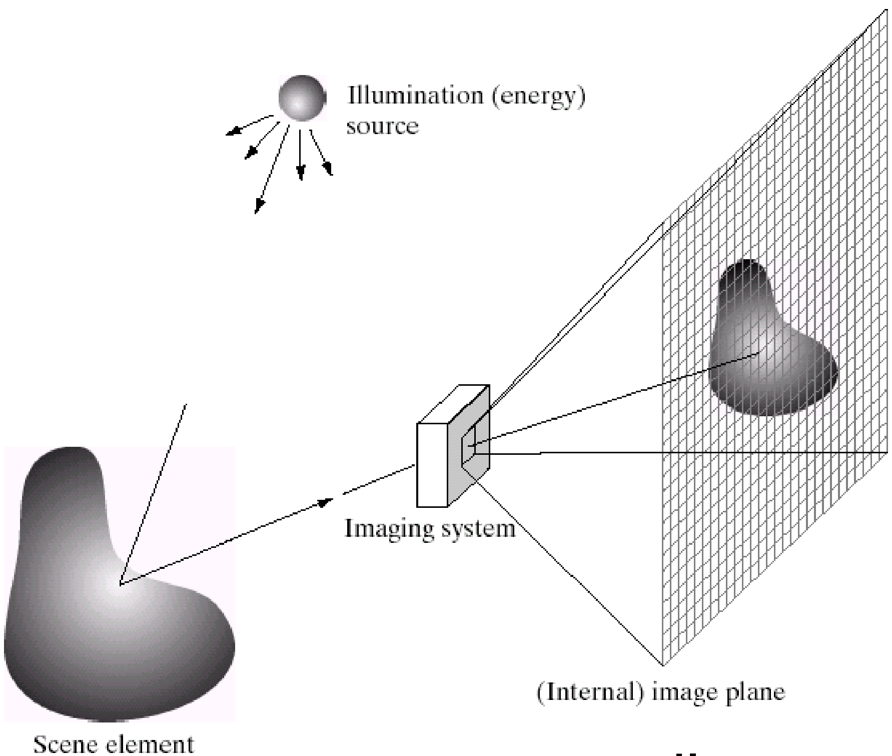
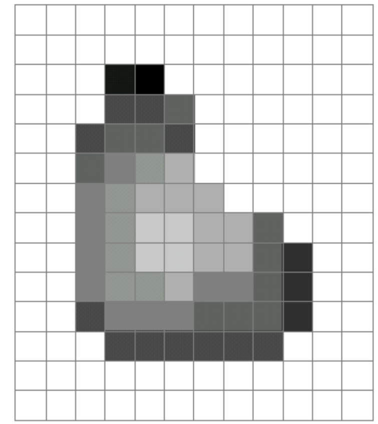
Announcement

- A total of 5 (five) late days are allowed for projects.
- Office hours
  - Me: 3:50-4:50pm Thursday (or by appointment)
  - Jake: 12:30-1:30PM Monday and Wednesday

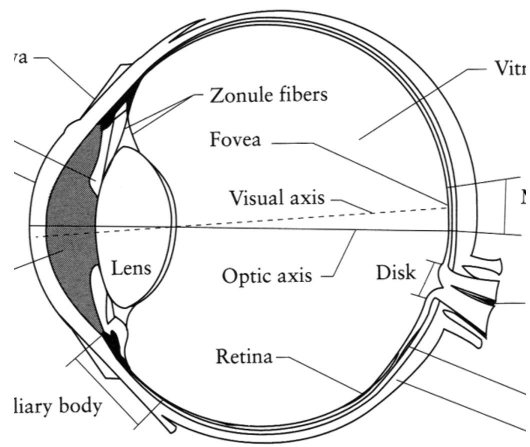
Image Formation



Film



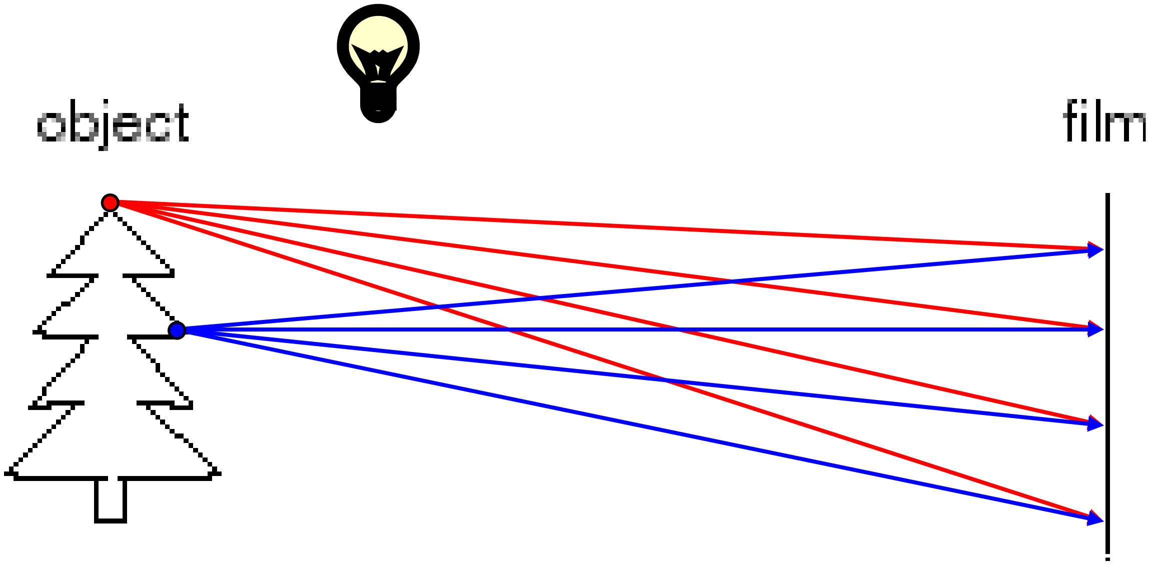
Digital Camera



The Eye

Alexei Efros' slide

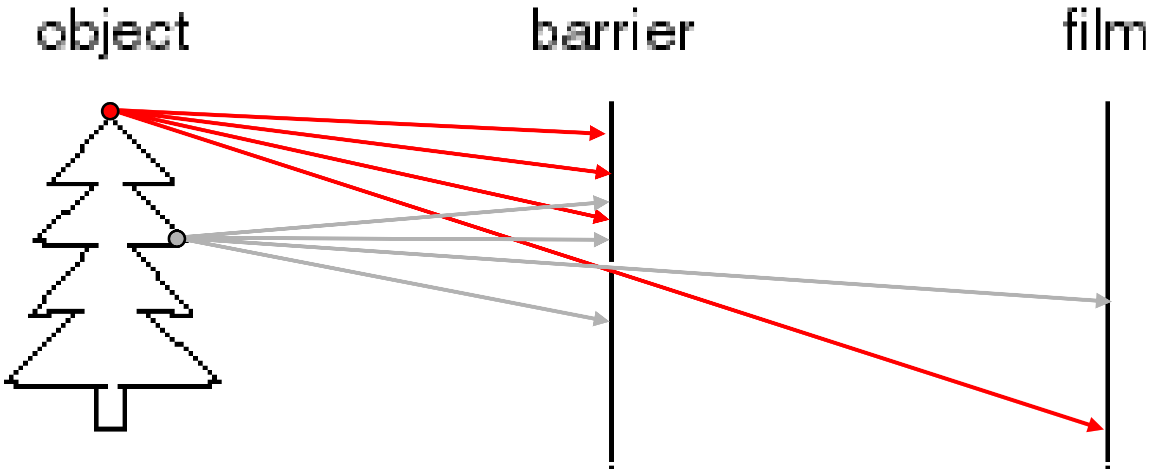
Image Formation



- Let's design a camera
  - Idea 1: put a piece of film in front of an object
  - Do we get a reasonable image?

Steve Seitz's slide

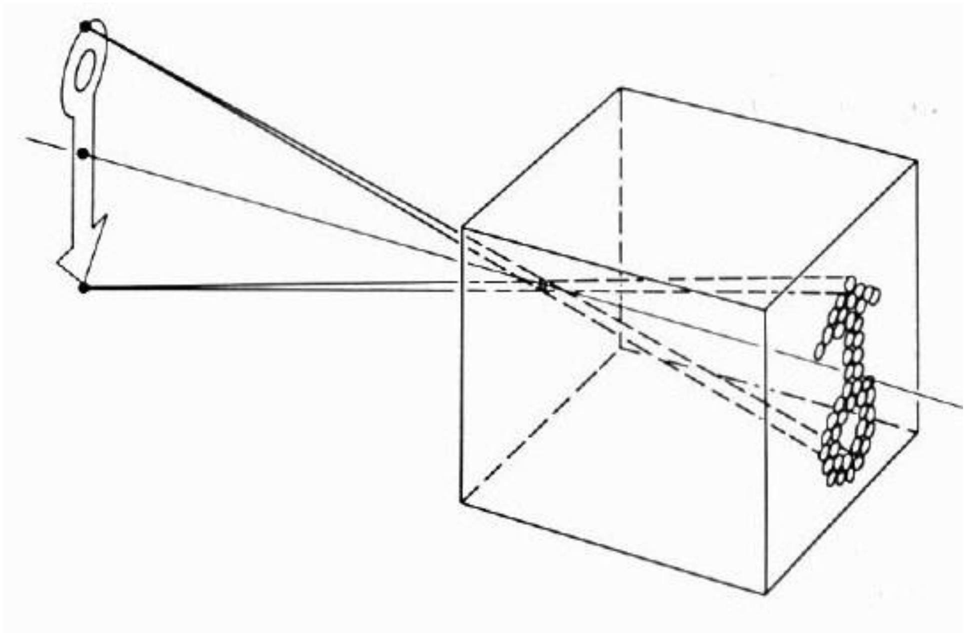
Pinhole Camera



- Add a barrier to block off most of the rays
  - This reduces blurring
  - The opening known as the **aperture**
  - How does this transform the image?

Steve Seitz's slide

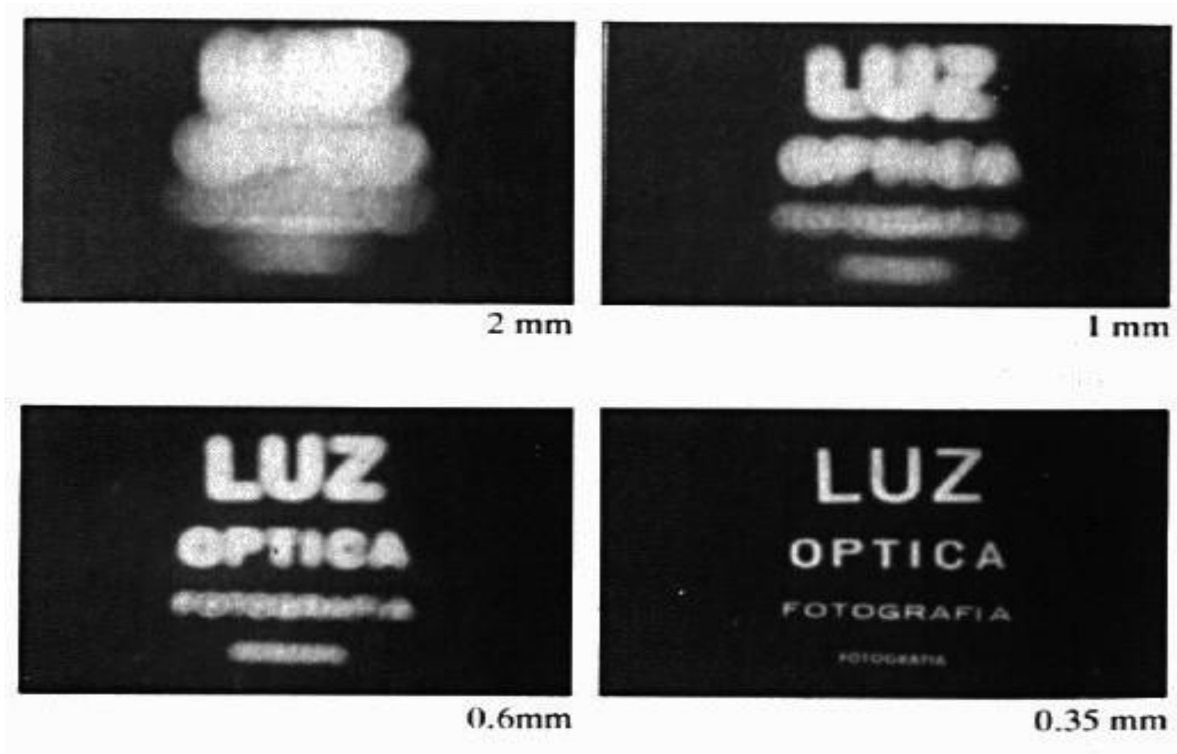
Camera Obscura



- The first camera
  - 5th B.C. Aristotle, Mozi (Chinese: 墨子)
  - How does the aperture size affect the image?

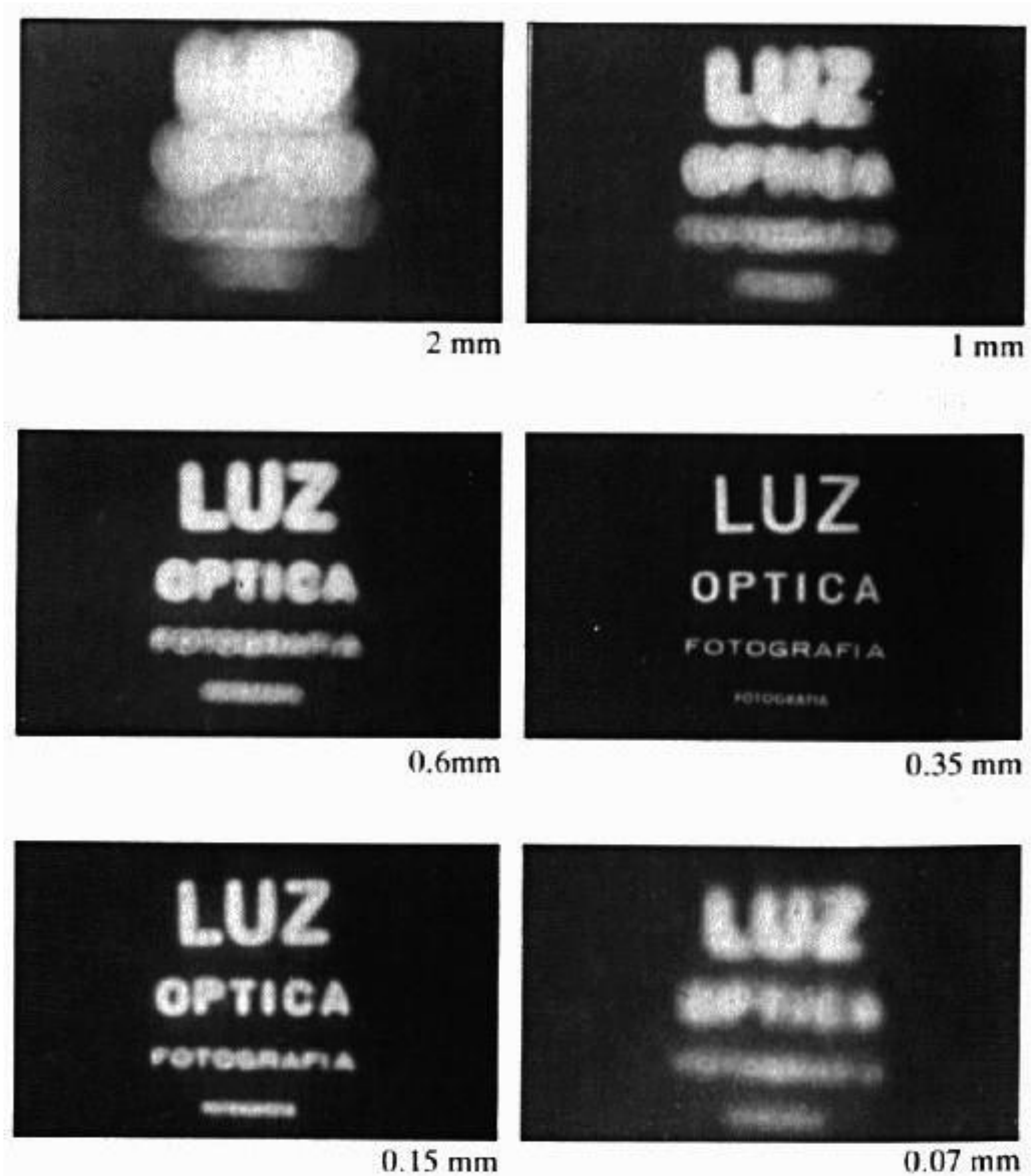
http://en.wikipedia.org/wiki/Pinhole_camera

Shrinking the aperture



- Why not make the aperture as small as possible?
  - Less light gets through
  - *Diffraction* effects...

Shrinking the aperture



Shrinking the aperture

Sharpest image is obtained when:

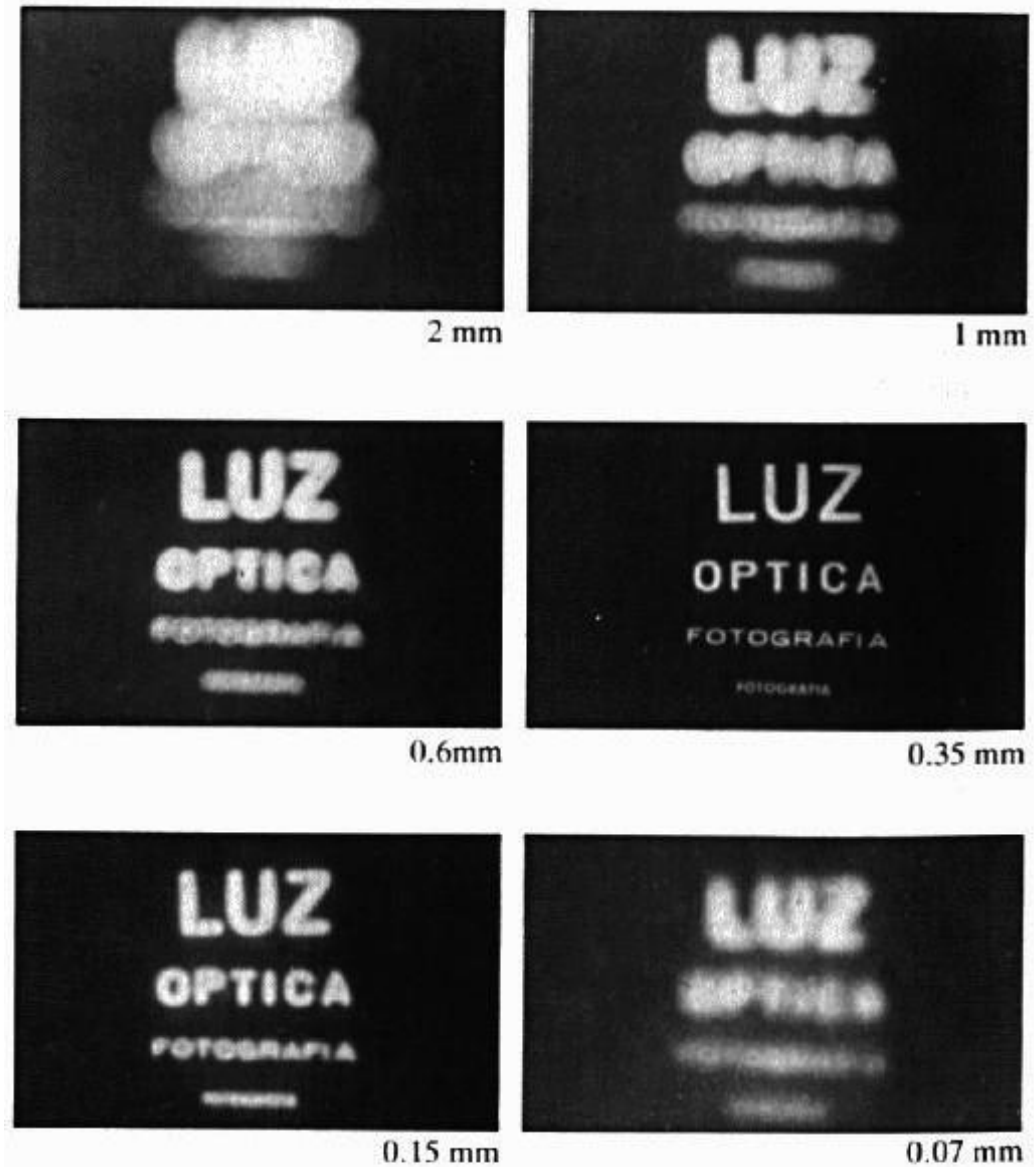
$$d = 2\sqrt{f\lambda}$$

d is diameter,
f is distance from hole to film
λ is the wavelength of light,
all given in metres.

Example: If $f = 50mm$,

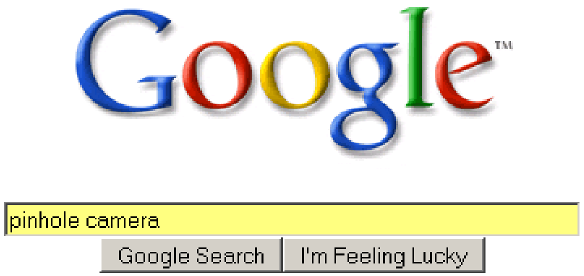
$\lambda = 600nm$ (red),

$d = 0.36mm$



Srinivasa Narasimhan's slide

Pinhole cameras are popular



Jerry Vincent's Pinhole Camera

Impressive Images

Jerry Vincent's Pinhole Photos

What’s wrong with Pinhole Cameras?

- Low incoming light => Long exposure time => Tripod

KODAK Film or Paper	Bright Sun	Cloudy Bright
TRI-X Pan	1 or 2 seconds	4 to 8 seconds
T-MAX 100 Film	2 to 4 seconds	8 to 16 seconds
KODABROMIDE Paper, F2	2 minutes	8 minutes

http://www.kodak.com/global/en/consumer/education/lessonPlans/pinholeCamera/pinholeCanBox.shtml

What’s wrong with Pinhole Cameras

People are ghosted

What’s wrong with Pinhole Cameras

People become ghosts!

Pinhole Camera Recap

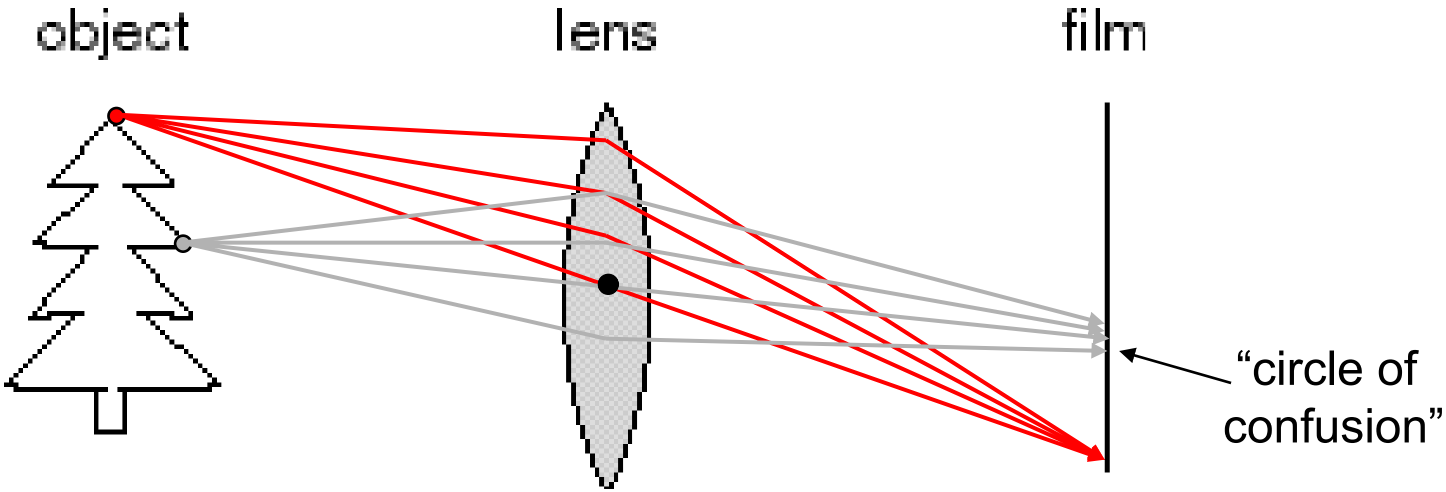
- Pinhole size (aperture) must be "very small" to obtain a clear image.

- 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!

What's the solution?

- Lens

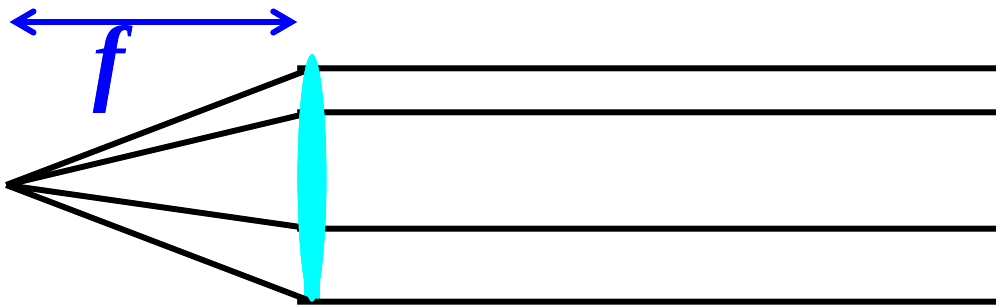


- A lens focuses light onto the film
  - There is a specific distance at which objects are "in focus"
    - other points project to a "circle of confusion" in the image
  - Changing the shape of the lens changes this distance

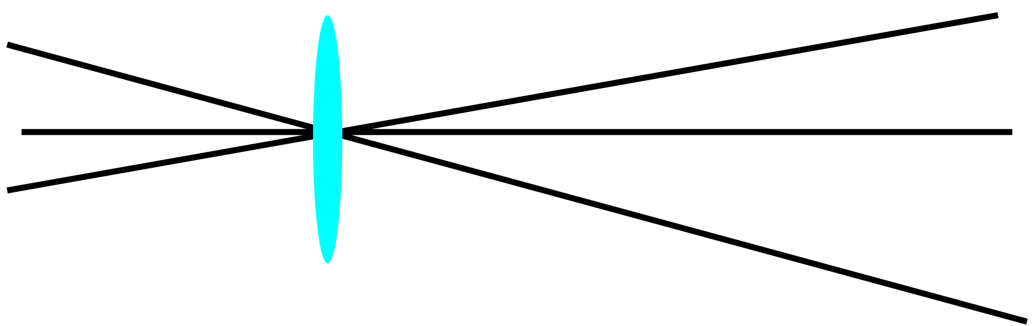
Steve Seitz's slide

Thin lens optics

- Simplification of geometrical optics for well-behaved lenses
- All parallel rays converge to one point on a plane located at the focal length *f*



- All rays going through the center are not deviated
  - Hence same perspective as pinhole

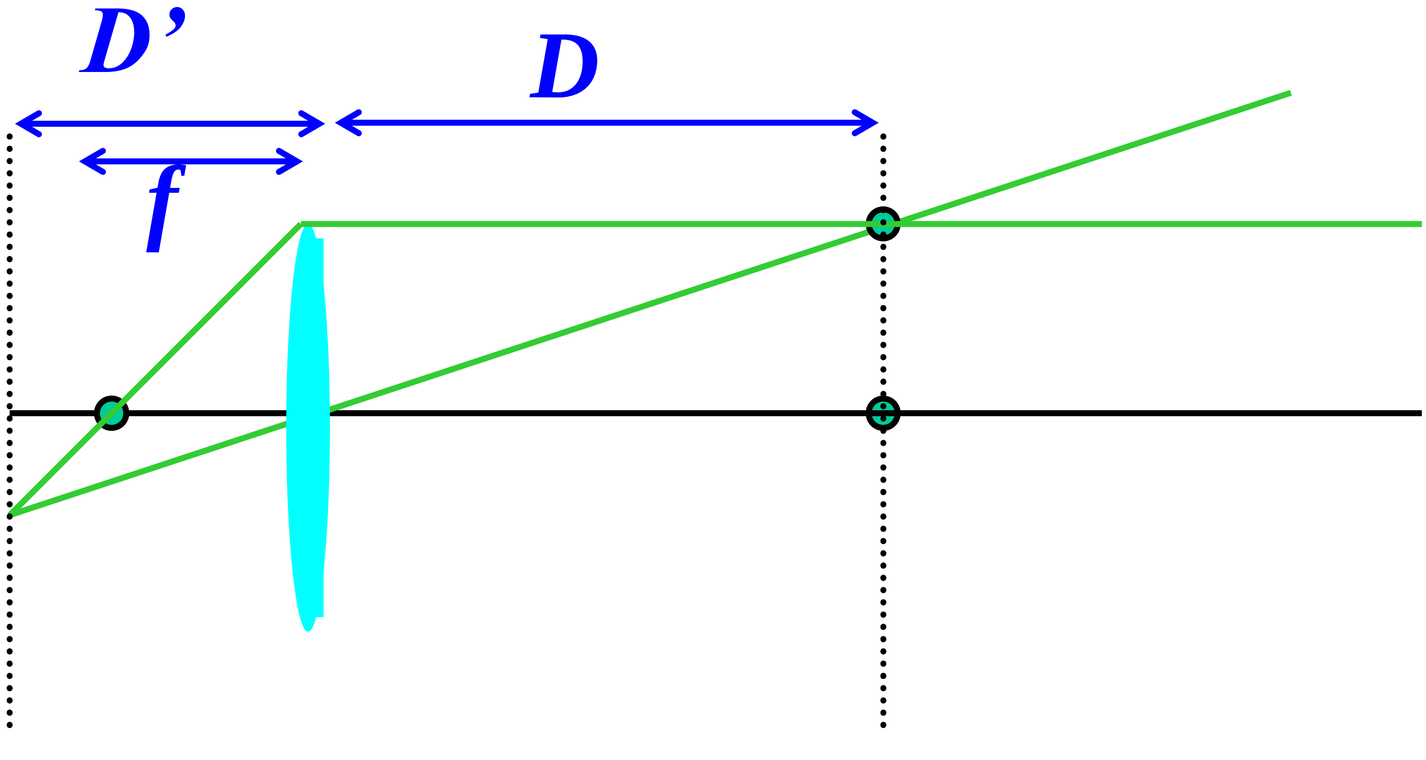


Frédo Durand’s slide

Demo!

– http://www.phy.ntnu.edu.tw/java/Lens/lens_e.html (by Fu-Kwun Hwang)

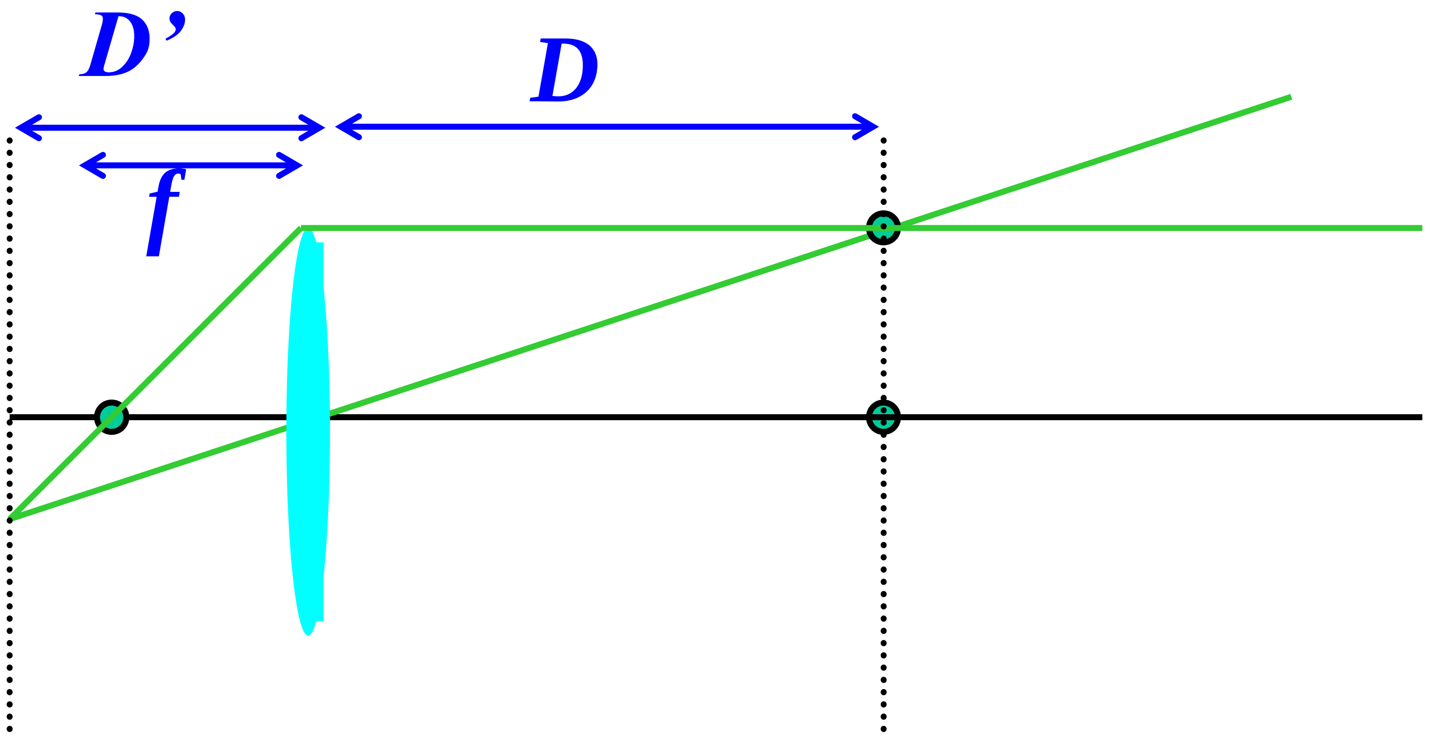
Thin lens formula



Frédo Durand's slide

Thin lens formula

Similar triangles everywhere!

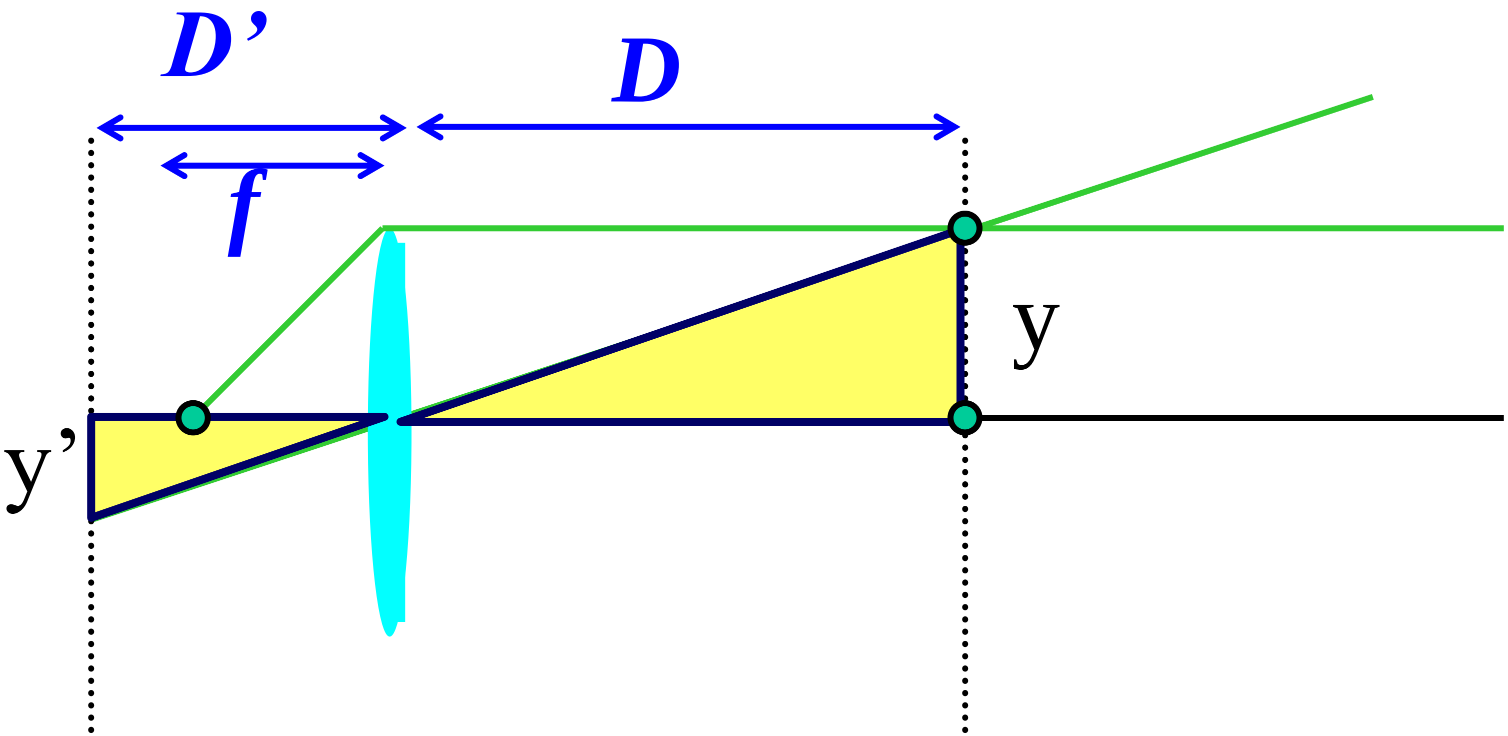


Frédo Durand's slide

Thin lens formula

Similar triangles everywhere!

$$y'/y = D'/D$$



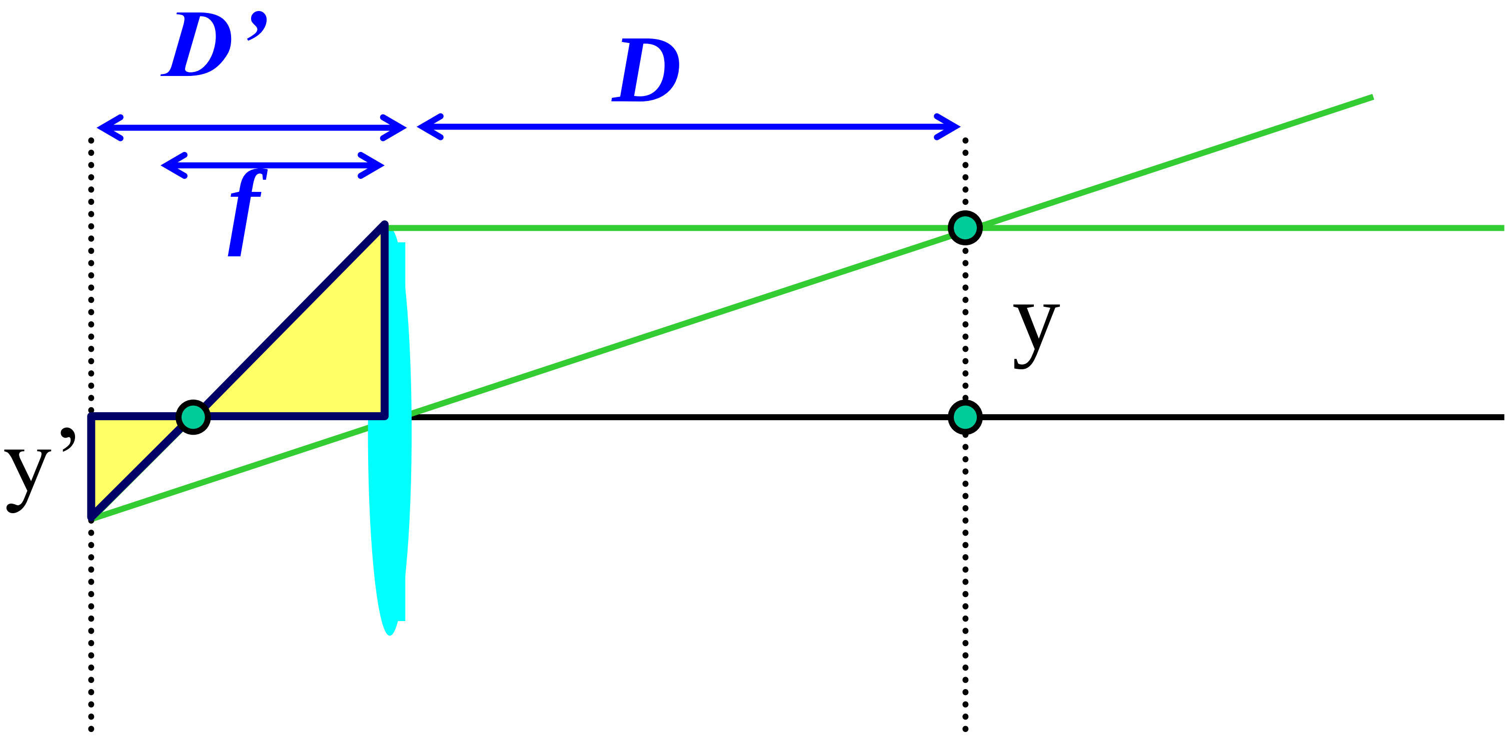
Frédo Durand's slide

Thin lens formula

Similar triangles everywhere!

$$y'/y = D'/D$$

$$y'/y = (D'-f)/D$$

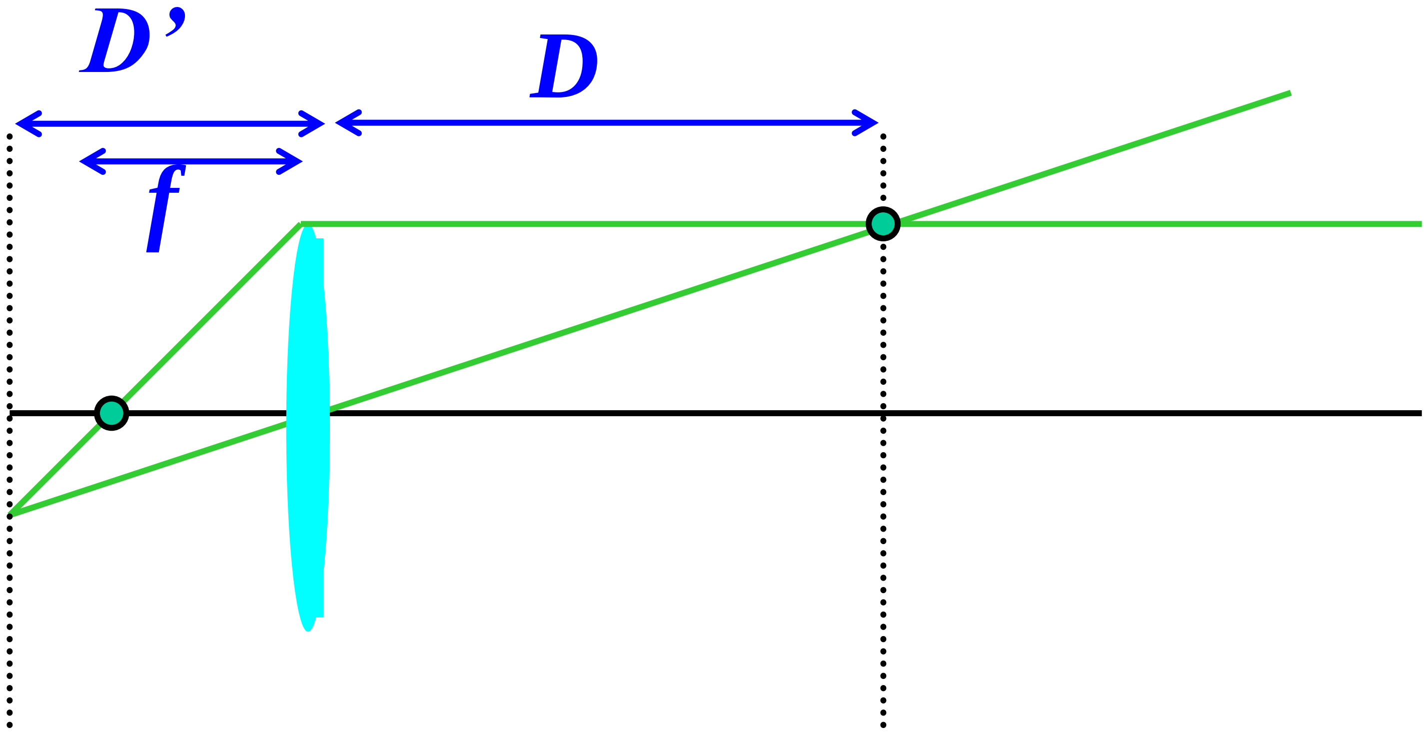


Frédo Durand's slide

Thin lens formula

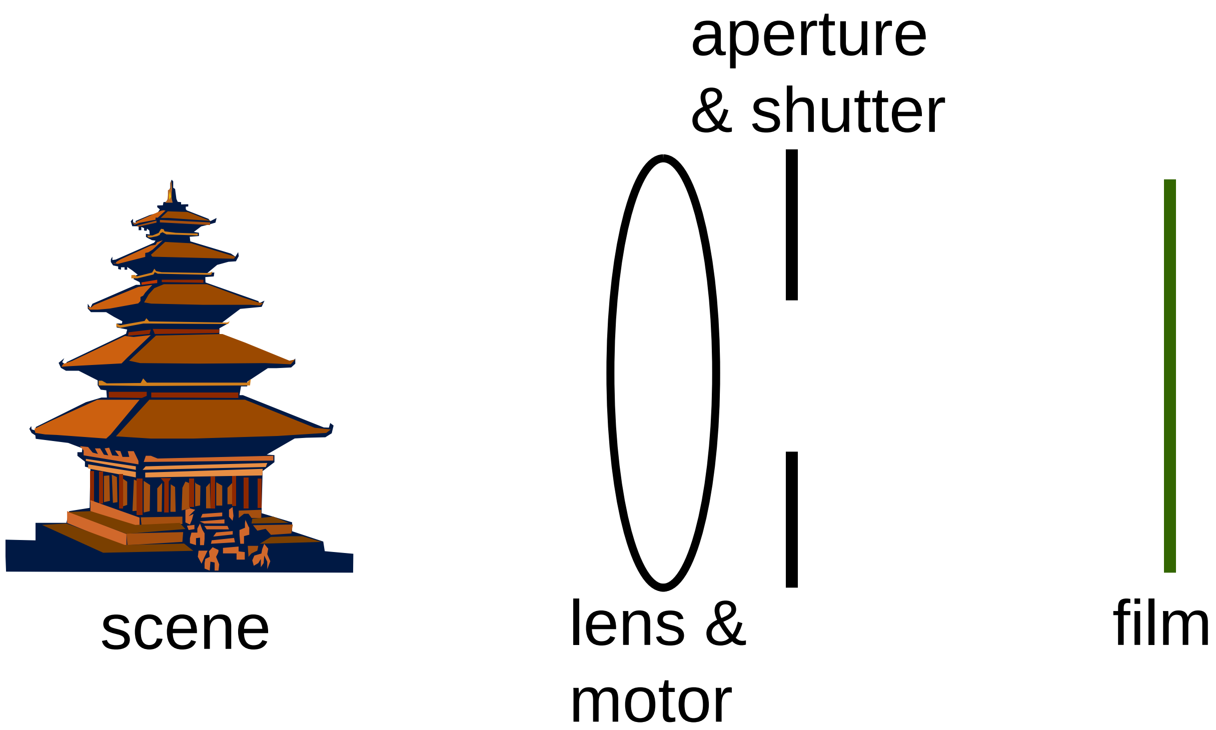
$$\frac{1}{D'} + \frac{1}{D} = \frac{1}{f}$$

The focal length f determines the lens's ability to bend (refract) light. It is a function of the shape and index of refraction of the lens.



Frédo Durand's slide

Film camera



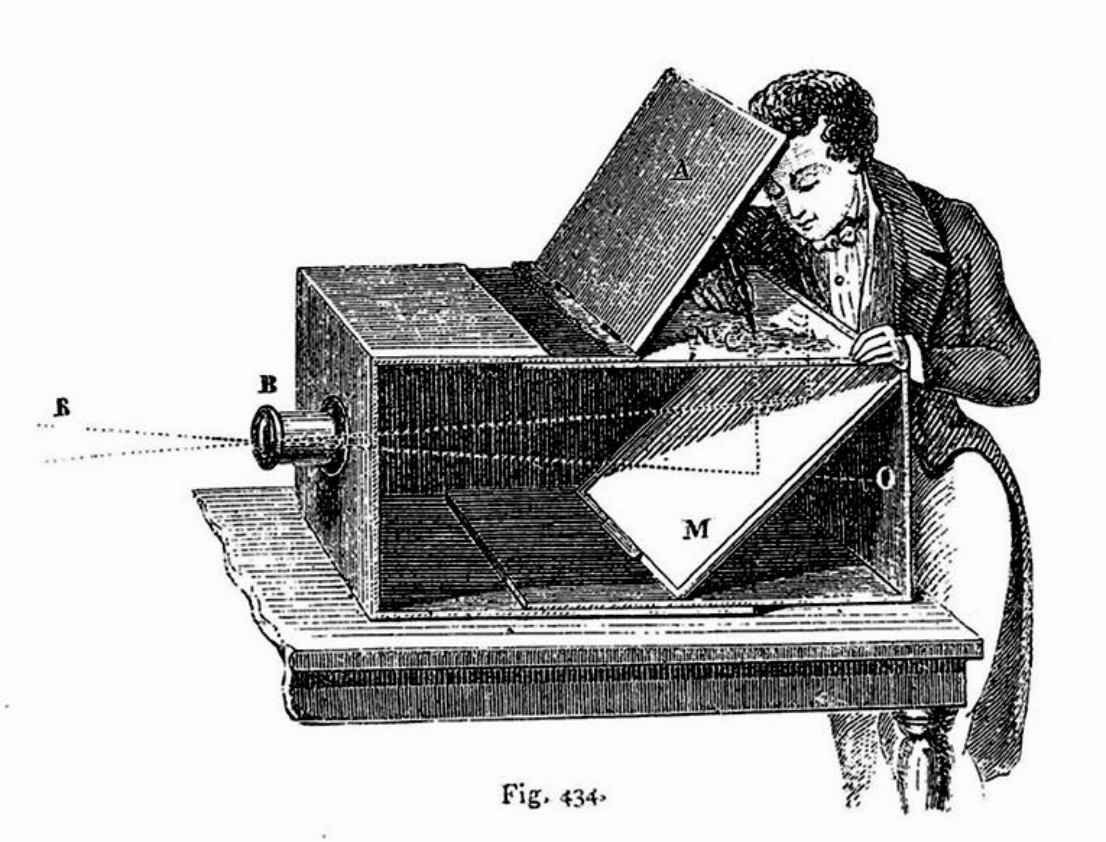
YungYu Chuang's slide

Film camera

Still Life, Louis Jaques Mande Daguerre, 1837

Srinivasa Narasimhan's slide

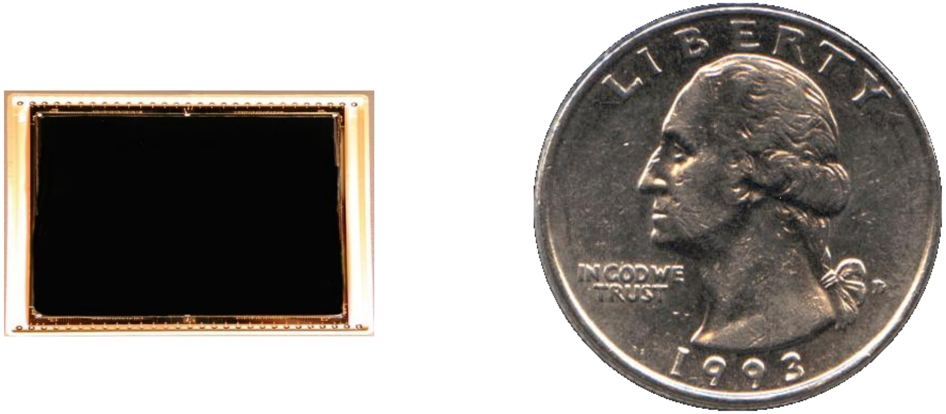
Before Film was invented



Lens Based Camera Obscura, 1568

Srinivasa Narasimhan's slide

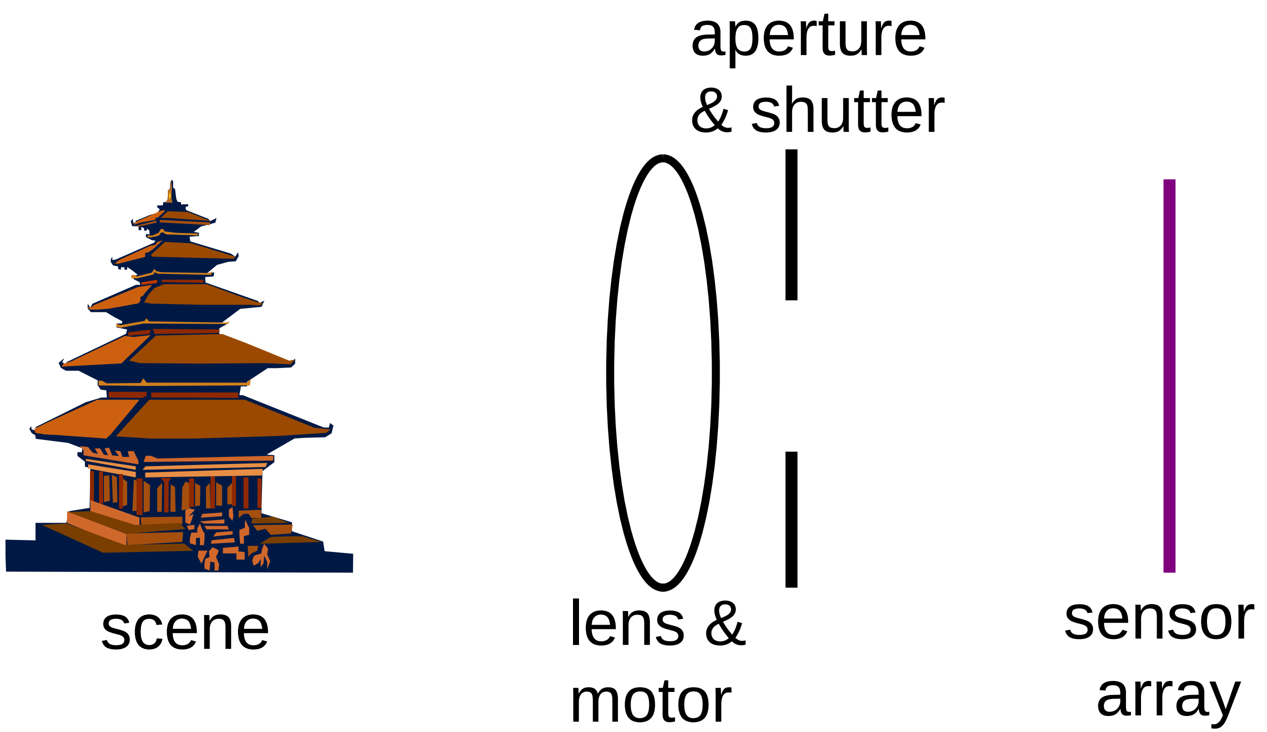
Silicon Image Detector



Silicon Image Detector, 1970

Shree Nayar’s slide

Digital camera



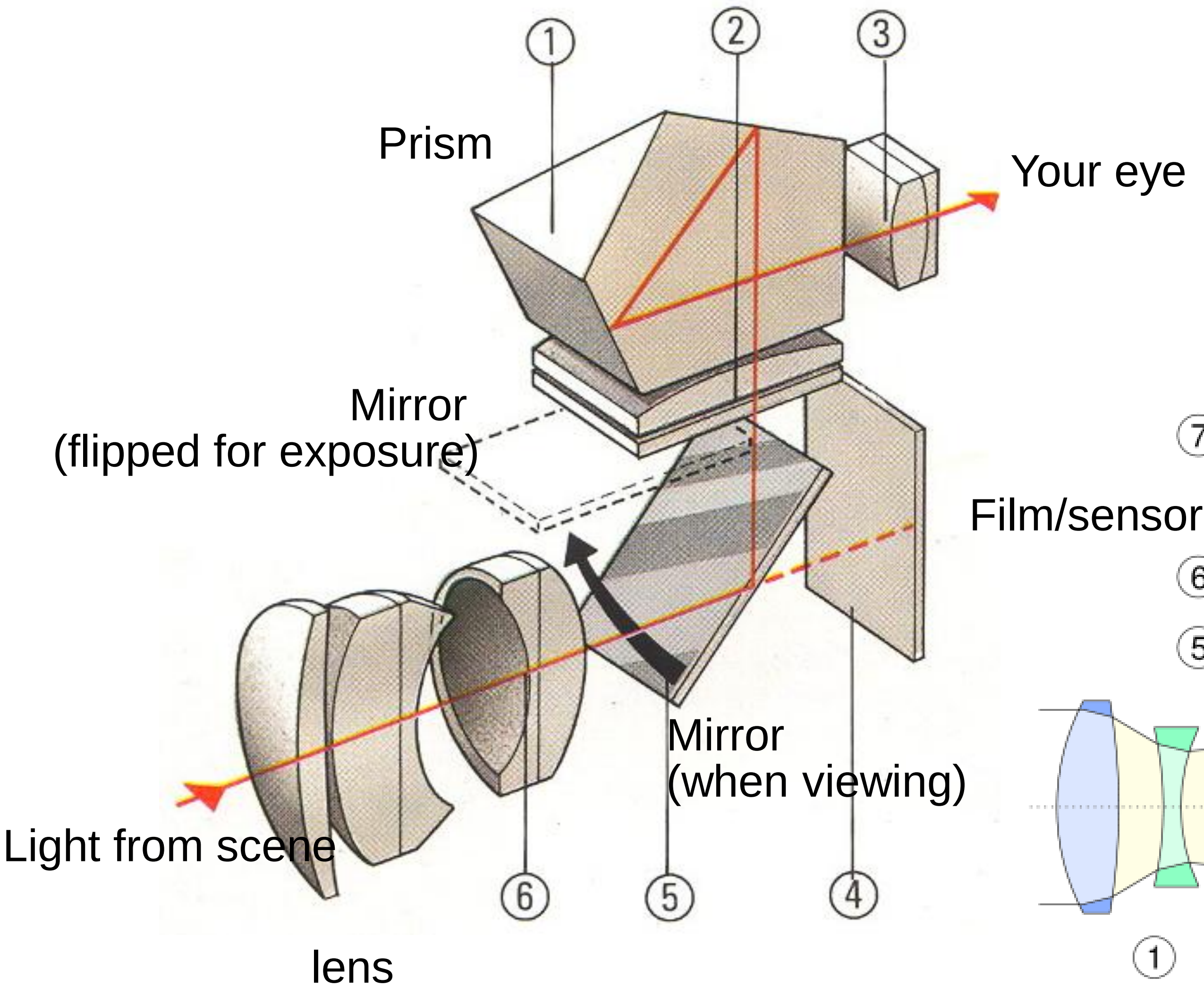
- A digital camera replaces film with a sensor array
- Each cell in the array is a light-sensitive diode that converts photons to electrons

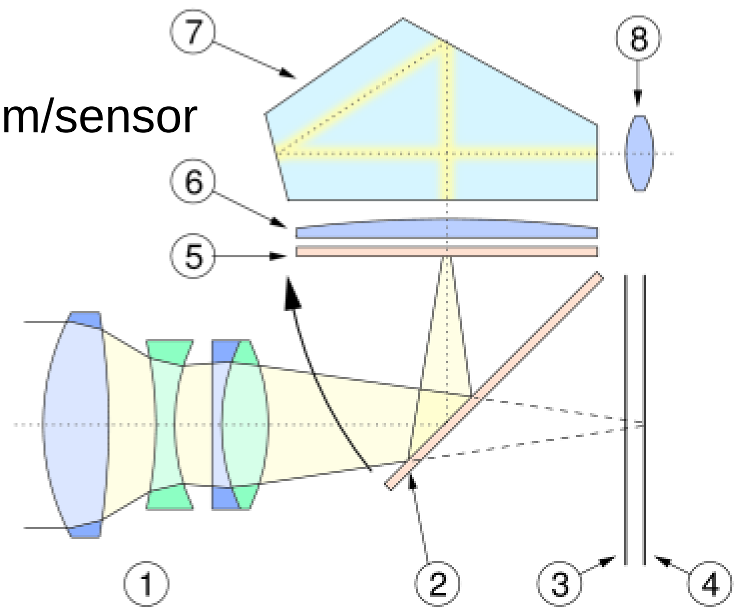
YungYu Chuang's slide

SLR (Single-Lens Reflex)

- Reflex (R in SLR) means that we see through the same lens used to take the image.
- Not the case for compact cameras

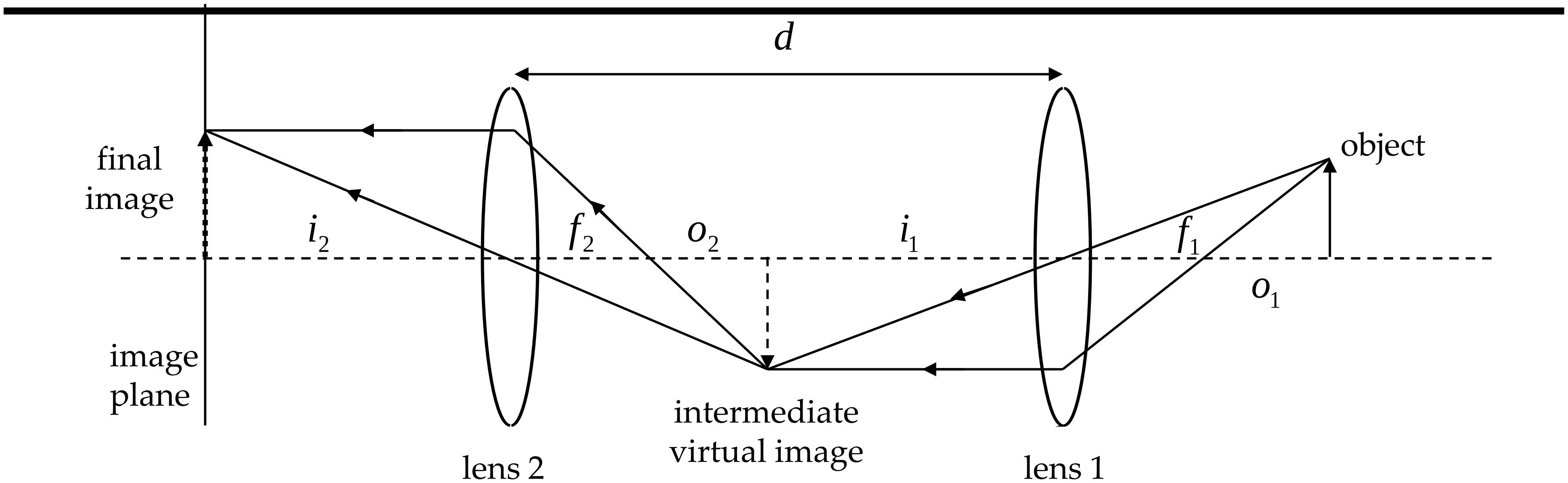
SLR view finder





YungYu Chuang's slide

Compound Lens System



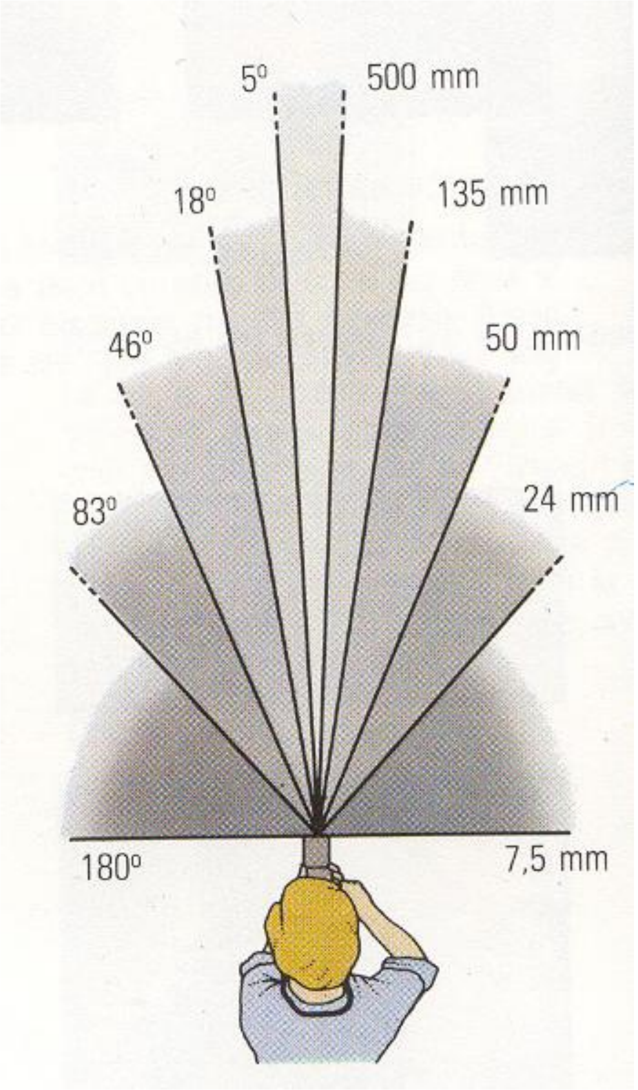
- Rule : Image formed by first lens is the object for the second lens.
- If d ≈ 0, the combined focal length f is

$$f = \frac{f_1 f_2}{f_1 + f_2}$$

Field of View (FoV) vs Focal Length

Canon EF-S 60mm f/2.8 | Canon EF 100mm f/2.8 | Canon EF 180mm f/3.5

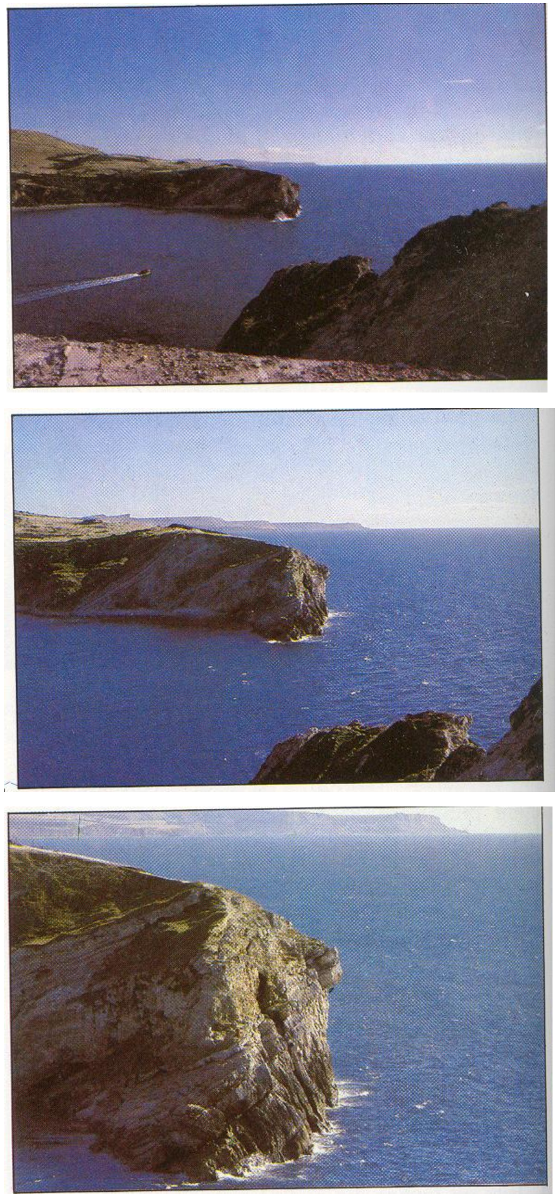
Field of View (FoV) vs Focal Length



24mm

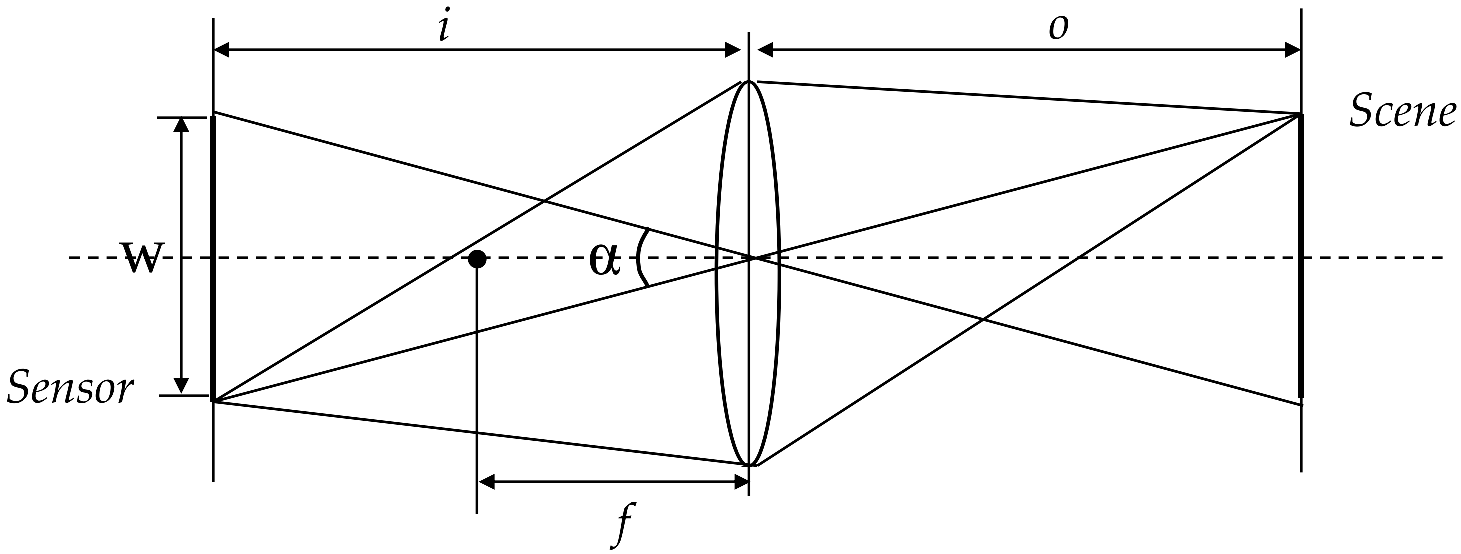
50mm

135mm



Frédo Durand's slide

Field of View (FoV) vs Focal Length



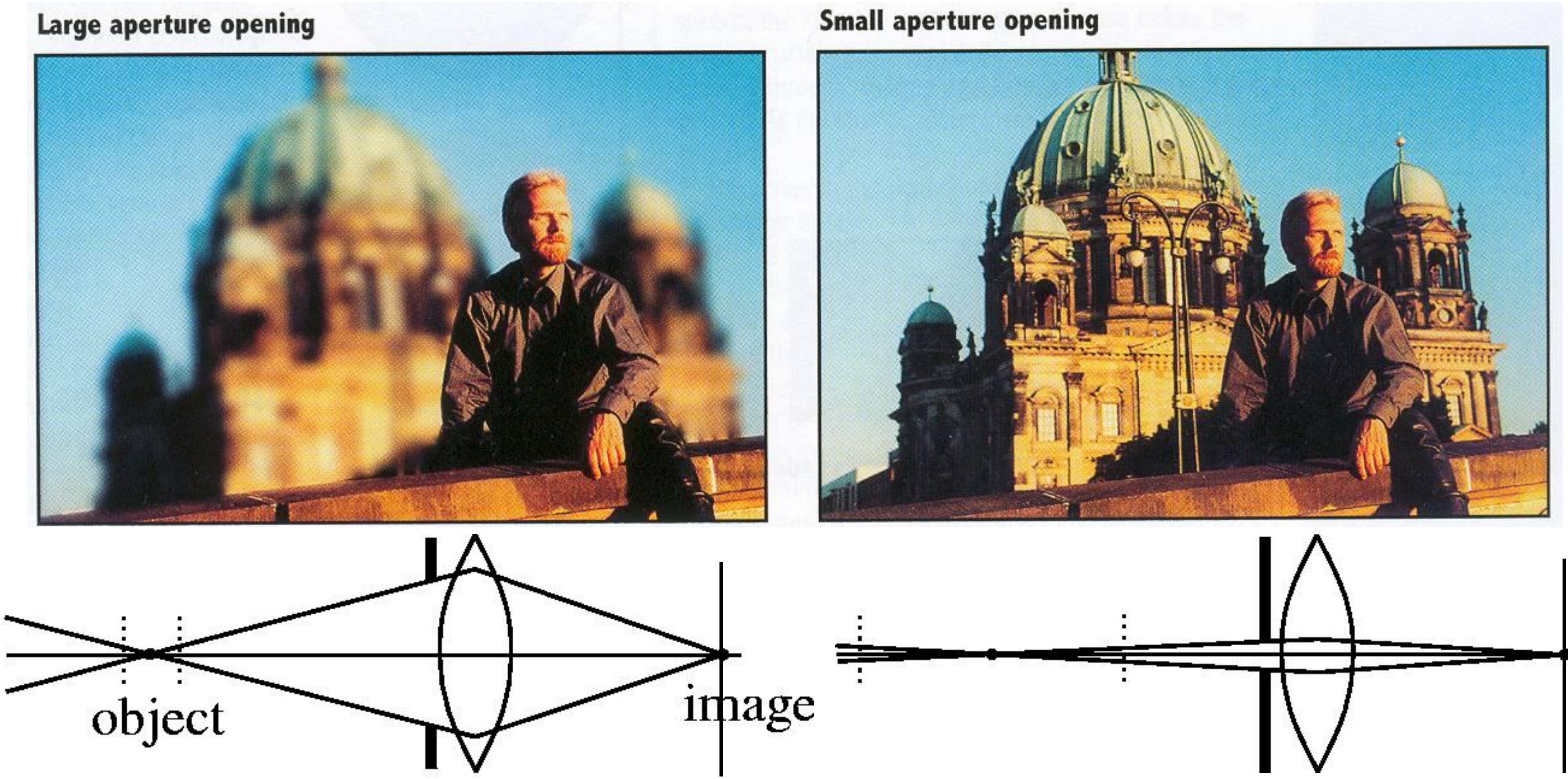
Gaussian Lens Formula: $$\frac{1}{i} + \frac{1}{o} = \frac{1}{f}$$

Field of View: $\alpha = 2\arctan(w/(2i)) \approx 2\arctan(w/(2f))$

Example: w = 30mm, f = 50mm => $\alpha \approx 33.4^{o}$

Question: How does FoV change when we focus on closer objects?

Depth of Field



Changing the aperture size affects depth of field. A smaller aperture increases the range in which the object is approximately in focus

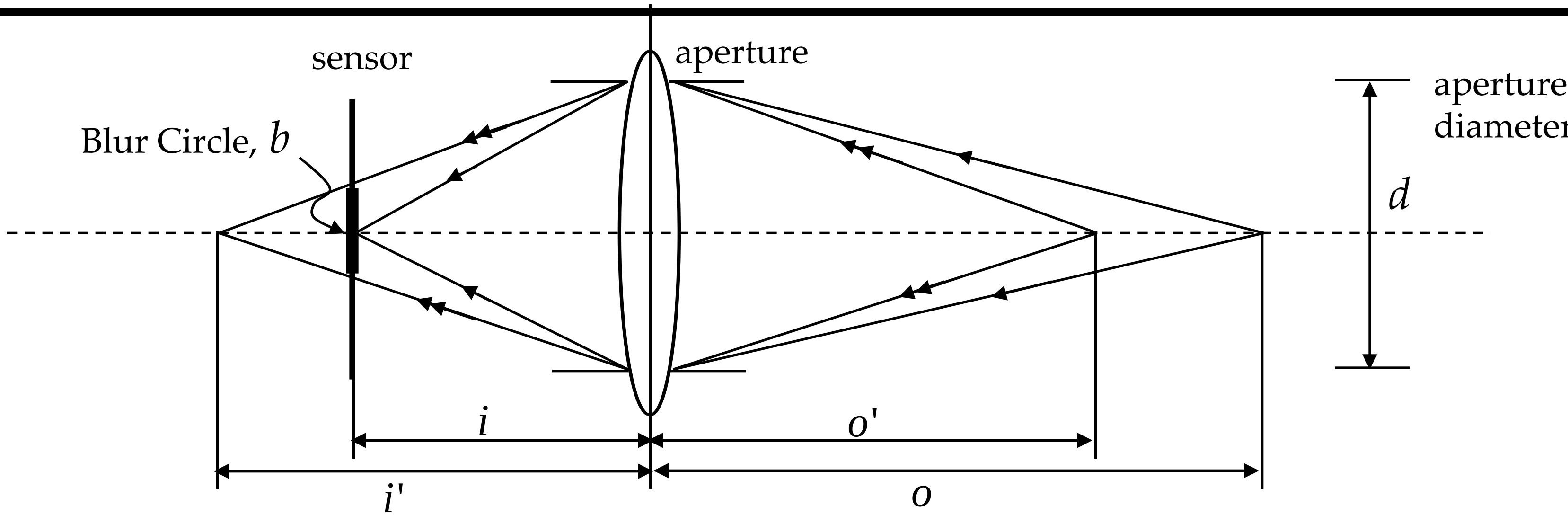
Aperture

- Aperture is the diameter of the lens opening, usually specified by f-stop, f/D, a fraction of the focal length.
  - f/2.0 on a 50mm means that the aperture is 25mm
  - f/2.0 on a 100mm means that the aperture is 50mm

- When a change in f-stop occurs, the light is either doubled or cut in half.
- Lower f-stop, more light (larger lens opening)
- Higher f-stop, less light (smaller lens opening)

YungYu Chuang's slide

F-stop



Gaussian Law: $\frac{1}{i} + \frac{1}{o} = \frac{1}{f}$ $\frac{1}{i'} + \frac{1}{o'} = \frac{1}{f}$ $\Rightarrow$ $(i' - i) = \frac{f}{(o' - f)} \frac{f}{(o - f)} (o - o')$

Blur Circle Diameter : $b = \frac{d}{i'} (i' - i) \approx \frac{d}{f} (i' - i)$

f-stop: $\# = \frac{f}{d}$

F-stop

Canon EF-S 60mm f/2.8

Canon EF 100mm f/2.8

Canon EF 180mm f/3.5

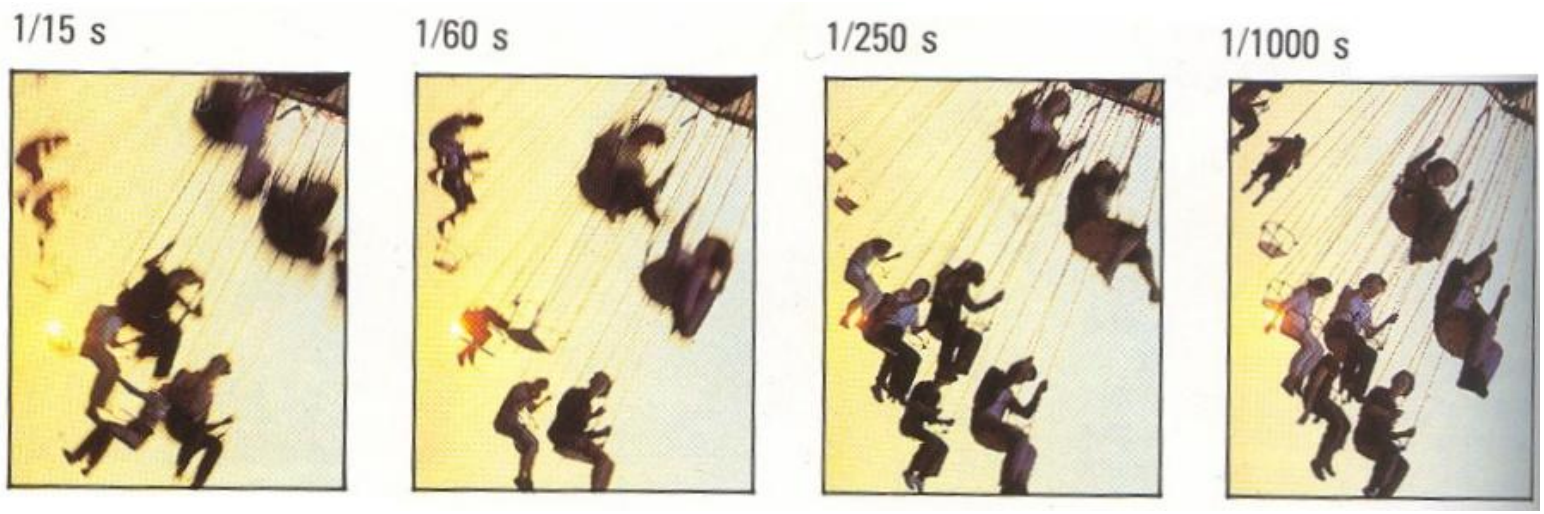
Exposure

- Two main parameters:
  - Aperture (in f stop)
  - shutter speed (in fraction of a second)

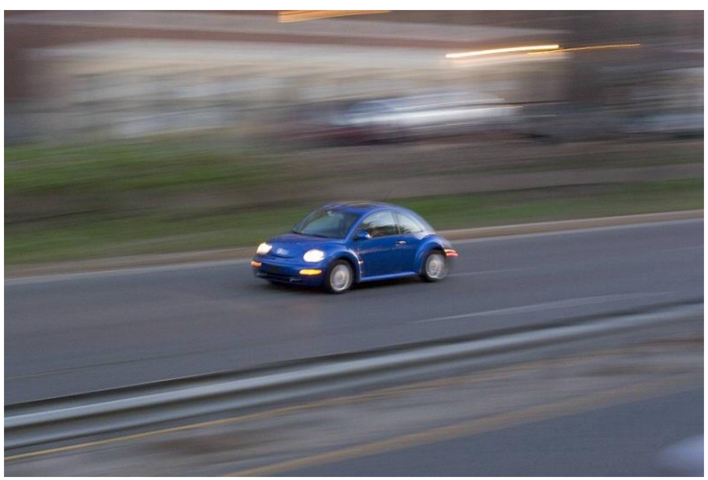
See http://www.photonhead.com/simcam/

Effects of shutter speeds

- Slower shutter speed => more light, but more motion blur



- Faster shutter speed freezes motion



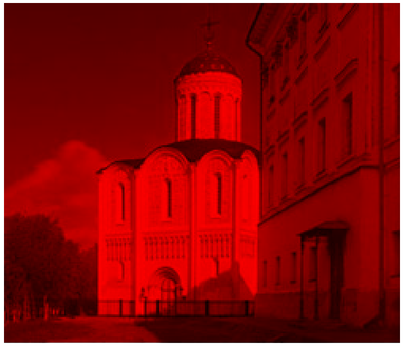
YungYu Chuang’s slide

Color

So far, we've only talked about monochrome sensors. Color imaging has been implemented in a number of ways:

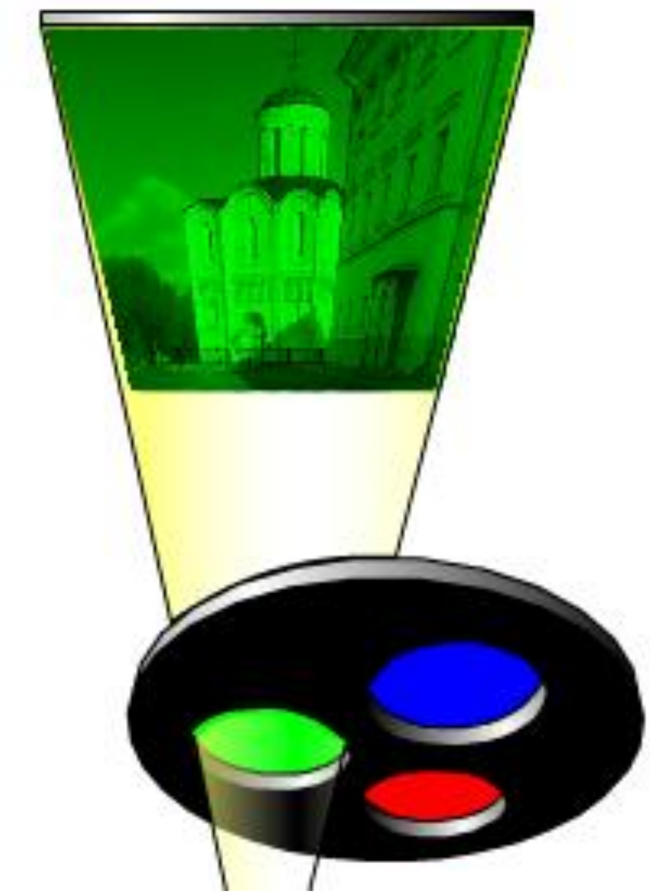
- Field sequential
- Multi-chip
- Color filter array
- X3 sensor

Field sequential



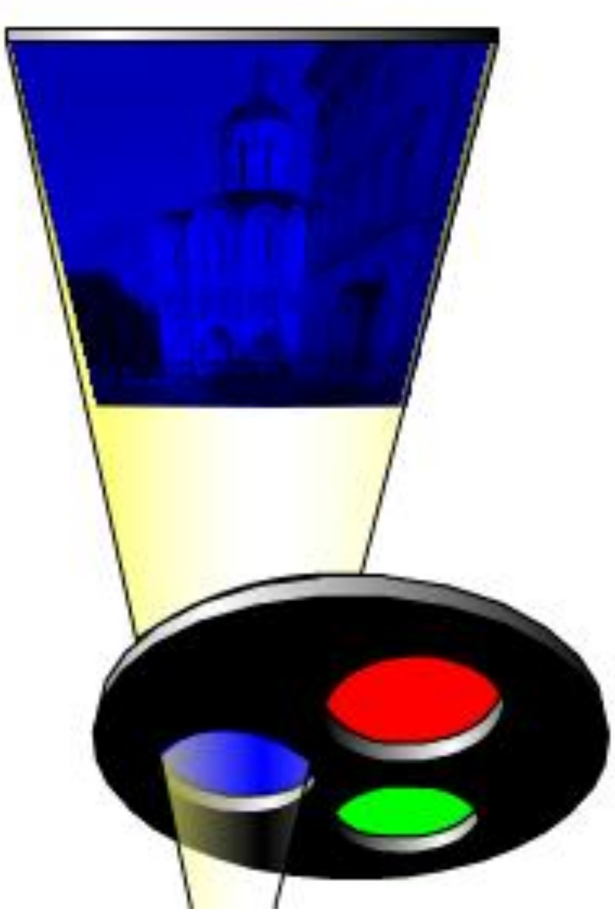
YungYu Chuang's slide

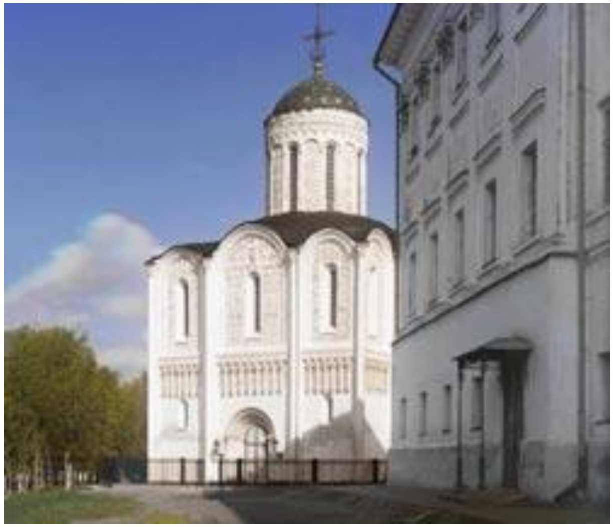
Field sequential



YungYu Chuang's slide

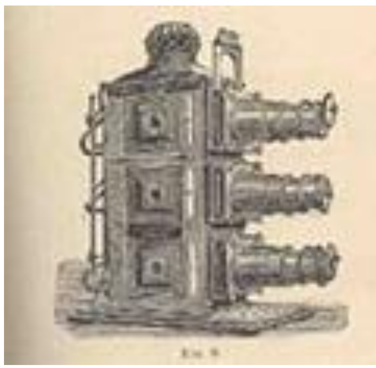
Field sequential





YungYu Chuang's slide

Prokudin-Gorskii (early 1900's)



Lantern projector

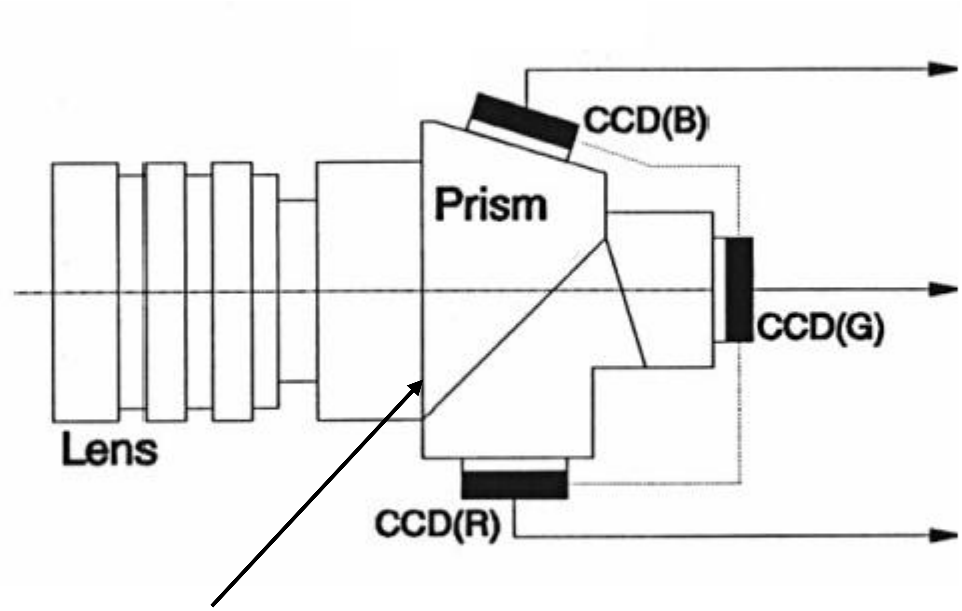
http://www.loc.gov/exhibits/empire/

YungYu Chuang's slide

Prokudin-Gorskii (early 1990's)

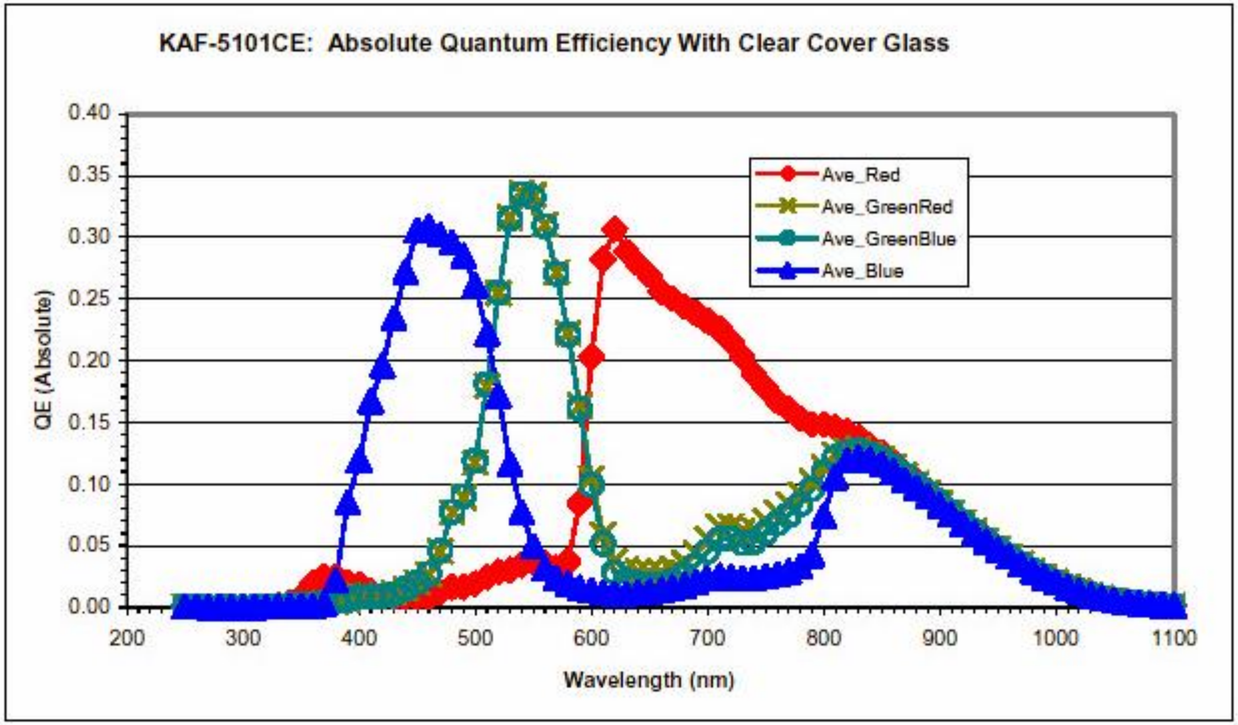
YungYu Chuang's slide

Multi-chip



wavelength
dependent

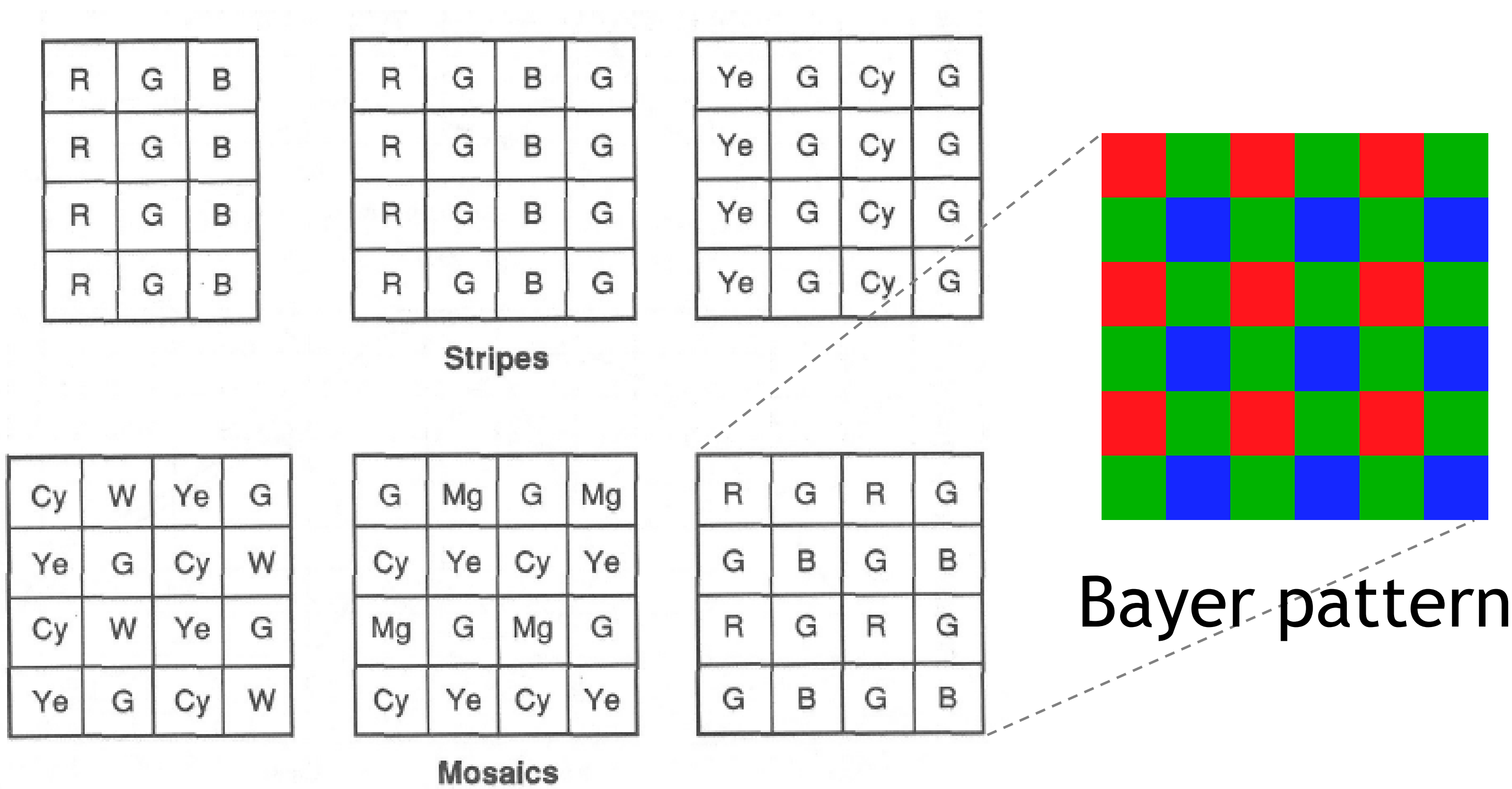
Embedded color filters



Color filters can be manufactured directly onto the photodetectors.

YungYu Chuang's slide

Color filter array



Color filter arrays (CFAs)/color filter mosaics

YungYu Chuang's slide

Color filter array

R	G	B
R	G	B
R	G	B
R	G	B

R	G	B	G
R	G	B	G
R	G	B	G
R	G	B	G

Ye	G	Cy	G
Ye	G	Cy	G
Ye	G	Cy	G
Ye	G	Cy	G

Stripes

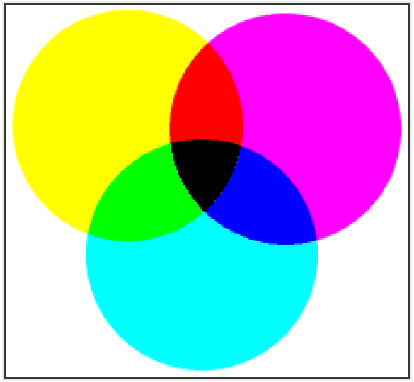
Cy	W	Ye	G
Ye	G	Cy	W
Cy	W	Ye	G
Ye	G	Cy	W

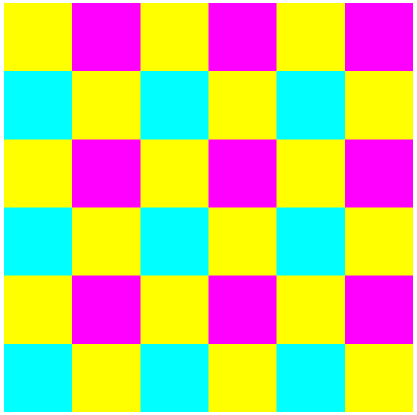
G	Mg	G	Mg
Cy	Ye	Cy	Ye
Mg	G	Mg	G
Cy	Ye	Cy	Ye

R	G	R	G
G	B	G	B
R	G	R	G
G	B	G	B

Mosaics

Kodak DCS620x



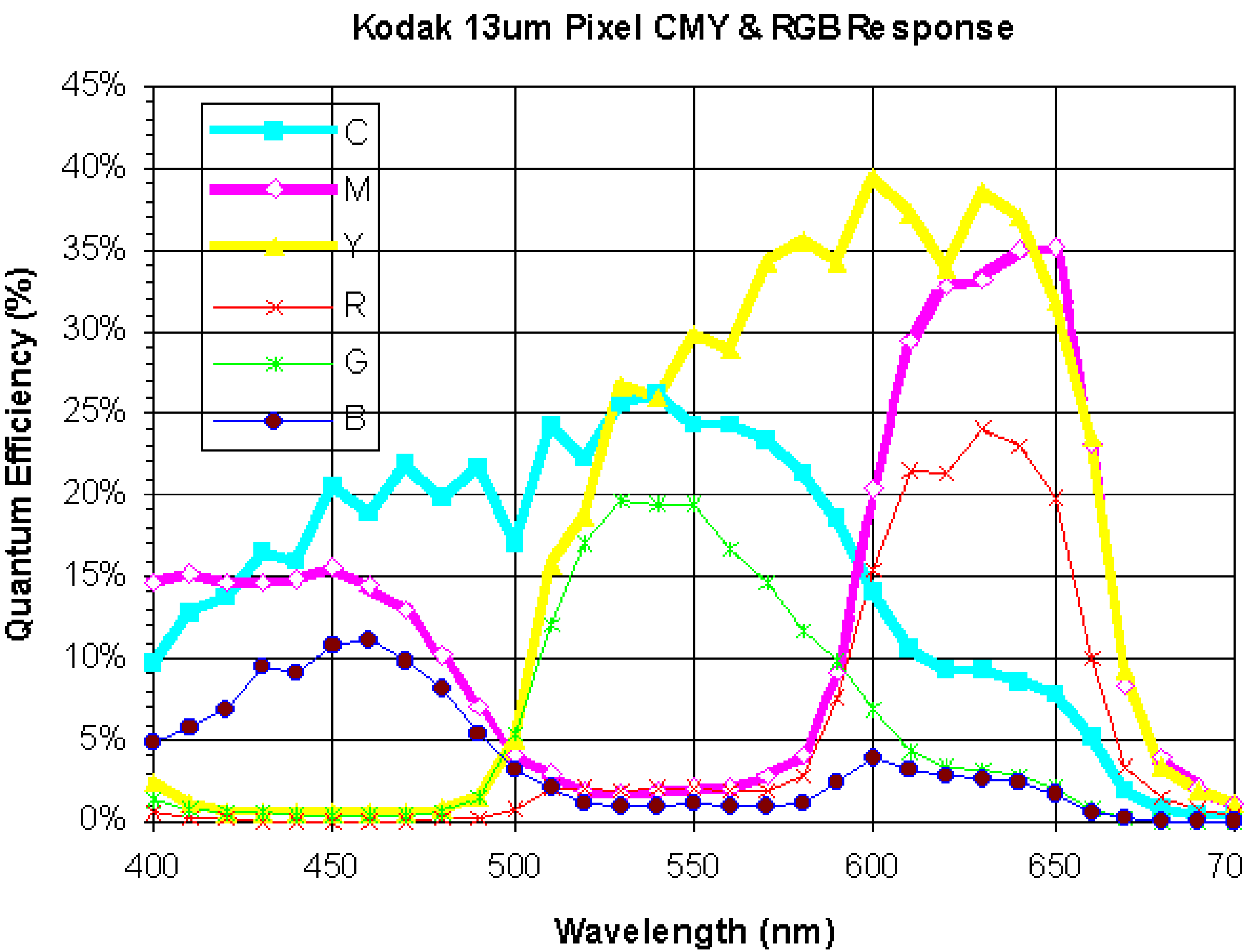


CMY

Color filter arrays (CFAs)/color filter mosaics

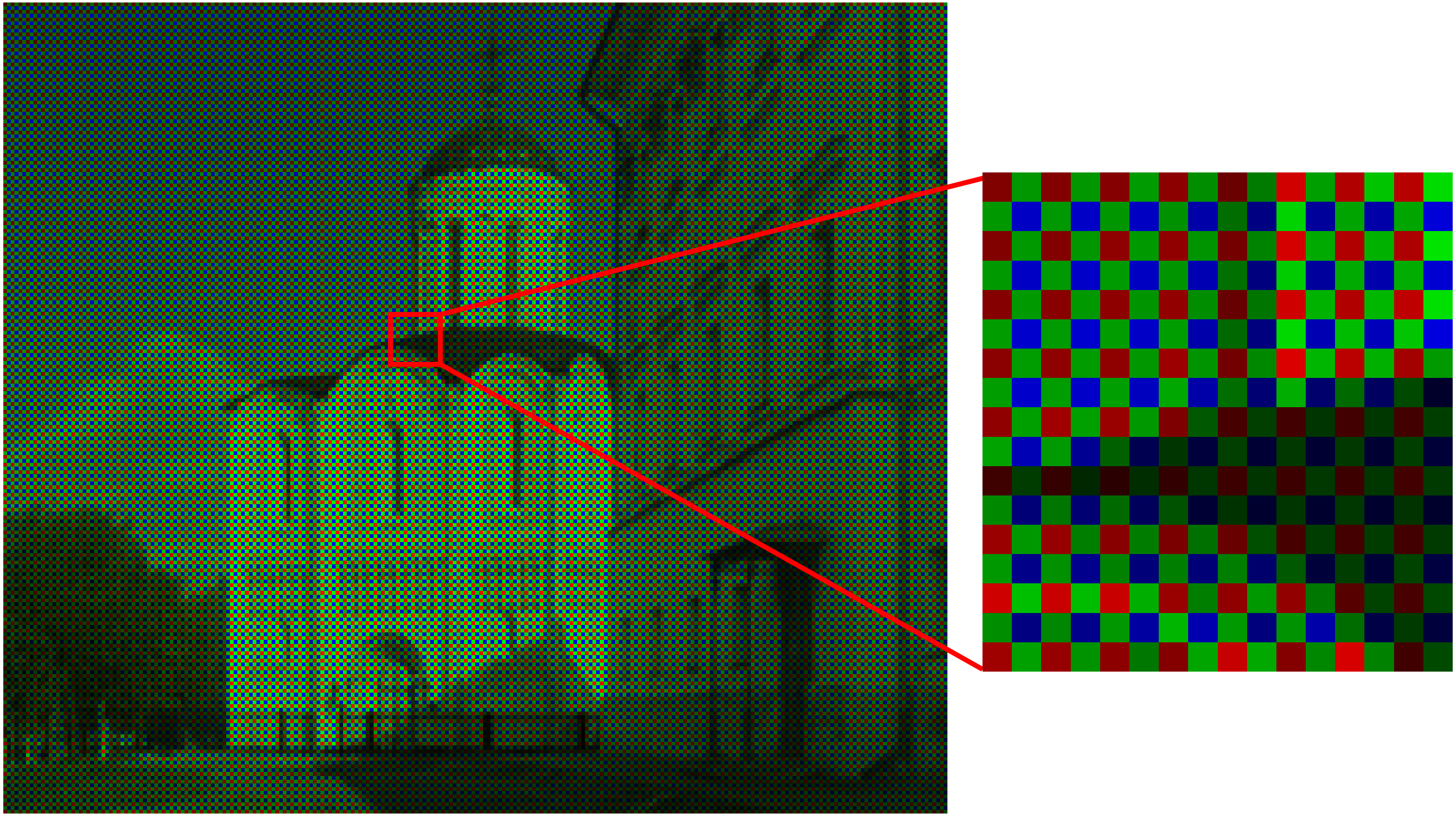
YungYu Chuang's slide

Why CMY CFA might be better



YungYu Chuang's slide

Bayer's pattern



YungYu Chuang's slide

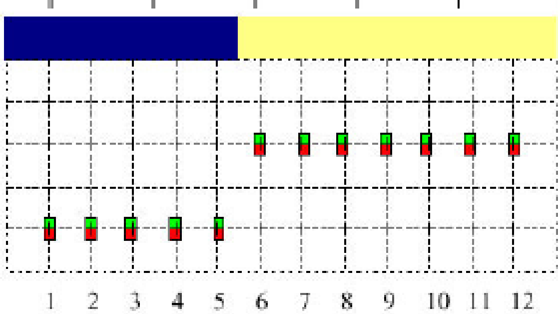
Demosaicking CFA's

R 11	G 12	R 13	G 14	R 15	G 16	R 17
G 21	B 22	G 23	B 24	G 25	B 26	G 27
R 31	G 32	R 33	G 34	R 35	G 36	R 37
G 41	B 42	G 43	B 44	G 45	B 46	G 47
R 51	G 52	R 53	G 54	R 55	G 56	R 57

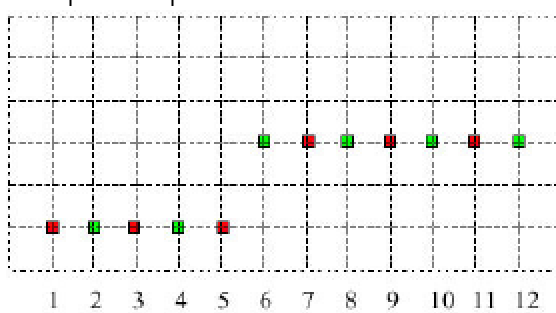
bilinear interpolation

$$G_{44} = (G_{34} + G_{43} + G_{45} + G_{54})/4$$

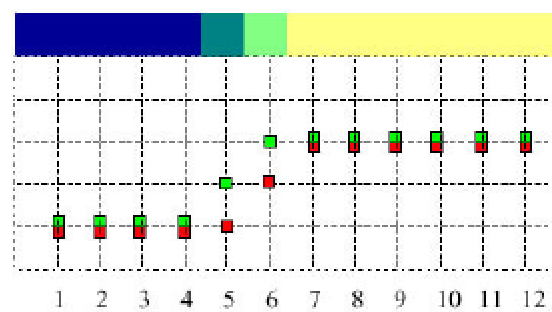
$$R_{44} = (R_{33} + R_{35} + R_{53} + R_{55})/4$$



original



input



linear interpolation

YungYu Chuang's slide

Demosaicking CFA's

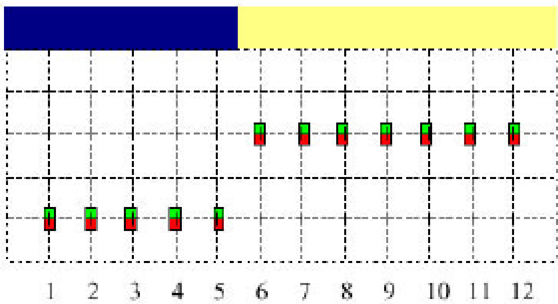
R 11	G 12	R 13	G 14	R 15	G 16	R 17
G 21	B 22	G 23	B 24	G 25	B 26	G 27
R 31	G 32	R 33	G 34	R 35	G 36	R 37
G 41	B 42	G 43	B 44	G 45	B 46	G 47
R 51	G 52	R 53	G 54	R 55	G 56	R 57
G 61	B 62	G 63	B 64	G 65	B 66	G 67
R 71	G 72	R 73	G 74	R 75	G 76	R 77

Median-based interpolation (Freeman)

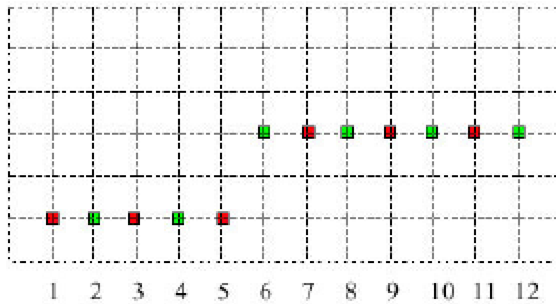
1. Linear interpolation
2. Median filter on color differences

Demosaicking CFA's

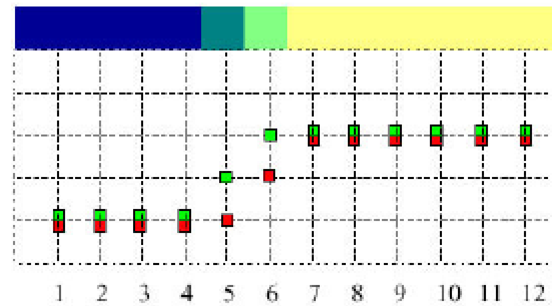
Median-based interpolation (Freeman)



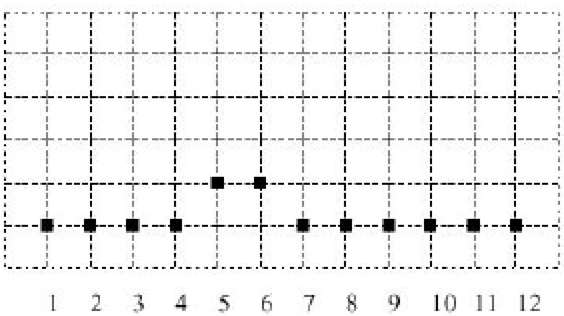
original



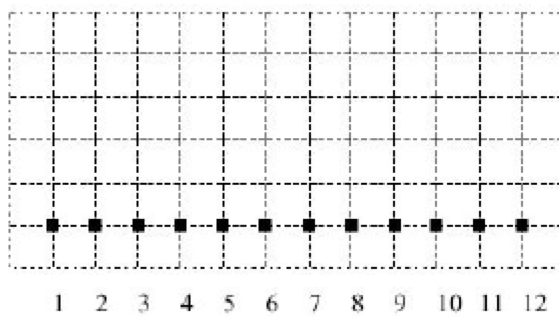
input



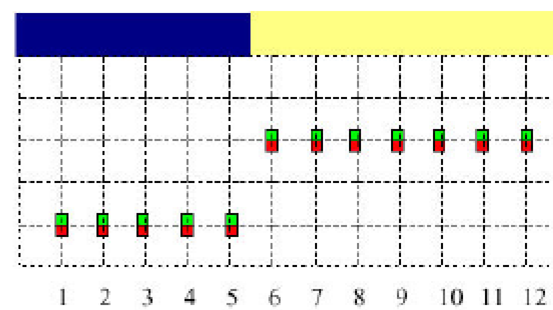
linear interpolation



color difference
(e.g. G-R)



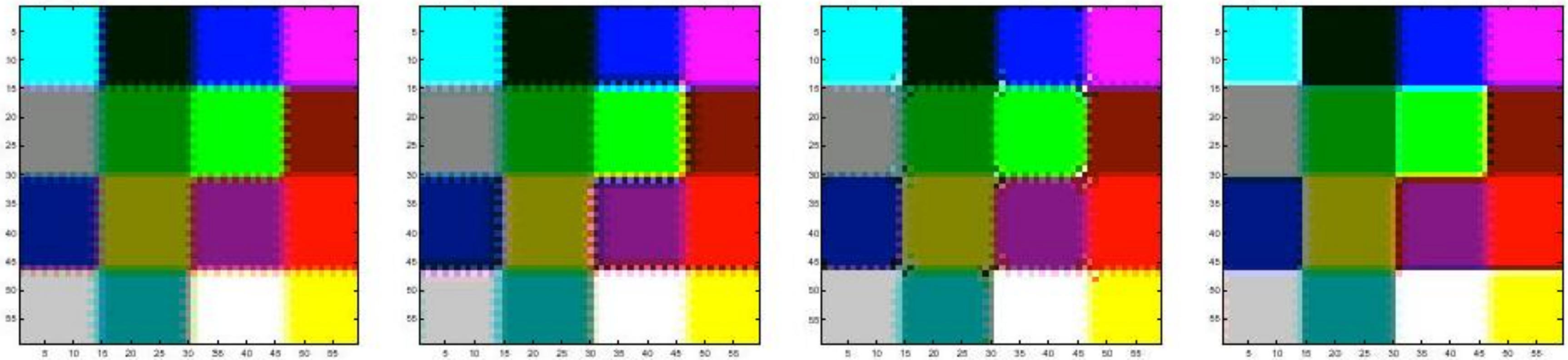
median filter
(kernel size 5)



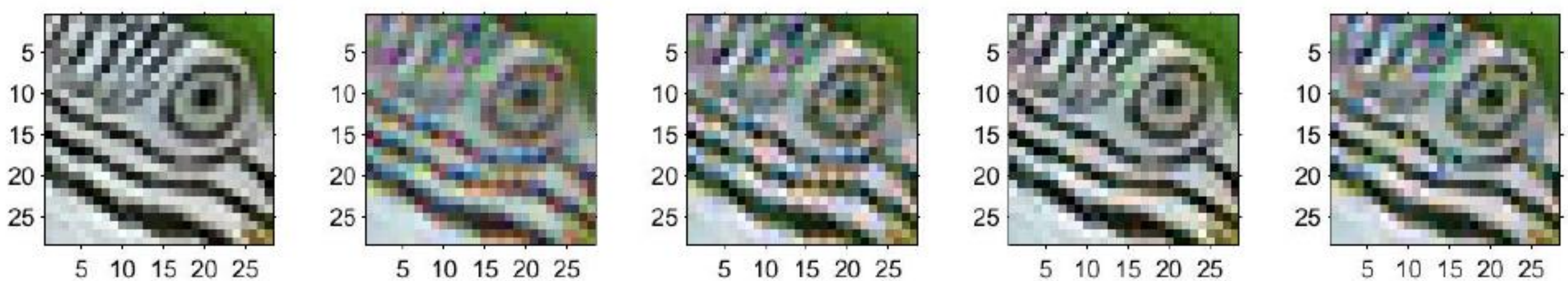
Reconstruction
(G=R+filtered
difference)

YungYu Chuang's slide

Demosaicking CFA's



Bilinear *Cok* *Freeman* *LaRoche*

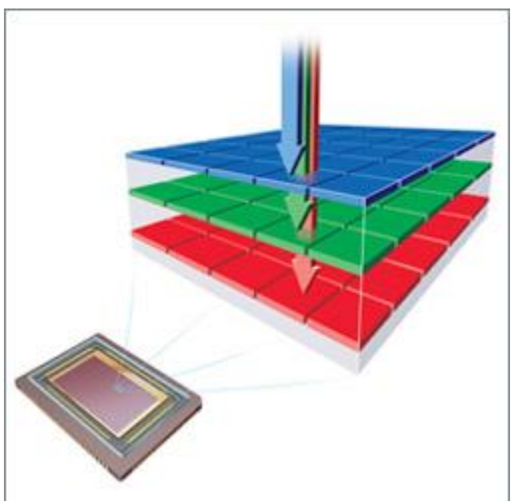


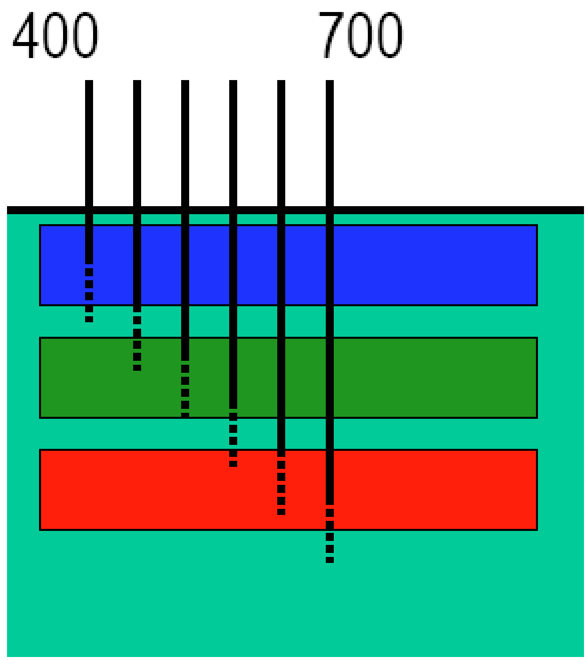
Input *Bilinear* *Cok* *Freeman* *LaRoche*

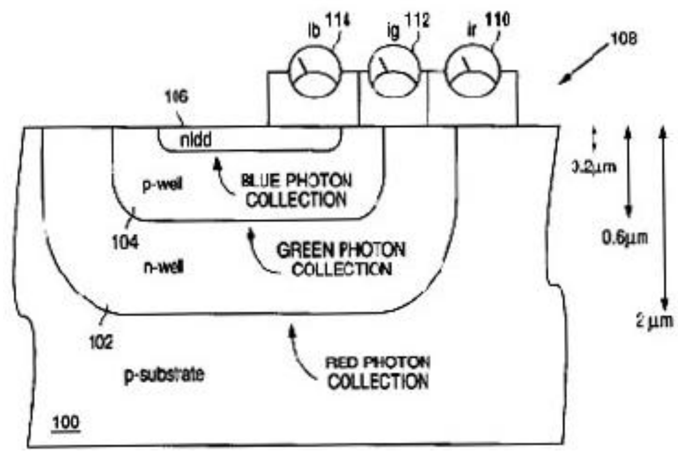
Generally, Freeman's is the best, especially for natural images.

Foveon X3 sensor

- light penetrates to different depths for different wavelengths
- multilayer CMOS sensor gets 3 different spectral sensitivities

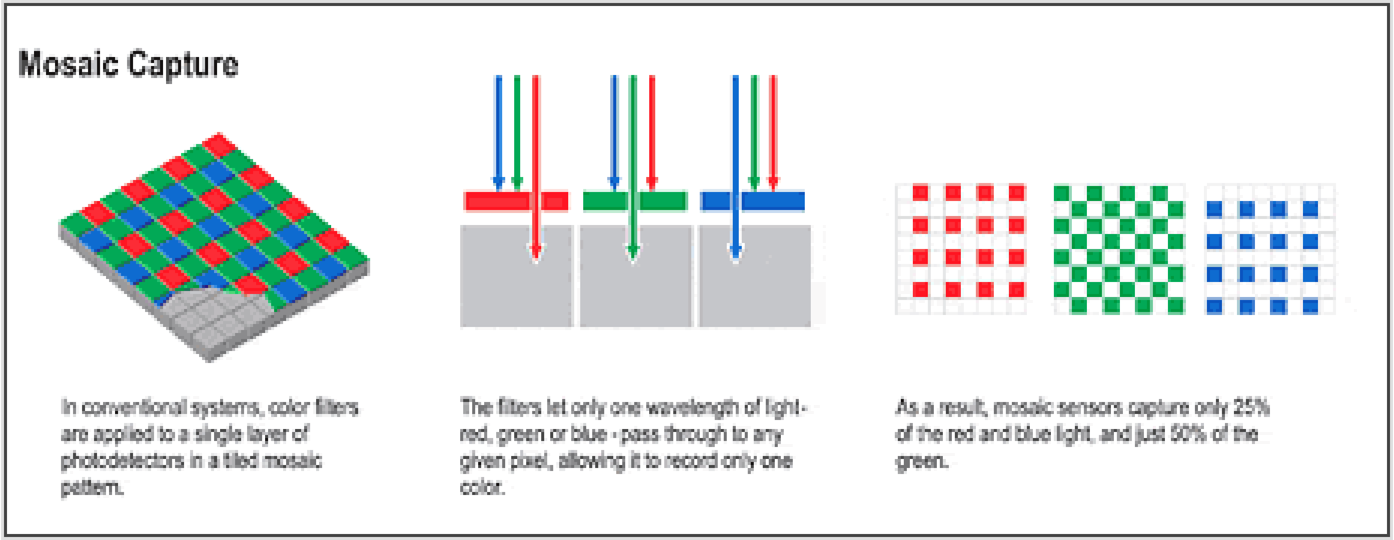


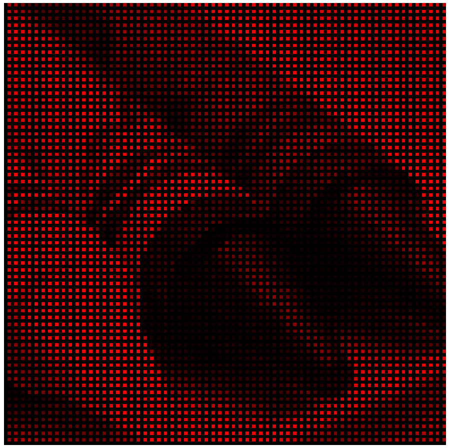




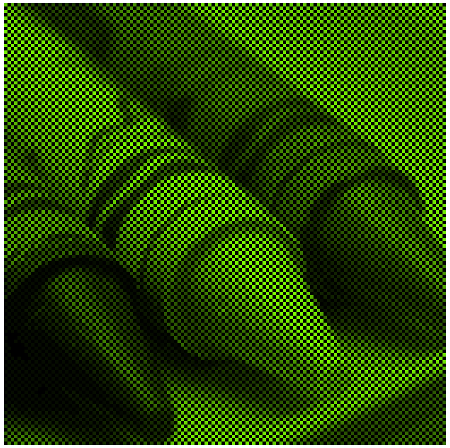
YungYu Chuang's slide

Color filter array

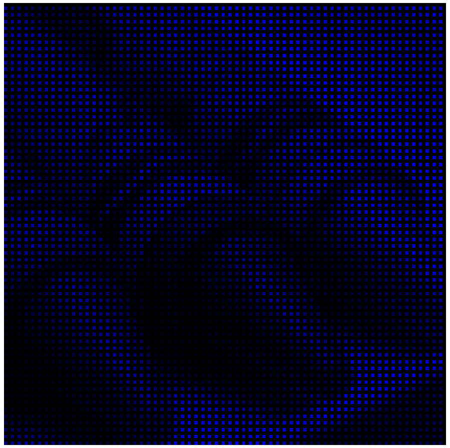




red



green

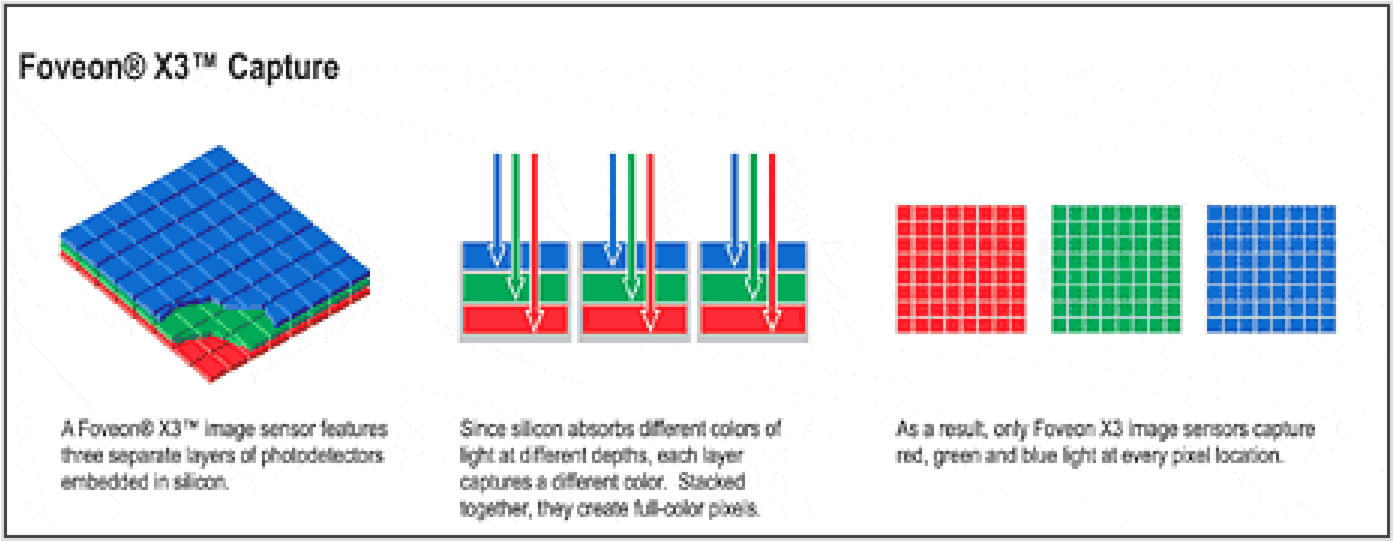


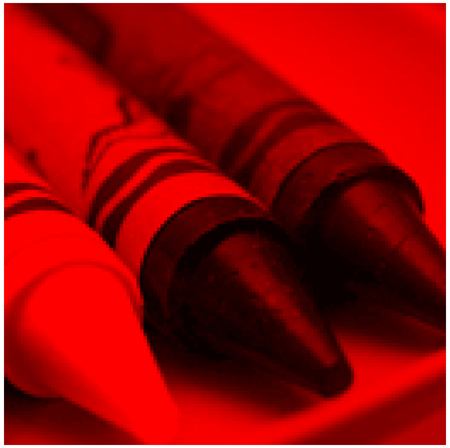
blue

output

YungYu Chuang's slide

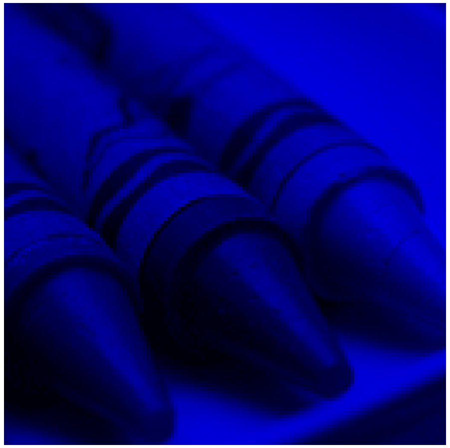
X3 technology





red

green

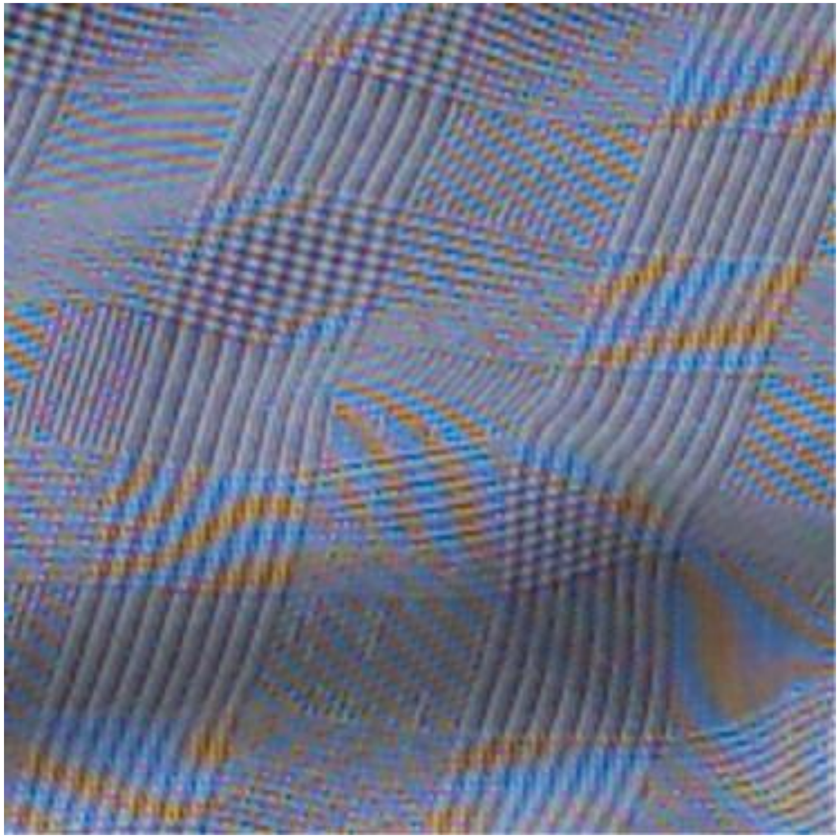


blue

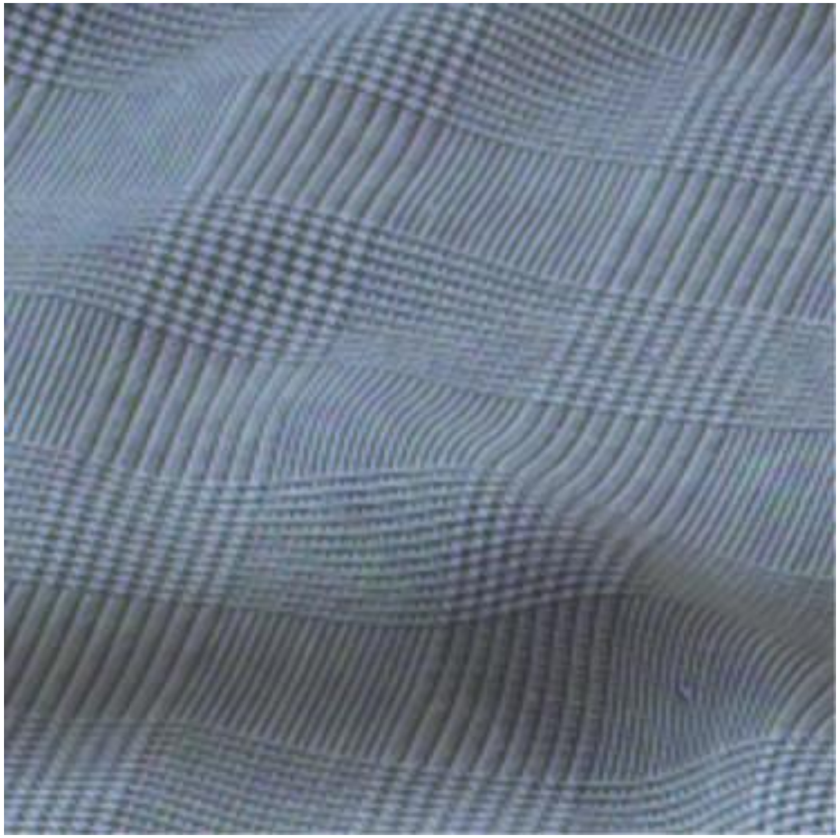
output

YungYu Chuang's slide

Foveon X3 sensor



Bayer CFA



X3 sensor

YungYu Chuang's slide

Cameras with X3

Sigma SD10, SD9 **Polaroid X530**

YungYu Chuang's slide

Sigma SD9 vs Canon D30

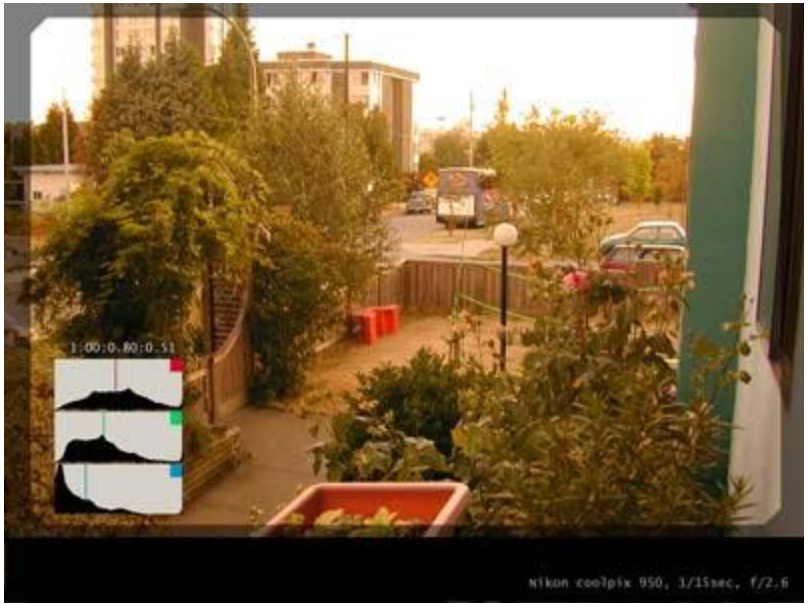
YungYu Chuang's slide

Color processing

- After color values are recorded, more color processing usually happens:
  – White balance
  – Non-linearity to approximate film response or match TV monitor gamma

YungYu Chuang's slide

Auto White Balance



warmer

automatic white balance

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 255/R'_w & 0 & 0 \\ 0 & 255/G'_w & 0 \\ 0 & 0 & 255/B'_w \end{bmatrix} \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix}$$

YungYu Chuang’s slide

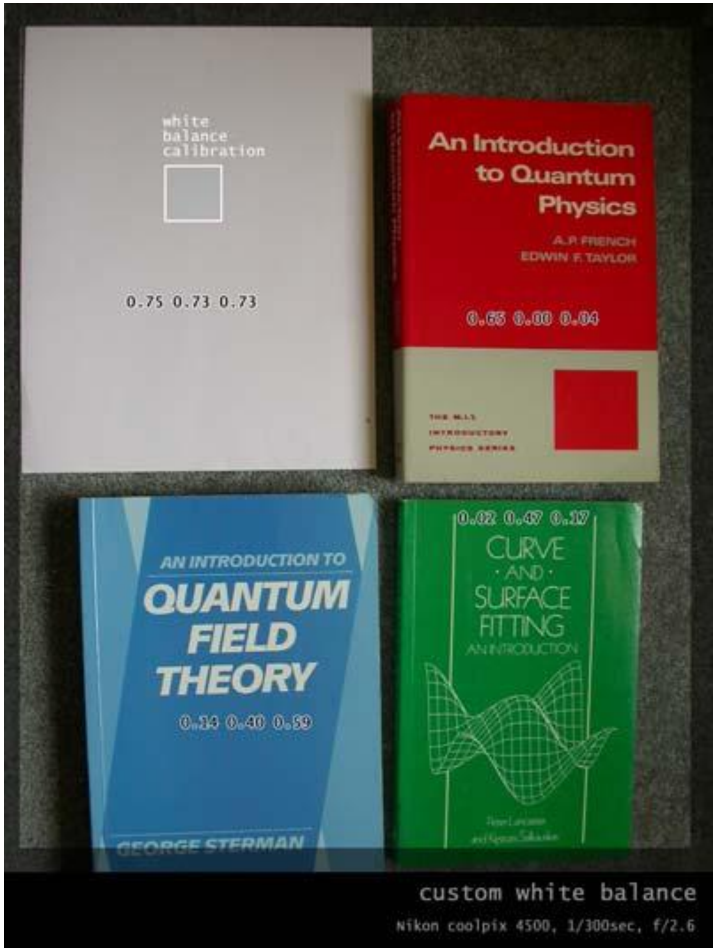
Auto White Balance

The auto white balance was unable to find a white reference, resulting in dull and artificial colors.

The auto white balance got it right this time in a very similar scene because it could use the clouds as its white reference.

http://www.dpreview.com/learn/?/Glossary/Digital_Imaging/White_Balance_01.htm

Manual white balance

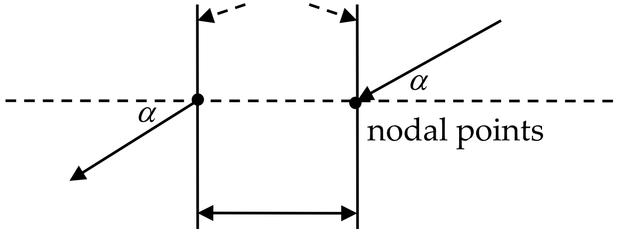


white balance with the white book

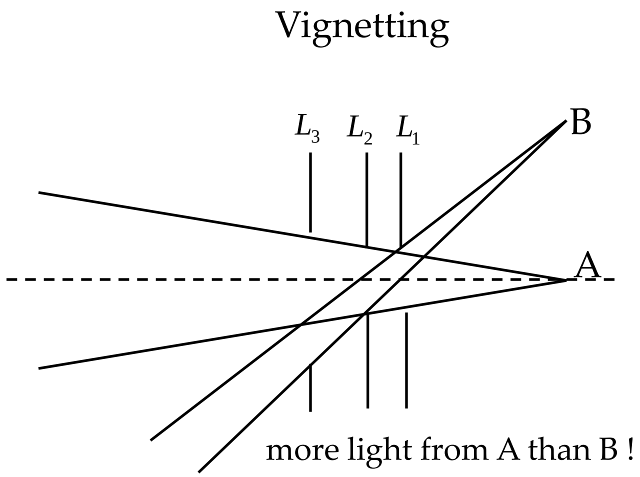
white balance with the red book

YungYu Chuang’s slide

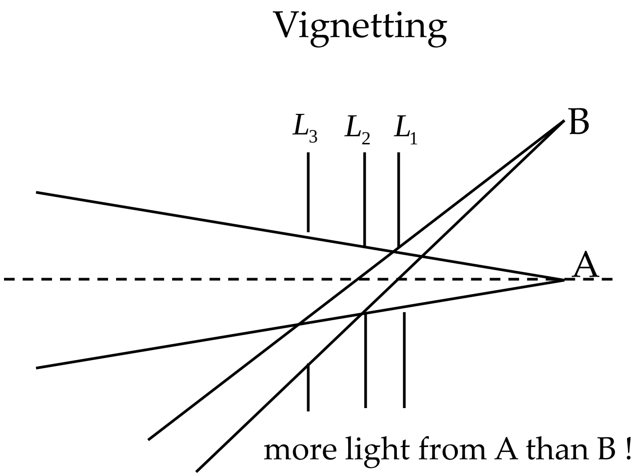
Lens related issues: Coumpound Thick Lens



Lens related issues: Vignetting



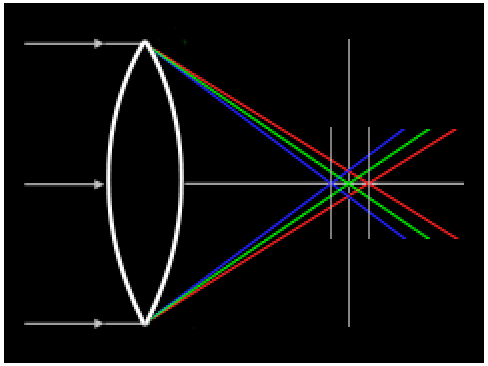
Lens related issues: Vignetting



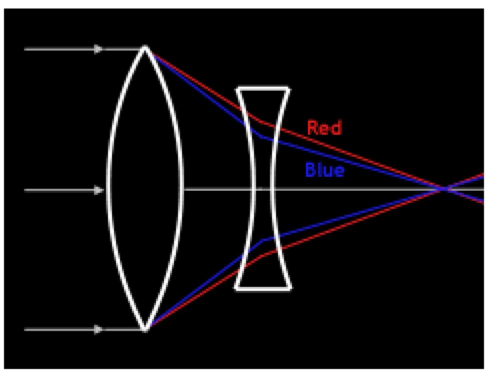
original corrected

Goldman & Seitz ICCV 2005

Lens related issues: Chromatic Abberation



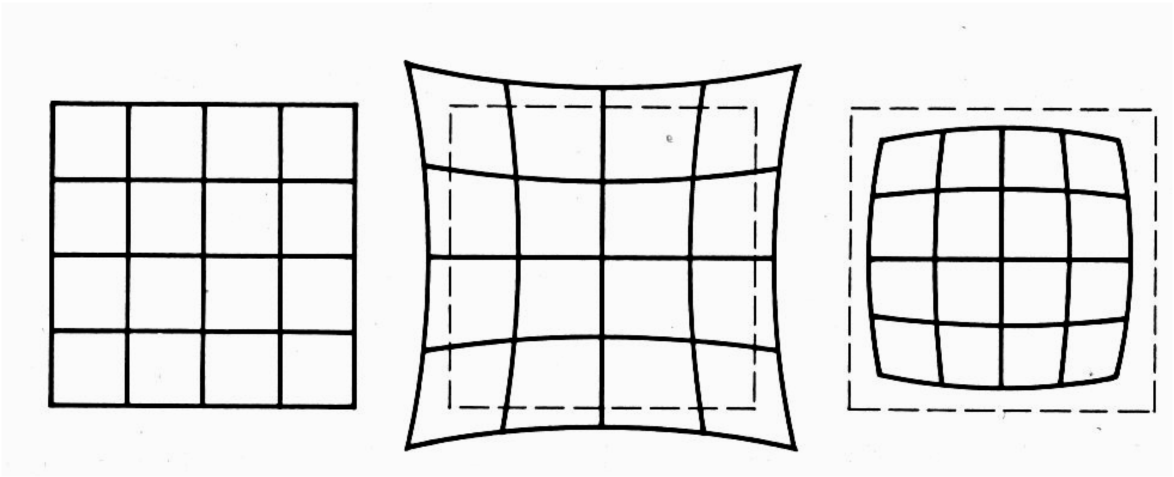
Lens has different refractive indices for different wavelengths.



Special lens systems using two or more pieces of glass with different refractive indexes can reduce or eliminate this problem.

http://www.dpreview.com/learn/?/Glossary/Optical/chromatic_aberration_01.htm

Lens related issues: Distortion



No distortion Pin cushion Barrel

- Radial distortion of the image
  - Caused by imperfect lenses
  - Deviations are most noticeable for rays that pass through the edge of the lens

Steve Seitz's slide

Correcting radial distortion

from Helmut Dersch

Steve Seitz's slide

Digital camera review website

- http://www.dpreview.com/
- http://www.imaging-resource.com/
- http://www.steves-digicams.com/