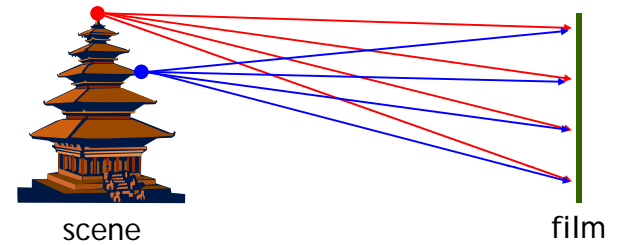


Cameras

Digital Visual Effects
Yung-Yu Chuang

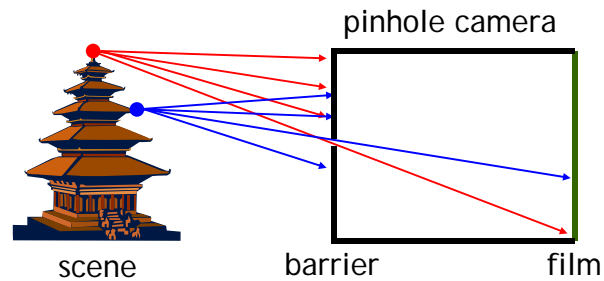
with slides by Fredo Durand, Brian Curless, Steve Seitz and Alexei Efros

Camera trial #1



Put a piece of film in front of an object.

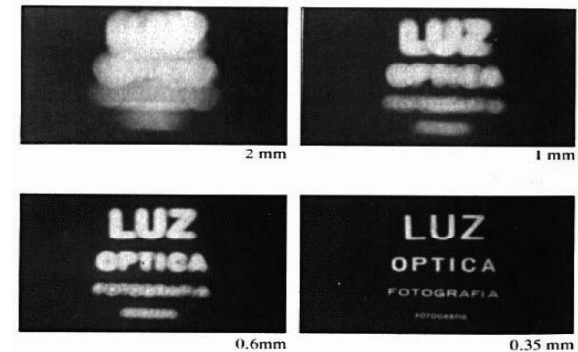
Pinhole camera



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

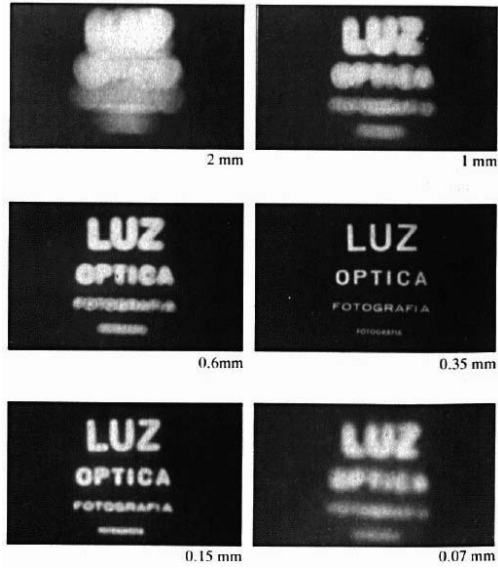


Why not making the aperture as small as possible?

- Less light gets through
- Diffraction effect

Shrinking the aperture

DigiVFX

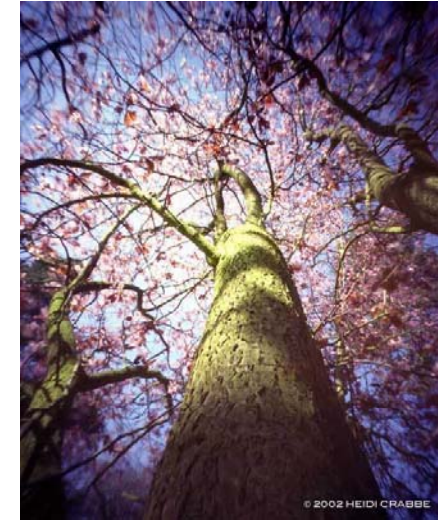


High-end commercial pinhole cameras

DigiVFX



\$200~\$700



Adding a lens

DigiVFX



scene



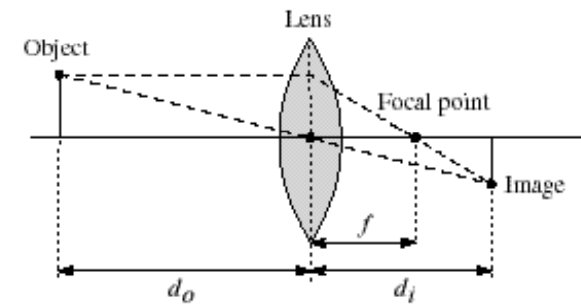
lens



film

Lenses

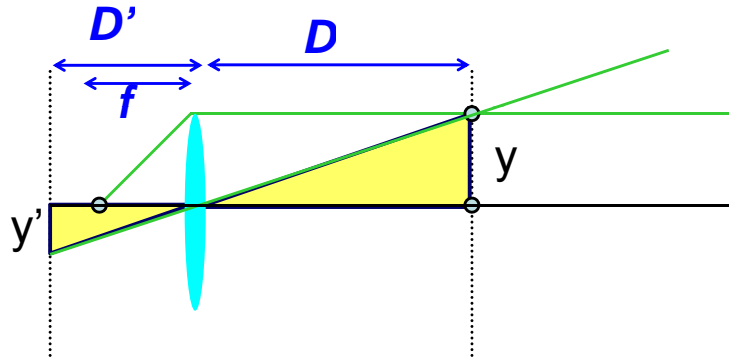
DigiVFX



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

Thin lens formula

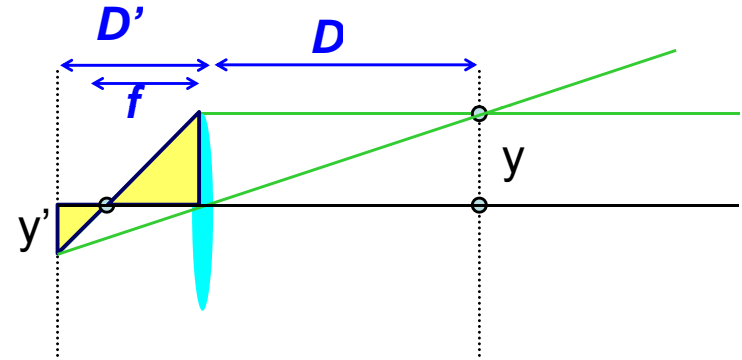
Similar triangles everywhere! $y'/y = D'/D$



Frédo Durand's slide

Thin lens formula

Similar triangles everywhere! $y'/y = D'/D$
 $y'/y = (D'-f)/f$

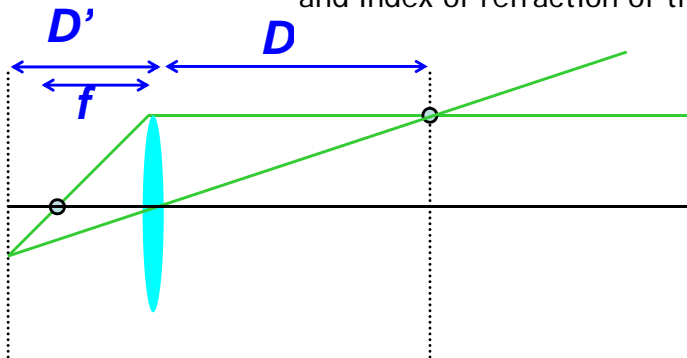


Frédo Durand's slide

Thin lens formula

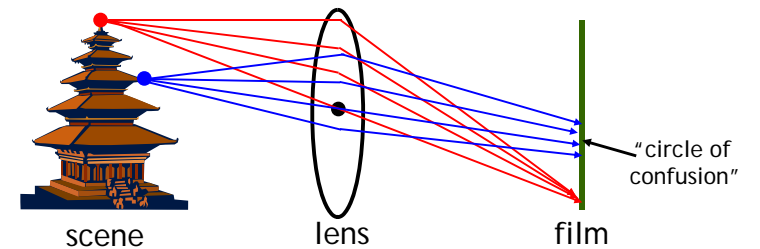
$$\frac{1}{D'} + \frac{1}{D} = \frac{1}{f}$$

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

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

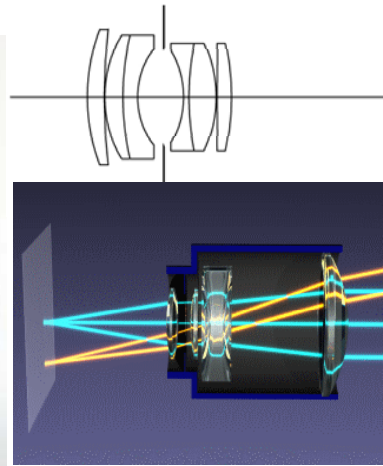
Thin lens applet:

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

Zoom lens

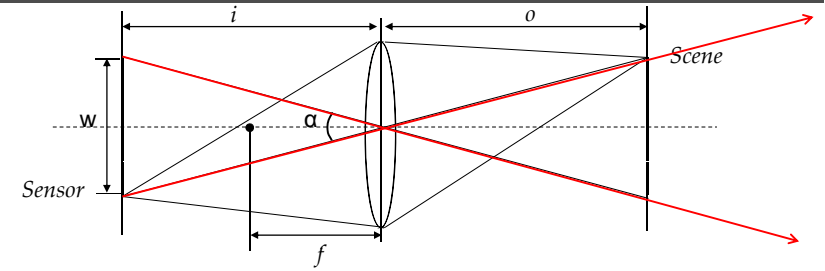


Nikon 28-200mm zoom lens.



simplified zoom lens in operation
From wikipedia

Field of view vs focal length

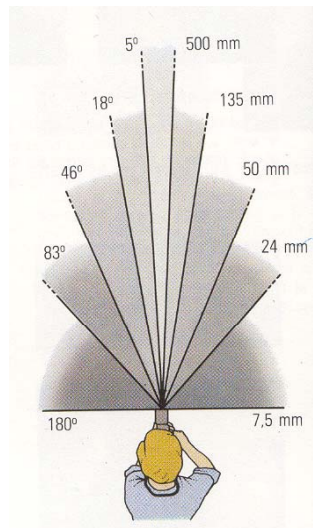


Gaussian Lens Formula: $\frac{1}{i} + \frac{1}{o} = \frac{1}{f}$

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



24mm



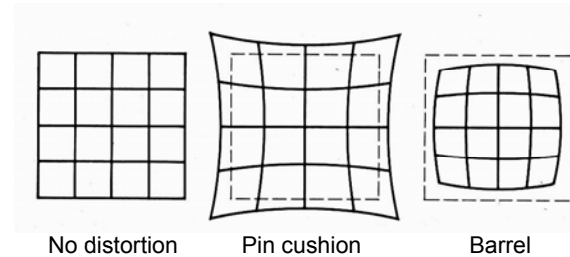
50mm



135mm



Distortion



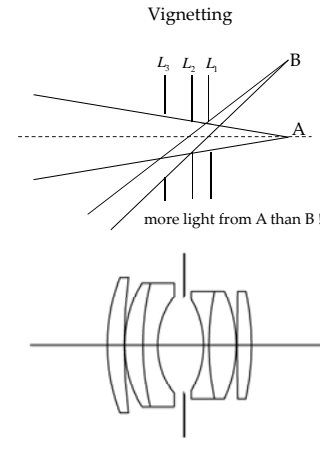
- Radial distortion of the image
 - Caused by imperfect lenses
 - Deviations are most noticeable for rays that pass through the edge of the lens

Correcting radial distortion



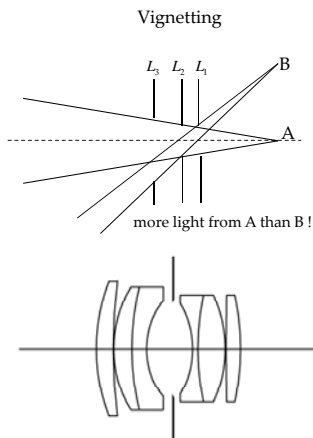
from [Helmut Dersch](#)

Vignetting



Slides from Li Zhang

Vignetting

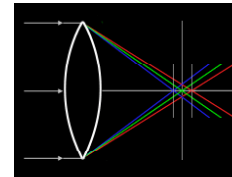


original corrected

Goldman & Chen ICCV 2005

Slides from Li Zhang

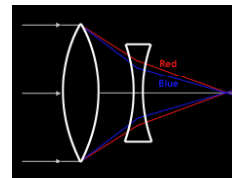
Chromatic Aberration



Lens has different refractive indices for different wavelengths.



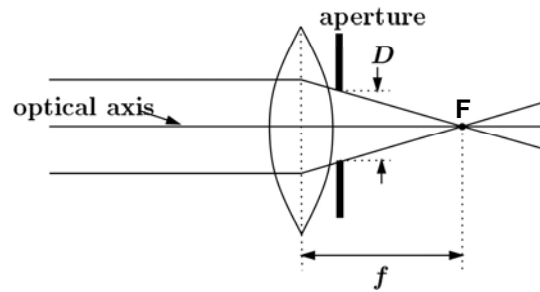
http://www.dpreview.com/learn/?/Glossary/Optical/chromatic_aberration_01.htm



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

Slides from Li Zhang

Exposure = aperture + shutter speed DigiVFX

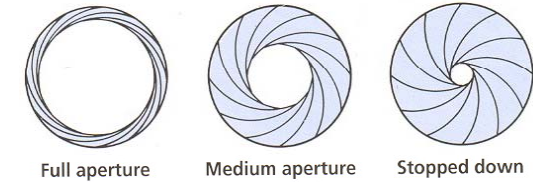


- Aperture of diameter D restricts the range of rays (aperture may be on either side of the lens)
- Shutter speed is the amount of time that light is allowed to pass through the aperture

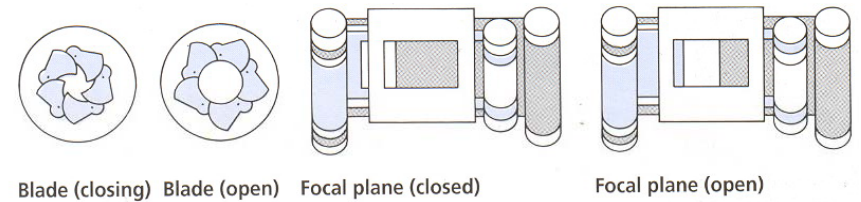
Exposure DigiVFX

- Two main parameters:

- Aperture (in f stop)

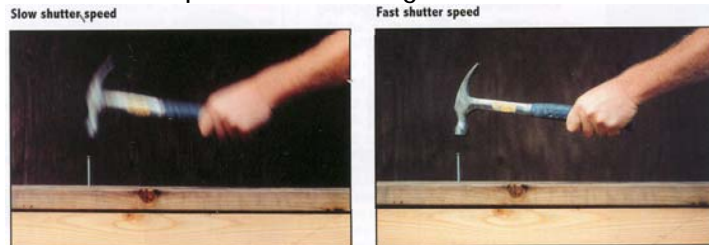


- Shutter speed (in fraction of a second)



Effects of shutter speeds DigiVFX

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



- Faster shutter speed freezes motion

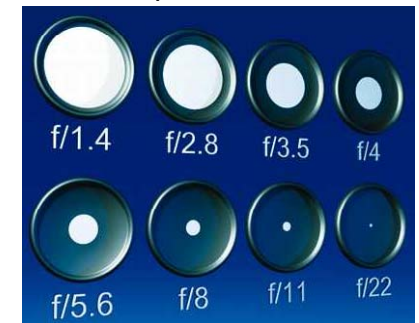
From Photography, London et al.

Walking people Running people Car Fast train



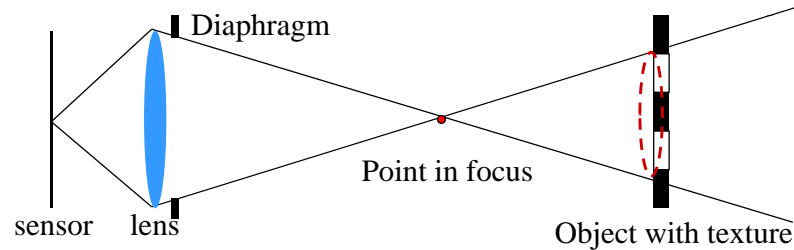
Aperture DigiVFX

- 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)



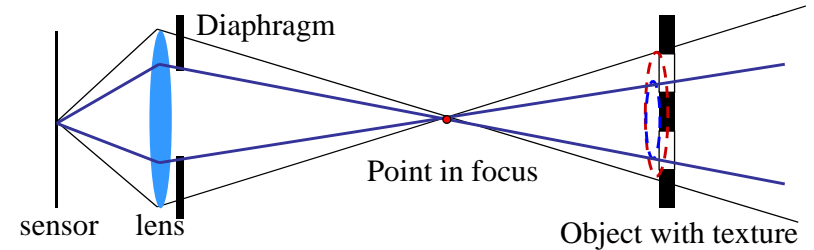
Depth of field

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

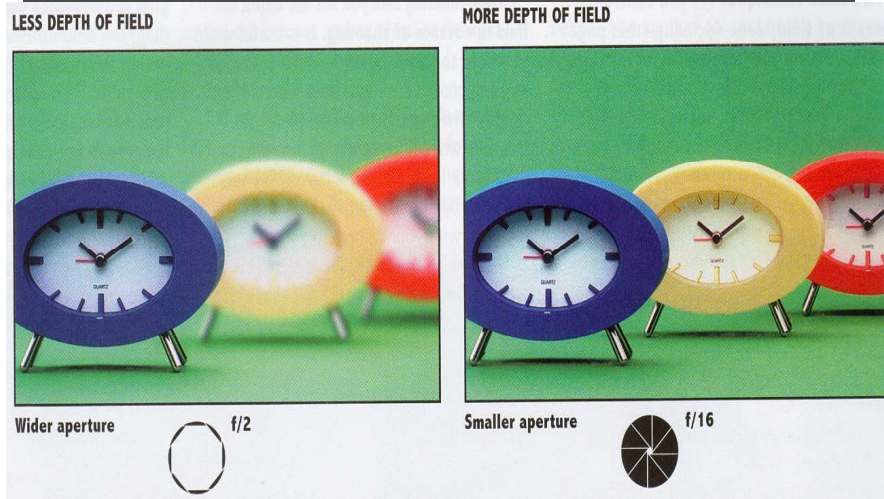


Depth of field

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




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



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

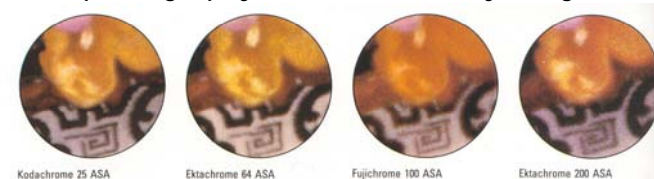
- The camera metering system measures how bright the scene is
- In Aperture priority mode, the photographer sets the aperture, the camera sets the shutter speed
- In Shutter-speed priority mode, photographers sets the shutter speed and the camera deduces the aperture
- In Program mode, the camera decides 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



- Digital photography: trade sensitivity for noise



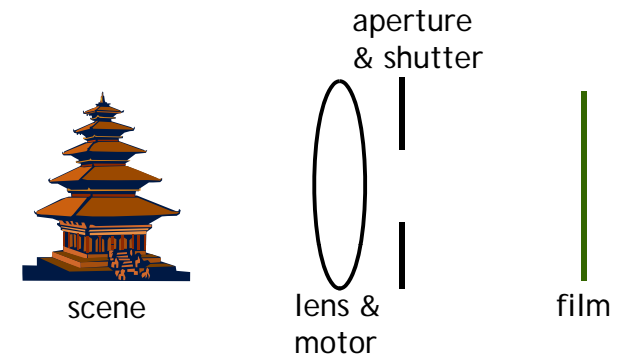
Demo

DigiVFX

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

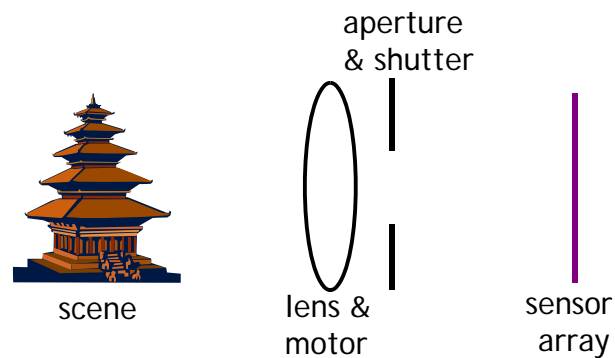
Film camera

DigiVFX



Digital camera

DigiVFX

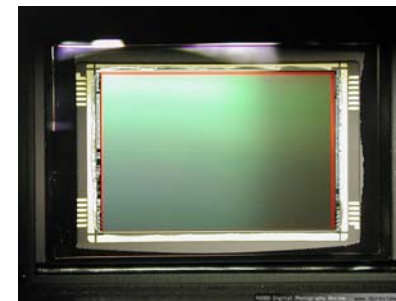


- A digital camera replaces film with a sensor array
- Each cell in the array is a light-sensitive diode that converts photons to electrons

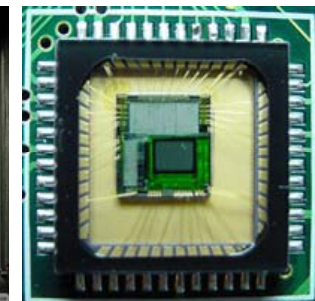
CCD v.s. CMOS

DigiVFX

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



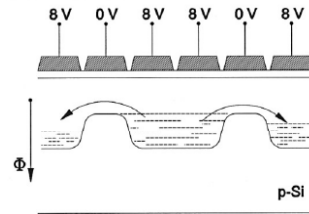
CCD



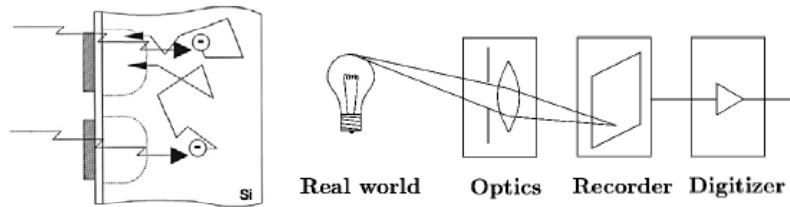
CMOS

Sensor noise

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



Blooming

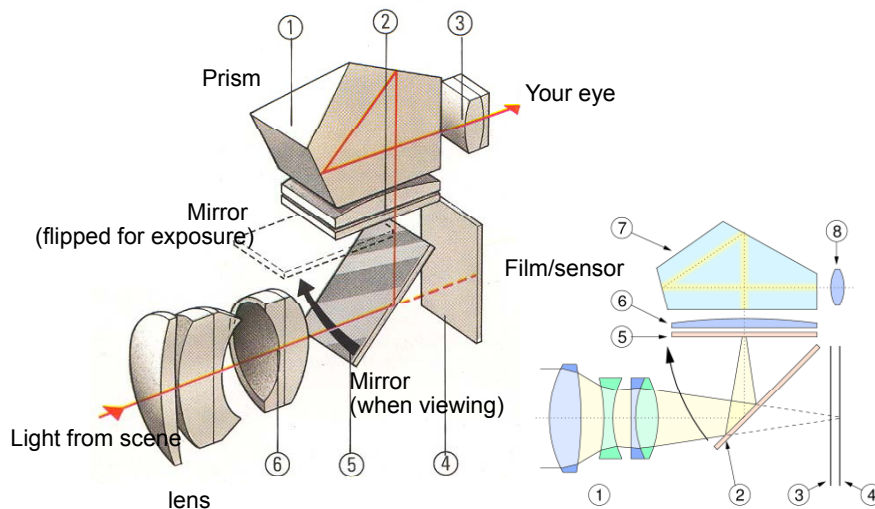


SLR (Single-Lens Reflex)

- 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



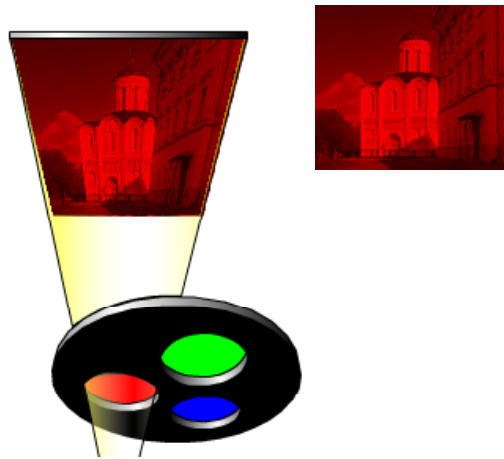
Color

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

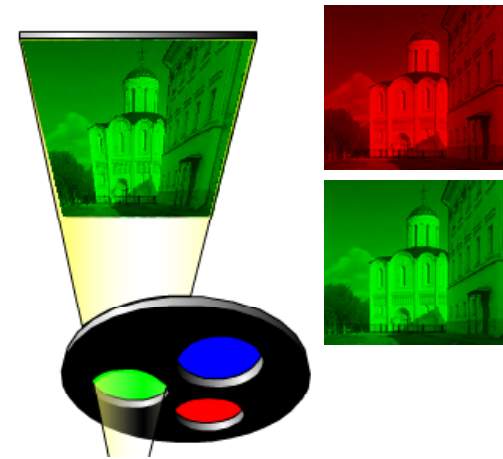
Field sequential

DigiVFX



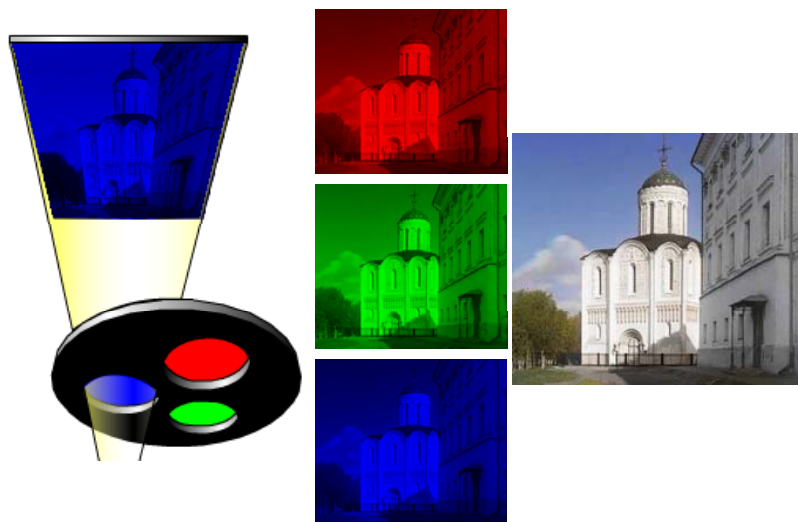
Field sequential

DigiVFX



Field sequential

DigiVFX



Prokudin-Gorskii (early 1900's)

DigiVFX

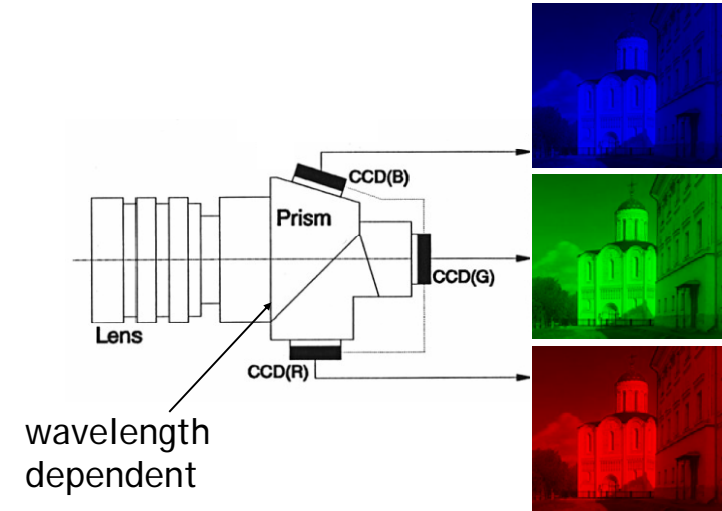


<http://www.loc.gov/exhibits/empire/>

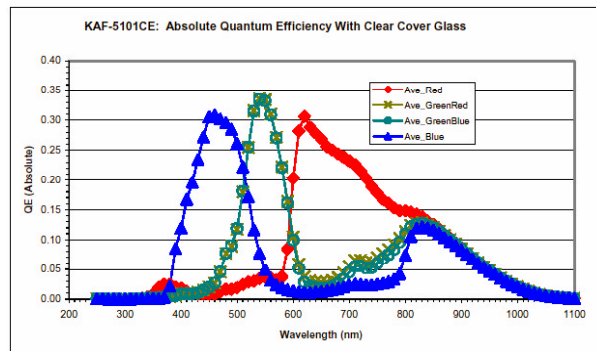
Prokudin-Gorskii (early 1990's)



Multi-chip

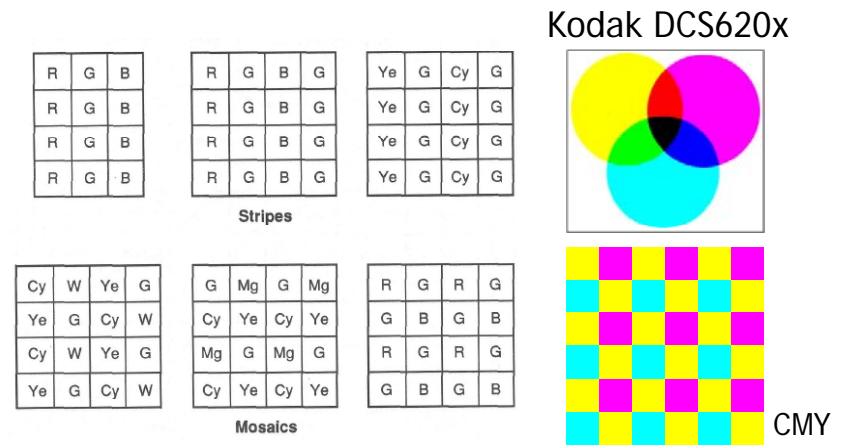


Embedded color filters



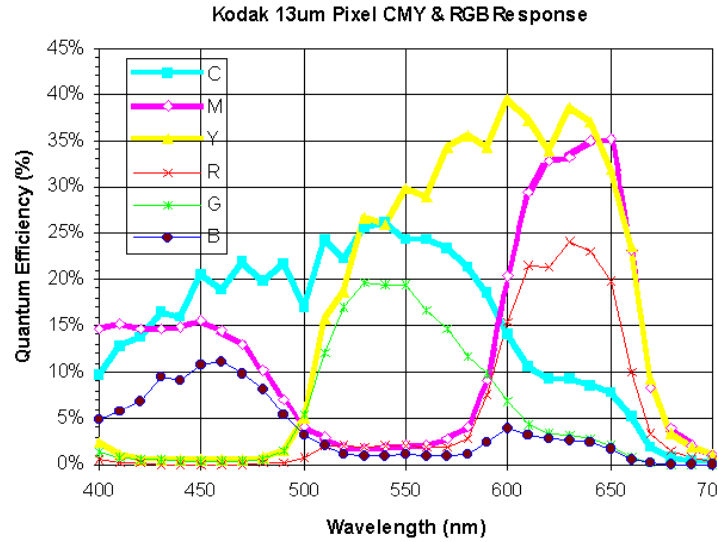
Color filters can be manufactured directly onto the photodetectors.

Color filter array

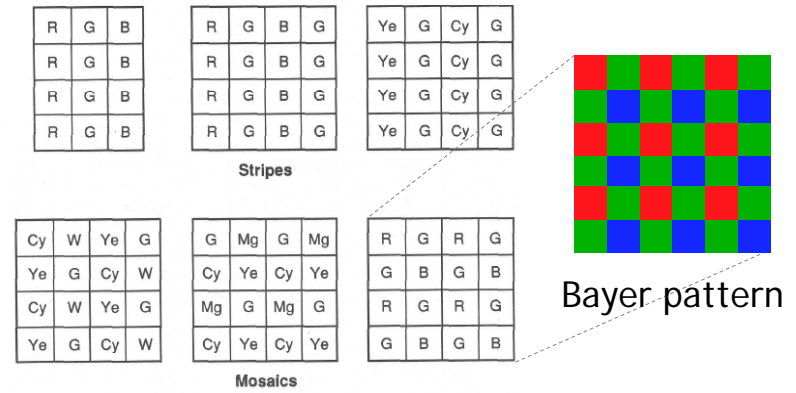


Color filter arrays (CFAs)/color filter mosaics

Why CMY CFA might be better

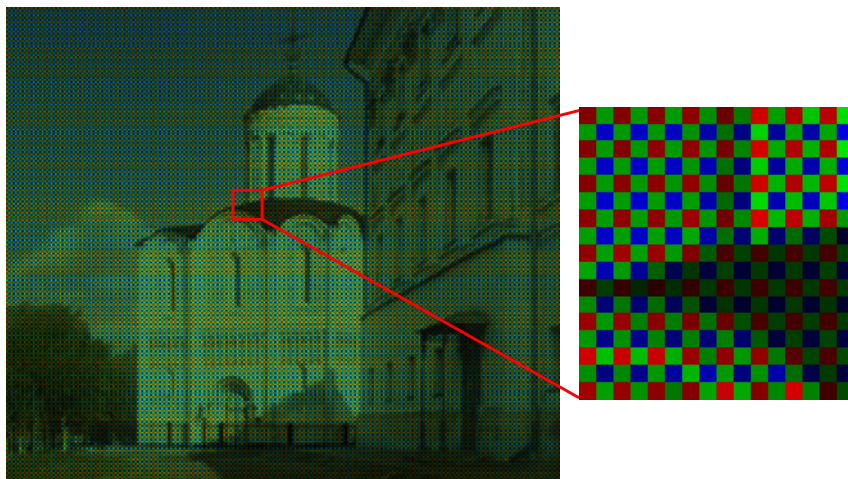


Color filter array



Color filter arrays (CFAs)/color filter mosaics

Bayer's pattern



Demosaicking CFA's

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

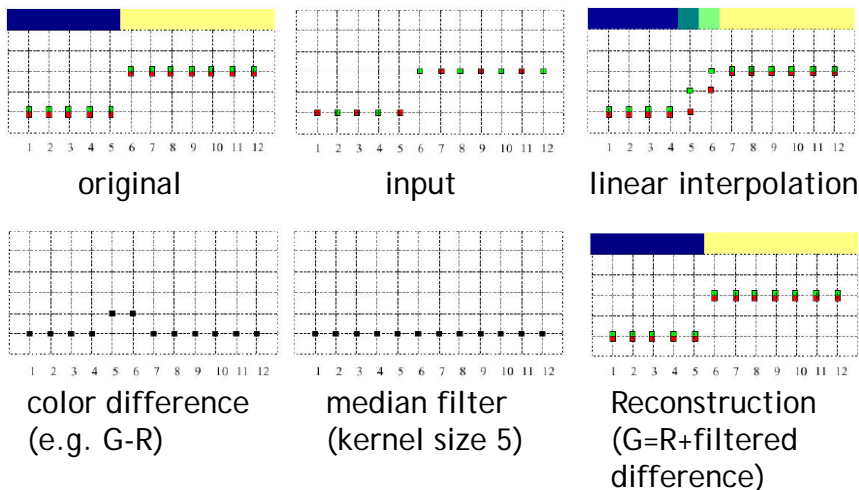
Median-based interpolation (Freeman)

1. Linear interpolation
2. Median filter on color differences

Demosaicking CFA's



Median-based interpolation (Freeman)



Demosaicking CFA's



Gradient-based interpolation (LaRoche-Prescott)

1. Interpolation on G
- $$\alpha = \text{abs}[(B_{42} + B_{46})/2 - B_{44}]$$
- $$\beta = \text{abs}[(B_{24} + B_{64})/2 - B_{44}]$$

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

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

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)

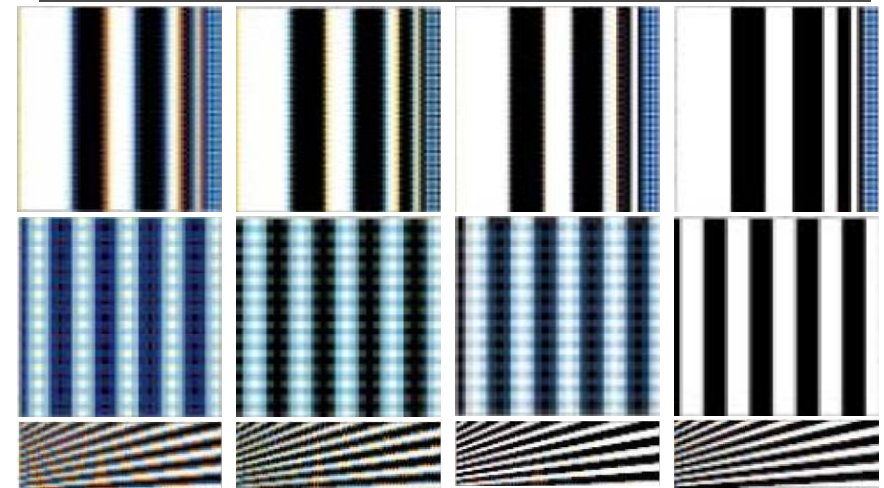
2. Interpolation of color differences

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

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

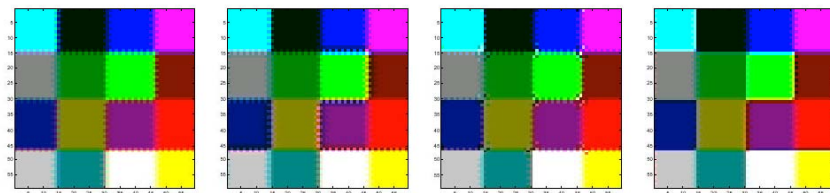
$$R_{44} = \frac{(R_{33} - G_{33}) + (R_{35} - G_{35}) + (R_{53} - G_{53}) + (R_{55} - G_{55})}{4} + G_{44}$$

Demosaicking CFA's

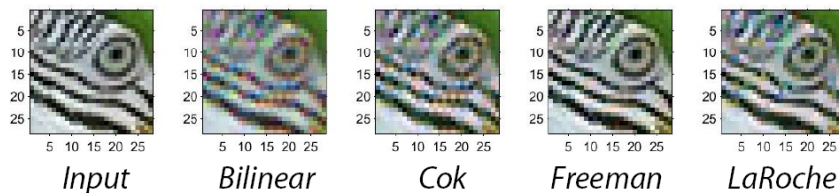


bilinear Cok Freeman LaRoche

Demosaicking CFA's



Bilinear Cok Freeman LaRoche

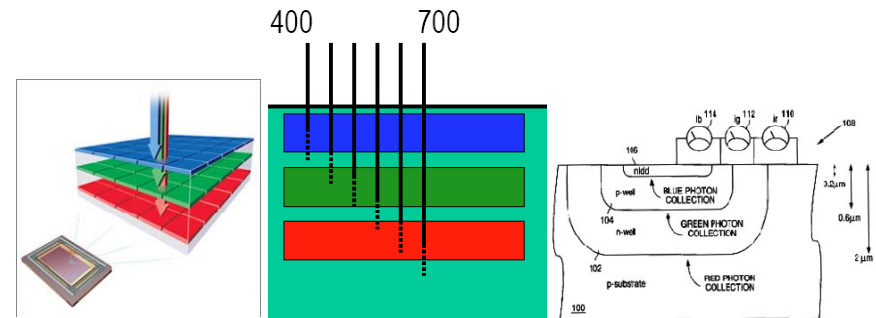


Input Bilinear Cok Freeman LaRoche

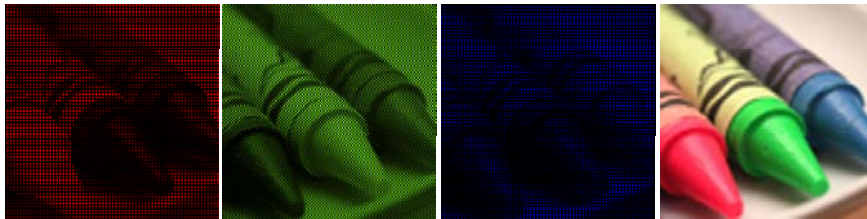
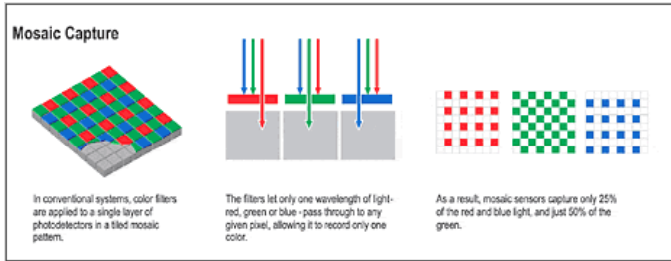
Generally, Freeman's is the best, especially for natural images.

Foveon X3 sensor

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

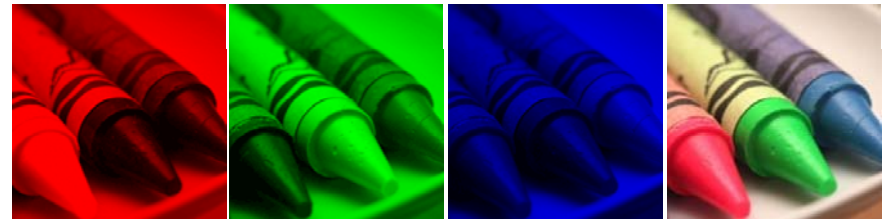
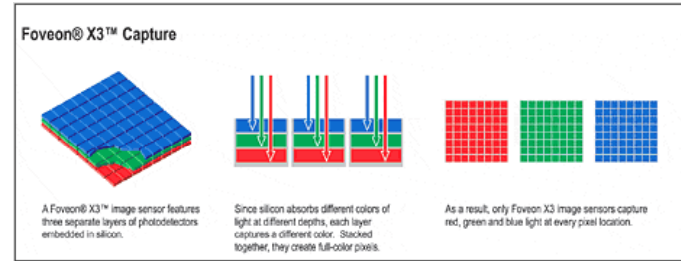


Color filter array



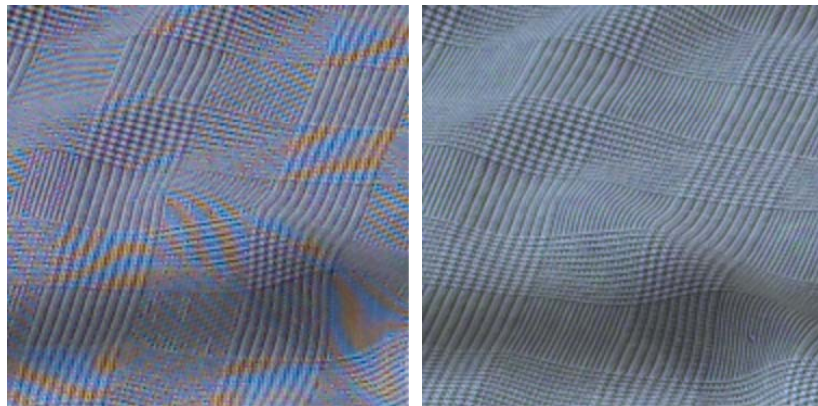
red green blue output

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

DigiVFX



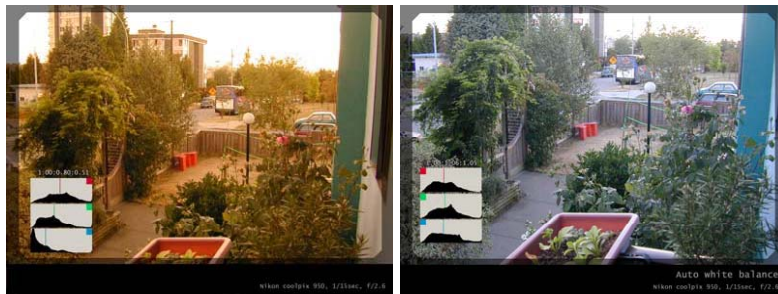
Color processing

DigiVFX

- 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

DigiVFX

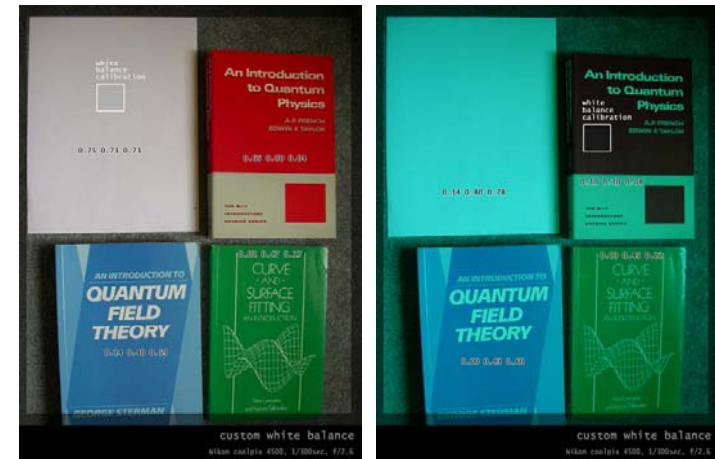


warmer +3

automatic white balance

Manual white balance

DigiVFX



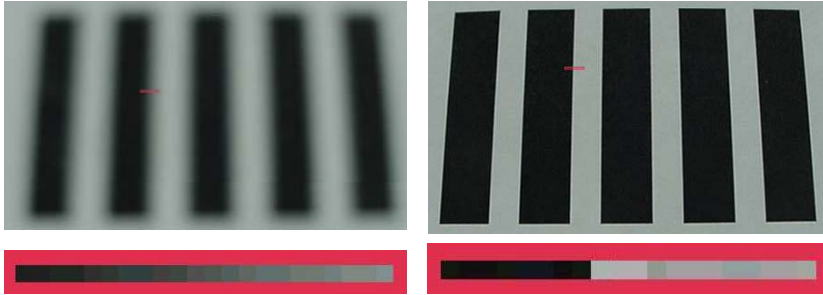
white balance with the white book

white balance with the red book

Autofocus

DigiVFX

- Active
 - Sonar
 - Infrared
- Passive



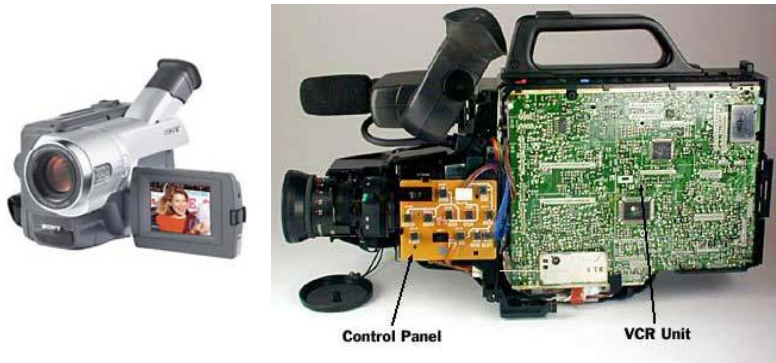
Digital camera review website

DigiVFX

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

Camcorder

DigiVFX



Interlacing

DigiVFX



without interlacing

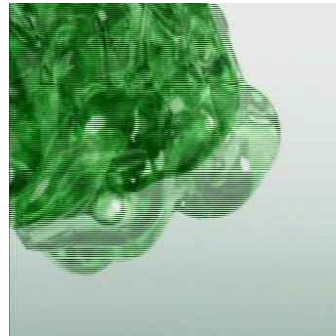
with interlacing

Deinterlacing

DigiVFX



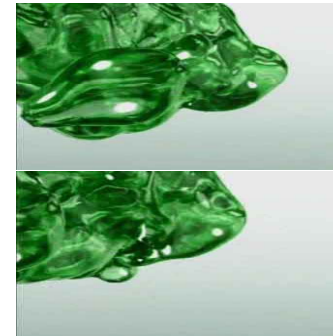
blend



weave

Deinterlacing

DigiVFX



Discard
(even field only or
odd field only)



Progressive scan

Hard cases

DigiVFX



References

DigiVFX

- <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/>