Cameras

Digital Visual Effects, Spring 2005

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2005/3/2

with slides by Brian Curless, Steve Seitz and Alexei Efros

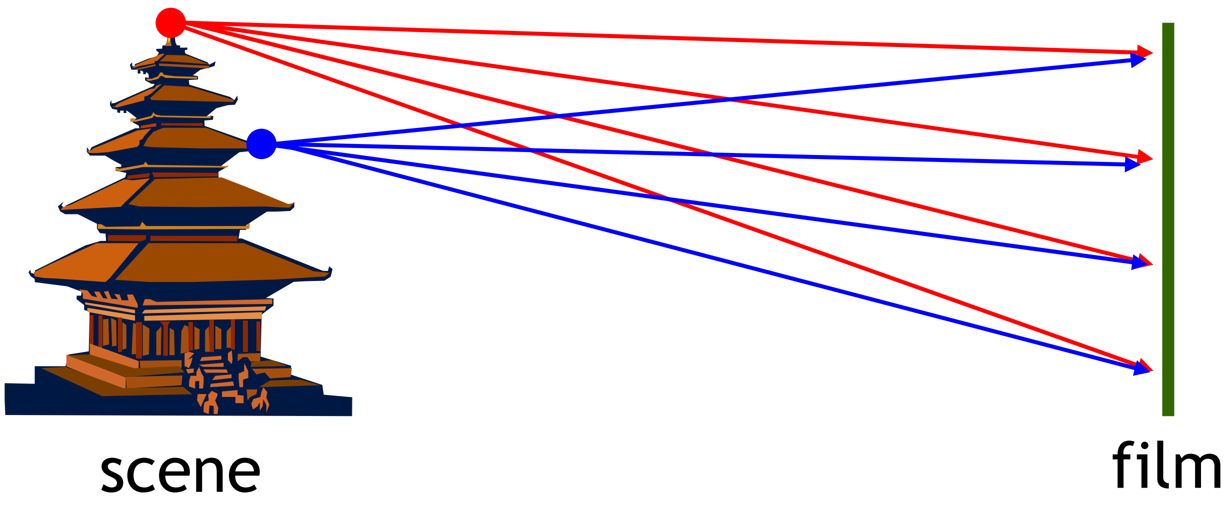
Announcements

- Classroom is changed to Room101
- Assignment schedule
  - Image morphing (3/9-3/30)
  - Image stitching (3/30-4/20)
  - Matchmove (4/20-5/11)
  - Final project (5/11-6/22)
- Scribe
- Send cyy@csie.ntu.edu.tw to subscribe vfx

Outline

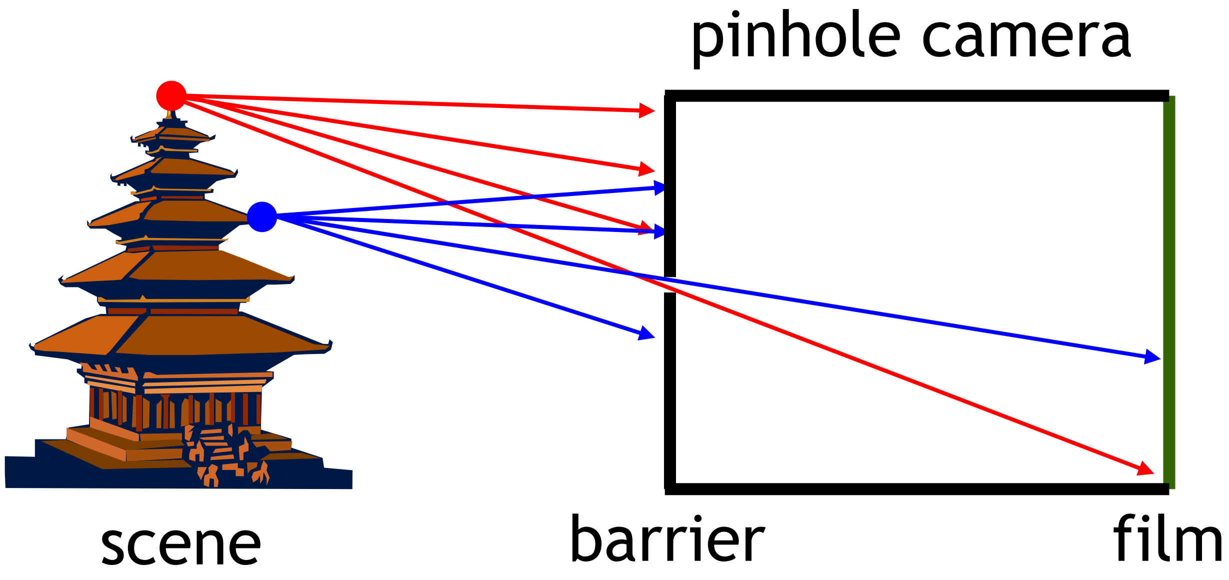
- Pinhole camera
- Film camera
- Digital camera
- Video camera
- High dynamic range imaging

Camera trial #1



Put a piece of film in front of an object.

Pinhole camera

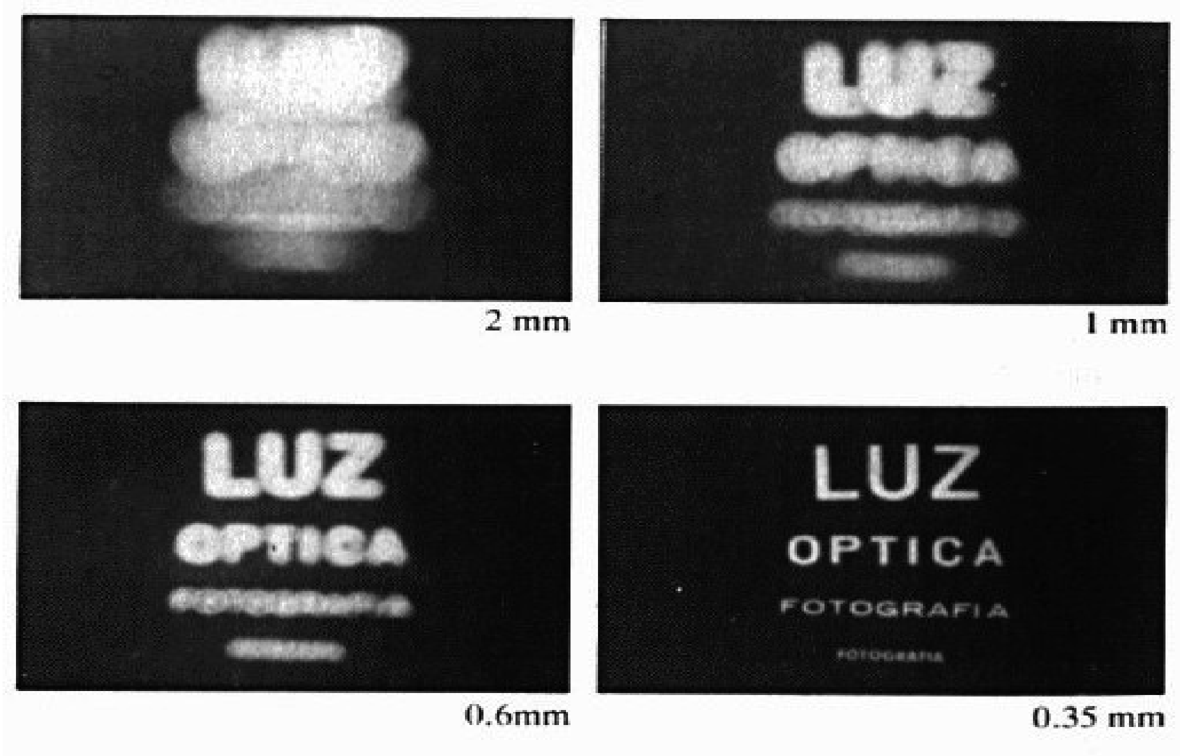


Add a barrier to block off most of the rays.

- It reduces blurring
- The pinhole is known as the aperture
- The image is inverted

Shrinking the aperture

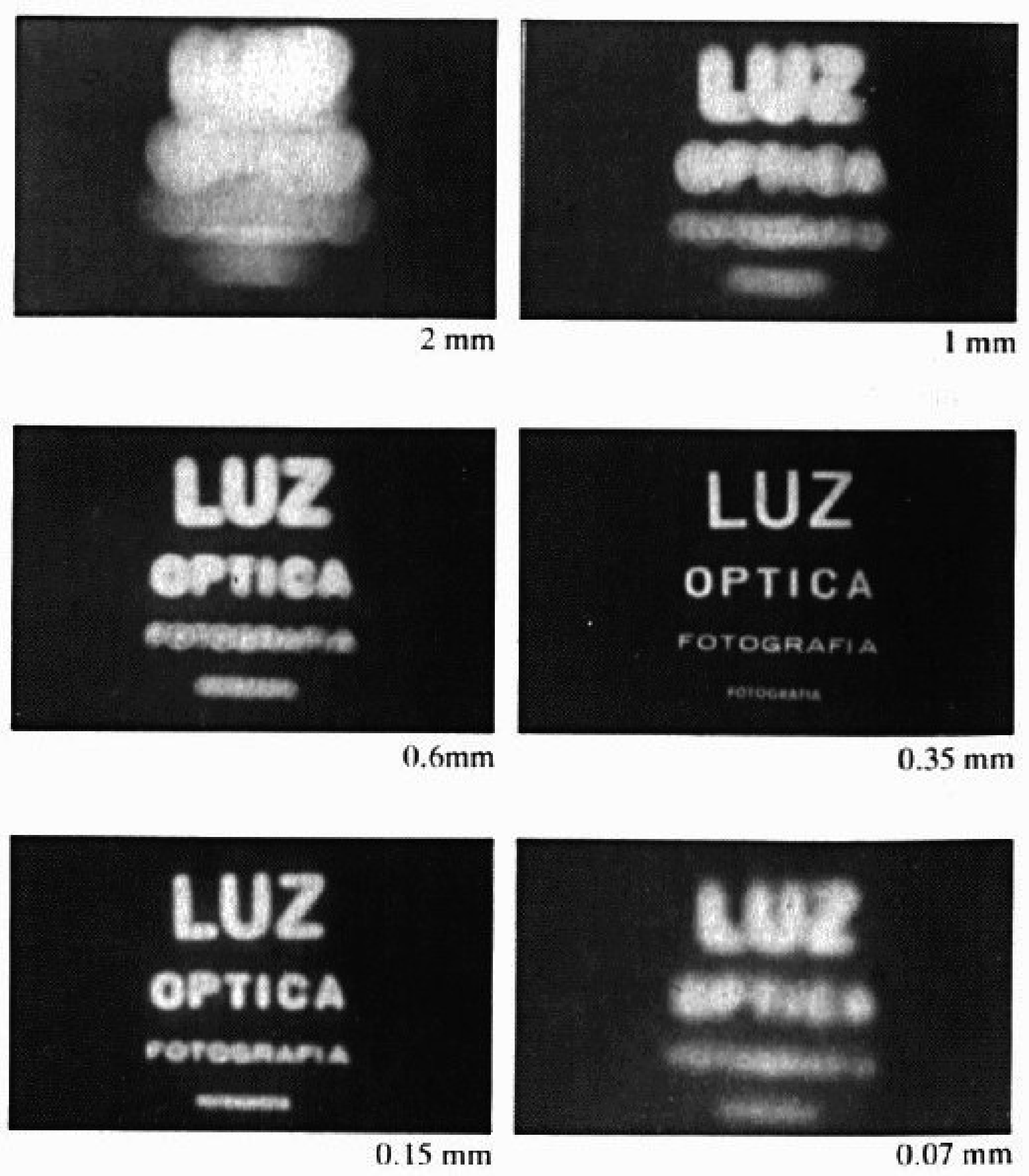
DigiVFX



Why not make the aperture as small as possible?

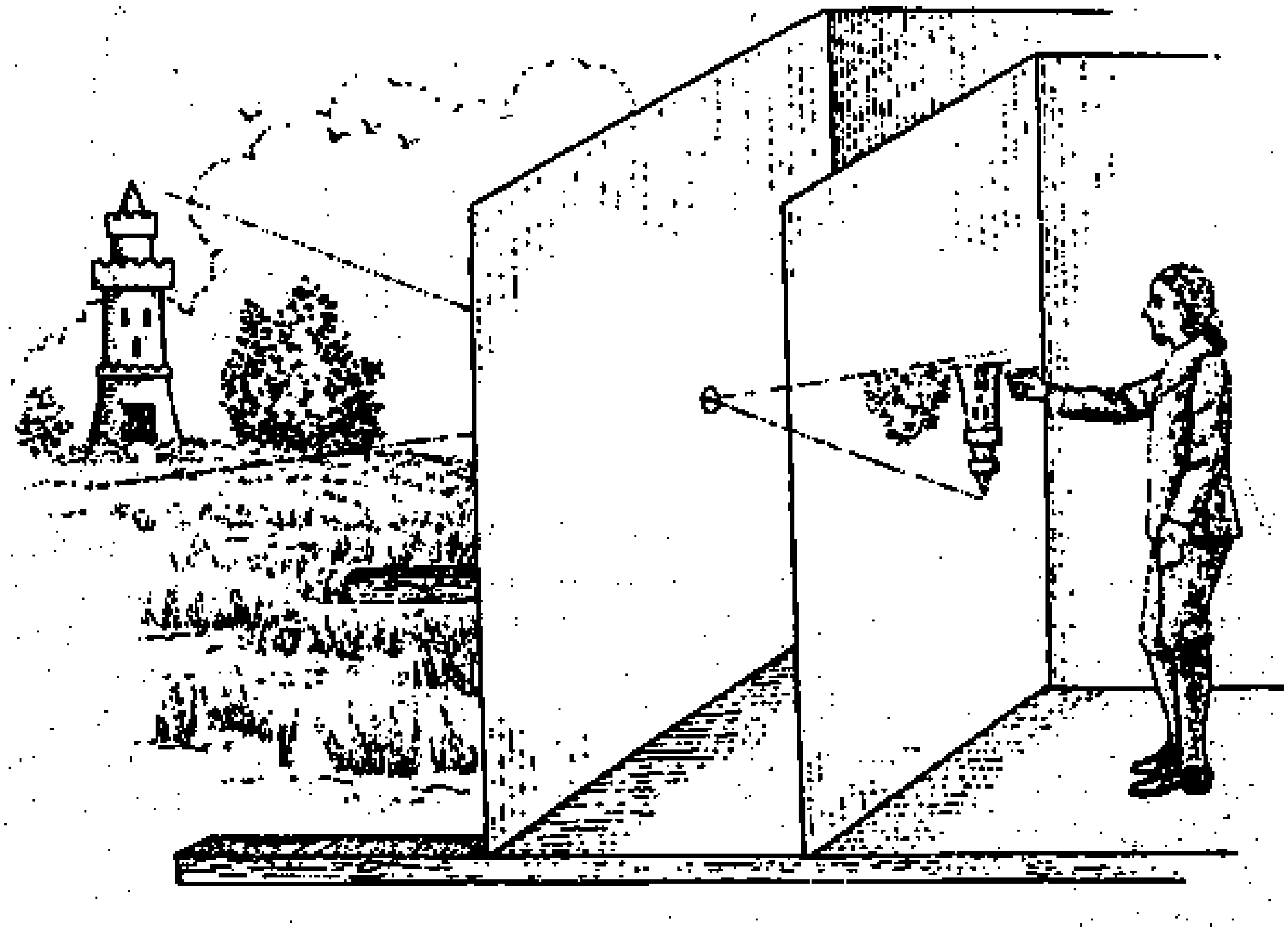
- Less light gets through
- Diffraction effect

Shrinking the aperture

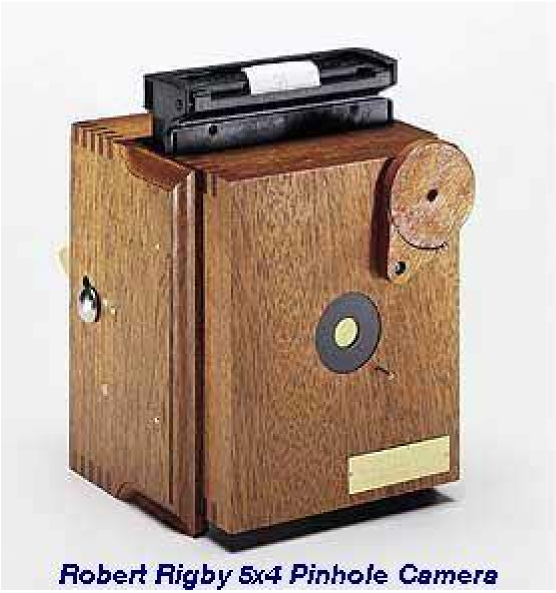


Camera Obscura

Drawing from "The Great Art of Light and Shadow "
Jesuit Athanasius Kircher, 1646.

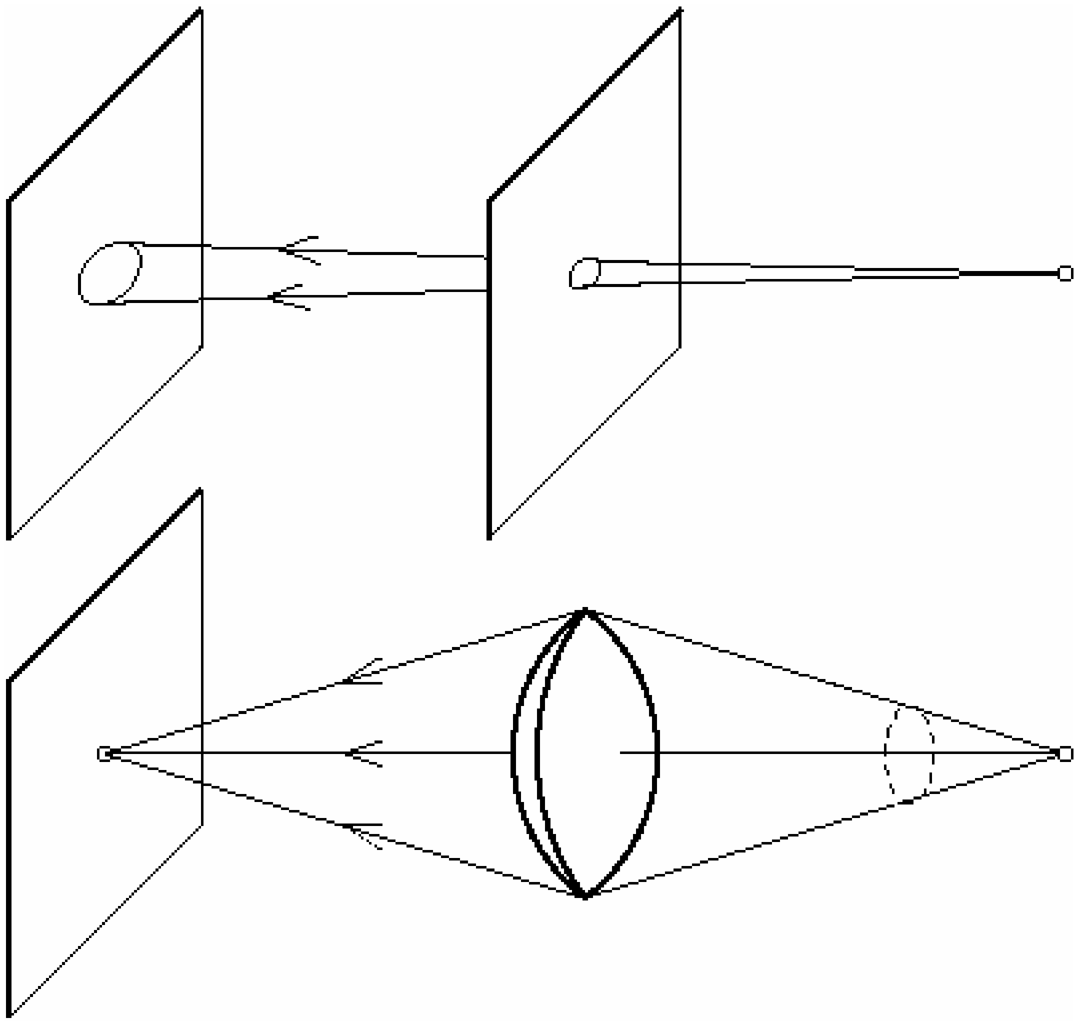


High-end commercial pinhole cameras

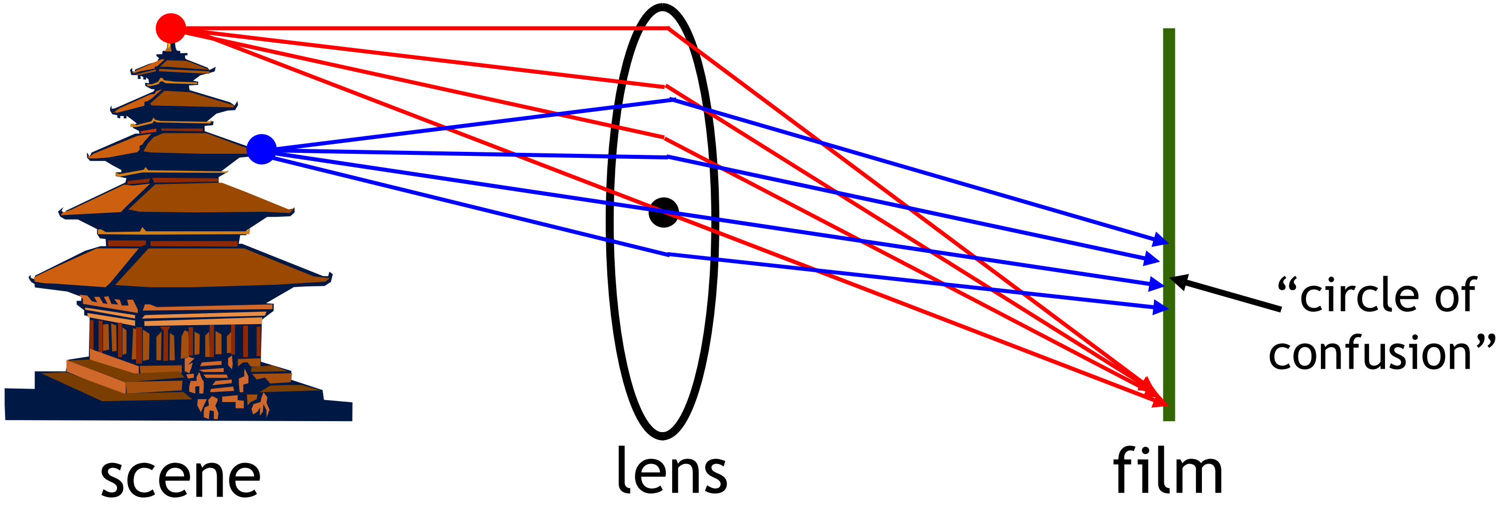


http://www.bobrigby.com/html/pinhole.html

Adding a lens



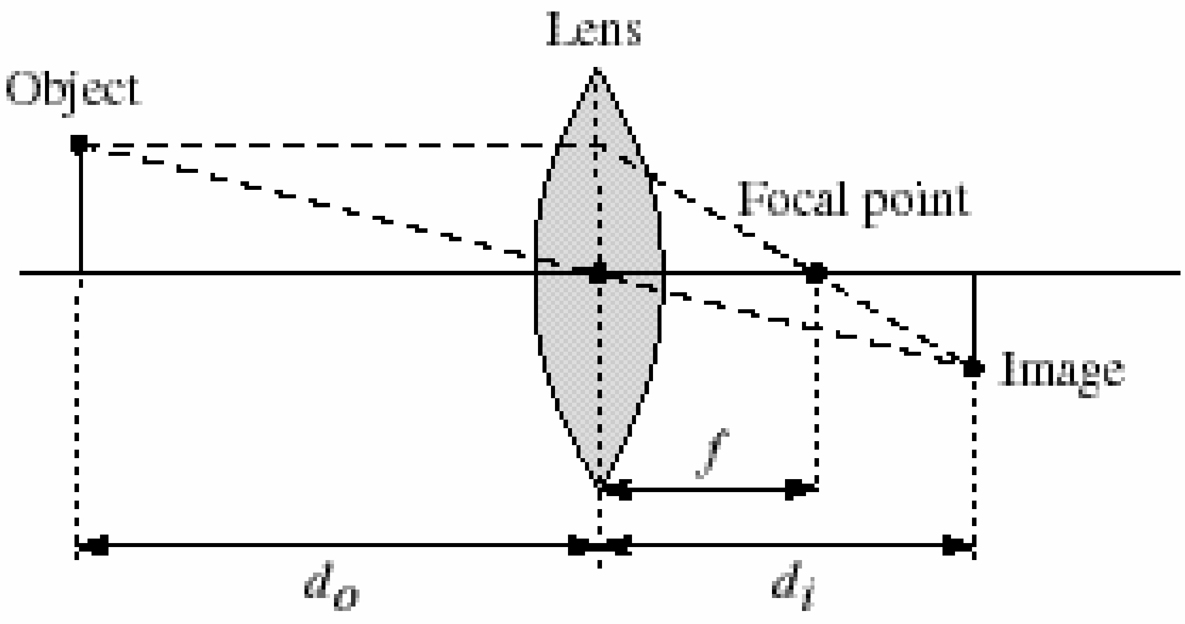
Adding a lens



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

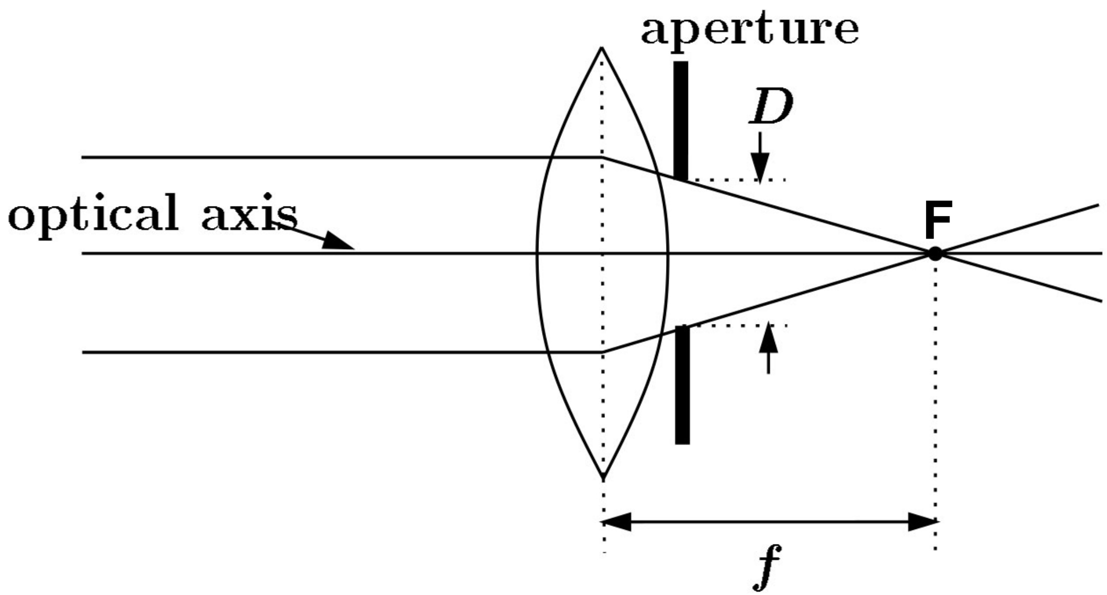
Lenses



Thin lens equation: $\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$

- Any object point satisfying this equation is in focus
- Thin lens applet: http://www.phy.ntnu.edu.tw/java/Lens/lens_e.html

Exposure = aperture + shutter speed



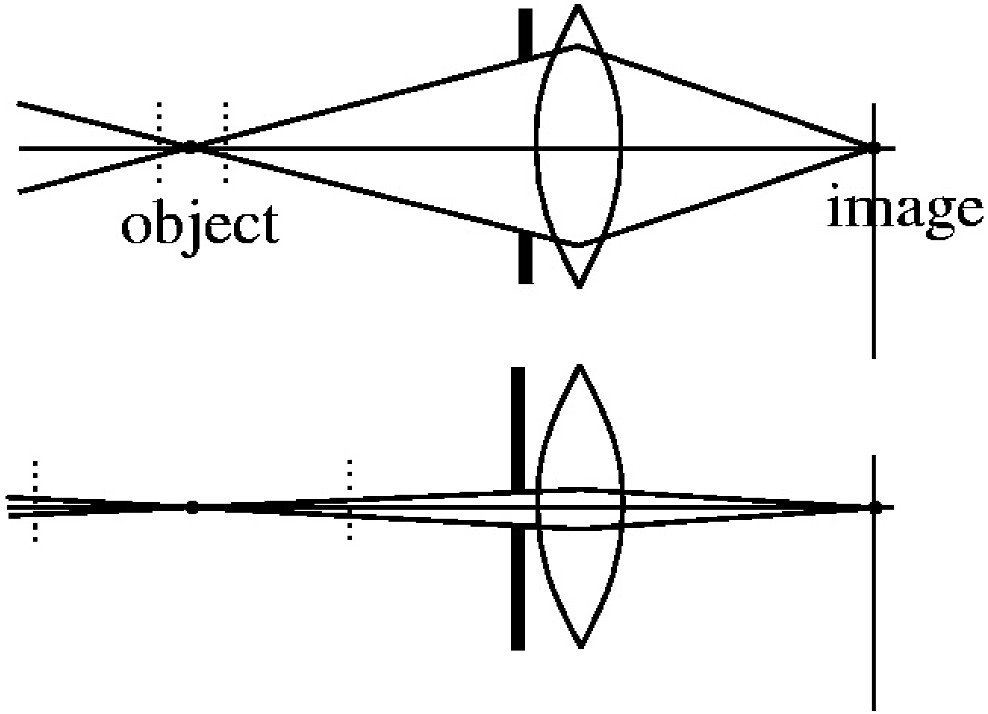
- Aperture of diameter D restricts the range of rays (aperture may be on either side of the lens)
- Shutter speed is the amount of light is allowed to pass through the aperture

Aperture

DigiVFX

- Aperture is usually specified by f-stop, f/D. 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)

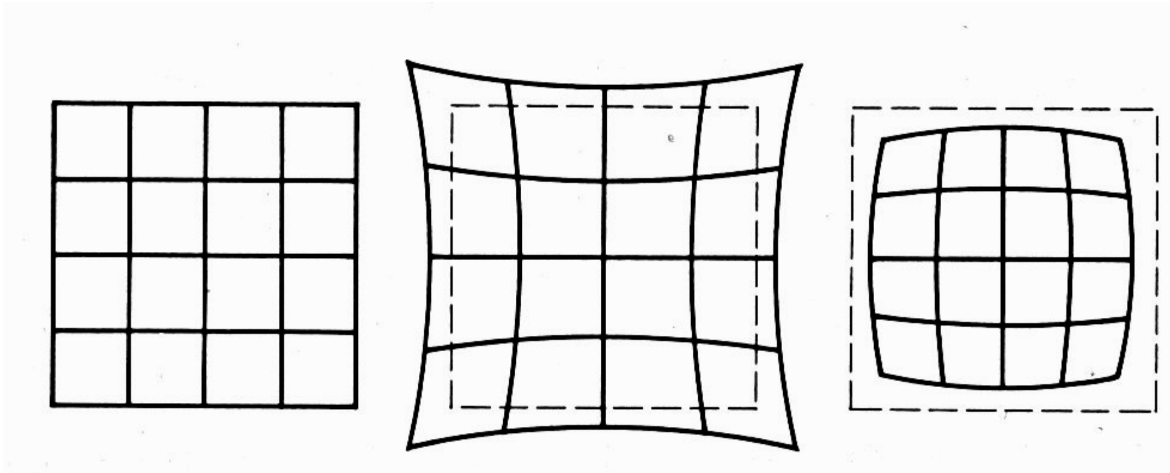
Depth of field



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

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

Distortion

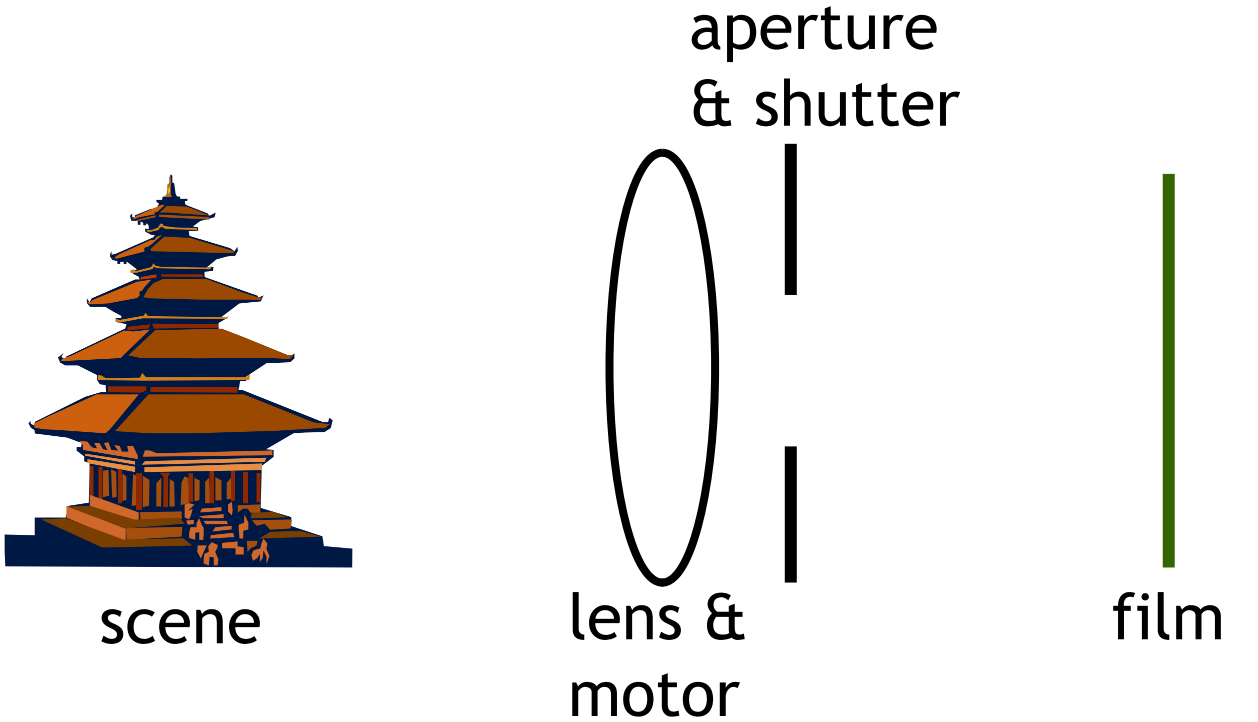


- Radial distortion of the image
  - Caused by imperfect lenses
  - Deviations are most noticeable for rays that pass through the edge of the lens

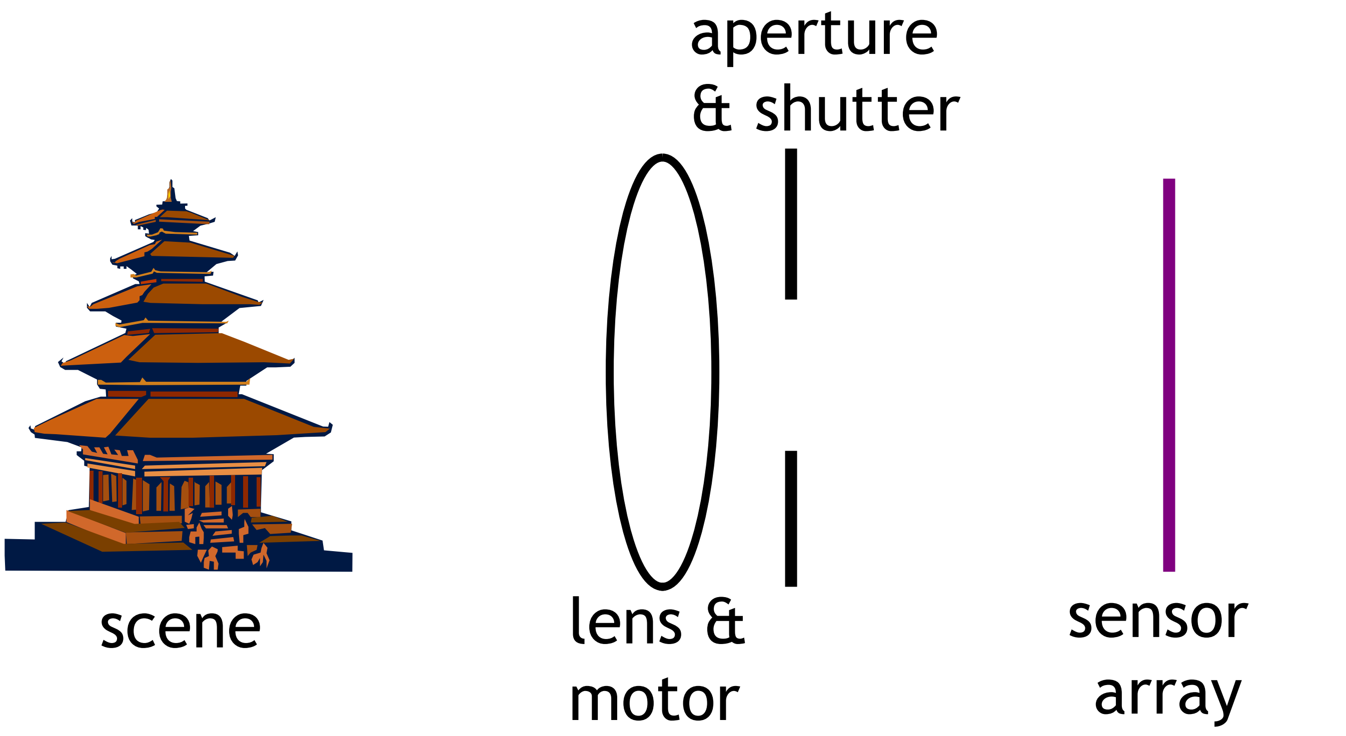
Correcting radial distortion

from Helmut Dersch

Film camera



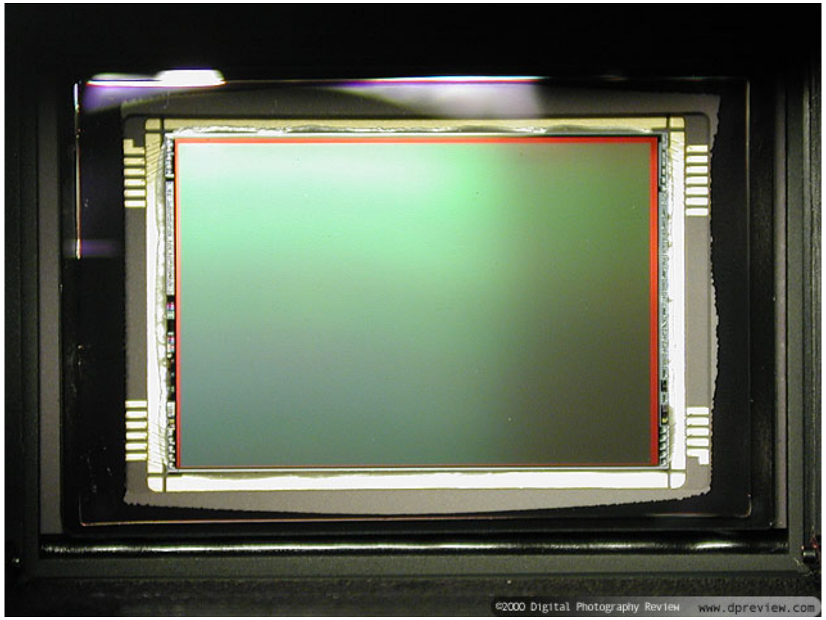
Digital camera



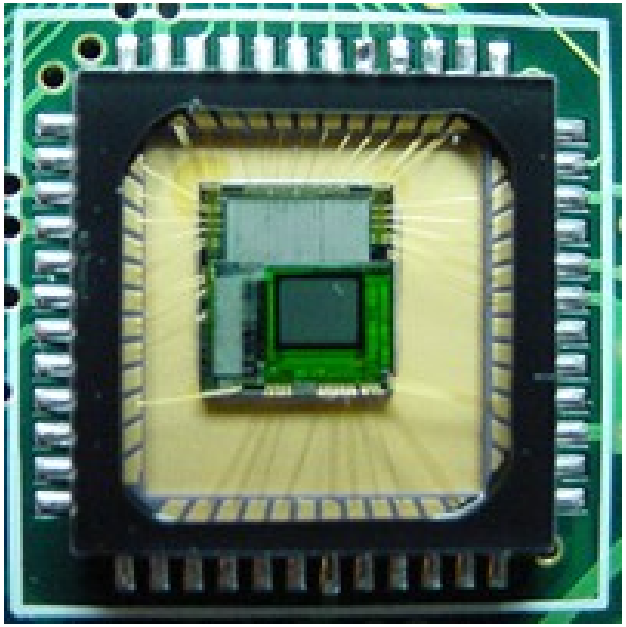
- A digital camera replaces film with a sensor array
- Each cell in the array is a light-sensitive diode that converts photons to electrons

CCD v.s. CMOS

- CCD is less susceptible to noise (special process, higher fill factor)
- CMOS is more flexible, less expensive (standard process), less power consumption



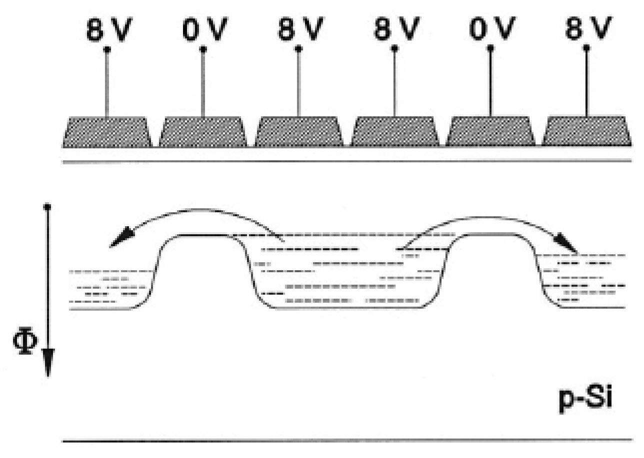
CCD



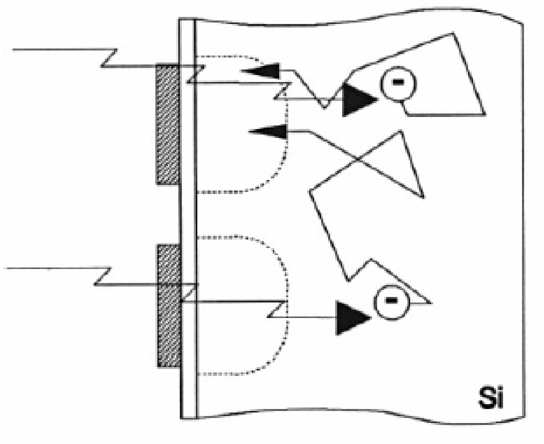
CMOS

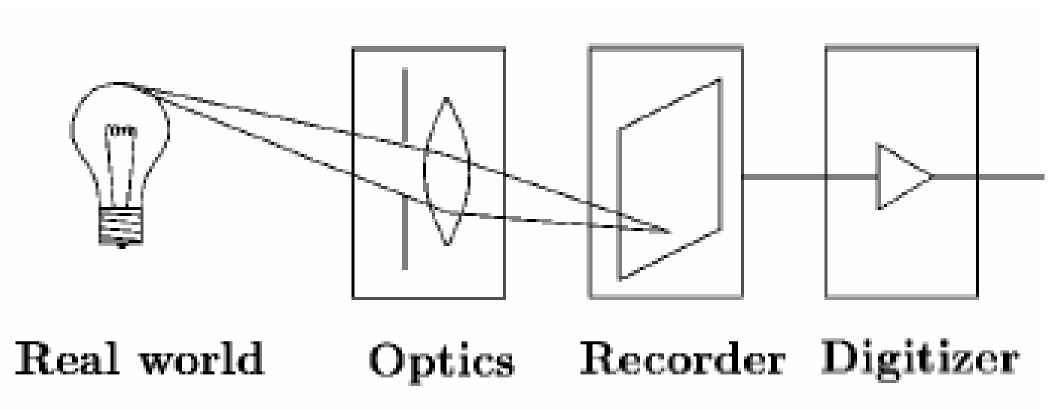
Sensor noise

- Blooming
- Diffusion
- Dark current
- Photon shot noise
- Amplifier readout noise



Blooming



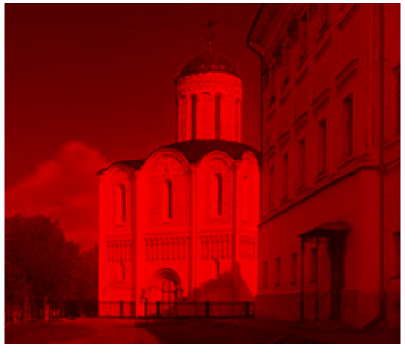


Color

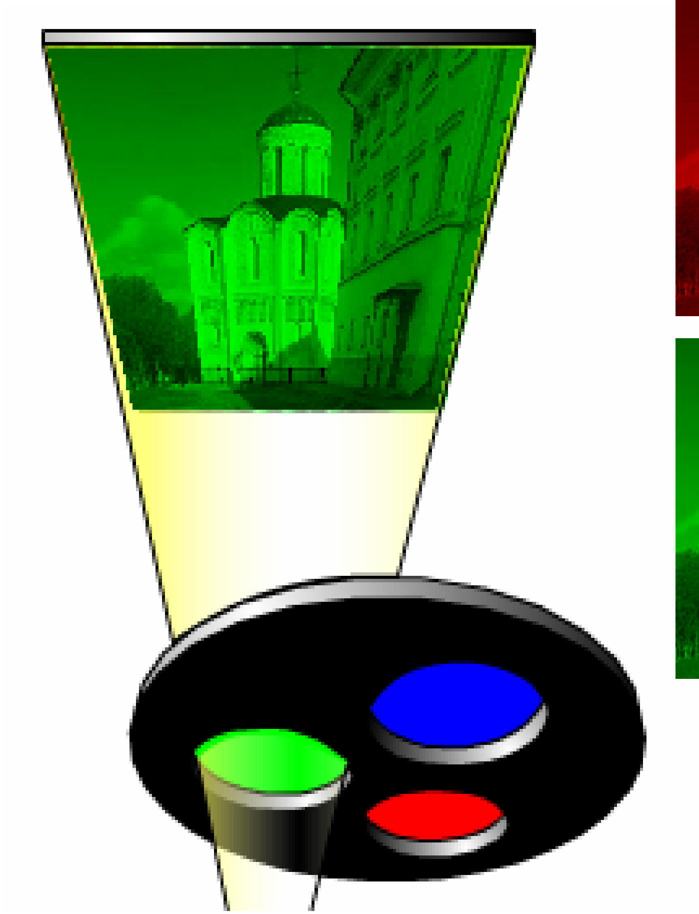
So far, we've only talked about monochrome sensors. Color imaging has been implemented in a number of ways:

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

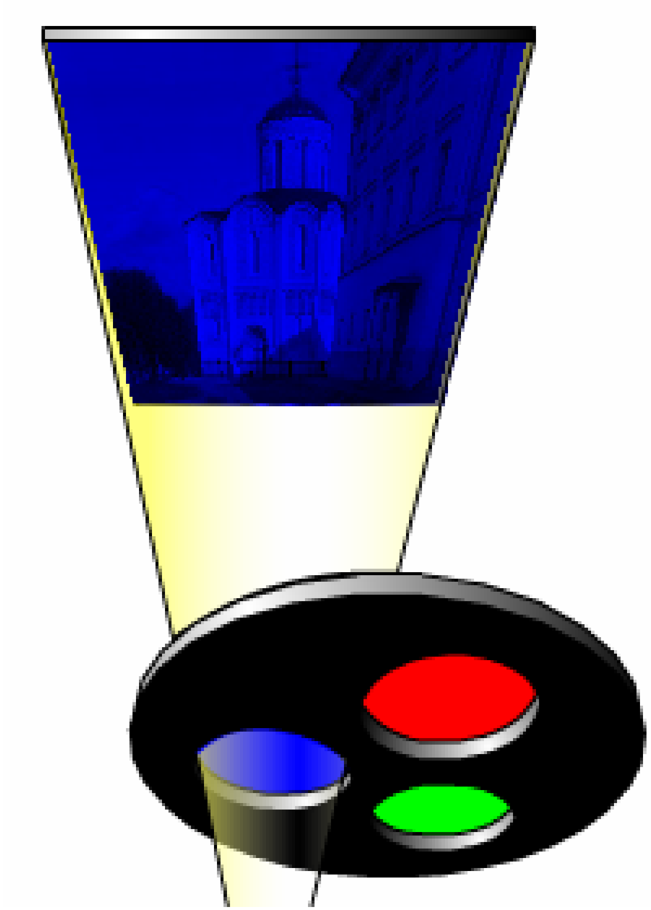
Field sequential

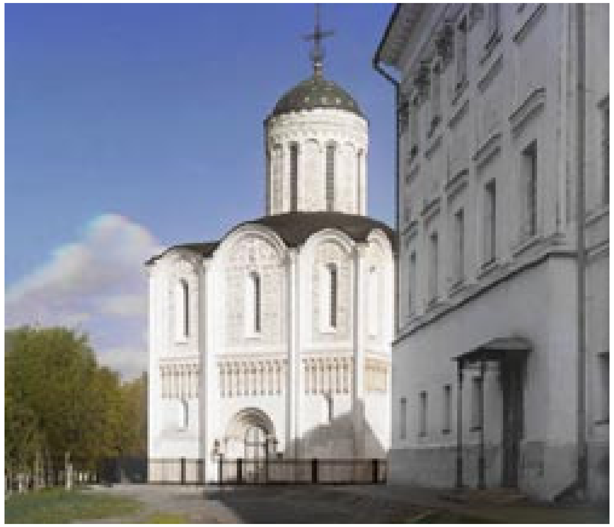


Field sequential

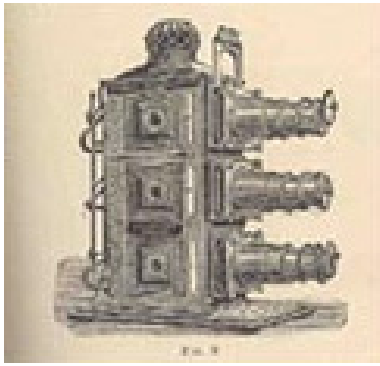


Field sequential





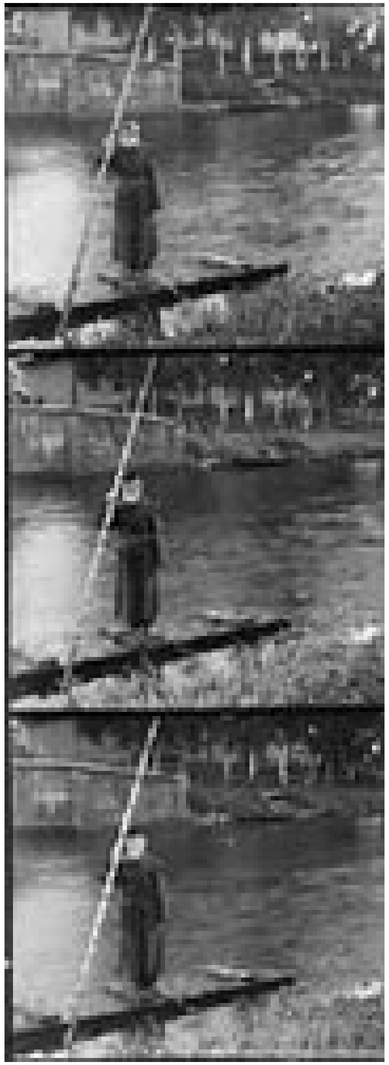
Prokudin-Gorskii (early 1990’s)



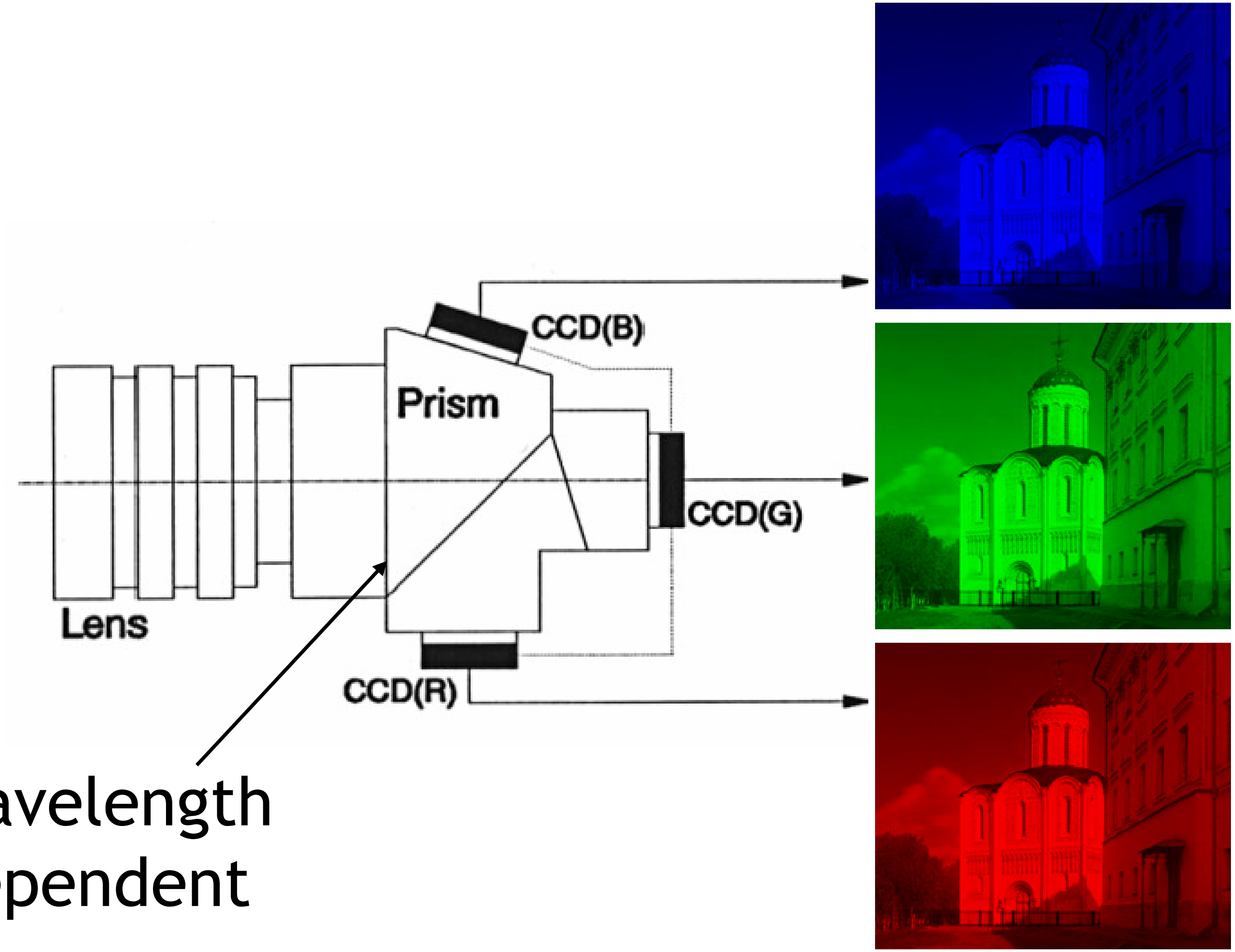
Lantern projector

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

Prokudin-Gorskii (early 1990's)

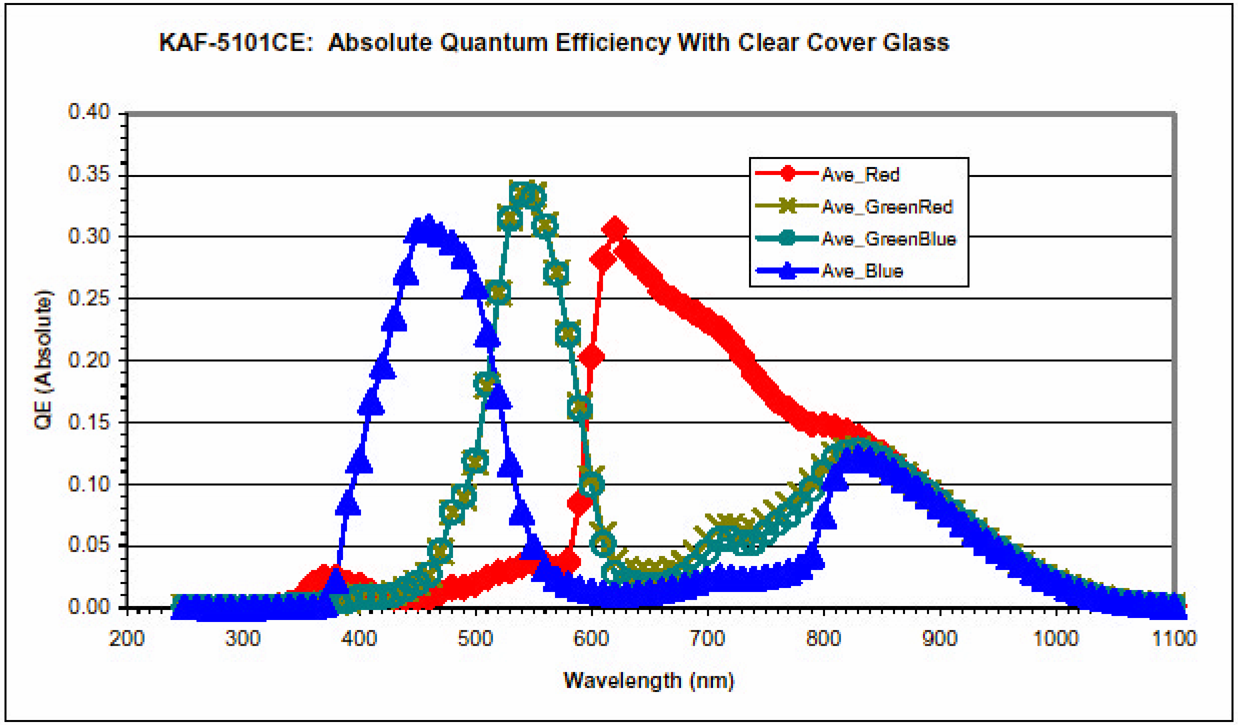



Multi-chip



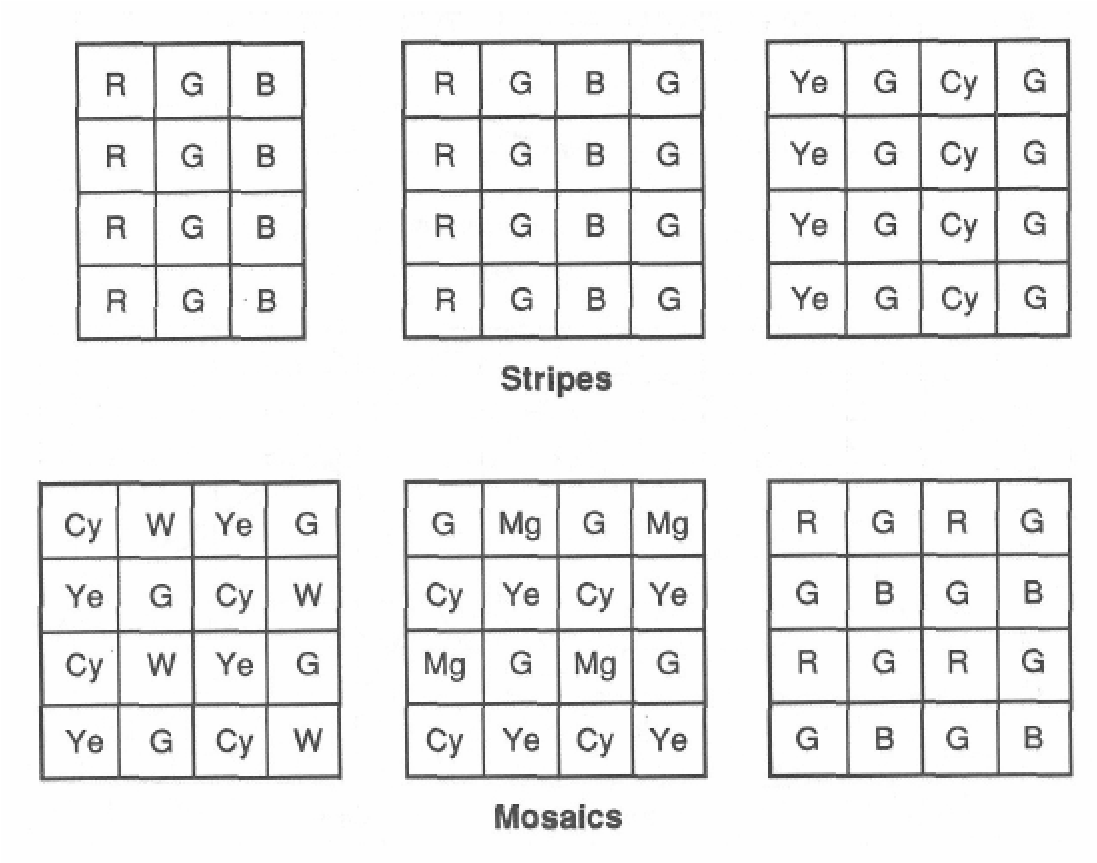
wavelength
dependent

Embedded color filters

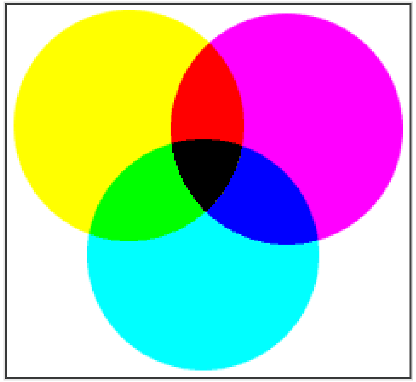


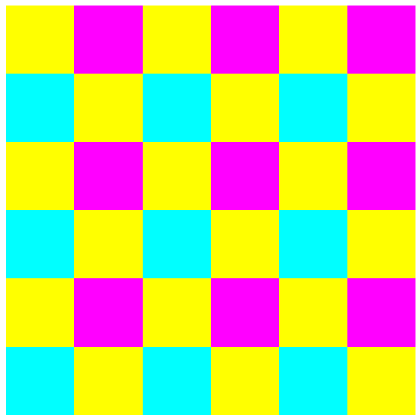
Color filters can be manufactured directly onto the photodetectors.

Color filter array



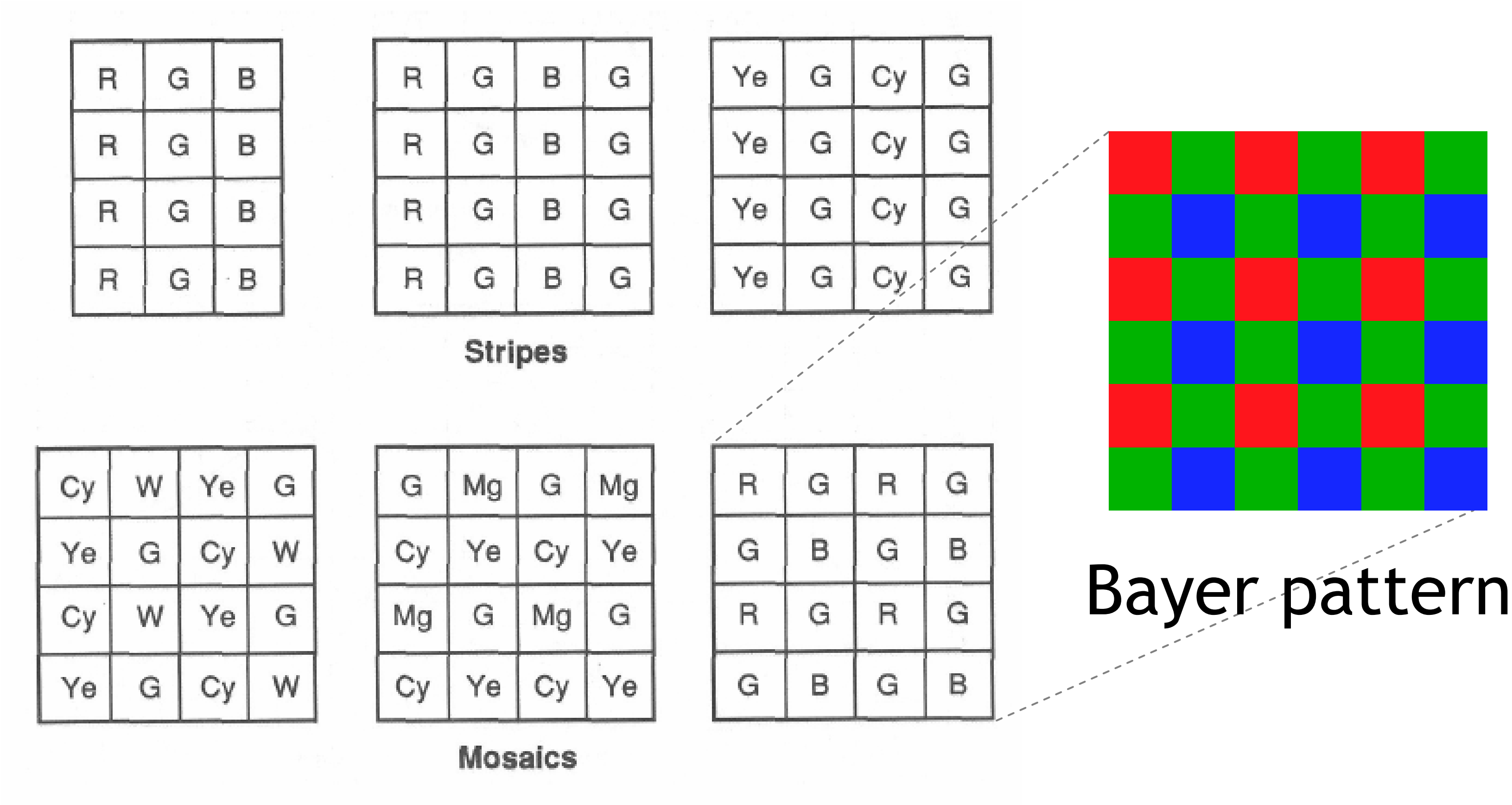
Kodak DCS620x





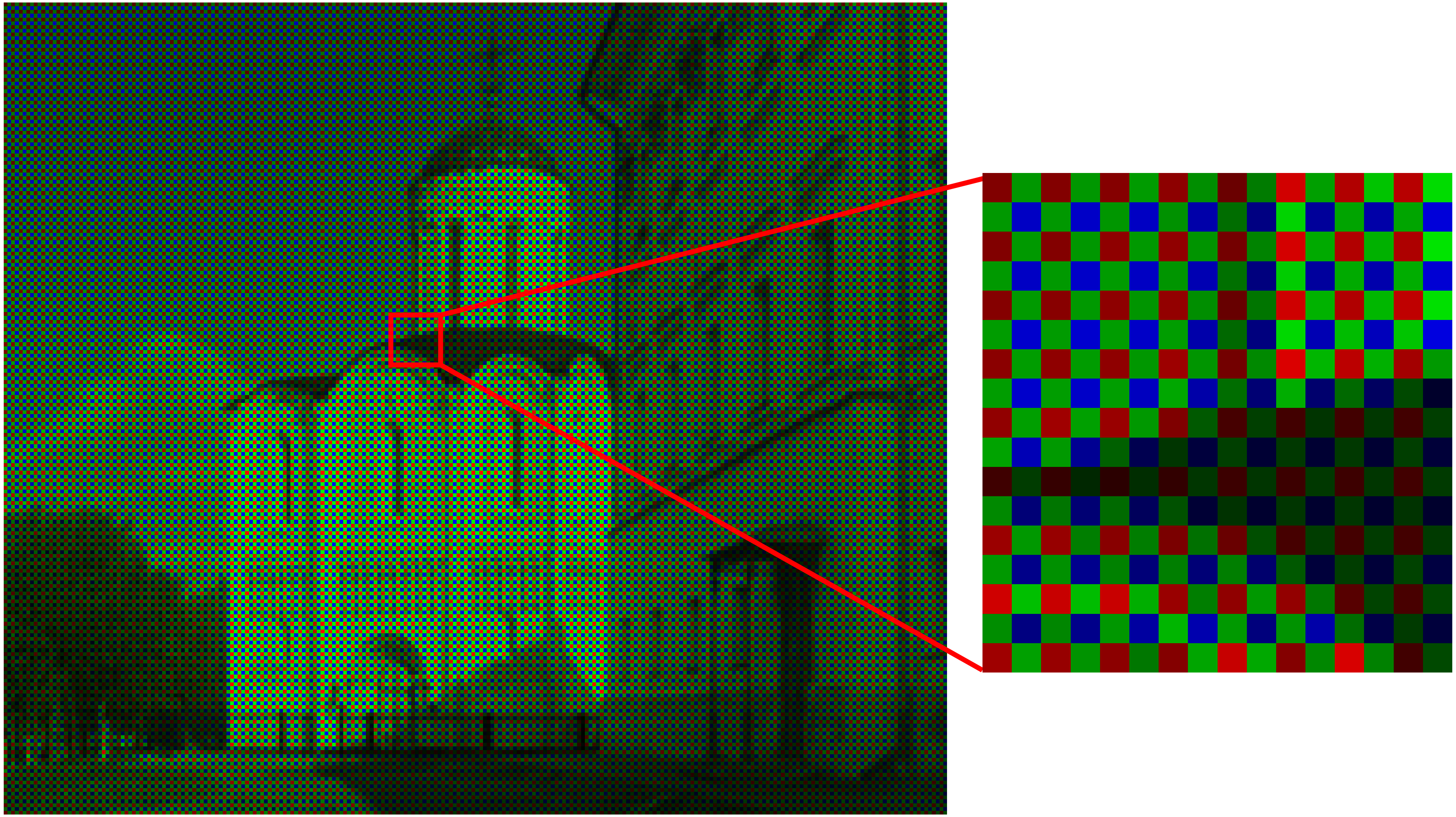
Color filter arrays (CFAs)/color filter mosaics

Color filter array



Color filter arrays (CFAs)/color filter mosaics

Bayer's pattern



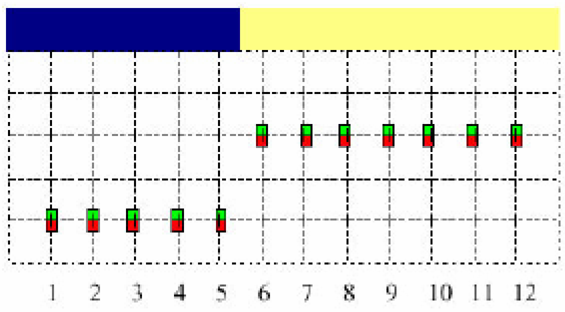
Demosaicking CFA's

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

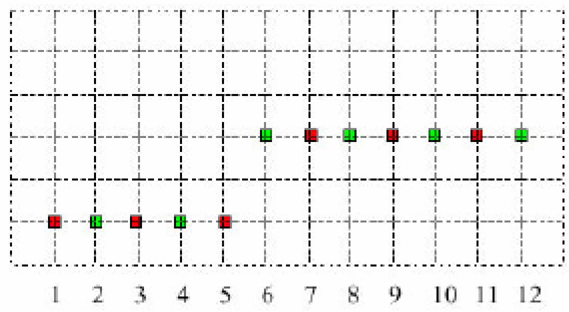
bilinear interpolation

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

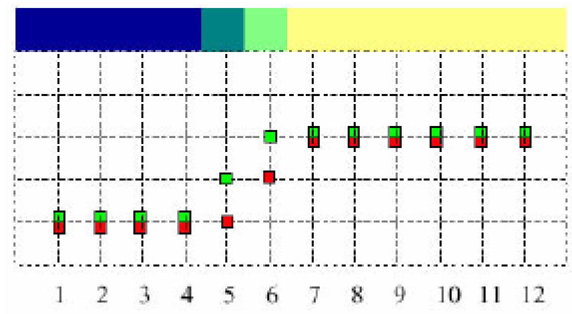
$$R_{44} = (R_{33} + R_{35} + R_{53} + R_{55})/4$$



original



input



linear interpolation

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}

Constant hue-based interpolation (Cok)

Hue: $(R/G, B/G)$

Interpolate G first

$$R_{44} = \mathbf{G}_{44} \frac{\frac{R_{33}}{\mathbf{G}_{33}} + \frac{R_{35}}{\mathbf{G}_{35}} + \frac{R_{53}}{\mathbf{G}_{53}} + \frac{R_{55}}{\mathbf{G}_{55}}}{4}$$

$$B_{33} = \mathbf{G}_{33} \frac{\frac{B_{22}}{\mathbf{G}_{22}} + \frac{B_{24}}{\mathbf{G}_{24}} + \frac{B_{42}}{\mathbf{G}_{42}} + \frac{B_{44}}{\mathbf{G}_{44}}}{4}$$

Demosaicking CFA's

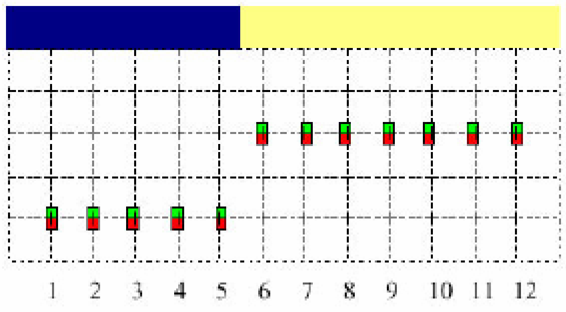
R_{11}	G_{12}	R_{13}	G_{14}	R_{15}	G_{16}	R_{17}
G_{21}	B_{22}	G_{23}	B_{24}	G_{25}	B_{26}	G_{27}
R_{31}	G_{32}	R_{33}	G_{34}	R_{35}	G_{36}	R_{37}
G_{41}	B_{42}	G_{43}	B_{44}	G_{45}	B_{46}	G_{47}
R_{51}	G_{52}	R_{53}	G_{54}	R_{55}	G_{56}	R_{57}
G_{61}	B_{62}	G_{63}	B_{64}	G_{65}	B_{66}	G_{67}
R_{71}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

Median-based interpolation (Freeman)

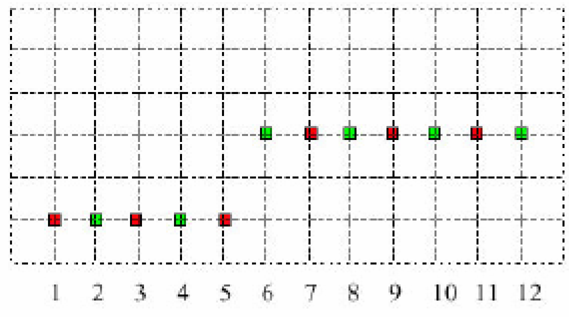
1. Linear interpolation
2. Median filter on color differences

Demosaicking CFA's

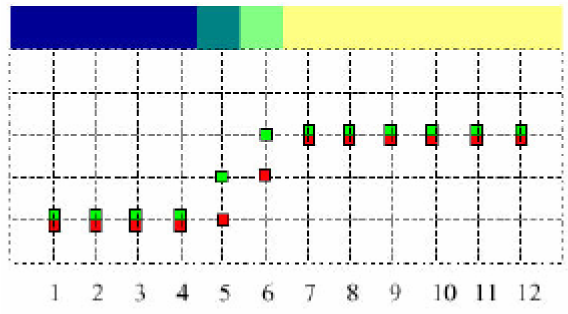
Median-based interpolation (Freeman)



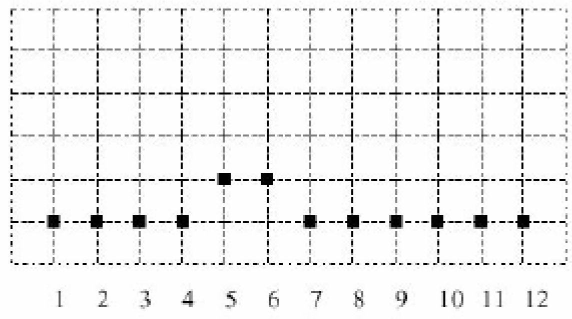
original



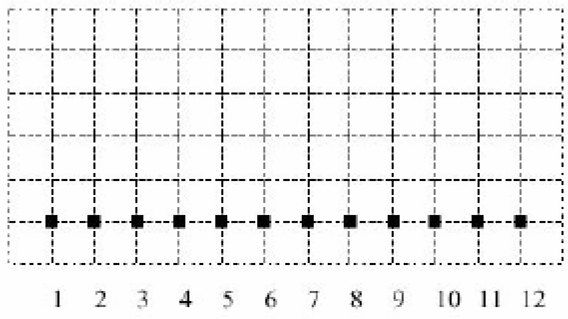
input



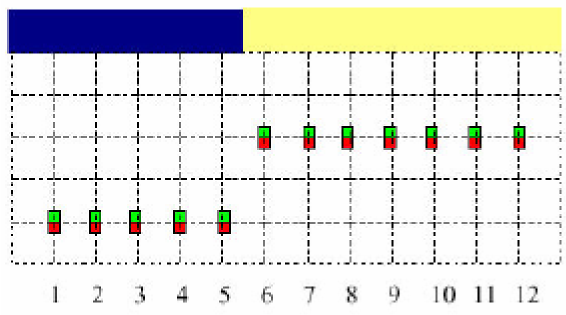
linear interpolation



color difference



median filter



reconstruction

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

Gradient-based interpolation (LaRoche-Prescott)

1. Interpolation on G

$$\alpha = \text{abs}[(B_{42}+B_{46})/2 - B_{44}]$$

$$\beta = \text{abs}[(B_{24}+B_{64})/2 - B_{44}]$$

$$\mathbf{G}_{44} = \begin{cases} \dfrac{G_{43}+G_{45}}{2} & \text{if } \alpha < \beta \\ \dfrac{G_{34}+G_{54}}{2} & \text{if } \alpha > \beta. \\ \dfrac{G_{43}+G_{45}+G_{34}+G_{54}}{4} & \text{if } \alpha = \beta \end{cases}$$

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

Gradient-based interpolation (LaRoche-Prescott)

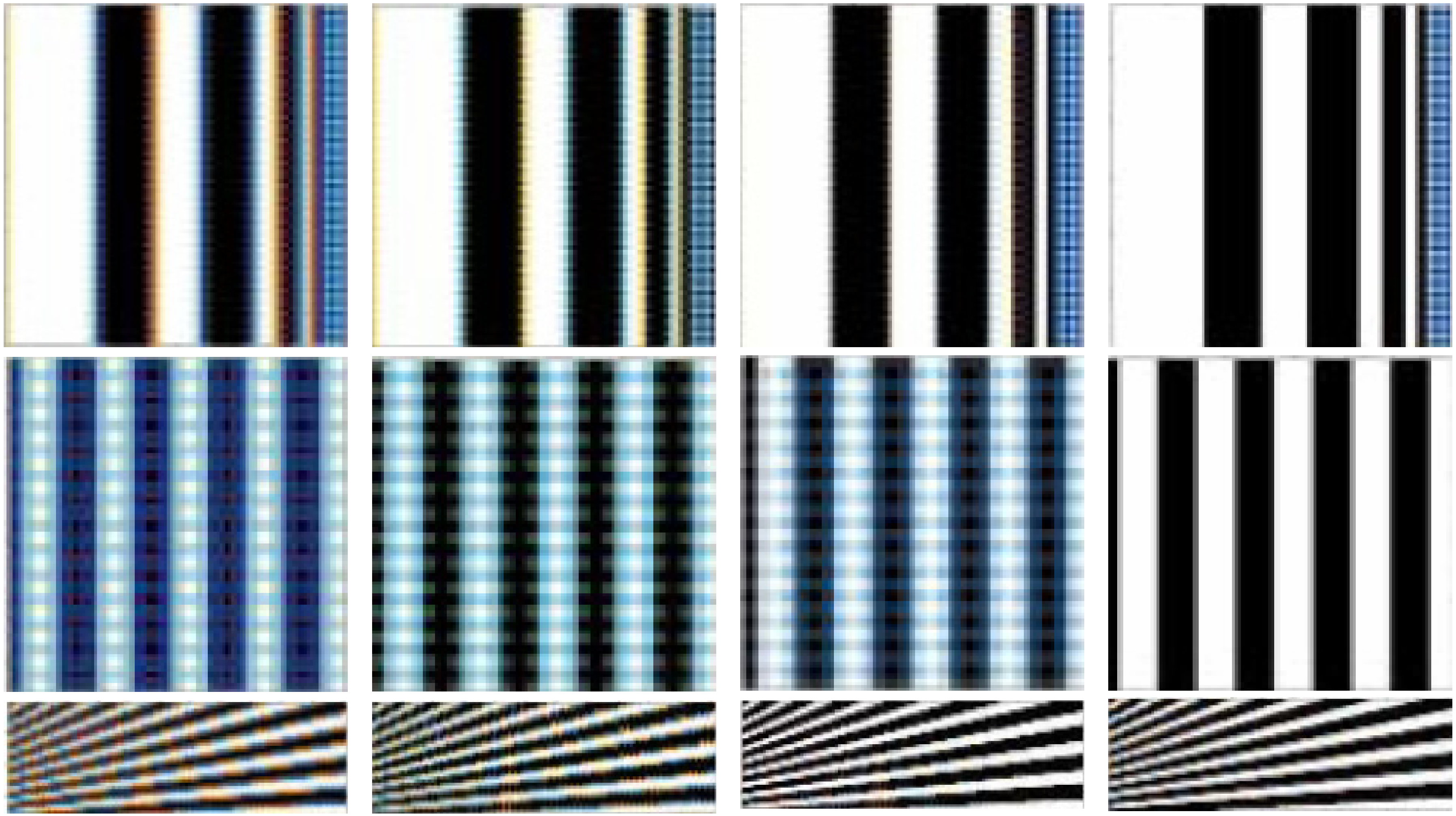
2. Interpolation of color differences

$$R_{34}=\frac{(R_{33}-\mathbf{G}_{33})+(R_{35}-\mathbf{G}_{35})}{2}+G_{34},$$

$$R_{43}=\frac{(R_{33}-\mathbf{G}_{33})+(R_{35}-\mathbf{G}_{35})}{2}+G_{43},$$

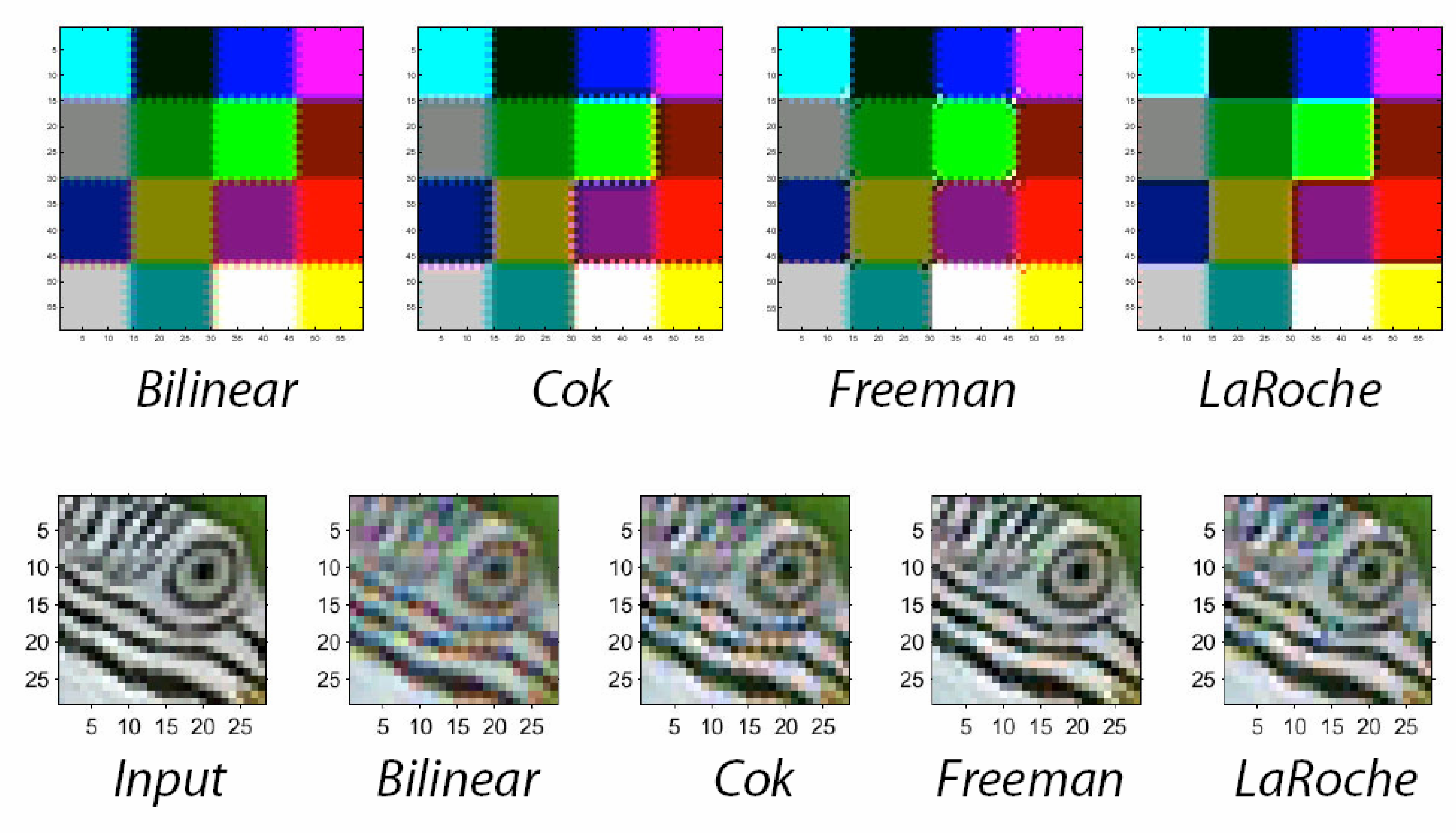
$$R_{44}=\frac{(R_{33}-\mathbf{G}_{33})+(R_{35}-\mathbf{G}_{35})+(R_{53}-\mathbf{G}_{53})+(R_{55}-\mathbf{G}_{55})}{4}+G_{44}.$$

Demosaicking CFA's



bilinear Cok Freeman LaRoche

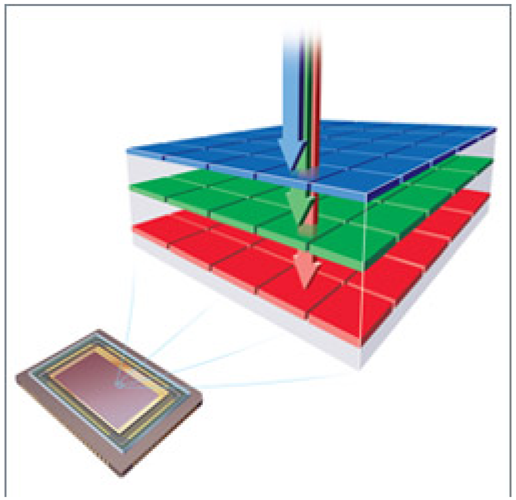
Demosaicking CFA's

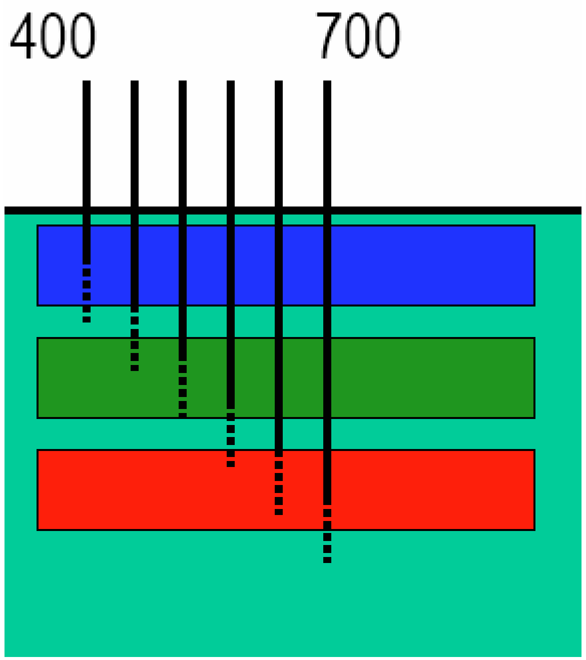


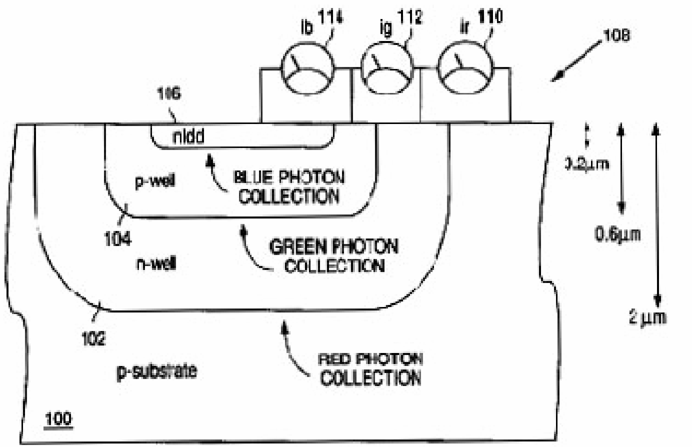
Generally, Freeman's is the best, especially for natural images.

Foveon X3 sensor

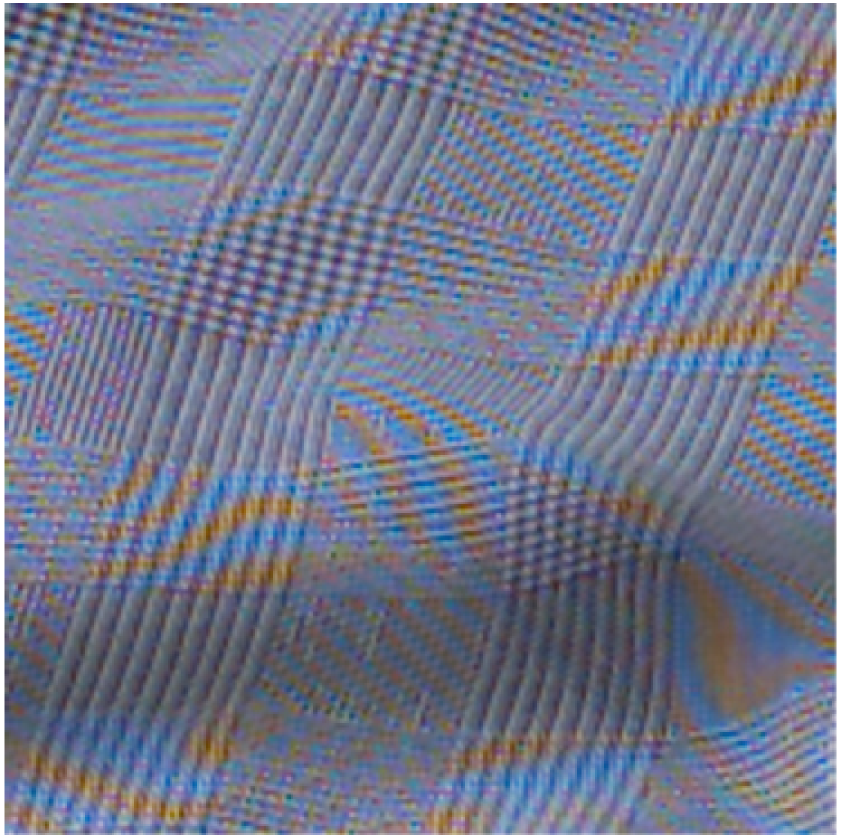
- light penetrates to different depths for different wavelengths
- multilayer CMOS sensor gets 3 different spectral sensitivities



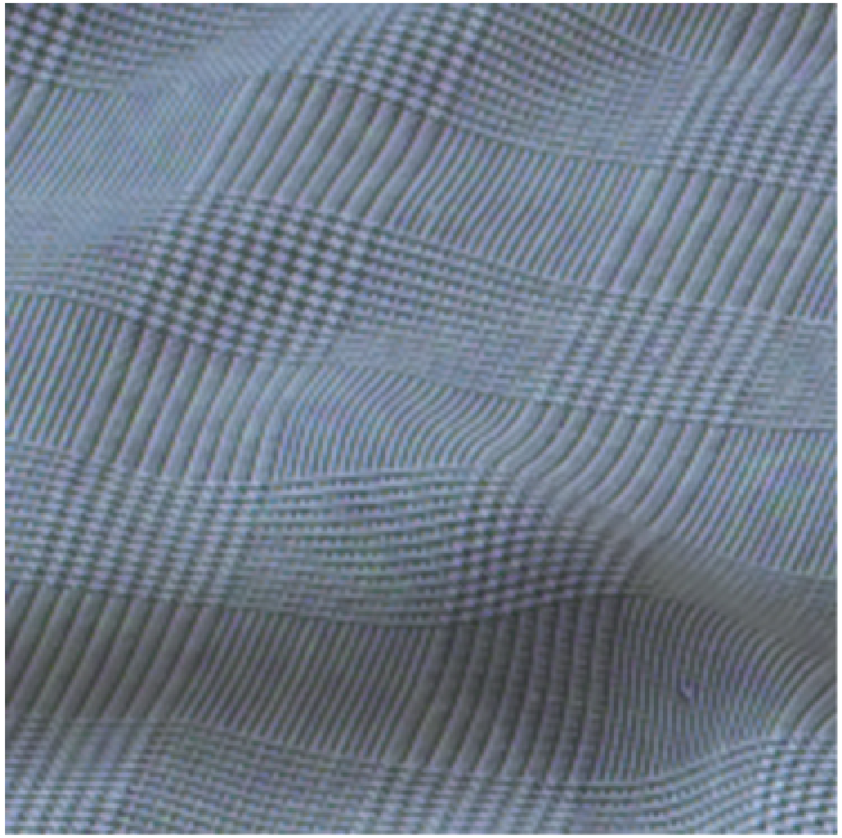




Foveon X3 sensor



Bayer CFA

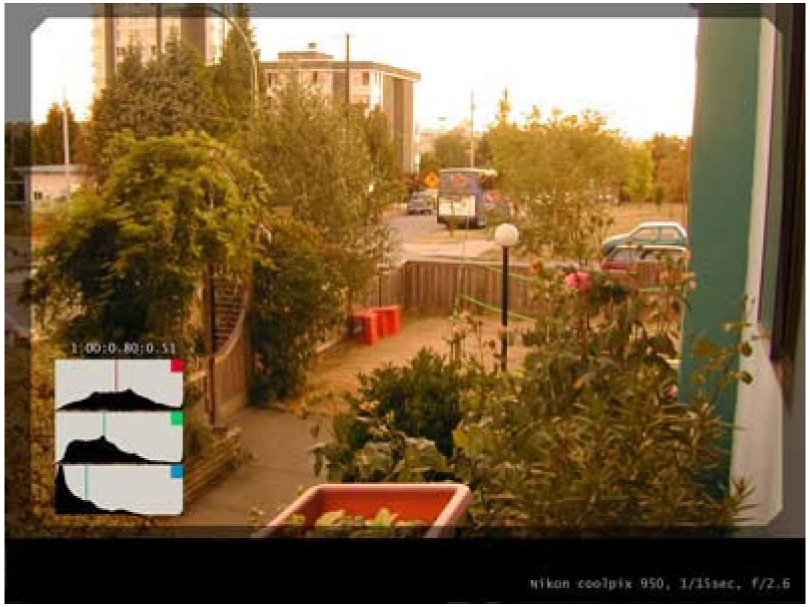


X3 sensor

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

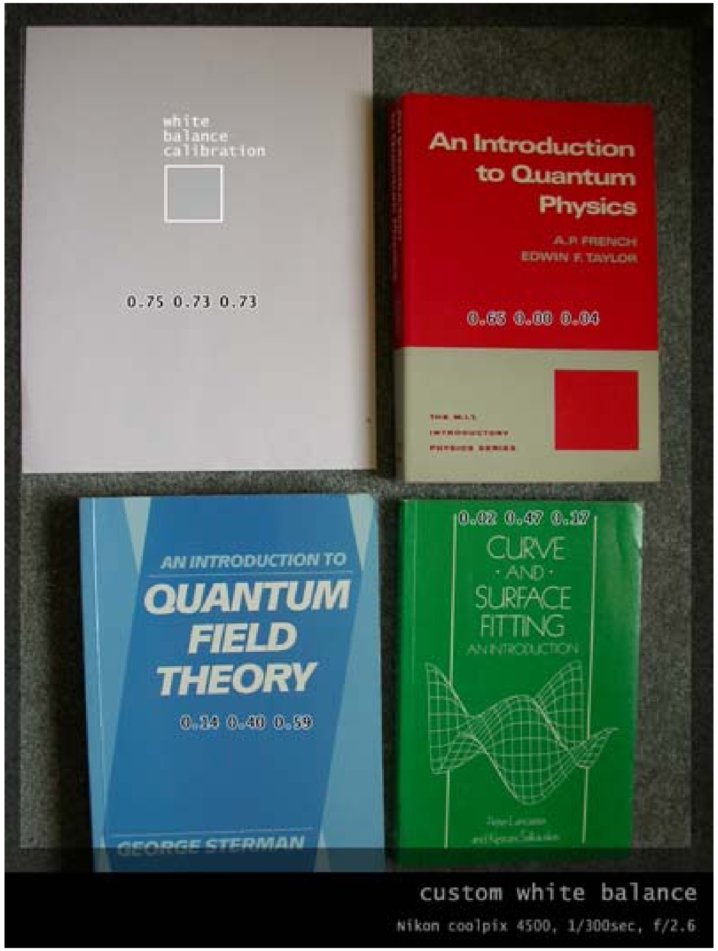
White Balance



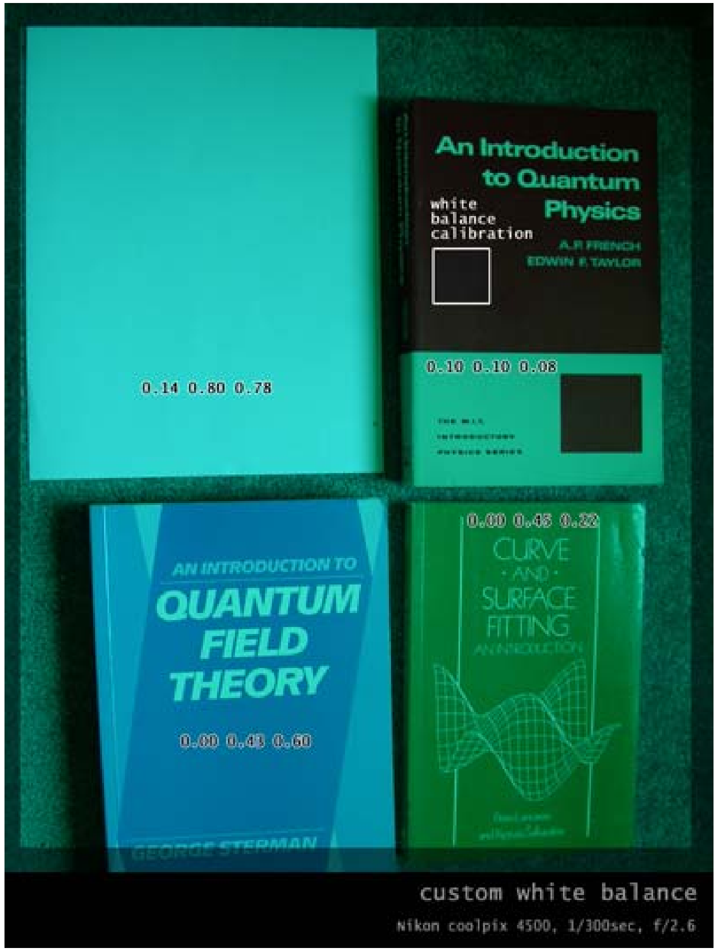
warmer +3

automatic white balance

Manual white balance



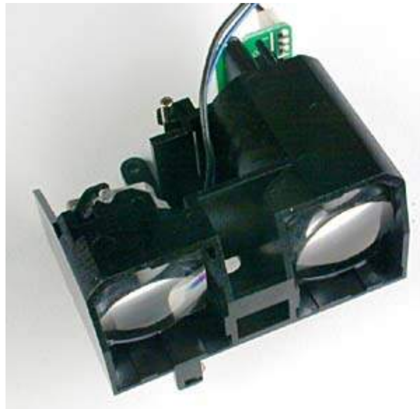
white balance with
the white book

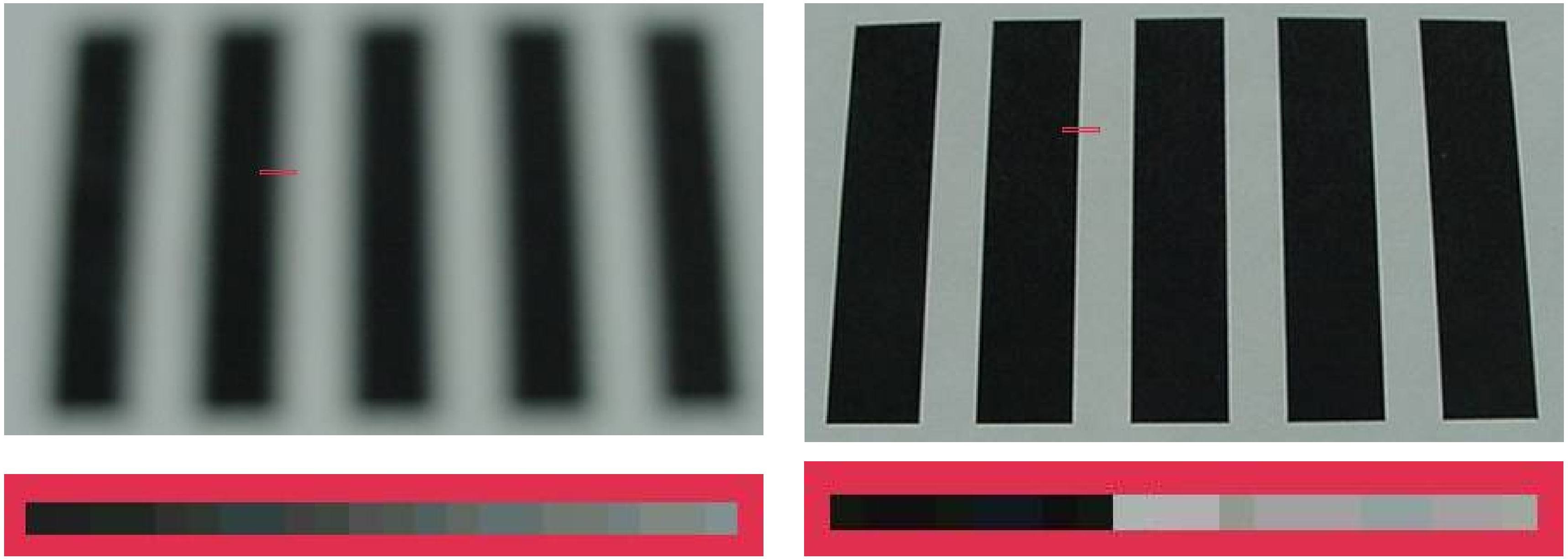


white balance with
the red book

Autofocus

- Active
  - Sonar
  - Infrared
- Passive

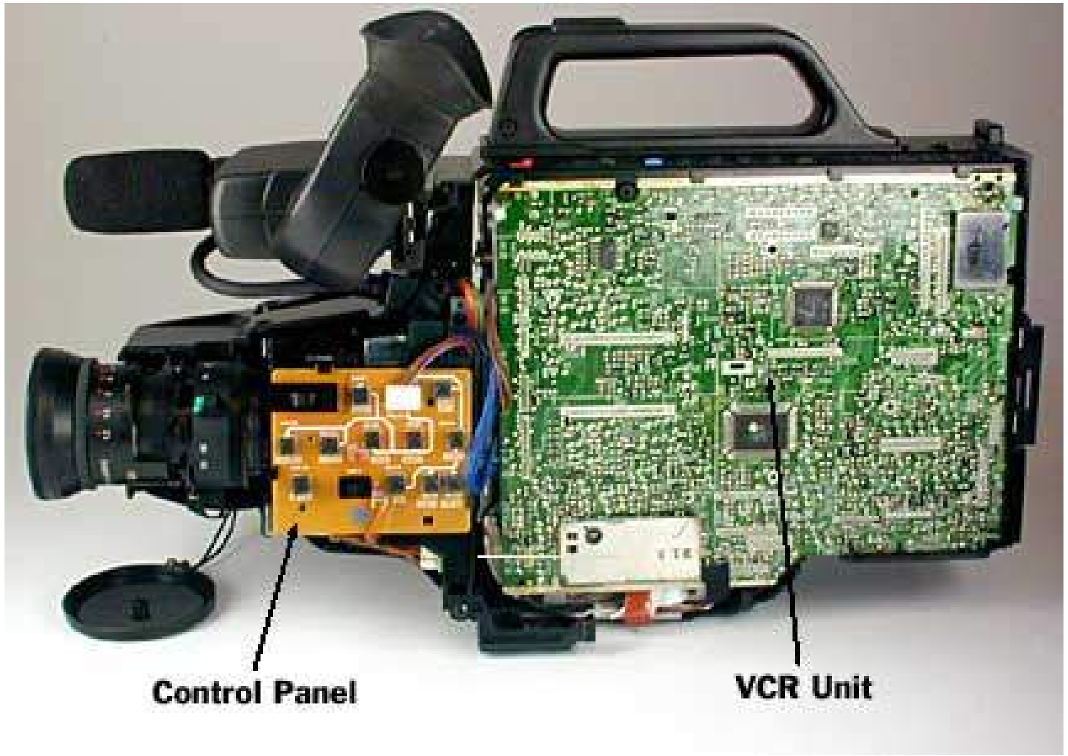




Digital camera review website

- http://www.dpreview.com/

Camcorder



Interlacing

DigiVFX

without interlacing

with interlacing

deinterlacing

blend

weave

deinterlacing

Discard

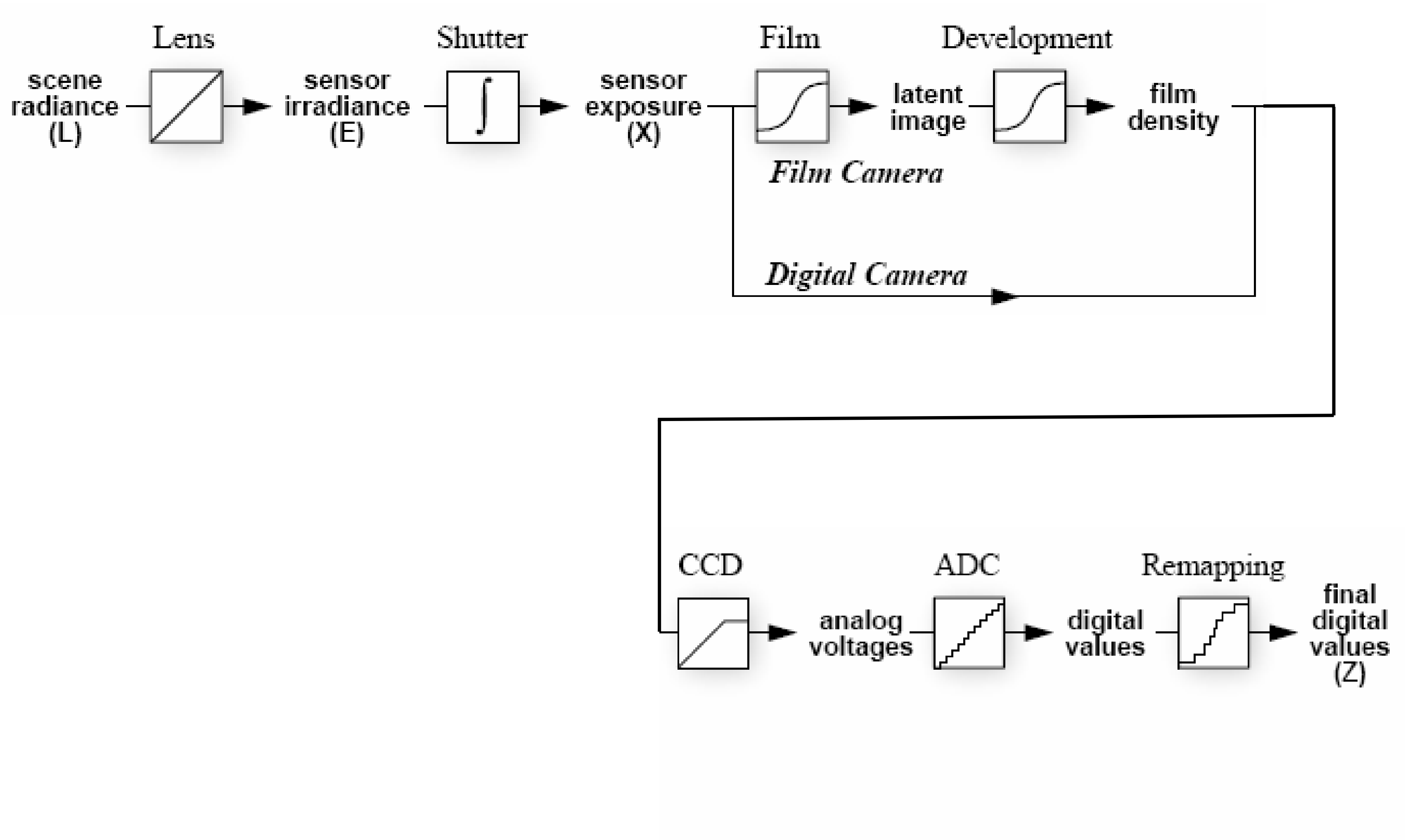
Progressive scan

Hard cases

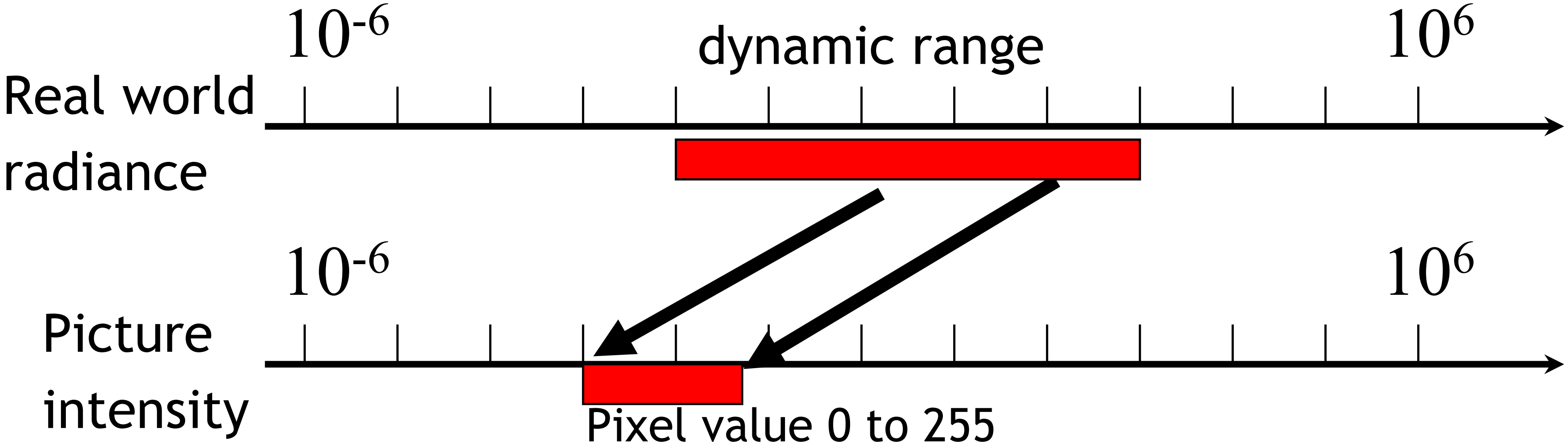
High dynamic range imaging

Camera pipeline

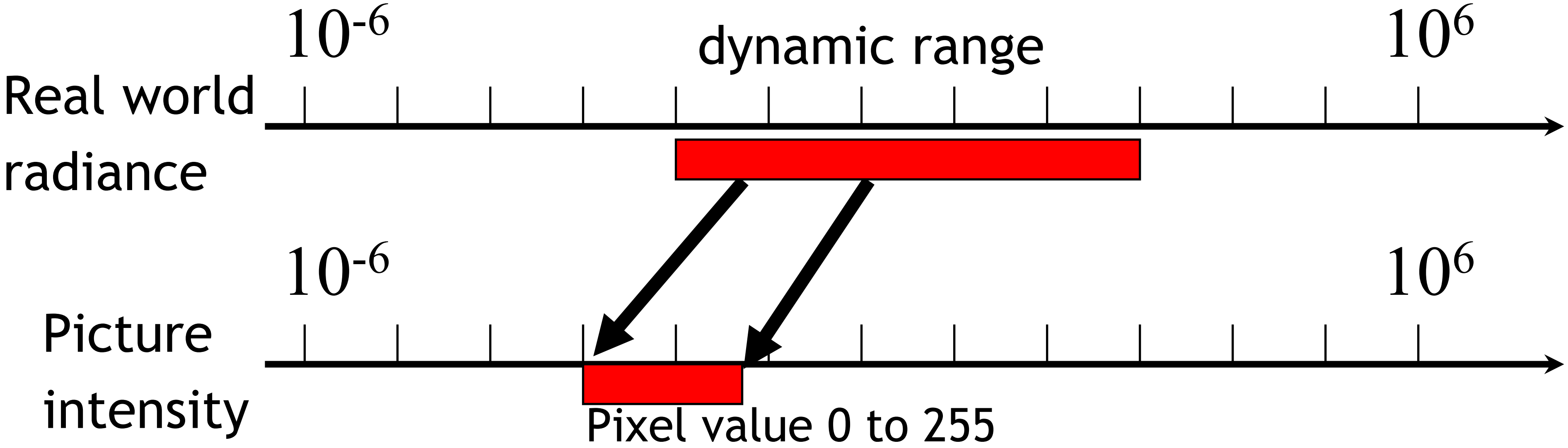


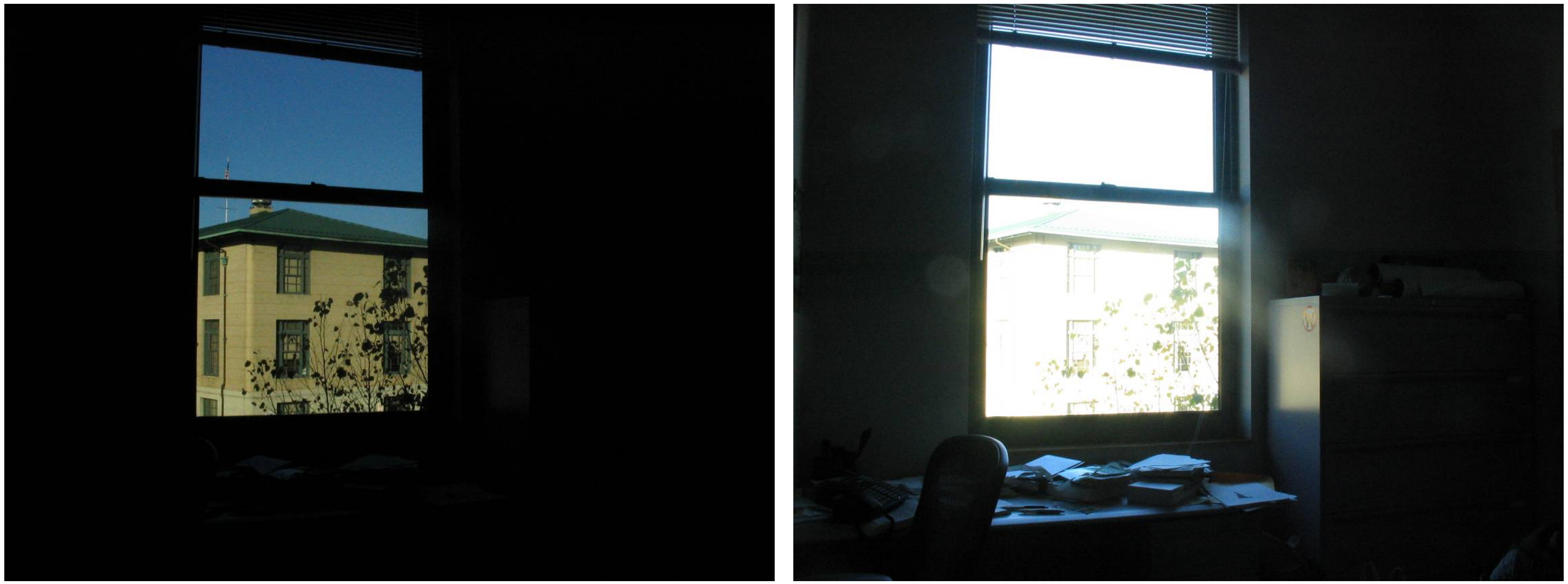
High dynamic range image

Short exposure

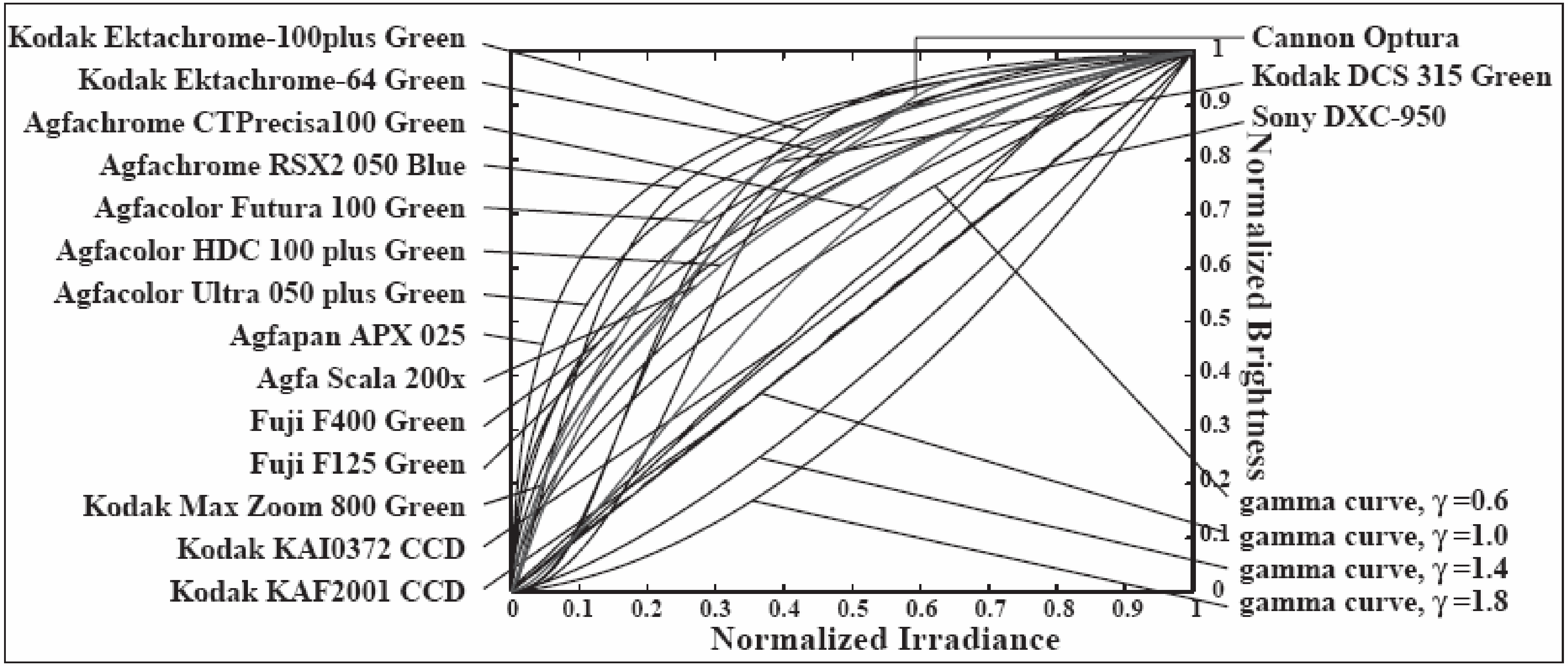


Long exposure





Real-world response functions



Camera calibration

- Geometric
  - How pixel **coordinates** relate to **directions** in the world
- Photometric
  - How pixel **values** relate to **radiance** amounts in the world

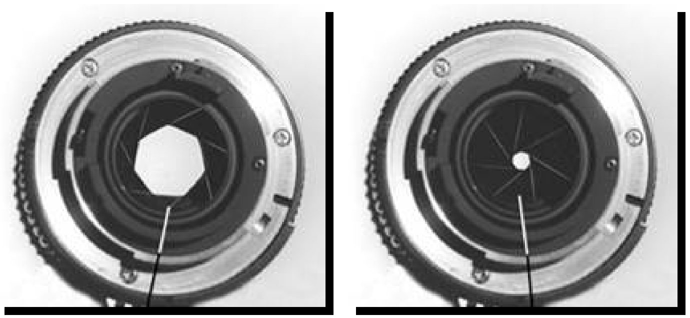
Camera is not a photometer

DigiVFX

- Limited dynamic range
  - ⇒ Perhaps use multiple exposures?
- Unknown, nonlinear response
  - ⇒ Not possible to convert pixel values to radiance
- Solution:
  - – Recover response curve from multiple exposures, then reconstruct the ***radiance map***

Varying exposure

- Ways to change exposure
  - Shutter speed
  - Aperture
  - Natural density filters



Shutter speed

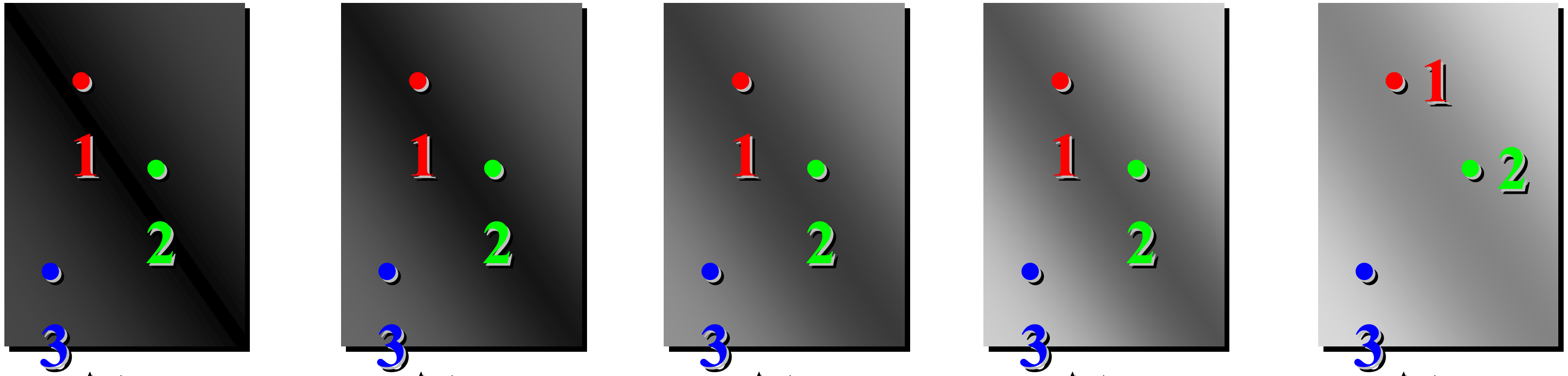
- Note: shutter times usually obey a power series – each “stop” is a factor of 2
- ¼, 1/8, 1/15, 1/30, 1/60, 1/125, 1/250, 1/500, 1/1000 sec

Usually really is:

¼, 1/8, 1/16, 1/32, 1/64, 1/128, 1/256, 1/512, 1/1024 sec

Varying shutter speeds

Algorithm



$\Delta t =$ 1/64 sec | $\Delta t =$ 1/16 sec | $\Delta t =$ 1/4 sec | $\Delta t =$ 1 sec | $\Delta t =$ 4 sec

$$Z = F(\text{exposure})$$

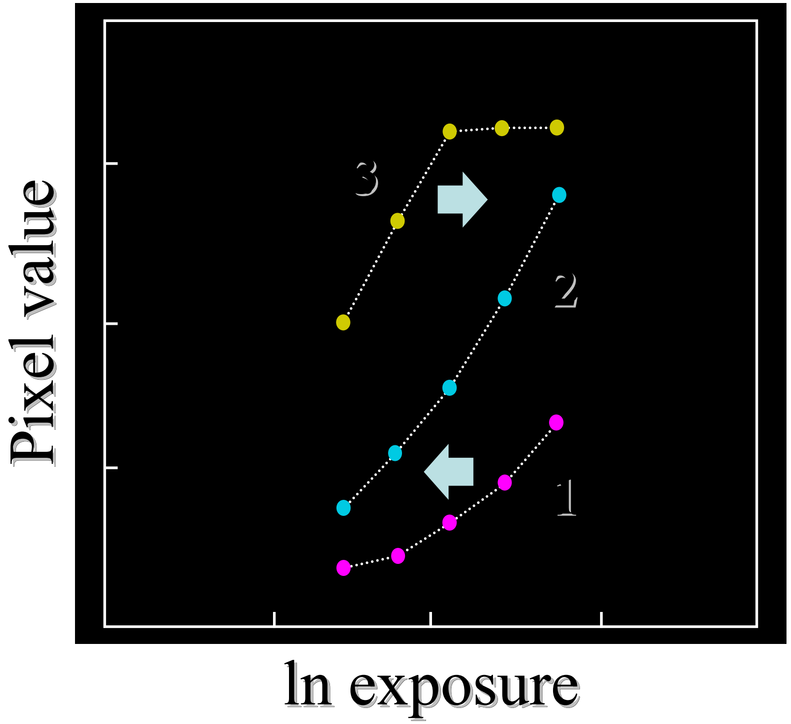
$$\text{exposure} = \text{radiance} * \Delta t$$

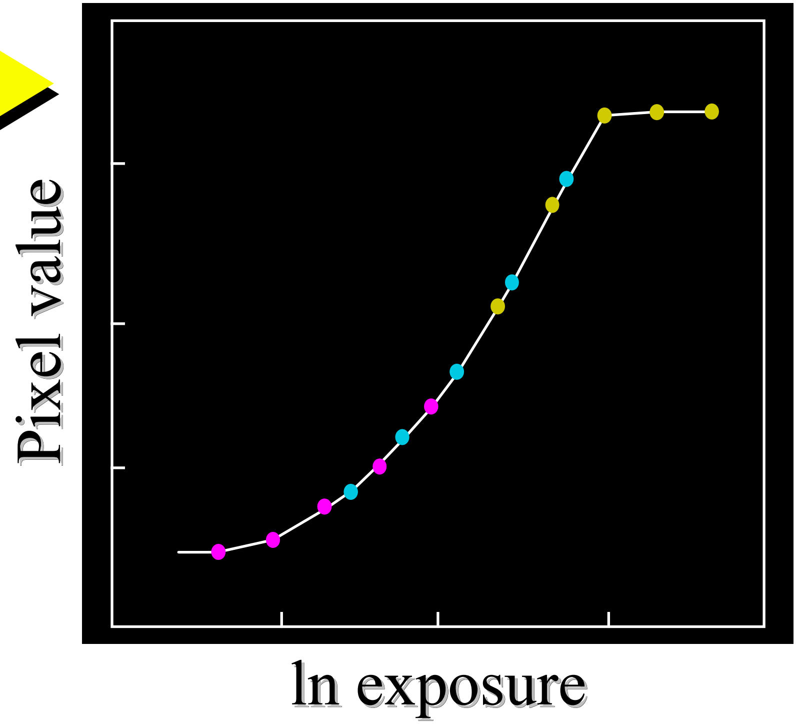
$$\log \text{exposure} = \log \text{radiance} + \log \Delta t$$

Response curve

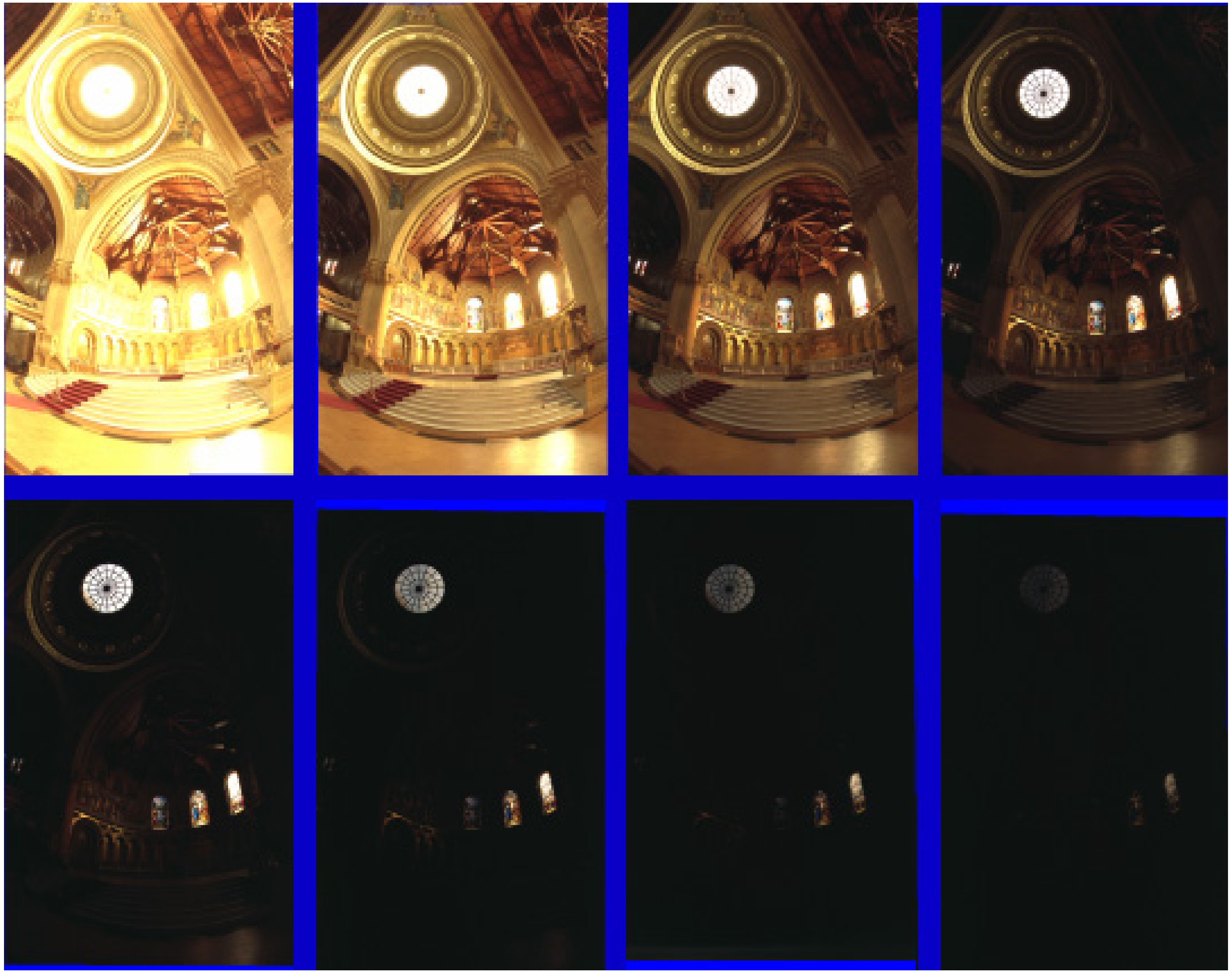
Assuming unit radiance for each pixel

After adjusting radiances to obtain a smooth response

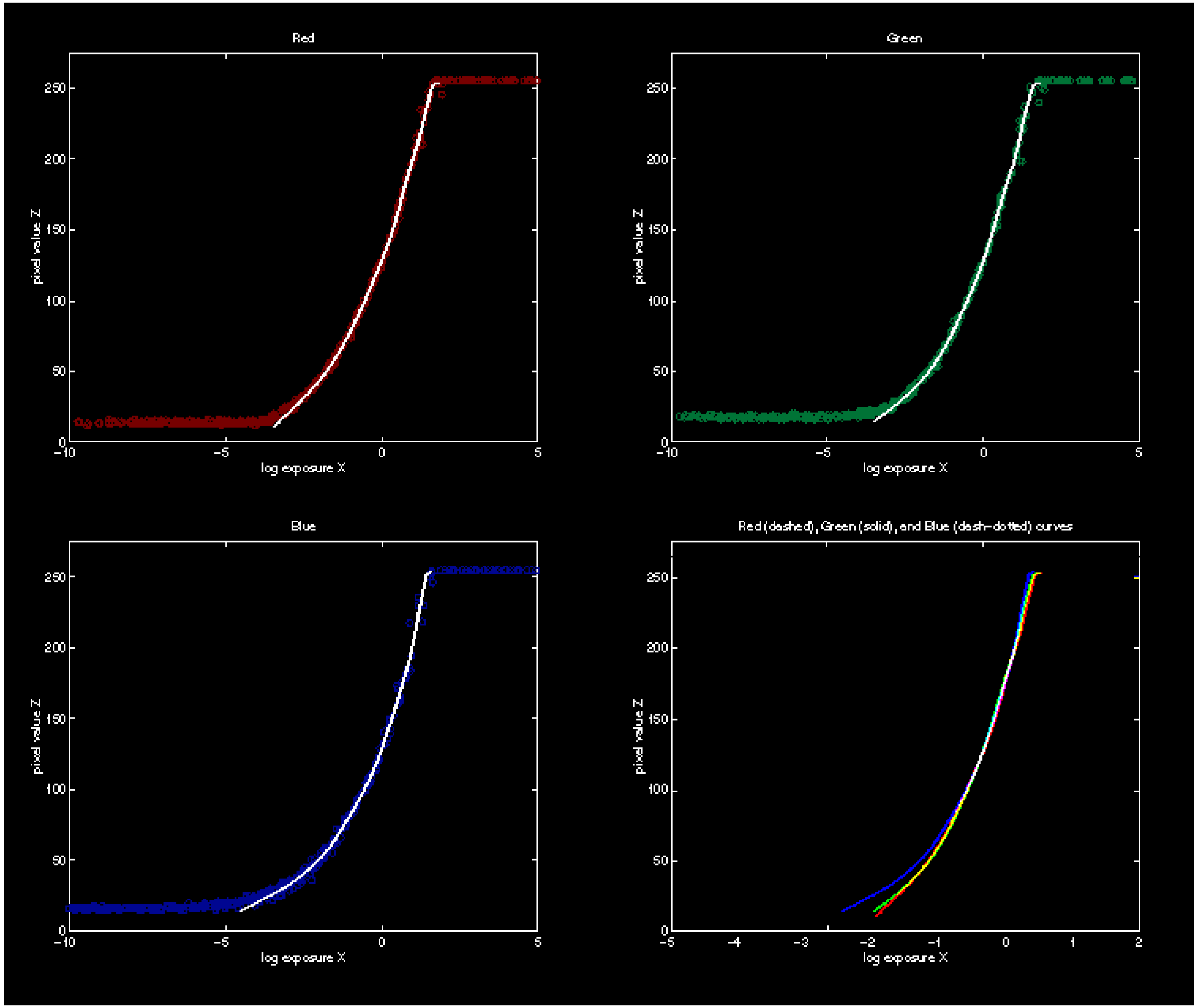




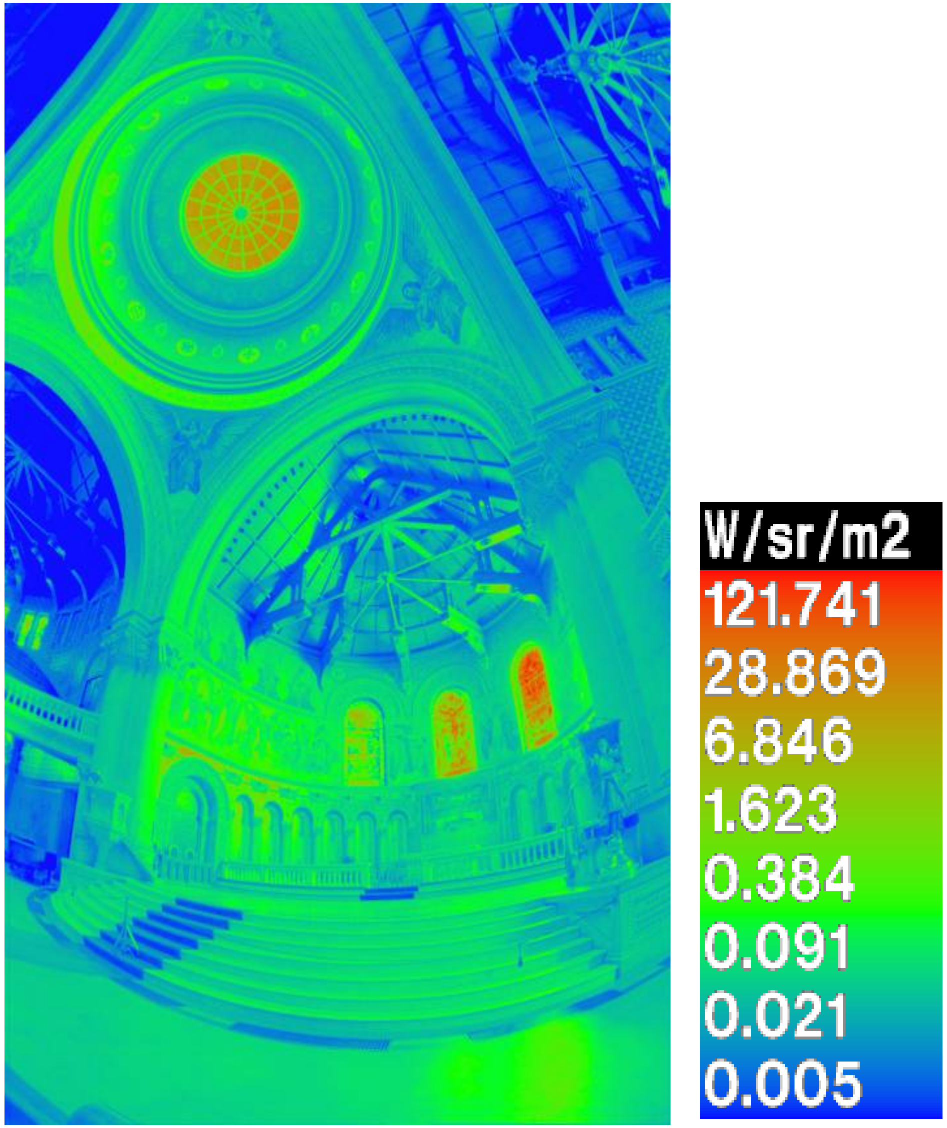
Results (color film)



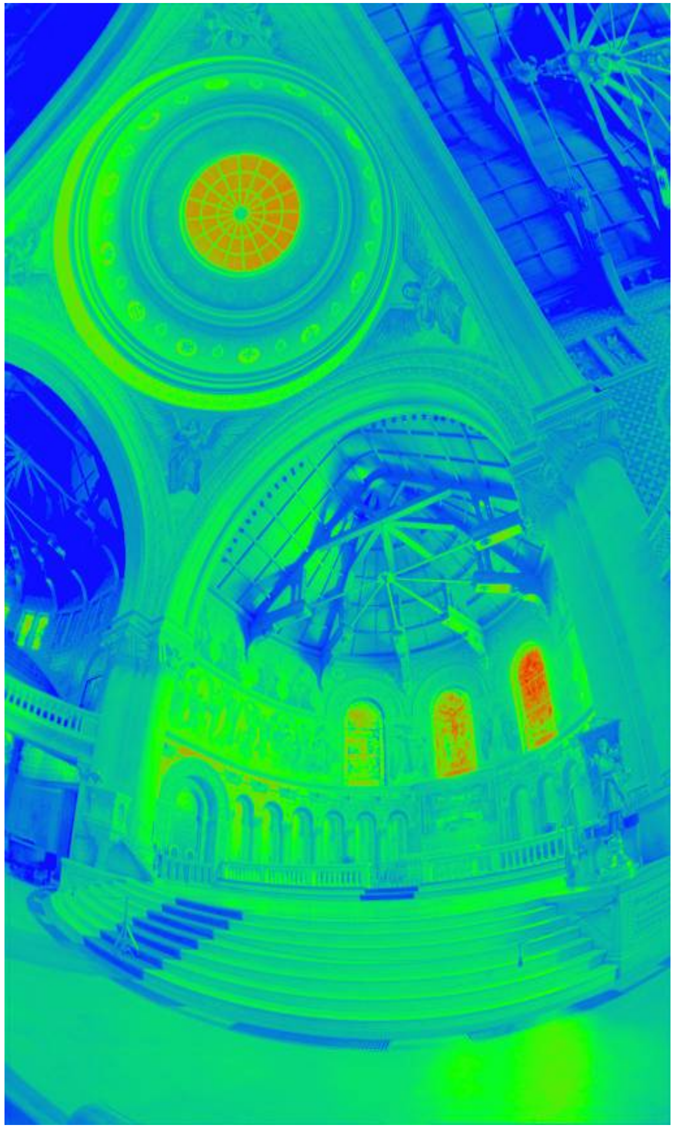
Recovered response function



Reconstructed radiance map

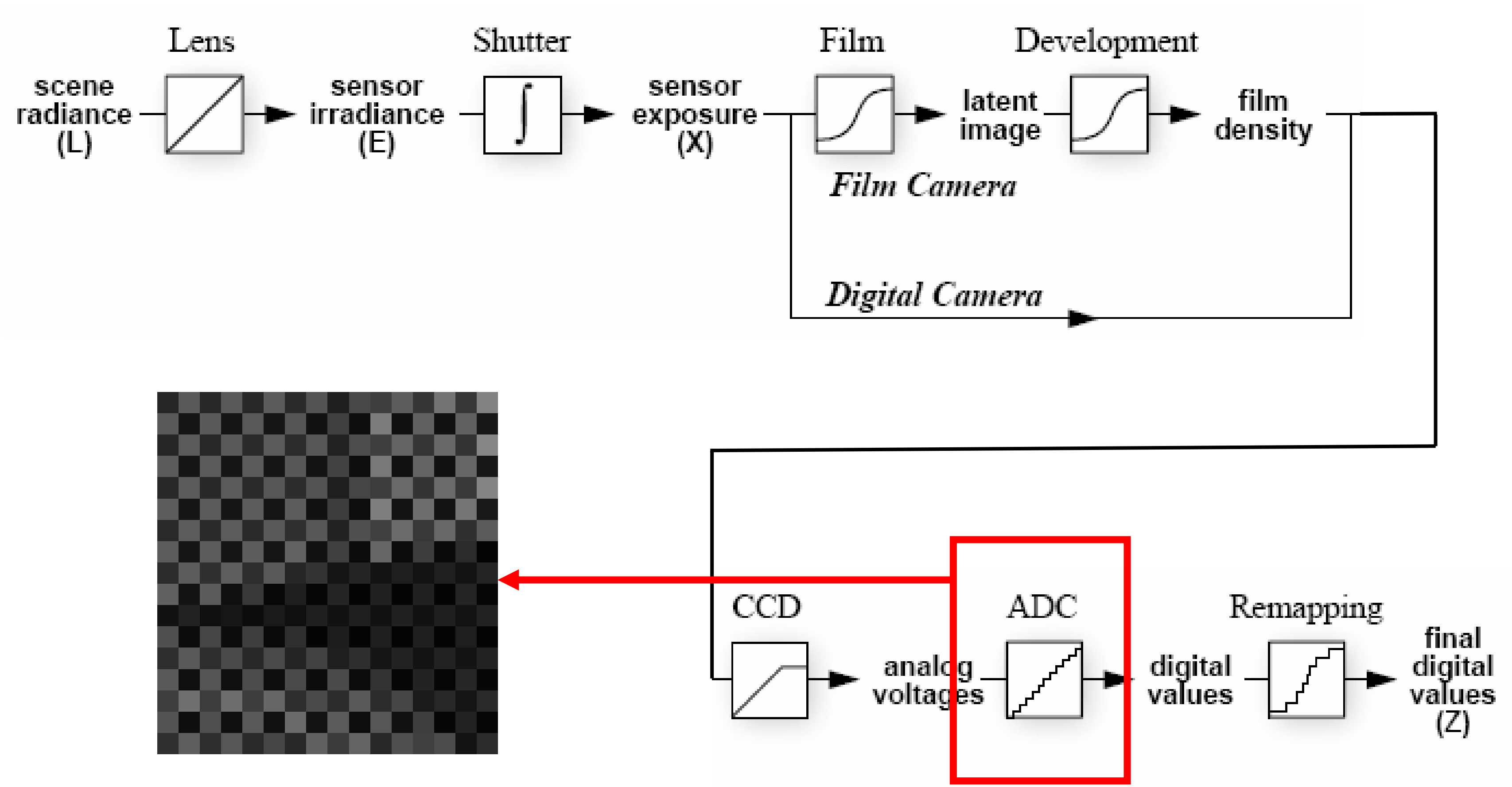


What is this for?



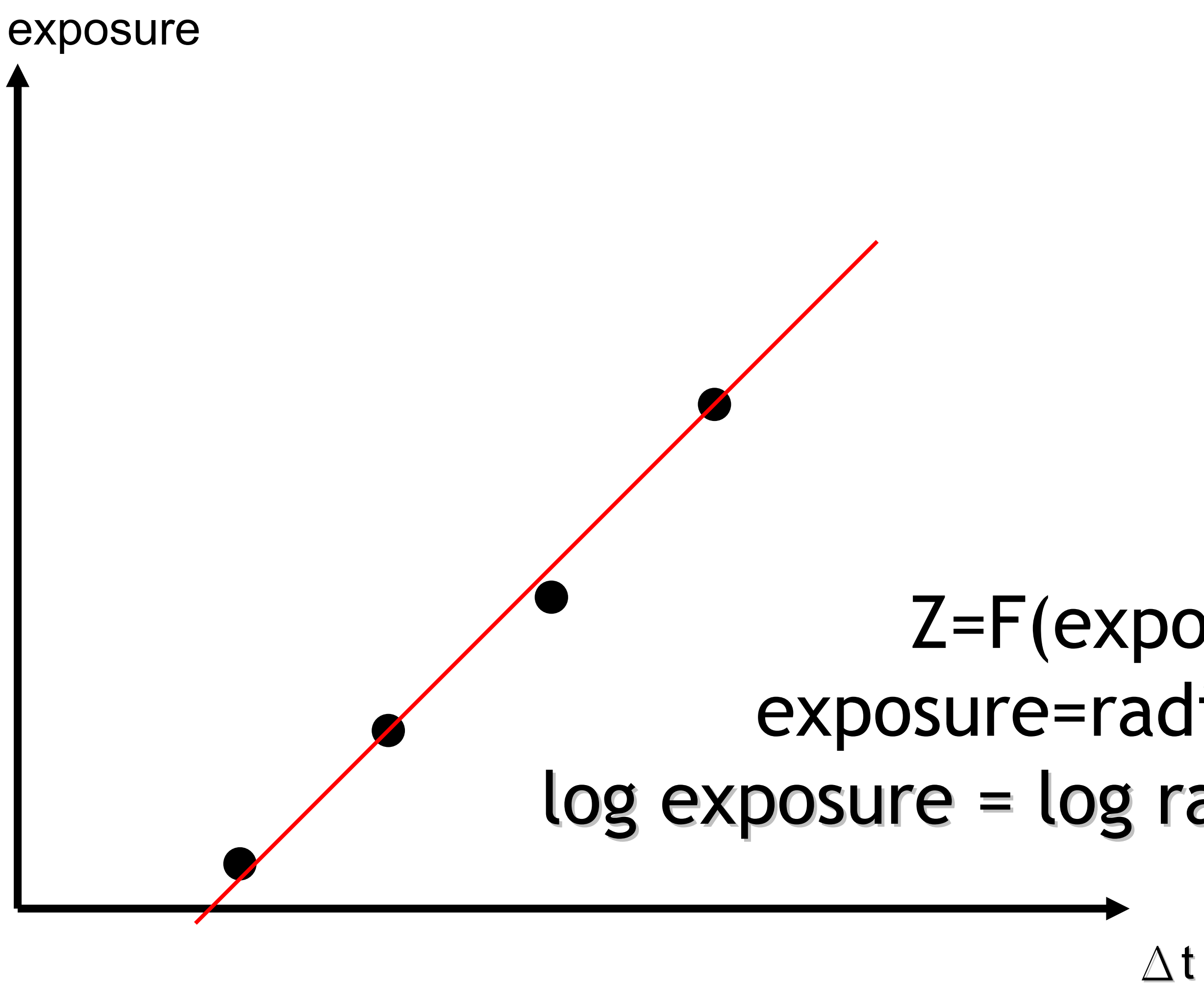
- Human perception
- Vision/graphics applications

Easier HDR reconstruction



raw image =
12-bit CCD snapshot

Easier HDR reconstruction



$$Z=F(\text{exposure})$$

$$\text{exposure}=\text{radiance}*\Delta t$$

$$\log \text{exposure} = \log \text{radiance} + \log \Delta t$$

Reference

- http://www.howstuffworks.com/digital-camera.htm
- http://electronics.howstuffworks.com/autofocus.htm
- Ramanath, Snyder, Bilbro, and Sander. Demosaicking Methods for Bayer Color Arrays, Journal of Electronic Imaging, 11(3), pp306-315.
- Paul E. Debevec, Jitendra Malik, Recovering High Dynamic Range Radiance Maps from Photographs, SIGGRAPH 1997.
- http://www.worldatwar.org/photos/whitebalance/index.mhtml
- http://www.100fps.com/