Cameras and Lenses

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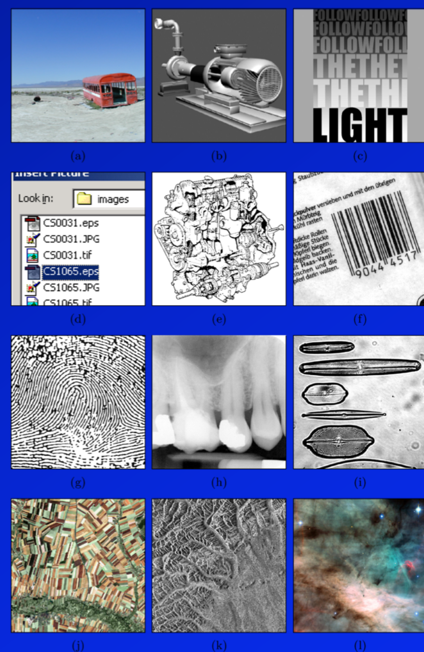
Outlines

Cameras and lenses !



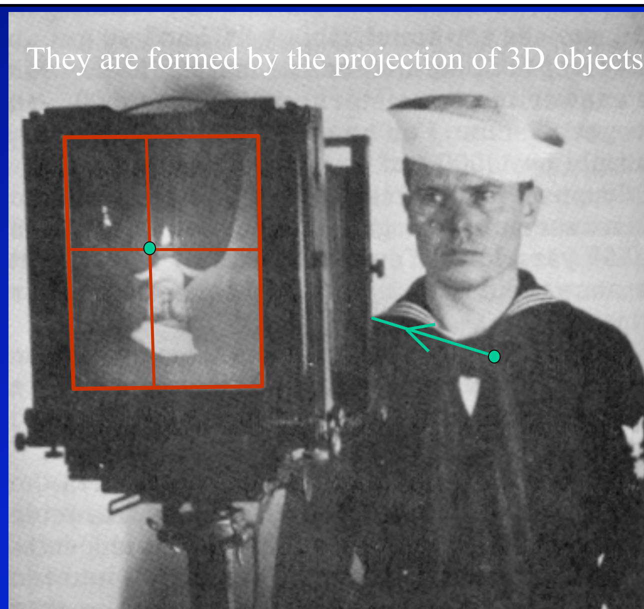
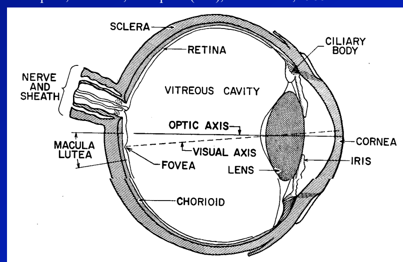


Figure from US Navy Manual of Basic Optics and Optical Instruments, prepared by Bureau of Naval Personnel. Reprinted by Dover Publications, Inc., 1969.

Images are two-dimensional patterns of brightness values.

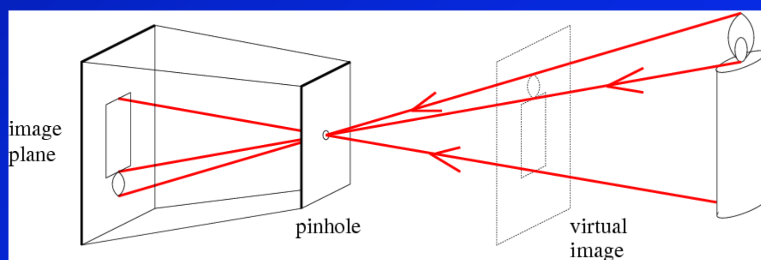
Reproduced by permission, the American Society of Photogrammetry and Remote Sensing. A.L. Nowicki, "Stereoscopy." Manual of Photogrammetry, Thompson, Radlinski, and Speert (eds.), third edition, 1966.



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.

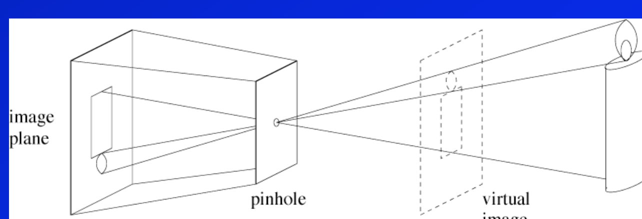
Photographic camera: Niepce, 1816.



Pinhole perspective projection: Brunelleschi, XVth Century. Camera obscura: XVIth Century.

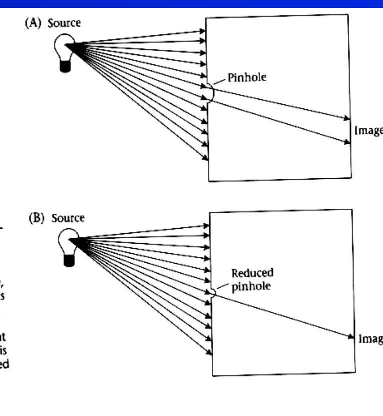
Lens-less imaging systems - Pinhole cameras

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



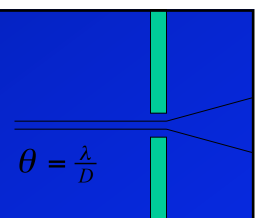
pinhole optics

- 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.

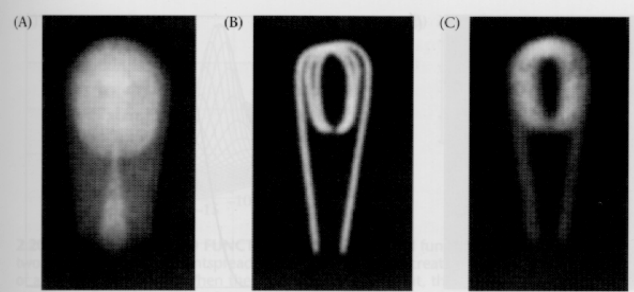
Diffraction



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

- 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

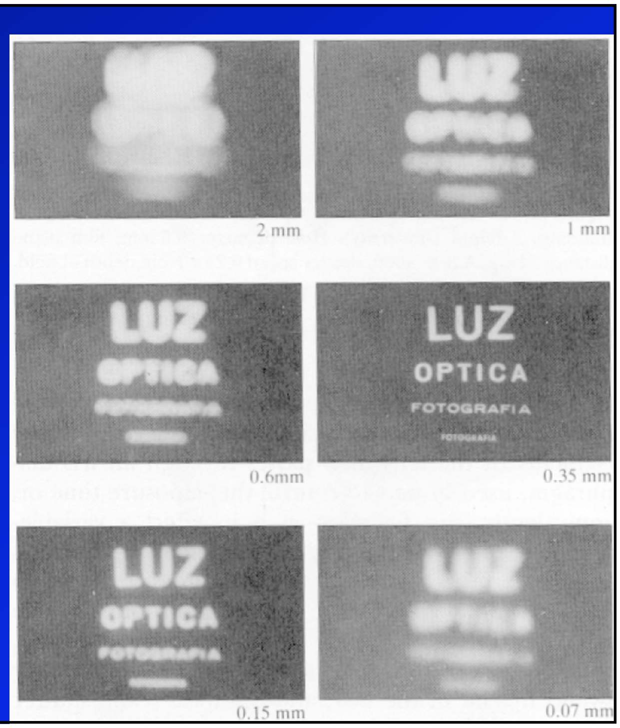


2.18 DIFFRACTION LIMITS THE QUALITY OF PINHOLE OPTICS. These three images of a bulb filament were made using pinholes with decreasing size. (A) When the pinhole is relatively large, the image rays are not properly converged, and the image is blurred. (B) Reducing the size of the pinhole improves the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

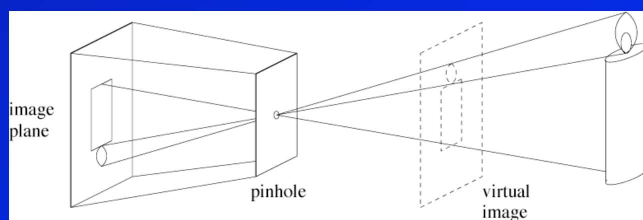
Pinhole too small- diffraction effects blur the image

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

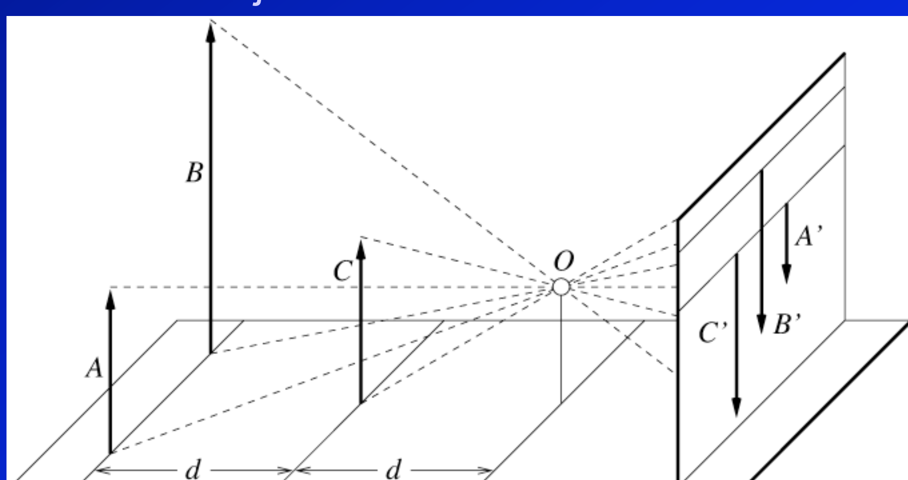


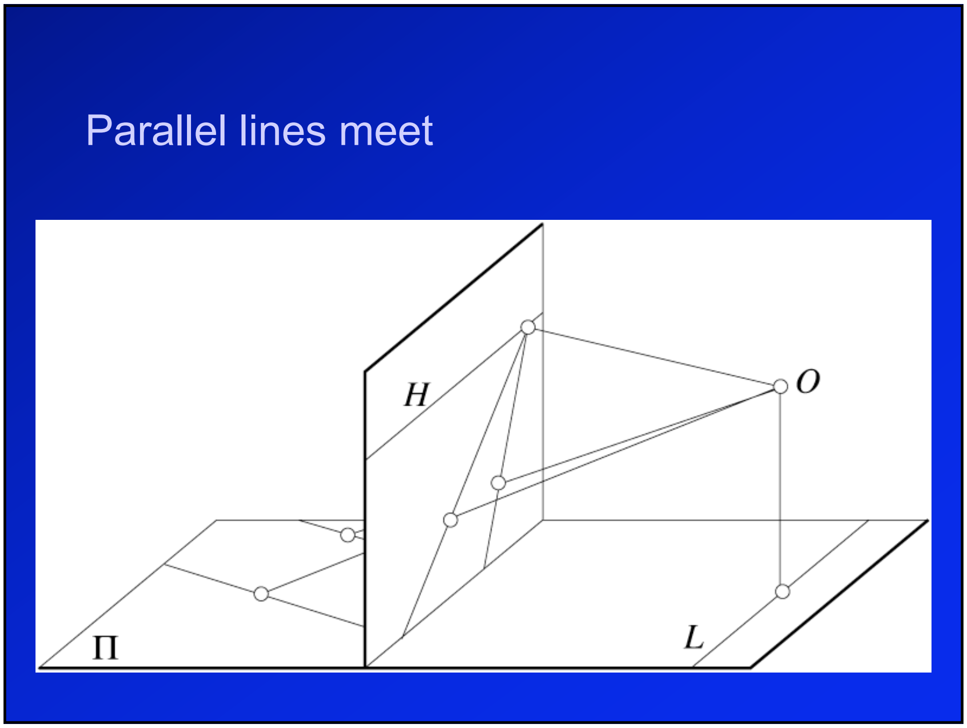
Pinhole Perspective

- 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
H
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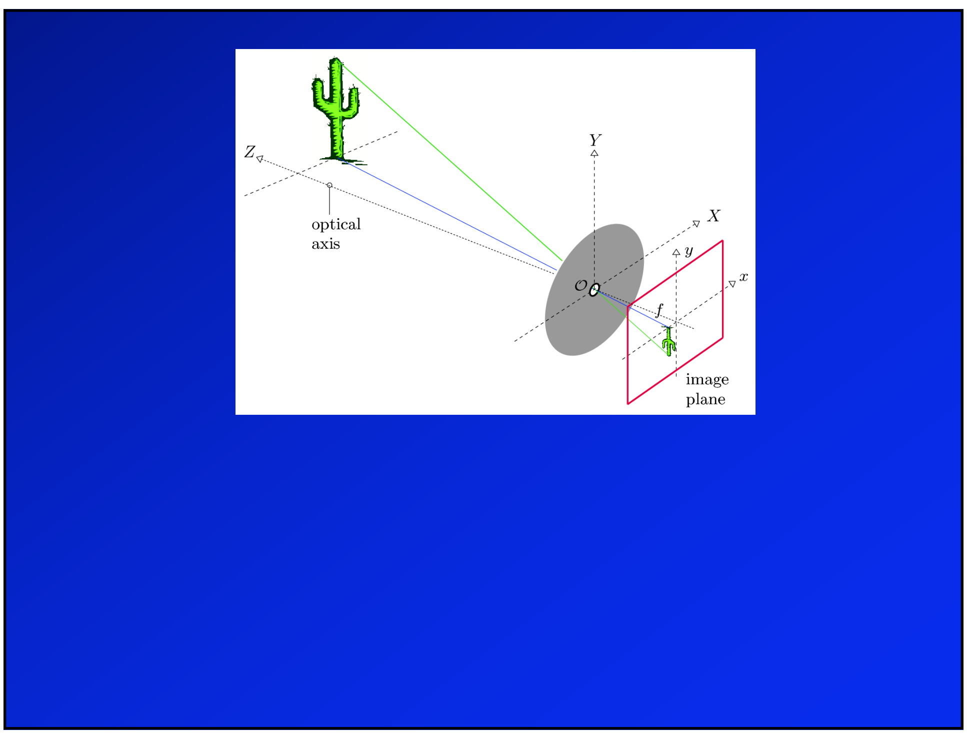
L


Z
Y
X
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axis
O
f
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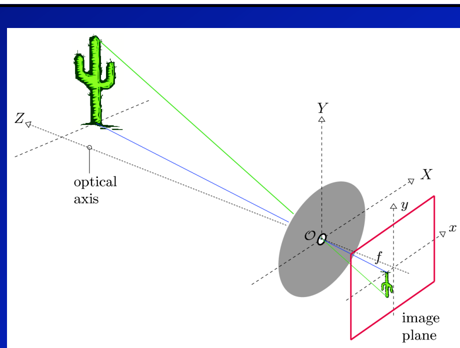
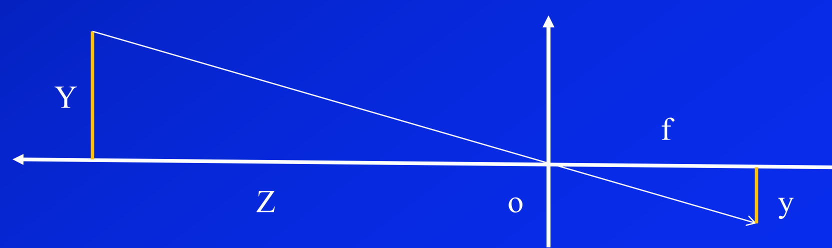
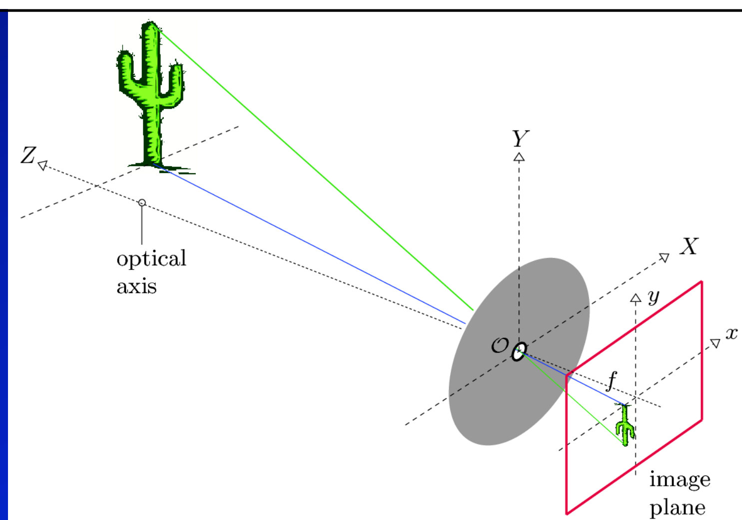


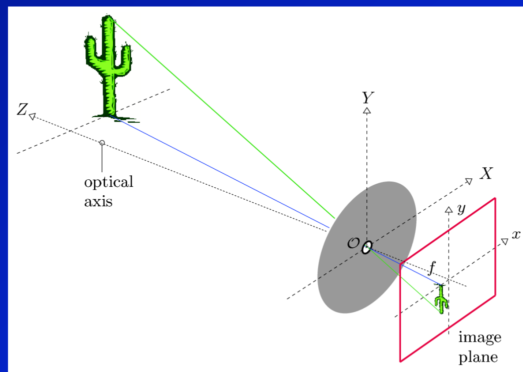
y/f = Y/Z

y= f Y/Z





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

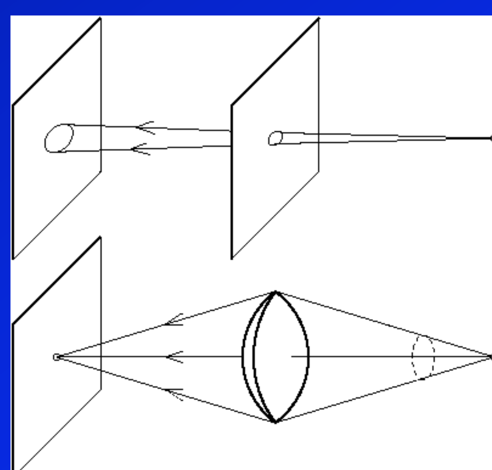


$$y = -f\frac{Y}{Z} \qquad x = -f\frac{X}{Z}$$

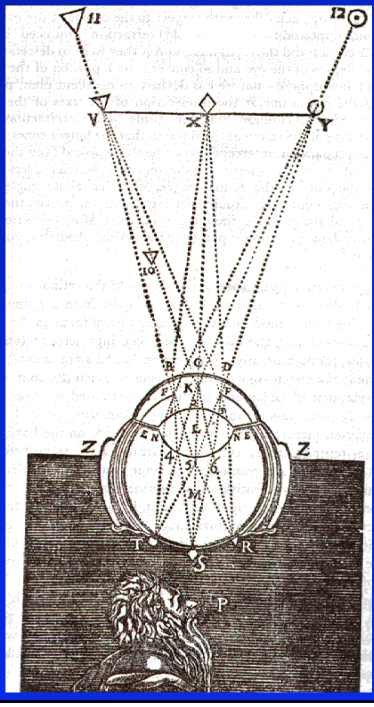
$$\begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \frac{-1}{z}\begin{bmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}\begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

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 $\phi 1$ is the angle of incidence and $\phi 2$ is the angle of refraction then

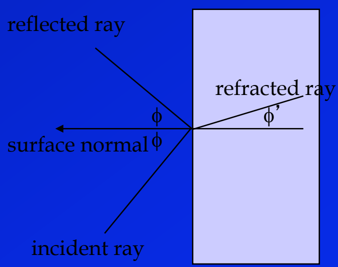
$$\frac{\sin\phi_1}{\sin\phi_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1}$$

$$n_1 \sin\phi_1 = n_2 \sin\phi_2$$

$$n_i = c / v_i$$

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

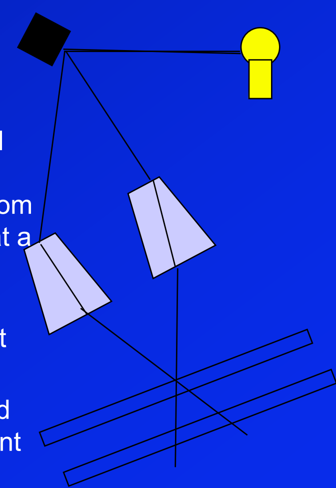
- Refractive index is the ratio of speed of light in a vacuum (c) to speed of light in the medium (v)
- Paraxial approximation: $n\phi = n'\phi'$



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

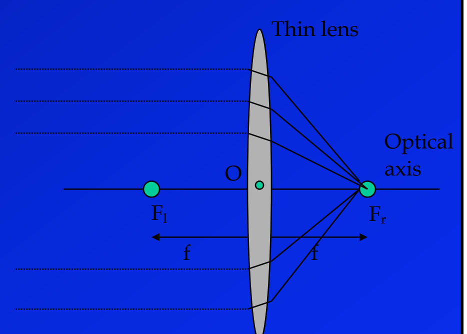
Applying Snell's Law twice

- 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



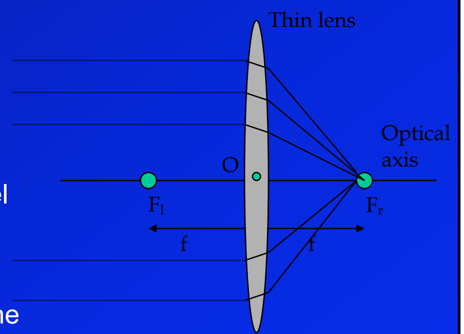
Thin lenses

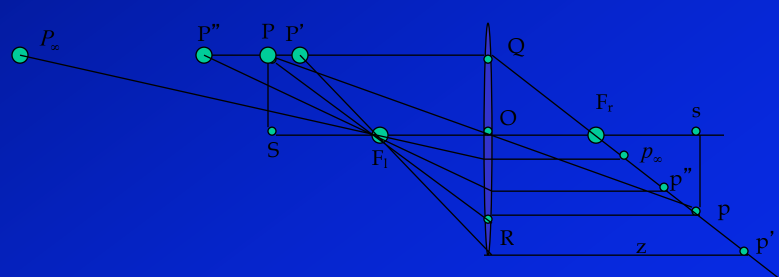
- The optical behavior is determined by:
  - optical axis going through the lens center O and perpendicular to the lens center plane
  - the left and right focus (F_l and F_r) located a distance f, called the focal length, from the lens center



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.





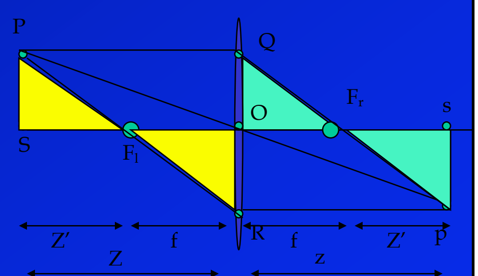
Thin-lens equation

- relates the distance between the point being viewed and the lens to the distance between the lens and the ideal image (where the rays from that point are brought into focus by the lens)
  - Let P be a point being viewed that is not too far from the optical axis.
    - Z + f is the distance of P from the lens along the optical axis
    - The thin lens focuses all the rays from P onto the same point, the image point, p

Thin-lens equation

$$\frac{1}{Z} + \frac{1}{z} = \frac{1}{f}$$

- p can be determined by intersecting two known rays, PQ and PR.
  - PQ is parallel to the optical axis, so it must be refracted to pass through F_r.
  - PR passes through the left focus, so emerges parallel to the optical axis.
- Note two pairs of similar triangles
  - PF_lS <-> ROF_l and psF_r <-> QOF_r

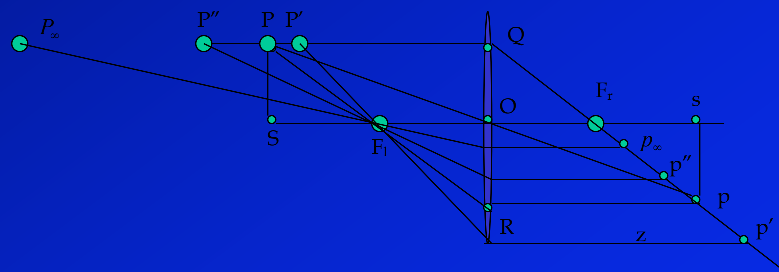


- PS/OR = Z'/f
- QO/sp = f/z'
- But PS = QO and OR = sp
- So, Z'/f = f/z', or Z'z' = f^2
- Let Z = Z' + f and z = z' + f

$$\frac{1}{Z} + \frac{1}{z} = \frac{1}{f}$$

Thin-lens equation

$$\frac{1}{Z} + \frac{1}{z} = \frac{1}{f}$$

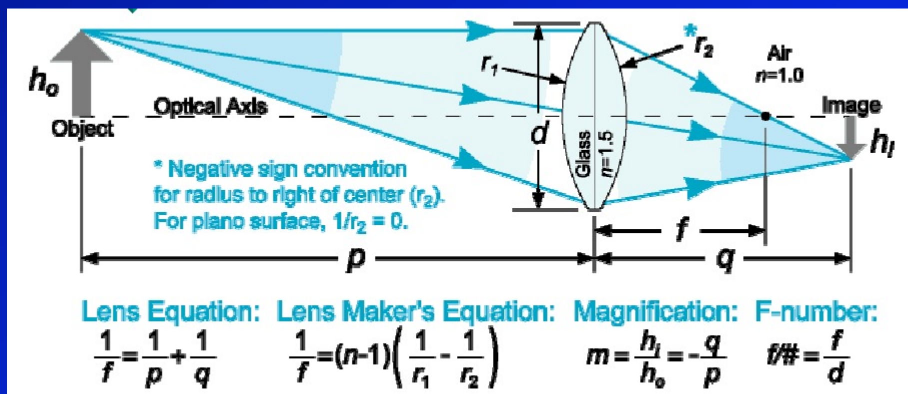


- Z: distance between object and lens
- z: distance between object’s image and lens
- Note:
  - as Z gets large, z approaches f
  - as Z approaches f, z approaches infinity

Depth of field

$$\frac{1}{Z} + \frac{1}{z} = \frac{1}{f}$$

- Notice that the distance behind the lens, z, at which a point, P, is brought into focus depends on Z, the distance of that point from the lens
  - familiar to us from rotating the focus ring of any camera.
- In real lenses, system is designed so that all points within a given range of distances [Z_1, Z_2] are brought into focus at the same distance behind the lens center.
  - This is called the <u>depth of field</u> of the lens.



$$f = \frac{r}{2(n-1)}$$

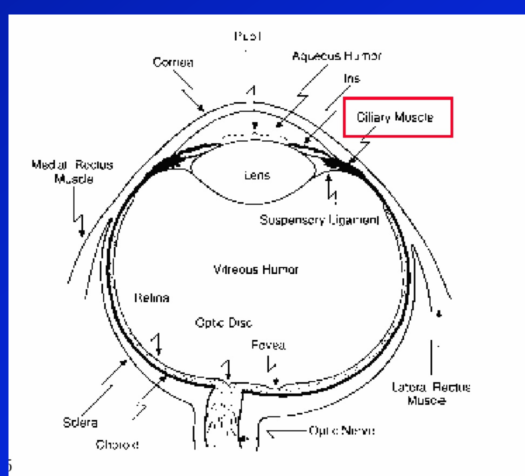
Optical power and accommodation

- 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

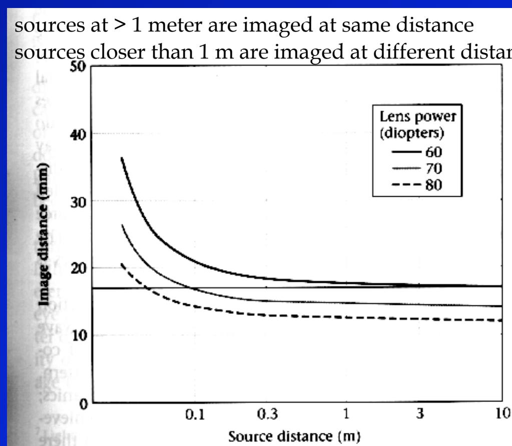
Accommodation

- 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



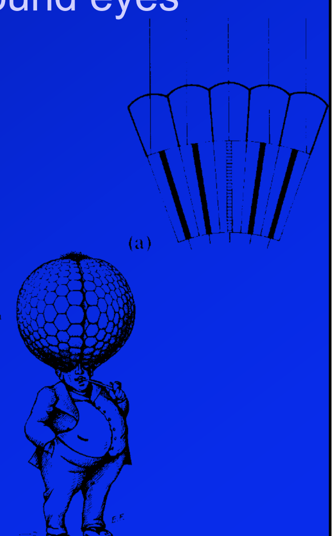
Accommodation



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.

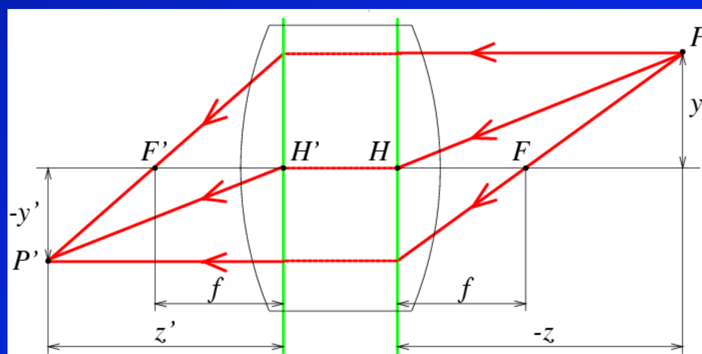
The structure of eyes -compound eyes

- 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



Real lenses

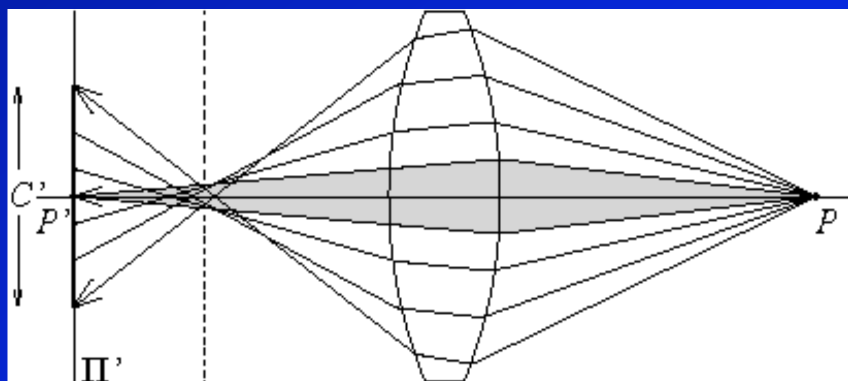
- Thick lenses



Lens imperfection

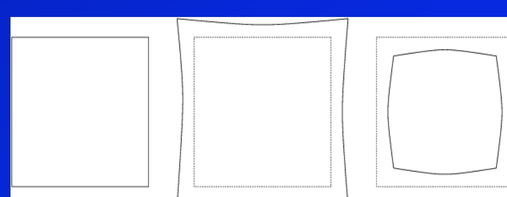
- Lens imperfections might cause rays not to intersect at a point
  - deviations in shape from the ideal lens
  - material imperfections that might cause the refractive index to vary within the lens
- Scattering at the lens surface
  - Some light entering the lens system is reflected off each surface 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

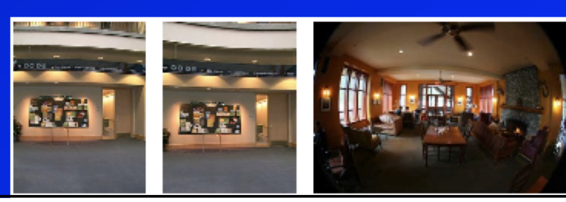


Radial Distortion

- Barrel: image magnification decreases with distance from the optical axis.
- Pincushion: image magnification increases with the distance from the optical axis.

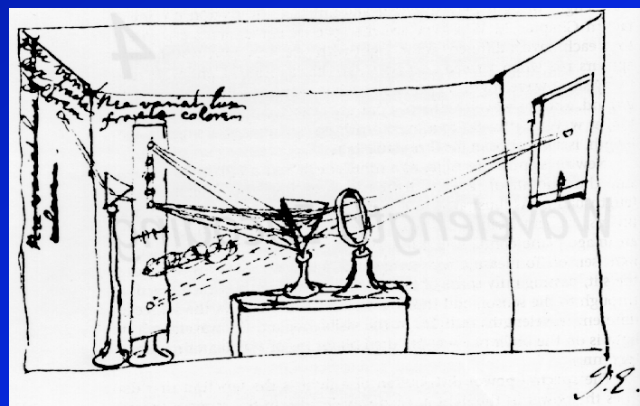


$$
\begin{aligned}
\hat{x}_c &= x_c(1+\kappa_1 r_c^2+\kappa_2 r_c^4) \\
\hat{y}_c &= y_c(1+\kappa_1 r_c^2+\kappa_2 r_c^4),
\end{aligned}
$$



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

- 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

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

* - viewed in isolation

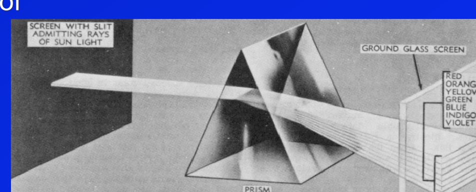
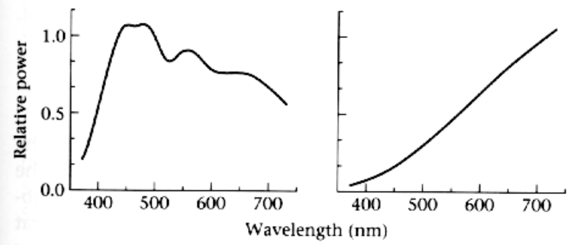


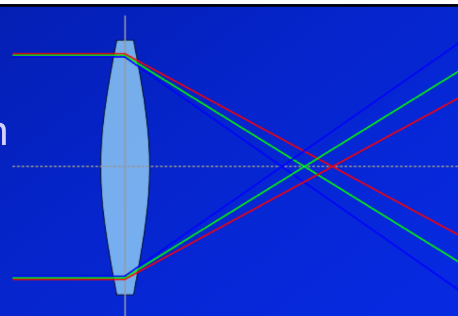
Figure from US Navy Manual of Basic Optics and Optical Instruments, prepared by Bureau of Naval Personnel. Reprinted by Dover Publications, Inc., 1969.

Complications of color



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

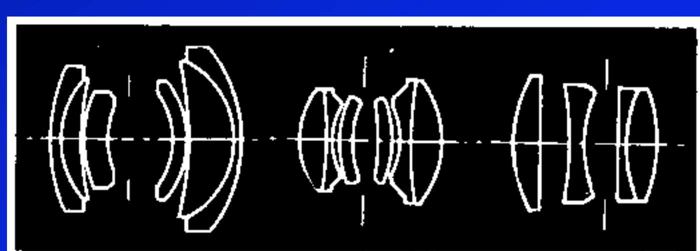
Chromatic aberration



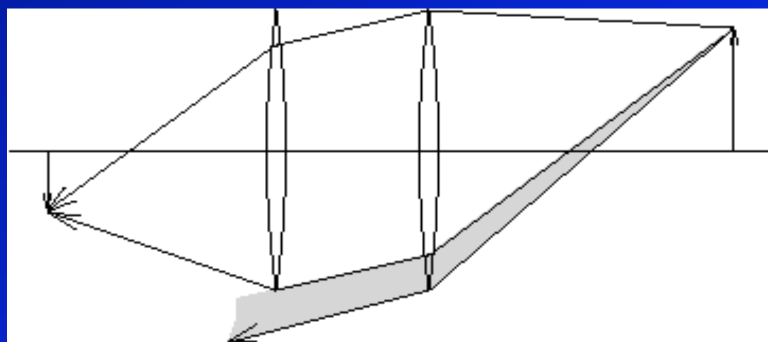
- Chromatic aberration
  - The prism effect of focusing different wavelengths of light from the same point source at different distances behind the lens
  - when incident light is a mixture of wavelengths, we can observe a chromatic fringe at edges
  - accommodation can bring any wavelength into good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

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: Louis Daguerre (1839)
Photographic Film (Eastman, 1889)
Cinema (Lumière Brothers, 1895)
Color Photography (Lumière Brothers, 1908)
Television (Baird, Farnsworth, Zworykin, 1920s)

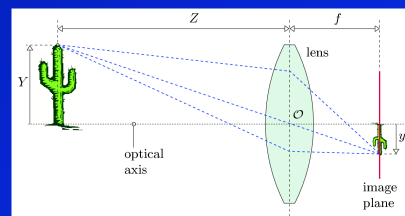
Collection Harlingue-Viollet.
Photographs (Niepce, "La Table Servie," 1822)

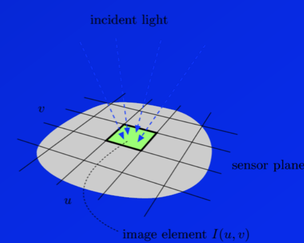
CCD Cameras (Charge Couple Device) (1970)
CMOS Cameras (Complementary Metal Oxide Silicon)

"Boulevard du Temple", taken by Daguerre in 1838 in Paris
First person in a photograph. 10 mins exposure

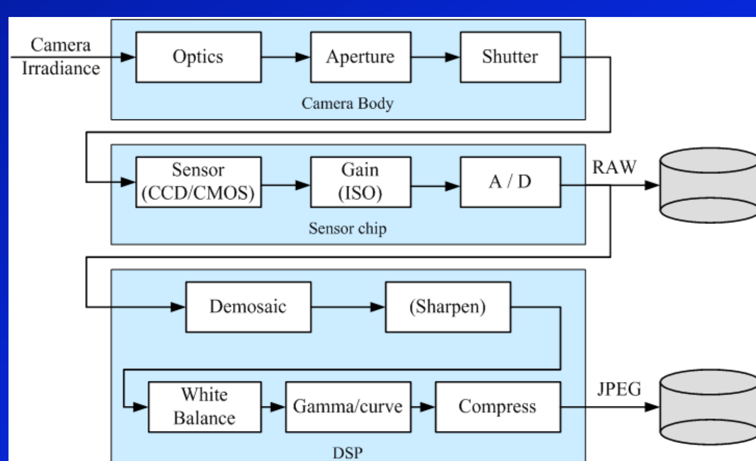
Digitizing images

- What is projected on the image plan is a distribution of light energy that is:
  - Two-dimensional
  - Time-dependent
  - Continuous
- To go digital:
  - Spatial sampling
  - Temporal sampling
  - Quantization of pixel values





Digital camera



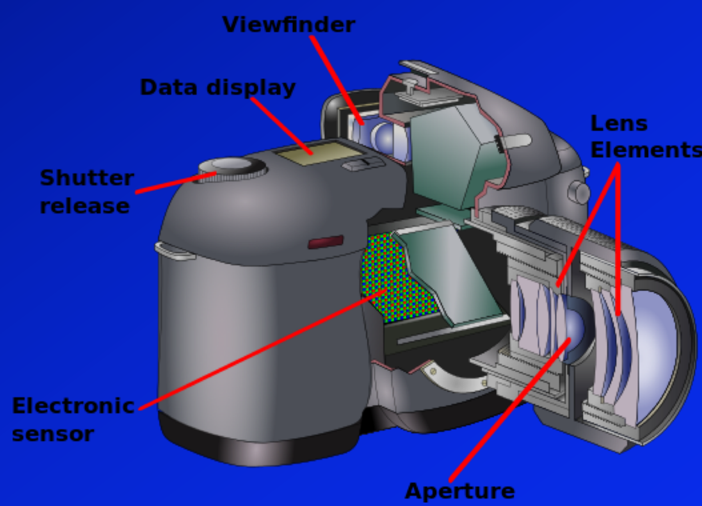


Image from Wikipedia

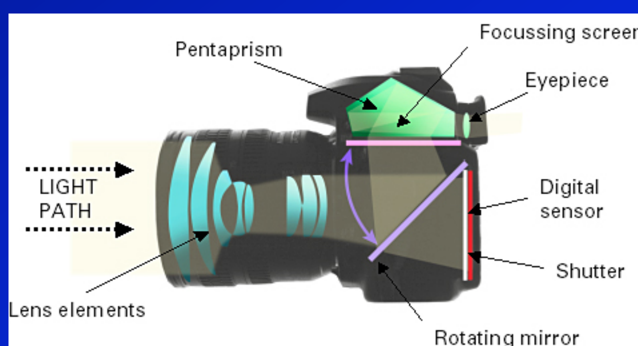


Image from http://www.jiscdigitalmedia.ac.uk

- Three concepts from film-based cameras:
  - Aperture
  - Shutter Speed
  - ISO: film density

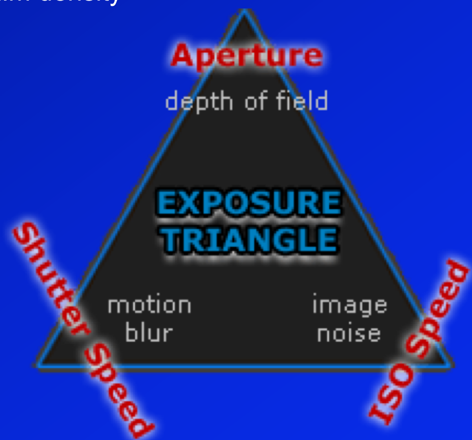
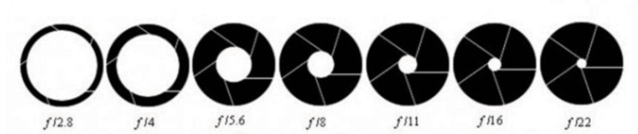


Image from: http://www.cambridgeincolour.com

APERTURE SCALE

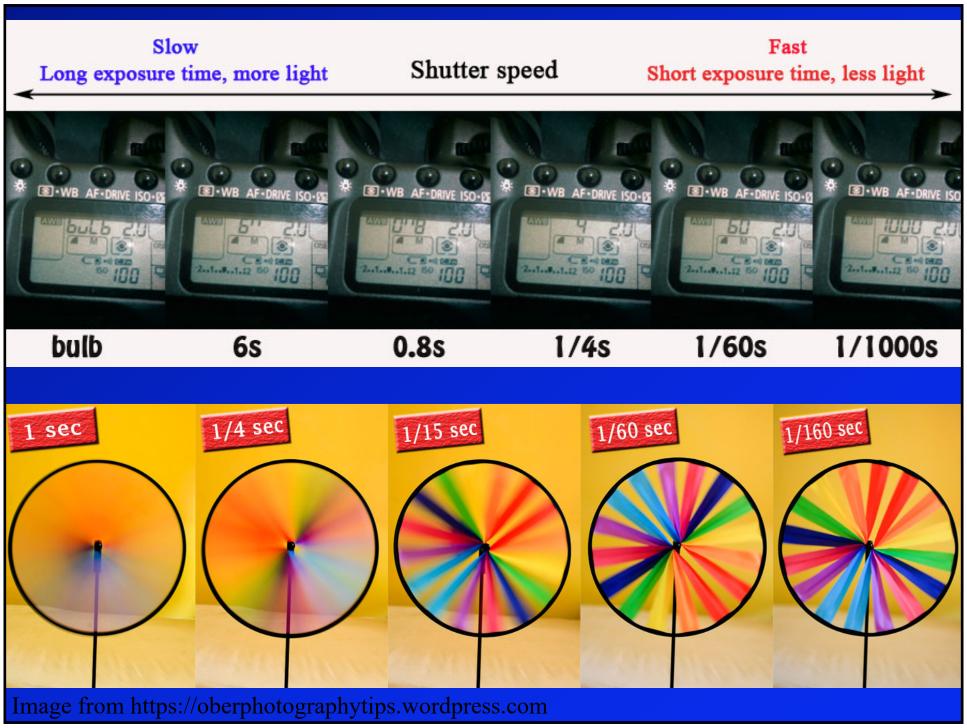


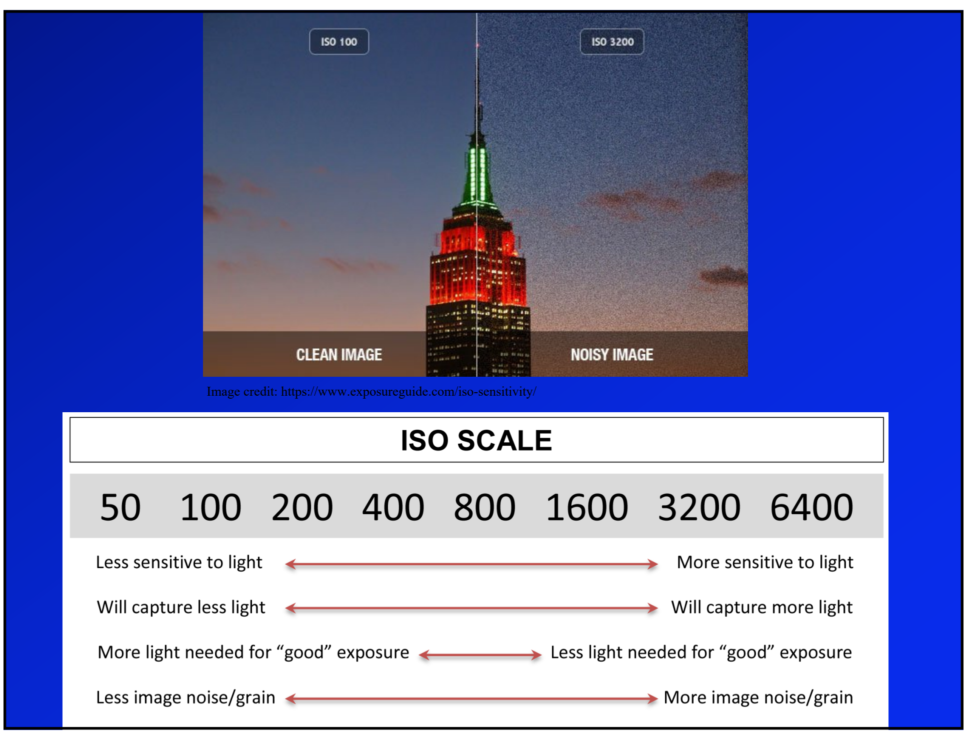
Large aperture ↔ Small aperture

More light strikes image sensor ↔ Less light strikes image sensor

Shallow Depth of Field (Focus) ↔ Deep Depth of Field (Focus)

Image from https://oberphotographytips.wordpress.com


Slow
Long exposure time, more light
Shutter speed
Fast
Short exposure time, less light
bulb
6s
0.8s
1/4s
1/60s
1/1000s
1 sec
1/4 sec
1/15 sec
1/60 sec
1/160 sec
Image from https://oberphotographytips.wordpress.com


ISO 100
ISO 3200
CLEAN IMAGE
NOISY IMAGE
Image credit: https://www.exposureguide.com/iso-sensitivity/
ISO SCALE
50 100 200 400 800 1600 3200 6400
Less sensitive to light
More sensitive to light
Will capture less light
Will capture more light
More light needed for "good" exposure
Less light needed for "good" exposure
Less image noise/grain
More image noise/grain

CCD & CMOS

- CCD Cameras (Charge Couple Device) (1970)
  - Accumulate signal charge in each pixel proportional to the local illumination intensity
  - CCD transfers each pixel's charge packet sequentially to convert its charge to a voltage
- CMOS Cameras (Complementary Metal Oxide Silicon)
  - Accumulate signal charge in each pixel proportional to the local illumination intensity
  - The charge-to-voltage conversion takes place in each pixel

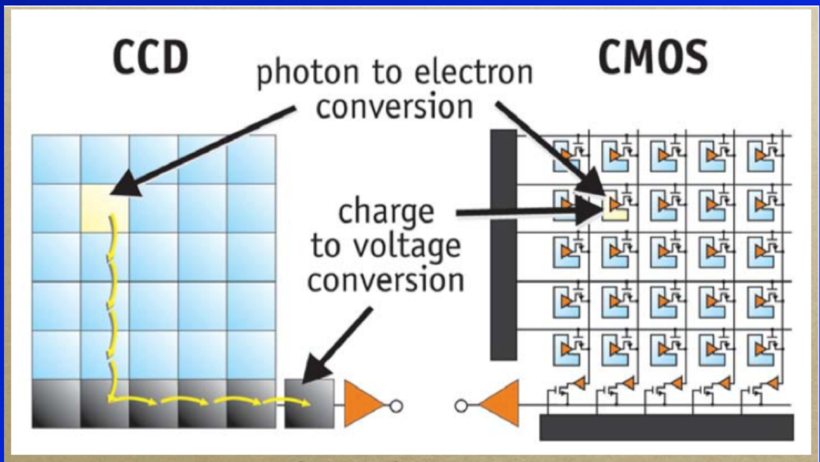


Image from Photonics Spectra

CMOS	*CCD*
◦ *Easier to manufacture*	◦ *Higher fill factor*
◦ *Camera-on-a-chip*	◦ *Smaller noise*
◦ *Lower power consumption*	◦ *Smaller dark current*
◦ *Smaller sensor*	◦ *Better pixel uniformity*
◦ *Higher speeds*	◦ *Better dynamic range*
◦ *Selective ROI windowing*	◦ *Non-rolling electronic shutter*
◦ *Natural anti-blooming*	

Check out: CCD vs. CMOS: Facts and Fiction by Dave Litwiller, in Photonics Spectra, January 2001

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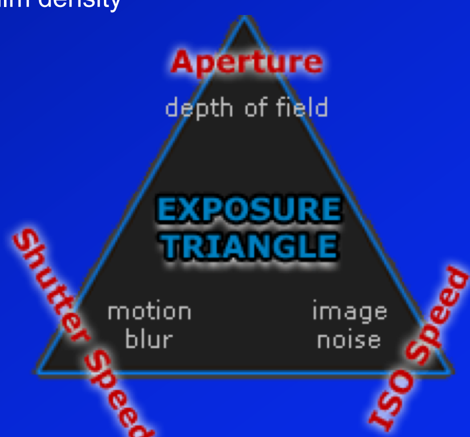
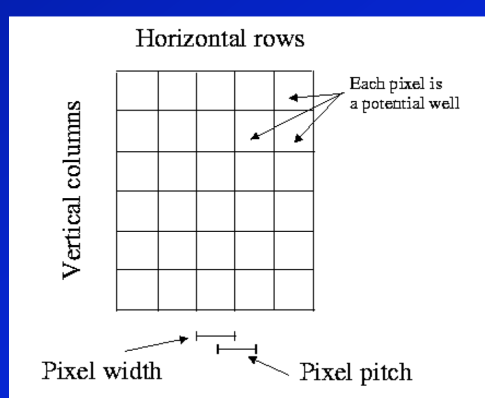


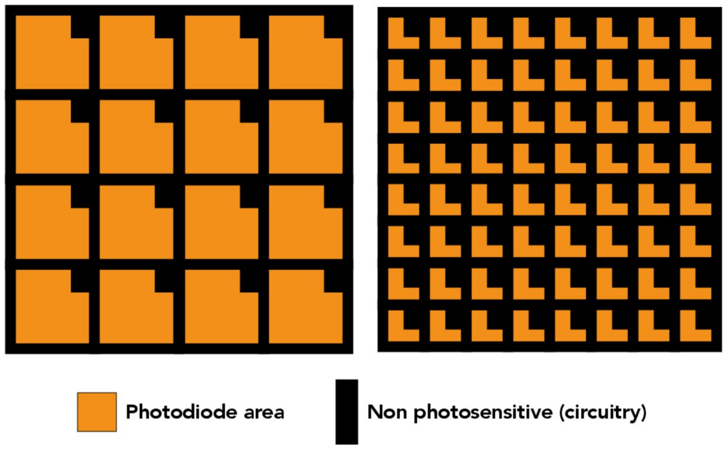
Image from: http://www.cambridgeincolour.com

- Several Parameters for a Digital camera
  - Mechanical and/or Electronic shutter
    - Rolling shutter vs. global shutter
  - Sampling pitch: the physical spacing between adjacent sensors (typically in ***μm***)
    - Small sampling pitch -> higher sampling density -> higher resolution. But also implies smaller area per sensor -> less light sensitivity + more noise
  - Fill Factor: the active sensing area size as a fraction of the available sensing area
  - Chip Size: larger chip size is preferred since each sensor can be more photo-sensitive, however more expensive.



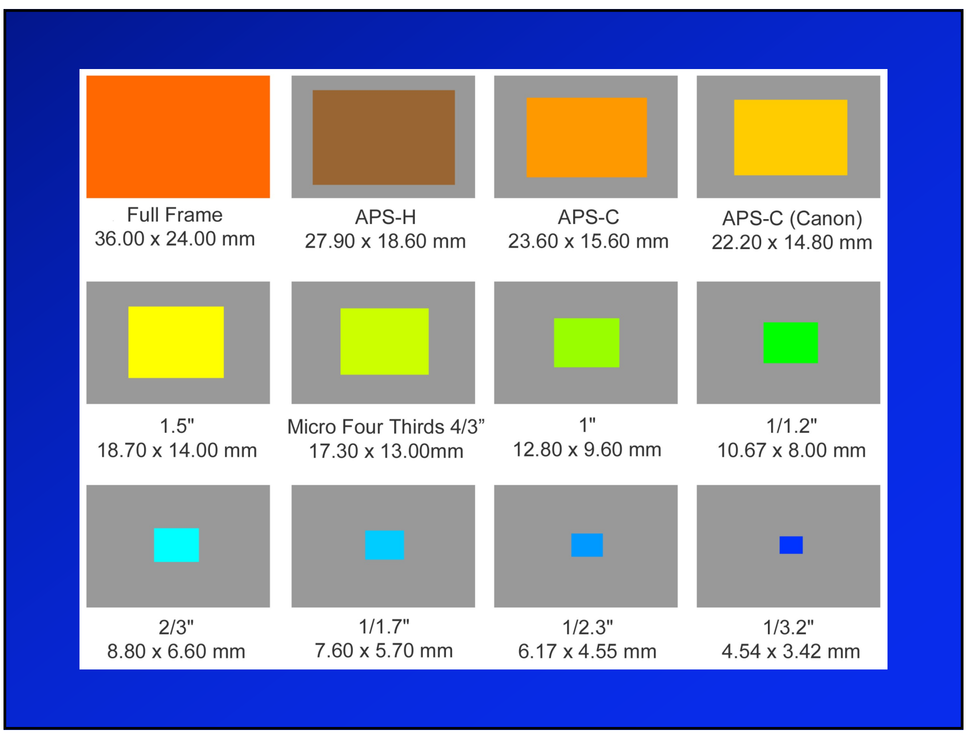
Pixel Fill Factor

Fraction of pixel area that integrates incoming light.



CS184/284A, Lecture 18

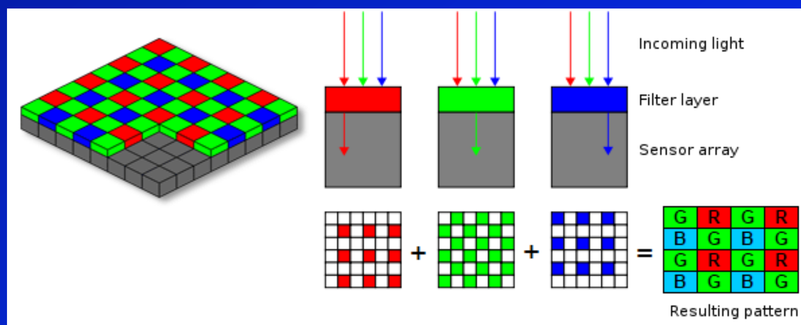
Ren Ng, Spring 2016



- Analog gain: sensed signal is amplified
  - Automatic gain control: amplification is a function of the exposure
  - Manual setting: digital ISO setting
    - Higher ISO: more gain which implies better under low light condition.
    - However more noise (amplifies the sensor noise)
- ADC resolution: Analog to digital conversion: how many bits are used to quantize the received signal at each senor unit
  - 16 bits for RAW format
  - 8 bits for JPEG
  - Less bits: quantization error
  - More bits increases the noise (effect of input noise – more bits than is actually needed)

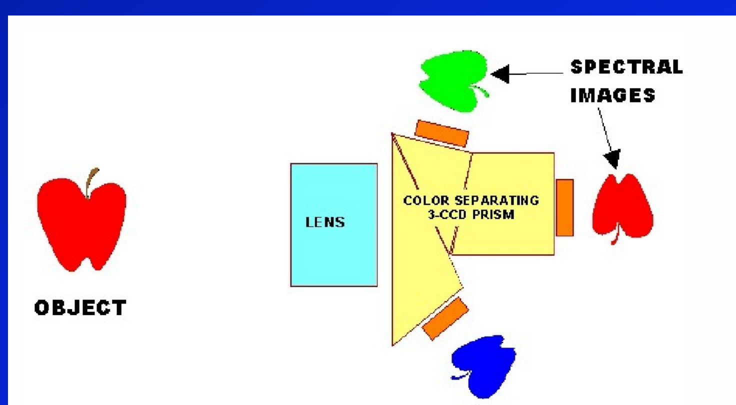
Color cameras

- 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



Bayer Filter/Pattern

3 CCD cameras



Depth Cameras

- Stereo camera
- Laser scanners
- Structured-Light cameras
- Time-of-Flight Cameras

Sources

- Computer Vision a Modern approach: 1.1
- Szeliski "Computer Vision Algorithms and Application"

Sec 2.3.1

- Burger and Burge, Digital Image Processing Ch 2
- Wandell, Foundations of Vision
- Some Slides by:
  - D. Forsyth @UC Berkeley
  - J. Ponce @UIUC
  - L. Davis @UMD