CS 443: Imaging and Multimedia
Cameras and Lenses

Spring 2008
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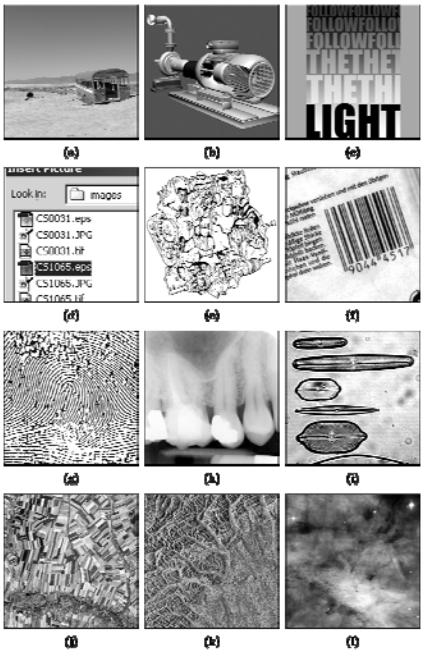
Outlines

Cameras and lenses !



They are formed by the projection of 3D objects.

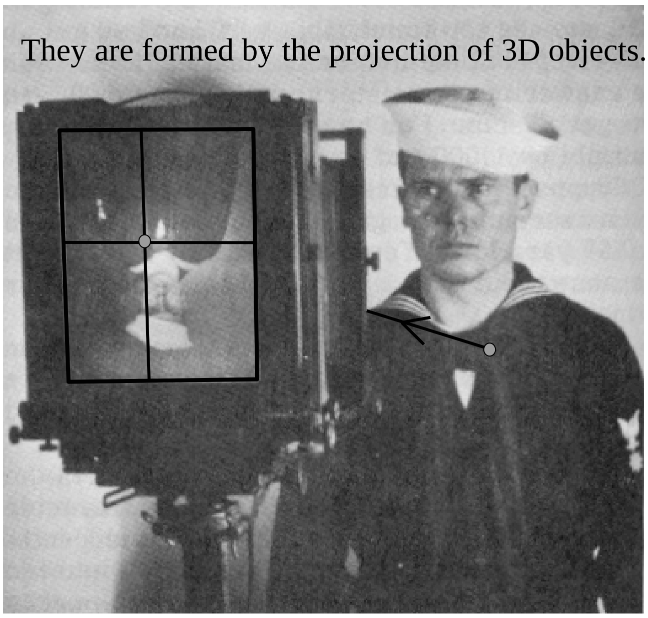
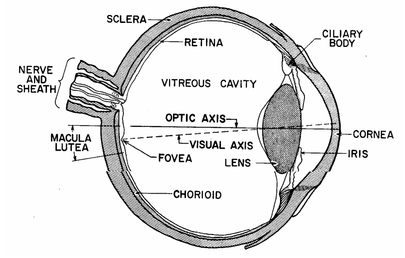


Figure from US Navy Manual of Basic Optics and Optical Instruments, prepared by Bureau of Naval Personnel. Reprinted by Dover Publications, Inc., 1969.

Images are two-dimensional patterns of brightness values.

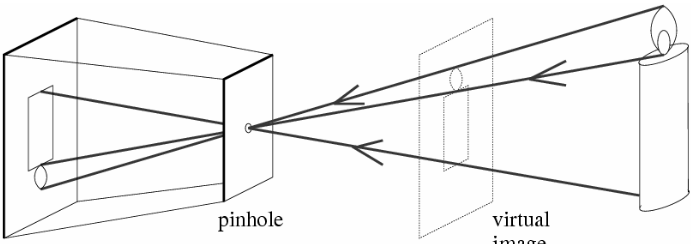
Reproduced by permission, the American Society of Photogrammetry and Remote Sensing. A.L. Nowicki, "Stereoscopy." Manual of Photogrammetry, Thompson, Radlinski, and Speert (eds.), third edition, 1966.



Animal eye: a looonnng time ago.

Figure from US Navy Manual of Basic Optics and Optical Instruments, prepared by Bureau of Naval Personnel. Reprinted by Dover Publications, Inc., 1969.

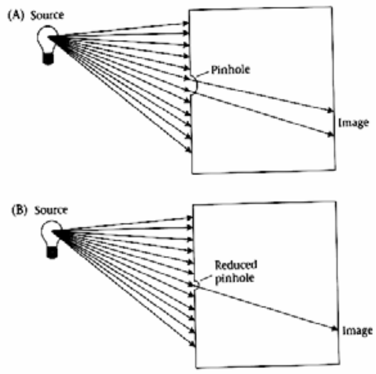
Photographic camera: Niepce, 1816.



Pinhole perspective projection: Brunelleschi, XV^th Century.
Camera obscura: XVI^th Century.

Lensless imaging systems - pinhole optics

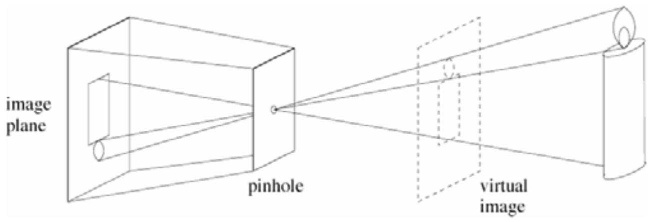
- Pinhole optics focuses images
  - without lens
  - with infinite depth of field
- Smaller the pinhole
  - better the focus
  - less the light energy from any single point



2.17 PINHOLE OPTICS. Using ray-tracing, we see that only a small pencil of rays passes through a pinhole. (A) If we use a wide pinhole, light from the source spreads across the image, making it blurry. (B) If we narrow the pinhole, only a small amount of light is let in. The image is sharp; the sharpness is limited by diffraction.

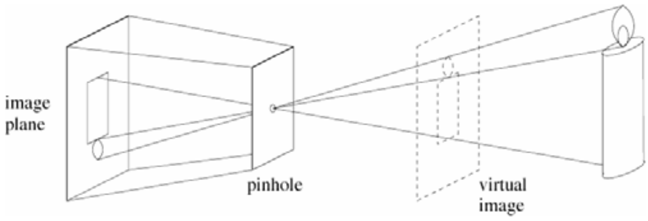
Pinhole cameras

- Abstract camera model - box with a small hole in it
- Each point in the image plane collect light from a cone of rays.
- If the pinhole is reduced to a single point (impossible) exactly one ray would pass through each point.

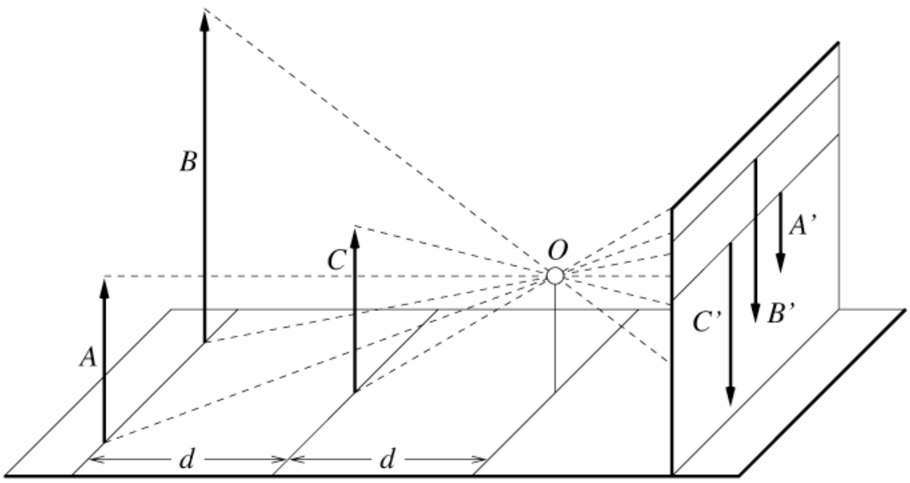


Pinhole Perspective

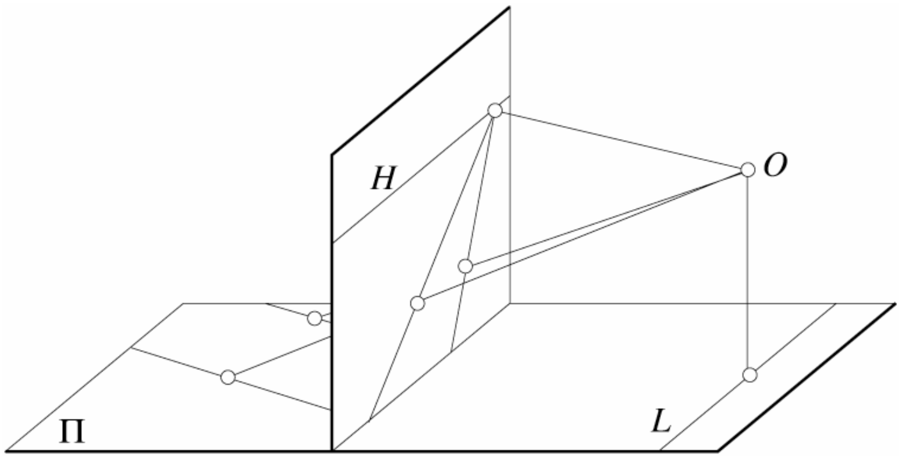
- Abstract camera model - box with a small hole in it
- Assume a single point pinhole:
  - Pinhole (central) perspective projection {Brunellleschi 15th Century}
  - Extremely simple model for imaging geometry
  - Doesn't strictly apply
  - Mathematically convenient – acceptable approximation.
  - Concepts: image plane, virtual image plane
  - Moving the image plane merely scales the image.



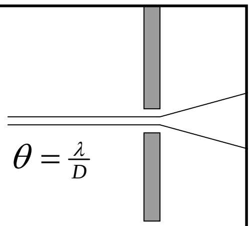
Distant objects are smaller



Parallel lines meet



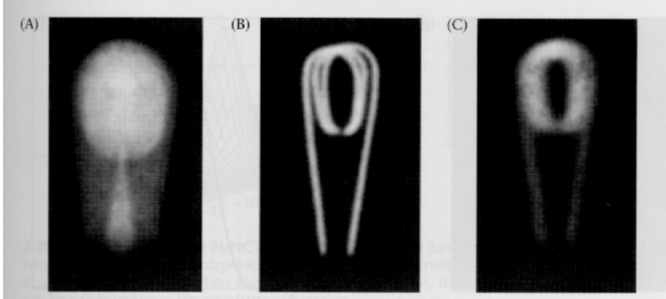
Diffraction



$\theta = \frac{\lambda}{D}$

- Two disadvantages to pinhole systems
  - light collecting power
  - diffraction
- Diffraction
  - when light passes through a small aperture it does not travel in a straight line
  - it is scattered in many directions
  - process is called diffraction and is a quantum effect
- Human vision
  - at high light levels, pupil (aperture) is small and blurring is due to diffraction
  - at low light levels, pupil is open and blurring is due to lens imperfections

Diffraction and pinhole optics

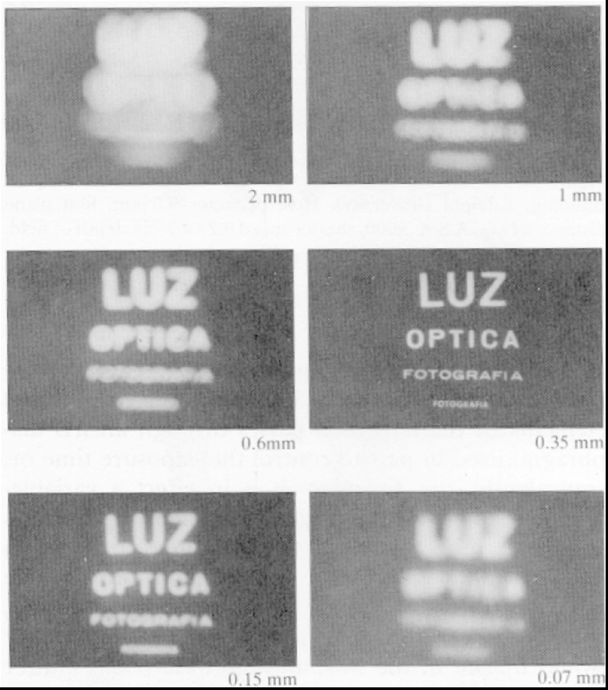


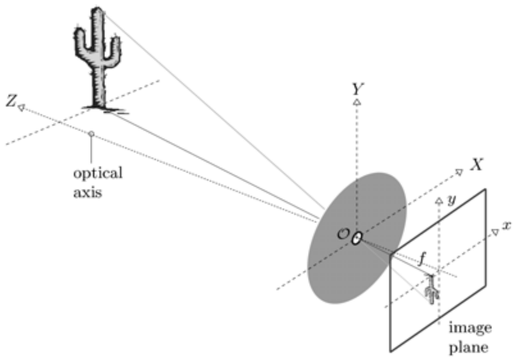
2.18 DIFFRACTION LIMITS THE QUALITY OF PINHOLE OPTICS. These three images of a bulb filament were made using pinholes with decreasing size. (A) When the pinhole is relatively large, the image rays are not properly converged, and the image is blurred. (B) Reducing the size of the pinhole improves the focus. (C) Reducing the size of the pinhole further worsens the focus, due to diffraction. From Ruechardt, 1958.

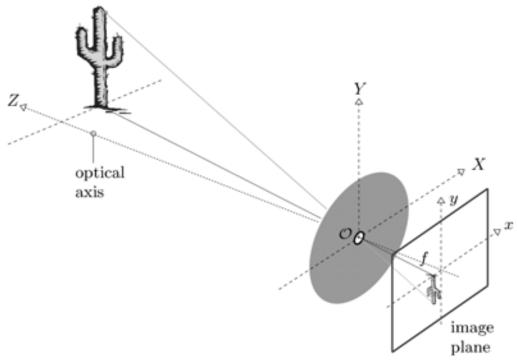
Pinhole too big - many directions are averaged, blurring the image

Pinhole too small- diffraction effects blur the image

Generally, pinhole cameras are *dark*, because a very small set of rays from a particular point hits the screen.



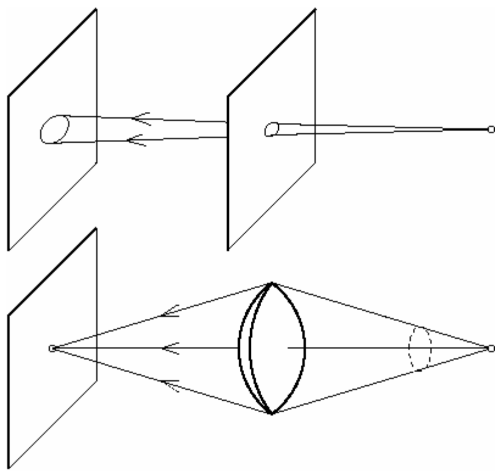




$$y = -f\frac{Y}{Z} \qquad x = -f\frac{X}{Z}$$

The reason for lenses

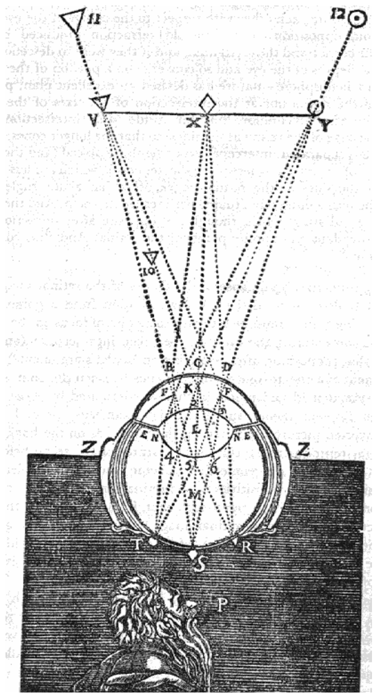
- Because of pinhole cameras limitations, we do need lenses
- With a lens, diverging rays from a scene point are converged back to an image point



Kepler's retinal theory

Even though light rays from "many" surface points hit the same point on the lens, they approach the lens from different directions.

Therefore, they are refracted in different directions - separated by the lens



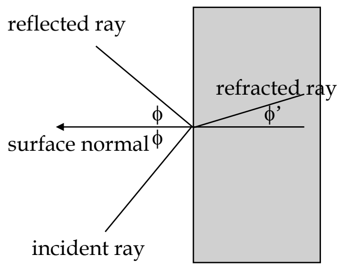
Snell's law

- Willebrord Snellius (Snel) 1621
- Descartes' law !, Earlier known by Ibn Sahl 940-1000!, earlier by Ptolemy!
- If ϕ is the angle of incidence and ϕ' is the angle of refraction then

$$n \sin\phi = n' \sin\phi'$$

Where n and n' are the refractive indices of the two media

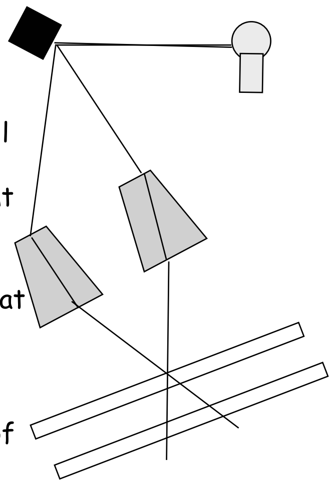
- Refractive index is the ratio of speed of light in a vacuum to speed of light in the medium



Refractive indices
glass - 1.52
water - 1.333
air - 1.000 - mercifully

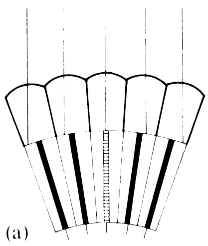
Applying Snell's Law twice

- Pass light into and out of a prism (symmetric piece of glass)
  - By combining many infinitesimally small prisms we form a convex lens that will bring all of the refracted rays incident from a given surface point into coincidence at a point behind the lens
  - If the image or film plane is placed that distance behind the lens, then that point will be in focus
  - If the image plane is in front of or behind that ideal location, the image of that point will be out of focus



The structure of eyes -compound eyes

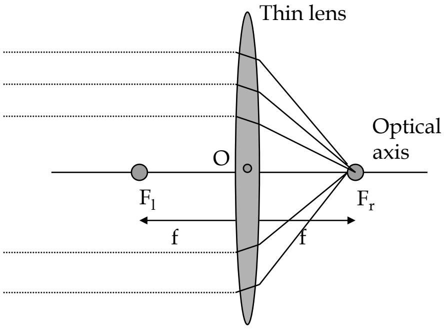
- Many (small) animals have compound eyes
  - each photoreceptor has its own lens
  - images seen by these eyes are equally sharp in all directions
  - images seen by these eyes are equally "bright" in all directions when viewing a field of constant brightness
  - examples: flies and other insects
- But these eyes do not "scale" well biologically



(a)

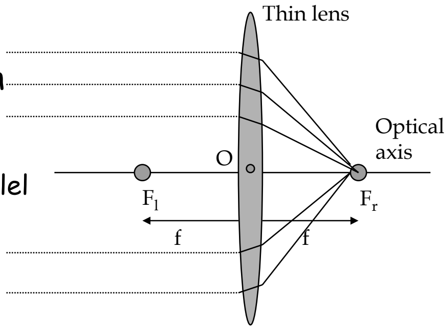
Thin lenses

- The optical behavior is determined by:
  - optical axis going through the lens center O and perpendicular to the lens center plane
  - the left and right focus (F_l and F_r) located a distance f, called the focal length, from the lens center



Thin lenses

- The shape of the lens is designed so that all rays parallel to the optical axis on one side are focused by the lens on the other side:
  - Any ray entering the lens parallel to the optical axis on one side goes through the focus on the other side.
  - Any ray entering the lens from the focus on one side, emerges parallel to the optical axis on the other side.



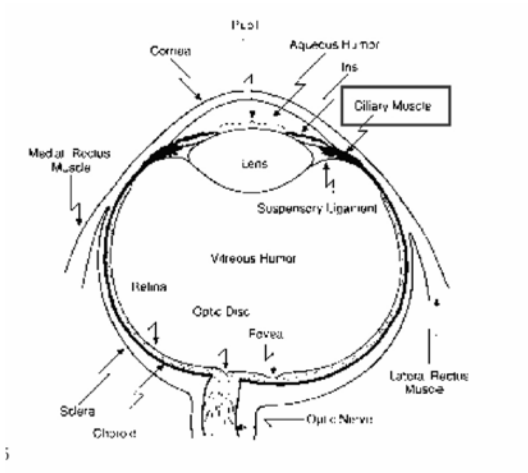
Optical power and accommodation

- Optical power of a lens - how strongly the lens bends the incoming rays
  - short focal length lens bends rays significantly
  - it images a point source at infinity at distance *f* behind the lens. The smaller *f*, the more the rays must be bent to bring them into focus sooner.
  - optical power is *1/f*, measured in meters. The unit is called the *diopter*
  - Human vision: when viewing faraway objects the distance from the lens to the retina is .017m. So the optical power of the eye is 58.8 diopters

Accommodation

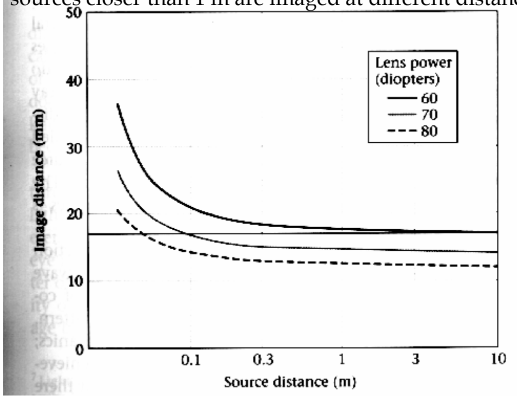
- How does the human eye bring nearby points into focus on the retina?
  - by increasing the power of the lens
  - muscles attached to the lens change its shape to change the lens power
  - accommodation: adjusting the focal length of the lens
  - bringing points that are nearby into focus causes faraway points to go out of focus
  - depth-of-field: range of distances in focus
- Physical cameras - mechanically change the distance between the lens and the image plane

Accommodation



Accommodation

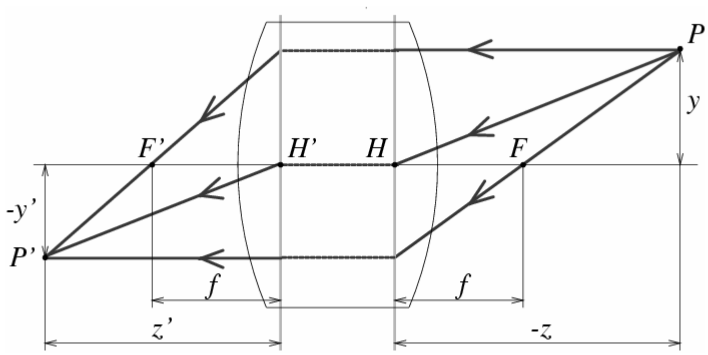
sources at > 1 meter are imaged at same distance
sources closer than 1 m are imaged at different distances



2.16 DEPTH OF FIELD OF THE HUMAN EYE. Image distance is shown as a function of source distance. The solid horizontal line shows the distance of the retina from the lens center. A lens power of 60 diopters brings distant objects into focus, but not nearby objects; to bring nearby objects into focus the power of the lens must increase. The depth of field (the distance over which objects will continue to be in reasonable focus) can be estimated from the slope of the curve.

Real lenses

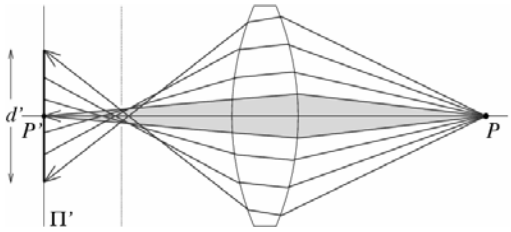
- Thick lenses



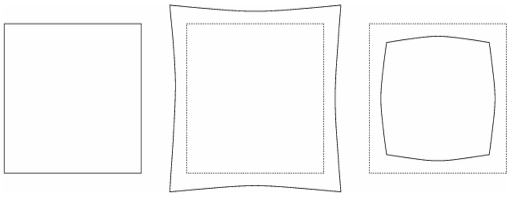
Lens imperfection

- Lens imperfections might cause rays not to intersect at a point
  - deviations in shape from the ideal lens
  - material imperfections that might cause the refractive index to vary within the lens
- Scattering at the lens surface
  - Some light entering the lens system is reflected off each surface it encounters (Fresnel's law gives details)
  - Machines: coat the lens, interior
  - Humans: live with it (various scattering phenomena are visible in the human eye)
- Geometric aberrations.
- Chromatic aberrations.

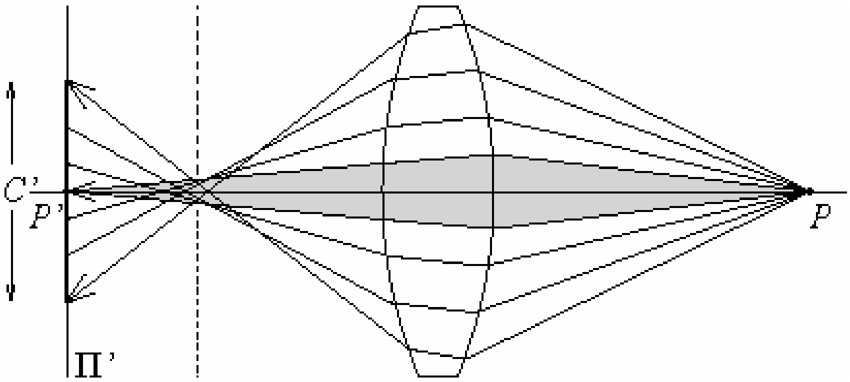
Spherical Aberration



Distortion

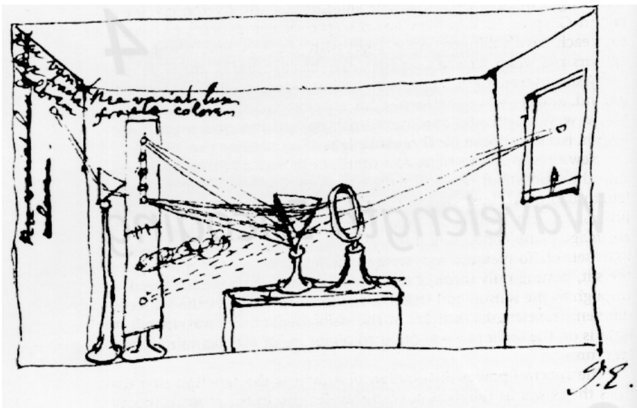


Spherical aberration



Complications of color

- Spectral composition of light
  - Newton's original prism experiment
  - light decomposed into its spectral components



4.1 NEWTON'S SUMMARY DRAWING of his experiments with light. Using a point source of light and a prism, Newton separated sunlight into its fundamental components. By reconverging the rays, he also showed that the decomposition is reversible.

Complications of color

Wavelength	Color (*)
700	Red
610	Orange
580	Yellow
540	Green
480	Blue
400	Violet

* - viewed in isolation

- Why does the prism separate the light into its spectral components?
  - prism bends different wavelengths of light by different amounts
  - refractive index is a function of wavelength
  - shorter wavelengths are refracted more strongly than longer wavelengths

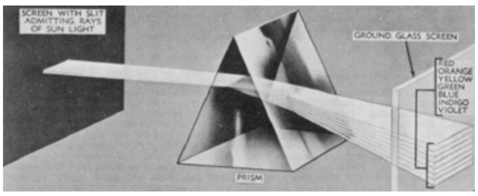
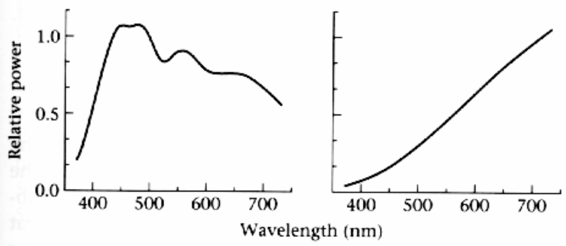


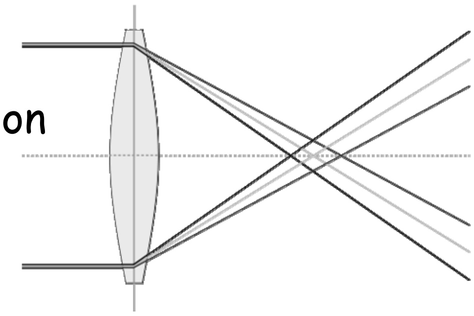
Figure from US Navy Manual of Basic Optics and Optical Instruments, prepared by Bureau of Naval Personnel. Reprinted by Dover Publications, Inc., 1969.

Complications of color



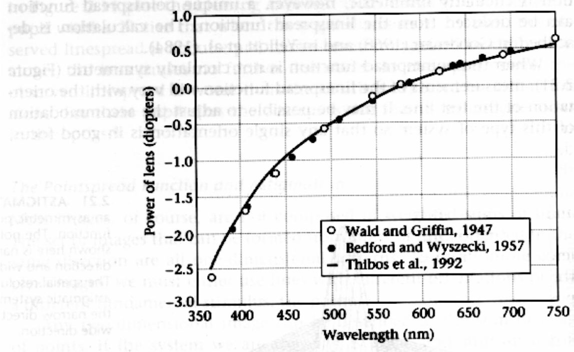
4.4 THE SPECTRAL POWER DISTRIBUTION of two important light sources are shown: (left) blue skylight and (right) a tungsten bulb.

Chromatic aberration



- Chromatic aberration
  - The prism effect of focusing different wavelengths of light from the same point source at different distances behind the lens
  - when incident light is a mixture of wavelengths, we can observe a chromatic fringe at edges
  - accommodation can bring any wavelength into good focus, but not all simultaneously
  - human visual system has other mechanisms for reducing chromatic aberration (adapt to it)
  - color cameras have similar problems

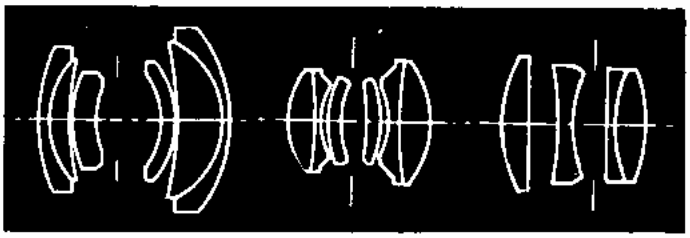
Chromatic abberation



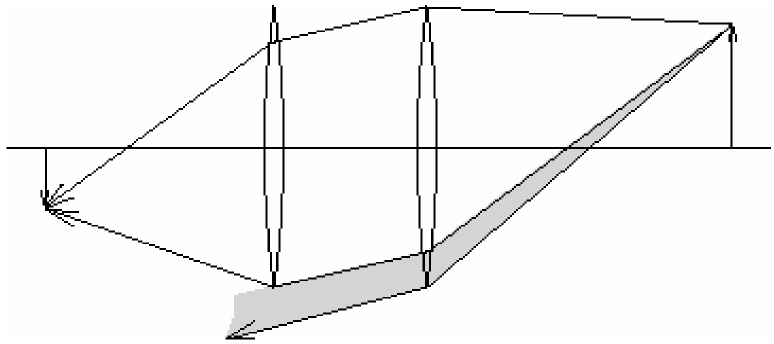
2.22 CHROMATIC ABERRATION OF THE HUMAN EYE. The data points measure the optical power one must add to the human eye in order to bring different wavelengths into a common focus with a 578-nm light. The smooth curve plots a formula created by Thibos et al. (1992) that predicts the measurements and interpolates smoothly between them. The formula is $D(\lambda) = p - q/(\lambda - c)$, where λ is wavelength in micrometers, $D(\lambda)$ is the defocus in diopters, $p = 1.7312$, $q = 0.63346$, and $c = 0.21410$. After Marimont and Wandell, 1993.

Lens systems

- Aberrations can be minimized by aligning several simple lenses (compound lenses)



Vignetting



- Vignetting effect in a two-lens system. The shaded part of the beam never reaches the second lens.
- Result: brightness drops at image periphery.

Sensing

Milestones:
First Photograph: Niepce 1816
Daguerreotypes (1839)
Photographic Film (Eastman, 1889)
Cinema (Lumière Brothers, 1895)
Color Photography (Lumière Brothers, 1908)
Television (Baird, Farnsworth, Zworykin, 1920s)

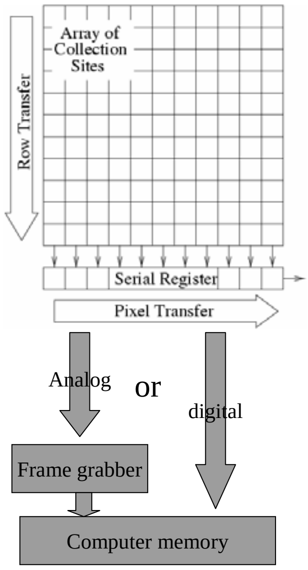
CCD Devices (1970)

Collection Harlingue-Viollet. .

Photographs (Niepce, “La Table Servie,” 1822)

CCD cameras

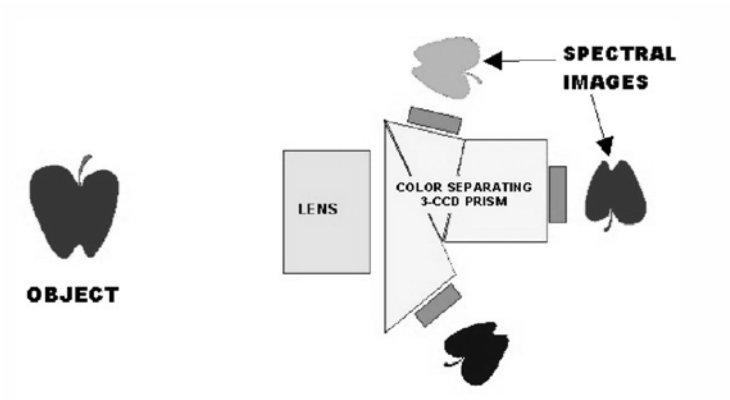
- Charge-coupled device CCD
- Image is read one row at a time
- This process is repeated several times per second (frame rate)



Color cameras

- Two types of color cameras
  - Single CCD array
    - in front of each CCD element is a filter - red, green or blue
    - color values at each pixel are obtained by hardware interpolation
      - subject to artifacts
      - lower intensity quality than a monochromatic camera
      - similar to human vision
  - 3 CCD arrays packed together, each sensitive to different wavelengths of light

3 CCD cameras



Sources

- Computer Vision a Modern approach: 1.1, 1.2,1.4
- Wandell, Foundations of Vision
- Slides by:
  - D. Forsyth @UC Berkeley
  - J. Ponce @UIUC
  - L. Davis @UMD