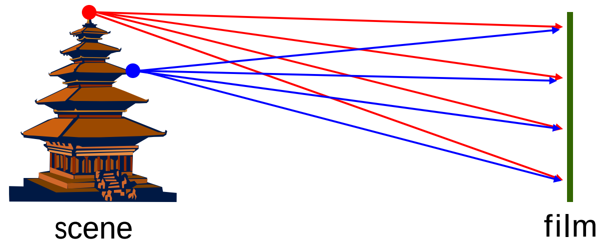
Cameras

Digital Visual Effects

Yung-Yu Chuang

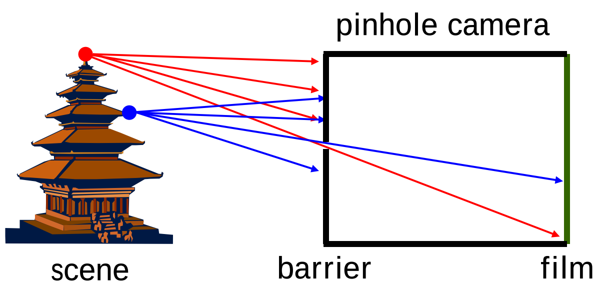
with slides by Fredo Durand, Brian Curless, Steve Seitz and Alexei Efros

Camera trial #1



Put a piece of film in front of an object.

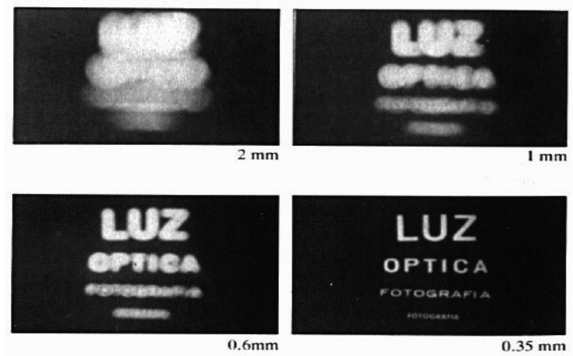
Pinhole camera



Add a barrier to block off most of the rays.

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

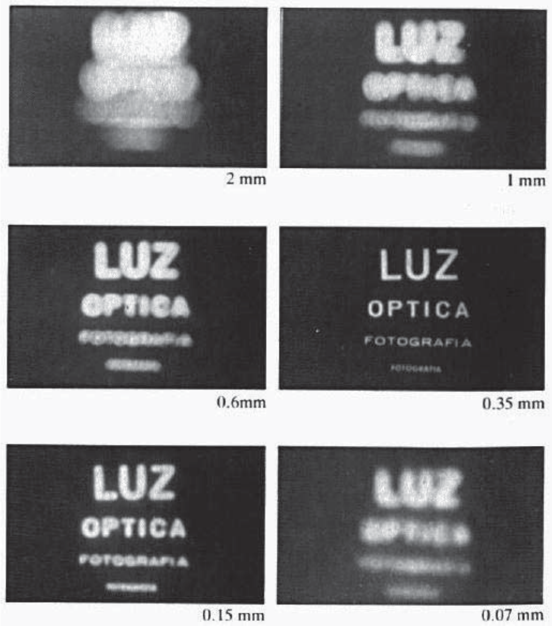
Shrinking the aperture



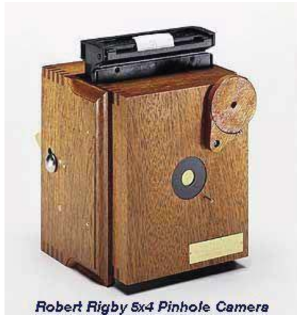
Why not making the aperture as small as possible?

- Less light gets through
- Diffraction effect

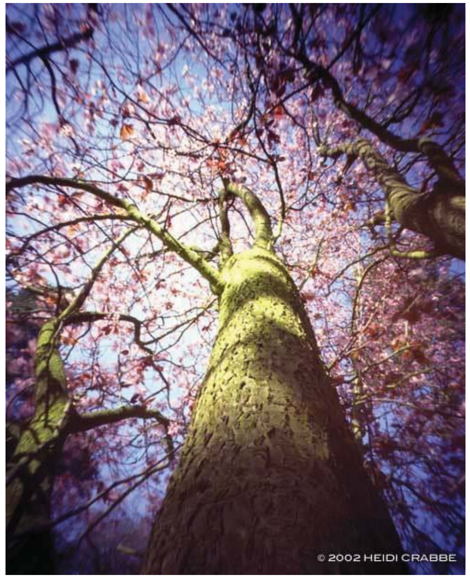
Shrinking the aperture



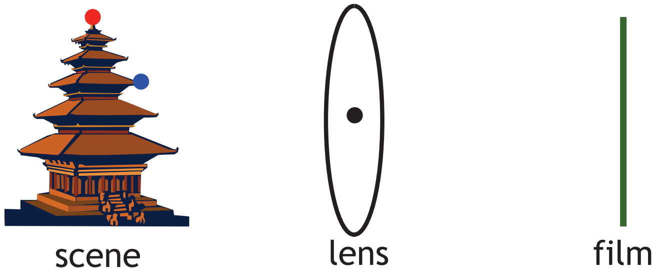
High-end commercial pinhole cameras



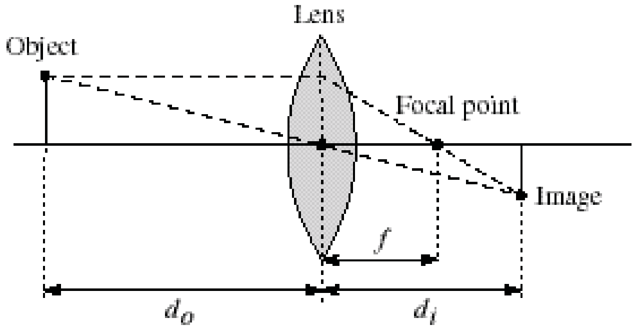
$200~$700



Adding a lens



Lenses

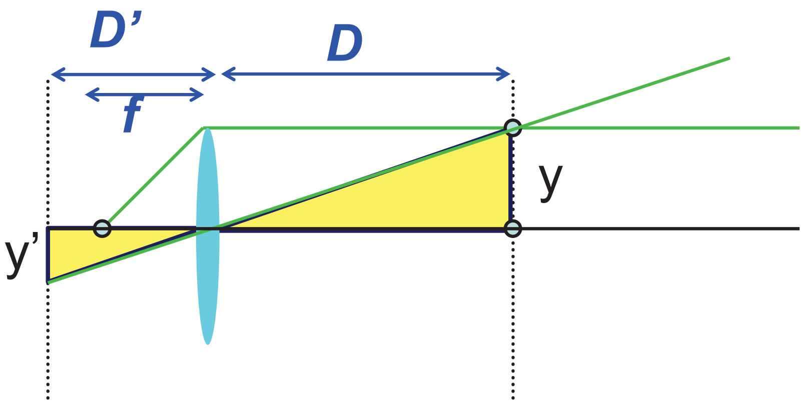


Thin lens equation: $\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$

Thin lens formula

Similar triangles everywhere!

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



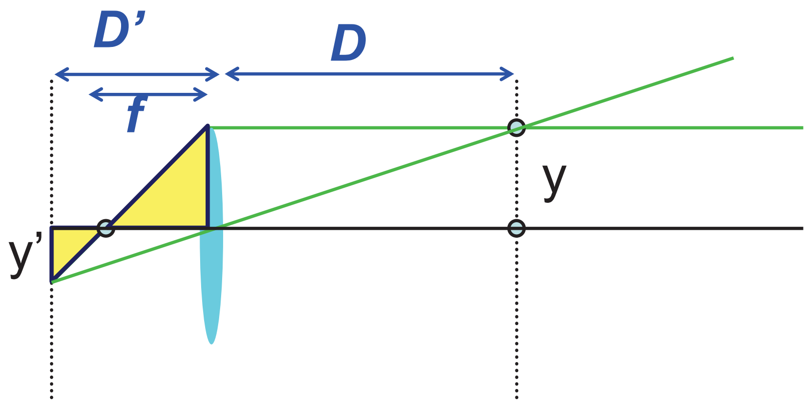
Frédo Durand's slide

Thin lens formula

Similar triangles everywhere!

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

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

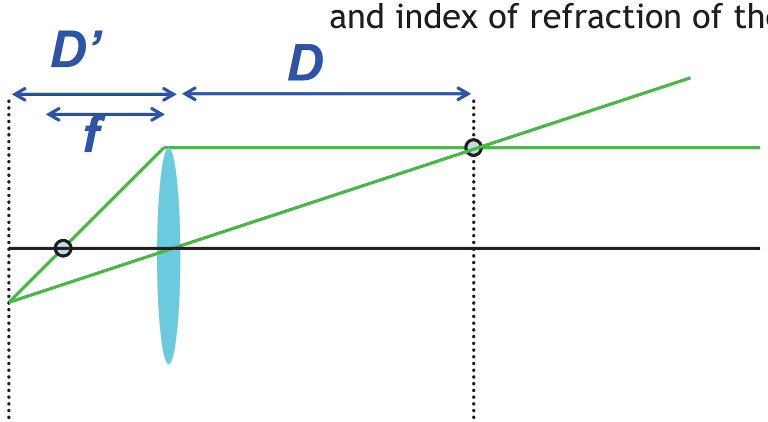


Frédo Durand's slide

Thin lens formula

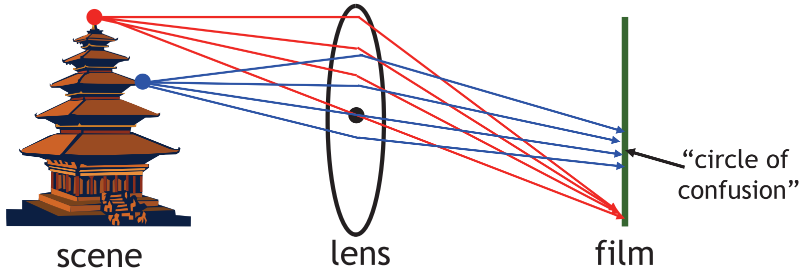
$$\frac{1}{D'} + \frac{1}{D} = \frac{1}{f}$$

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

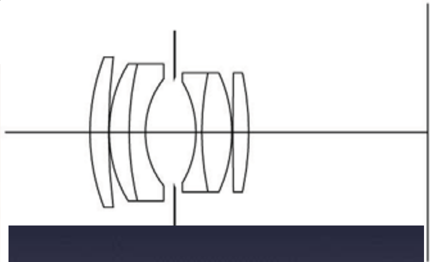
- There is a specific distance at which objects are "in focus"
- other points project to a "circle of confusion" in the image
- Thin lens applet: http://www.phy.ntnu.edu.tw/java/Lens/lens_e.html

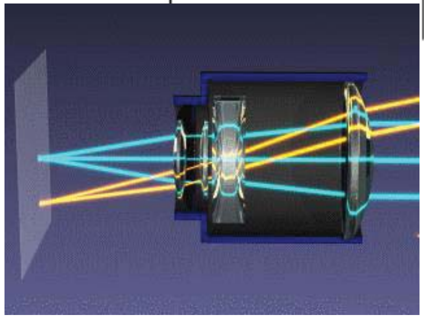
Zoom lens

200mm

28mm

Nikon 28-200mm zoom lens.

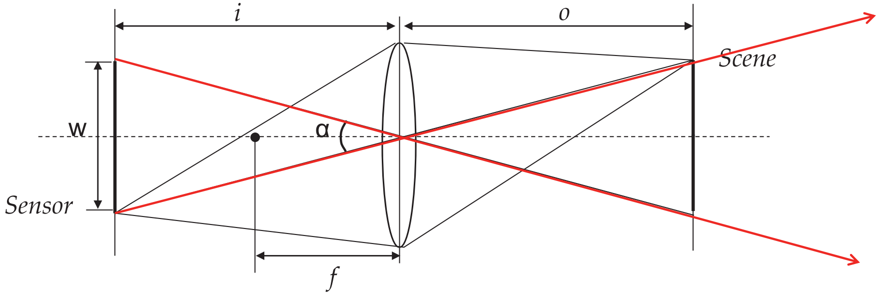




simplified zoom lens in operation

From wikipedia

Field of view vs focal length



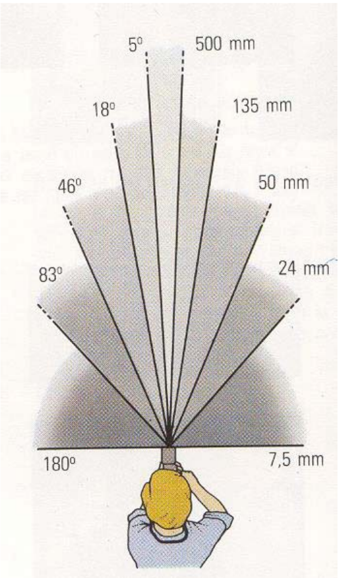
Gaussian Lens Formula: $\frac{1}{i} + \frac{1}{o} = \frac{1}{f}$

Field of View: α = 2arctan(w/(2i)) ≈ 2arctan(w/(2f))

Example: w = 30mm, f = 50mm => α ≈ 33.4°

Slides from Li Zhang

Focal length in practice

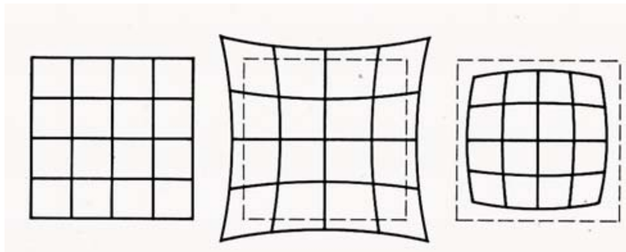


24mm

50mm

135mm

Distortion



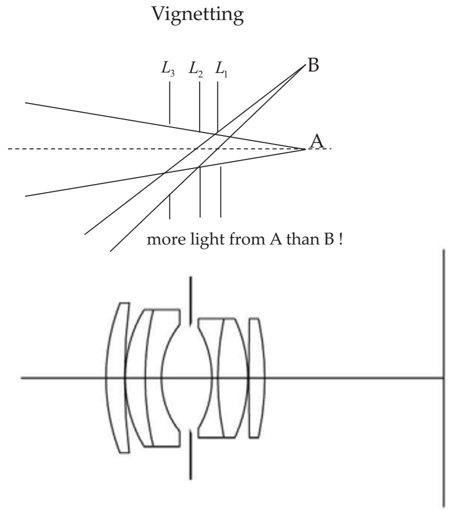
No distortion | Pin cushion | Barrel

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

Correcting radial distortion

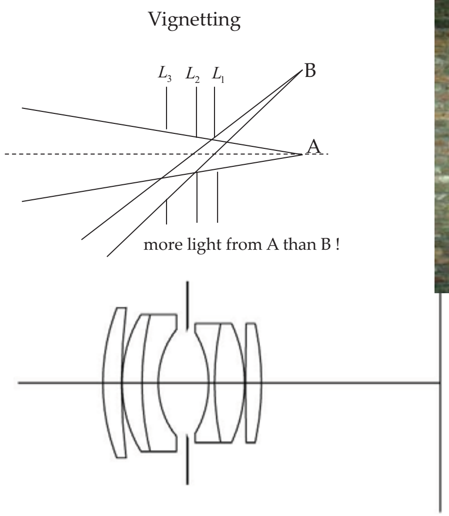
from Helmut Dersch

Vignetting



Slides from Li Zhang

Vignetting

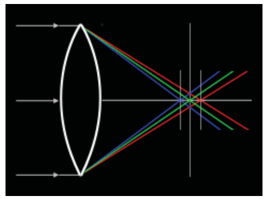


original corrected

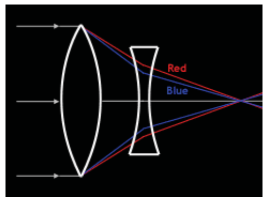
Goldman & Chen ICCV 2005

Slides from Li Zhang

Chromatic Aberration



Lens has different refractive indices for different wavelengths.

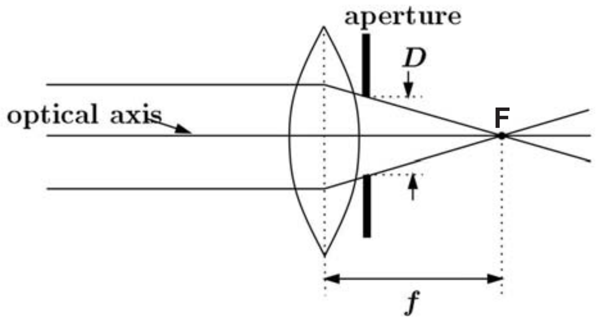


http://www.dpreview.com/learn/?/Glossary/Optical/chromatic_aberration_01.htm

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

Slides from Li Zhang

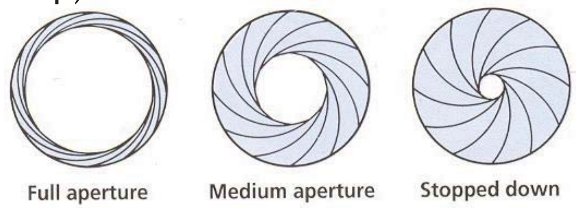
Exposure = aperture + shutter speed



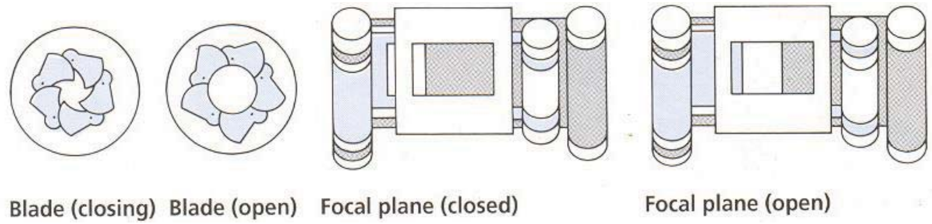
- Aperture of diameter D restricts the range of rays (aperture may be on either side of the lens)
- Shutter speed is the amount of time that light is allowed to pass through the aperture

Exposure

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

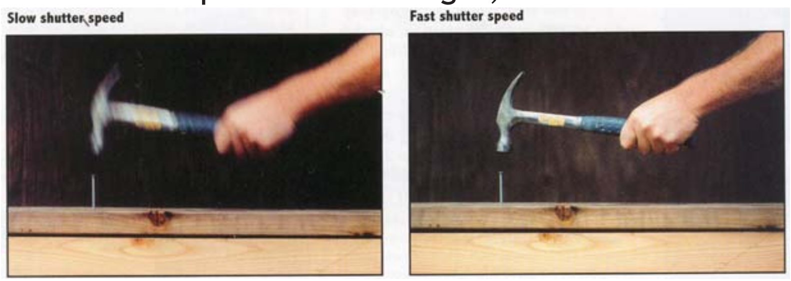


  - Shutter speed (in fraction of a second)



Effects of shutter speeds

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



- Faster shutter speed freezes motion

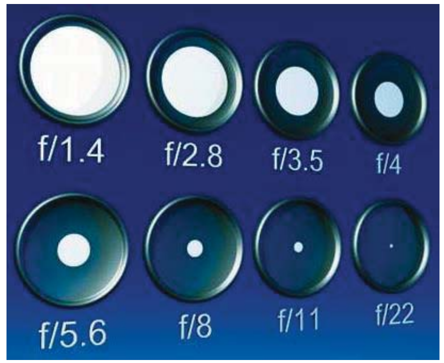
From Photography, London et al.

Walking people	Running people	Car	Fast train

1/125	1/250	1/500	1/1000

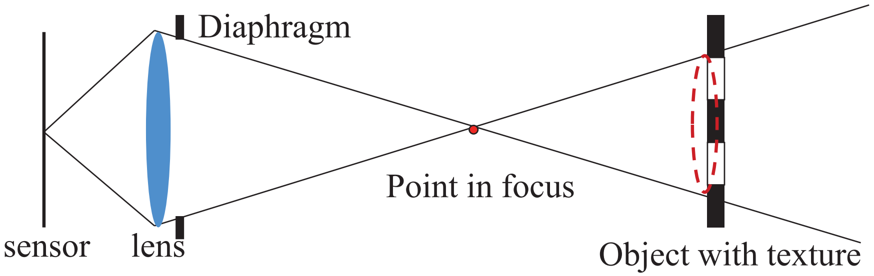
Aperture

- 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

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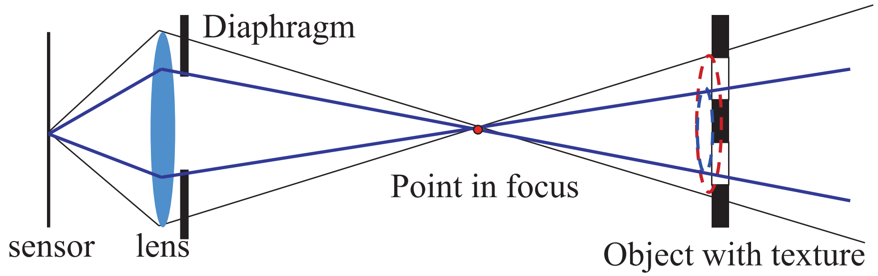
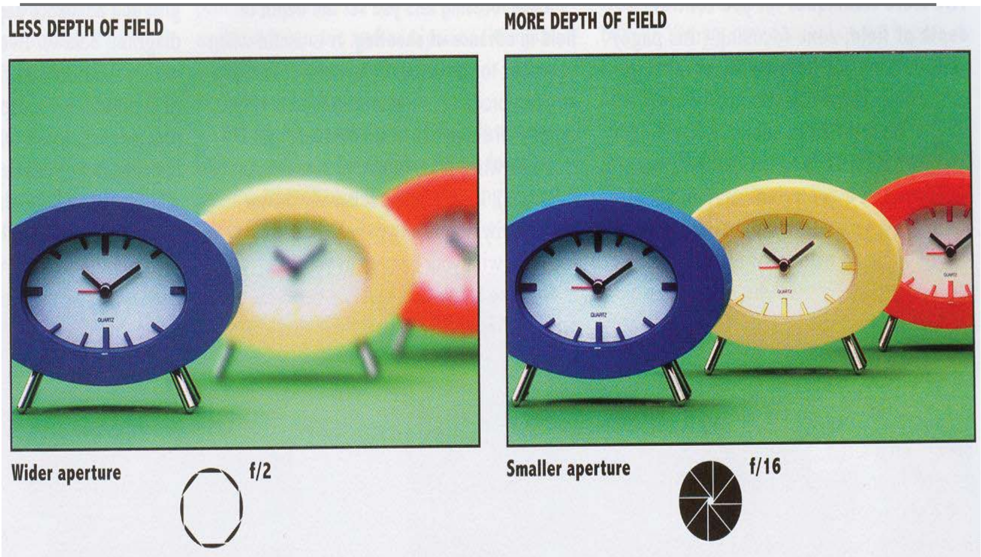


Depth of field



From Photography, London et al.

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

DigiVFX

- 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

DigiVFX

- 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

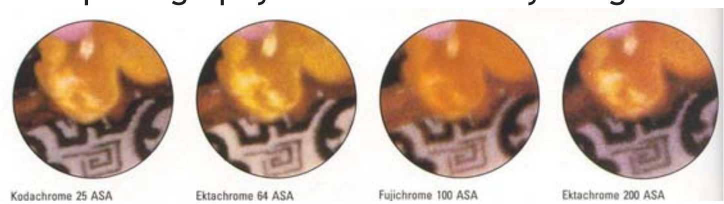
DigiVFX

- 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)

DigiVFX

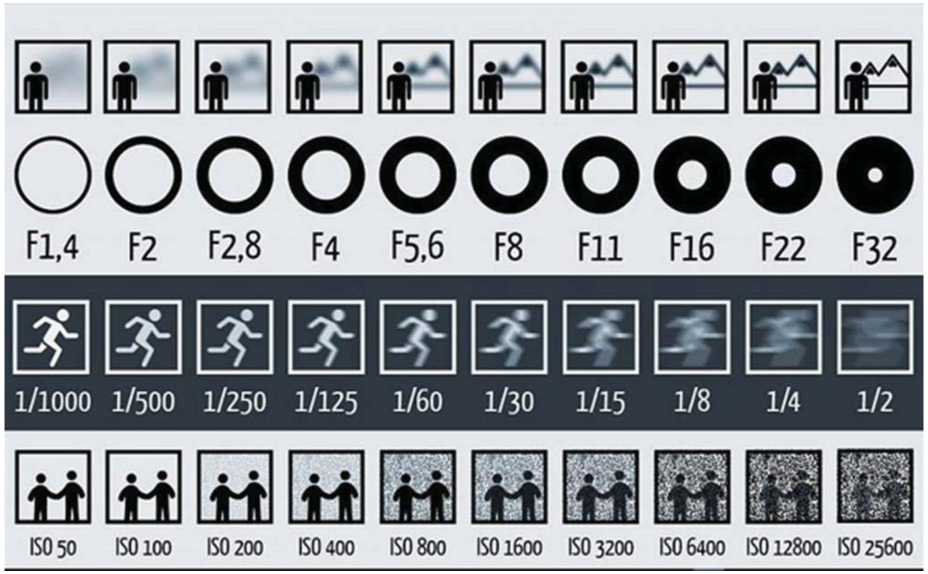
- Third variable for exposure
- Linear effect (200 ISO needs half the light as 100 ISO)
- Film photography: trade sensitivity for grain



- Digital photography: trade sensitivity for noise

From dpreview.com

Summary in a picture

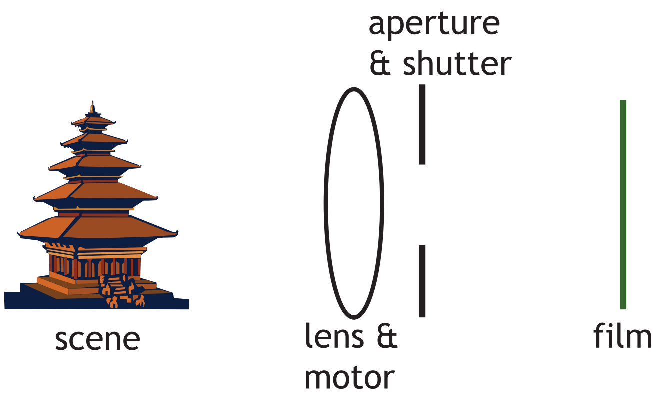


source hamburgerfotospots.de

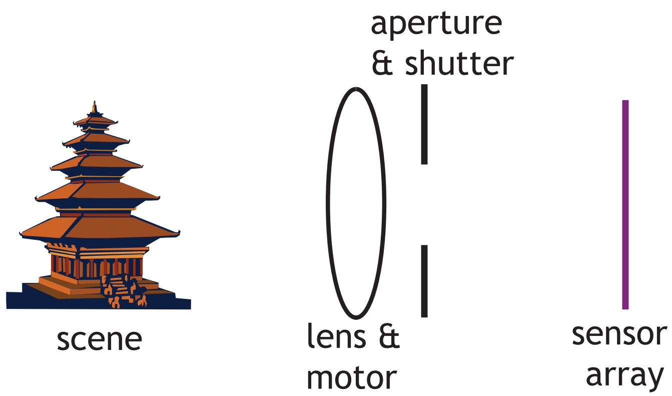
Demo

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

Film camera



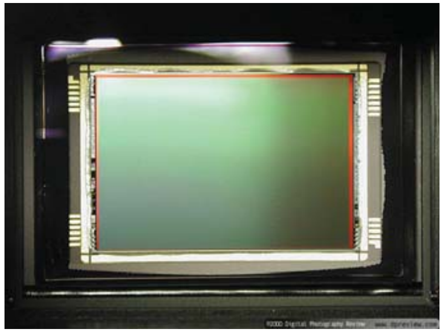
Digital camera



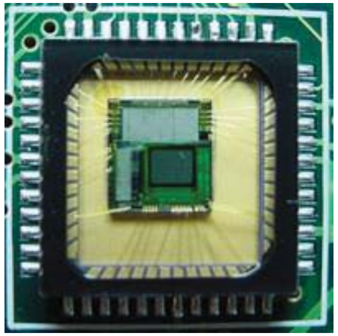
- A digital camera replaces film with a sensor array
- Each cell in the array is a light-sensitive diode that converts photons to electrons

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



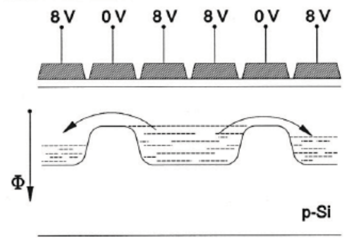
CCD



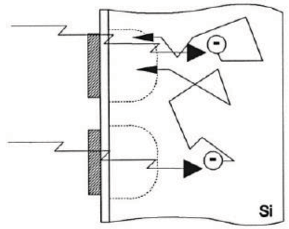
CMOS

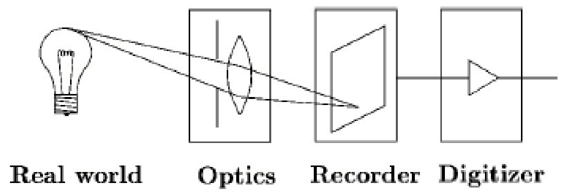
Sensor noise

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



Blooming

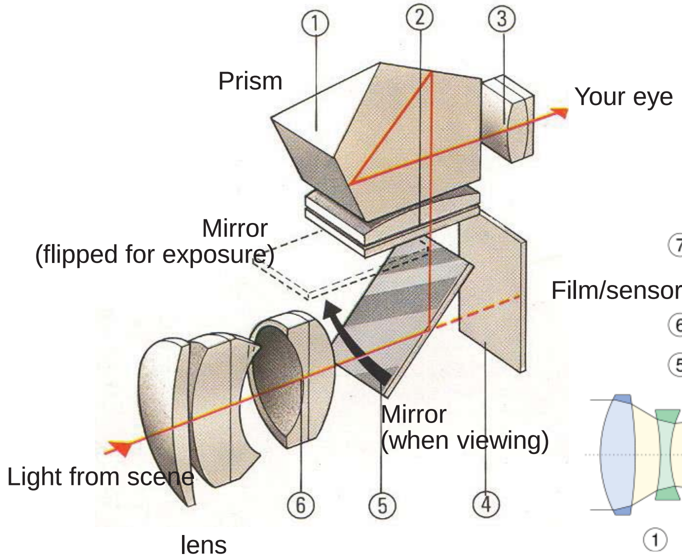


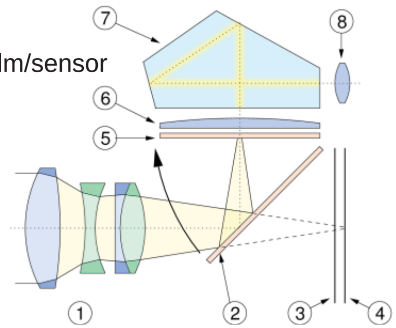


SLR (Single-Lens Reflex)

- 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



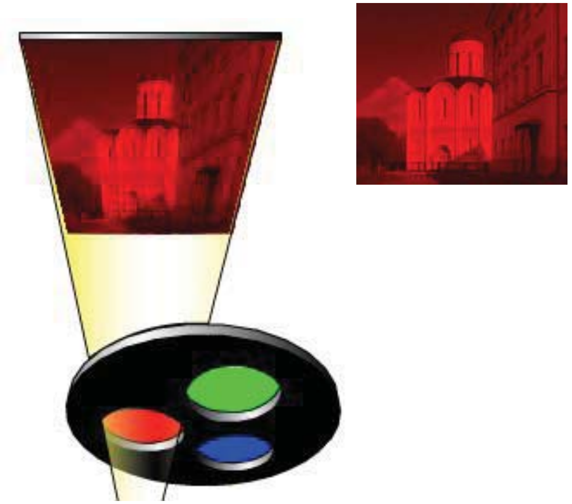


Color

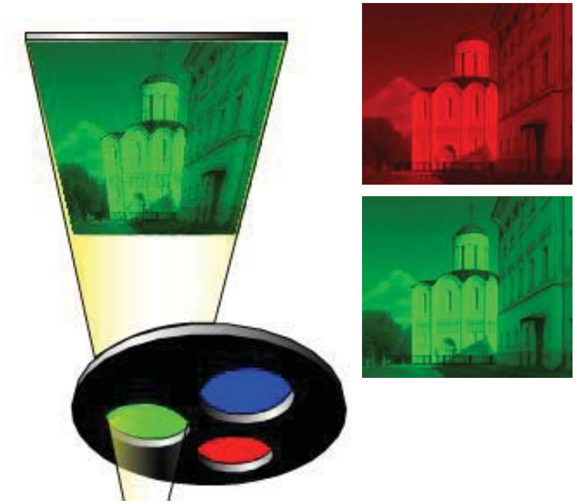
So far, we've only talked about monochrome sensors. Color imaging has been implemented in a number of ways:

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

Field sequential

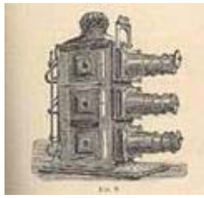


Field sequential



Field sequential

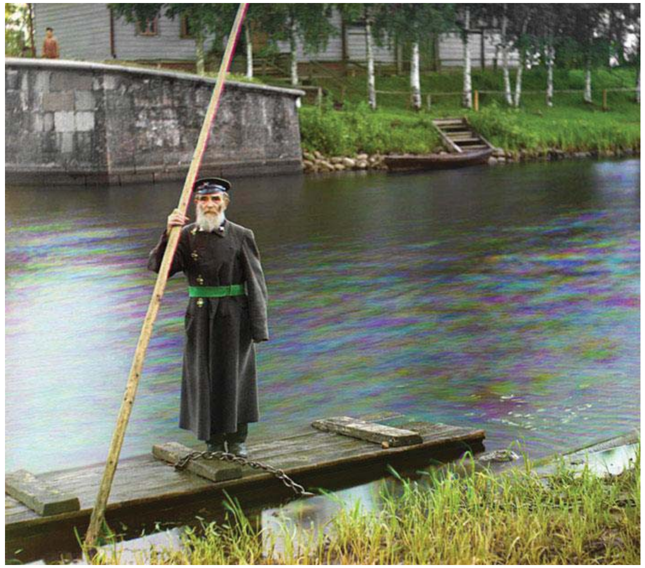
Prokudin-Gorskii (early 1900's)



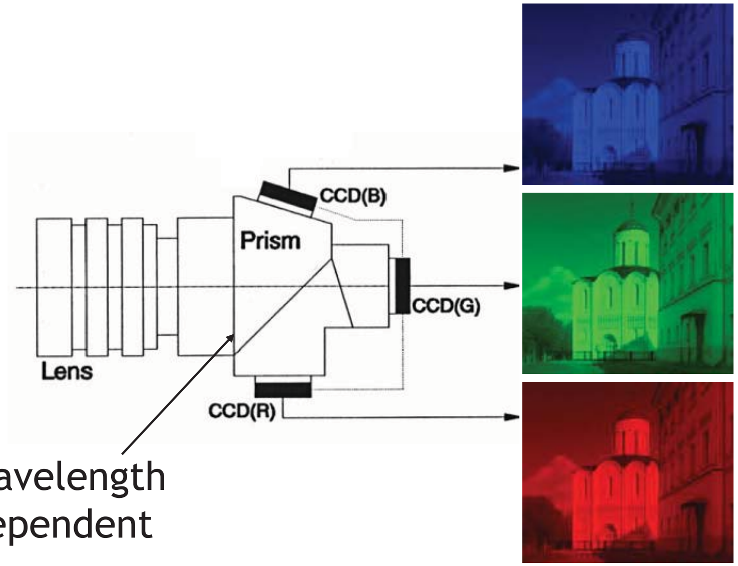
Lantern projector

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

Prokudin-Gorskii (early 1900's)

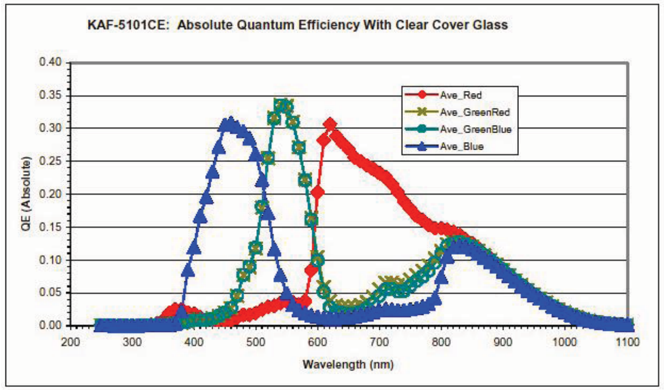


Multi-chip



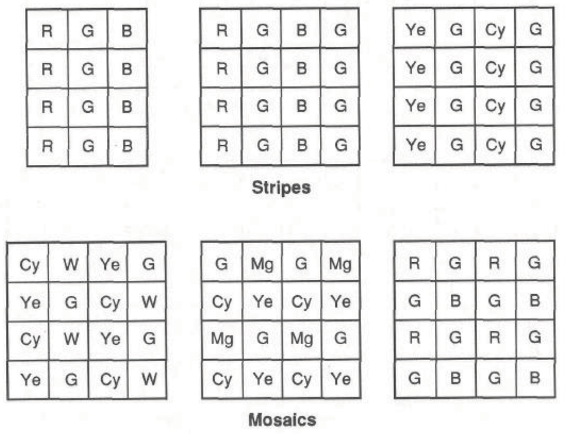
wavelength dependent

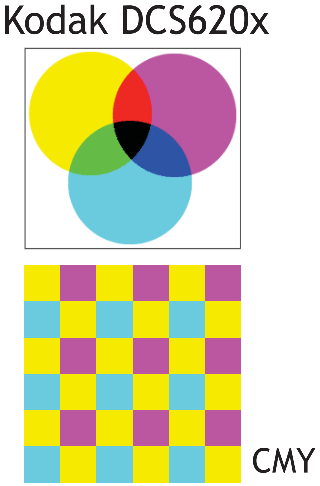
Embedded color filters



Color filters can be manufactured directly onto the photodetectors.

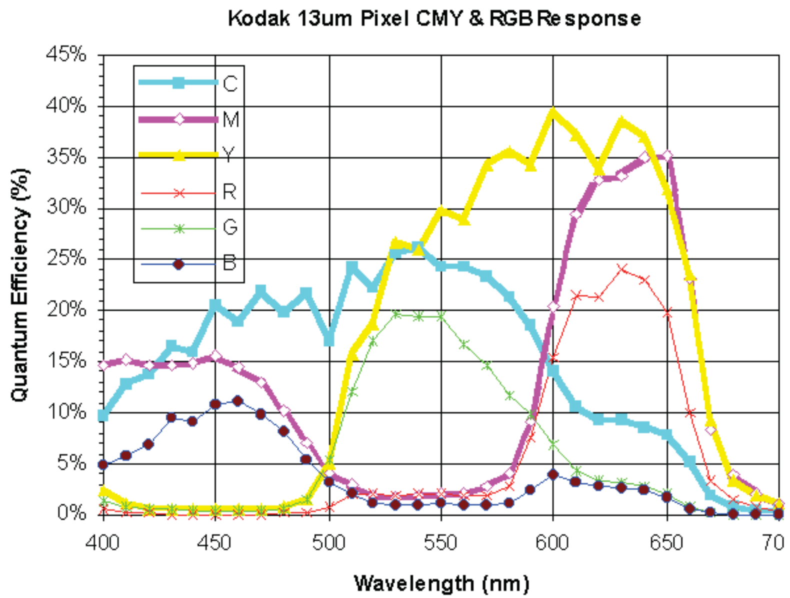
Color filter array



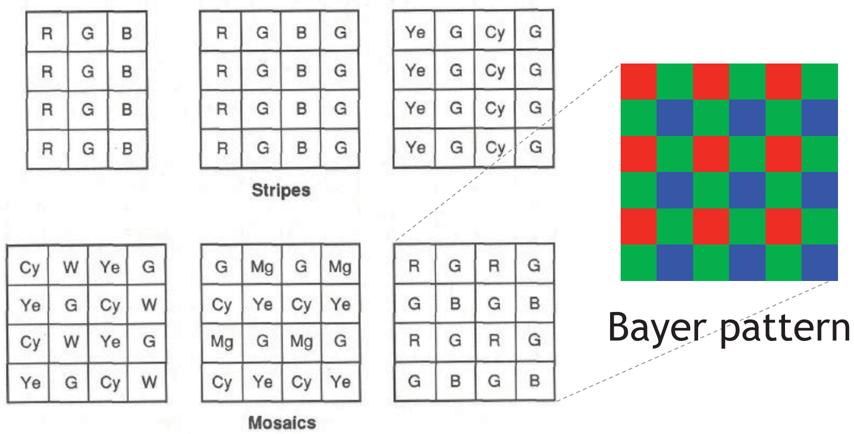


Color filter arrays (CFAs)/color filter mosaics

Why CMY CFA might be better

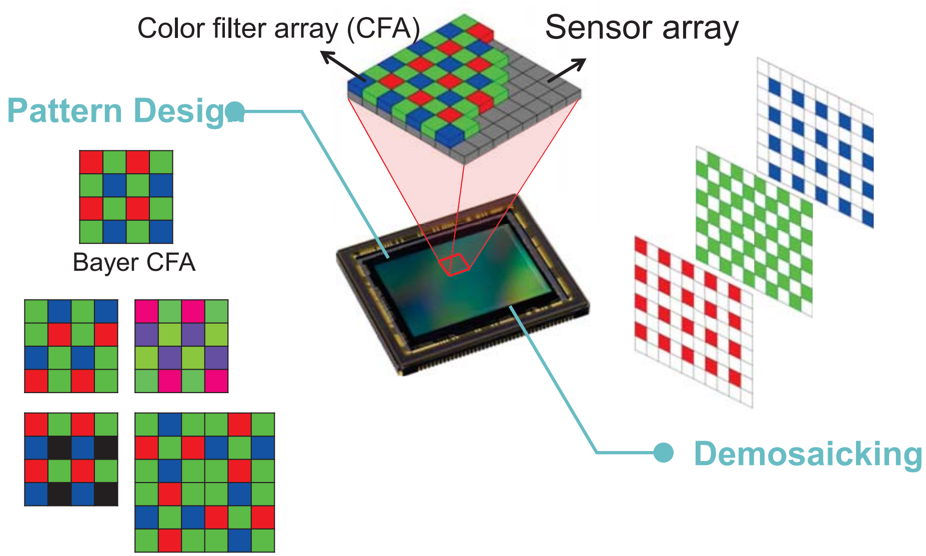


Color filter array



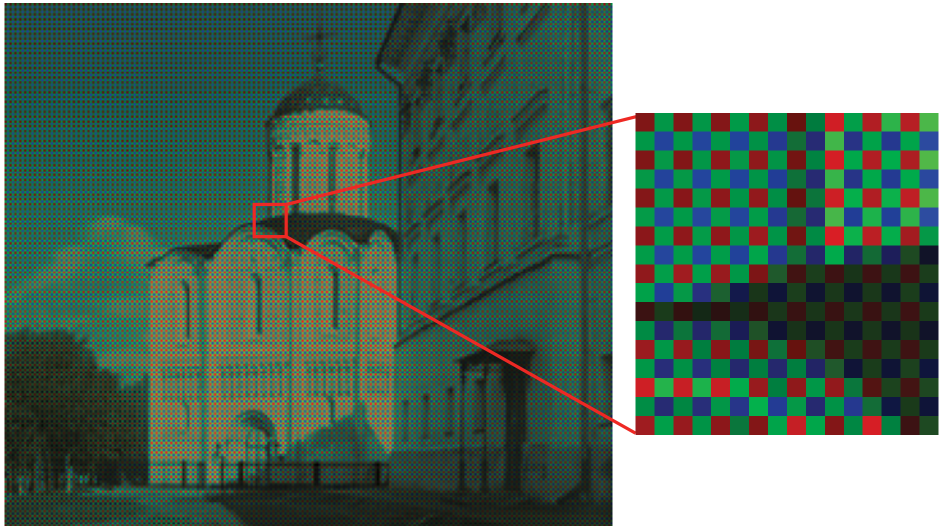
Color filter arrays (CFAs)/color filter mosaics

Demosaicking



Bayer's pattern

DigiVFX



Demosaicking CFA's

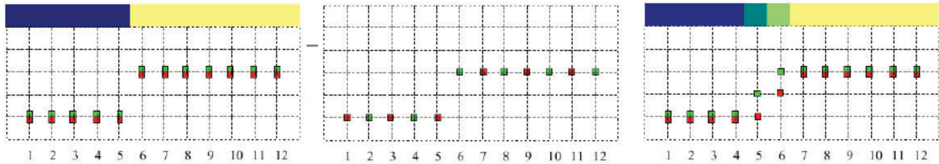
DigiVFX

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

DigiVFX

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

DigiVFX

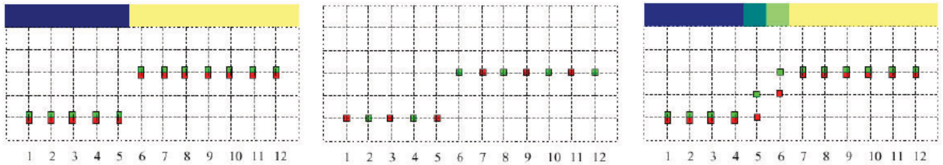
R_{11}	G_{12}	R_{13}	G_{14}	R_{15}	G_{16}	R_{17}
G_{21}	B_{22}	G_{23}	B_{24}	G_{25}	B_{26}	G_{27}
R_{31}	G_{32}	R_{33}	G_{34}	R_{35}	G_{36}	R_{37}
G_{41}	B_{42}	G_{43}	B_{44}	G_{45}	B_{46}	G_{47}
R_{51}	G_{52}	R_{53}	G_{54}	R_{55}	G_{56}	R_{57}
G_{61}	B_{62}	G_{63}	B_{64}	G_{65}	B_{66}	G_{67}
R_{71}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

Median-based interpolation (Freeman)

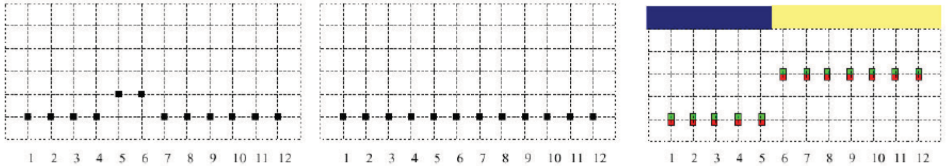
1. Linear interpolation
2. Median filter on color differences

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)

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)

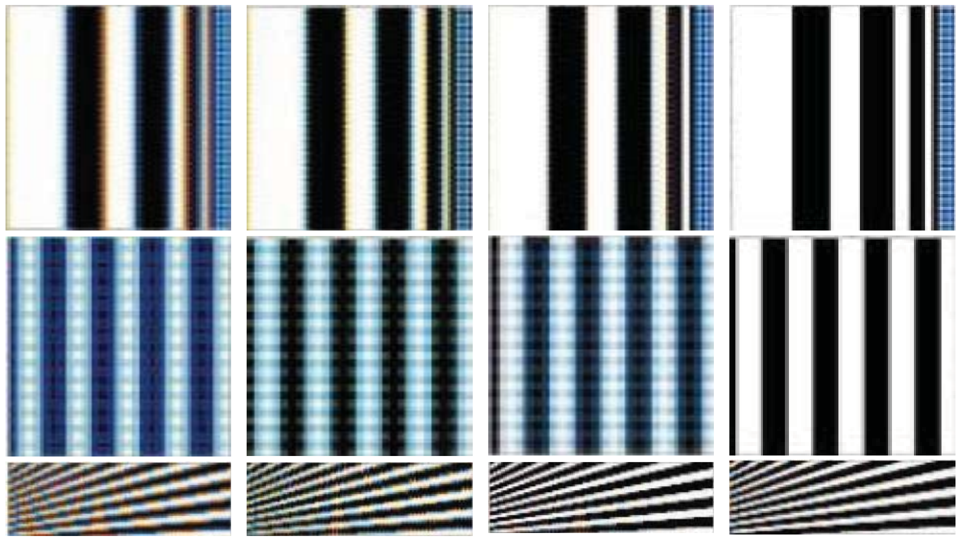
2. Interpolation of color differences

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

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

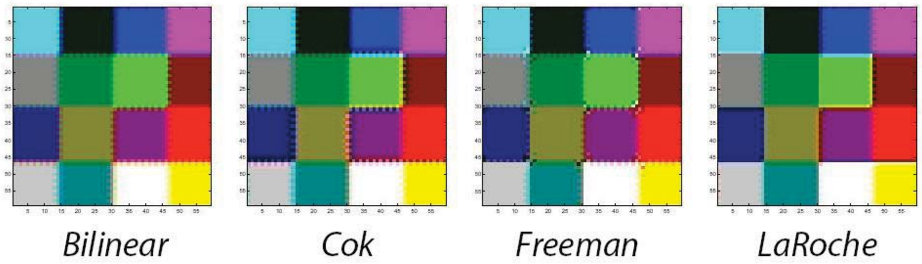
$$R_{44} = \frac{(R_{33}-\mathbf{G}_{33})+(R_{35}-\mathbf{G}_{35})+(R_{53}-\mathbf{G}_{53})+(R_{55}-\mathbf{G}_{55})}{4} + G_{44}.$$

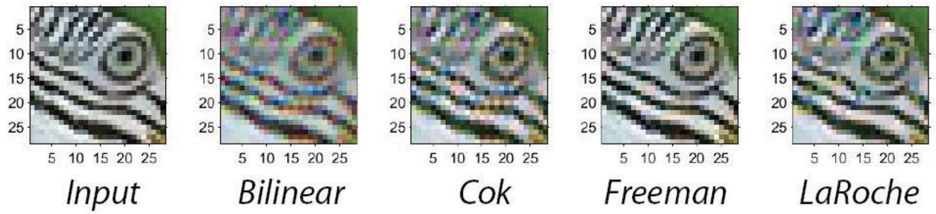
Demosaicking CFA's



bilinear | Cok | Freeman | LaRoche

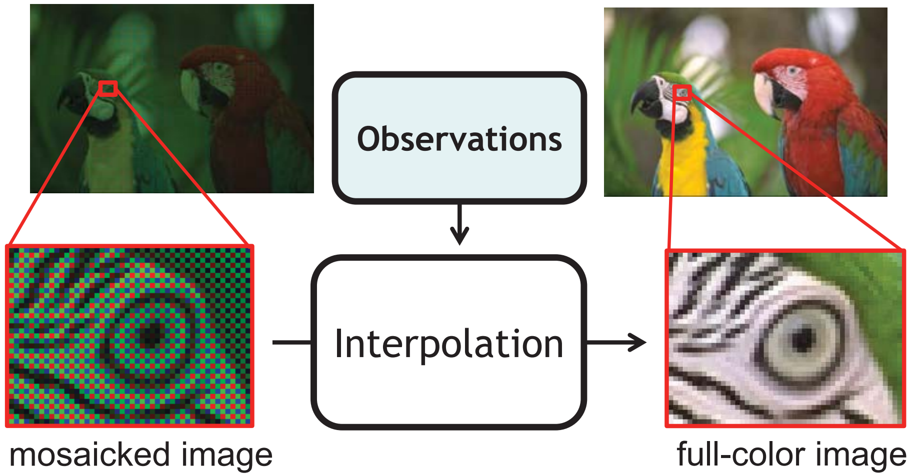
Demosaicking CFA’s



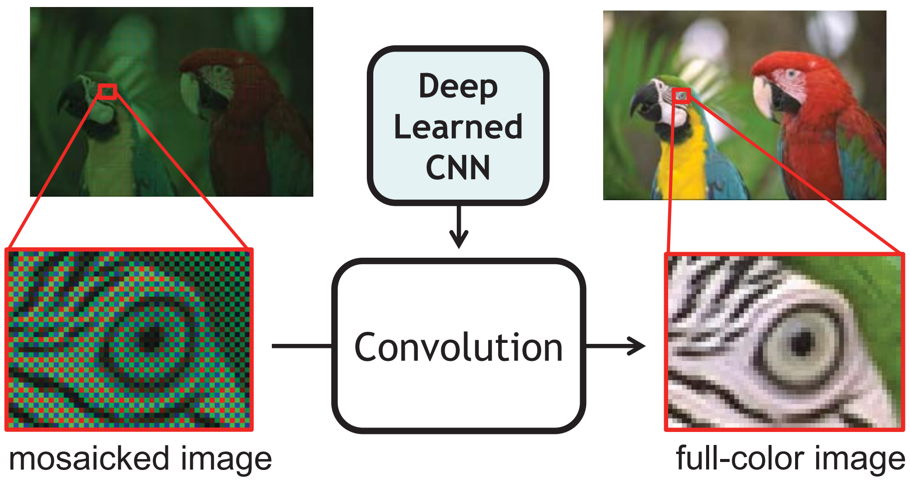


Generally, Freeman’s is the best, especially for natural images.

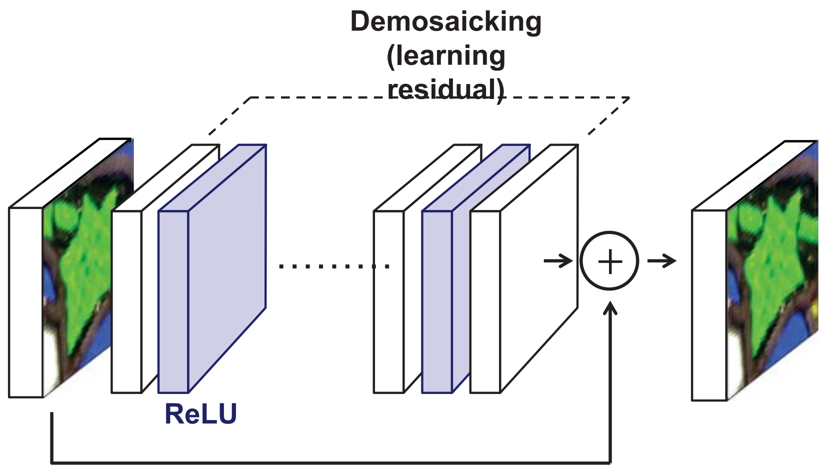
Interpolation-based methods



Deep learning approach



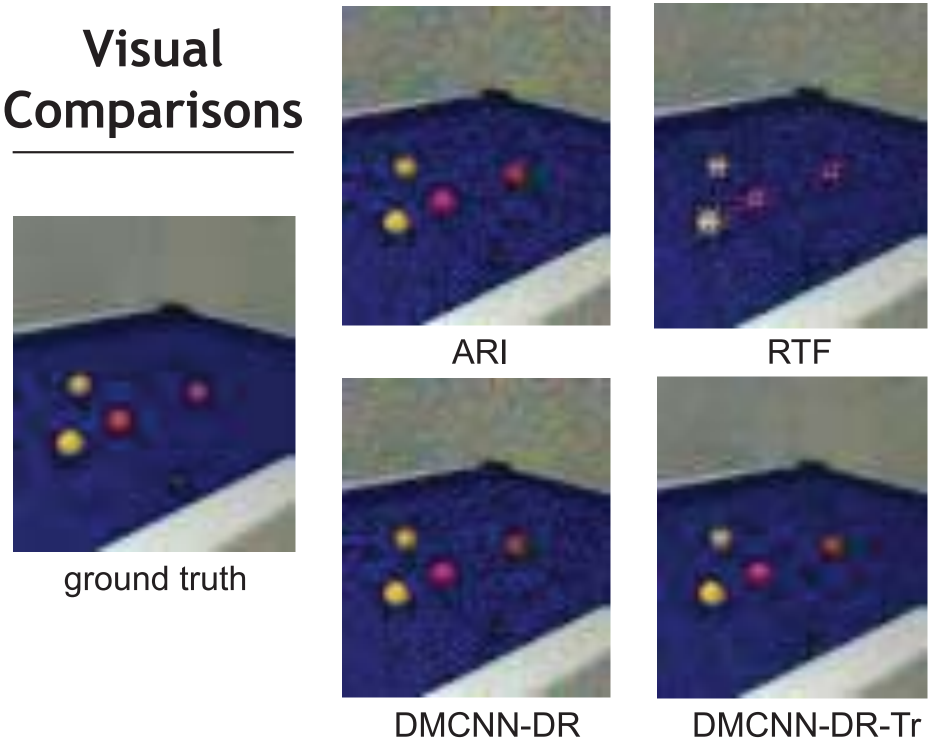
CNN-based demosaicking



evaluation

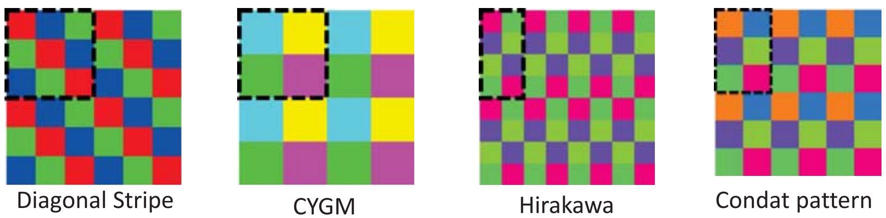
Algorithm	Kodak (12 photos)				McM (18 photos)				Kodak + McM (30 photos)			
	PSNR			CPSNR	PSNR			CPSNR	PSNR			CPSNR
	R	G	B		R	G	B		R	G	B	
SA	39.8	43.31	39.5	40.54	32.73	34.73	32.1	32.98	35.56	38.16	35.06	36.01
SSD	38.83	40.51	39.08	39.4	35.02	38.27	33.8	35.23	36.54	39.16	35.91	36.9
NLS	42.34	45.68	41.57	42.85	36.02	38.81	34.71	36.15	38.55	41.56	37.46	38.83
CS	41.01	44.17	40.12	41.43	35.56	38.84	34.58	35.92	37.74	40.97	36.8	38.12
ECC	39.87	42.17	39.00	40.14	36.67	39.99	35.31	36.78	37.95	40.86	36.79	38.12
RI	39.64	42.17	38.87	39.99	36.07	39.99	35.35	36.48	37.5	40.86	36.76	37.88
MLRI	40.59	42.97	39.86	40.94	36.35	39.9	35.36	36.62	38.04	41.13	37.16	38.35
ARI	40.81	43.66	40.21	41.31	37.41	40.72	36.05	37.52	38.77	41.9	37.72	39.03
PAMD	41.88	45.21	41.23	42.44	34.12	36.88	33.31	34.48	37.22	40.21	36.48	37.66
AICC	42.04	44.51	40.57	42.07	35.66	39.21	34.34	35.86	38.21	41.33	36.83	38.34
DMCNN	39.86	42.97	39.18	40.37	36.50	39.34	35.21	36.62	37.85	40.79	36.79	38.12
DMCNN-DR	42.43	45.66	41.55	42.86	39.37	42.24	37.45	39.14	40.59	43.61	39.09	40.63

Visual Comparisons

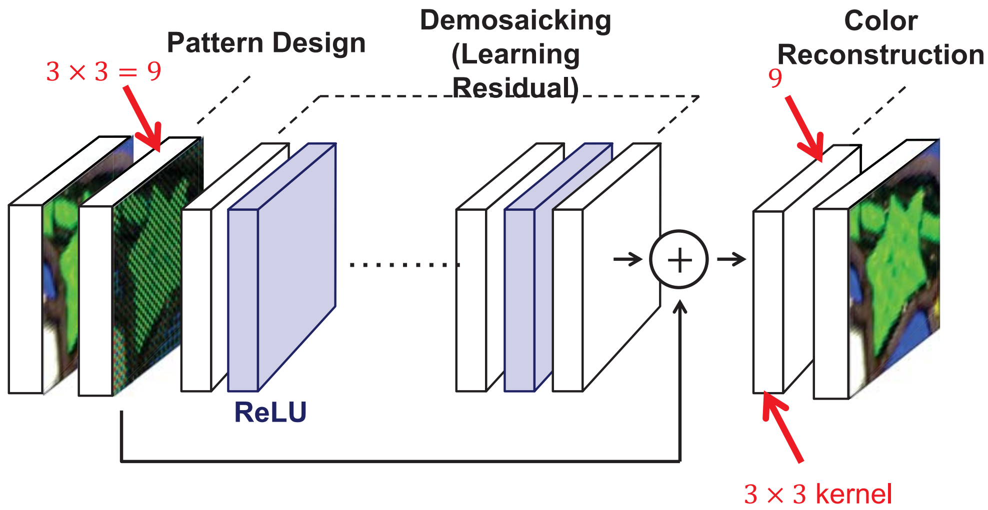


Evaluation with different patterns

Algorithms	Patern	Kodak (12 photos)				McM (18 photos)				Kodak + McM (30 photos)			
		PSNR			CPSNR	PSNR			CPSNR	PSNR			CPSNR
		R	G	B		R	G	B		R	G	B	
NLS	Bayer	42.34	45.68	41.57	42.85	36.02	38.81	34.71	36.15	38.55	41.56	37.46	38.83
ARI	Bayer	40.75	43.59	40.16	41.25	37.39	40.68	36.03	37.49	38.73	41.84	37.68	39.00
DMCNN-DR	Bayer	42.43	45.66	41.55	42.86	39.37	42.24	37.45	39.14	40.59	43.61	39.09	40.63
DMCNN-DR	Diagonal Stripe	42.00	42.47	41.36	41.91	39.70	39.5	38.02	38.87	40.62	40.69	39.36	40.08
DMCNN-DR	CYGM	41.16	46.00	41.80	42.48	38.64	41.98	38.44	39.36	39.65	43.59	39.78	40.60
DMCNN-DR	Hirakawa	43.20	44.95	42.53	43.43	39.59	40.52	38.42	39.38	41.03	42.29	40.06	41.00
Condat	Hirakawa	41.99	43.18	41.53	42.16	33.93	34.83	33.44	33.94	37.15	38.17	36.68	37.23
Condat	Condat	41.68	42.7	41.27	41.83	34.05	35.08	33.57	34.1	37.1	38.13	36.65	37.19

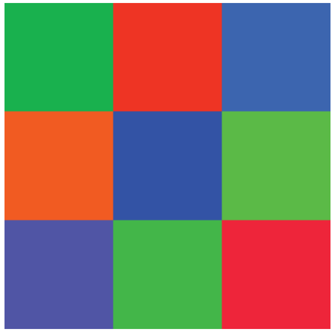


Pattern optimization



Learned pattern

Without non-negative constraints



With non-negative constraints

Evaluation with the learned pattern

Algorithm	Kodak (12 photos)				McM (18 photos)				Kodak + McM (30 photos)			
	PSNR			CPSNR	PSNR			CPSNR	PSNR			CPSNR
	R	G	B		R	G	B		R	G	B	
SA	39.80	43.31	39.50	40.54	32.73	34.73	32.10	32.98	35.56	38.16	35.06	36.01
SSD	38.83	40.51	39.08	39.40	35.02	38.27	33.80	35.23	36.54	39.16	35.91	36.90
NLS	42.34	45.68	41.57	42.85	36.02	38.81	34.71	36.15	38.55	41.56	37.46	38.83
CS	41.01	44.17	40.12	41.43	35.56	38.84	34.58	35.92	37.74	40.97	36.80	38.12
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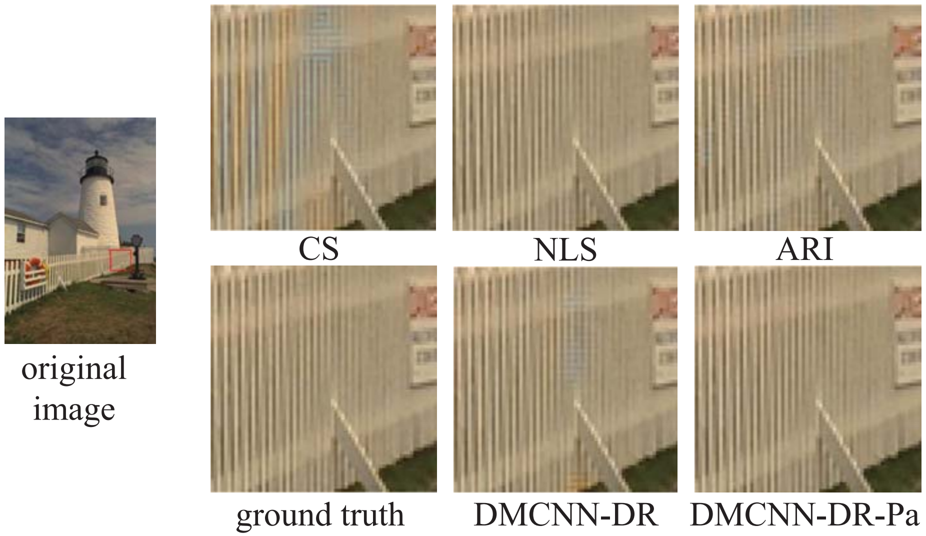
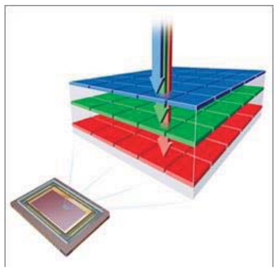
AICC	42.04	44.51	40.57	42.07	35.66	39.21	34.34	35.86	38.21	41.33	36.83	38.34
DMCNN	39.86	42.97	39.18	40.37	36.50	39.34	35.21	36.62	37.85	40.79	36.79	38.12
DMCNN-DR	42.43	45.66	41.55	42.86	39.37	42.24	37.45	39.14	40.59	43.61	39.09	40.63
DMCNN-Pa	43.06	43.76	42.13	42.92	40.63	40.14	38.74	39.68	41.60	41.59	40.01	40.98

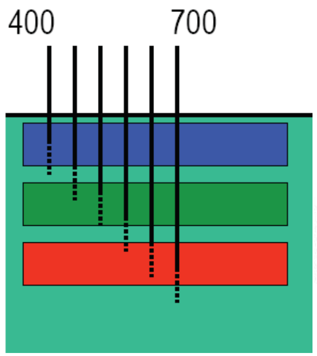
Visual Comparisons

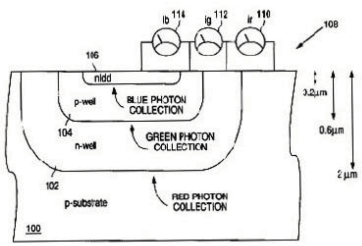


Foveon X3 sensor

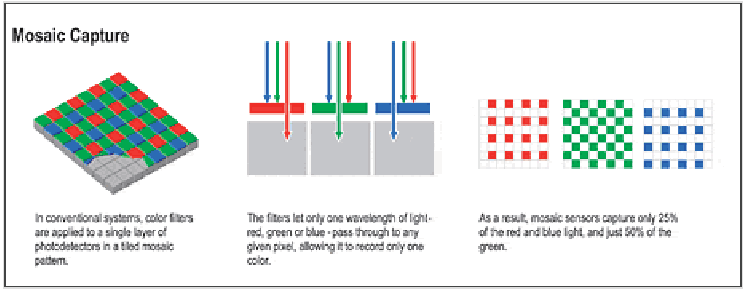
- light penetrates to different depths for different wavelengths
- multilayer CMOS sensor gets 3 different spectral sensitivities

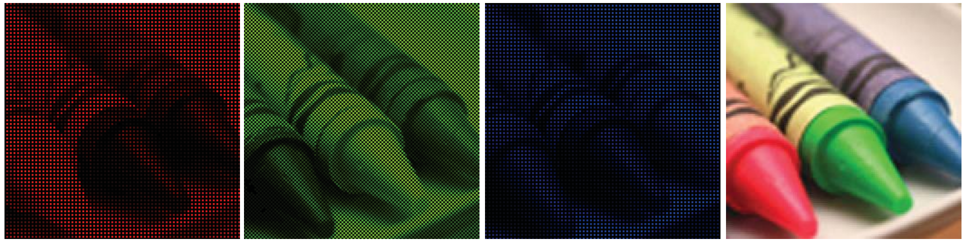






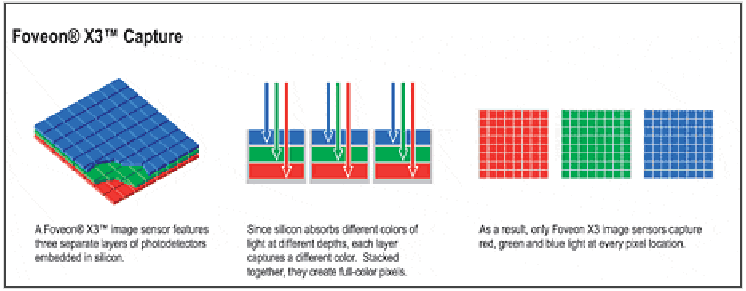
Color filter array





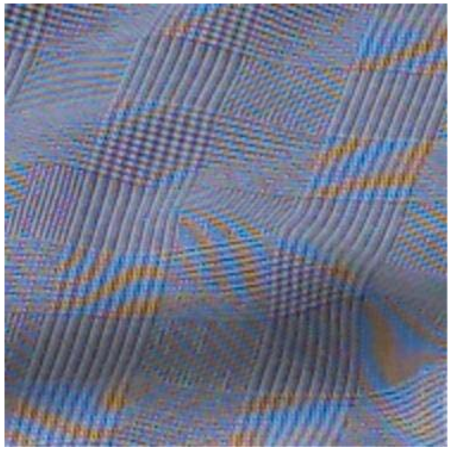
red green blue output

X3 technology

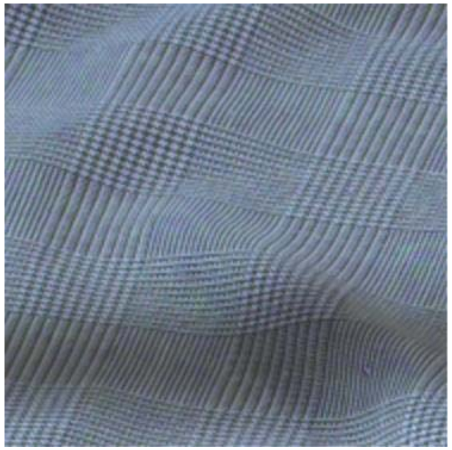


red green blue output

Foveon X3 sensor



Bayer CFA



X3 sensor

Cameras with X3

Sigma SD10, SD9

Polaroid X530

Sigma SD9 vs Canon D30

Color processing

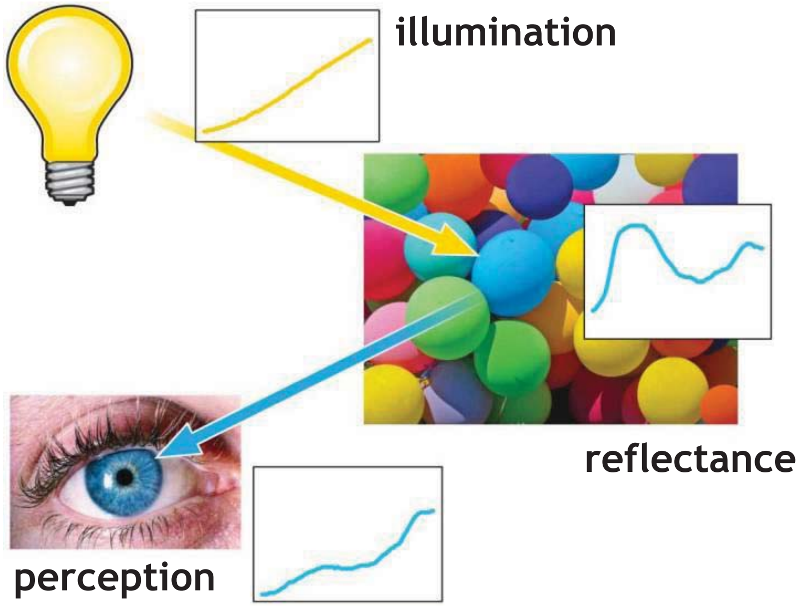
- After color values are recorded, more color processing usually happens:
  - White balance
  - Non-linearity to approximate film response or match TV monitor gamma

White Balance

warmer +3

automatic white balance

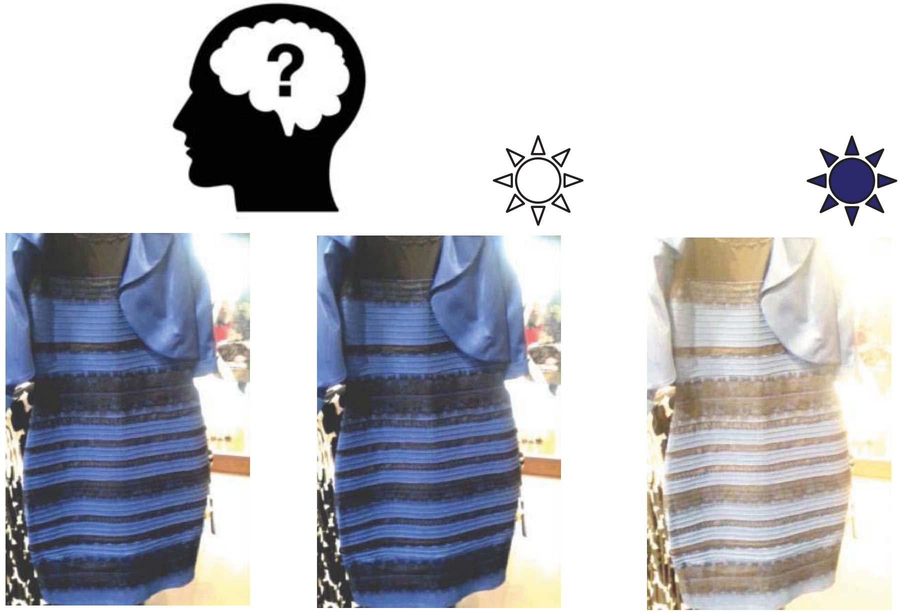
White Balance



Color constancy

What color is the dress?

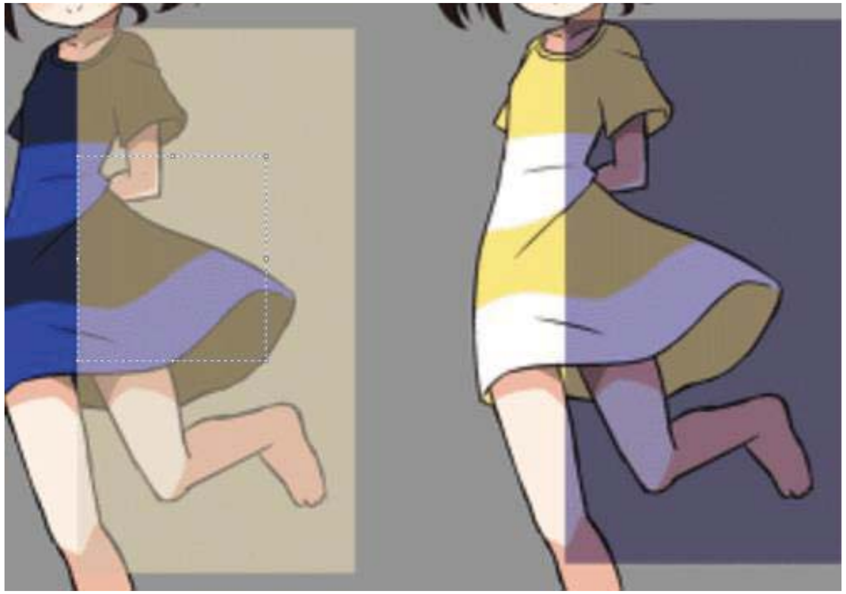
Color constancy



Human vision is complex

Color perception depends on surrounding

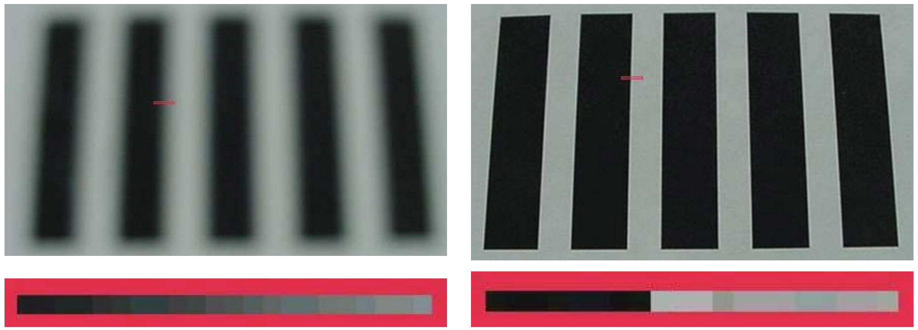
Color perception depends on surrounding



Color perception depends on surrounding

Autofocus

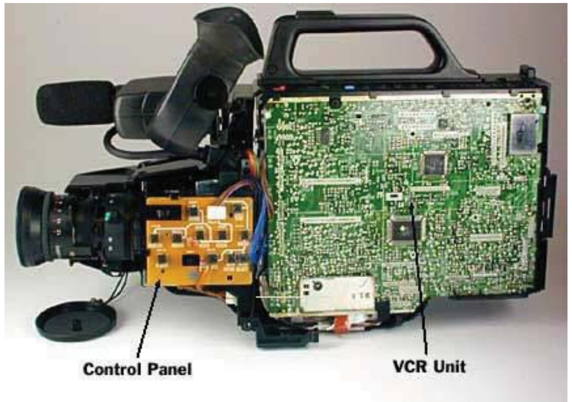
- Active
  - Sonar
  - Infrared
- Passive



Digital camera review website

- A cool video of digital camera illustration
- http://www.dpreview.com/

Camcorder

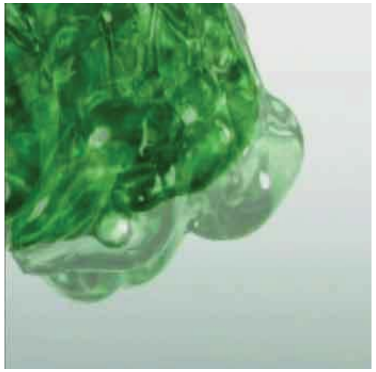


Interlacing


without interlacing


with interlacing

Deinterlacing


blend


weave

Deinterlacing


Discard
(even field only or
odd filed 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/