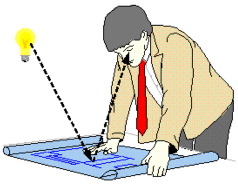
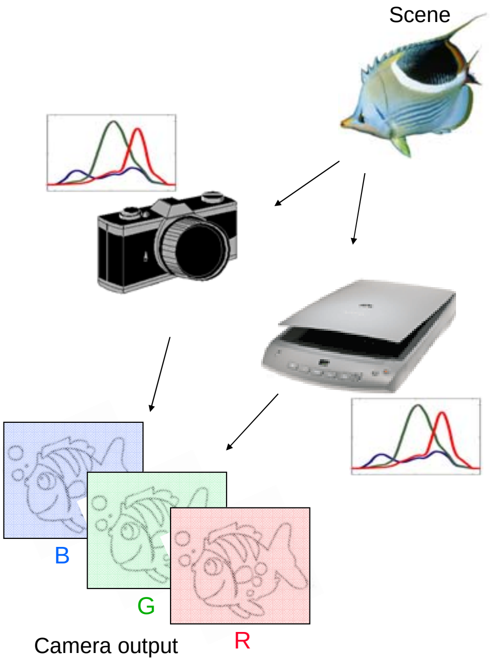
Lecture 7

Acquisition Devices

Optics
Sensors
Scanners
Digital Cameras
CCD Arrays vs CMOS
Applications: Camera calibration
    Gamma Insertion
    Color Correction
    Demosaicing



Acquisition Devices



Acquisition Devices

Two components:

Optics: Lens, zoom motor, shutter.

Sensors: CCD, acquisition pipeline

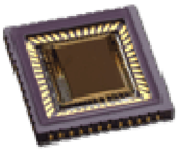
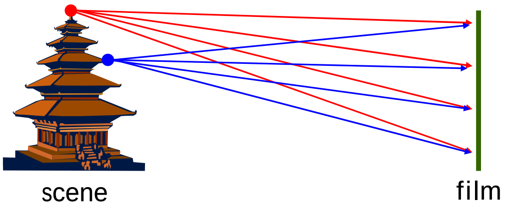


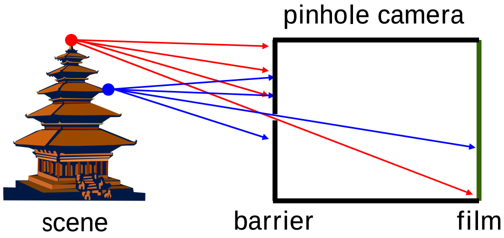
Image Formation - Optics



Put a piece of film in front of an object.

source: Yung-Yu Chuang

Image Formation - Optics

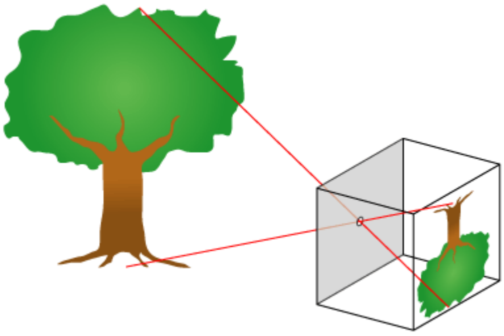


Add a barrier to block off most of the rays.

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

source: Yung-Yu Chuang

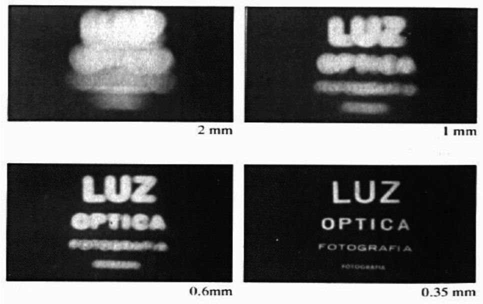
Pinhole camera



The image is inverted

Image Formation - Optics

Shrinking the aperture

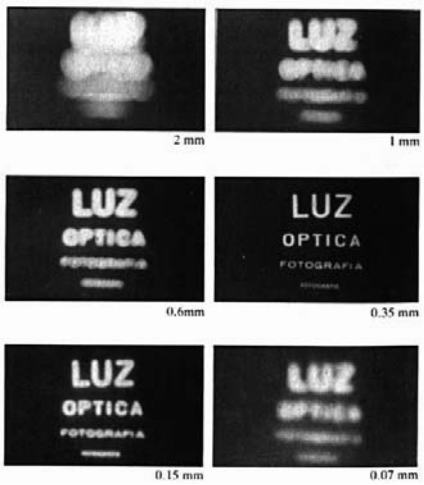


Why not create the aperture as small as possible?

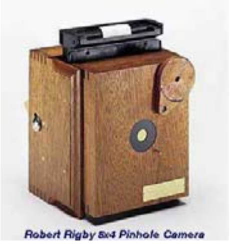
- Less light gets through
- Diffraction effect

Image Formation - Optics

Shrinking the aperture



High-end commercial pinhole cameras



Pinhole Images

Exposure 96 minutes

Images copyright © 2000 Zero Image Co.

Image Formation - Optics

Adding a Lens

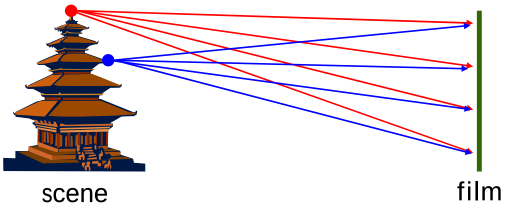
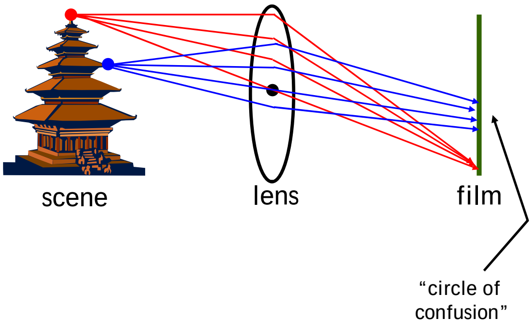
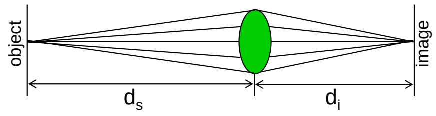


Image Formation - Optics

Adding a Lens



Lensmaker's Equation

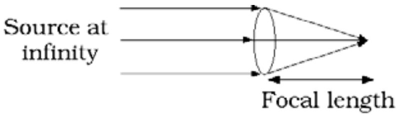


$$\frac{1}{d_s} + \frac{1}{d_i} = \frac{1}{f}$$

$d_s = source\ dist$

$d_i = image\ dist$

$f = focal\ length$

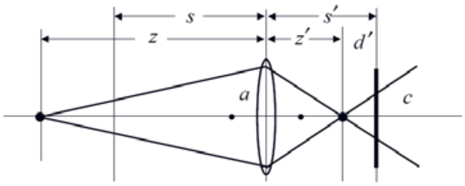


$$\text{Lens power (diopters)} = \frac{1}{\text{Focal length (m)}}$$

In-Focus
Out-of-Focus

If sensor plane position and object distance do not satisfy Lensmaker's equation then image is blurred.

Circle of Confusion



In-focus

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

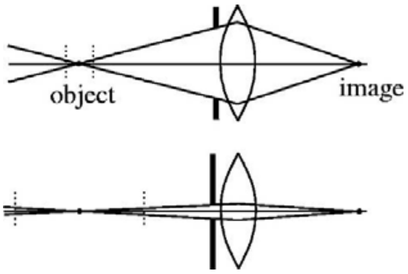
Out-of-focus

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

Circle of confusion is proportional to the size of the aperture.

$$\frac{c}{a} = \frac{d'}{z'} = \frac{s' - z'}{z'}$$

Depth of Field



Aperture affects depth of field:

Smaller aperture:

- better DOF
- increased exposure

Depth of Field

http://www.cambridgeincolour.com/tutorials/depth-of-field.htm

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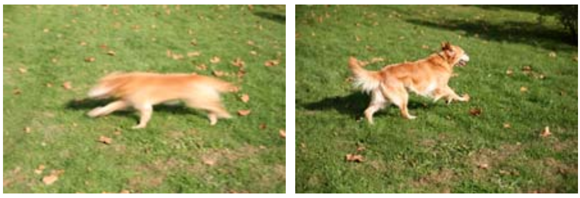
Aperture vs. Shutter

Depth of Field

f/22
Small Aperture
(Low speed)

f/4
Large Aperture
(High speed)

Motion Blur



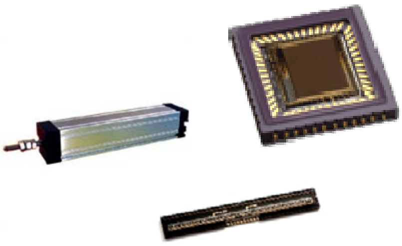
1/30 sec. @ f/22
Small Aperture
(Low speed)

1/6400 sec. @ f/2.5
Large Aperture
(High speed)

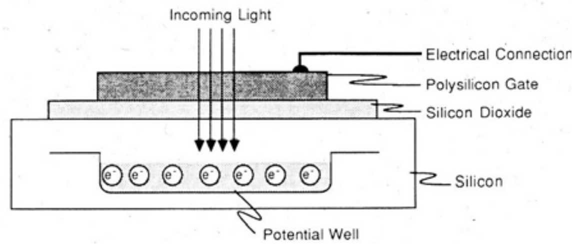
Camera optics - issues

- Lens Zoom
- Field of View (FOV)
- Lens Aberrations
  - Radial Distortion
  - Vignetting
  - Chromatic Aberration
  - Spherical aberration
  - Astigmatism
  - Coma
  - Lens Glare

Image Acquisition - Sensors



Simple Photodetector (Pixel)



Stores as many as 10^5 electrons, though 10^4 more typical

The photoelectric effect

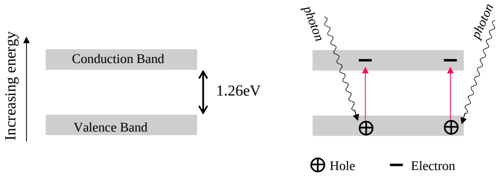
Atoms in a silicon crystal have electrons arranged in discrete energy bands

Valence Band (lower energy) Conduction Band (higher energy).

Most electrons occupy the Valence band but can be excited by photons or heat into the conduction band by the absorption of a photon. Requires 1.26 electron volts.

Once in the conduction band the electron is free to move about in the lattice of the silicon crystal, leaving a 'hole' in the valence band which acts like a positively charged carrier. In the absence of an external electric field the hole and electron will quickly re-combine and be lost.

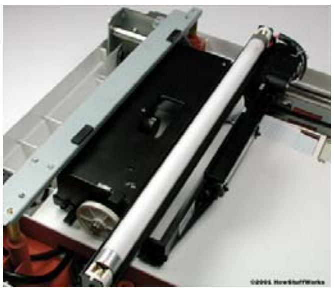
In a CCD an electric field is introduced to sweep these charge carriers apart and prevent recombination.



Thermally generated electrons are indistinguishable from photo-generated electrons → 'Dark Current'.

Keep CCDs cold!

Scanners



http://computer.howstuffworks.com/scanner.htm

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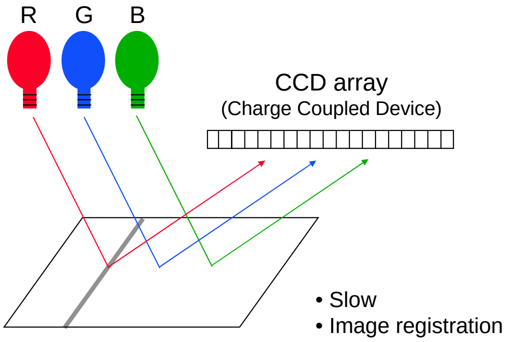
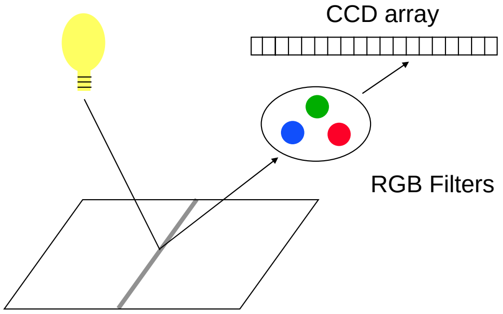
3 Pass Color Scanner



R G B

CCD array
(Charge Coupled Device)

- Slow
- Image registration

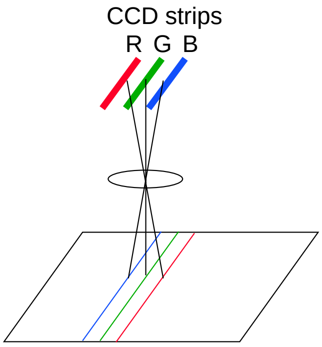


CCD array

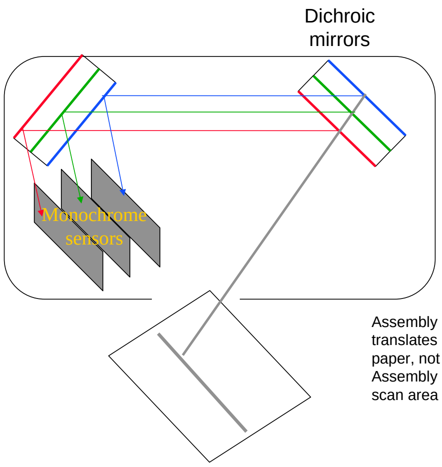
RGB Filters

1 Pass Color Scanner

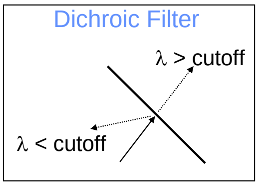
(Hitachi)
Pipeline design



1 Pass scanner - HP-Scanjet

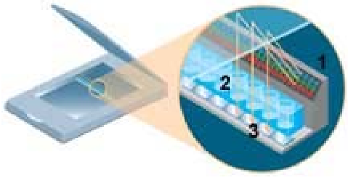


Assembly translates across paper, not to scale. Assembly is small, scan area is large



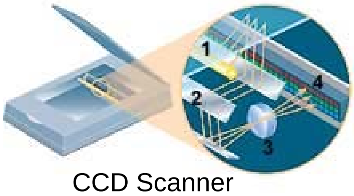
Contact Image Sensors (CIS) Scanner

CIS Scanner



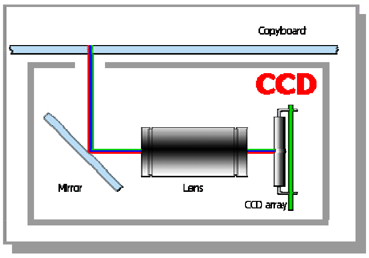
Array of image sensors lies just under the scanned document and catch the reflected light directly.

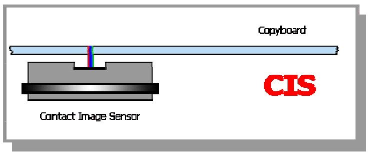
LEDs illuminate the scan line (using time multiplexing in RGB) and Light Pipes guide lights to sensors.



CCD Scanner

Contact Image Sensors (CIS) Scanner vs Charge Coupled Device (CCD) Scanners

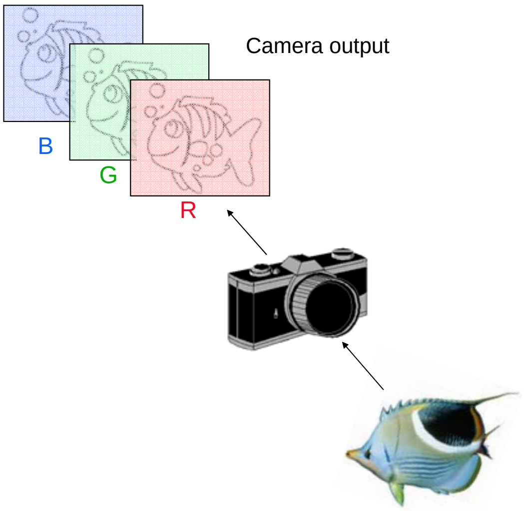




CIS scanners are :
- Cheaper to manufacture
- Smaller and more durable (good for handheld and small devices)
- Require less power (can use battery or USB port).

However:
CIS scan at lower resolution than CCD scanners.

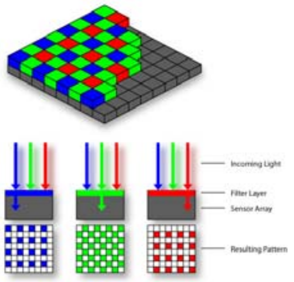
Digital Cameras

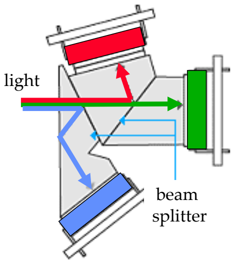


Digital Cameras

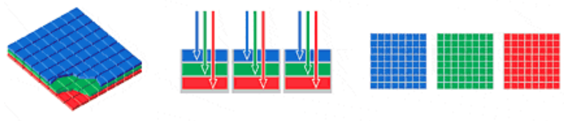
Architectures

Color Filter Array
(CFA)





3 CCD

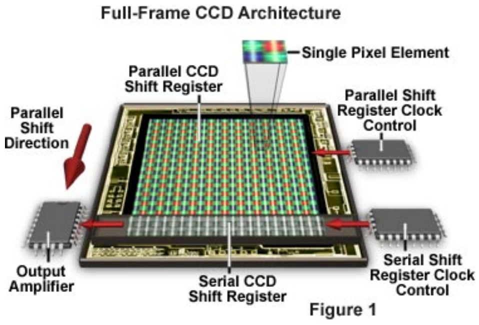


Foveon X3TM

CCD pixel structure

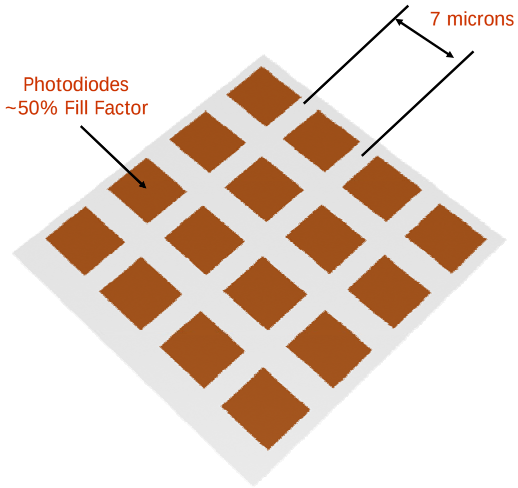
First charge coupled device was developed in 1973 by Sherman Fairchild For astronomy purposes. Increased sensitivity of telescopes by 100.

A 2001 amateur astronomer with a CCD camera and a 15 cm telescope collects as much light as an 1960 astronomer with a photographic plate and a 1m telescope. (Simon Tulloch)

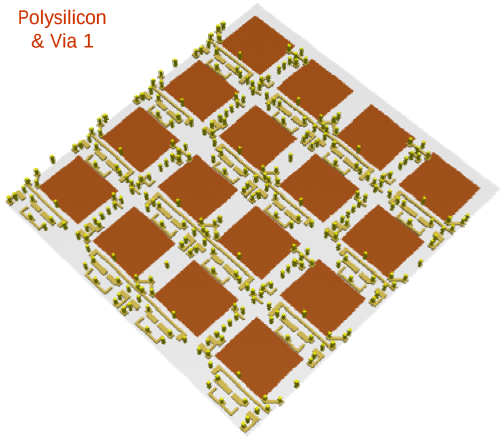


Digital Pixel Sensor (DPS) Structure

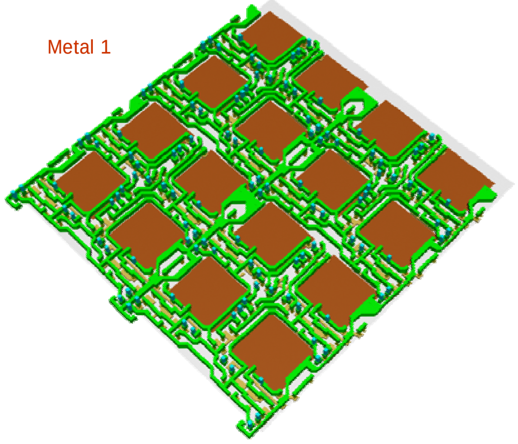
DPS – Pixel Structure



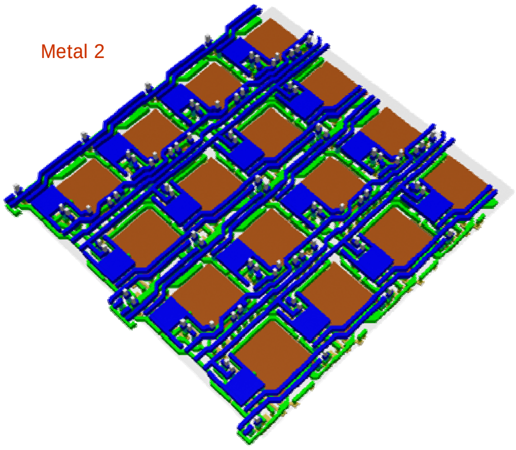
DPS – Pixel Structure



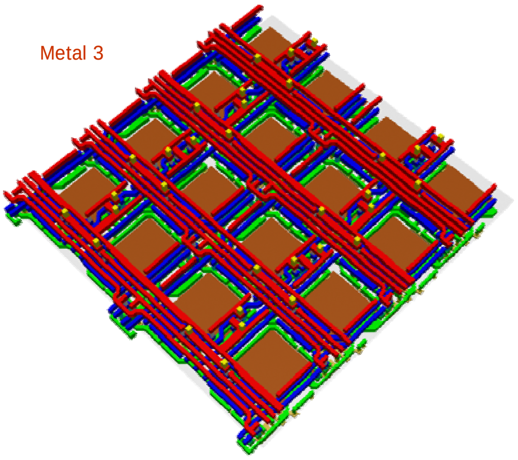
DPS – Pixel Structure



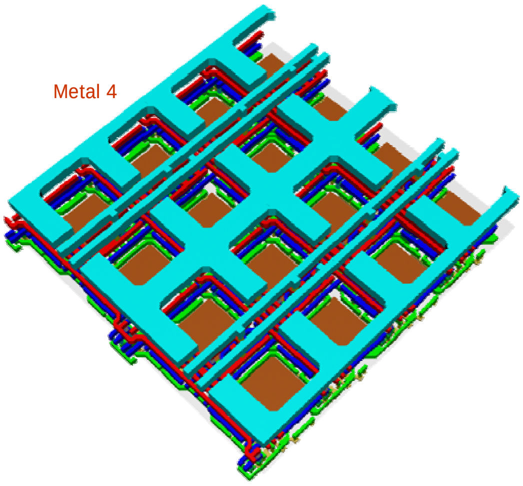
DPS – Pixel Structure



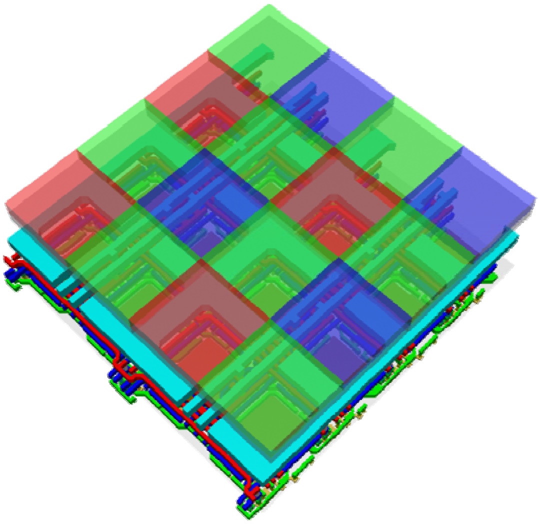
DPS – Pixel Structure



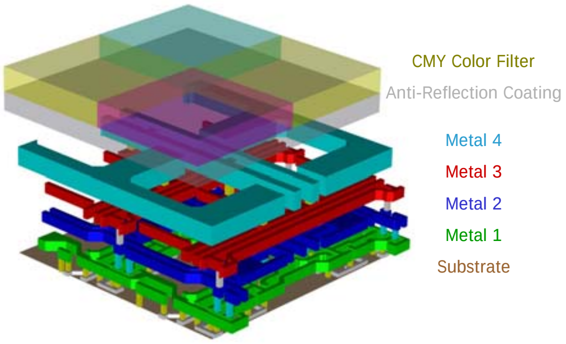
DPS – Pixel Structure



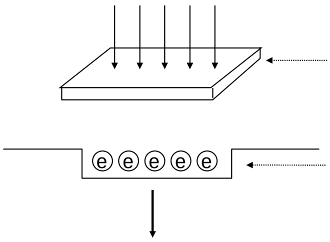
DPS – Pixel Structure



Dynamo Pixel Quad



Charge Coupled Device (CCD)

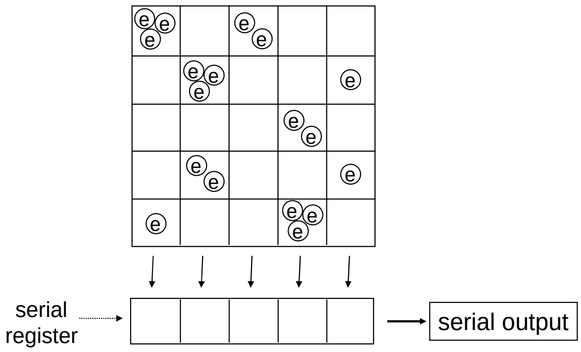


light

dye covered surface

potential well (bucket)

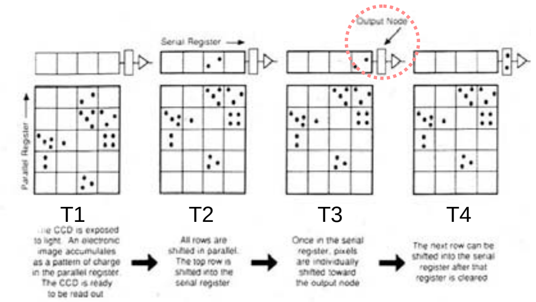
readout (Voltage)



serial register

serial output

Charge transfer in a full frame CCD



T1 The CCD is exposed to light. An electronic image accumulates as a pattern of charge in the parallel register. The CCD is ready to be read out

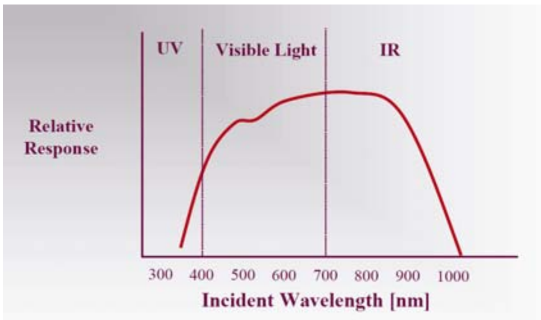
T2 All rows are shifted in parallel. The top row is shifted into the serial register

T3 Once in the serial register, pixels are individually shifted toward the output node

T4 The next row can be shifted into the serial register after that register is cleared

At Output node, analog-to-digital converter turns each pixel's value into a digital value.

Spectral Response of a Typical CCD



Camera Sensors

Two types of sensor technology:

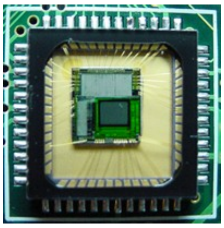
Charge Coupled Device (CCD).

Complementary Metal Oxide Semiconductor (CMOS)

CMOS Imagers

CMOS approach is more flexible because each pixel can be read individually.

- Fabrication cost
- Power
- Integration



Single Capture - Single Image

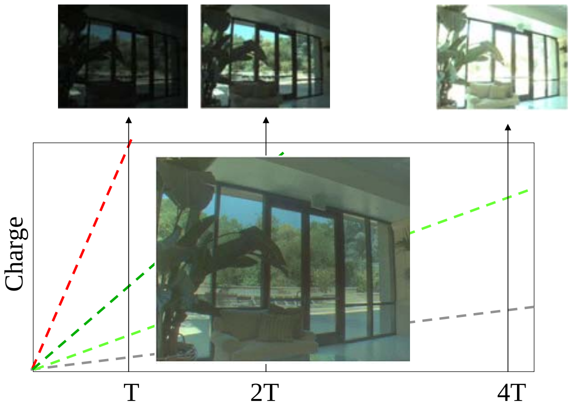
CCD image capture

OR

OR

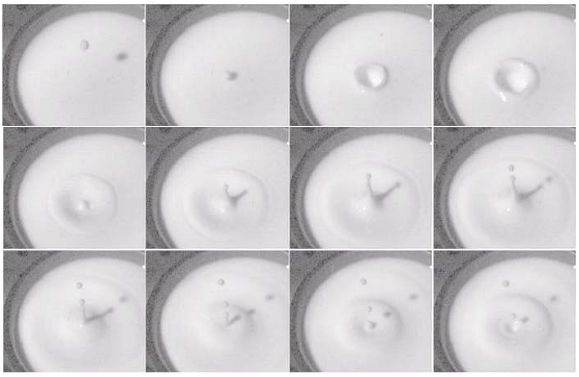
High Dynamic Range (HDR)

Multiple Capture Single Image



High Dynamic Range (HDR)

System Operation at 1400 fps (CDS, play back at 30 fps)



Programmable Digital Camera (PDC) project
Abbas El Gammal & Brian Wandell - Stanford University
10,000 Frames/Sec DPS Chip
http://www-isl.stanford.edu/~abbas/group/

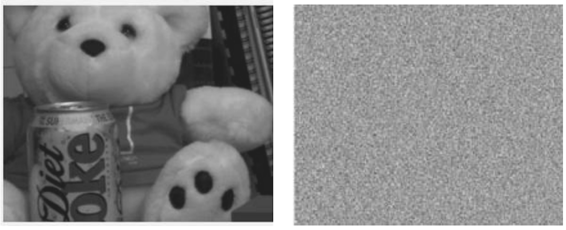
Noise Characteristics

Noise Sources
- Dark Noise (Constant)
- Photon noise (Poisson)
- Shot noise (Poisson)
- Thermal noise (Poisson)
- Resetting (fixed)
- Read-out noise (white)
- Read-out noise (1/f)

(After T. Lomheim, The Aerospace Corporation)

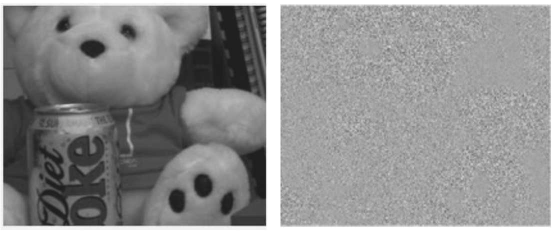
http://www.stw.tu-ilmenau.de/~ff/beruf_cc/cmos/cmos_noise.pdf

Dark Current and Dark Noise



Photon Noise

- More noise in bright parts of the image
- You can identify the white and black regions from the noise image



Fixed Pattern Noise

- Spatial variation in pixel output under uniform illumination due to device and interconnect parameter variations (mismatches across sensors).
- For CCD: appears random
- For CMOS: higher than CCD noise and may appear as ‘stripes’ (column noise).

CCD vs CMOS

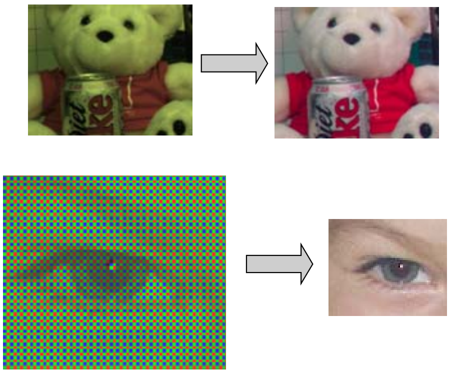
- CCD sensors create high-quality, low-noise images. CMOS sensors, are more susceptible to noise.
- Because each pixel on a CMOS sensor has several transistors located next to it, the light sensitivity of a CMOS chip is lower. Many of the photons hitting the chip hit the transistors instead of the photodiode.
- CMOS sensors consume little power. CCDs, consume lots of power (~ 100 times more power).
- CMOS chips can be fabricated on standard silicon production line, so they are inexpensive compared to CCDs.
- CCD sensors have been mass produced for a long time, so they are more mature. They tend to have higher quality pixels, and more of them.

CCDs tend to be used in cameras that focus on high-quality images with lots of pixels and excellent light sensitivity. CMOS sensors usually have lower quality, lower resolution and lower sensitivity. However, CMOS cameras are less expensive and have great battery life.

http://electronics.howstuffworks.com/digital-camera4.htm

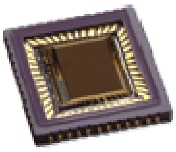
Acquisition Devices – Problems

- Calibration (raw to sRGB,Gamma)
- Color Correction (White Balancing)
- Demosiacing

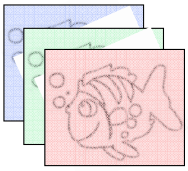


Camera Calibration

Given sensor output determine mapping to RGB values. LUT or Matrix.



Voltage Range:
0 ..10^4

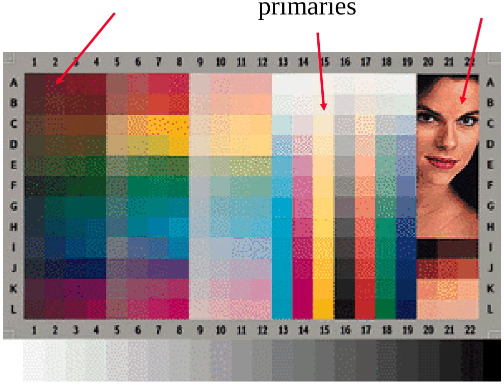


RGB Camera output:
0 ... 255

Linear Mapping is typically NOT sufficient

Camera Calibration

ANSI IT8.7 (Kodak-Q60)



Standard CIELAB

Printing primaries

Vendor area

- Columns 1-3, 5-7 and 9-11 have 108 standardized CIELAB values
- Accuracy to 10 ΔE_{ab}
- Produced by Kodak, Agfa, others

ftp://ftp.kodak.com/gastds/Q60DATA/TECHINFO.PDF

Camera Calibration

Altona TestSuite1.2a

ftp://ftp.kodak.com/gastds/Q60DATA/TECHINFO.PDF

Camera Calibration

Build sensor response matrixes:

$$\begin{bmatrix} | & | & & | \\ r_1 & r_2 & \cdots & r_n \\ | & | & & | \end{bmatrix} = M \begin{bmatrix} | & | & & | \\ r'_1 & r'_2 & \cdots & r'_n \\ | & | & & | \end{bmatrix}$$

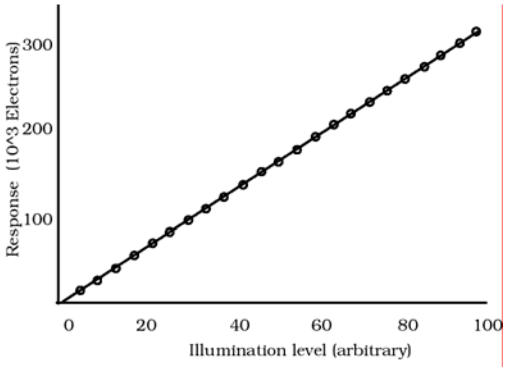
Target RGB (xyY) values

Sensor output

Solve

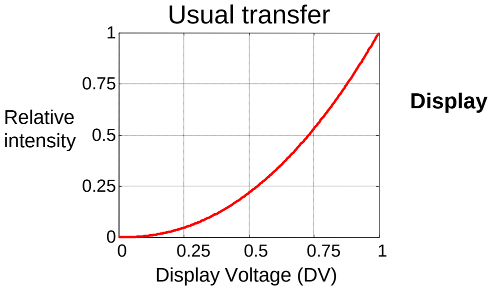
$$M = \begin{bmatrix} | & | & & | \\ r_1 & r_2 & \cdots & r_n \\ | & | & & | \end{bmatrix} \begin{bmatrix} | & | & & | \\ r'_1 & r'_2 & \cdots & r'_n \\ | & | & & | \end{bmatrix}^*$$

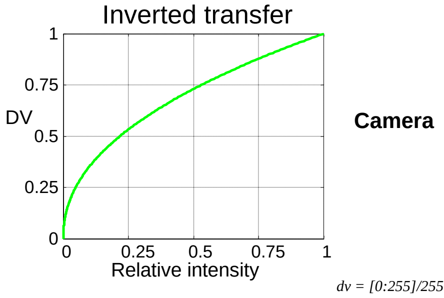
CCD and CMOS Sensor Transduction Functions Are Usually Linear



(Epperson, P.M. et al. Electro-optical characterization of the Tektronix TK5 ...., Opt Eng., 25, 1987)

Display transduction function is usually nonlinear

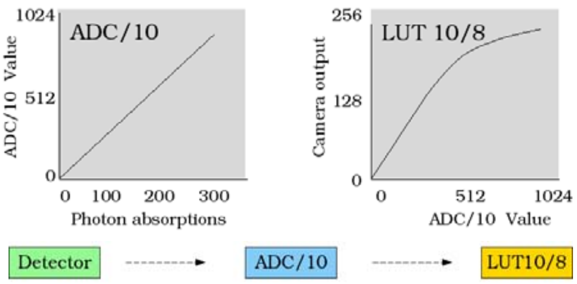




```
dv = [0:255]/255;
I = dv.^(2.2);
```

Digital camera transduction is often implemented by look-up tables (LUTs)

Gamma Correction



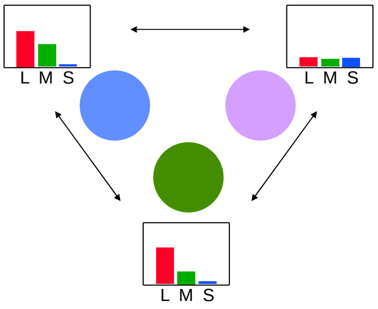
Color Correction
White Balance

Affects of Illumination

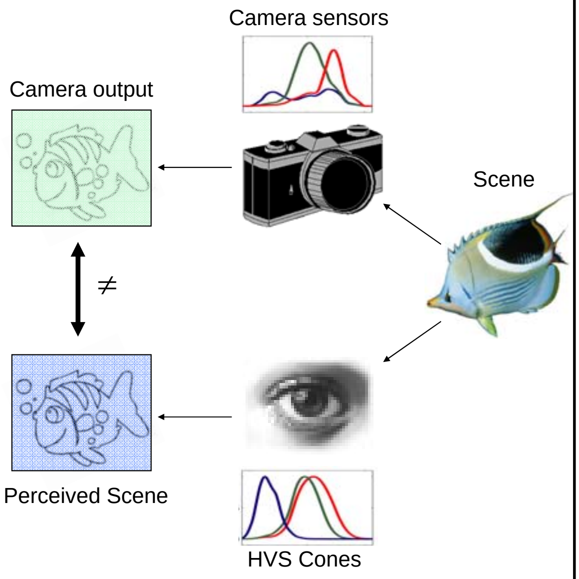
Color Constancy

Absolute level of cone responses does **not** define an object’s color appearance.

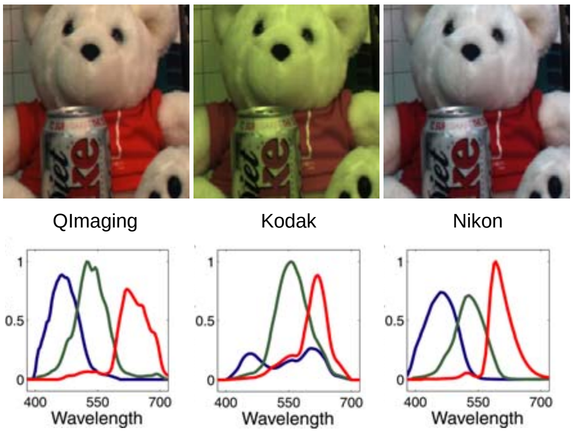
The level of sensor responses relative to responses to other objects in the scene defines the color appearance of an object..



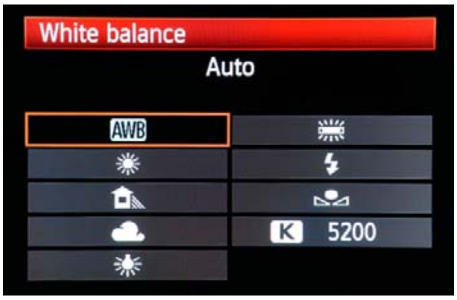
Camera vs Perceived



Additional Variations due to Camera Sensors


QImaging Kodak Nikon

White balance


White balance

Auto

User sets white balance manually - defines color mapping.

White balance

Tungsten

Sun

Yellow Balanced

Red Balanced

Blue Balanced

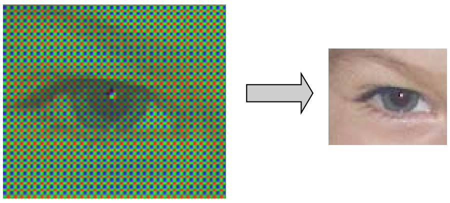
Auto

Illumination Correction

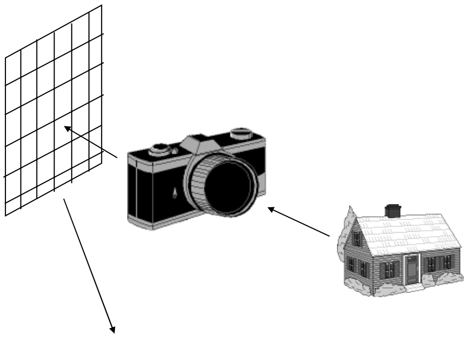
Change image acquired under one illumination, to appear as if taken under a different illumination.

- Linear Models
- Retinex
- Gray World Assumption
- Brightest Point Assumption
- Specularity

Demosaicing



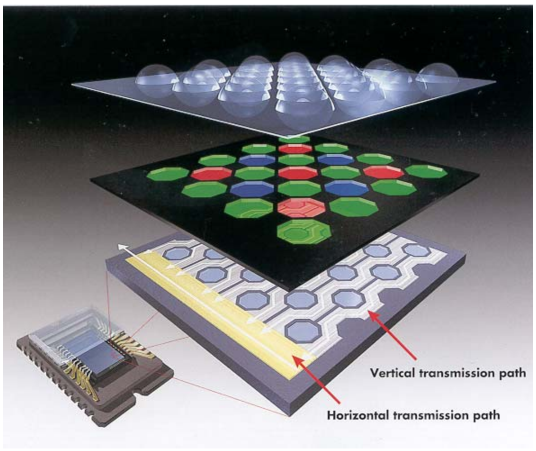
Digital Cameras - Color Filter Arrays (CFA)



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

CCD Array

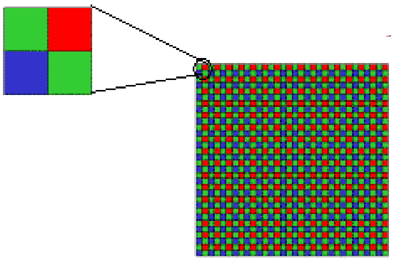
Sensor Architecture



Fuji Corporation

Color Filter Array (CFA)

Bayer CFA



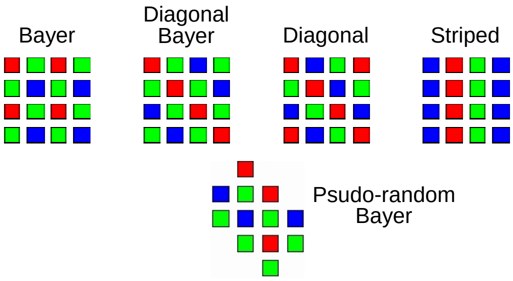
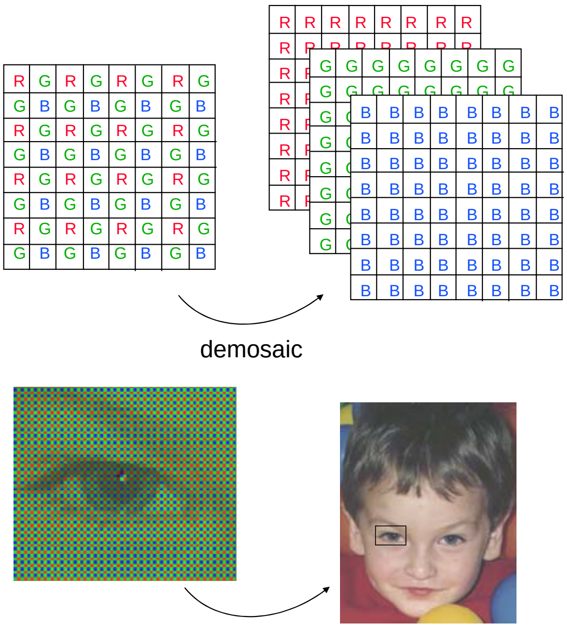


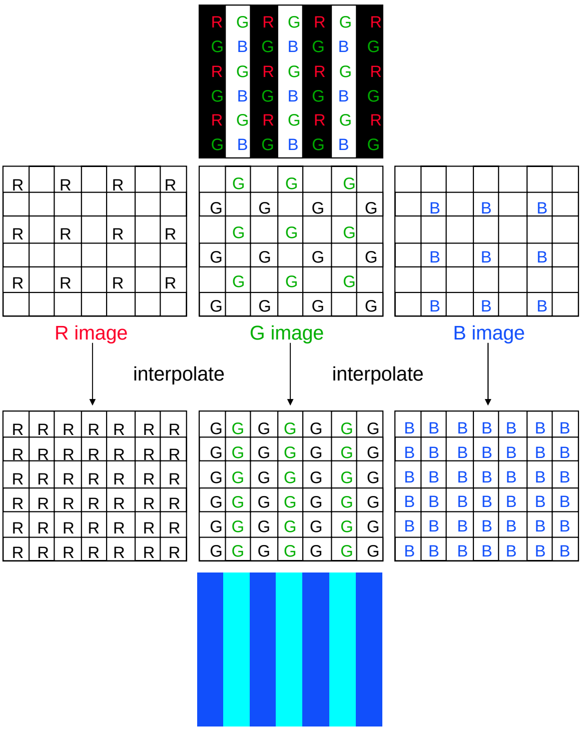
Image Demosaicing



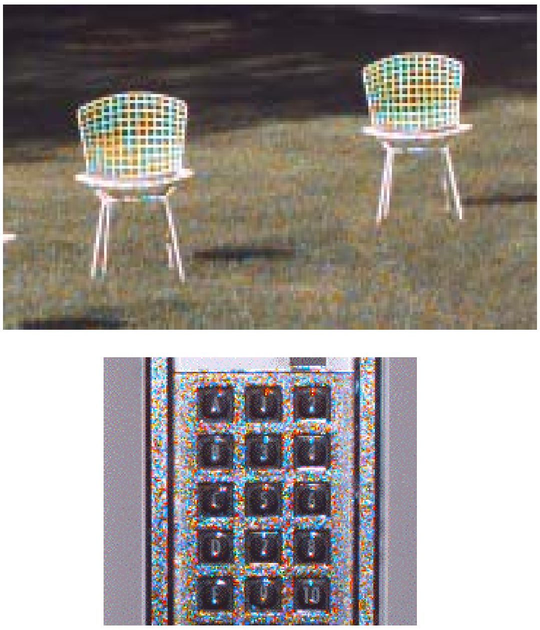
Demosaicing – Solutions

- Using spatial coherence:
  - Non adaptive:
    - Nearest Neighbor interpolation
    - Bilinear interpolation
    - Bicubic interpolation, etc.
  - Adaptive:
    - Edge sensing interpolation
- Using color coherence:
  - Non Adaptive
  - Adaptive

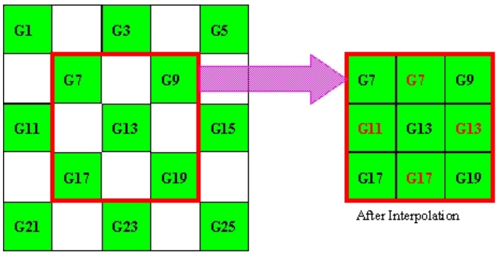
Demosaic Aliasing



Demosaicing - Example



Demosaicing: Nearest Neighbor



After Interpolation

Before Interpolation

Nearest neighbor interpolation: Take the value of a missing pixel from its nearest neighbor's value.

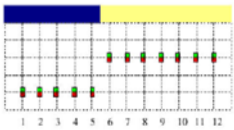
Problematic in gradient areas and near edges

Demosaicing: Linear interpolation

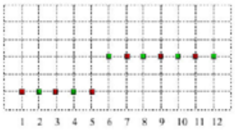
–Assuming piecewise linear function

–Artifacts near edges

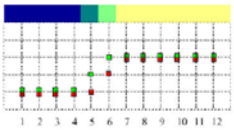
G(k)=(G(k+1)+G(k-1)) /2



original



input



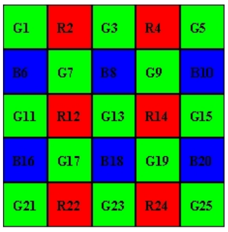
linear interpolation

Demosaicing: Bilinear Interpolation

Existing values are left untouched. The average of adjacent green pixel values is interpolated.

For example

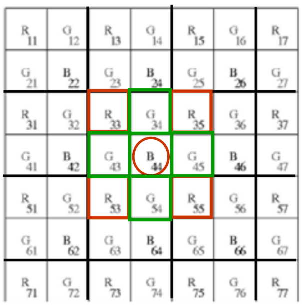
G8 = (G3+G7+G9+G13) / 4



Demosaicing: Bilinear Interpolation

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

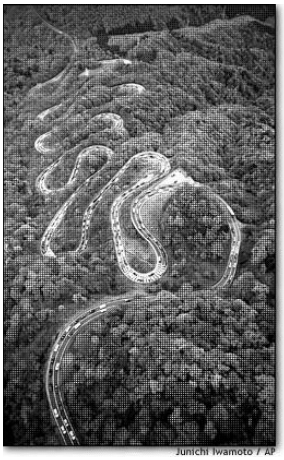
$$R_{44}=(R_{33}+R_{35}+R_{53}+R_{55})/4$$



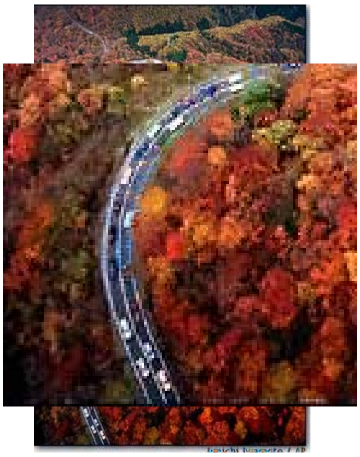

Mosaic Image


Bilinear Interpolation


Bilinear Interpolation


Junichi Iwamoto / AP

Mosaic image



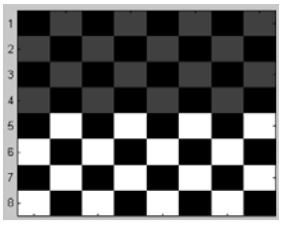
Bilinear Interpolation

Adaptive Demosaicing

R G R

G B G

R G R



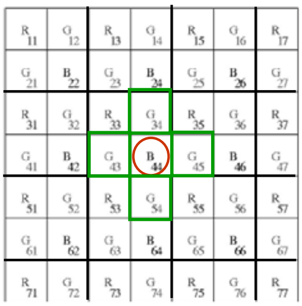
Goal: Don’t average across edges.

Method: Before averaging, check:
direction of gradient
and/or
check for outliers
Average only similar neighboring G values

Adaptive 2D Interpolation

$$\Delta h = \mathrm{abs}\left[G_{45} - G_{43}\right]$$
$$\Delta v = \mathrm{abs}\left[G_{34} - G_{54}\right]$$

$$G_{44} = \begin{cases} \dfrac{G_{34} + G_{54}}{2} & \text{if } \Delta h >> \Delta v \\ \dfrac{G_{43} + G_{45}}{2} & \text{if } \Delta v >> \Delta h \\ \dfrac{G_{34} + G_{54} + G_{43} + G_{45}}{4} & \text{if } \Delta v \approx \Delta h \end{cases}$$

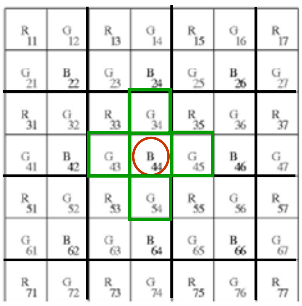


R_{11}	G_{12}	R_{13}	G_{14}	R_{15}	G_{16}	R_{17}
G_{21}	B_{22}	G_{23}	B_{24}	G_{25}	B_{26}	G_{27}
R_{31}	G_{32}	R_{33}	G_{34}	R_{35}	G_{36}	R_{37}
G_{41}	B_{42}	G_{43}	B_{44}	G_{45}	B_{46}	G_{47}
R_{51}	G_{52}	R_{53}	G_{54}	R_{55}	G_{56}	R_{57}
G_{61}	B_{62}	G_{63}	B_{64}	G_{65}	B_{66}	G_{67}
R_{71}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

Adaptive 2D Interpolation

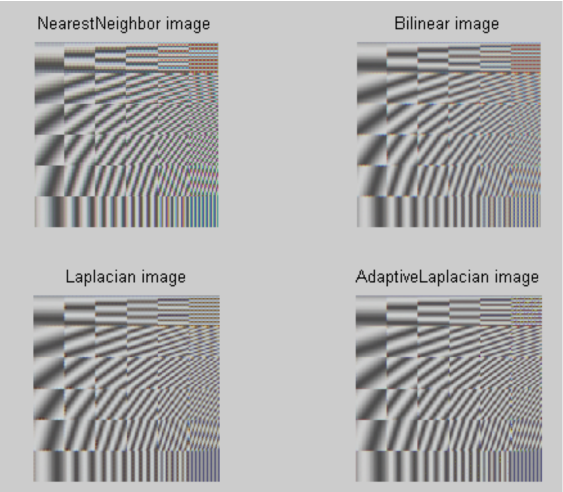
$$w_{45} = f\left(B_{46} - B_{44}\right)$$
$$w_{34} = f\left(B_{24} - B_{44}\right)$$
$$w_{43} = f\left(B_{42} - B_{44}\right)$$
$$w_{54} = f\left(B_{64} - B_{44}\right)$$

$$G_{44} = \frac{w_{45}G_{45} + w_{34}G_{34} + w_{43}G_{43} + w_{54}G_{54}}{w_{45} + w_{34} + w_{43} + w_{54}}$$



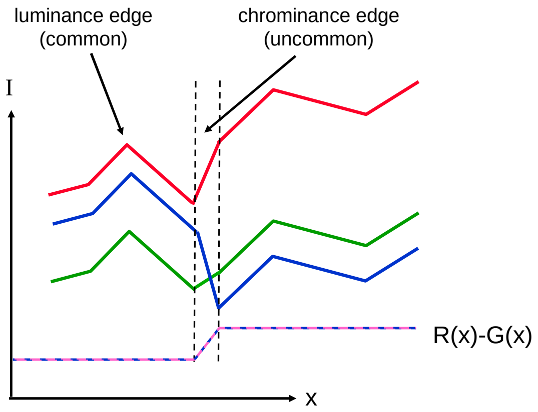
R_{11}	G_{12}	R_{13}	G_{14}	R_{15}	G_{16}	R_{17}
G_{21}	B_{22}	G_{23}	B_{24}	G_{25}	B_{26}	G_{27}
R_{31}	G_{32}	R_{33}	G_{34}	R_{35}	G_{36}	R_{37}
G_{41}	B_{42}	G_{43}	B_{44}	G_{45}	B_{46}	G_{47}
R_{51}	G_{52}	R_{53}	G_{54}	R_{55}	G_{56}	R_{57}
G_{61}	B_{62}	G_{63}	B_{64}	G_{65}	B_{66}	G_{67}
R_{71}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

Demosaicing Evaluation Tools



Demosaicing – Solutions

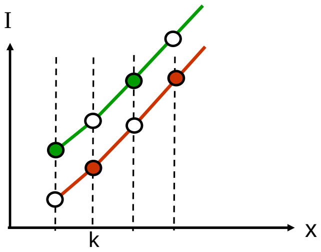
Color Coherence: Color bands are highly correlated in high frequencies



Spatial + Color Coherence

$R(x)-G(x) \approx C_{rg}$

$R'(x)=G'(x)=B'(x)$

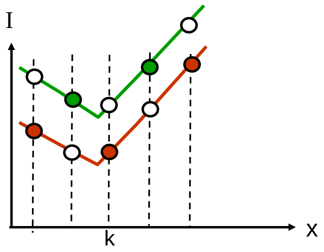


- Spatial coherence: $G(k)=(G(k-1)+G(k+1))/2$
- Color coherence: C_{rg}=average{R(x)-G(x)}

  $R(k)=G(k)+C_{rg}$

Problem: Fails near luminance and chrominance edges
Solution: Adaptive interpolation

Spatial + Color Coherence - Adaptive



Exploit color coherence for G interpolation:

Since R’(x)=G’(x) we have

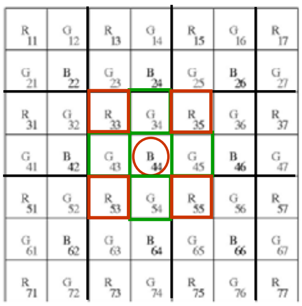
$$\tilde{G}_{k|k+1} = G_{k+1} + \frac{(R_k - R_{k+2})}{2}$$

$$\tilde{G}_{k|k-1} = G_{k-1} + \frac{(R_k - R_{k-2})}{2}$$

The estimates for G_k can be combined using an adaptive scheme

Spatial + Color Coherence - Adaptive

Edge Sensing Interpolation using Color Coherence:



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}

$$\tilde{G}_{44|45} = G_{45} + \frac{(B_{44} - B_{46})}{2}$$

$$\tilde{G}_{44|43} = G_{43} + \frac{(B_{44} - B_{42})}{2}$$

$$\tilde{G}_{44|34} = G_{34} + \frac{(B_{44} - B_{24})}{2}$$

$$\tilde{G}_{44|54} = G_{54} + \frac{(B_{44} - B_{64})}{2}$$

$$G_{44} = \frac{w_{45}\tilde{G}_{44|45} + w_{34}\tilde{G}_{44|34} + w_{43}\tilde{G}_{44|43} + w_{54}\tilde{G}_{44|54}}{w_{45} + w_{34} + w_{43} + w_{54}}$$

$$R_{44} = \frac{w_{33}\tilde{R}_{44|33} + w_{35}\tilde{R}_{44|35} + w_{55}\tilde{R}_{44|55} + w_{53}\tilde{R}_{44|53}}{w_{33} + w_{35} + w_{55} + w_{53}}$$

$$\tilde{R}_{44|ij} = G_{44} + (R_{ij} - G_{ij})$$

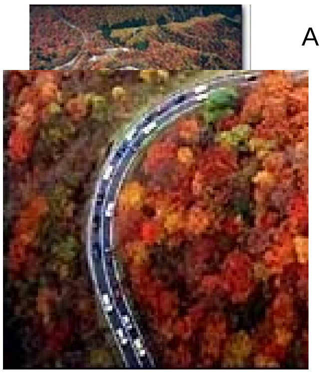
Bilinear

Adaptive + color coherence

Bilinear

Adaptive + color coherence

Bilinear



Adaptive

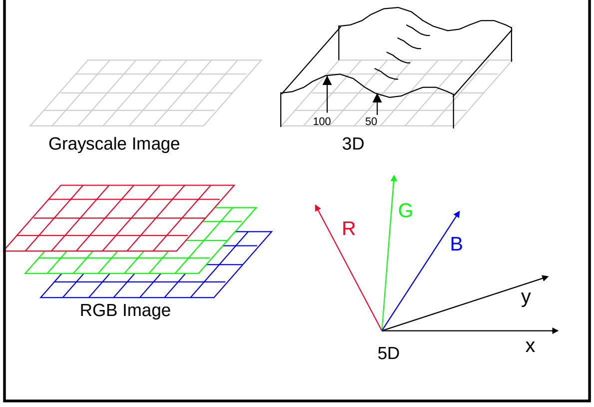
Demosaicing - Other Approaches

Regularization

Minimize over a functional with a data fit term and an inter-channel color correlation term.
(Gamer & Keren)

Minimal Surface

Minimize over a functional with a data fit term and a 5D surface area term. (Beltrami Flow)
(Kimmel)



Demosaicing Results

Original

Linear

Kimmel

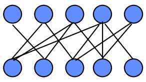
Kimmel + smooth

Demosaicing - Various Approaches

Learning Schemes

Learn linear and non linear optimal filters
for classes of images (ANN).

(Kapah & Hel-Or)



Demosaicing - Learning Schemes

Channel independent

Perceptron (Linear)

Quadratic - Learned on Image

Quadratic - Learned on Class

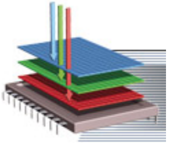
Foveon and Sigma

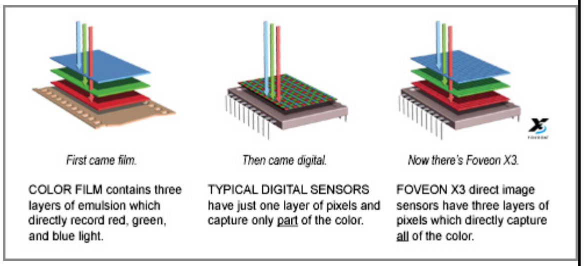
Figure 2. The Sigma SD9 is the first digital camera to use a full-color multi-layer sensor technology: The Foveon X3 sensor.

Polaroid X530

Hanvision HVDUO 5M/10M

Foveon and Sigma





First came film.

COLOR FILM contains three layers of emulsion which directly record red, green, and blue light.

Then came digital.

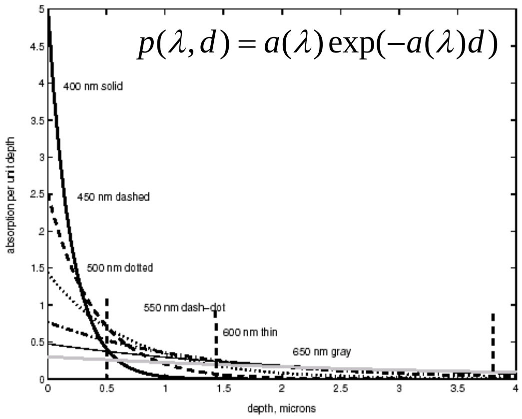
TYPICAL DIGITAL SENSORS have just one layer of pixels and capture only part of the color.

Now there's Foveon X3.

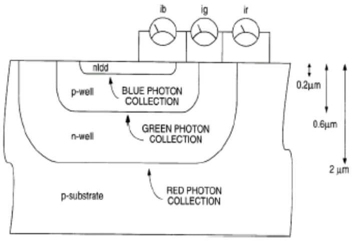
FOVEON X3 direct image sensors have three layers of pixels which directly capture all of the color.

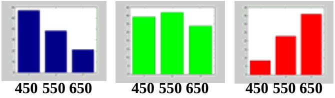
http://www.foveon.com/X3_tech.html

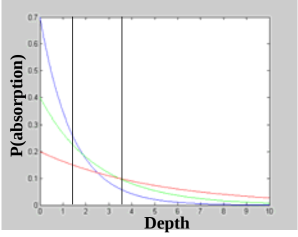
Light absorption in silicon as a function of depth and wavelength



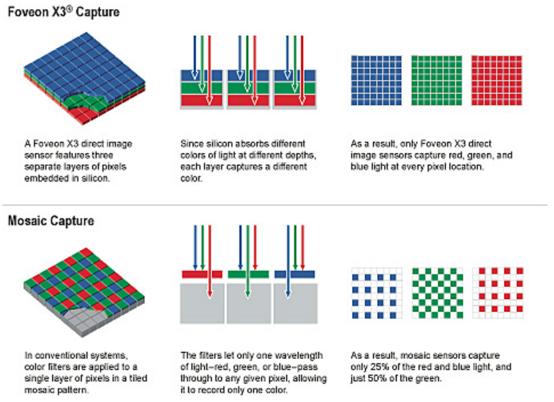
Foveon X3 Pixel (Triple-Well)







X3 Technology



Foveon X3® Capture

A Foveon X3 direct image sensor features three separate layers of pixels embedded in silicon.

Since silicon absorbs different colors of light at different depths, each layer captures a different color.

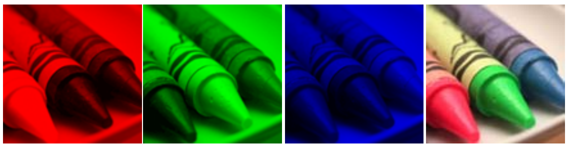
As a result, only Foveon X3 direct image sensors capture red, green, and blue light at every pixel location.

Mosaic Capture

In conventional systems, color filters are applied to a single layer of pixels in a tiled mosaic pattern.

The filters let only one wavelength of light–red, green, or blue–pass through to any given pixel, allowing it to record only one color.

As a result, mosaic sensors capture only 25% of the red and blue light, and just 50% of the green.



red green blue output

Foveon Technology - Examples

Mosaic Capture Foveon X3 Capture

Sharpness
Color
artifacts

Color pipeline Texas Instruments TMS320DSC21

A High Performance, Programmable, Single Chip Digital Signal Processing Solution to Digital Still Cameras