Basic Imaging Principles

Imaging

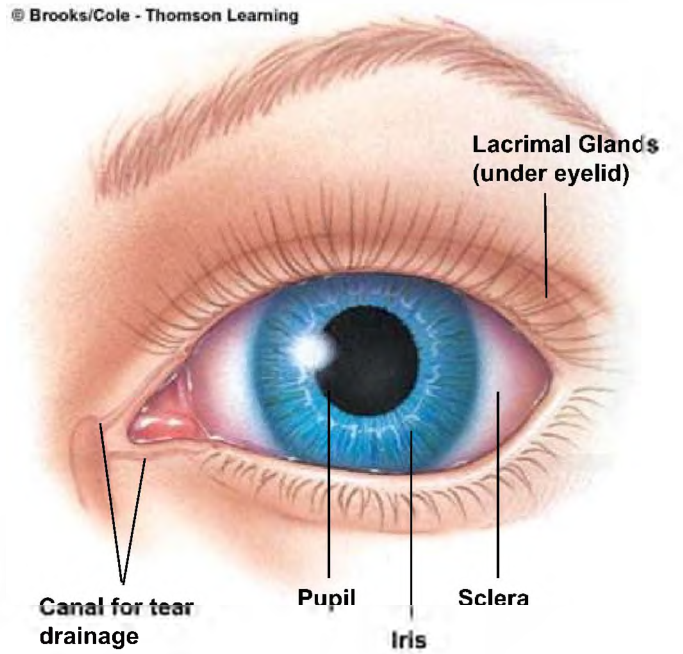
Real world → Opics → Sensor

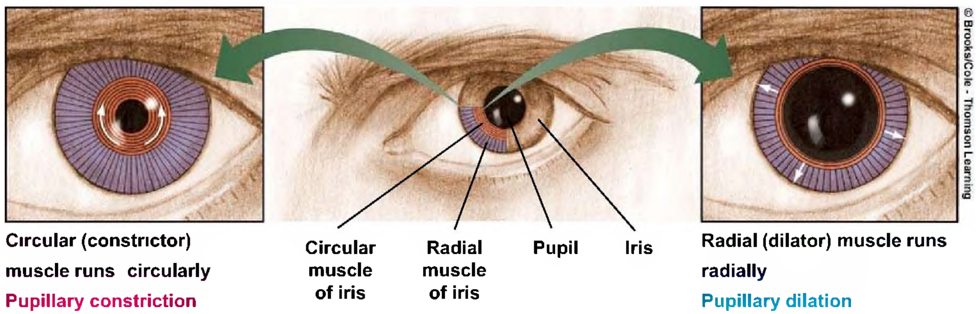
Vision

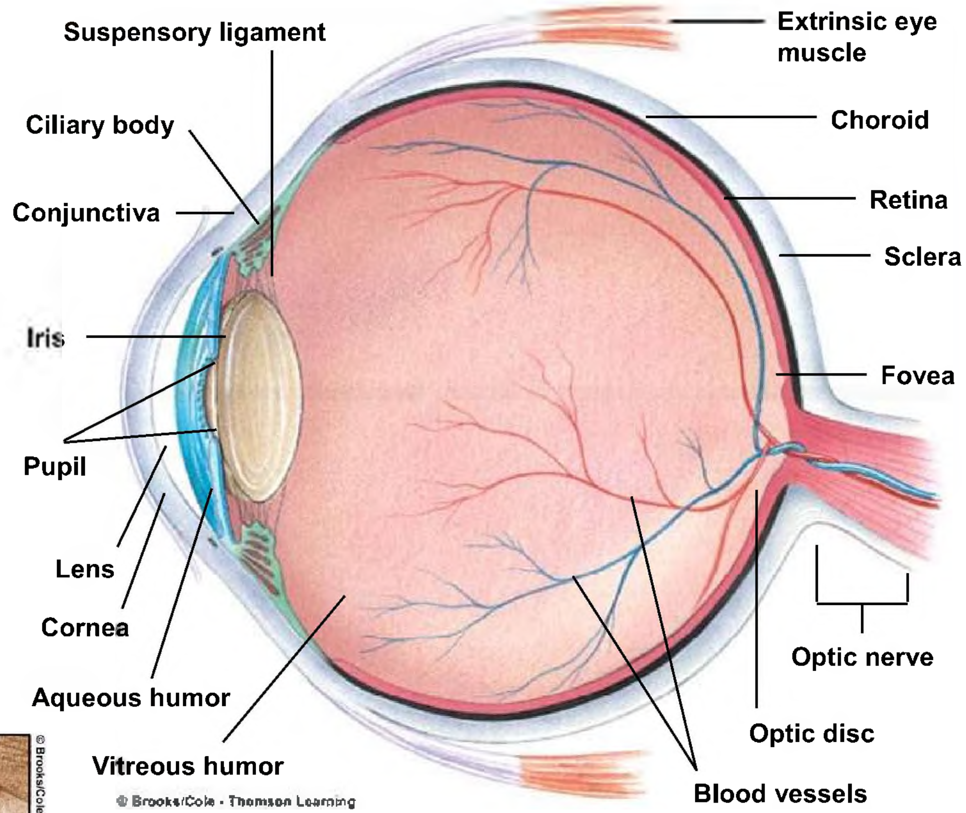
- **Sensation ≠ Perception**
- **Perception**
  - Our understanding (conscious interpretation) of the physical world
  - An interpretation of the senses
  - Different from what is out there because
    - Our receptors detect limited number of existing energy forms
    - The information does not reach our brain unaltered. Some features are accentuated and some are suppressed
    - The brain interprets the information and often distorts it ("completes the picture" or "feels in the gaps") to extract conclusions.
    - Interpretation is affected by cultural, social and personal experiences stored in our memory

Vision

- **Eye - Sensory organ for vision**

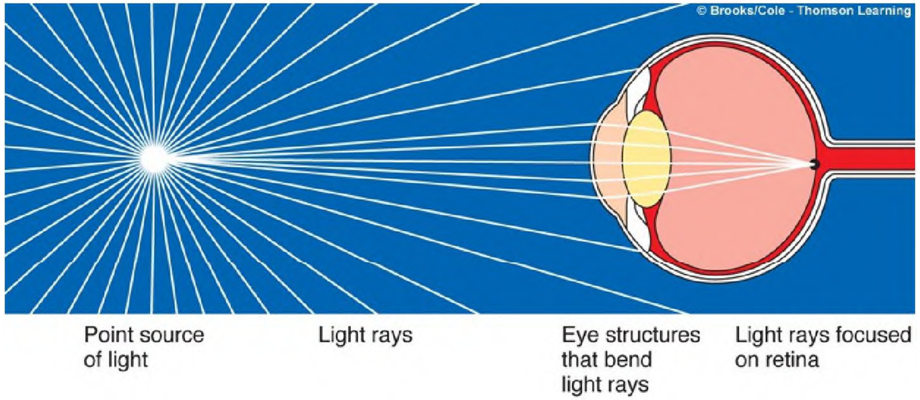


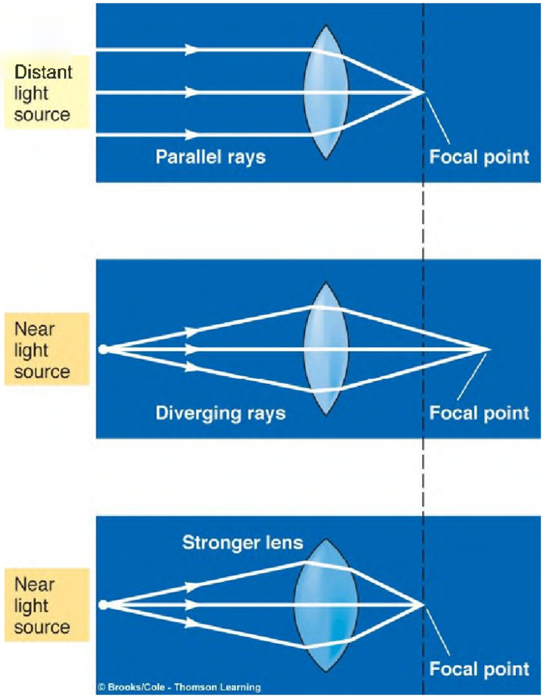


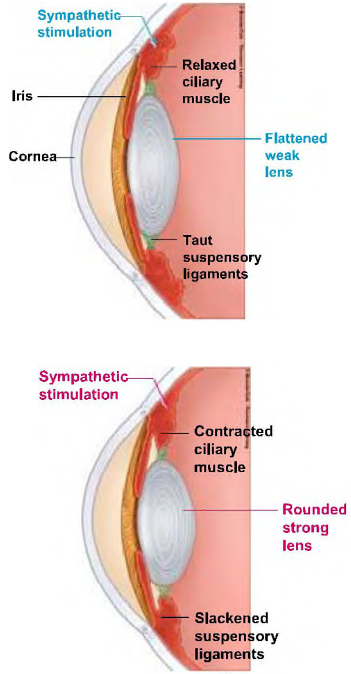


Vision

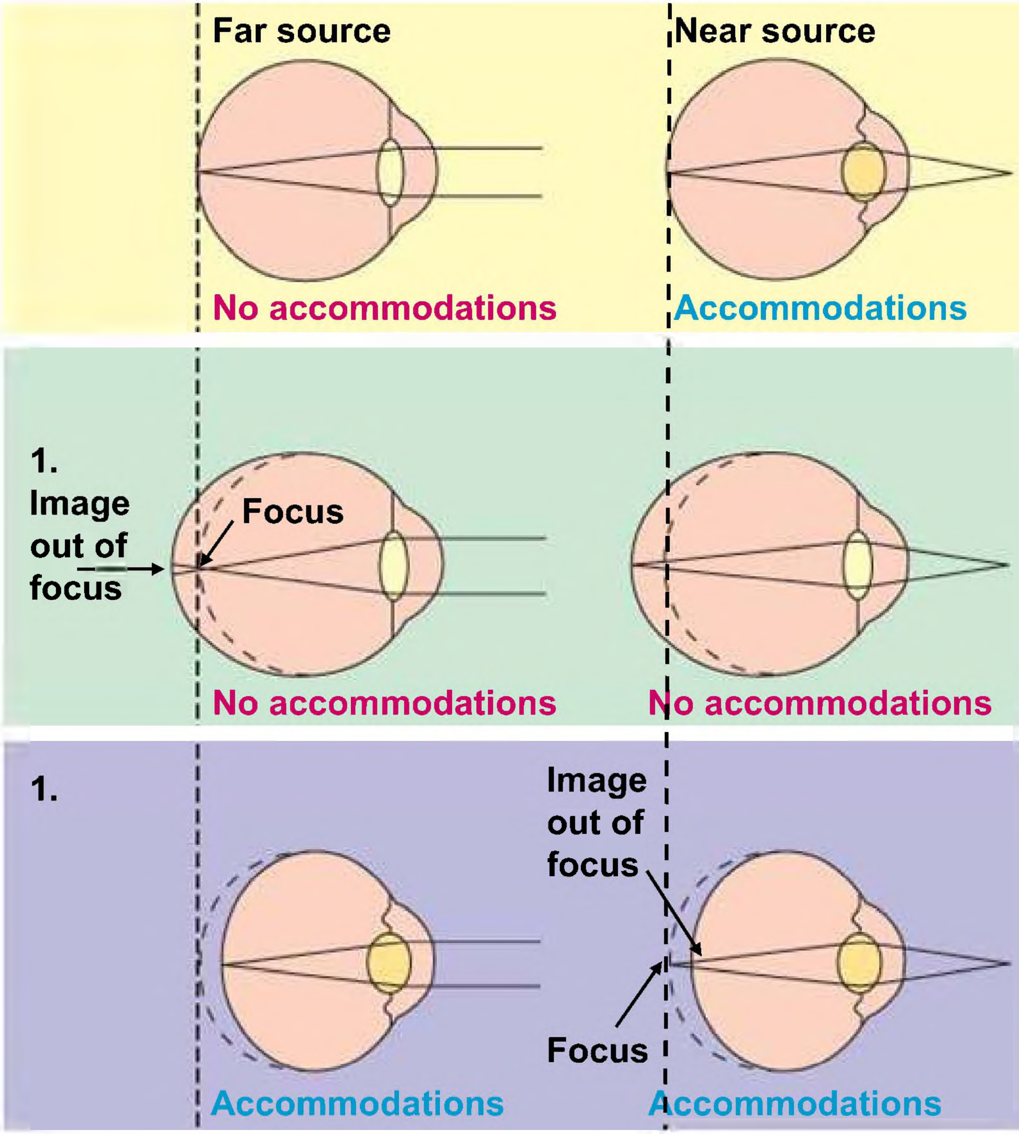
- **Convex structures of eye produce convergence of diverging light rays that reach eye**
- **Two structures most important in eye's refractive ability are**
  - Cornea
    - Contributes most extensively to eye's total refractive ability
    - Refractive ability remains constant because curvature never changes
  - Lens
    - Refractive ability can be adjusted by changing curvature as needed for near or far vision (***accommodation***)







Vision



Normal eye (Emmetropia)

Far source focused on retina without accommodation

Near source focused on retina with accommodation

Nearsightedness (Myopia)– Eyeball too long or lens too strong

1. Uncorrected

Far source focused in front of retina (where retina would be in eye of normal length)

Near source focused on retina with accommodations

Farsightedness (Hyperopia)– Eyeball too short or lens too weak

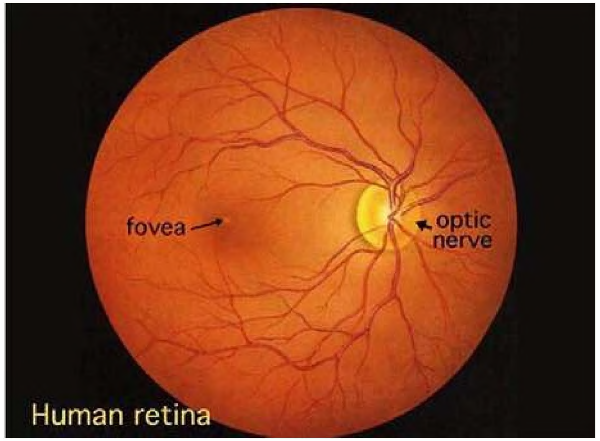
1. Uncorrected

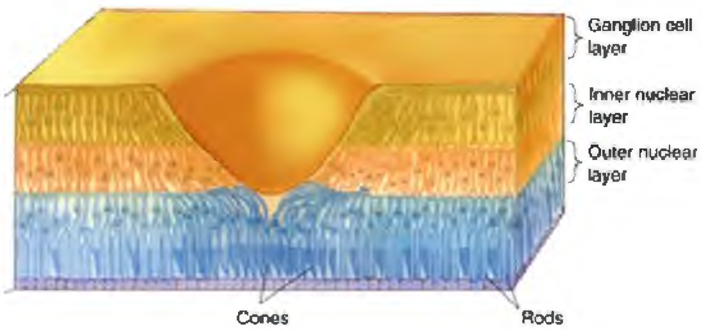
Far source focused on retina with accommodations

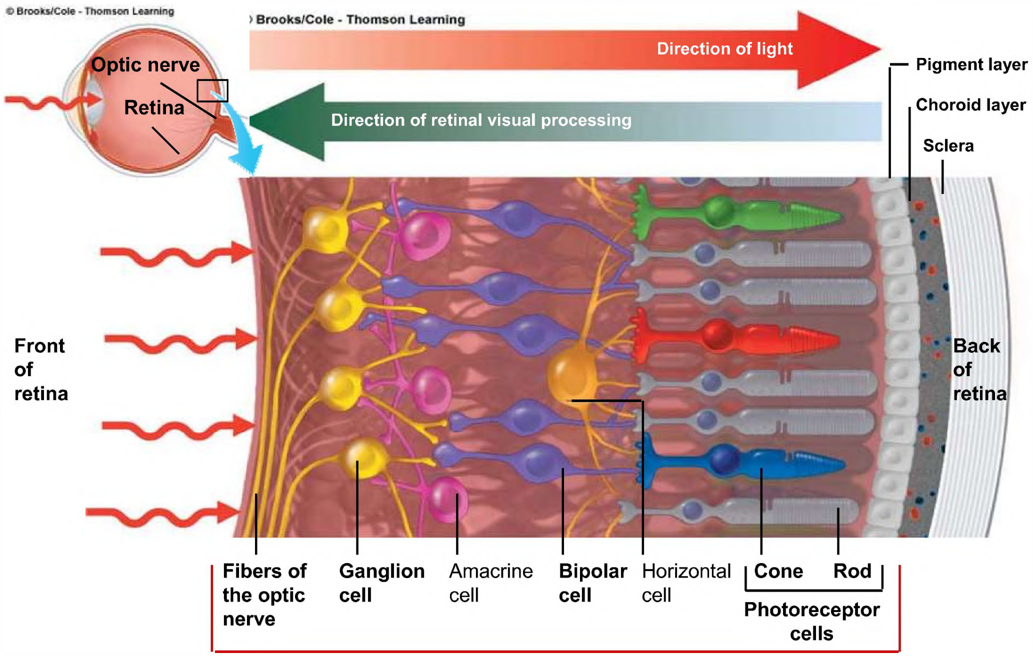
Near source focused behind retina even with accommodations

Vision

- **Retina**
  - Several layers of cells
  - Receptor containing portion is actually an extension of the CNS
- **Macula**
  - Center of vision
- **Fovea**
  - Pinhead-sized depression in exact center of retina
  - Point of most distinct vision
  - Has only cones



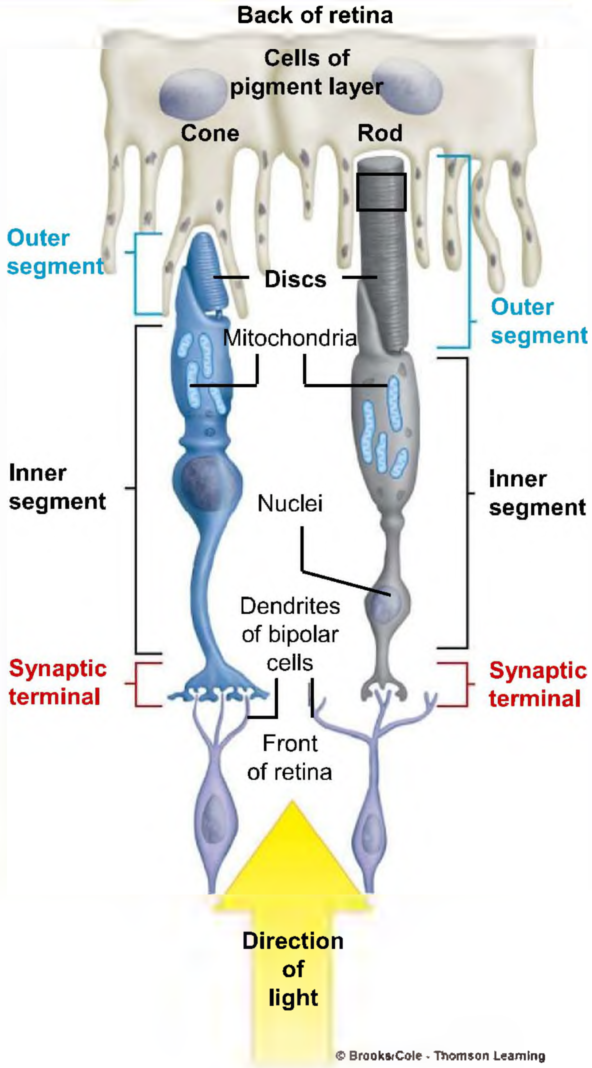




Vision

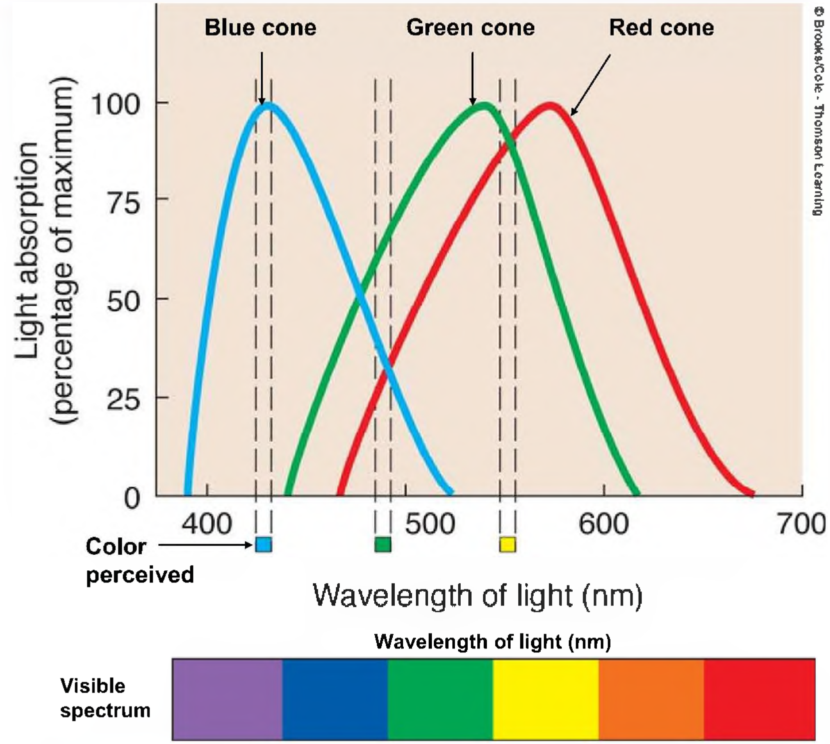
- **Photoreceptors**
  - Rod and cone cells
  - Photopigments on the disk membranes
    - Rod → one type
      - one pigment, high sensitivity
    - Cones → three different types
      - Red, green, blue sensing pigments, lower sensitivity
  - Undergo chemical alterations when activated by light
    - Change the receptor potential
    - Induce action potentials
    - Unlike other receptors, photoreceptors hyperpolarize!

Rods	Cones
100 million per retina	3 million per retina
Vision in shades of gray	Color vision
High sensitivity to light	Low sensitivity to light
Much convergence in retinal pathways	Little convergence in retinal pathways
Night vision (from sensitivity and convergence)	Day vision (lack sensitivity and convergence)
Low acuity	High acuity
More numerous in periphery	Concentrated in fovea



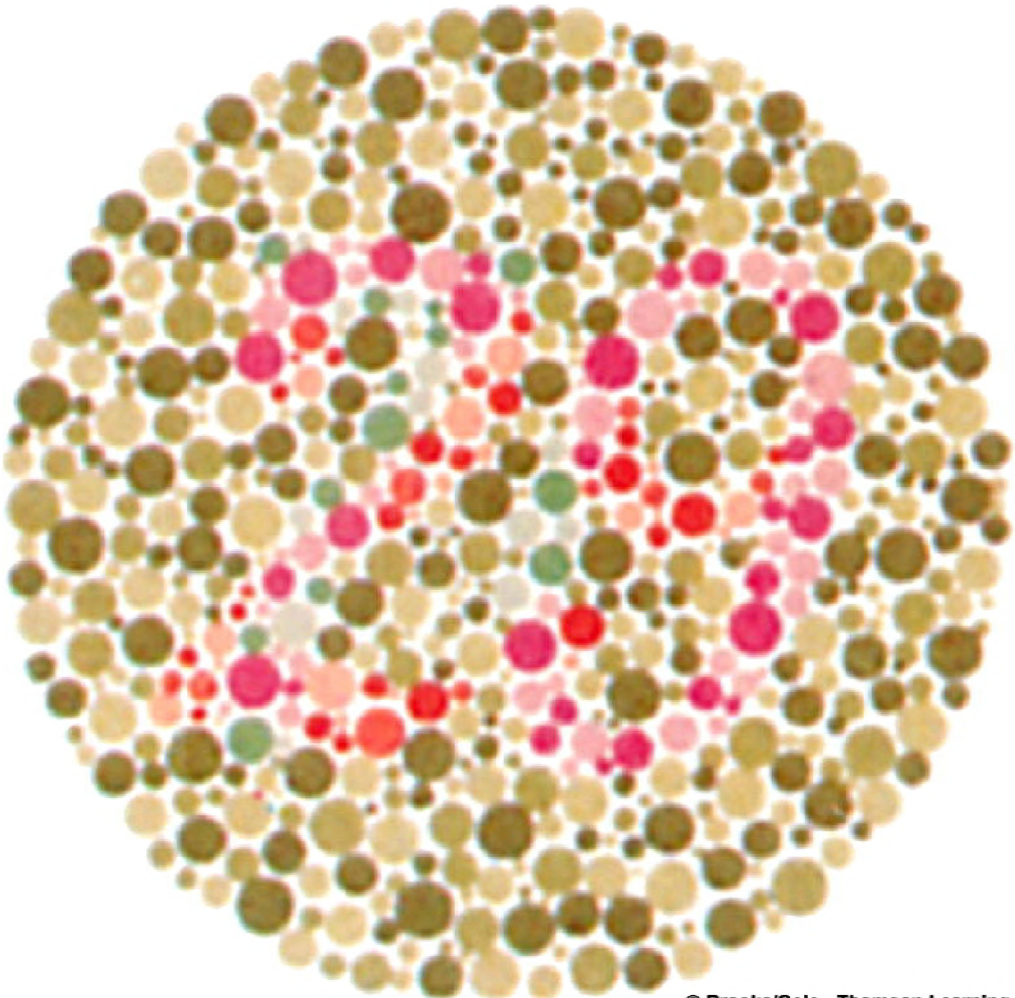
Vision

- **Color Vision**
  - Perception of color
  - Depends on the ratio of stimulation of three different cones
    - Different absorption of cone pigments
  - Coded and transmitter by different pathways
  - Processed in color vision center of primary visual cortex
  - Color blindness
    - Defective cone
    - Colors become combinations of two cones
    - Most common = red-green color blindness



Color perceived	Percent of maximum stimulation		
	Red cones	Green cones	Blue cones
	0	0	100
	31	67	36
	83	83	0

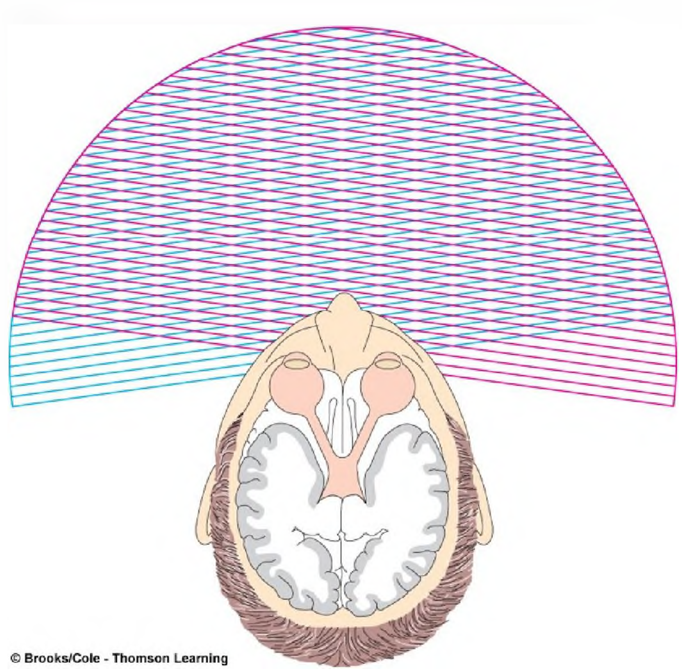
Vision



Vision

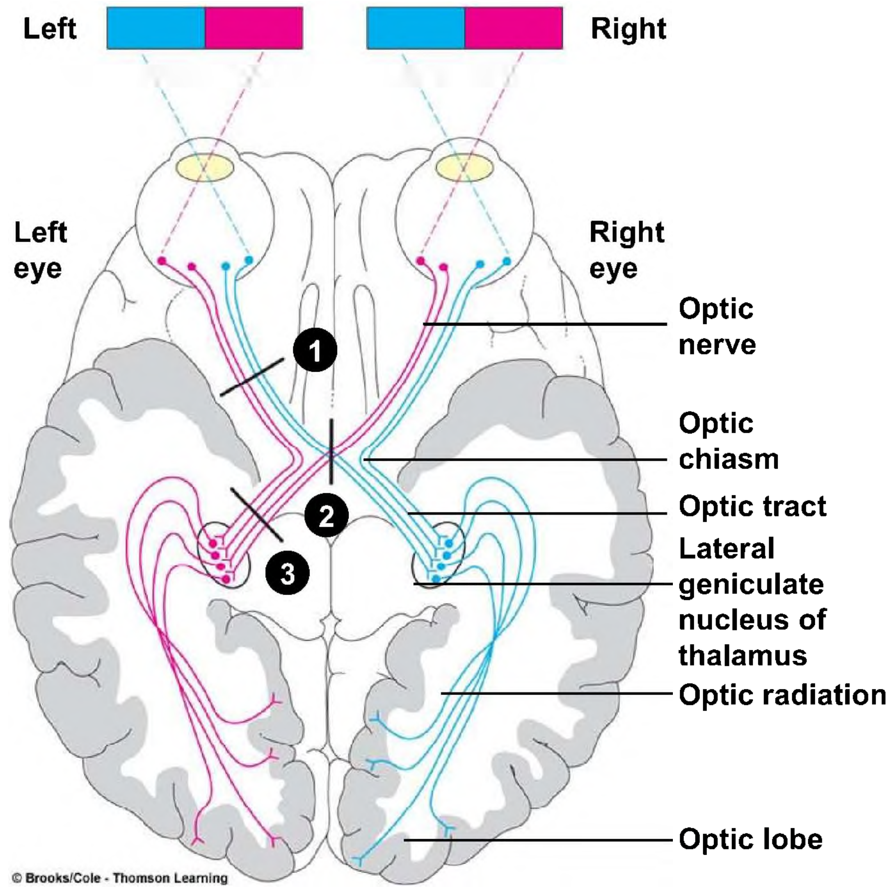
- **>30% of cortex participates in visual information processing**
  - “What” and “where” pathways

- **Depth Perception**
  - Visual field of two eyes slightly different
  - Depth perception with one eye
    - Other cues (such as size, location, experience)



Vision

- **Visual field**
  - Area which can be seen without moving the head) → overlap between eyes
- **Visual Pathway**
  - Optic nerve
  - Optic chiasm
  - Thalamus
  - Optic radiation
  - Primary visual cortex (occipital lobe)
  - Higher processing areas
- **Information arrives altered at the primary visual cortex**
  - Upside down and backward because of the lens
- **The left and right halves of the brain receive information from the left and right halves of the visual field**

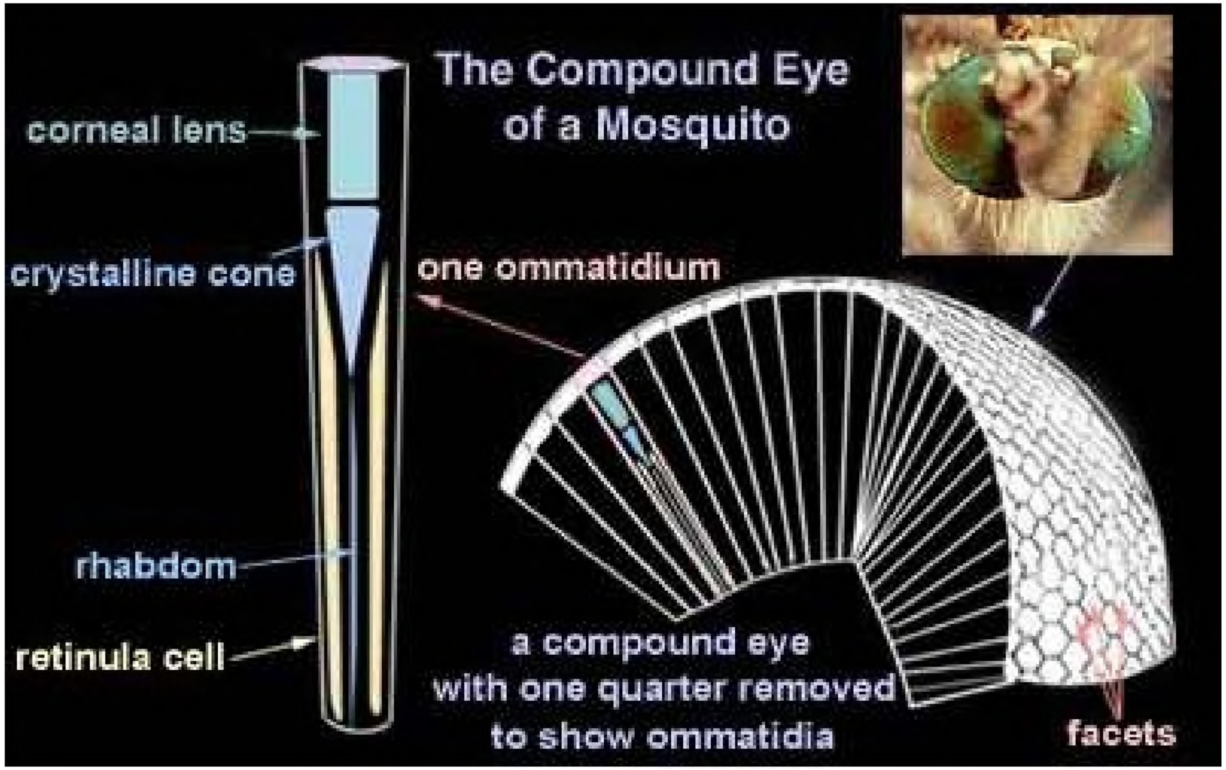


Vision

We make cameras that act "similar" to the human eye but …

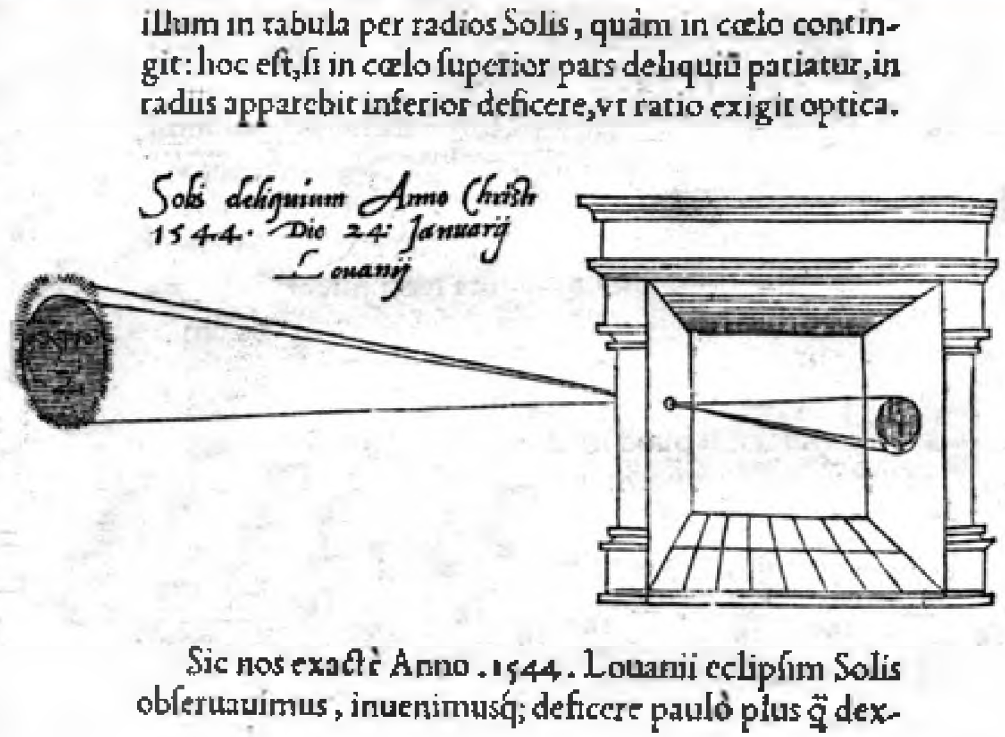
Insect Eyes

Fly



Mosquito

Camera Obscura


illum in tabula per radios Solis, quàm in cælo contin-
git: hoc est, si in cælo superior pars deliquiũ patiatur, in
radiis apparebit inferior deficere, vt ratio exigit optica.

Sic nos exactè Anno .1544. Louanii eclipsim Solis
obseruauimus, inuenimusq; deficere paulò plus q̃ dex-

"When images of illuminated objects ... penetrate through a small hole into a very dark room ... you will see [on the opposite wall] these objects in their proper form and color, reduced in size ... in a reversed position, owing to the intersection of the rays".
Leonardo *da Vinci*

http://www.acmi.net.au/AIC/CAMERA_OBSCURA.html (Russell Naughton)

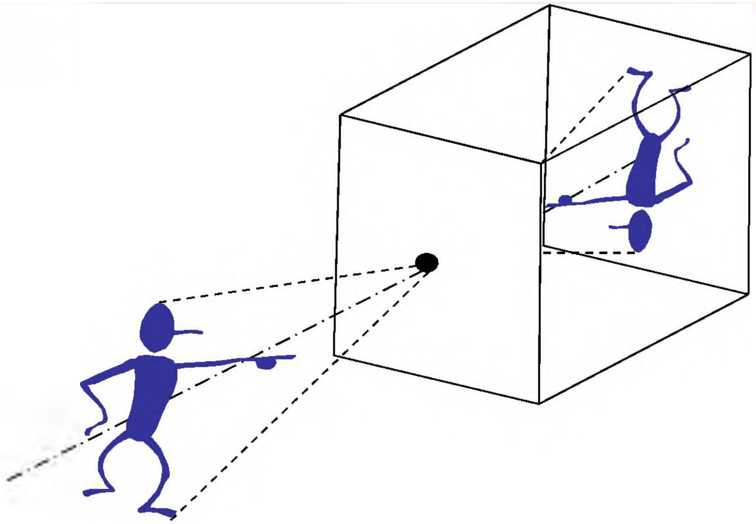
Slide credit: David Jacobs

Pinhole Cameras

- **Pinhole camera**
  - Box with a small hole in it
  - Image is upside down, but not mirrored left-to-right
  - Question: Why does a mirror reverse left-to-right but not top-to-bottom?
- **Problems with Pinhole Cameras**
  - Pinhole size (aperture) must be "very small" to obtain a clear image.
  - However, as pinhole size is made smaller, less light is received by image plane.
  - If pinhole is comparable to wavelength of incoming light, DIFFRACTION effects blur the image!
  - Sharpest image is obtained when:

    $$d = 2\sqrt{f'\lambda}$$

    - d: pinhole diameter
  - Example: If f' = 50mm, λ = 600nm (red), → d = 0.36mm



Lenses

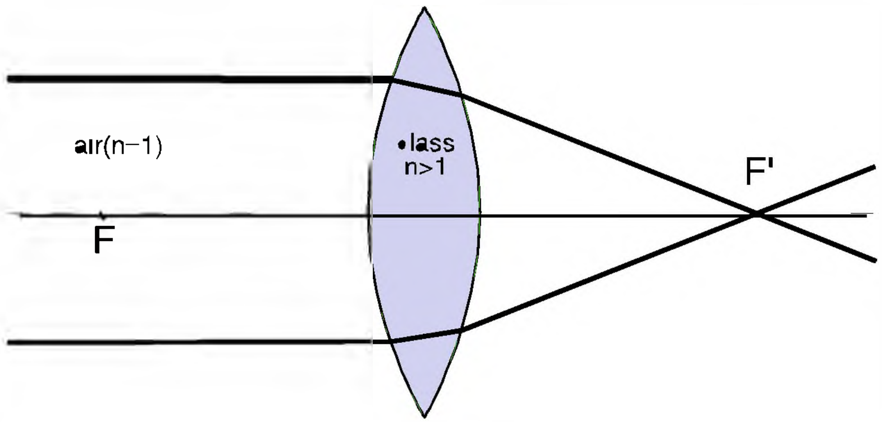
- **Image Formation using (Thin) Lenses**
  - Lenses are used to avoid problems with pinholes.
  - Ideal Lens: Same projection as pinhole but gathers more light!
- **Real Lenses**
  - High index material finite
  - Two radii of curvature
  - Lensmakers formula

$$\frac{1}{s_o} + \frac{1}{s_i} = (n_2 - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

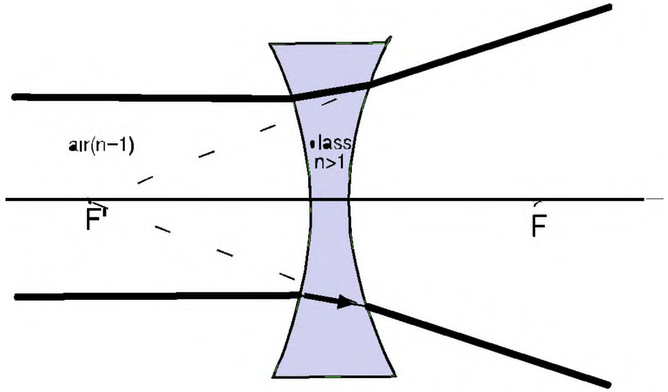
  - Focal length

$$\frac{1}{f} = (n_2 - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

Converging (focusing) Lens



Diverging (defocusing) Lens
(Focal length is negative)



Lenses

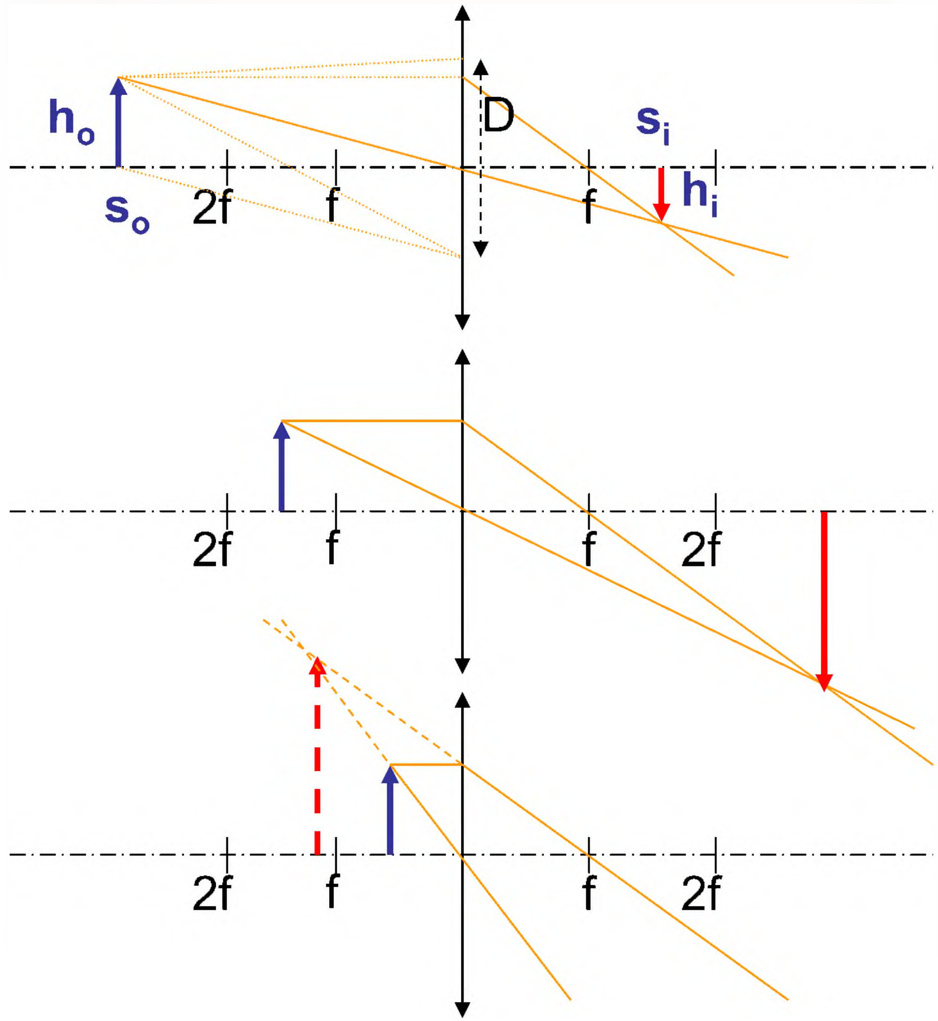
- **Image formation using one lens**
- **Ideal thin lens**

$$\frac{1}{f} = \frac{1}{s_o} + \frac{1}{s_i}$$

  - f = focal length
  - s_i = image distance
  - s_o = object distance

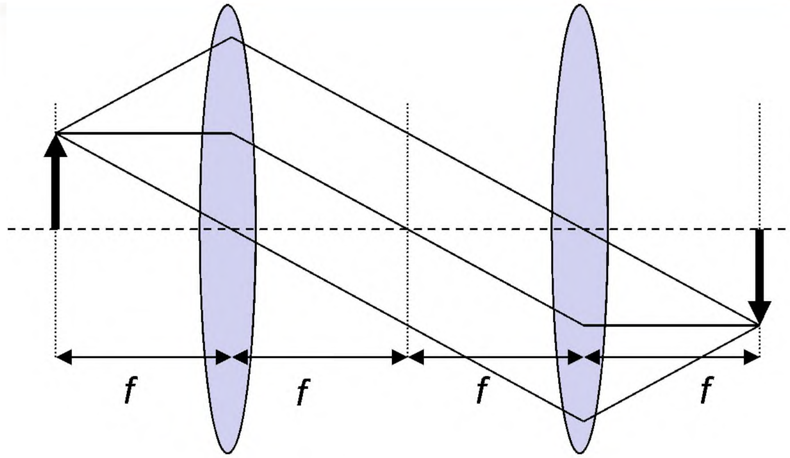
- **Magnification**

$$M = -\frac{s_i}{s_o} = -\frac{h_i}{h_o}$$

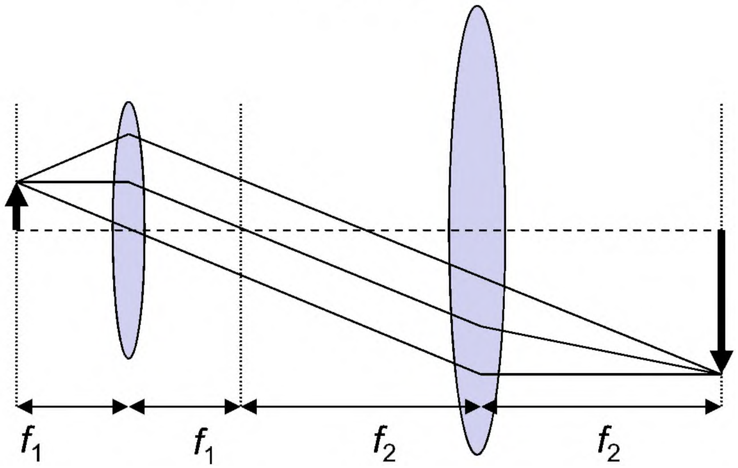


Lenses for imaging

- **Imaging with two lenses**
  - Depends on separation
- **Interesting case -- telescope**
  - equal focal lengths
    - 4 f imaging
  - unequal focal lengths
    - magnification = f_2/f_1



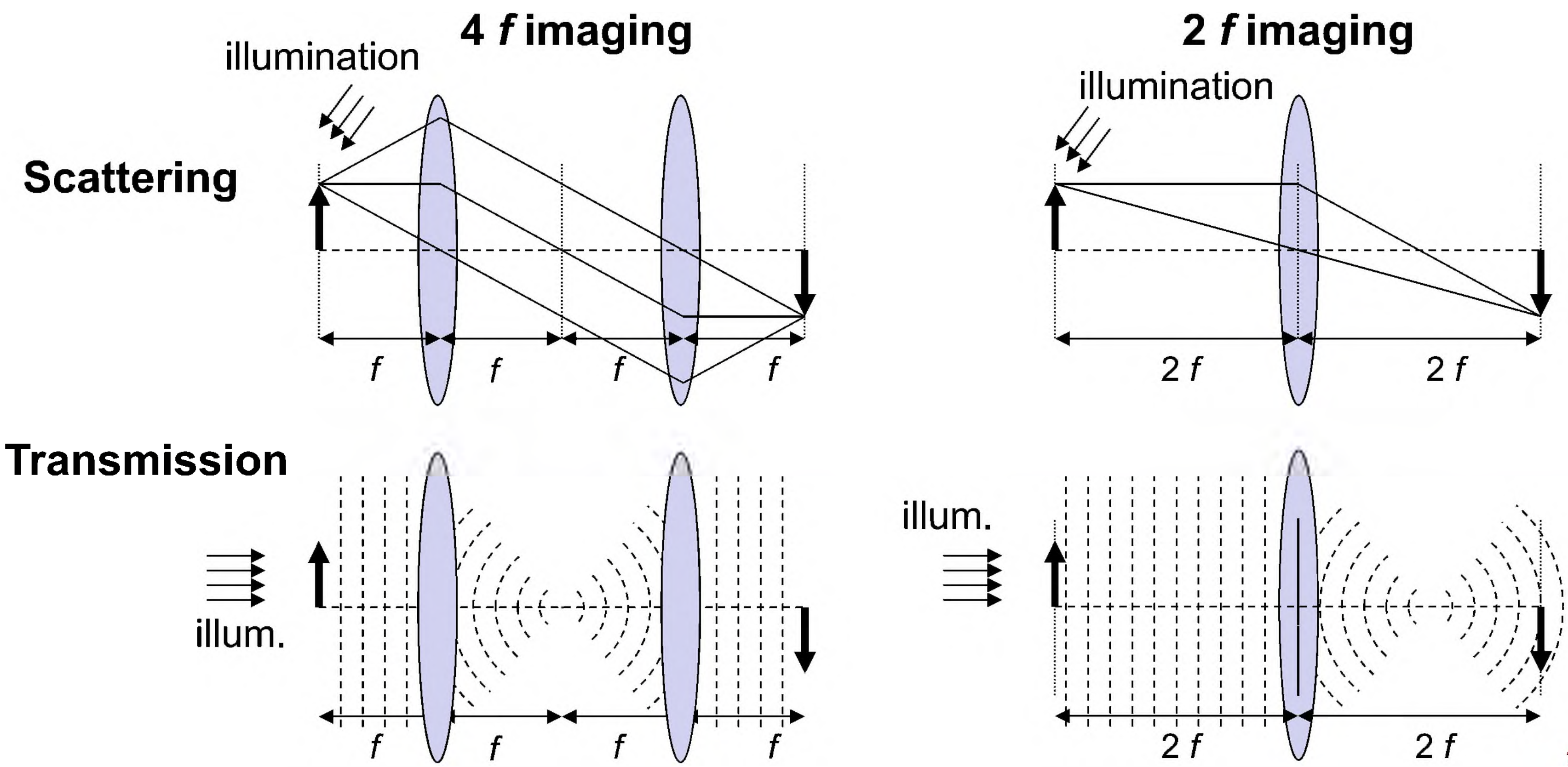
4 *f* imaging



Imaging telescope

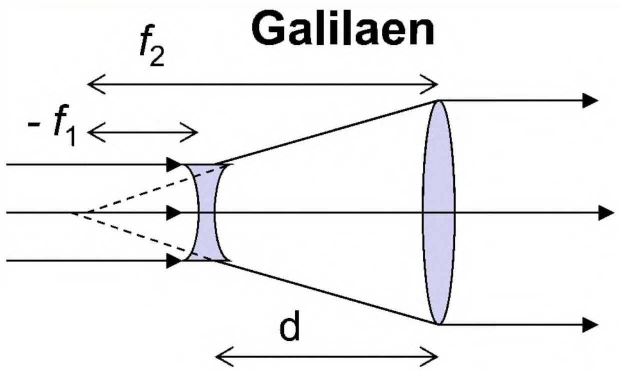
Lenses

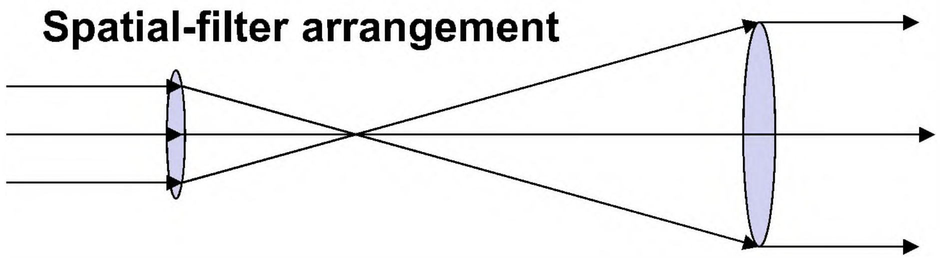
- **Imaging scattering vs. Transparent objects**
  - Scattering object acts as array of sources
  - Transmission object -- curvature important
    - 4 f configuration better

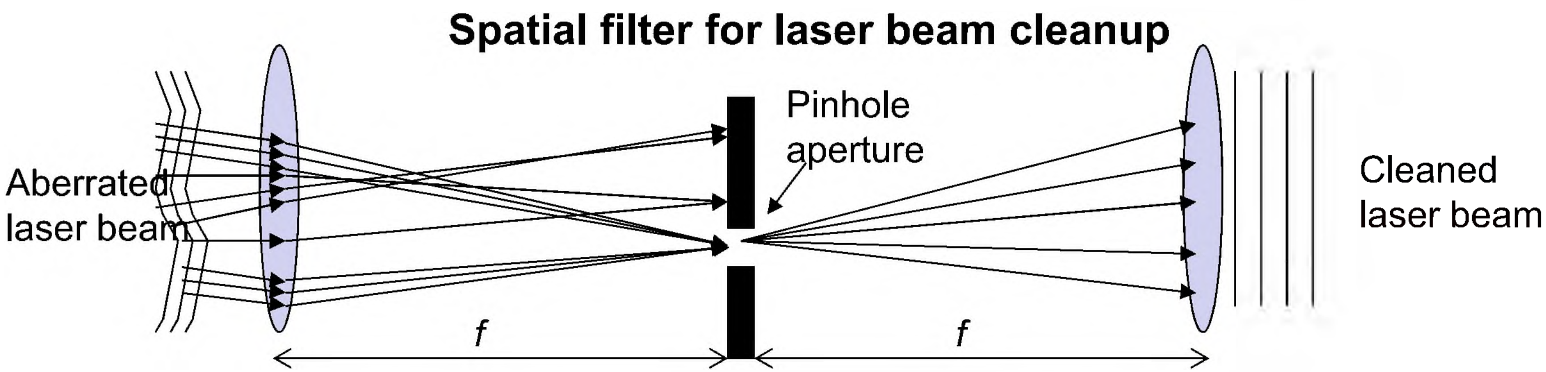


Lenses

- **Beam expanders**
  - Analogous to 4 f imaging
    - wavefront curvature preserved
    - magnification is focal length ratio
      - independent of lens spacing
  - Two types
    - Galilaen and spatial-filter arrangements
    - Galilaen easier to to set and maintain alignment

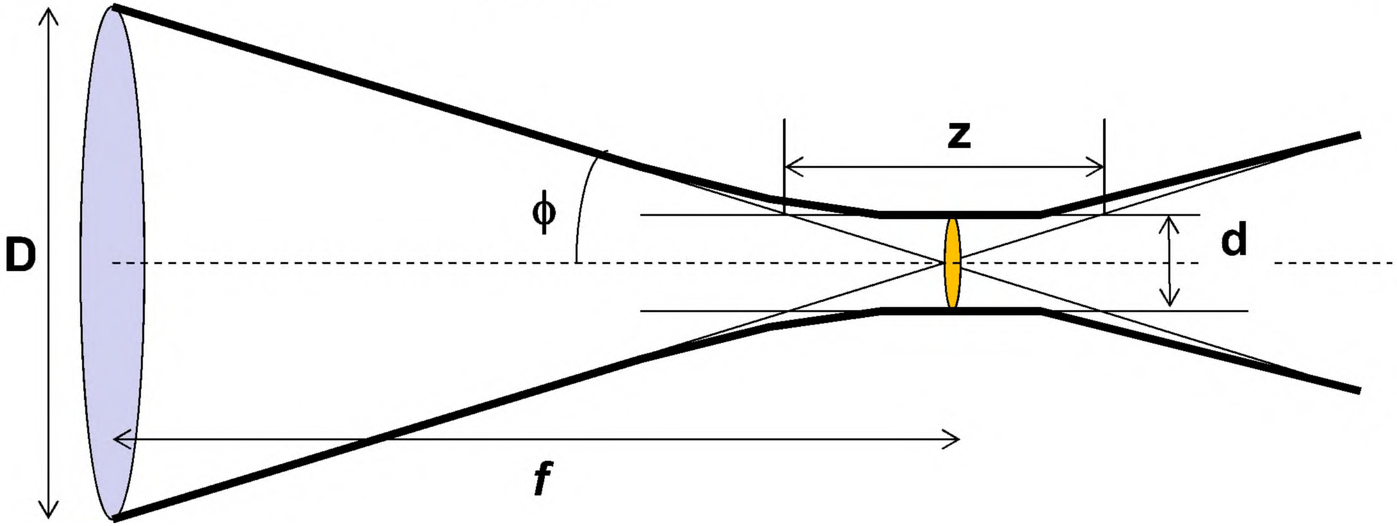






Lenses

- **F-number:** $f/\# = \frac{f}{D}$
  - (M is magnification)
- **Numerical aperture:** $NA = n\sin\phi$, for small angles: $NA = \frac{D}{2f} = \frac{1}{2f/\#}$
  - (n is refractive index)
- **Focal spot diameter:** $d = \frac{2.44 f\lambda}{D} = 2.44\lambda f/\# = \frac{1.22\lambda}{NA}$
- **Depth of focus:** $z = 1.22\lambda\left(\frac{2f}{D}\right)^2 \cos\phi$, for small angles: $z = \frac{1.22\lambda}{NA^2}$

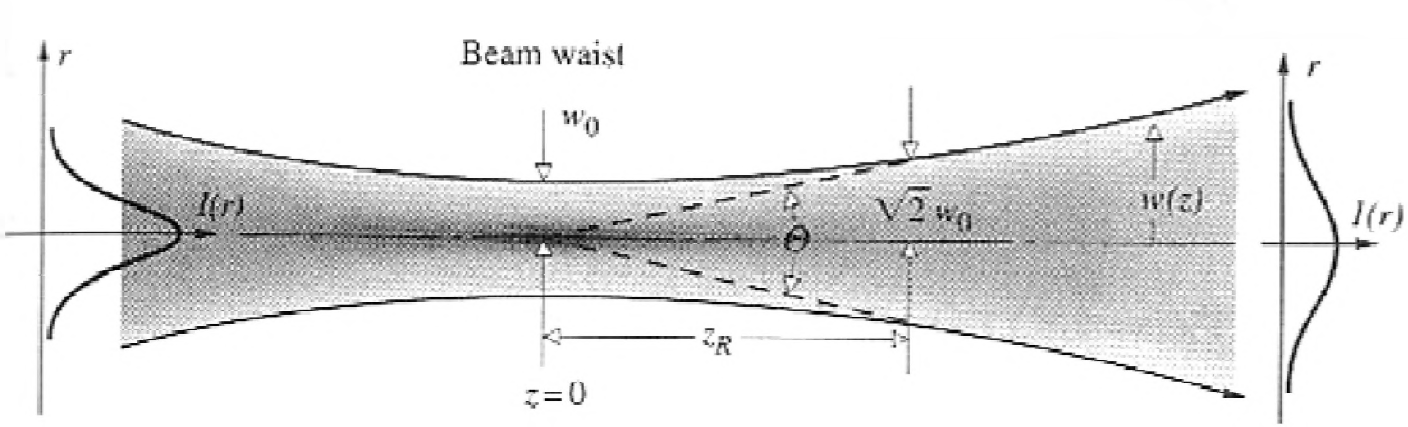


Lenses

- Gromit captured at f/22 (left) and at f/4 (right).

Lenses

- **Gaussian Beams**
  - E.g. from laser, or single mode fiber, 2w is the effective D
  - Intensity profile: $I = I_0 e^{-2r^2/w^2}$
  - Beam waist: $w = w_0\sqrt{1+\left(\frac{\lambda z}{\pi w_0^2}\right)^2}$
  - Confocal parameter: $z_R = \frac{\pi w_0^2}{\lambda}$
  - Far from waist: $w \to \frac{\lambda z}{\pi w_0}$, divergence angle: $\Theta = \frac{2\lambda}{\pi w_0} = 0.637\frac{\lambda}{w_0}$



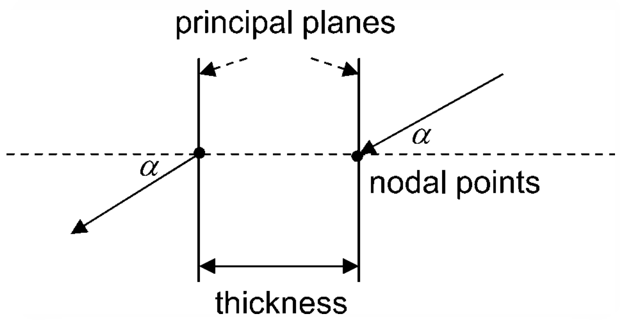
Lenses

	Standard Lens	Gaussian Beam
Aperture size	D	2w
Focal spot size	$d = \frac{2.44 f \lambda}{D}$	$d = 2w_0 = \frac{2.54 f \lambda}{2w}$
Depth of focus	$z = 1.22\lambda \left(\frac{2f}{D} \right)^2$	$z = 1.27\lambda \left(\frac{2f}{2w} \right)^2$

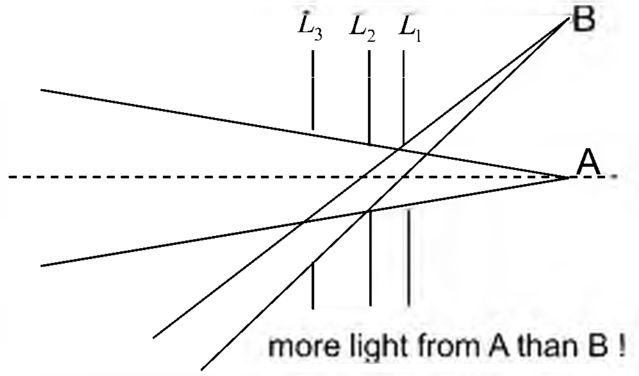
Lenses

- **Problems with Lenses**

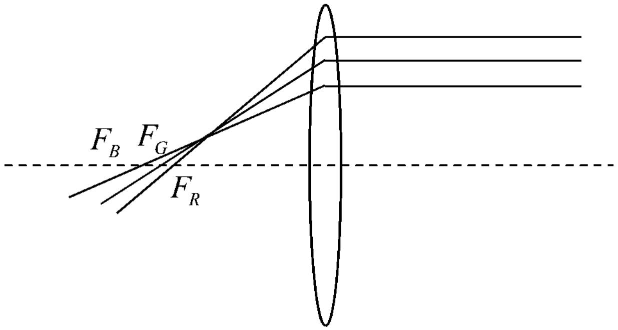
Compound (Thick) Lens



Vignetting



Chromatic Abberation



Lens has different refractive indices
for different wavelengths.

Radial and Tangential Distortion

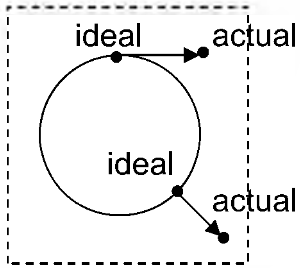
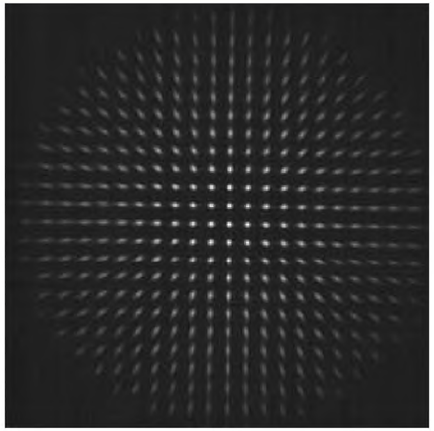


image plane

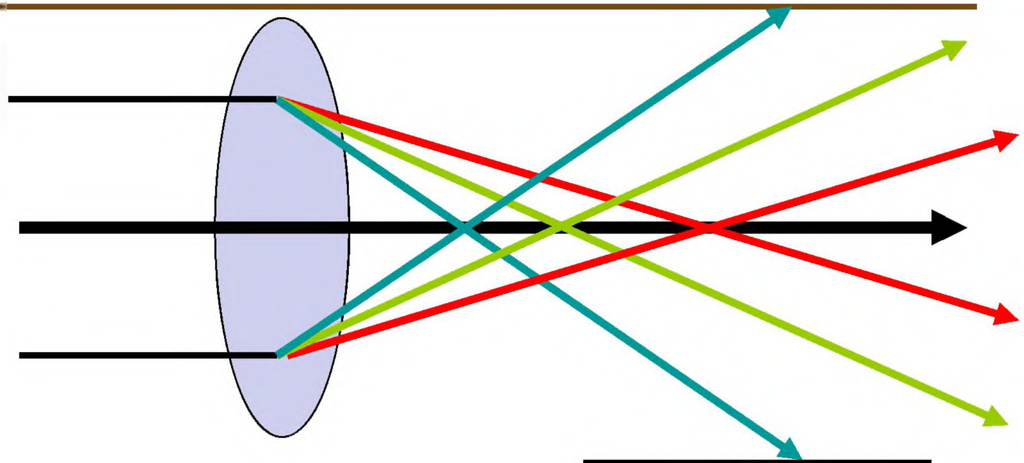
Lens Aberrations

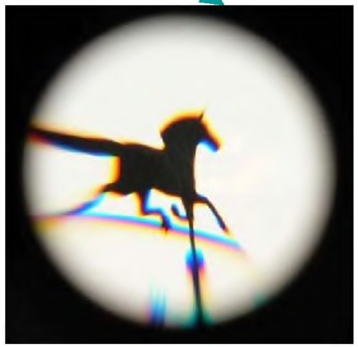
- **Lens Aberrations**
  - Chromatic
  - Spherical
  - Marginal Astigmatism
  - Coma
  - Curvature of Field
  - Distortion
  - Vignetting

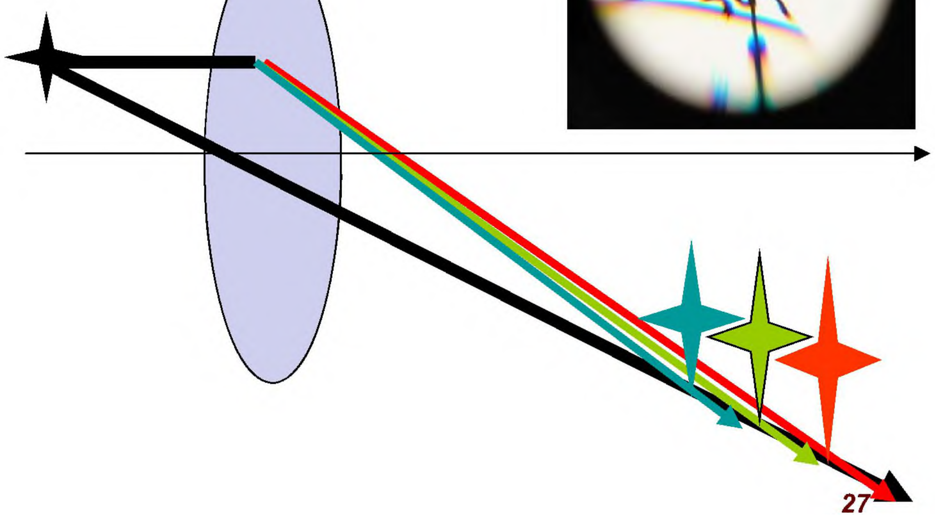


Lens Aberrations

- **Chromatic Aberrations**
  - Longitudinal (axial)
    - Various focal points on the axis.
  - Lateral (magnification)
    - Different image sizes
    - Result in colored ‘ghost’ images
  - Material dependent
    - λ dependent n
  - The higher the power of the lens, the more the chromatic aberration.
  - Correction:
    - Doublet lens or triplet lens
    - Change lens materials.
    - Control edge thickness

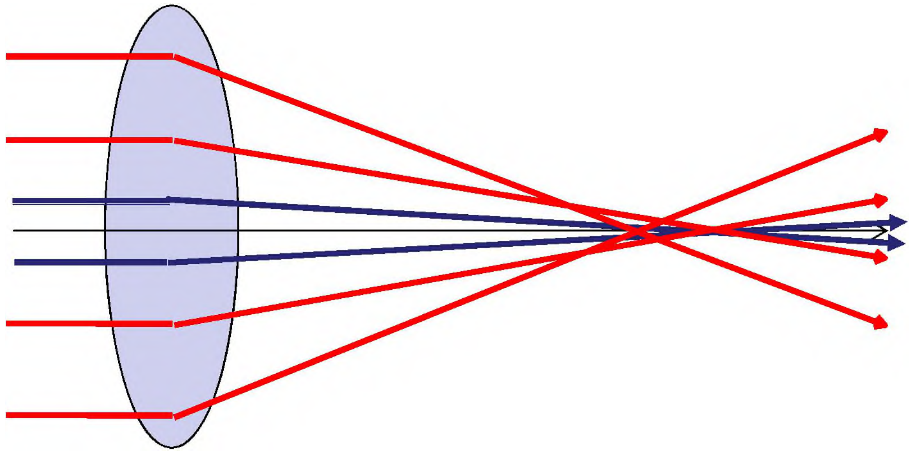


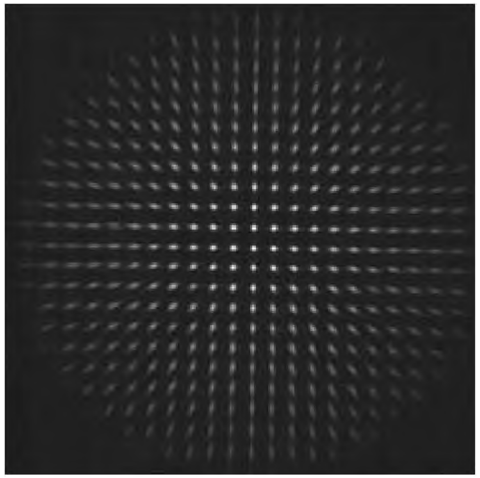




Lens Aberrations

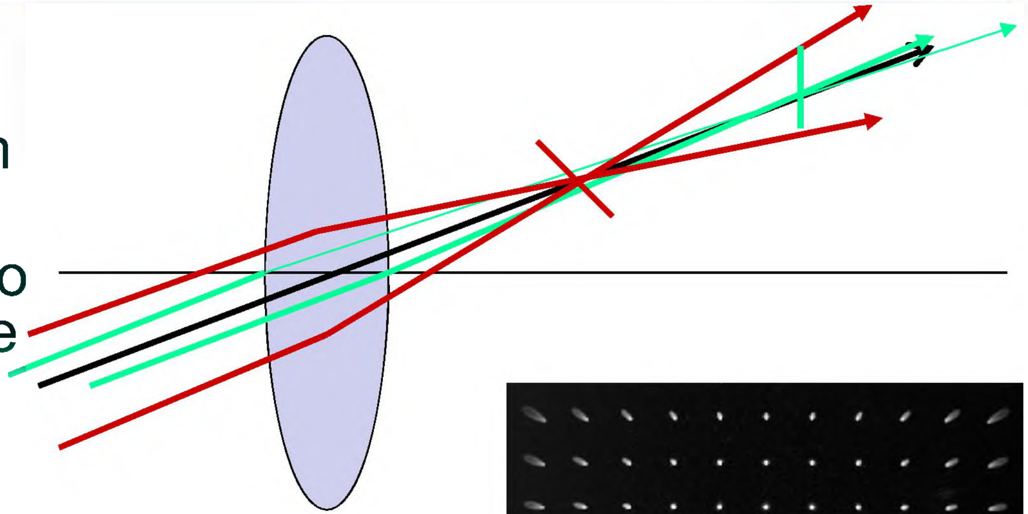
- **Spherical Aberrations**
  - Spherical lens
    - Peripheral rays have shorter focal length than paraxial rays → Peripheral rays refract more than paraxial rays.
  - Results in out-of-focus image.
  - Wide beam aberration – not important in narrow beam design.
  - On-axis aberration
  - Correction
    - Parabolic curves
    - Aplanatic lens design.

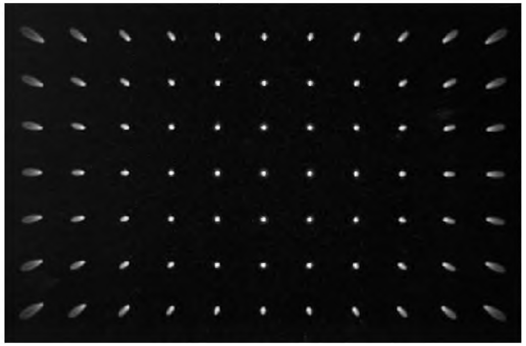




Lens Aberrations

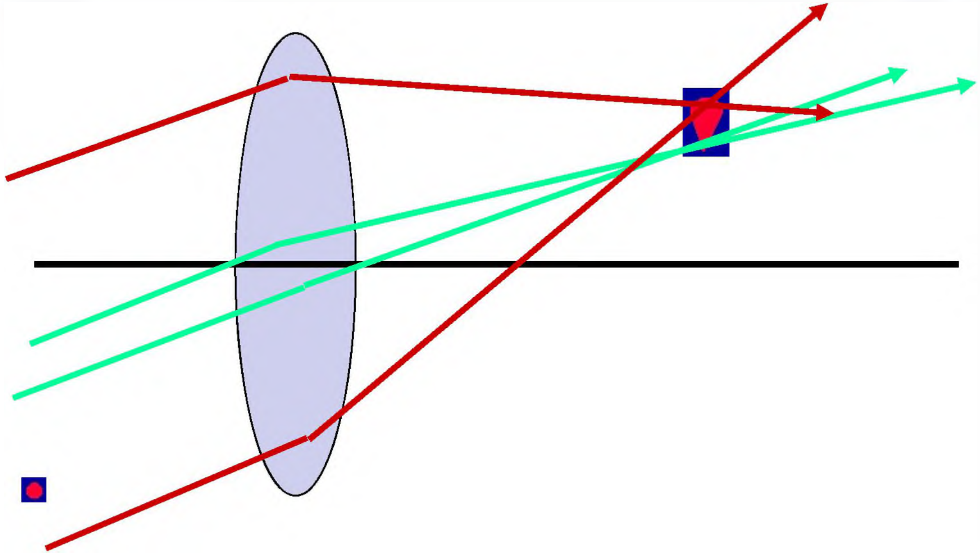
- **Marginal Astigmatism**
  - A.k.a Oblique astigmatism or Radial astigmatism
  - Rays that propagate in two perpendicular planes have different foci
  - Spherical lens, narrow beam entering off-axis.
  - Beam enters obliquely to lens axis, therefore effects periphery
  - Narrow beam aberration.
- **Correction**
  - Aspheric design for high powers and large lenses.





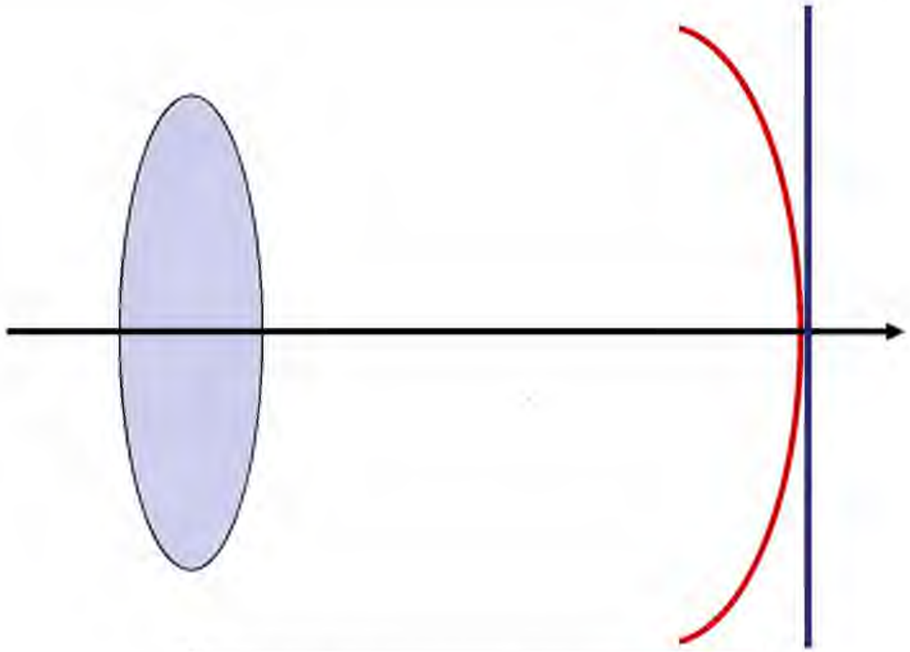
Lens Aberrations

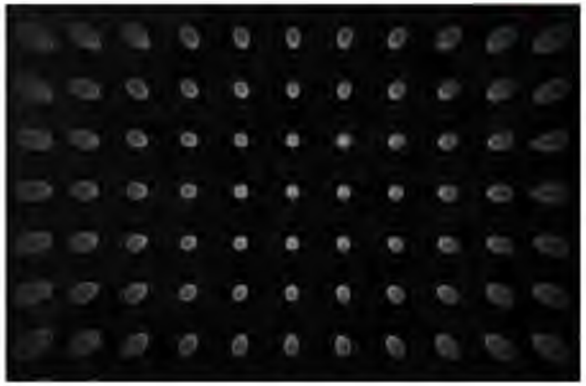
- **Coma**
  - Off-axis point sources appear distorted, like having a tail (coma)
  - Results in out-of-focus image
  - Wide beam aberration
- **Correction**
  - parabolic curves, planatic lens design.



Lens Aberrations

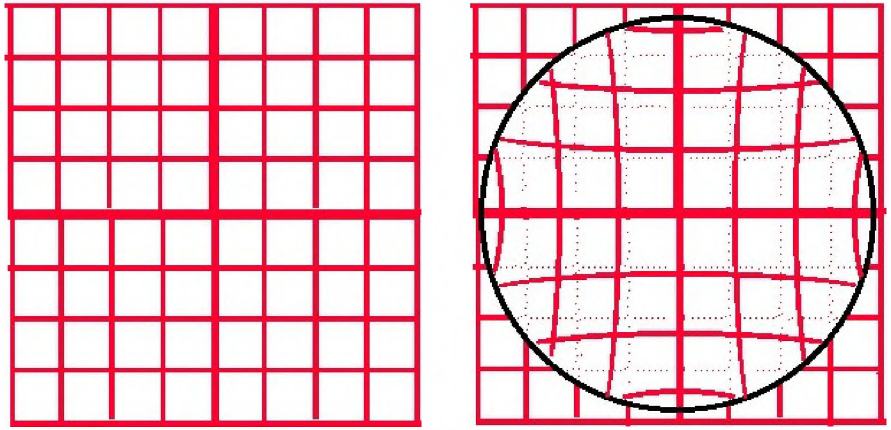
- **Curvature of Field**
  - A.k.a. Petzval field curvature
  - Light does not focus on a flat focal plane. The focal plane is curved.
    - Old movie screens → They were curved, not flat, to focus the sides of the movie as well as the center.
    - The retina is not a flat plane. It is curved.
  - Affects the periphery
- **Correction**
  - minimized with corrected curve design base curves.



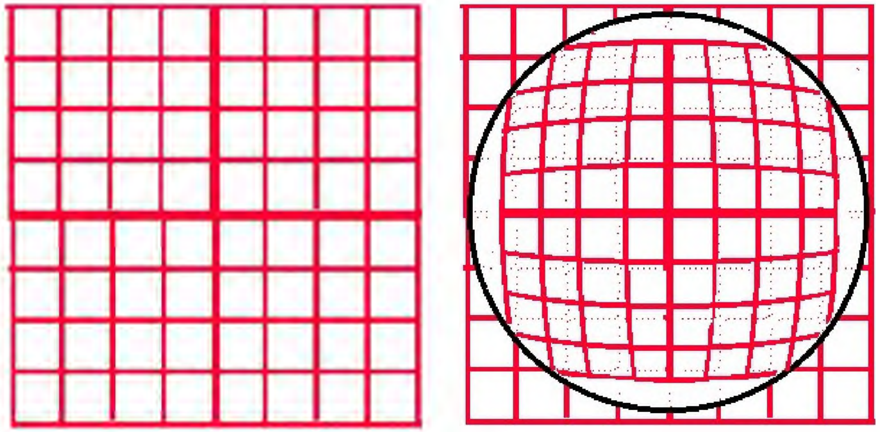


Lens Aberrations

- **Distortion**
  - A deviation from rectilinear projection → straight lines in a scene do not remain straight in an image
  - Image is in focus, but not shaped the same as the object
  - Usually from the presence of apertures in the system which distort the radial magnification
- **Correction:**
  - Aspheric design lenses



Distortion – pincushion – high plus lens



Distortion – barrel – high minus lens

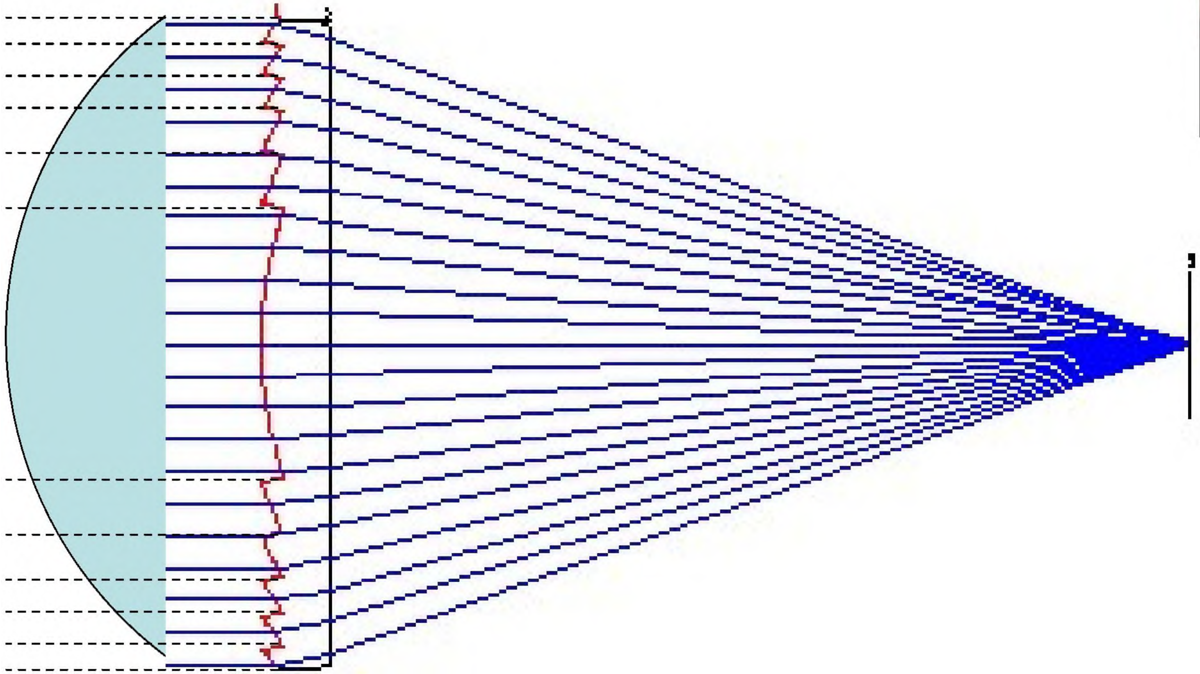
Lens Aberrations

- **Vignetting**
  - Reduction of an image's brightness or saturation at the periphery compared to the image center
  - Mechanical (block), optical (front lenses block light to the back), natural (light fall off not by blocking
- **Correction:**
  - Reduce aperture
  - Different design

Fresnel Lenses

- Start with conventional lens
- Constrain optical thickness to be modulo l
- Advantage -- thinner and lighter

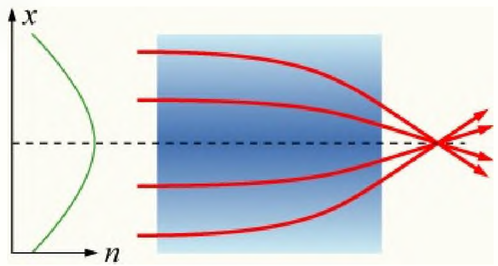
Fresnel vs conventional lens



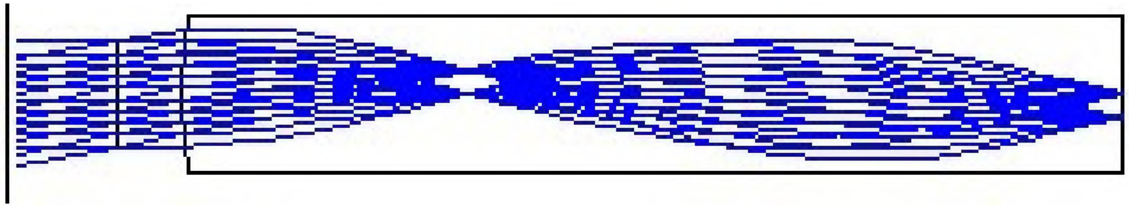
Graded index (GRIN) lens

- **Glass rod with radial index gradient**
- **Quadratic gradient -- high index in center**
  - like lens
  - optical path length varies quadratically from center
- **Periodic focusing**
  - laser spot size varies sinusoidally with distance

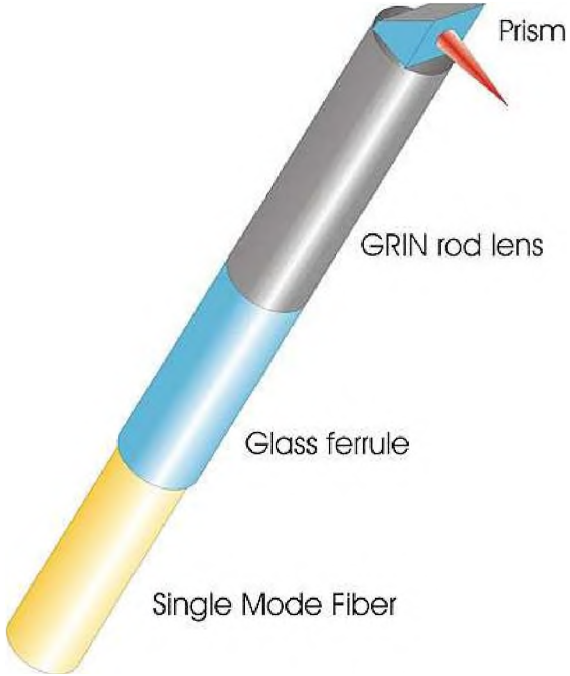
GRIN rod lens



GRIN periodic focusing



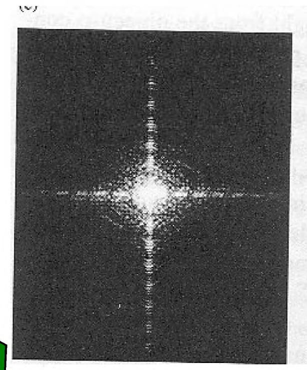
GRIN fiber probes



Lenses as Fourier Transformers

- **4 f configuration -- transform plane in center**

Fourier transform of letter "E"



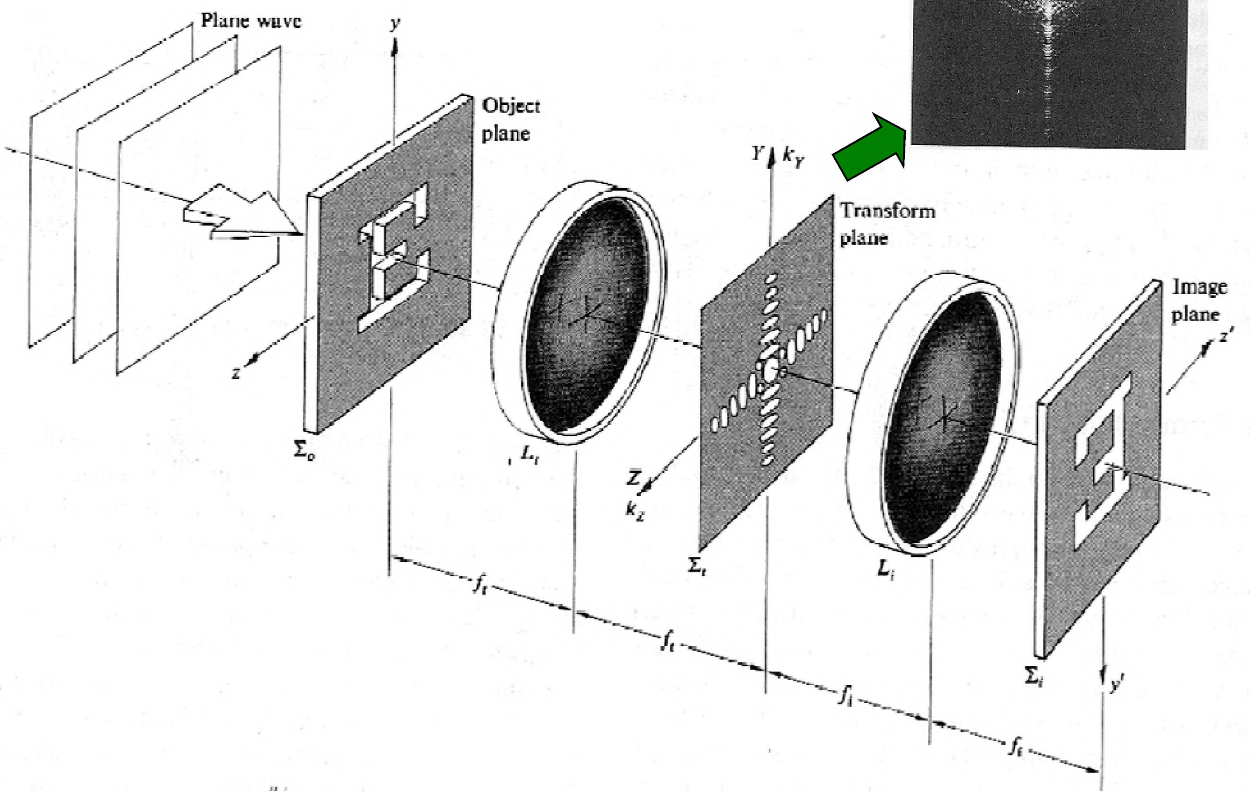
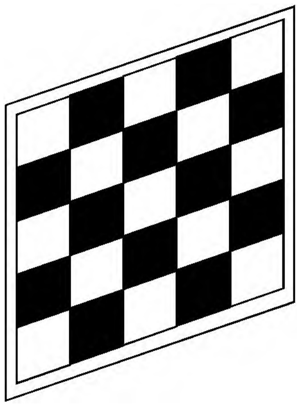
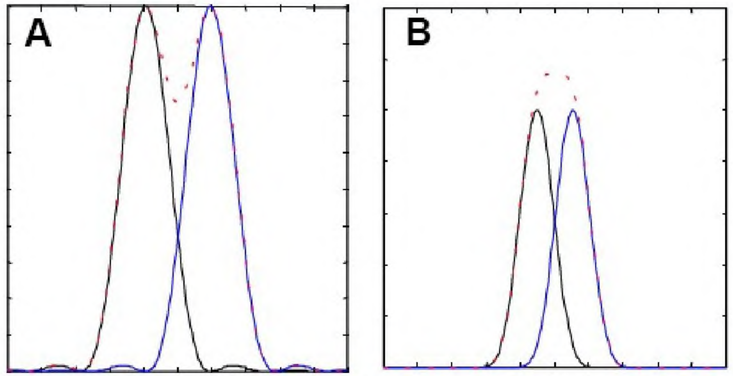


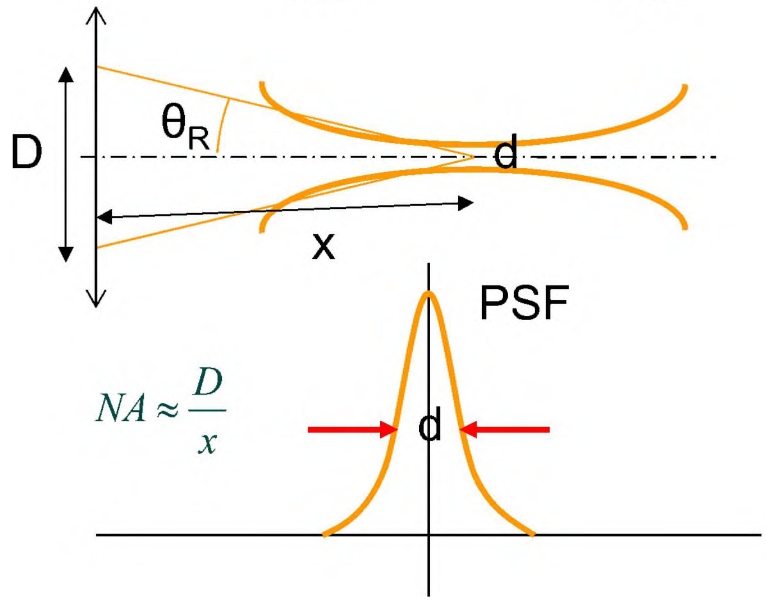
Image Formation

- **Image resolution**
  1. Number of pixels (e.g. 1024x1024)
  2. Smallest resolvable spatial frequency → smallest resolvable detail = optical resolution
- **Optical resolution**
  - Rayleigh criterion
    - 3 dB down between peaks
  - Sparrow criterion
    - Width of PSF
  - Aberrations degrade the resolution





$$d_{3dB} = \frac{1.02\lambda}{NA} \qquad d = \frac{1.22\lambda}{NA}$$



$$NA \approx \frac{D}{x}$$

Image Formation

Example

- **Characteristics**
  - Resolution: 1 mm
  - Field of View: 1 x 1 m
- **Choice of camera**
  - → 1m/1mm x 2 (Nyquist) =2000 pixels
  - ≥ 4 MPixel (2000 x 2000)
    - Π.χ. CCD, 5 MPixel, 2x2 cm Area
  - s_i = 17 mm (c-mount)
  - M = 2 cm / 1 m = 2×10^{-2}
  - s_o = s/M = 85 cm
  - f = 16,67 mm
- **Is this optically possible?**
  - d= M x 1 mm = 2×10^{-5} m
  - D = 2.44 λ s_i / d = 1.3 mm
  - Any lens with a diameter over 1.3 mm.
  - In the case of microscopic objects the diameter may be prohibitive!

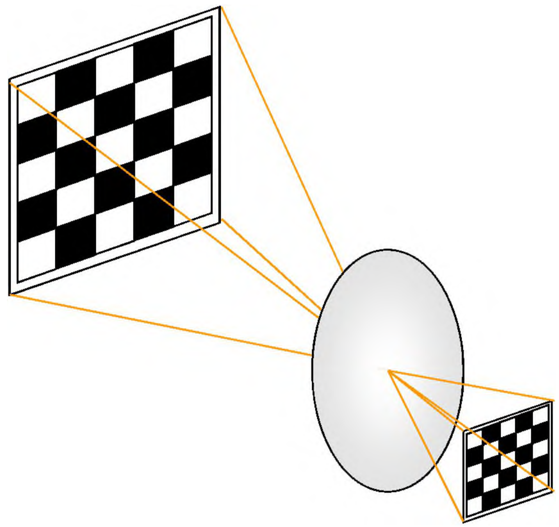


Image Formation

Example

- **Practical Problems**
  - f = 16,67 mm are not available commercially
  - Recalculate the system
  - M = $2x10^{-2}$
  - f = 20 mm
  - Solve the equations
    - S_{si} = 20,4 mm
    - S_o = 102 cm