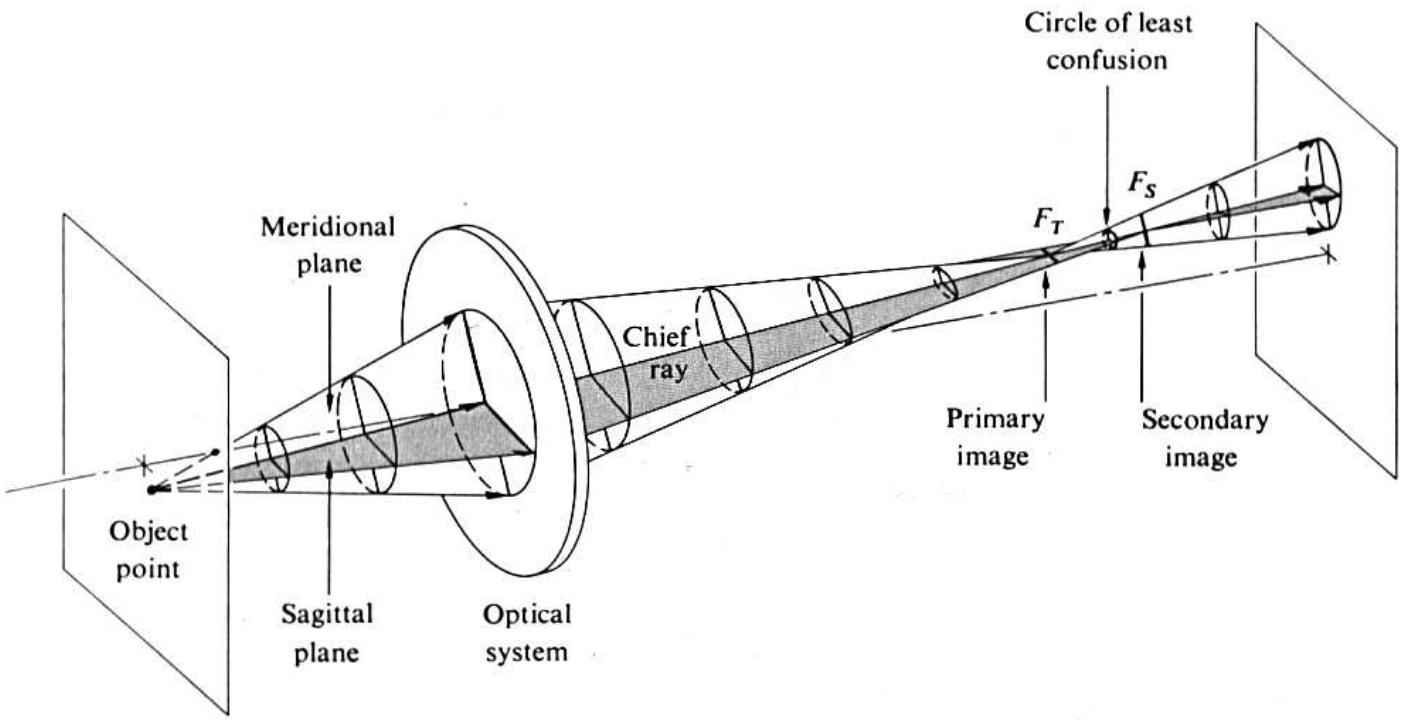
Astigmatism

Cause:
Asymmetrical refraction

Effect:
Vertical and horizontal objects focus at different distances

Where common:
Cheaper lenses

Ways of improving:
Stop down the aperture



[Figure from Hecht 1987]

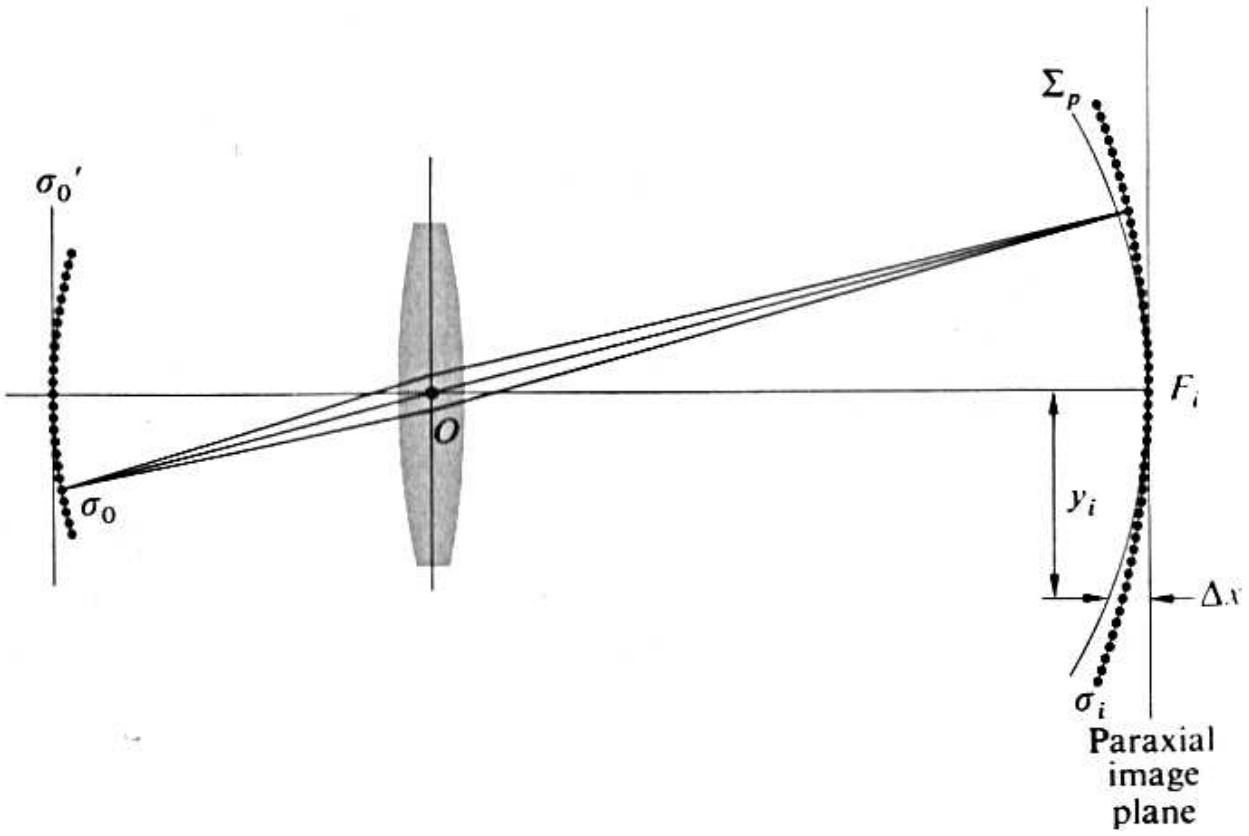
Petzval field curvature

Cause:
Focal plane is curved, because of lens surface curvature

Effect:
Focus position varies from center to edge

Where common:
Wide angle lenses, large apertures

Ways of improving:
Use special flat field lenses, stop down the aperture



[Figure from Hecht 1987]

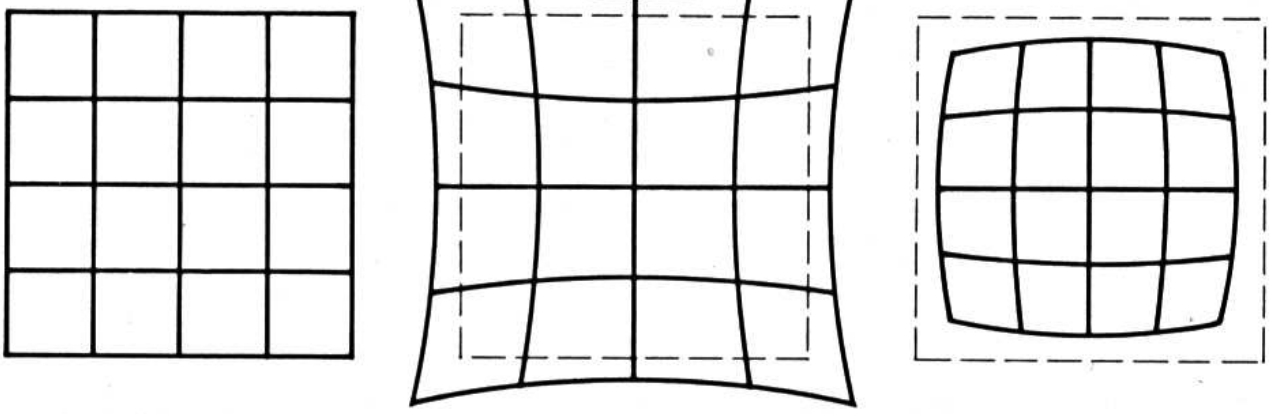
Distortion

Cause:
Oblique light rays bent by the edges of the lens

Effect:
Non−radial lines curve out (barrel) or curve in (pin−cushion)

Where common:
Assymetrical lenses

Ways of improving:
Symmetrical design



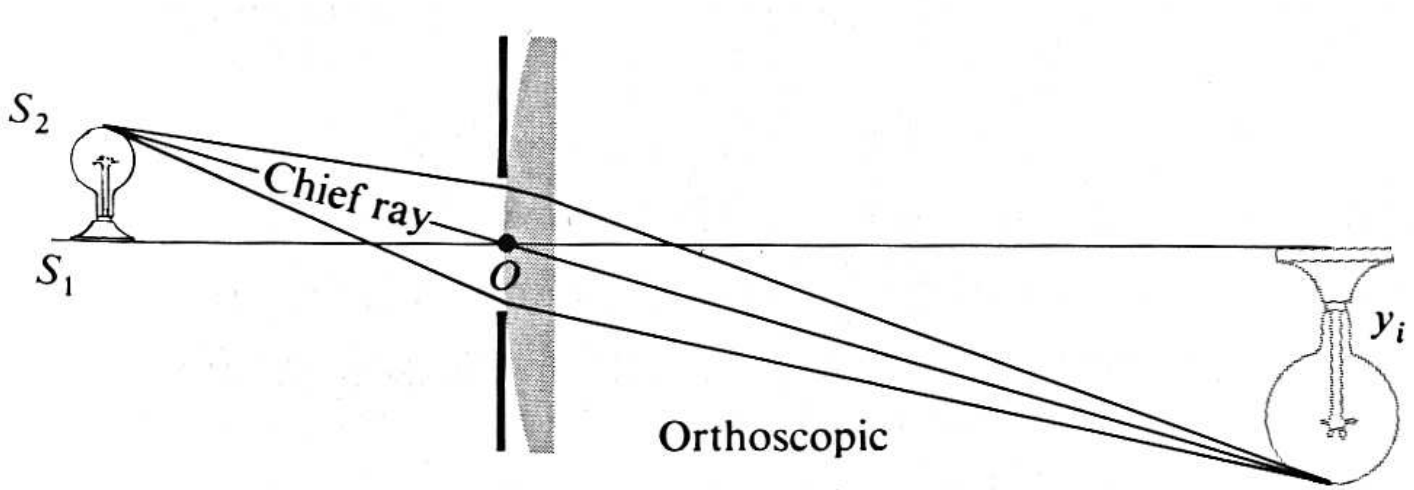
Orthoscopic

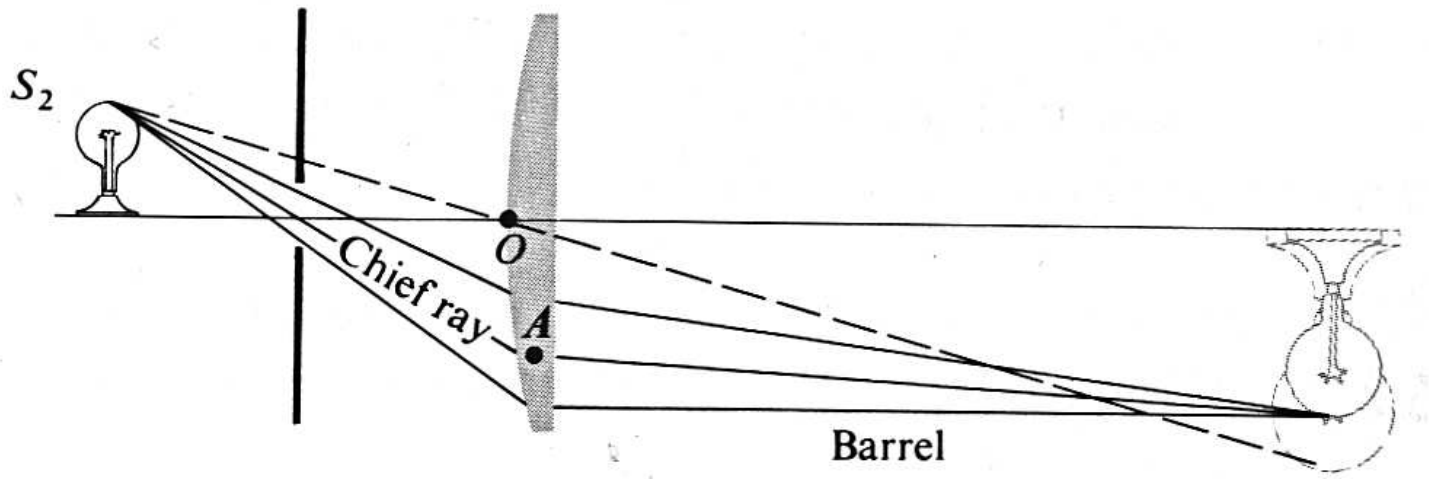
Pin−cushion distortion

Barrel distortion

[Figure from Hecht 1987]

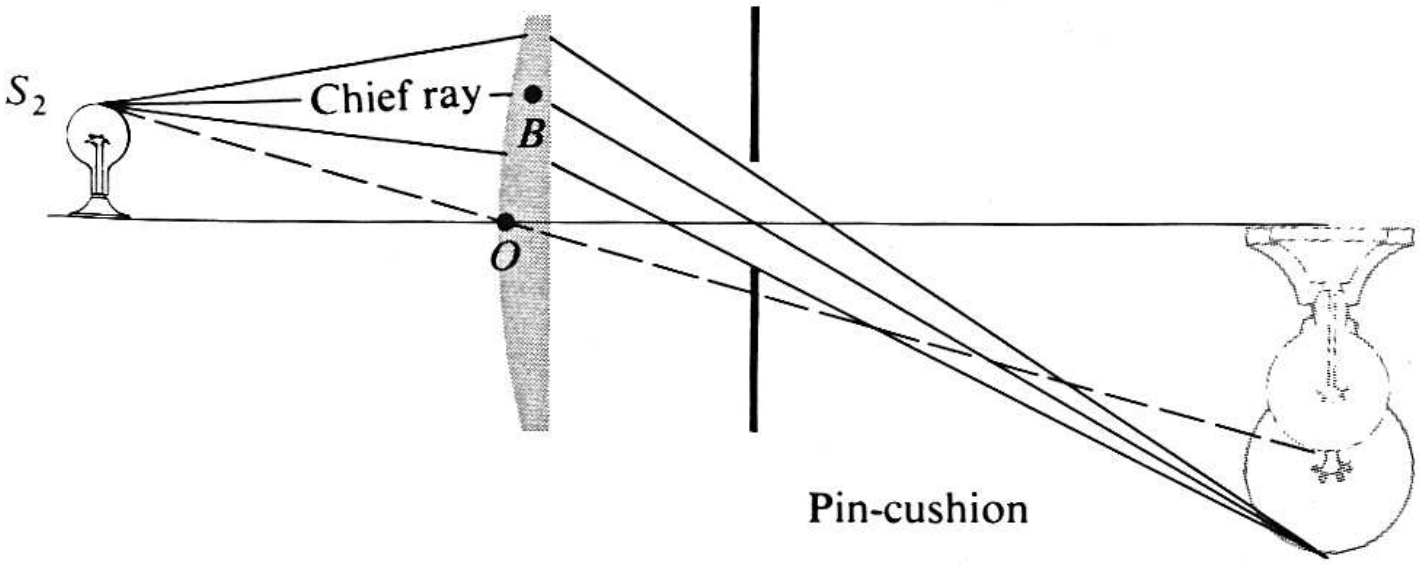
Distortion (cont'd)

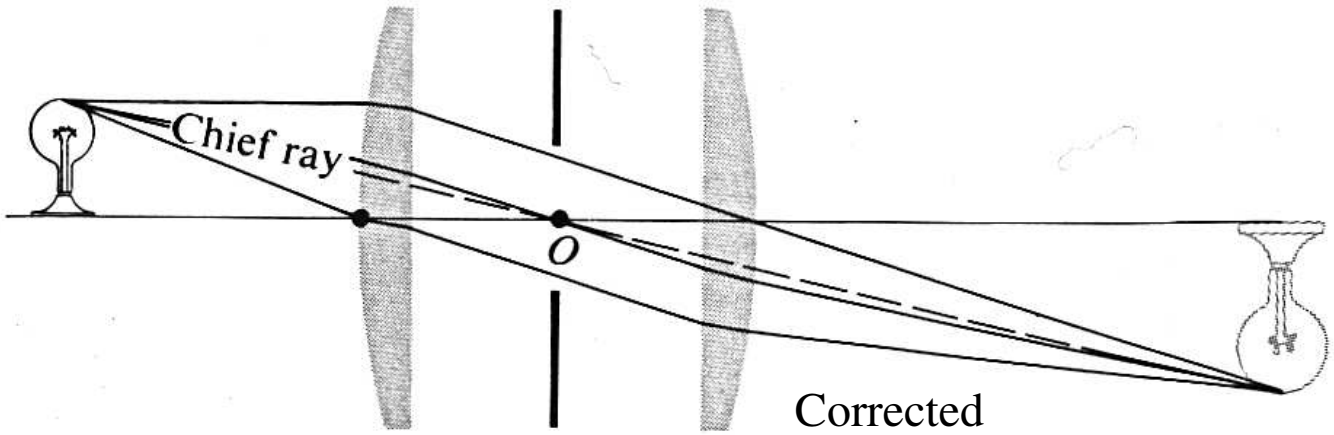




[Figures from Hecht 1987]

Distortion (cont'd)





[Figures from Hecht 1987]

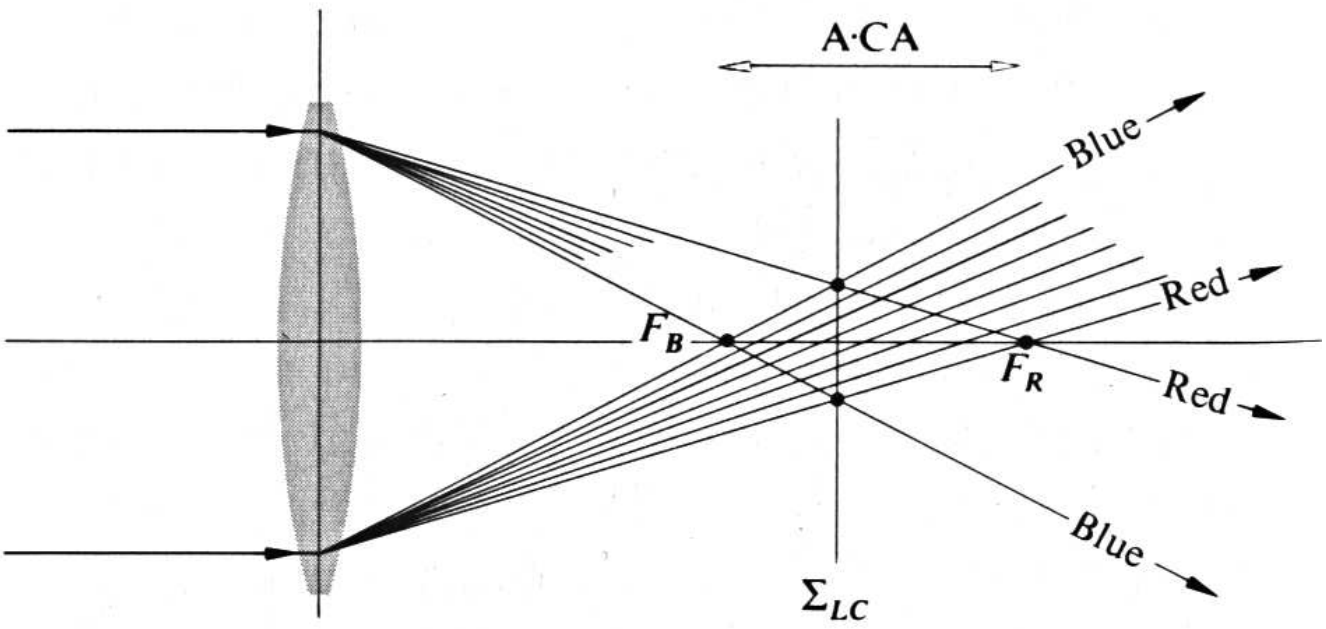
Chromatic aberration

Cause:
Index of refraction of lens varies with wavelength =>
dispersion of light into colors

Effect:
Colored fringes on highlights, focus shifts with color

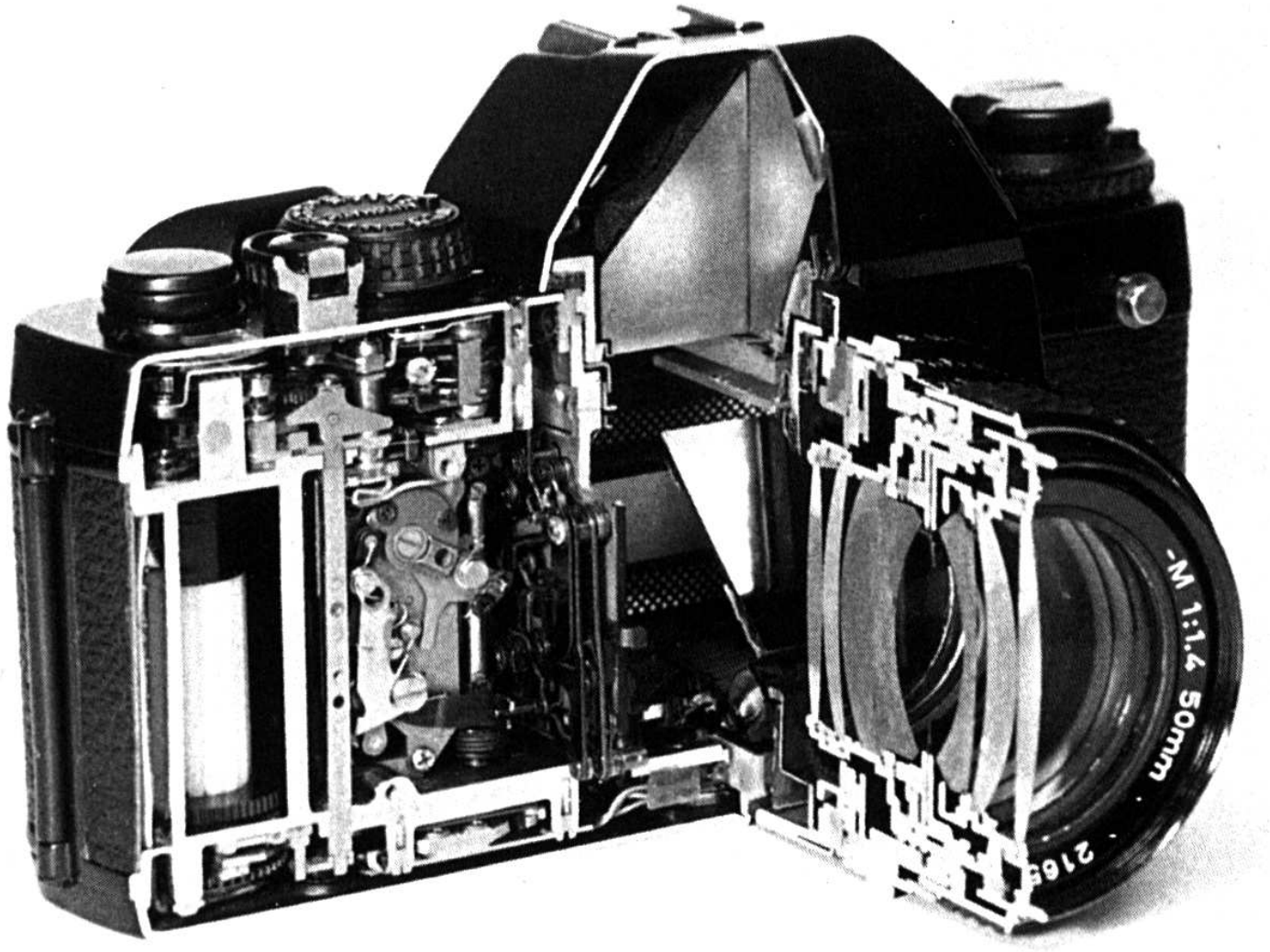
Where common:
Long focal length lenses

Ways of improving:
Achromatic designs



[Figure from Hecht 1987]

Don’t despair!



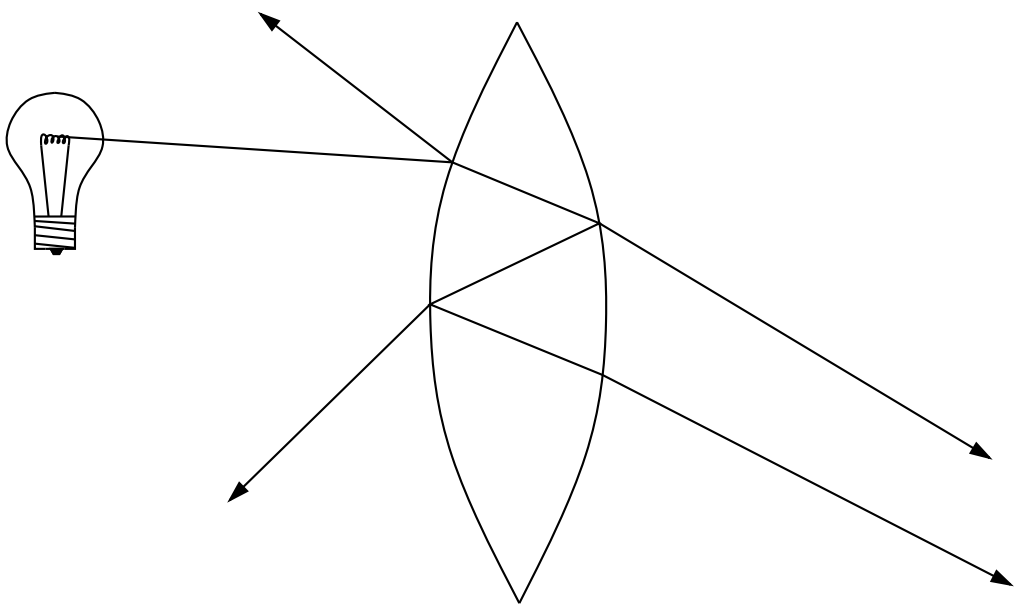
Sophisticated arrangements of multiple lenses can significantly reduce the effect of the chromatic and monochromatic aberrations.

[Figure from Goldberg 1992]

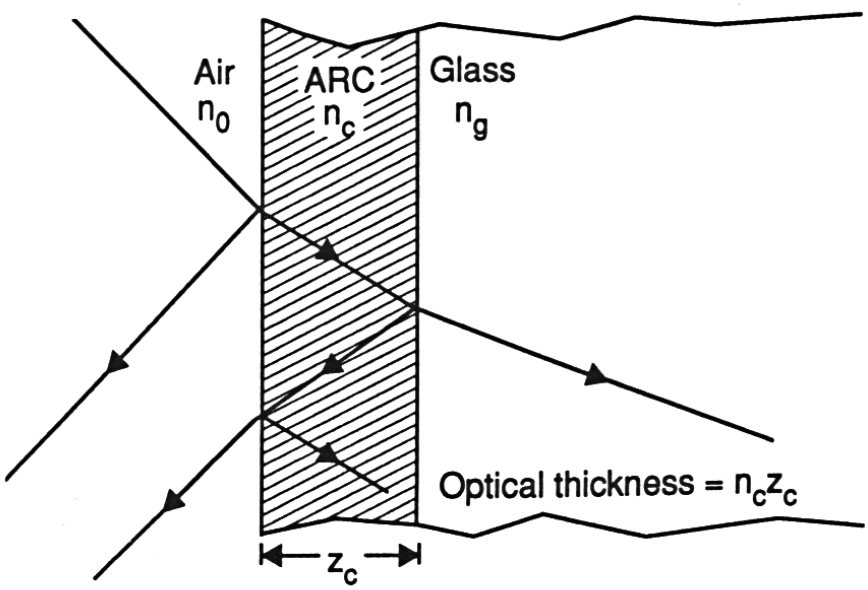
Flare

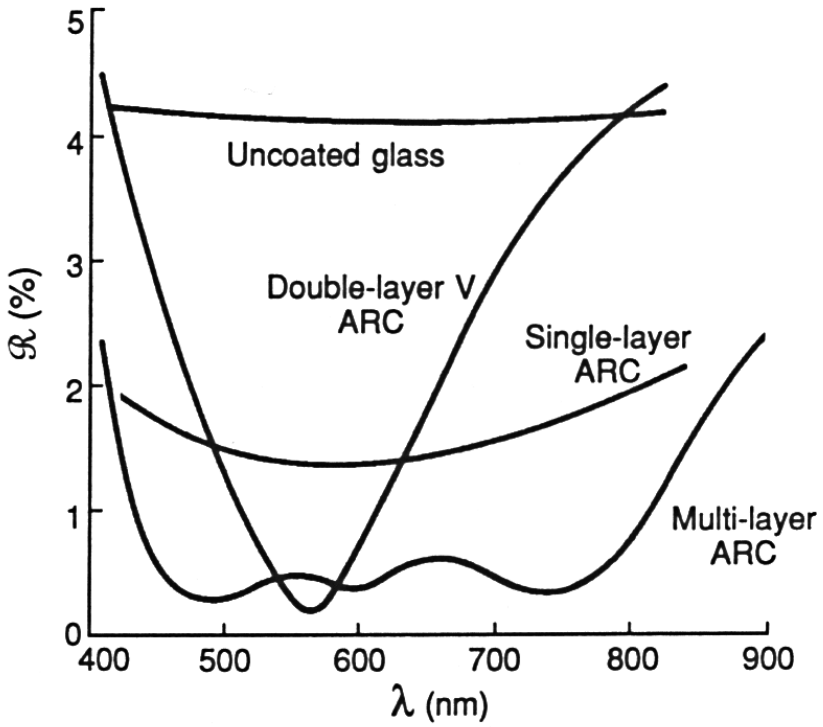
Light rays will refract at the interface between air and the lens, but they will also reflect. The reflected rays are "stray" light that is not focused to the desired point on the image plane.

Result: ghost images or haziness



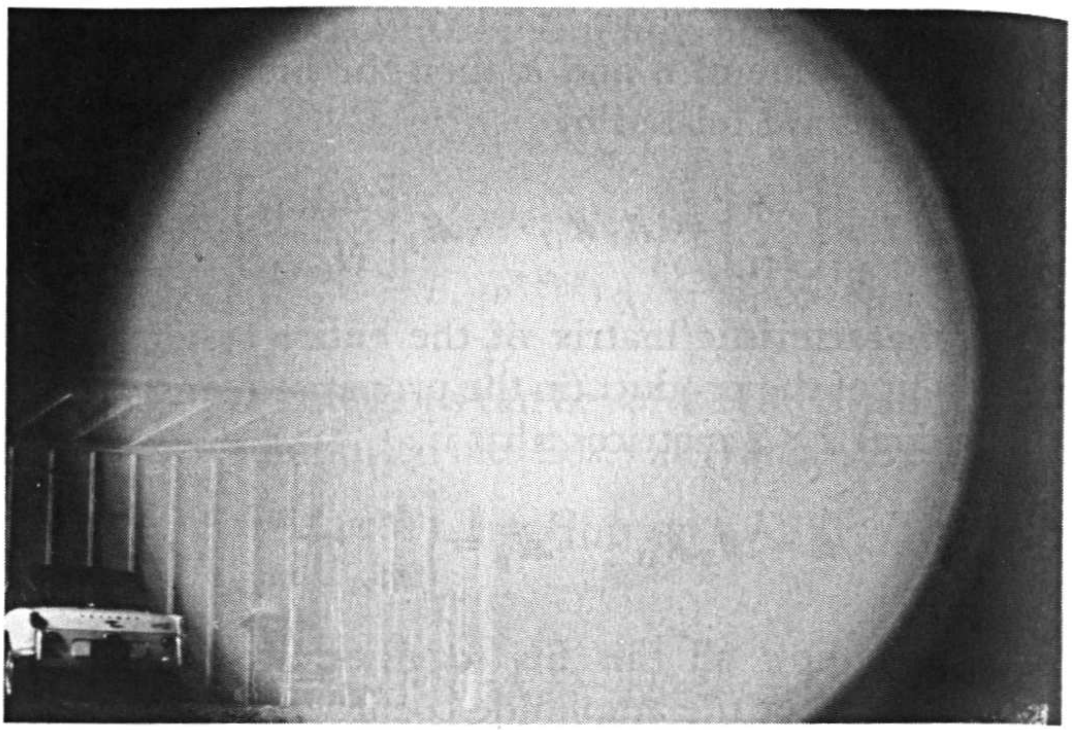
Optical coatings



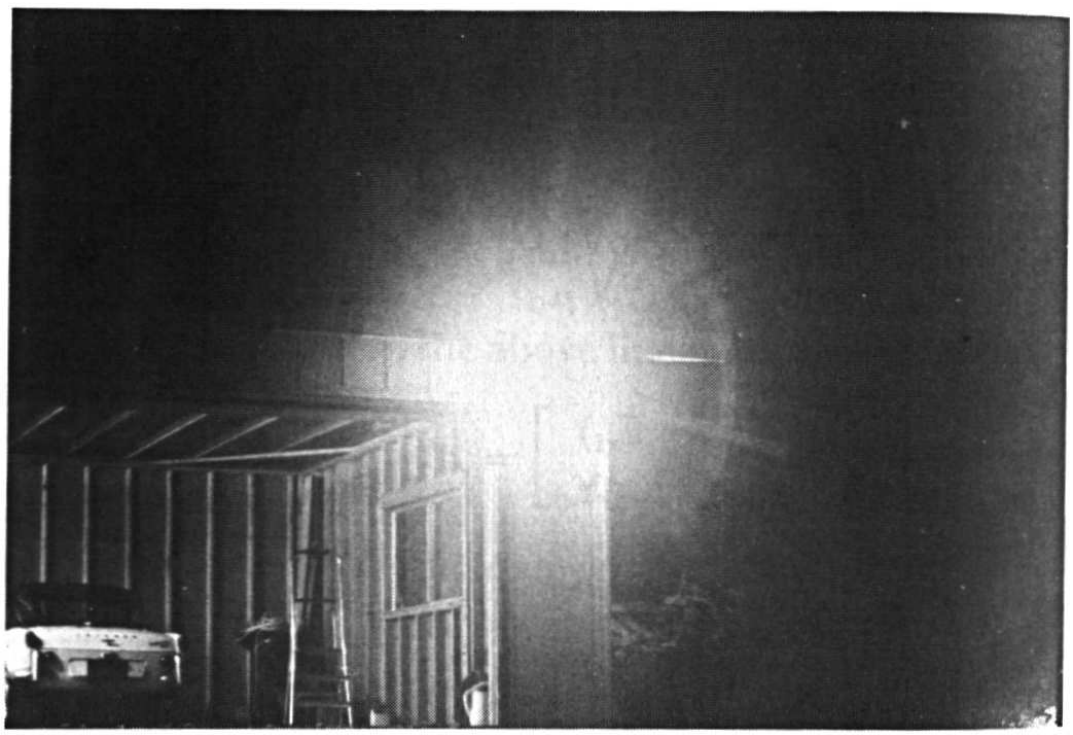


[Figures from Burke 1996]

Single vs. multiple optical coatings



Single coating



Multiple coatings

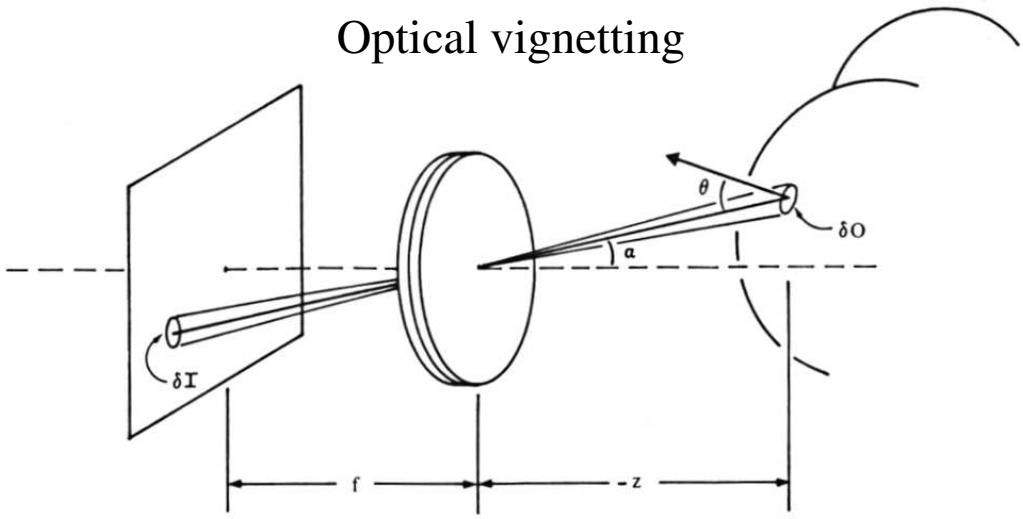
[Figures from Hecht 1987]

Vignetting

Light rays that are oblique to the lens system will deliver less power per unit area due to object angle with respect to the optical system (optical vignetting) and occlusion by apertures and lens extents (mechanical vignetting).

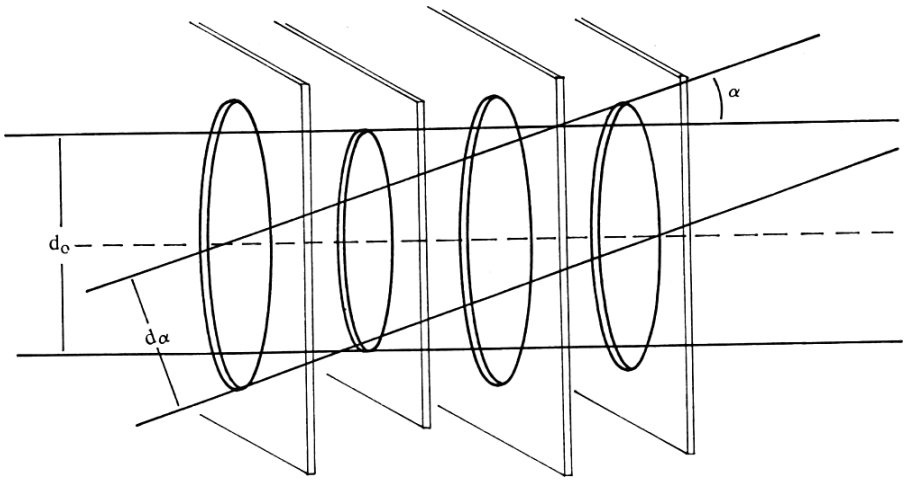
Result: darkening at the edges of the image

Optical vignetting



$$E(\delta I) \sim L(\delta O) \cos^4 \alpha$$

Mechanical vignetting

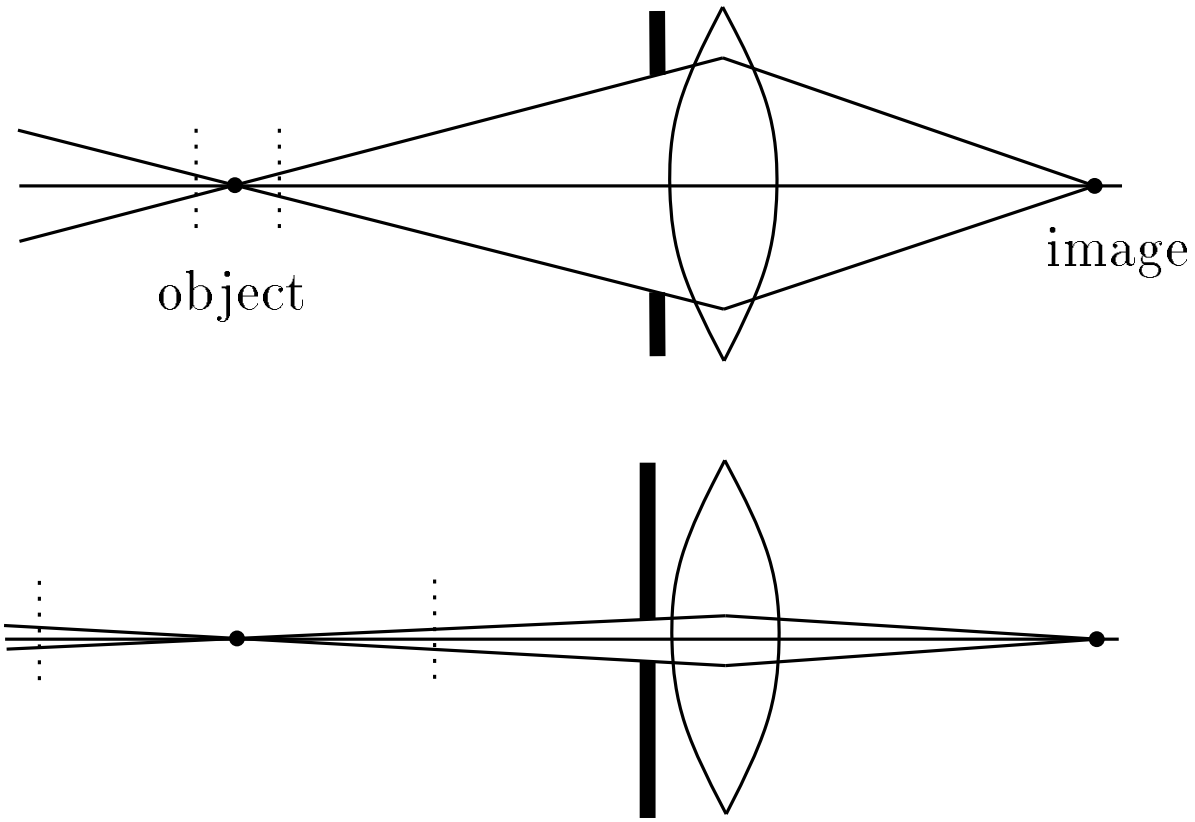


[Figures from Horn 1986]

Depth of field

Points that are in front or behind the object plane will be blurred. Given a threshold that defines what is in satisfactory focus, there is a range of object distances that will be considered in focus.

For fixed image plane and object distances, the depth of field is primarily controlled by the aperture size.



Bibliography

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