

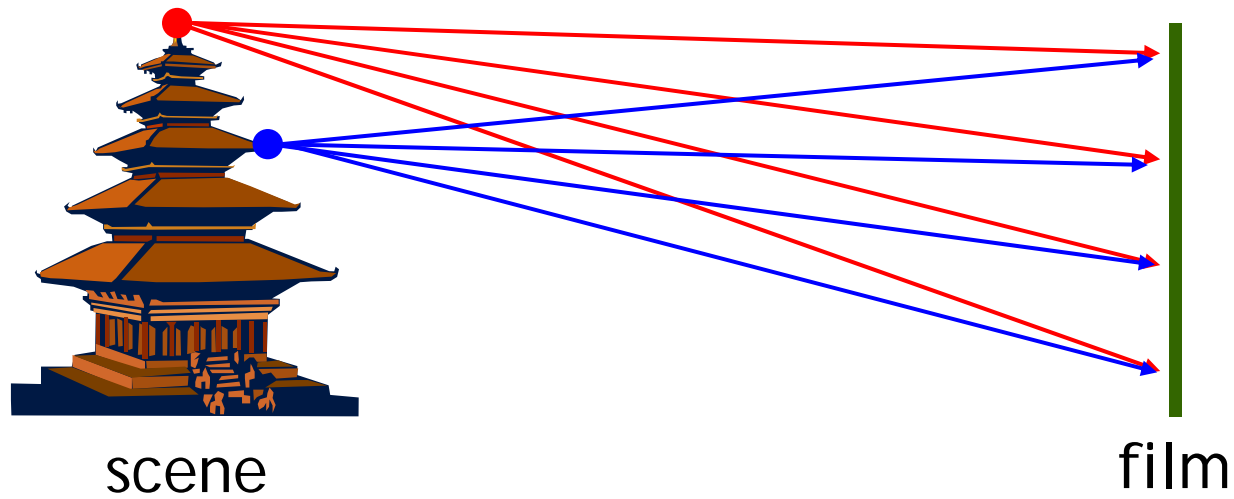
Cameras

Digital Visual Effects

Yung-Yu Chuang

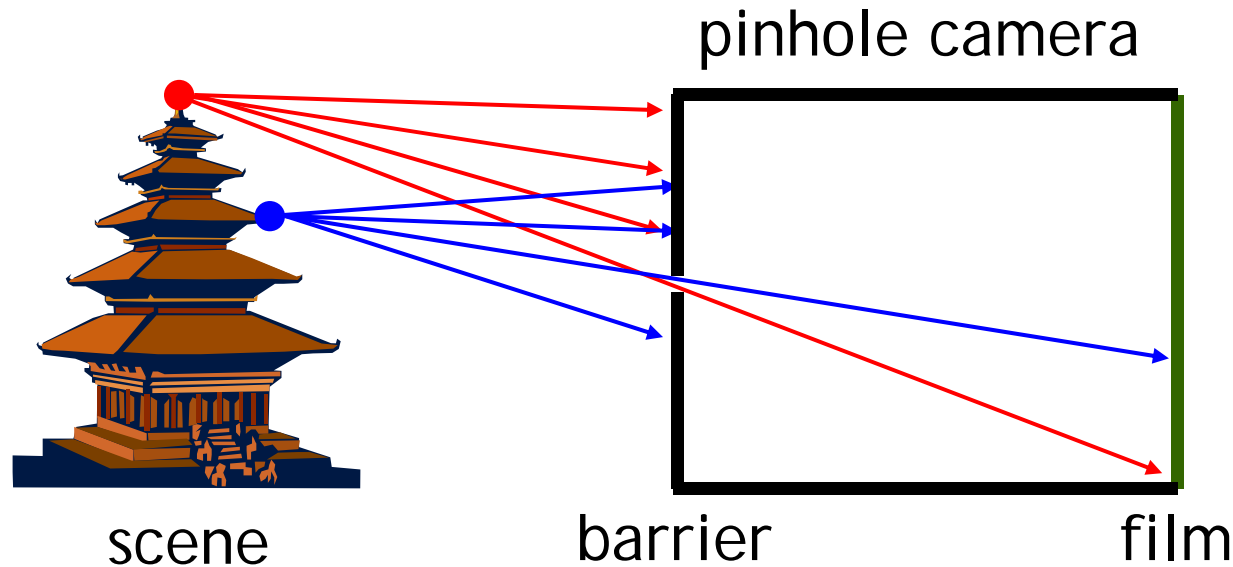
with slides by Fredo Durand, Brian Curless, Steve Seitz and Alexei Efros

Camera trial #1



Put a piece of film in front of an object.

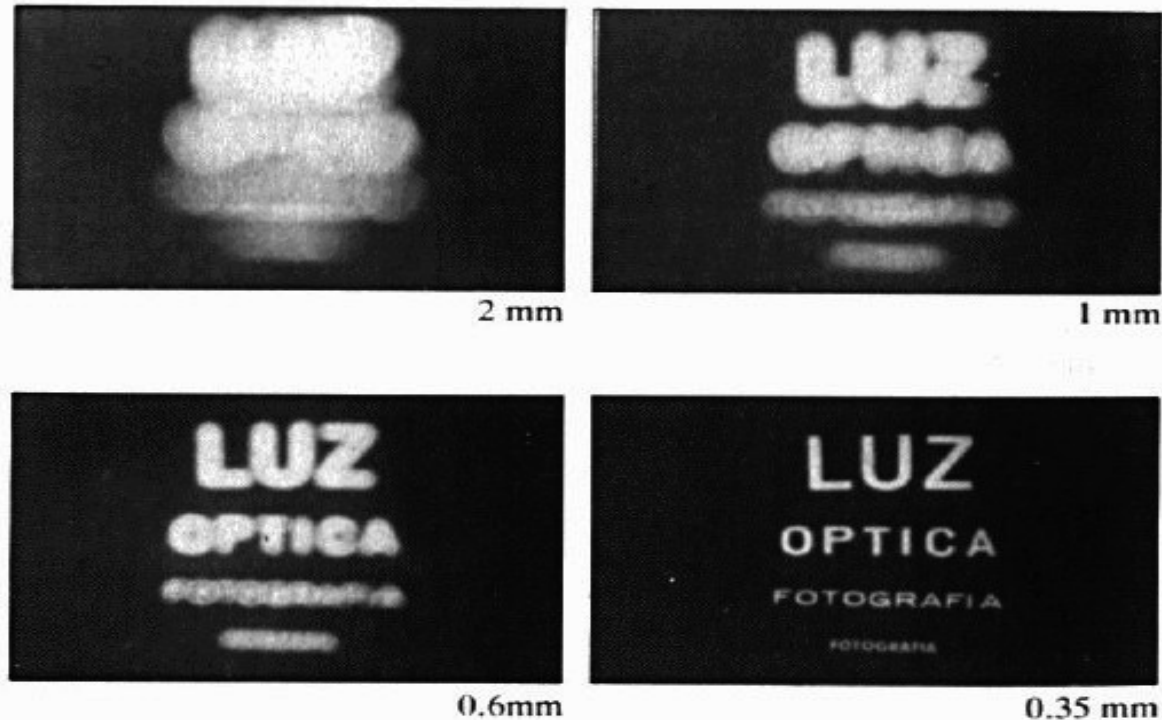
Pinhole camera



Add a barrier to block off most of the rays.

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

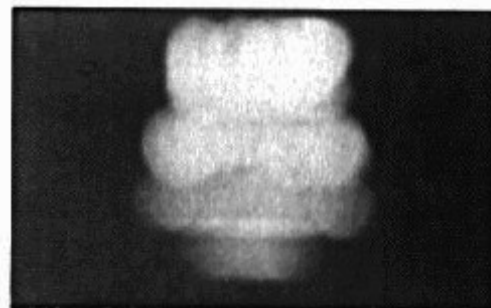
Shrinking the aperture



Why not making the aperture as small as possible?

- Less light gets through
- Diffraction effect

Shrinking the aperture



2 mm



1 mm



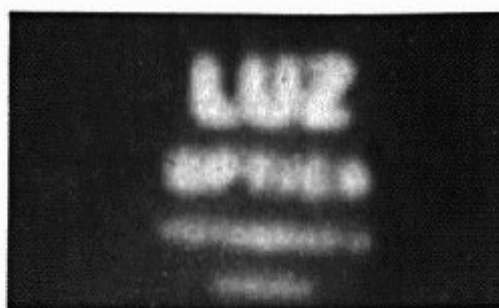
0.6 mm



0.35 mm

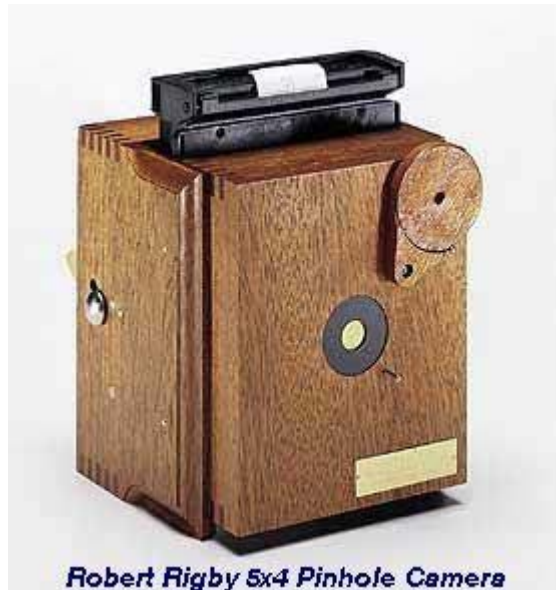


0.15 mm

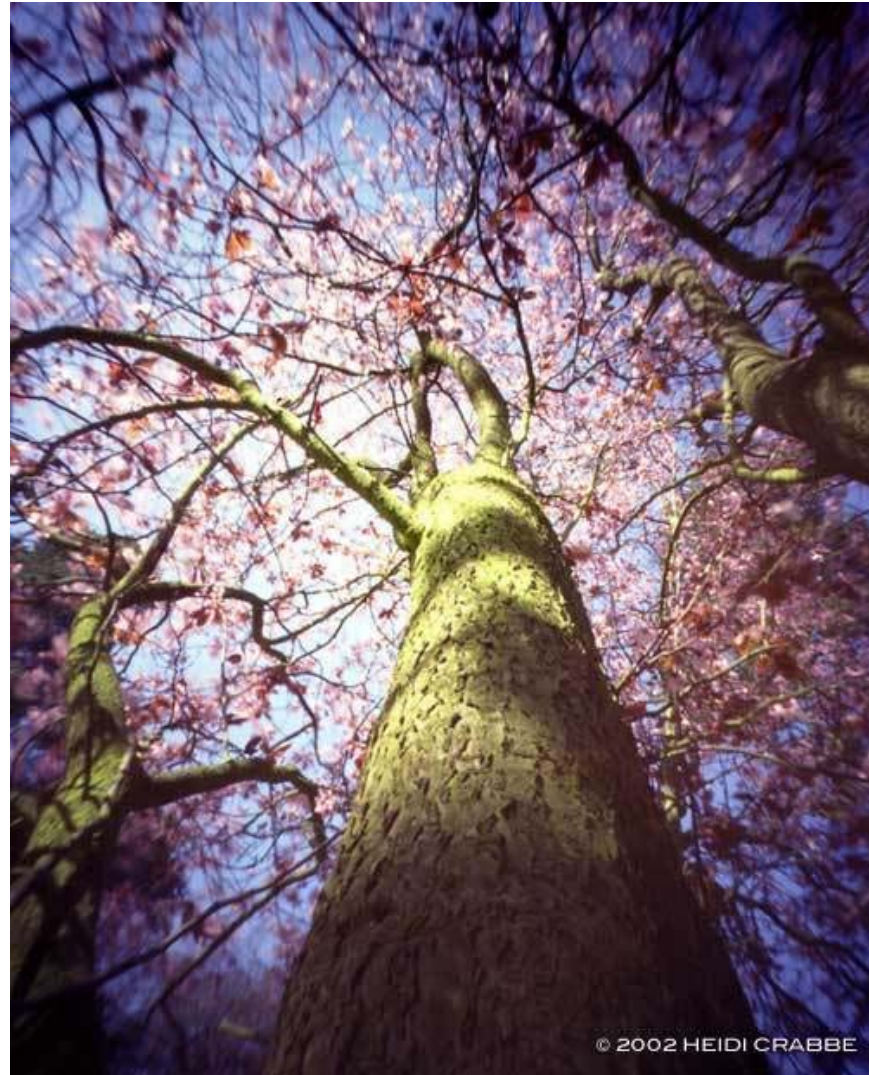


0.07 mm

High-end commercial pinhole cameras DigiVFX



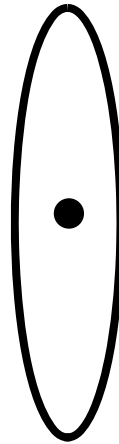
\$200~\$700



Adding a lens



scene

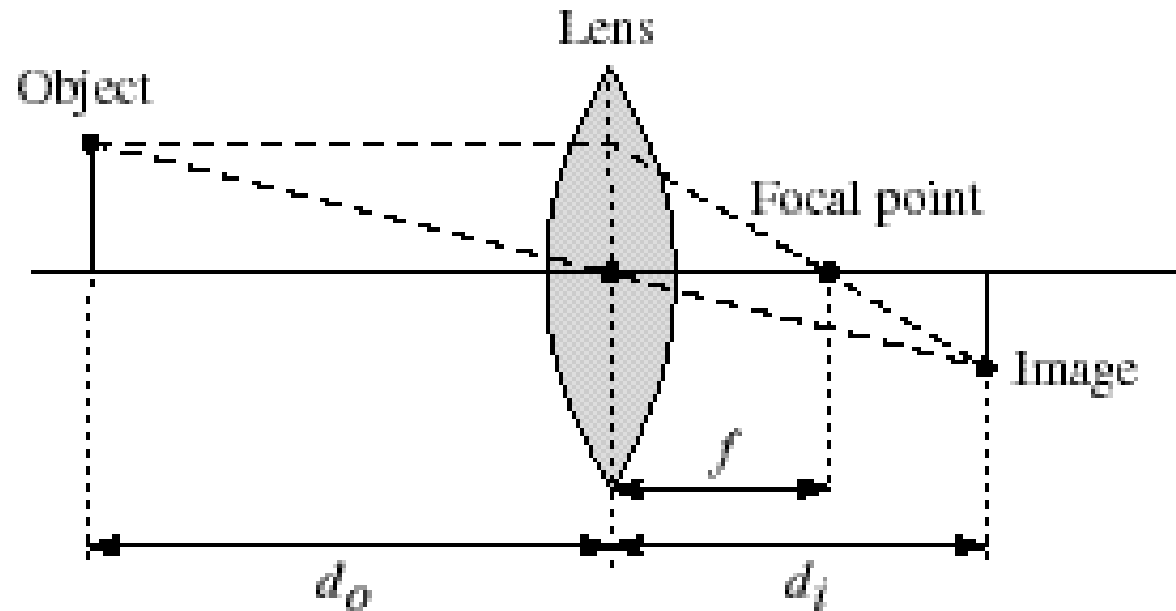


lens



film

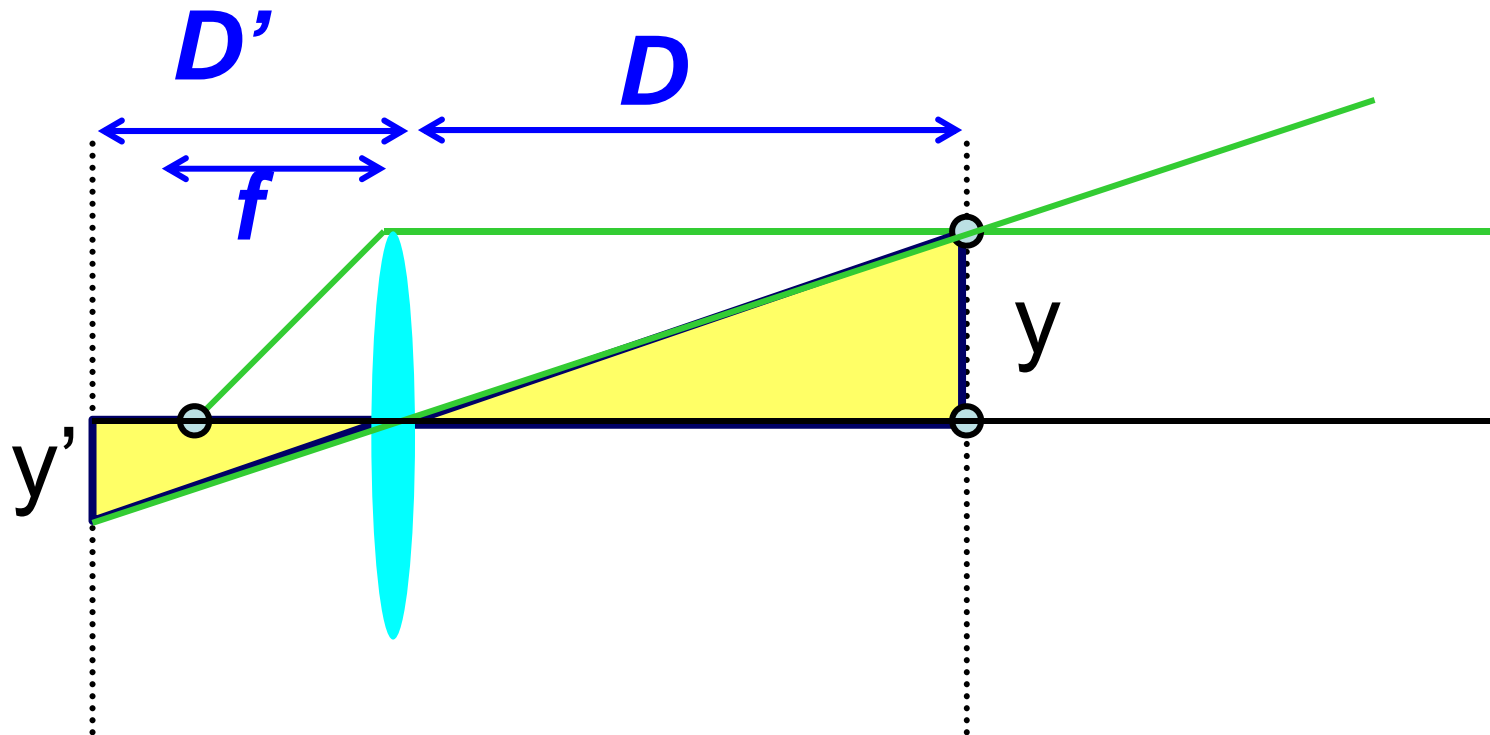
Lenses



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

Thin lens formula

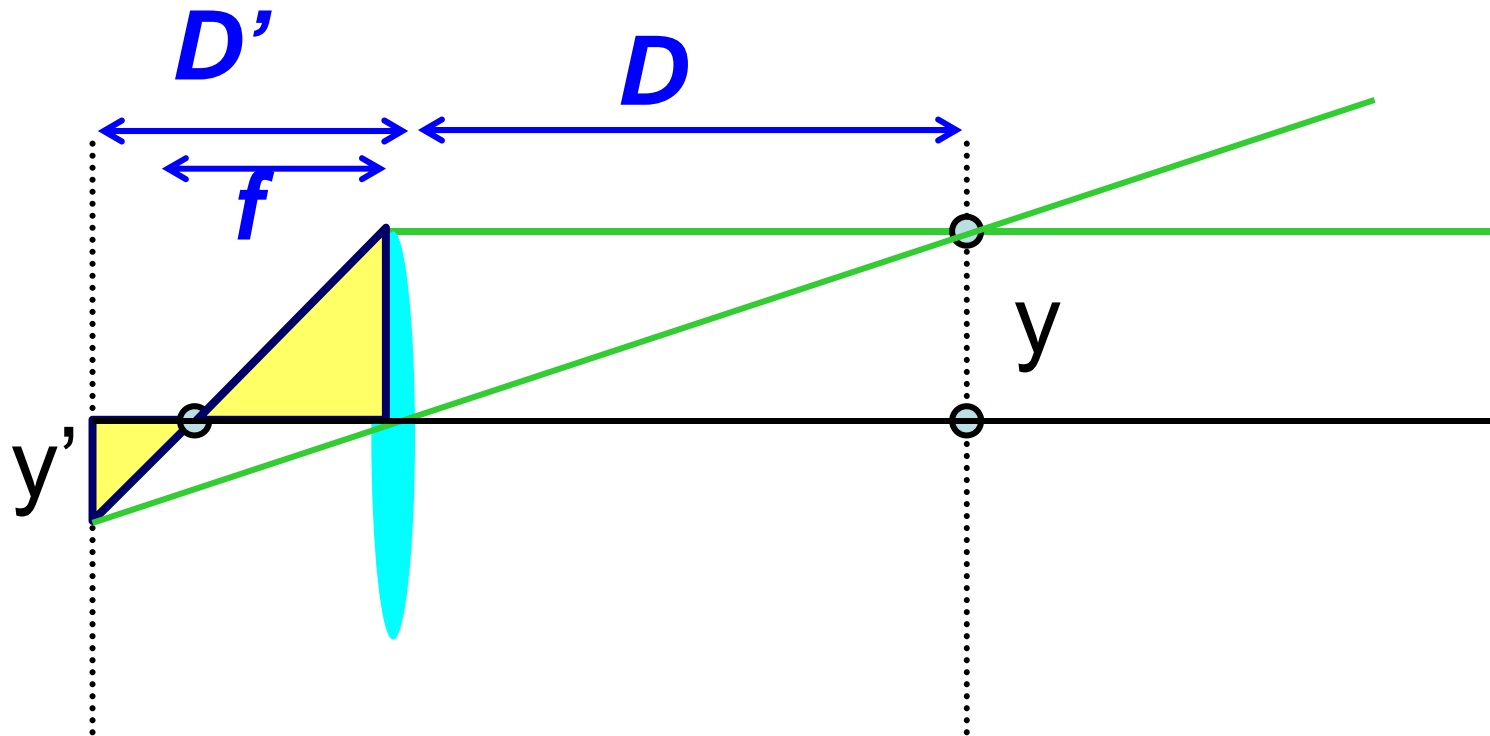
Similar triangles everywhere! $y'/y = D'/D$



Thin lens formula

Similar triangles everywhere! $y'/y = D'/D$

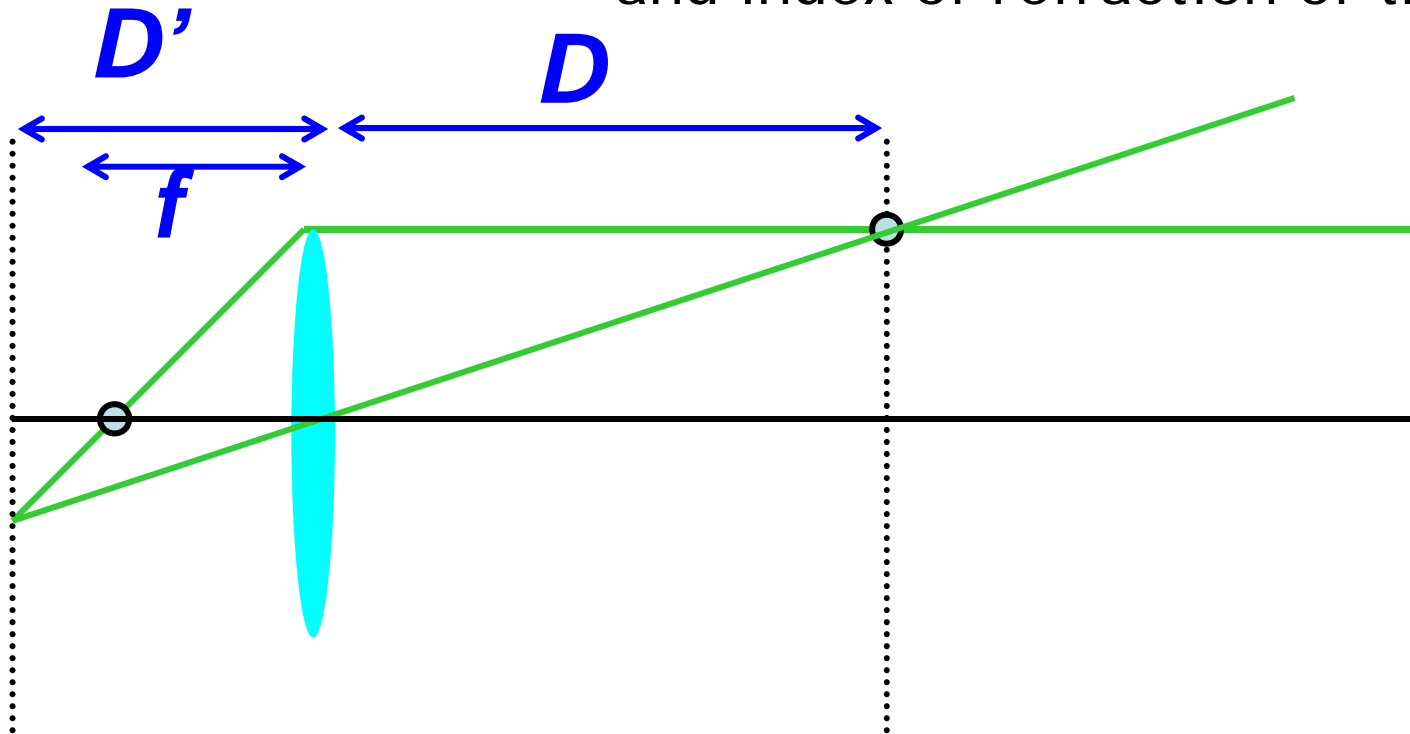
$$y'/y = (D' - f)/f$$



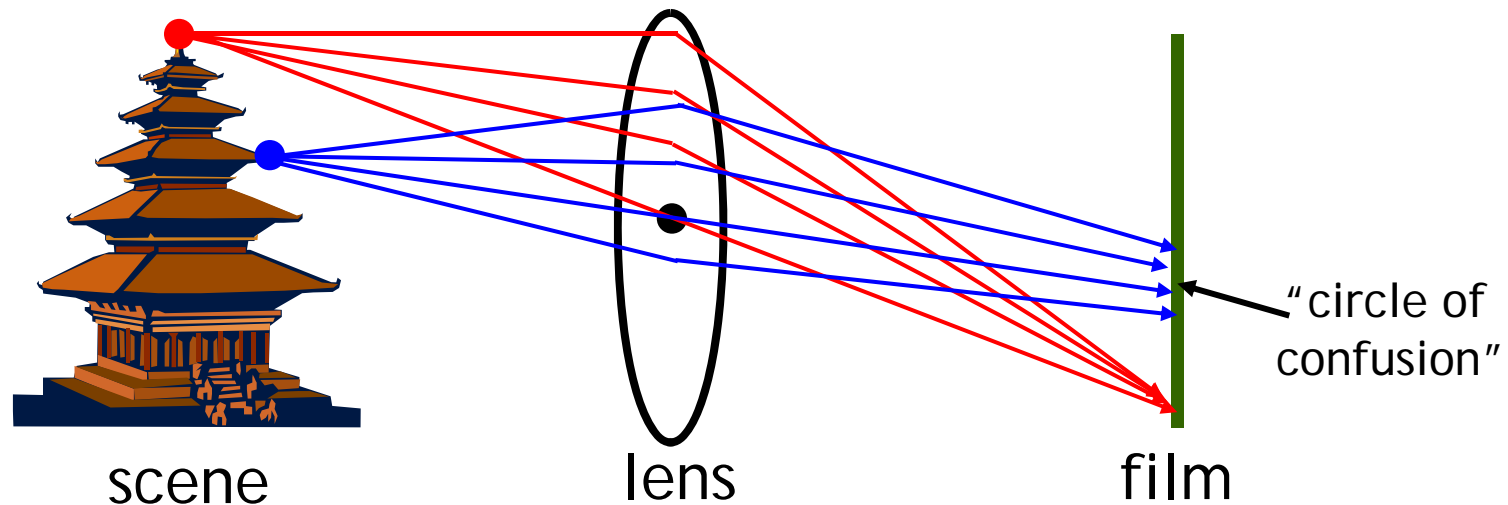
Thin lens formula

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

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.



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
- Thin lens applet:

http://www.phy.ntnu.edu.tw/java/Lens/lens_e.html

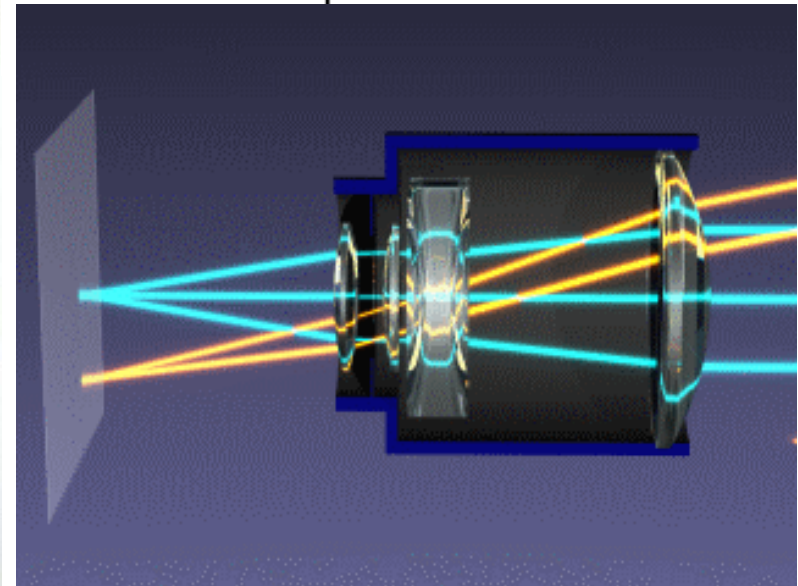
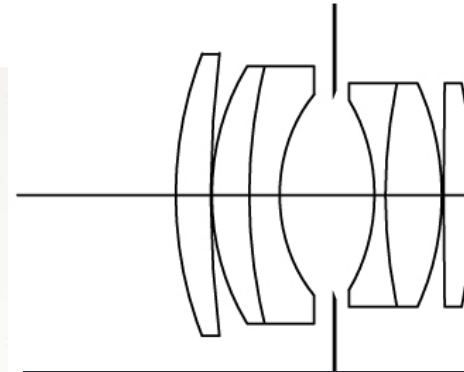
Zoom lens

200mm



28mm

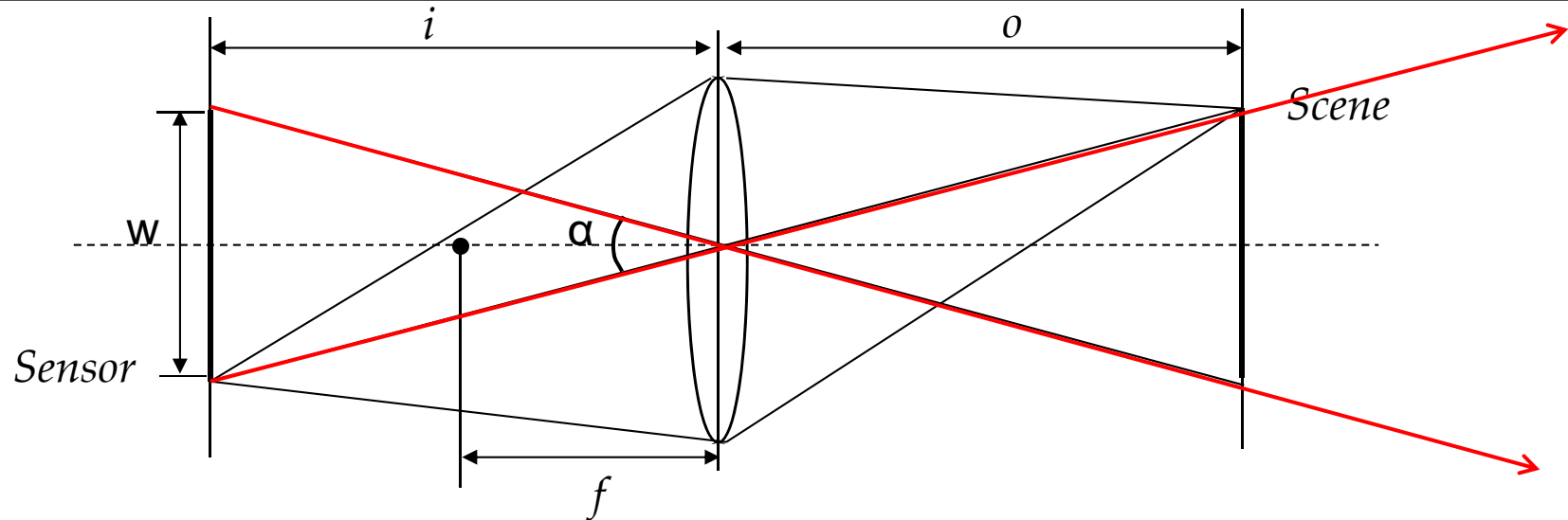
Nikon 28-200mm zoom lens.



simplified zoom lens
in operation

From wikipedia

Field of view vs focal length



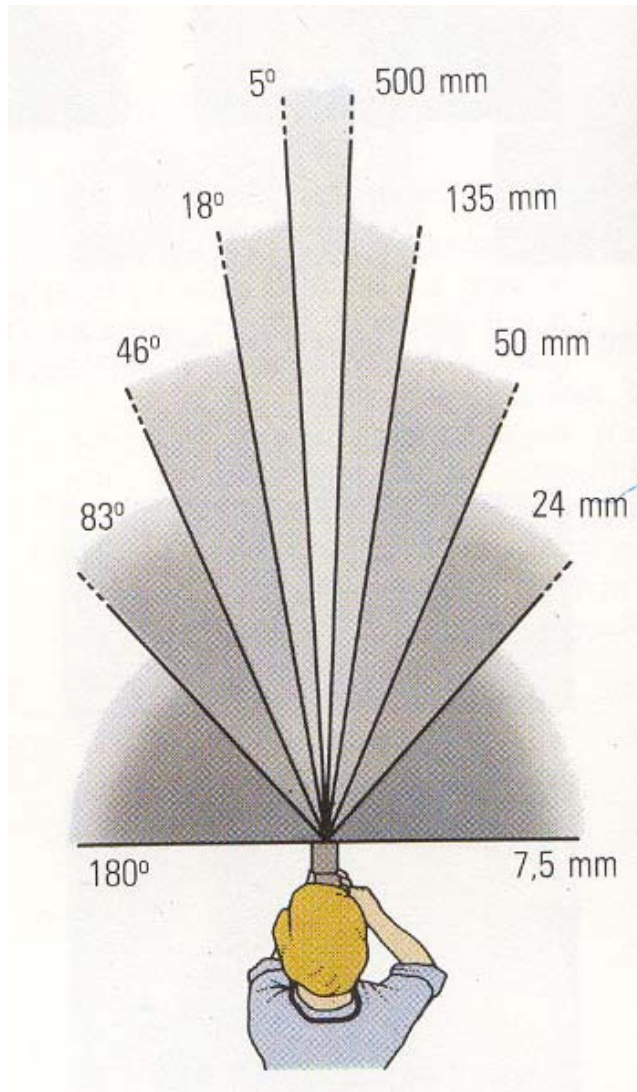
Gaussian Lens Formula:
$$\frac{1}{i} + \frac{1}{o} = \frac{1}{f}$$

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

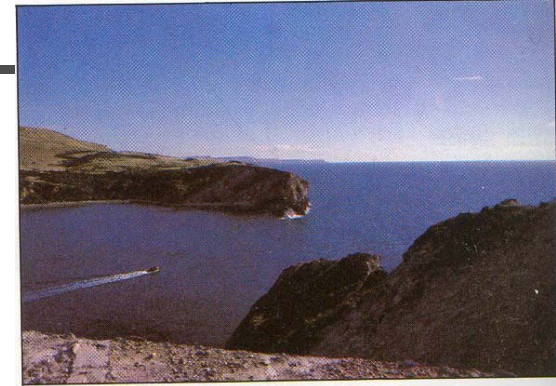
Example: $w = 30\text{mm}$, $f = 50\text{mm} \Rightarrow \alpha \approx 33.4^\circ$

Focal length in practice

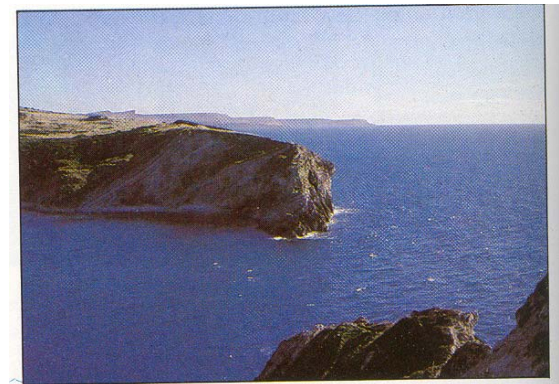
DigiVFX



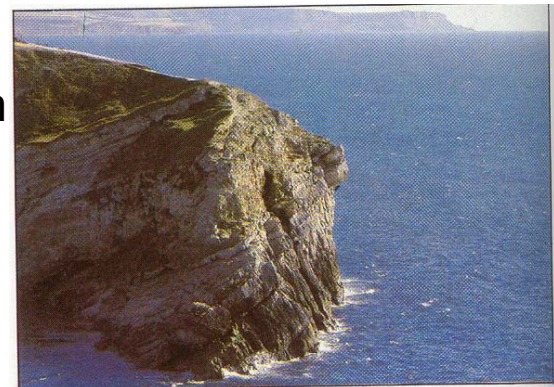
24mm



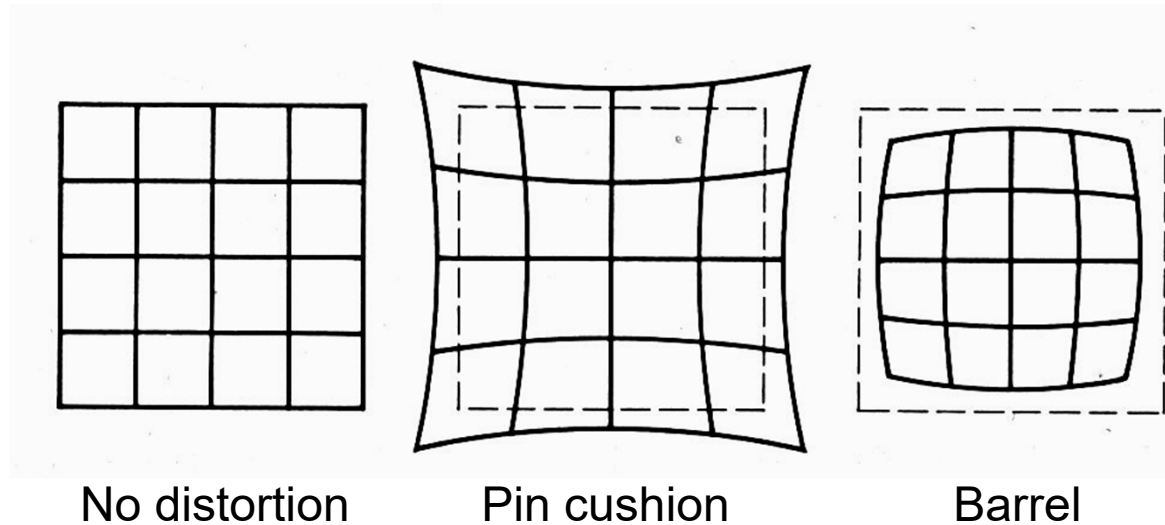
50mm



135mm



Distortion



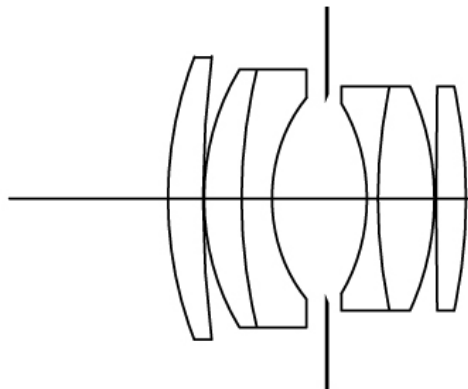
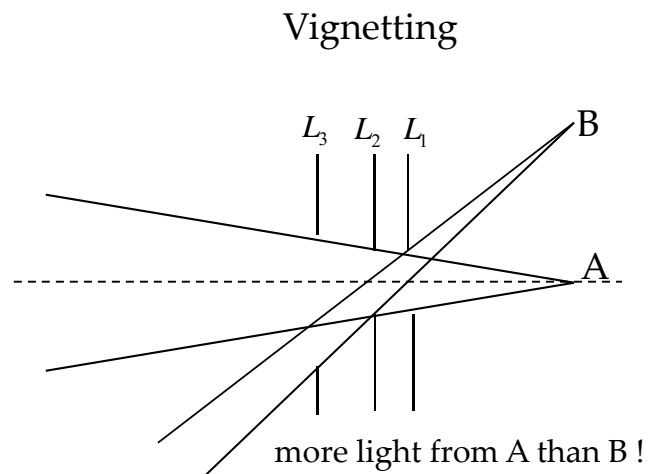
- Radial distortion of the image
 - Caused by imperfect lenses
 - Deviations are most noticeable for rays that pass through the edge of the lens

Correcting radial distortion

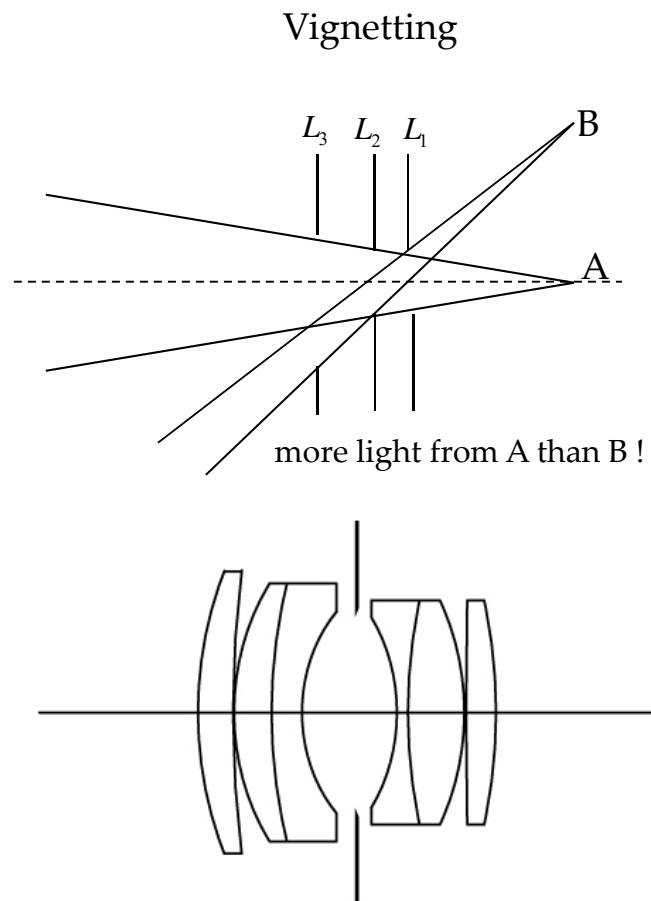


from [Helmut Dersch](#)

Vignetting



Vignetting



original

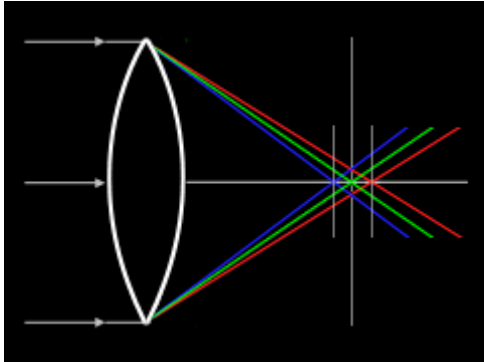


corrected

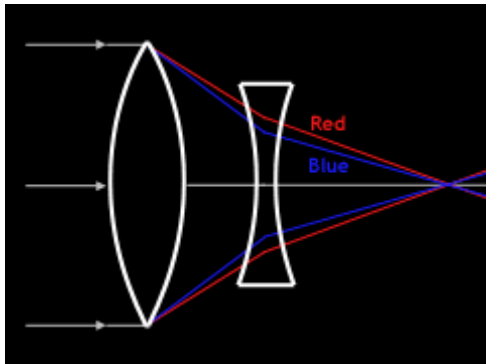
Goldman & Chen ICCV 2005

Slides from Li Zhang

Chromatic Aberration



Lens has different refractive indices for different wavelengths.

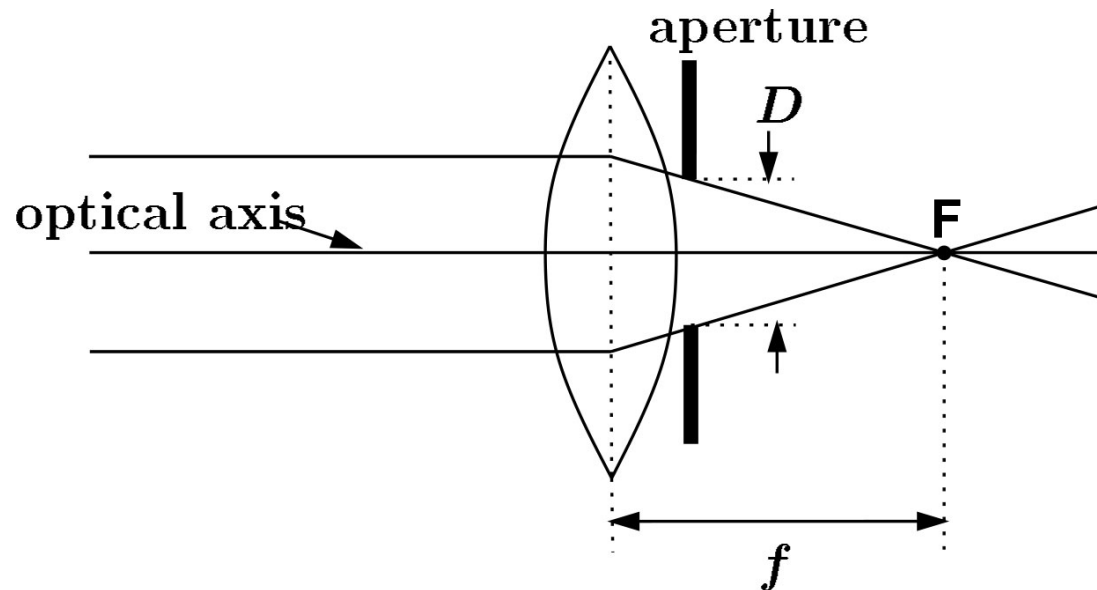


Special lens systems using two or more pieces of glass with different refractive indexes can reduce or eliminate this problem.



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

Exposure = aperture + shutter speed



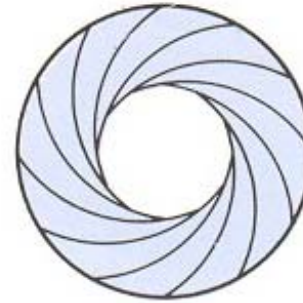
- Aperture of diameter D restricts the range of rays (aperture may be on either side of the lens)
- Shutter speed is the amount of time that light is allowed to pass through the aperture

Exposure

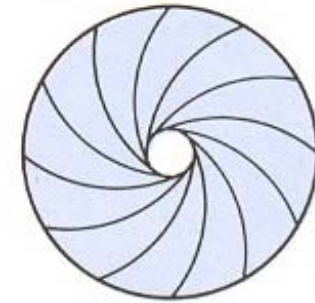
- Two main parameters:
 - Aperture (in f stop)



Full aperture



Medium aperture

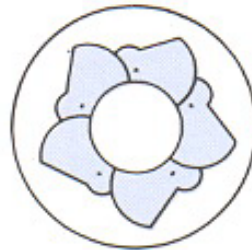


Stopped down

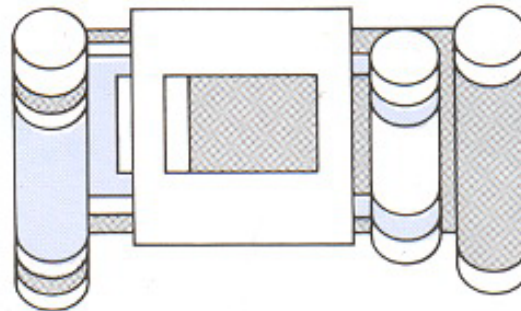
- Shutter speed (in fraction of a second)



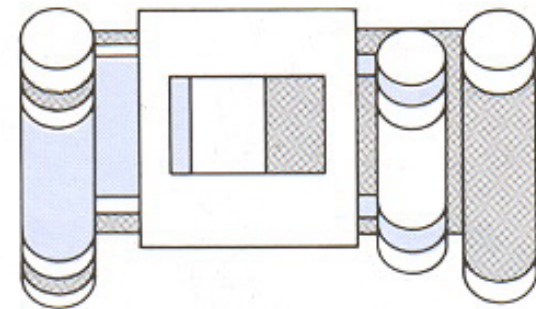
Blade (closing)



Blade (open)



Focal plane (closed)



Focal plane (open)

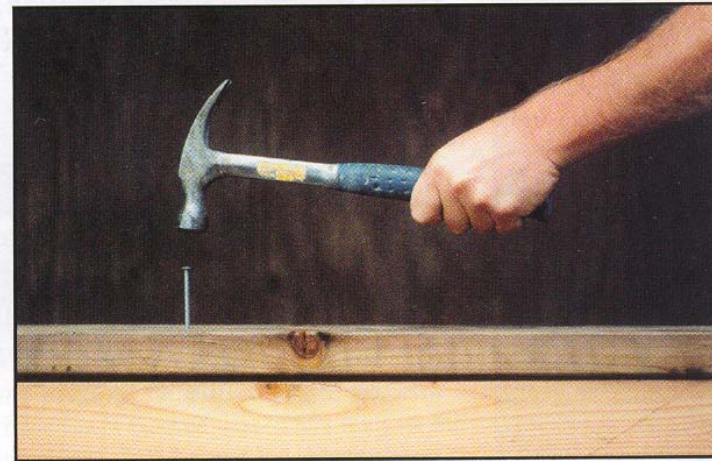
Effects of shutter speeds

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

Slow shutter speed



Fast shutter speed



- Faster shutter speed freezes motion

From Photography, London et al.

Walking people



1/125

Running people



1/250

Car



1/500

Fast train



1/1000

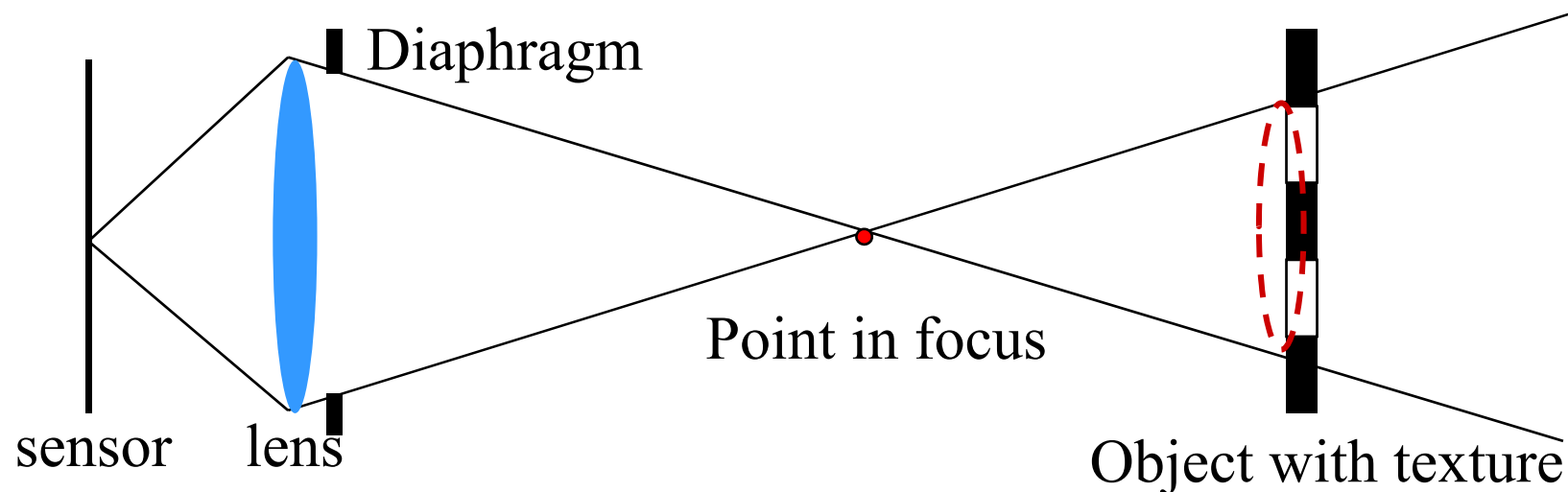
Aperture

- 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)



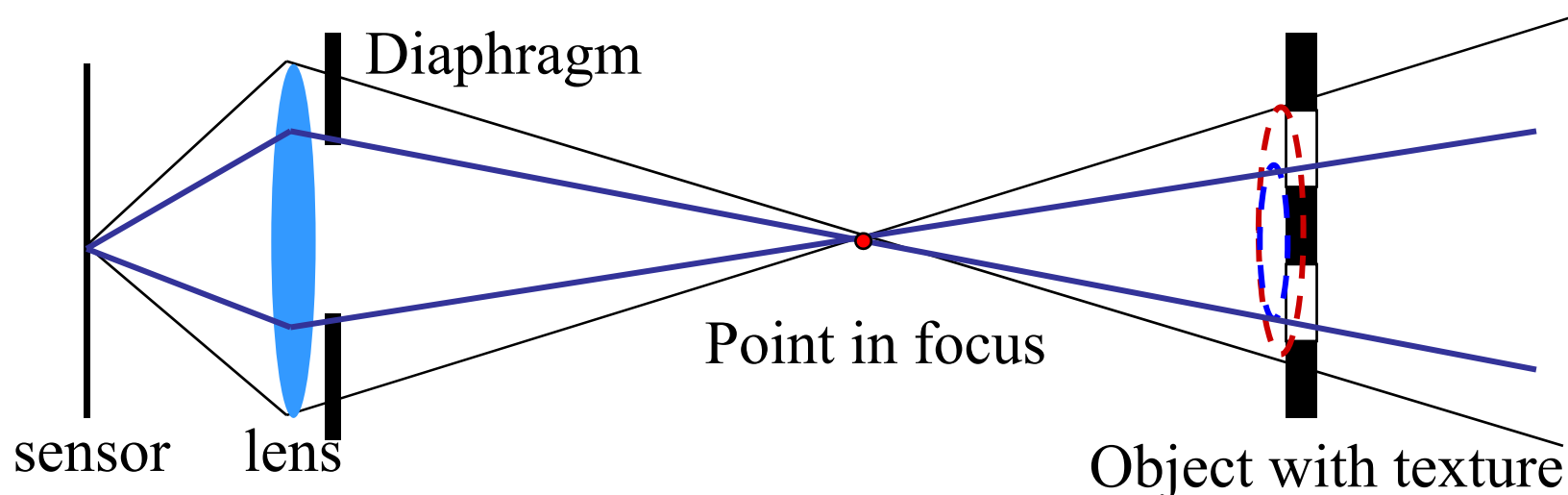
Depth of field

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



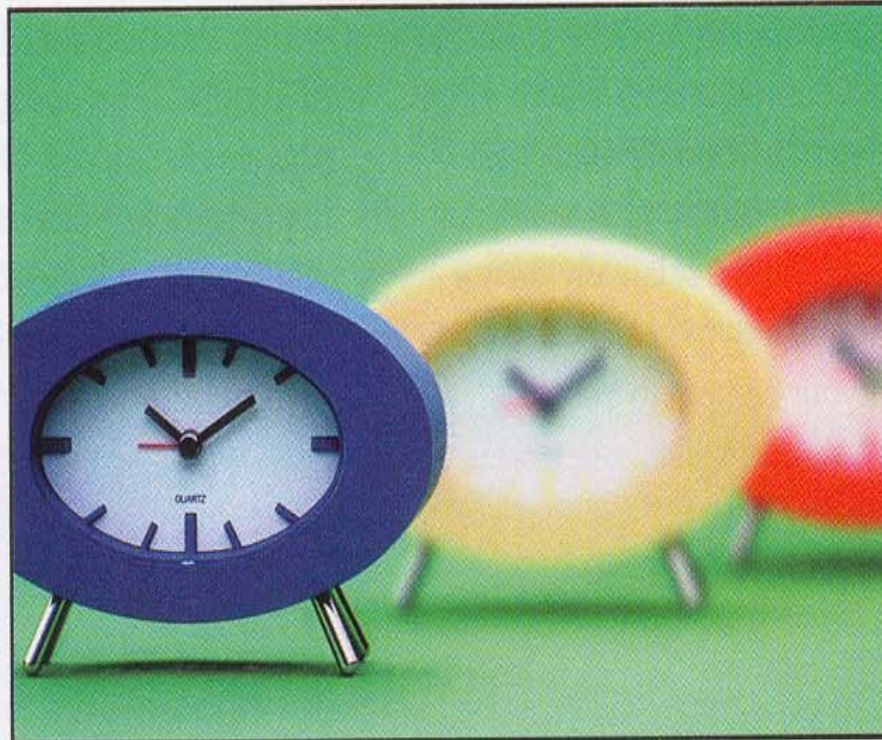
Depth of field

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



Depth of field

LESS DEPTH OF FIELD



Wider aperture



$f/2$

MORE DEPTH OF FIELD



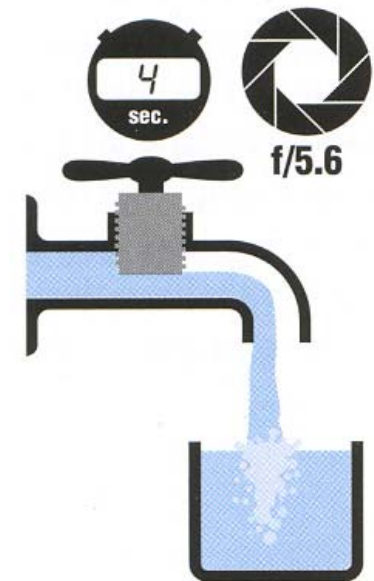
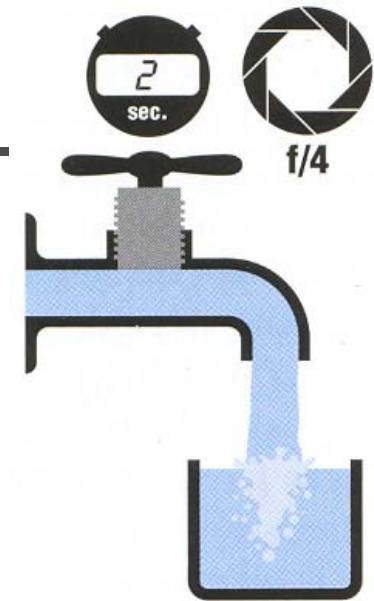
Smaller aperture



$f/16$

Exposure

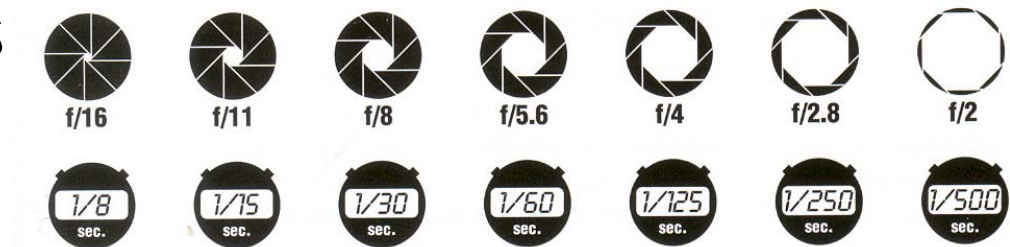
- Two main parameters:
 - Aperture (in f stop)
 - Shutter speed (in fraction of a second)
- Reciprocity
 - The same exposure is obtained with an exposure twice as long and an aperture *area* half as big
 - Hence square root of two progression of f stops vs. power of two progression of shutter speed
 - Reciprocity can fail for very long exposures



From Photography, London et al.

Reciprocity

- Assume we know how much light we need
- We have the choice of an infinity of shutter speed/aperture pairs



- What will guide our choice of a shutter speed?
 - Freeze motion vs. motion blur, camera shake
- What will guide our choice of an aperture?
 - Depth of field, diffraction limit
- Often we must compromise
 - Open more to enable faster speed (but shallow DoF)

Exposure & metering

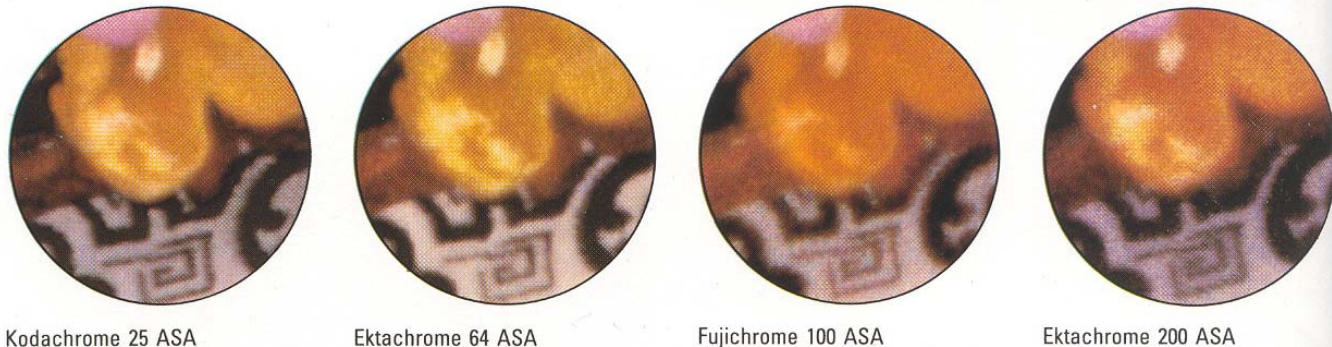
- The camera metering system measures how bright the scene is
- In Aperture priority mode, the photographer sets the aperture, the camera sets the shutter speed
- In Shutter-speed priority mode, photographers sets the shutter speed and the camera deduces the aperture
- In Program mode, the camera decides both exposure and shutter speed (middle value more or less)
- In Manual mode, the user decides everything (but can get feedback)

Pros and cons of various modes

- Aperture priority
 - Direct depth of field control
 - Cons: can require impossible shutter speed (e.g. with f/1.4 for a bright scene)
- Shutter speed priority
 - Direct motion blur control
 - Cons: can require impossible aperture (e.g. when requesting a 1/1000 speed for a dark scene)
 - Note that aperture is somewhat more restricted
- Program
 - Almost no control, but no need for neurons
- Manual
 - Full control, but takes more time and thinking

Sensitivity (ISO)

- Third variable for exposure
- Linear effect (200 ISO needs half the light as 100 ISO)
- Film photography: trade sensitivity for grain



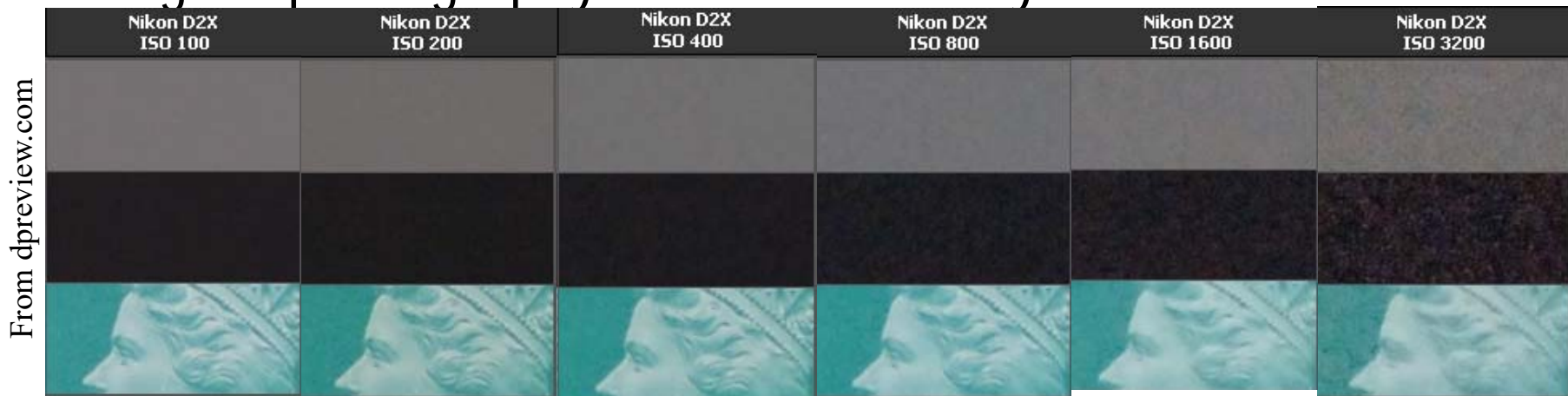
Kodachrome 25 ASA

Ektachrome 64 ASA

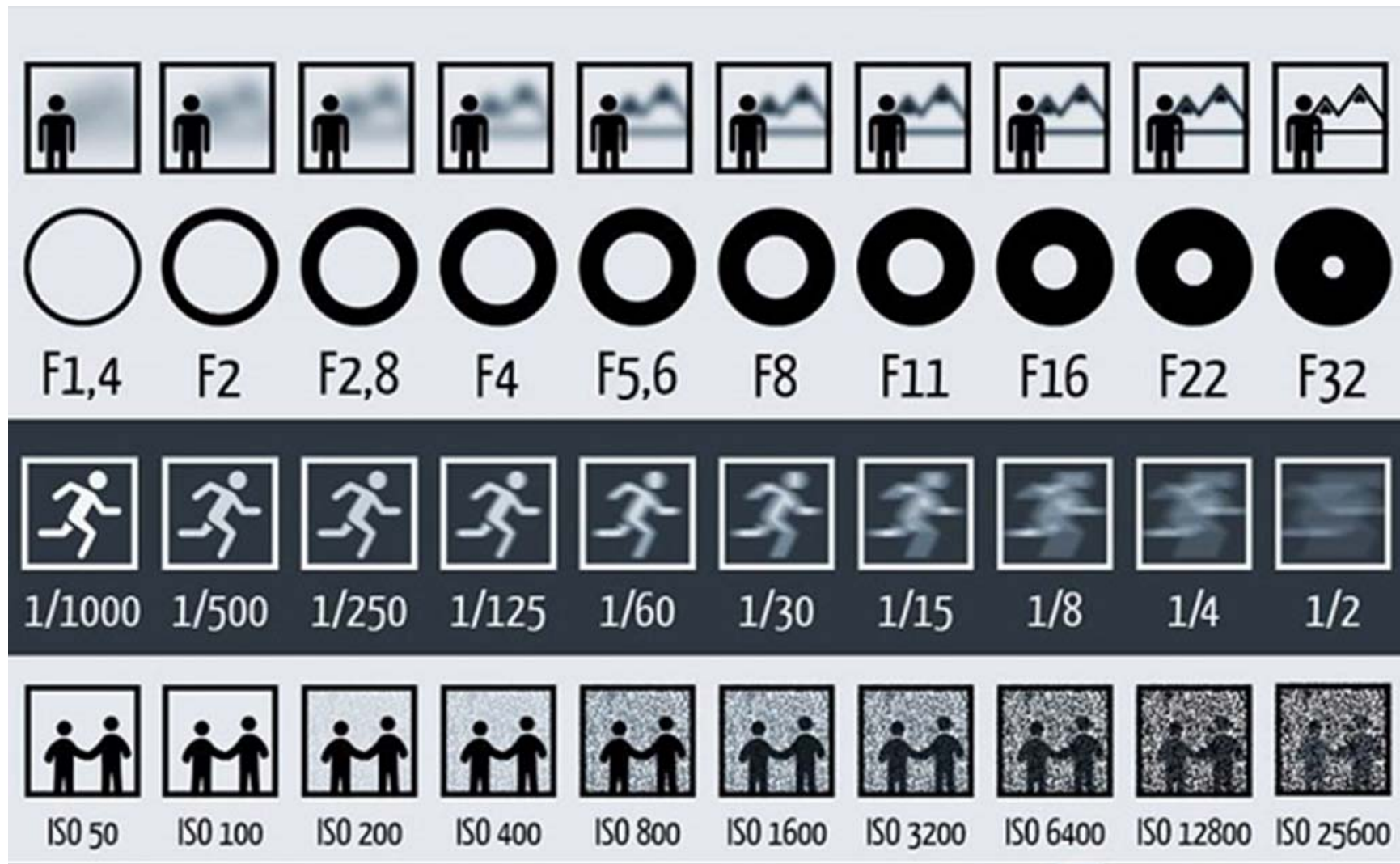
Fujichrome 100 ASA

Ektachrome 200 ASA

- Digital photography: trade sensitivity for noise



Summary in a picture

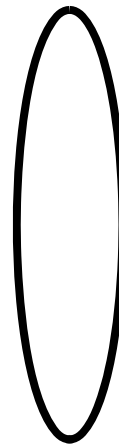


source hamburgerfotospots.de

Film camera



scene



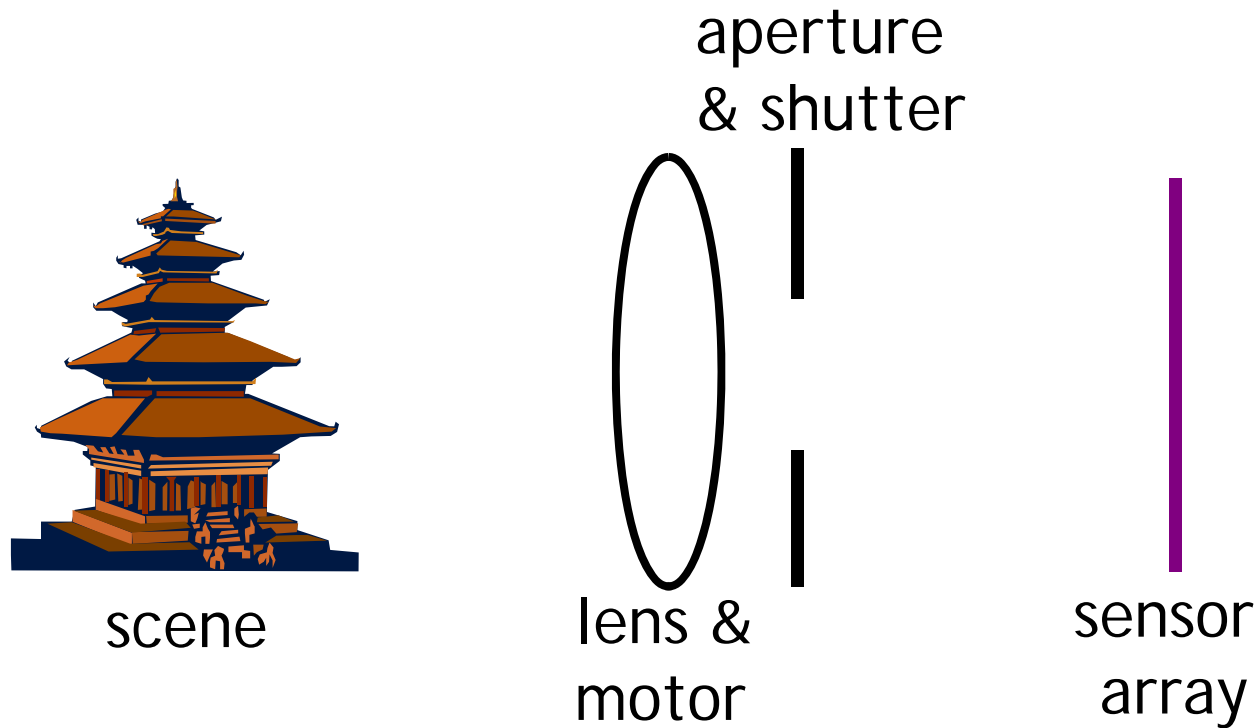
lens &
motor

aperture
& shutter



film

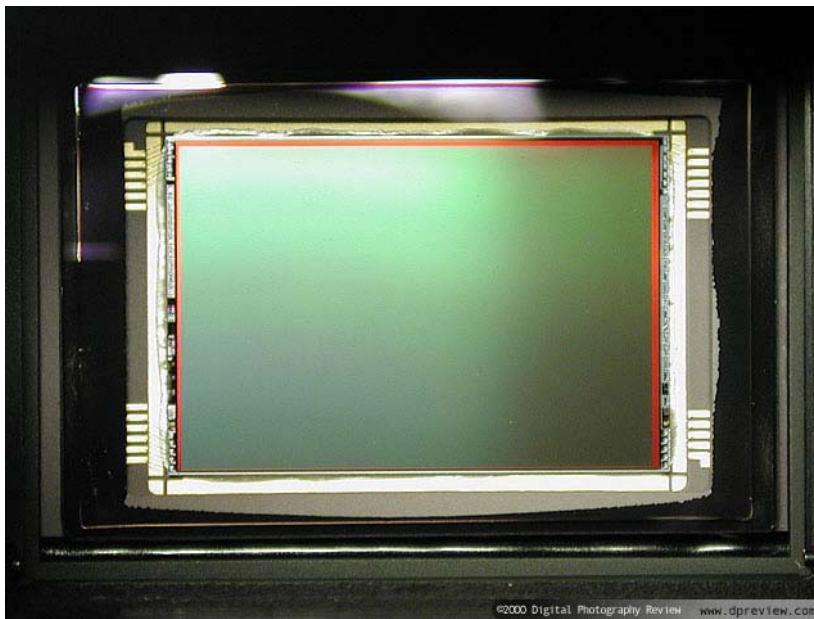
Digital camera



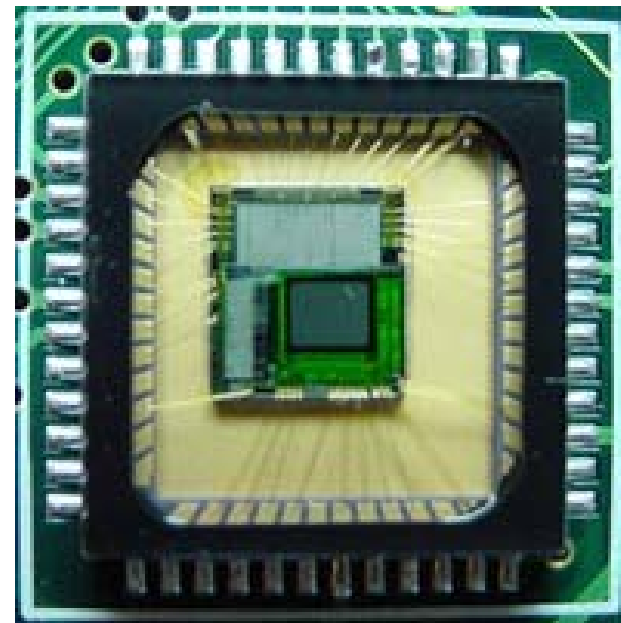
- A digital camera replaces film with a sensor array
- Each cell in the array is a light-sensitive diode that converts photons to electrons

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



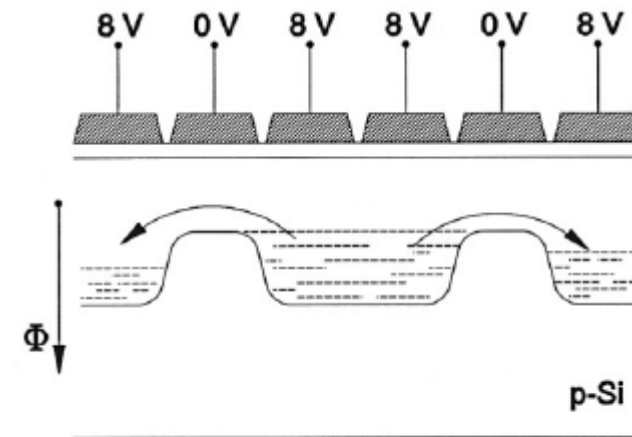
CCD



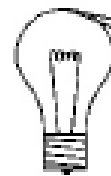
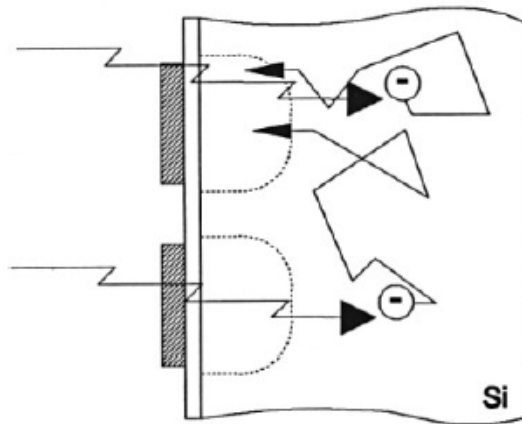
CMOS

Sensor noise

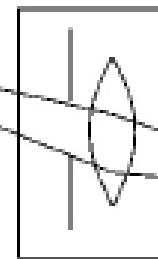
- Blooming
- Diffusion
- Dark current
- Photon shot noise
- Amplifier readout noise



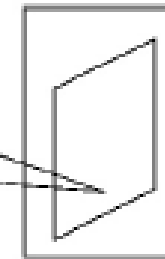
Blooming



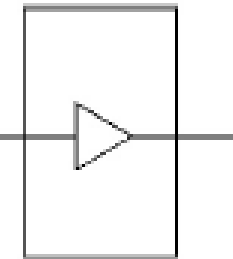
Real world



Optics



Recorder



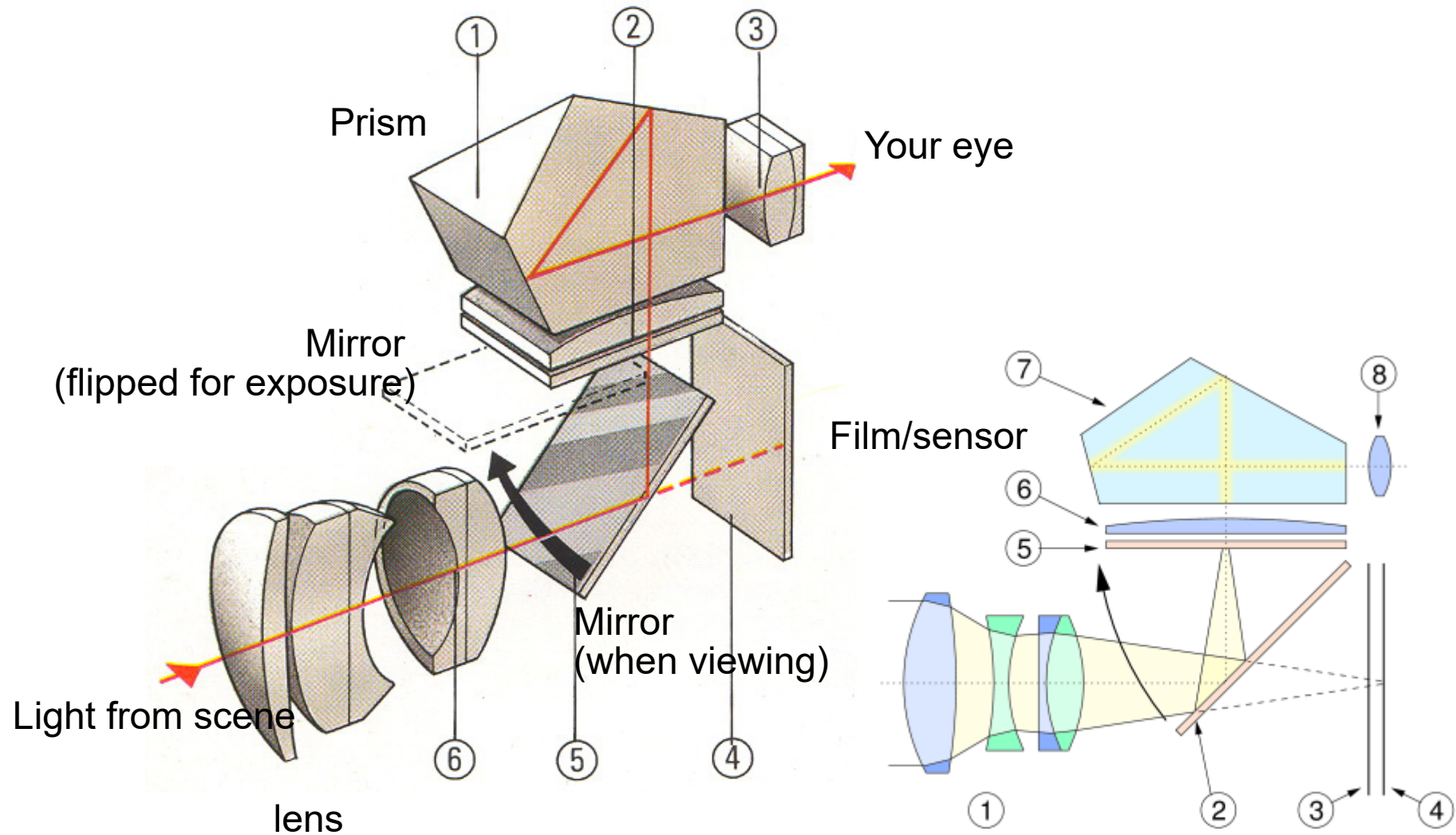
Digitizer

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

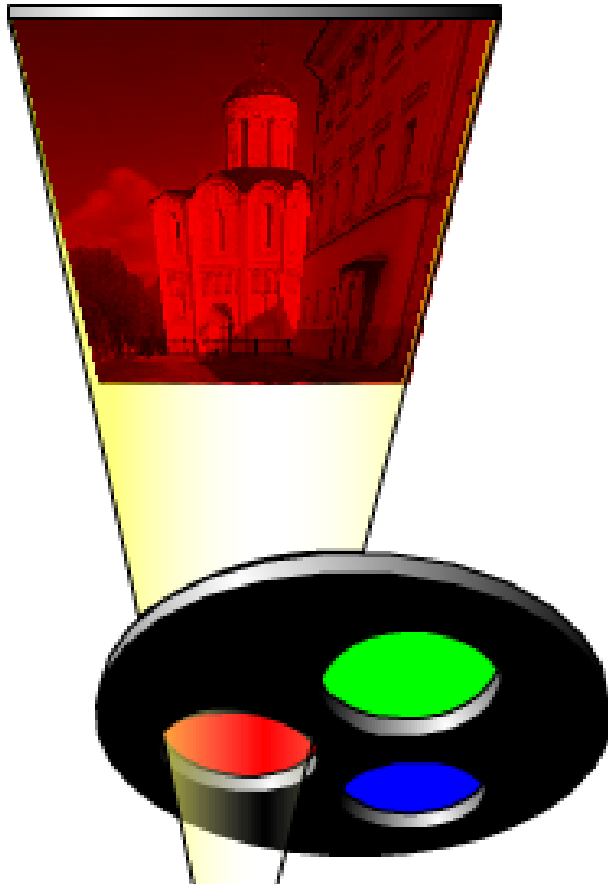


Color

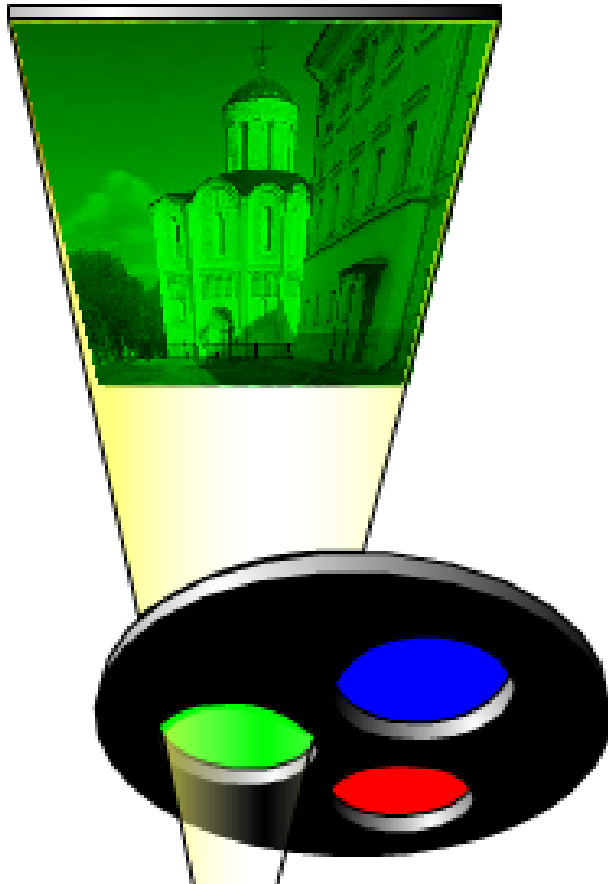
So far, we've only talked about monochrome sensors. Color imaging has been implemented in a number of ways:

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

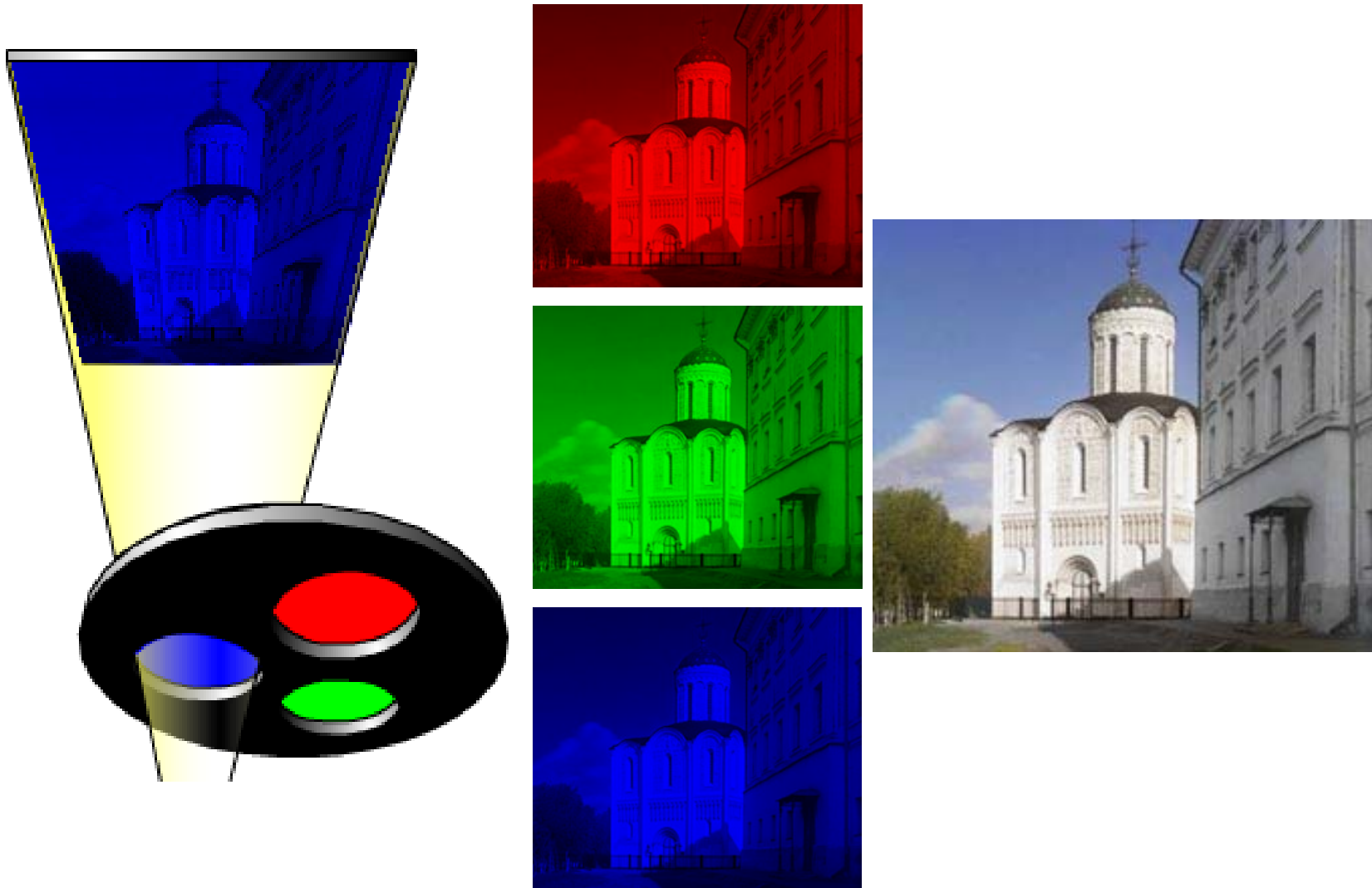
Field sequential



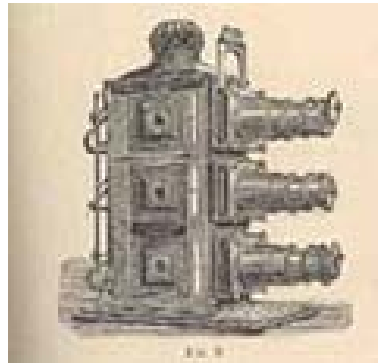
Field sequential



Field sequential



Prokudin-Gorskii (early 1900's)



Lantern
projector

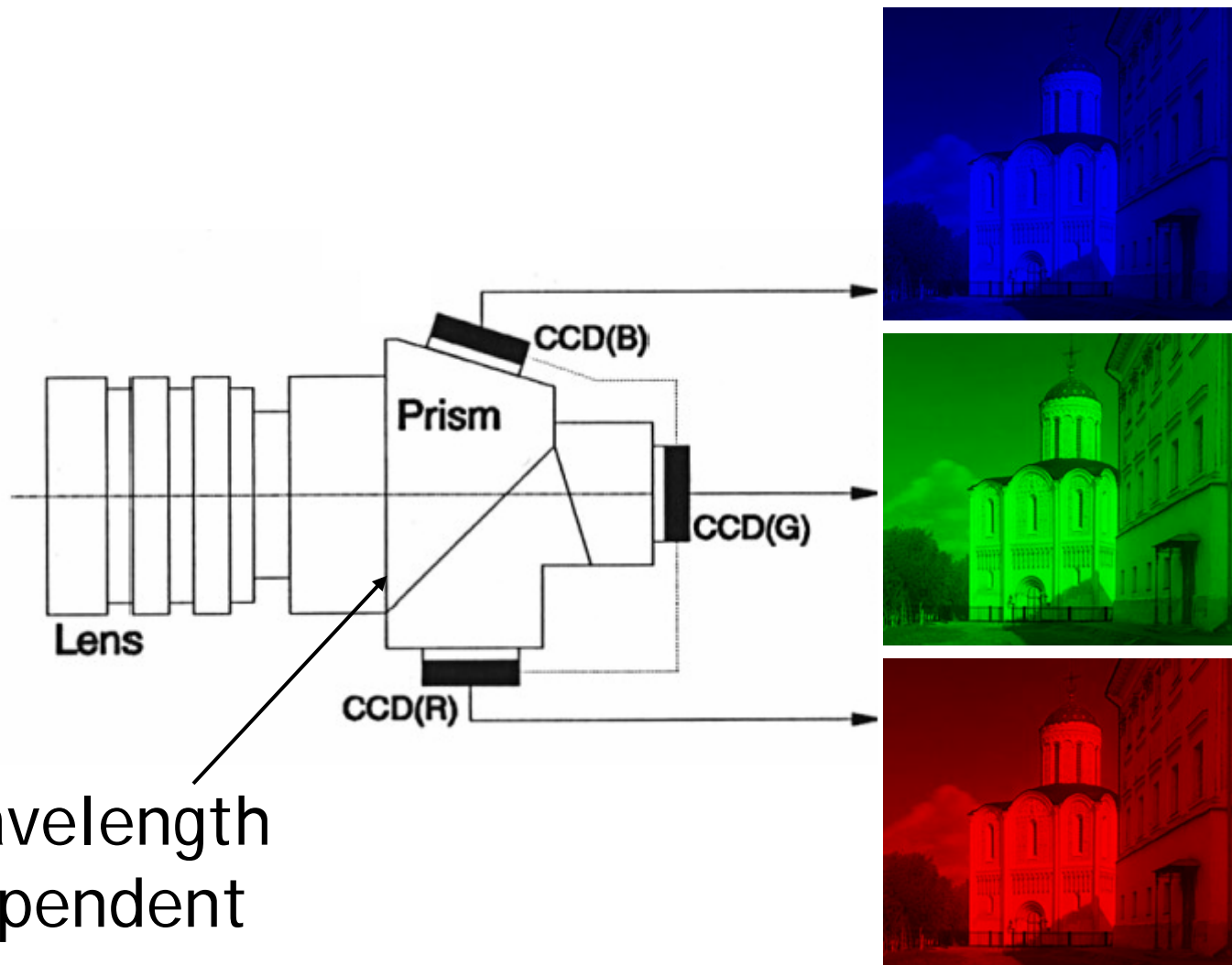


<http://www.loc.gov/exhibits/empire/>

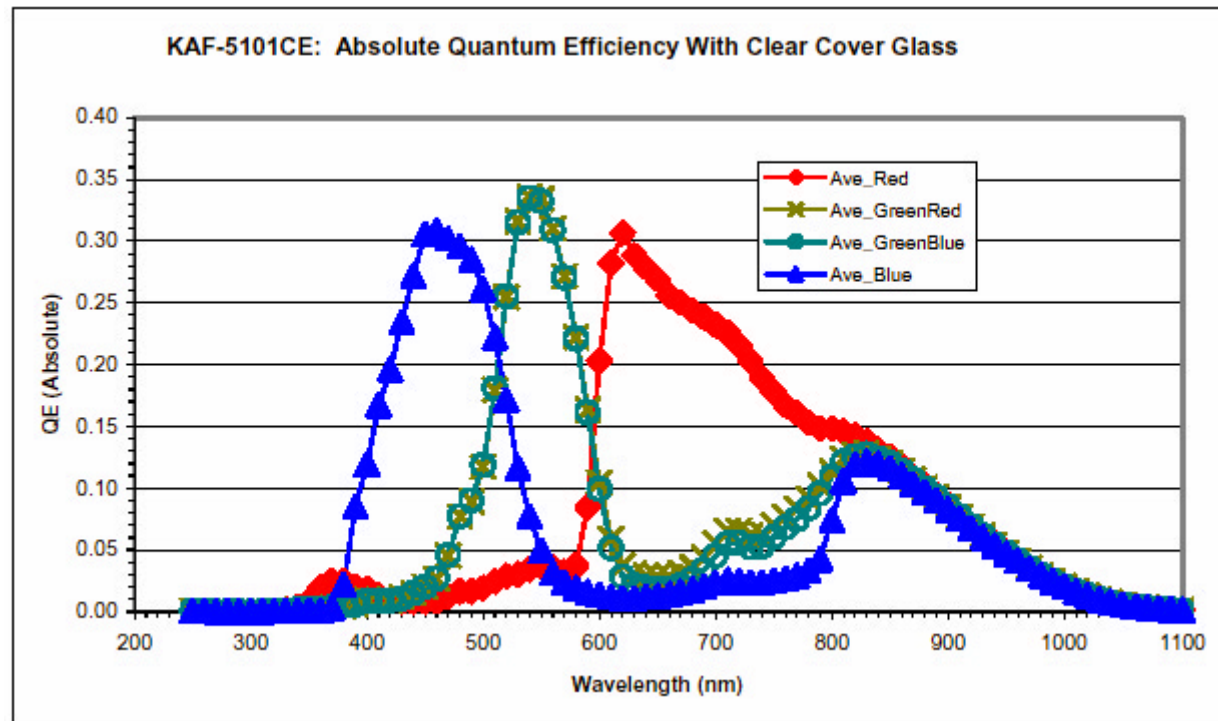
Prokudin-Gorskii (early 1900's)



Multi-chip



Embedded color filters



Color filters can be manufactured directly onto the photodetectors.

Color filter array

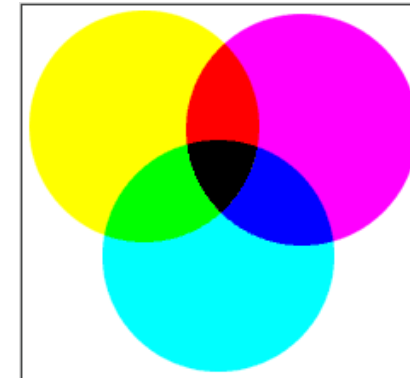
Kodak DCS620x

| | | |
|---|---|---|
| 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

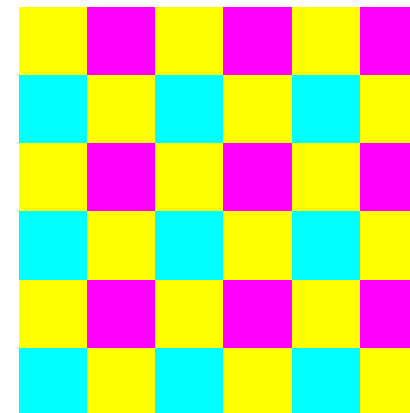


| | | | |
|----|---|----|---|
| Cy | W | Ye | G |
| Ye | G | Cy | W |
| Cy | W | Ye | G |
| Ye | G | Cy | W |

| | | | |
|----|----|----|----|
| 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 |

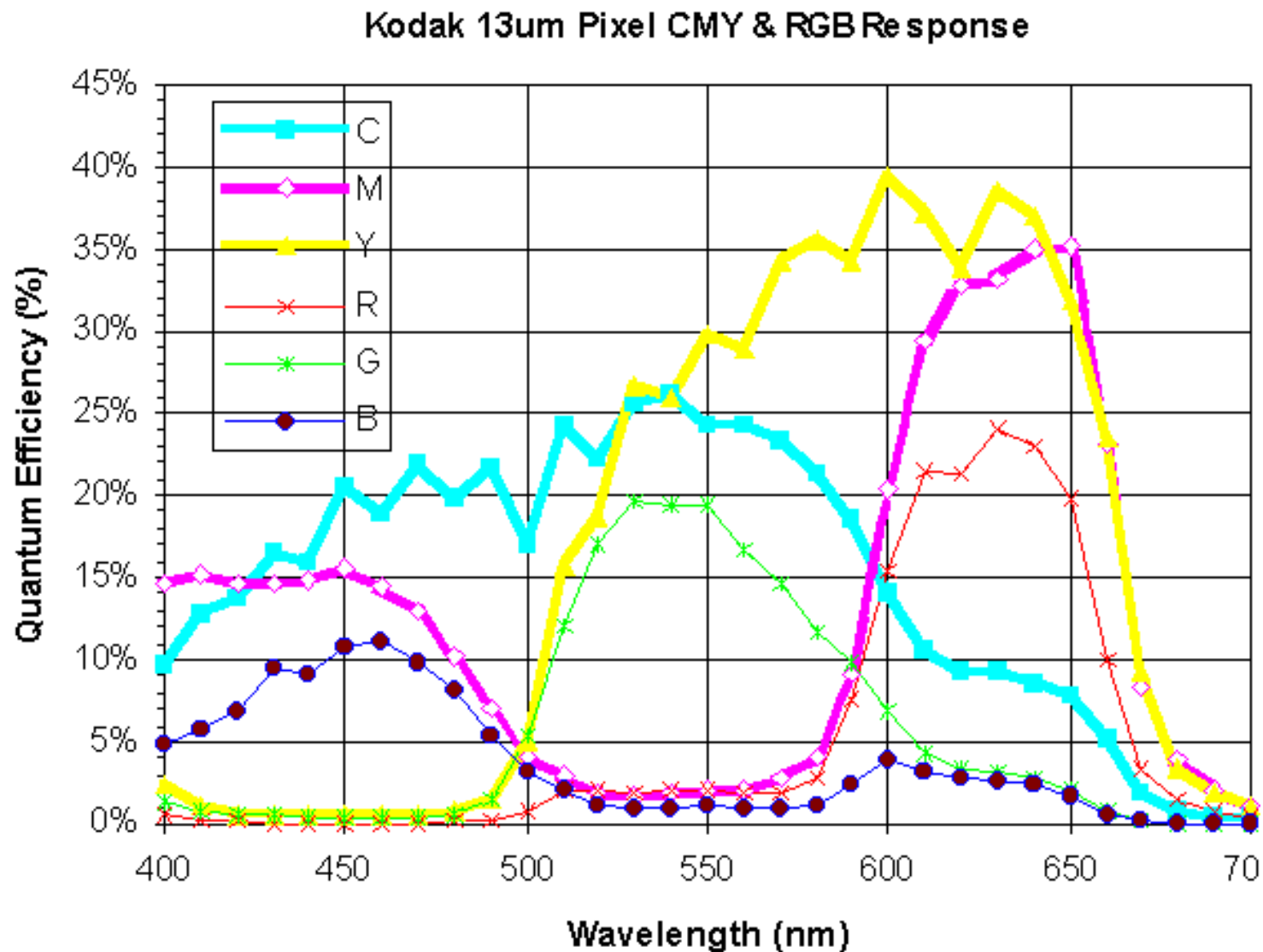
Mosaics



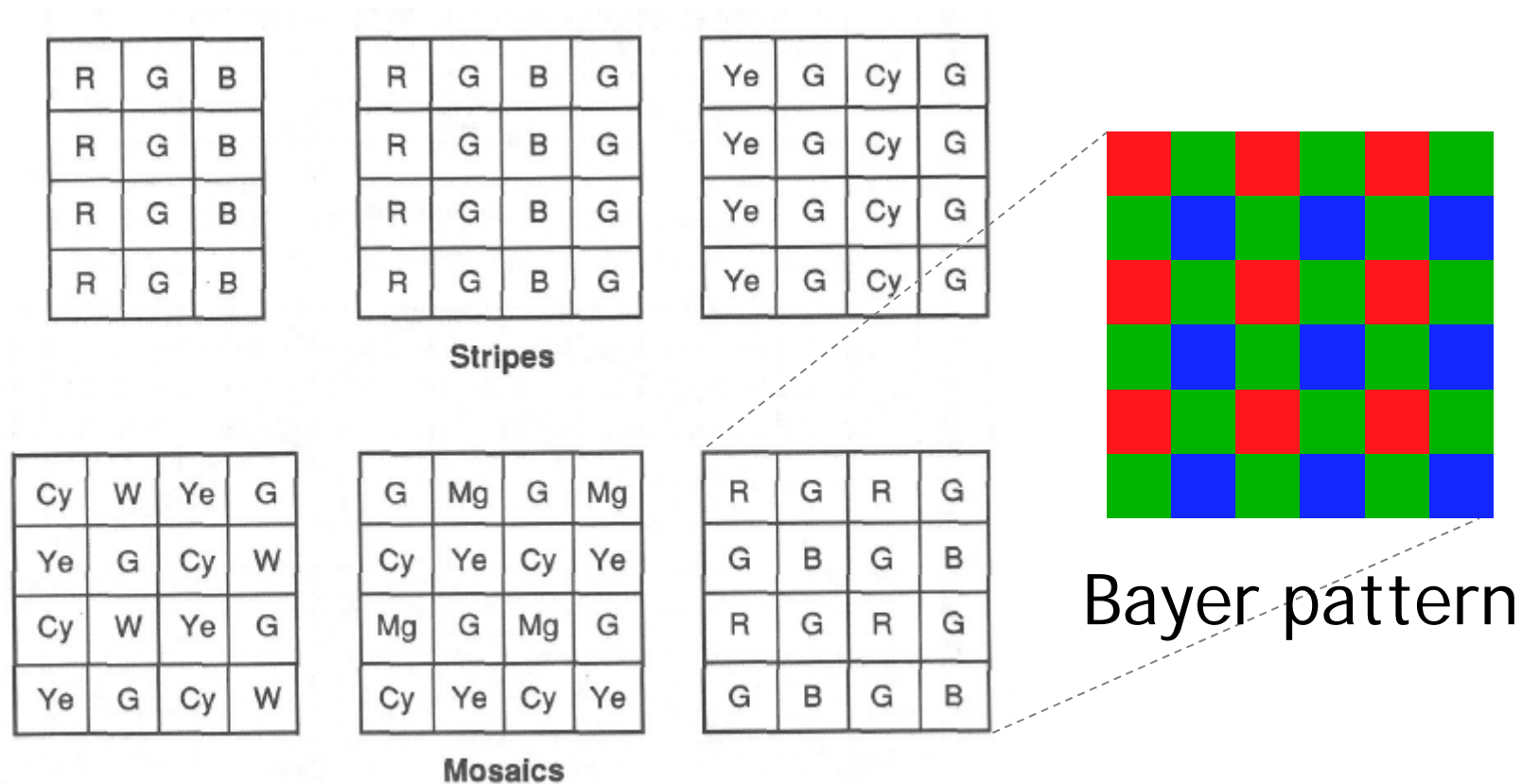
CMY

Color filter arrays (CFAs)/color filter mosaics

Why CMY CFA might be better

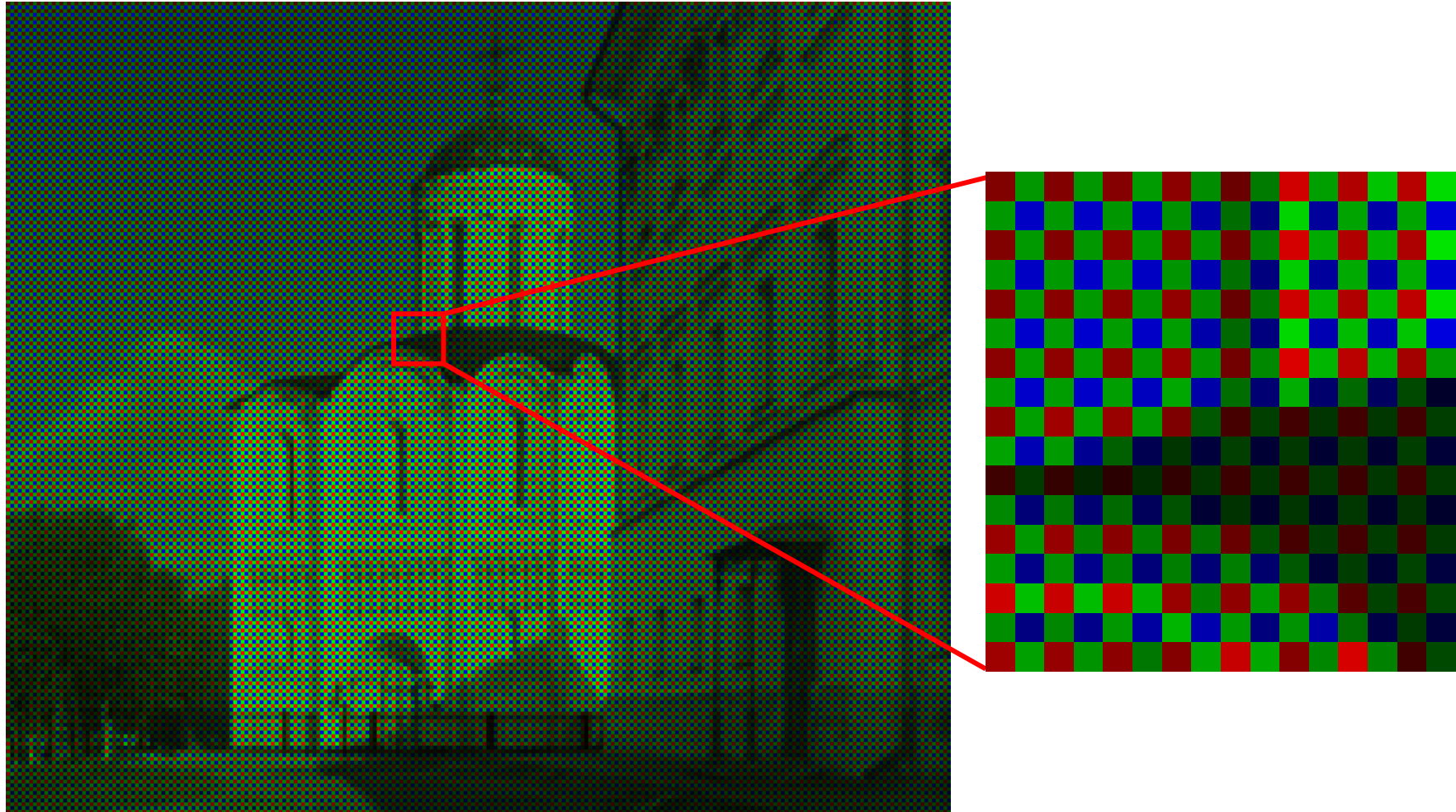


Color filter array



Color filter arrays (CFAs)/color filter mosaics

Bayer's pattern



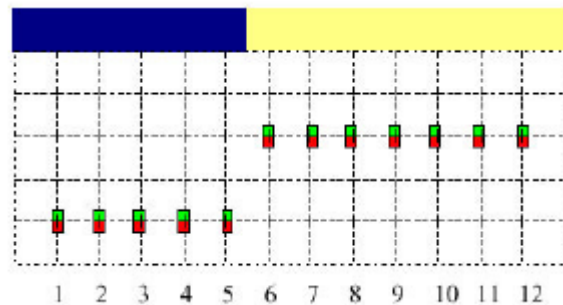
Demosaicking CFA's

| | | | | | | |
|----------|----------|----------|----------|----------|----------|----------|
| 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} |

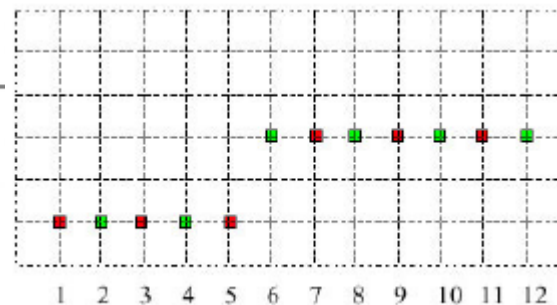
bilinear interpolation

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

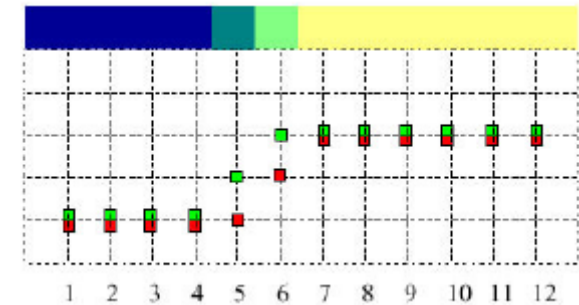
$$R_{44} = (R_{33} + R_{35} + R_{53} + R_{55}) / 4$$



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

$$R_{44} = G_{44} \frac{\frac{R_{33}}{G_{33}} + \frac{R_{35}}{G_{35}} + \frac{R_{53}}{G_{53}} + \frac{R_{55}}{G_{55}}}{4}$$

$$B_{33} = G_{33} \frac{\frac{B_{22}}{G_{22}} + \frac{B_{24}}{G_{24}} + \frac{B_{42}}{G_{42}} + \frac{B_{44}}{G_{44}}}{4}$$

Demosaicking CFA's

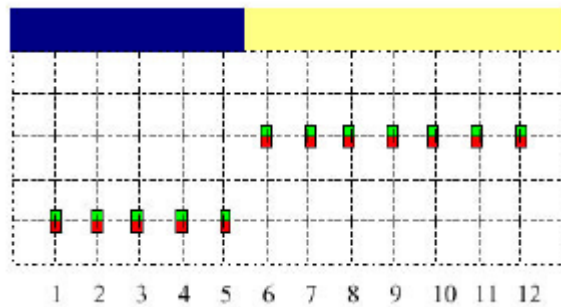
| | | | | | | |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| R ₁₁ | G ₁₂ | R ₁₃ | G ₁₄ | R ₁₅ | G ₁₆ | R ₁₇ |
| G ₂₁ | B ₂₂ | G ₂₃ | B ₂₄ | G ₂₅ | B ₂₆ | G ₂₇ |
| R ₃₁ | G ₃₂ | R ₃₃ | G ₃₄ | R ₃₅ | G ₃₆ | R ₃₇ |
| G 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)

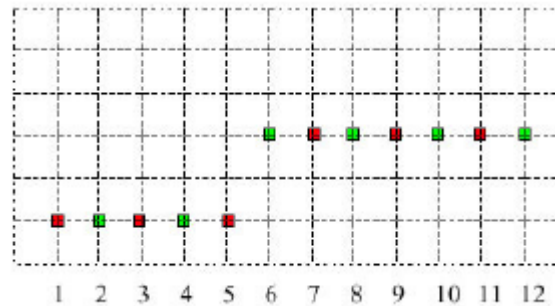
1. Linear interpolation
2. Median filter on color differences

Demosaicking CFA's

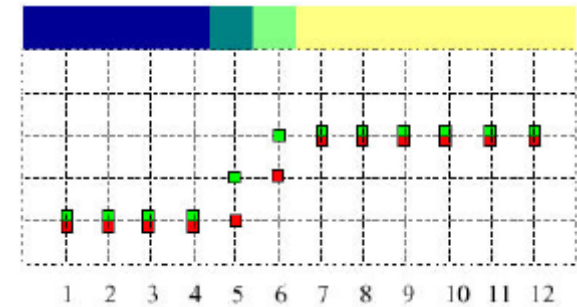
Median-based interpolation (Freeman)



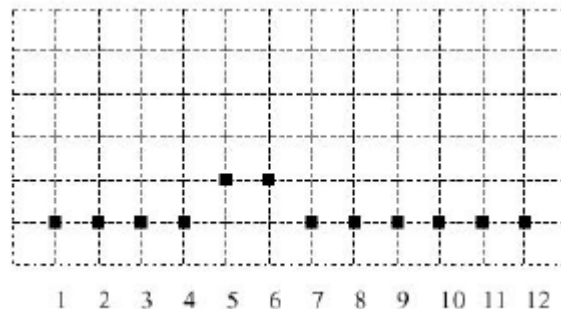
original



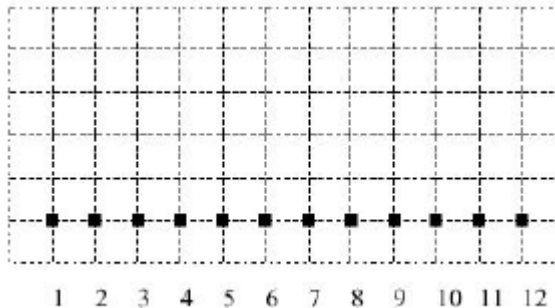
input



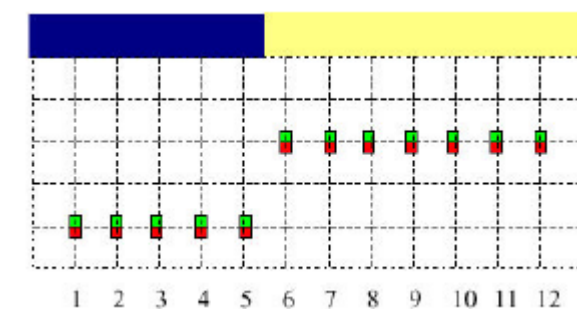
linear interpolation



color difference
(e.g. G-R)



median filter
(kernel size 5)



Reconstruction
($G=R+\text{filtered difference}$)

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

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

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

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

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)

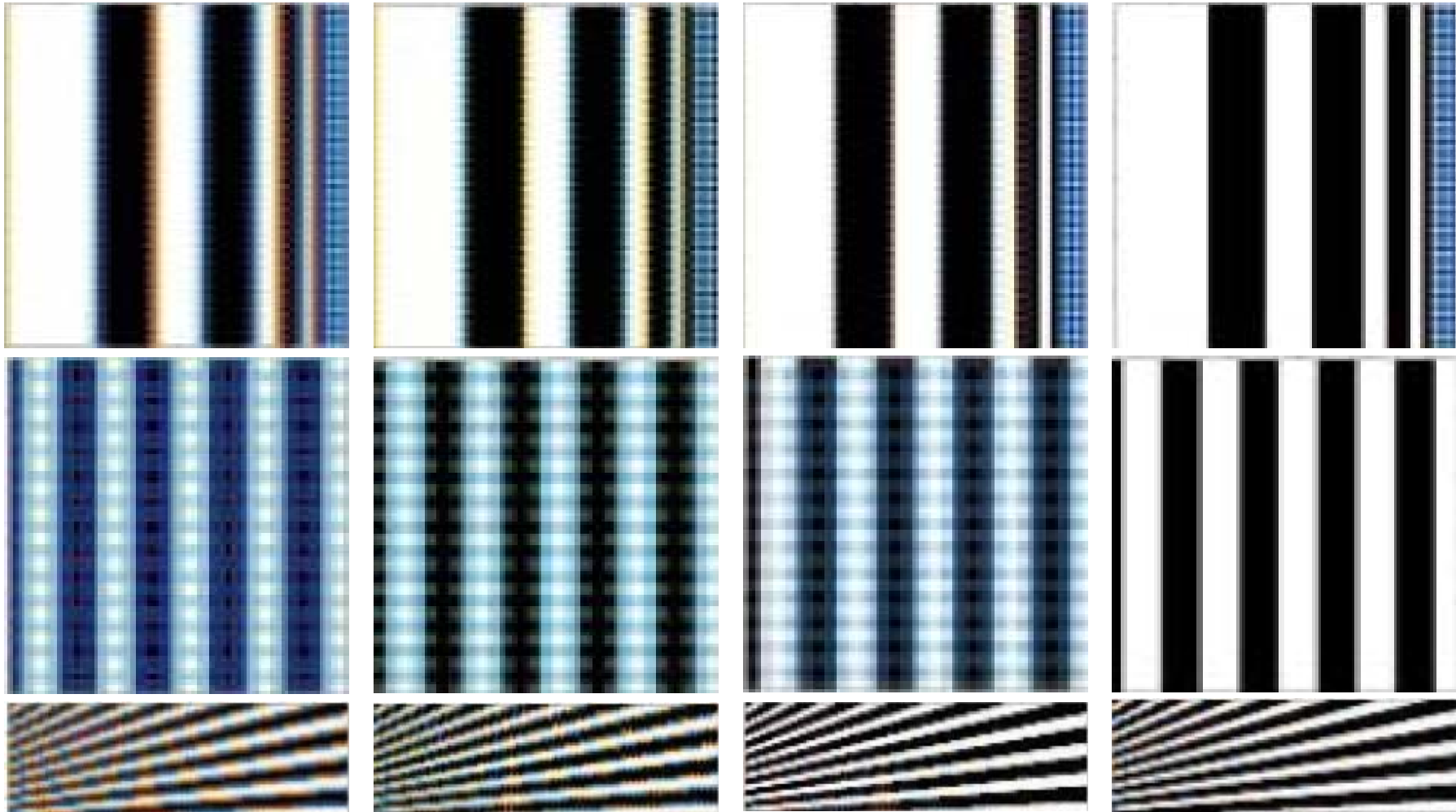
2. Interpolation of color differences

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

$$R_{43} = \frac{(R_{33} - G_{33}) + (R_{53} - G_{53})}{2} + G_{43},$$

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

Demosaicking CFA's



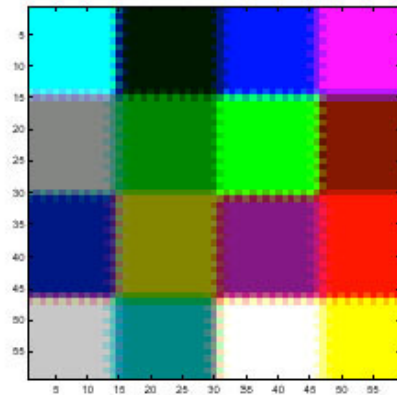
bilinear

Cok

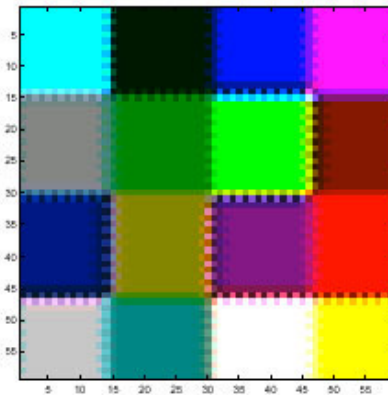
Freeman

LaRoche

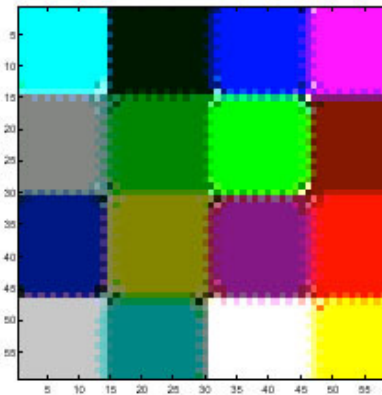
Demosaicking CFA's



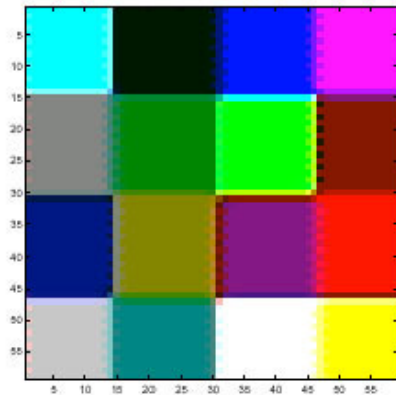
Bilinear



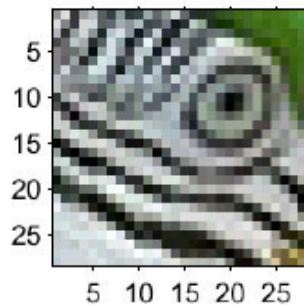
Cok



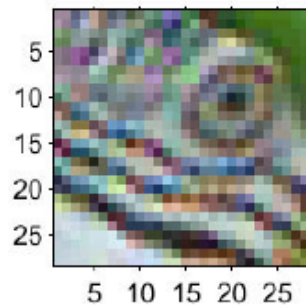
Freeman



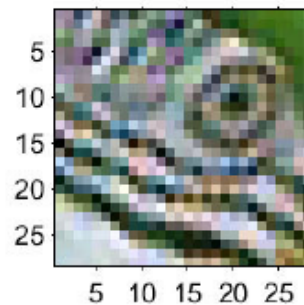
LaRoche



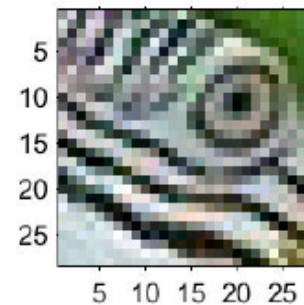
Input



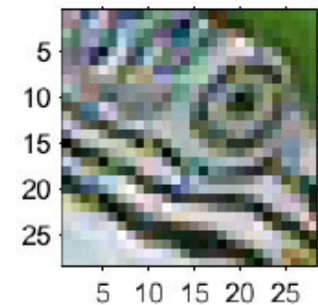
Bilinear



Cok



Freeman

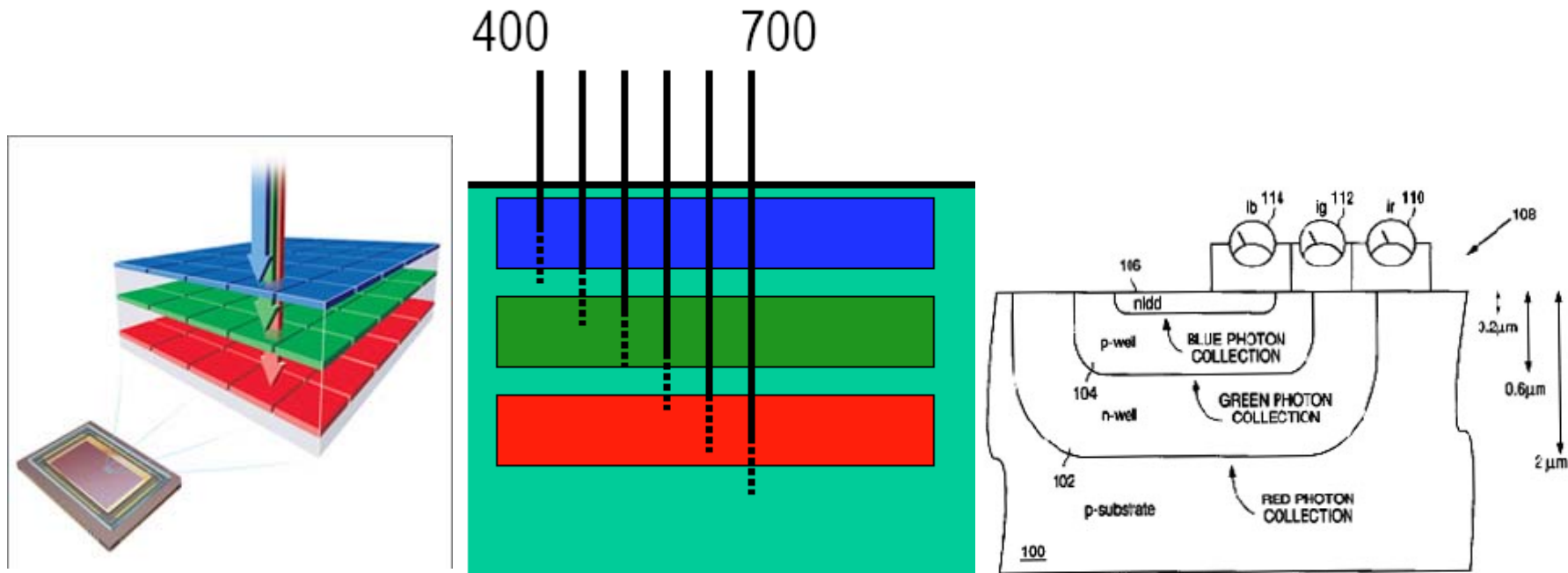


LaRoche

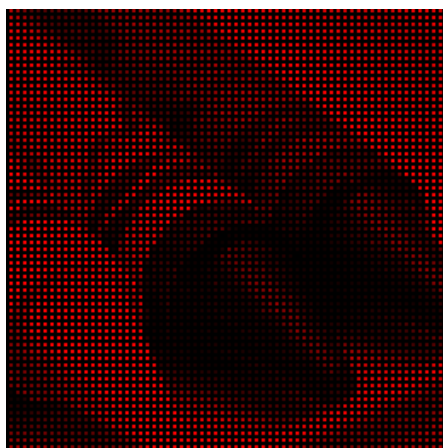
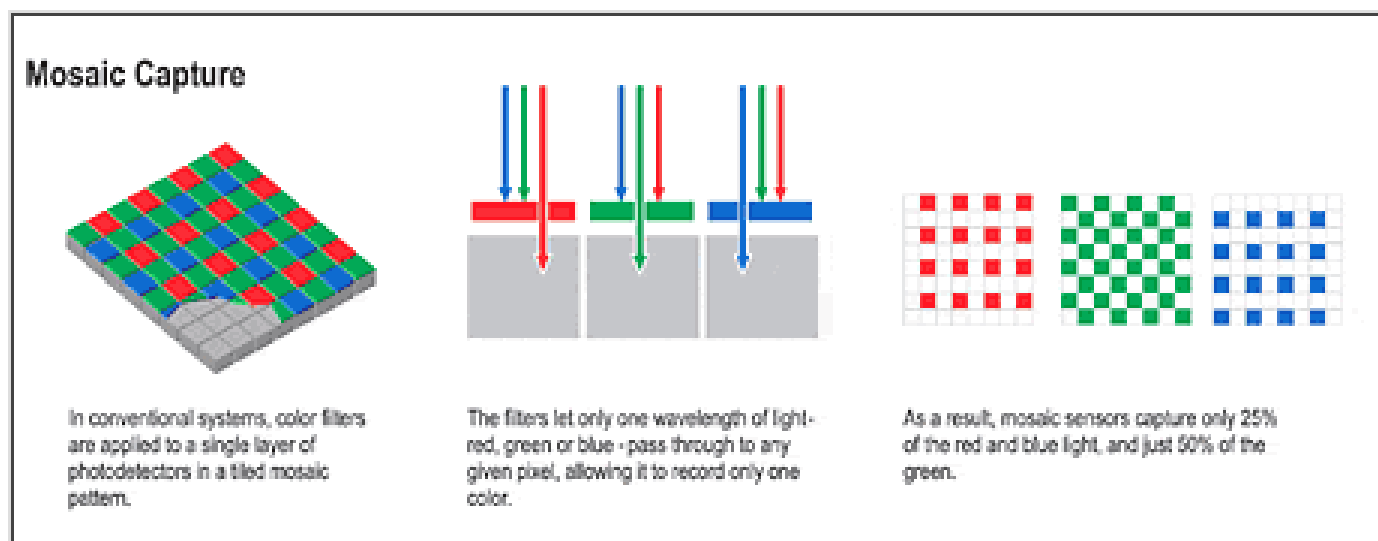
Generally, Freeman's is the best, especially for natural images.

Foveon X3 sensor

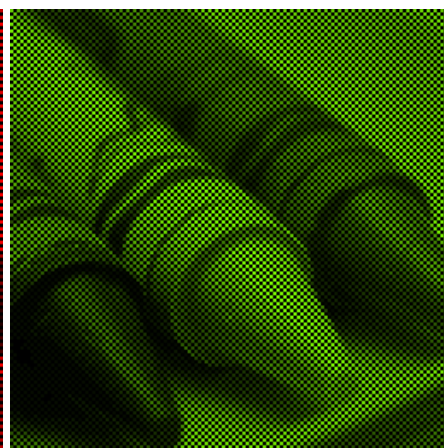
- light penetrates to different depths for different wavelengths
- multilayer CMOS sensor gets 3 different spectral sensitivities



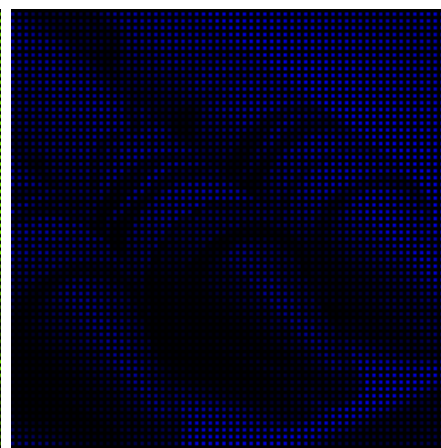
Color filter array



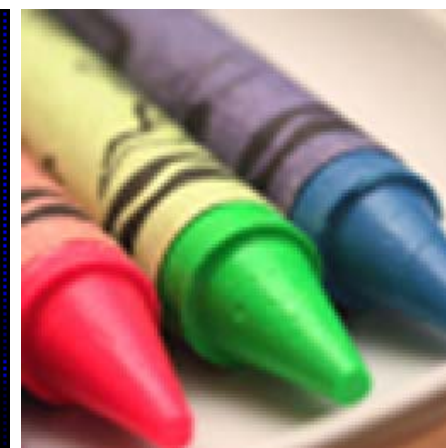
red



green

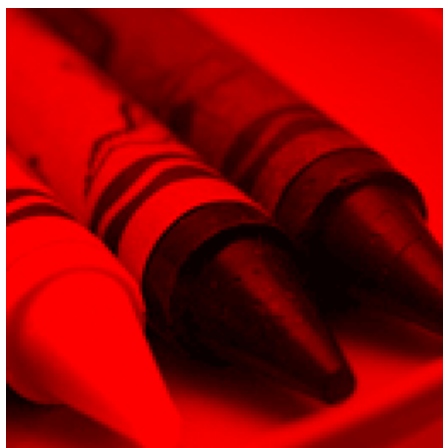
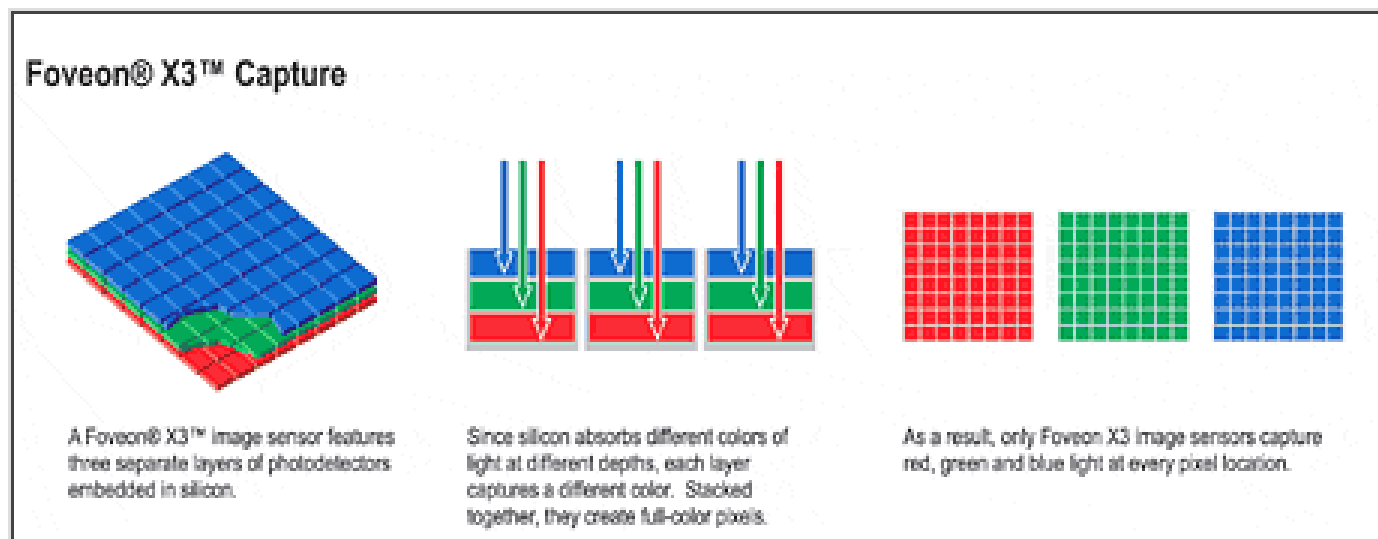


blue

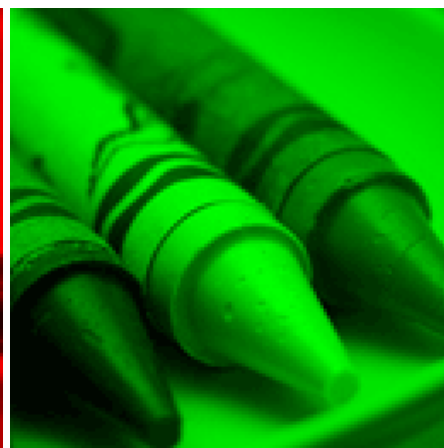


output

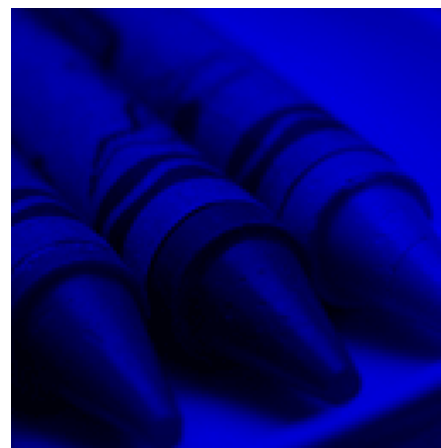
X3 technology



red



green

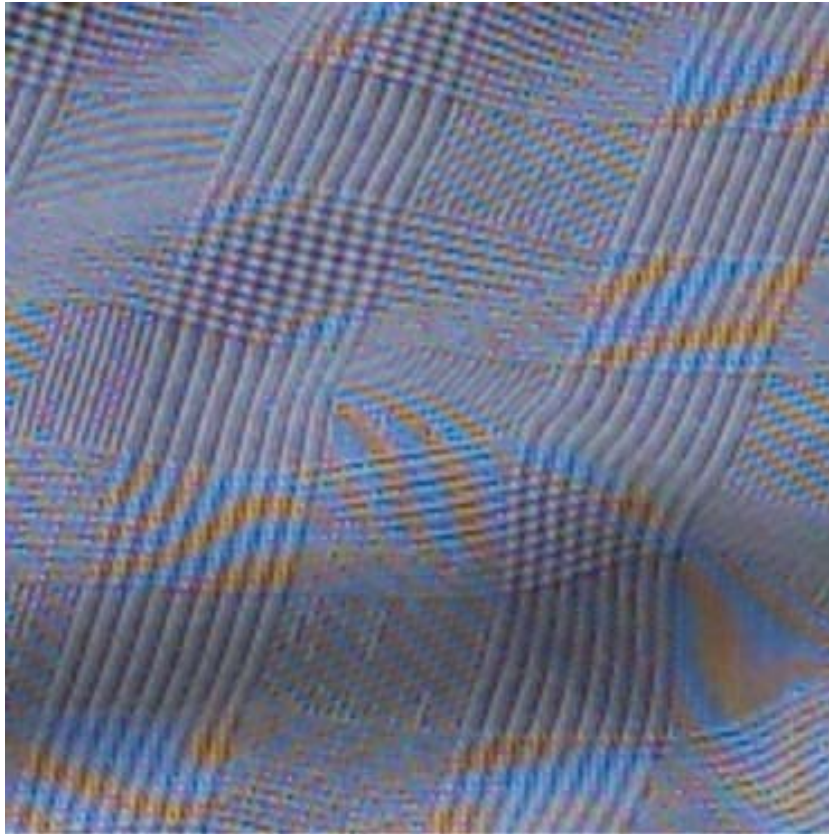


blue

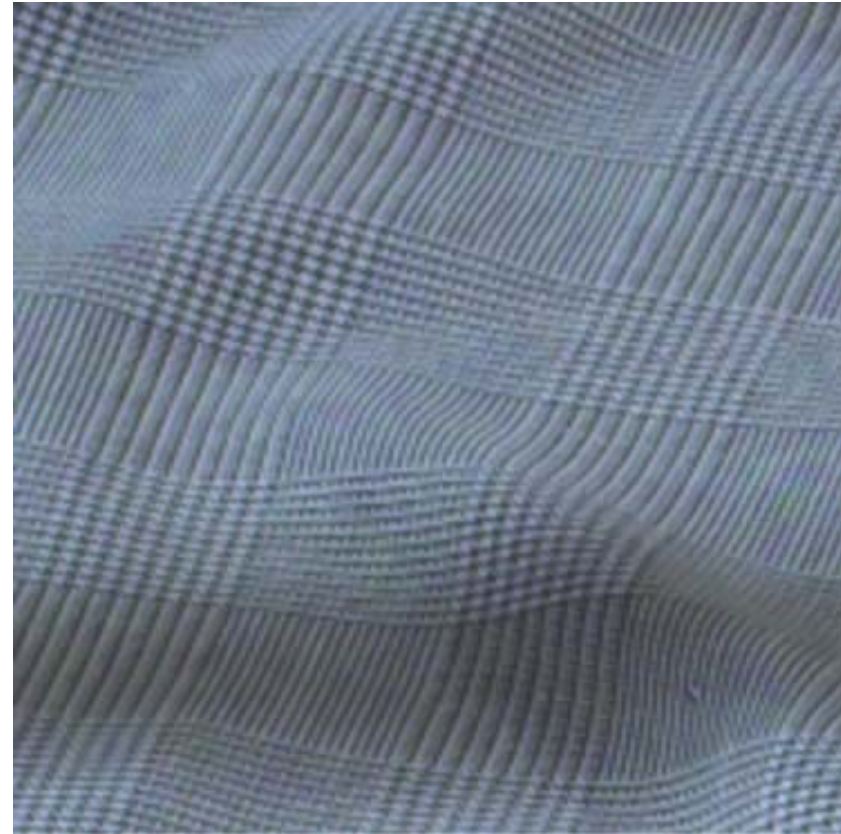


output

Foveon X3 sensor



Bayer CFA



X3 sensor

Cameras with X3



Sigma SD10, SD9



Polaroid X530

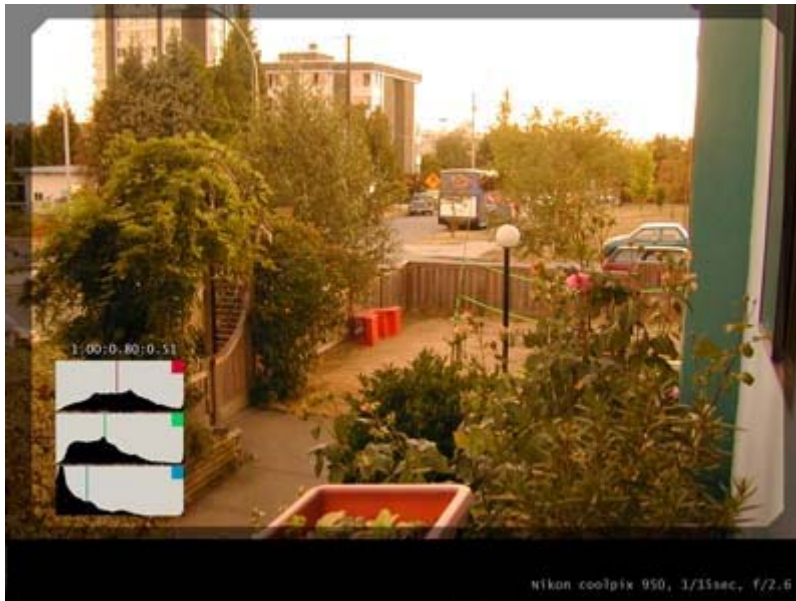
Sigma SD9 vs Canon D30



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

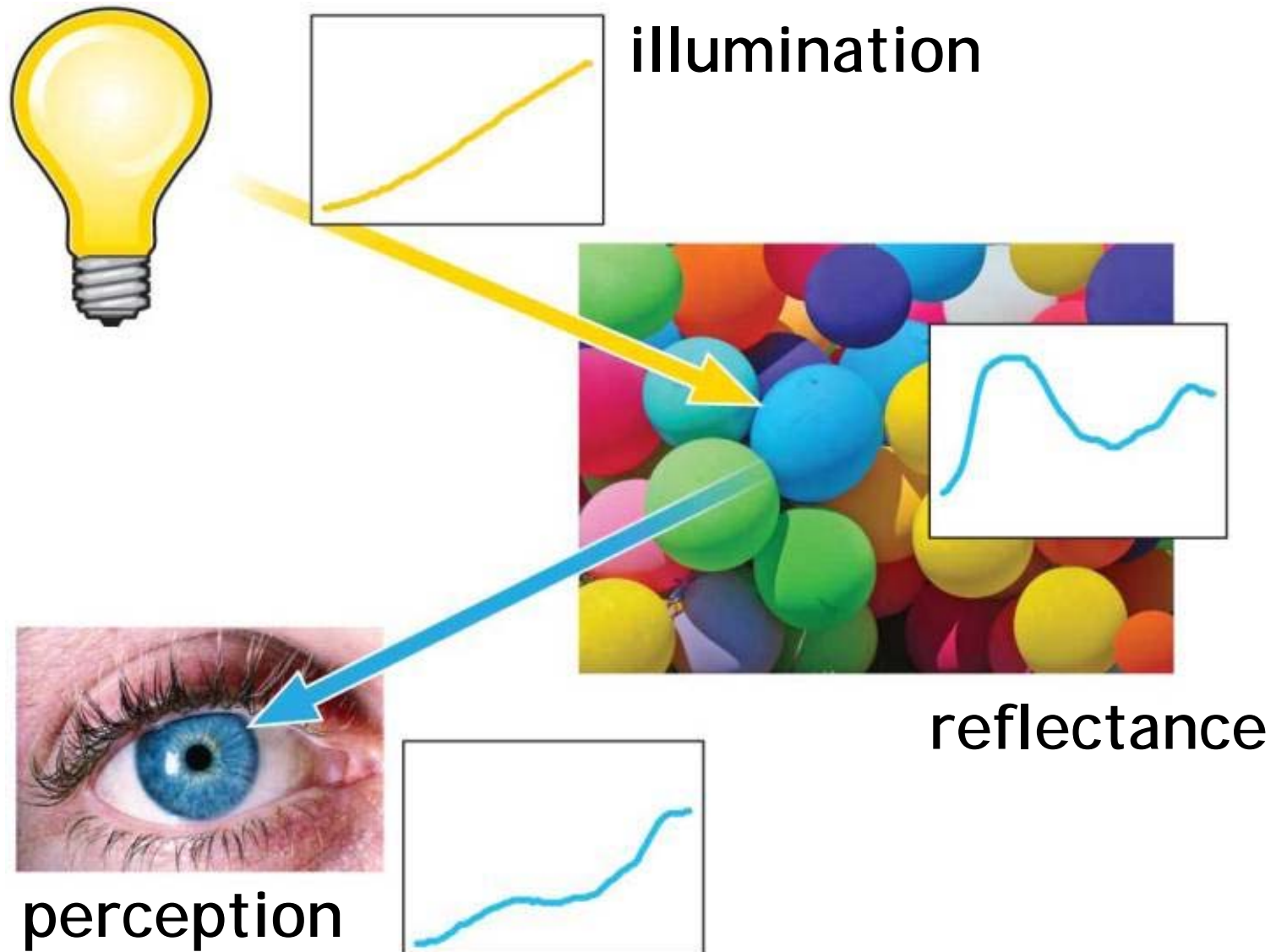


warmer +3



automatic white balance

White Balance

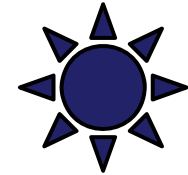
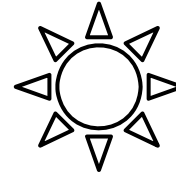


Color constancy



What color is the dress?

Color constancy



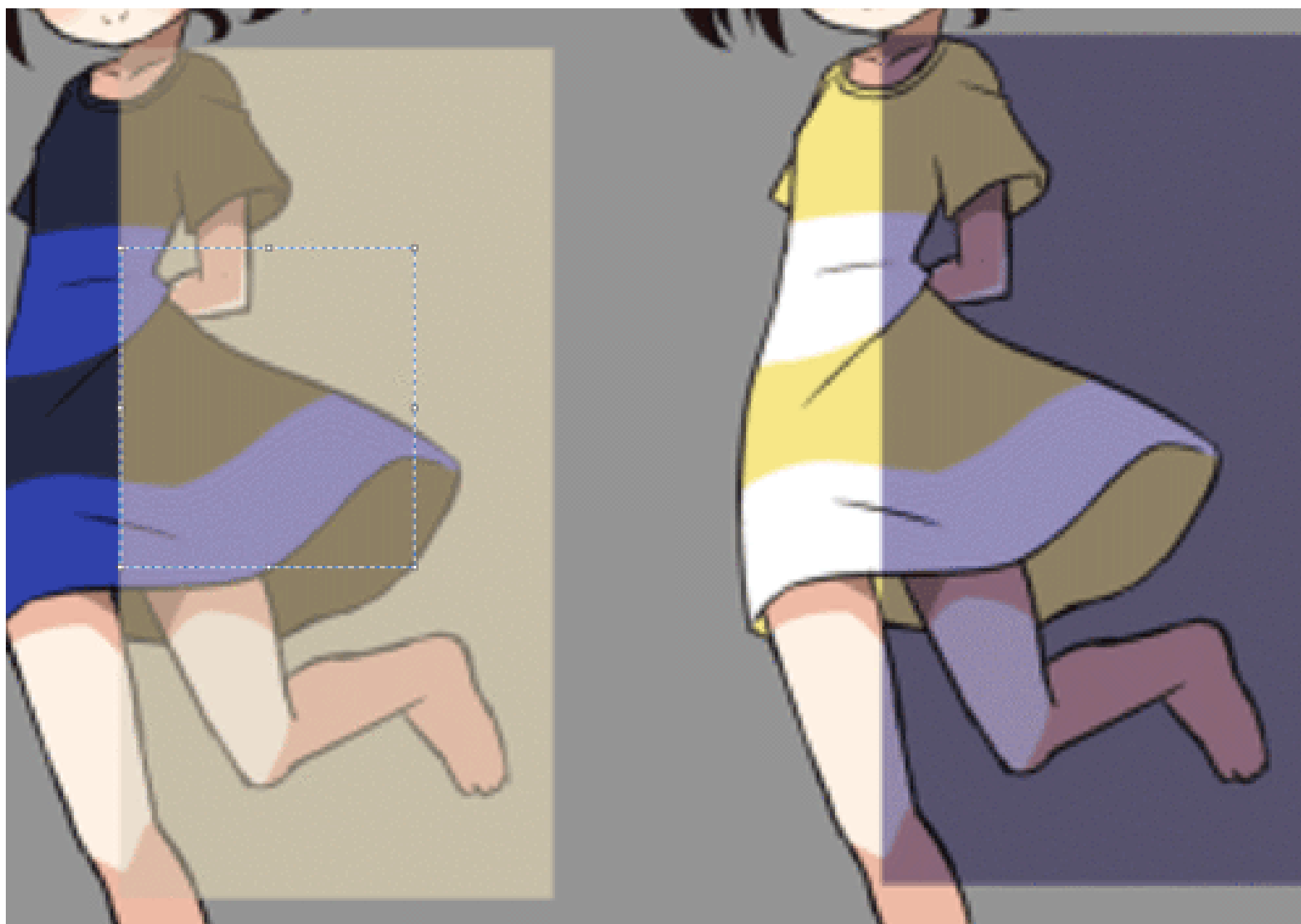
Human vision is complex



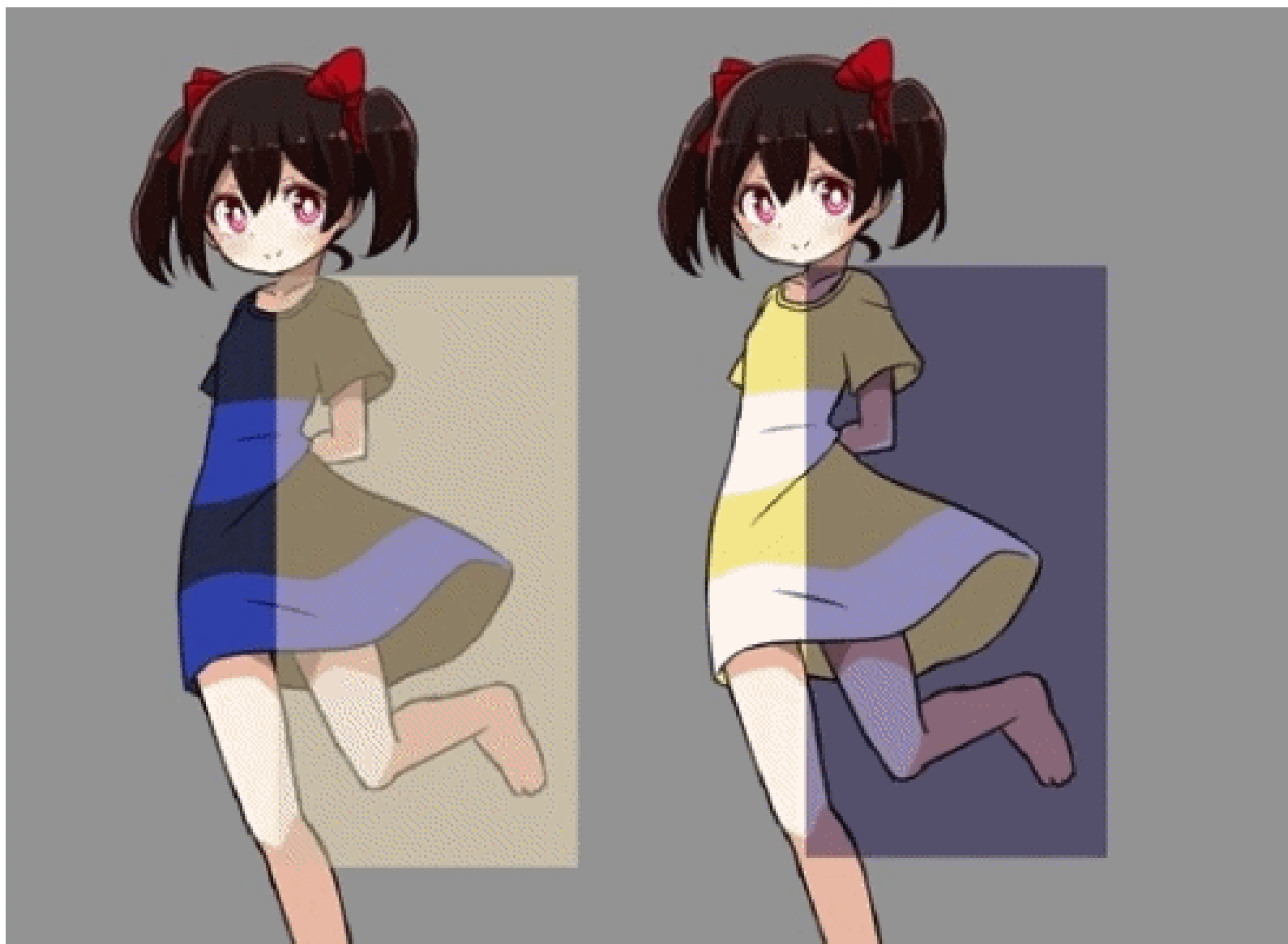
Color perception depends on surrounding



Color perception depends on surrounding

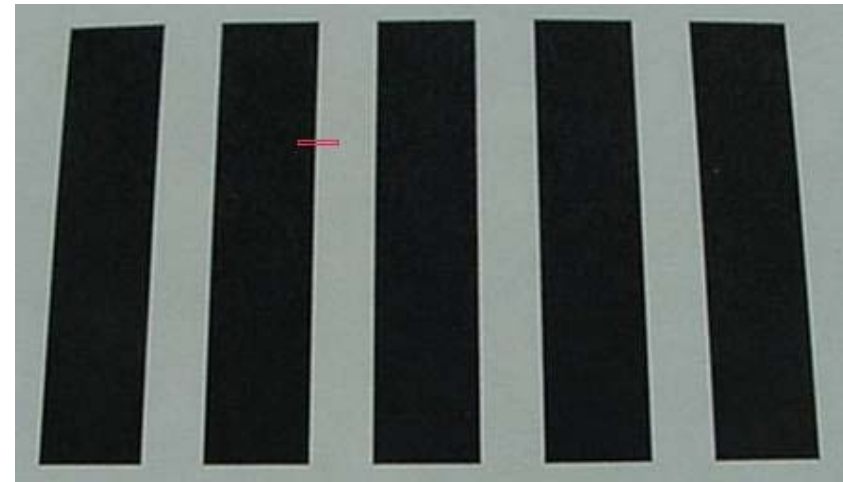
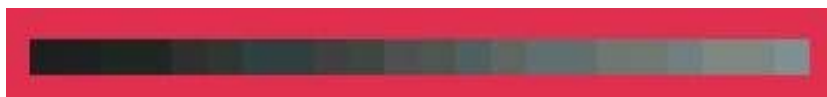
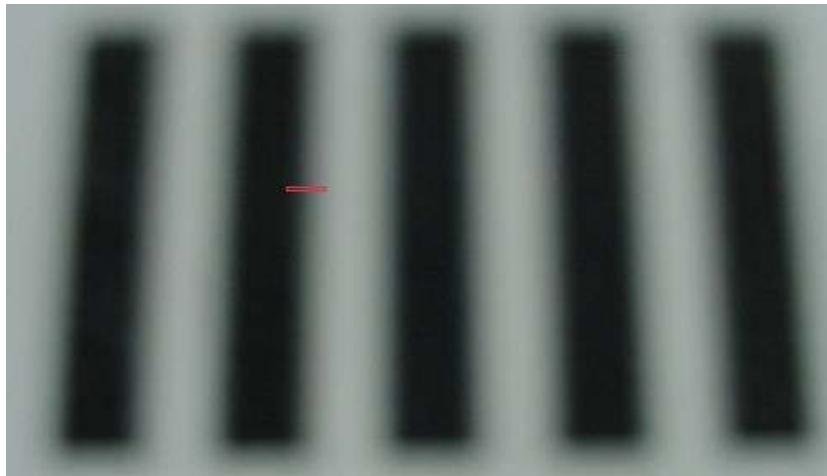
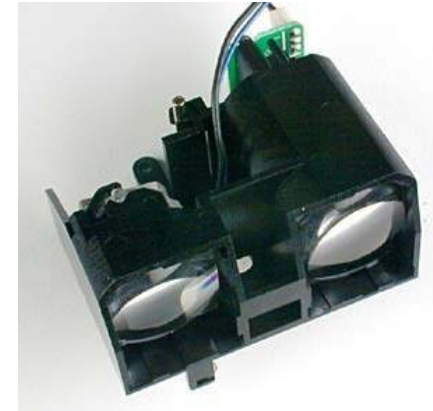


Color perception depends on surrounding



Autofocus

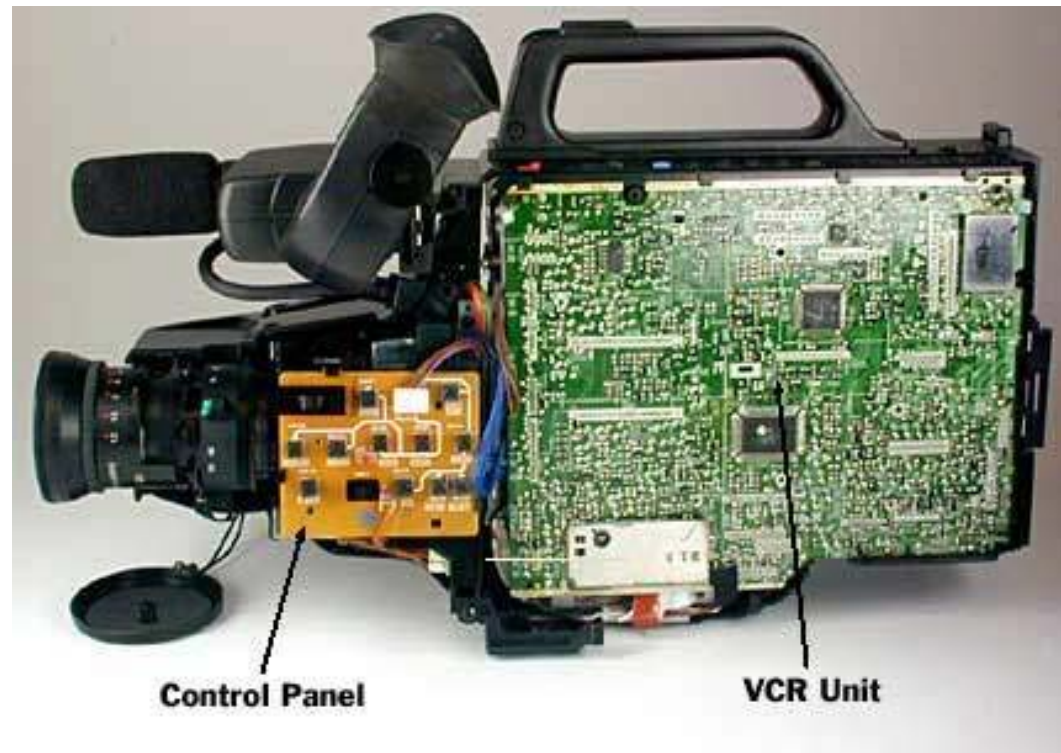
- Active
 - Sonar
 - Infrared
- Passive



Digital camera review website

- [A cool video of digital camera illustration](#)
- <http://www.dpreview.com/>

Camcorder



Interlacing



without interlacing

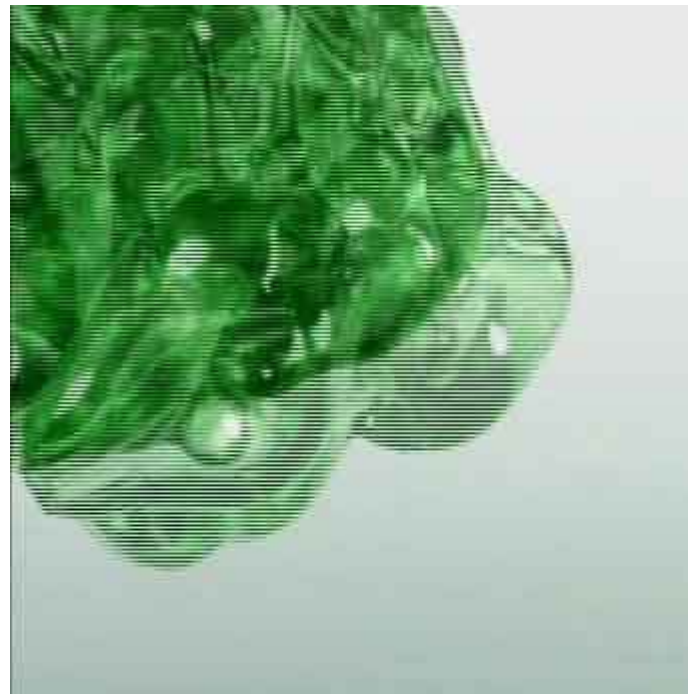


with interlacing

Deinterlacing



blend



weave

Deinterlacing



Discard
(even field only or
odd field only)



Progressive scan

Hard cases



Computational cameras



More emerging cameras



References

- <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.
- Rajeev Ramanath, Wesley E. Snyder, Youngjun Yoo, Mark S. Drew, [Color Image Processing Pipeline in Digital Still Cameras](#), IEEE Signal Processing Magazine Special Issue on Color Image Processing, vol. 22, no. 1, pp. 34-43, 2005.
- <http://www.worldatwar.org/photos/whitebalance/index.mhtml>
- <http://www.100fps.com/>