Digital Photography II

color & image processing pipeline

CSC2529
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*slides adapted from Gordon Wetzstein, Fredo Durand, Ioannis Gkioulekas, Marc Levoy, Todd Zickler, Michael Brown

Announcements

- HW 2 is out (due next Friday Sep 27)

- TA office hours (HW2) Wed 1-2pm BA 5256

Outline

- Review
- Color
- Camera processing pipeline

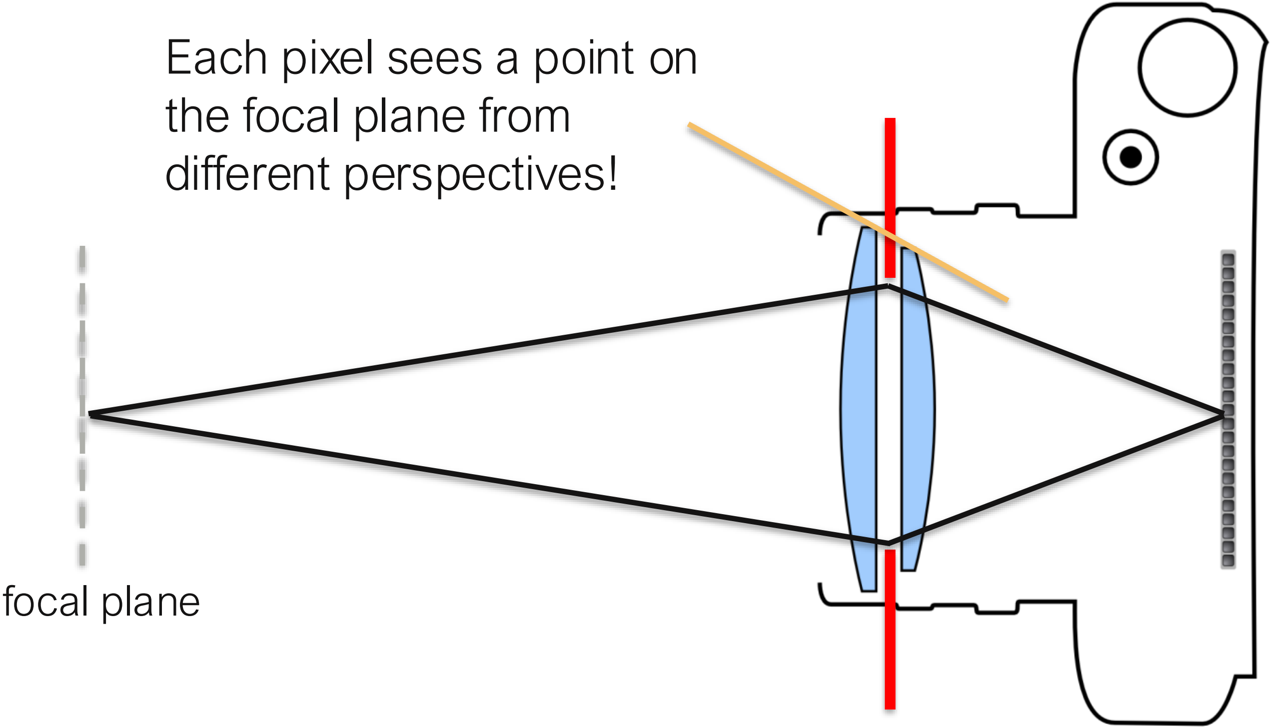
Review – "Sensors are Buckets"

collect photons like a bucket

integrate spectrum

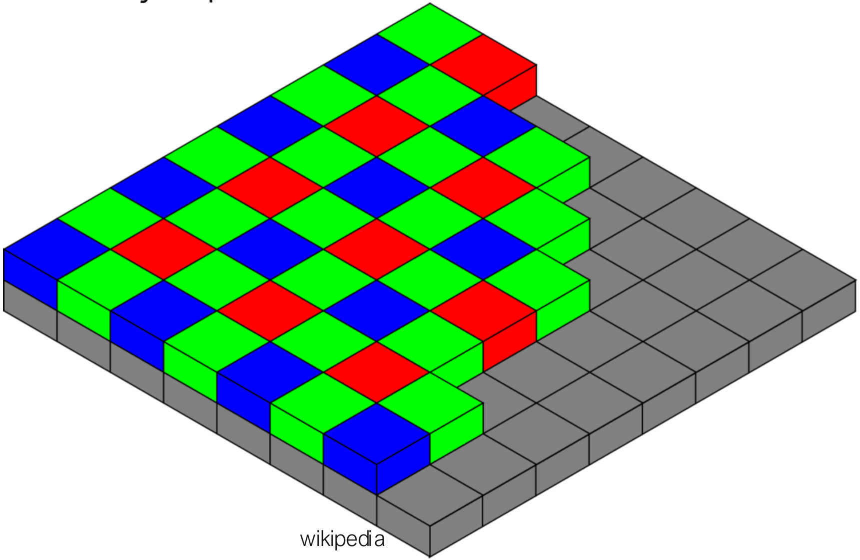
integrate incident directions

Each pixel sees a point on the focal plane from different perspectives!

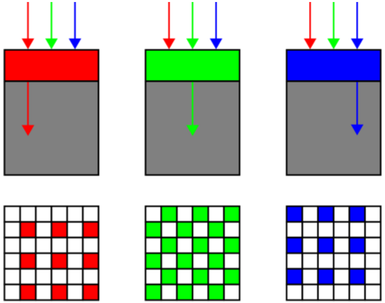


Review – Color Filter Arrays

Bayer pattern



wikipedia



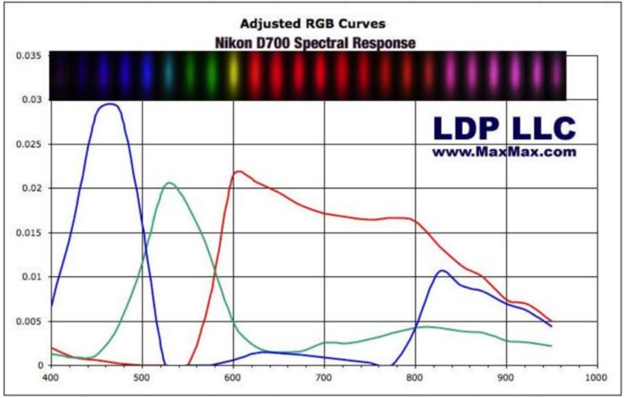


Image Formation

- high-dimensional integration over angle, wavelength, time

plenoptic function

$$i(x) \approx \iiint_{W_{q,l,t}} l(x,q,l,t)\,dq\,dl\,dt$$

plenoptic function:
[Adelson 1991]

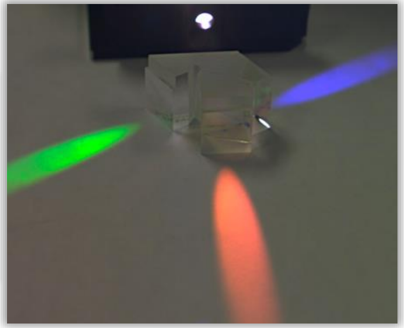
More Ways to Capture Color

field sequential

Prokudin-Gorsky

multiple sensors

green sensor

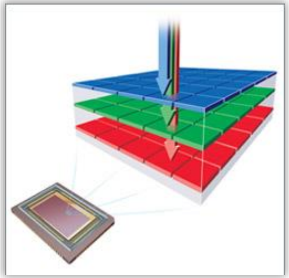


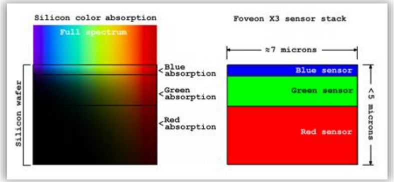
blue sensor

wikipedia

red sensor

vertically stacked





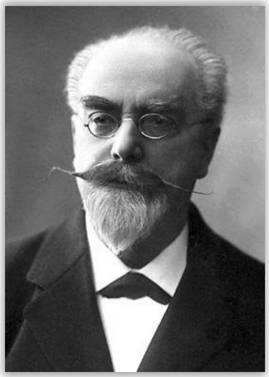
Foveon X3

More Ways to Capture Color

Sergei
Prokudin-Gorsky

Alim Khahn, Emir of Bukhara, 1911

More Ways to Capture Color



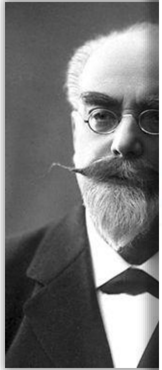
Gabriel Lippmann

- notable French inventor
- Nobel price for color photography in 1908

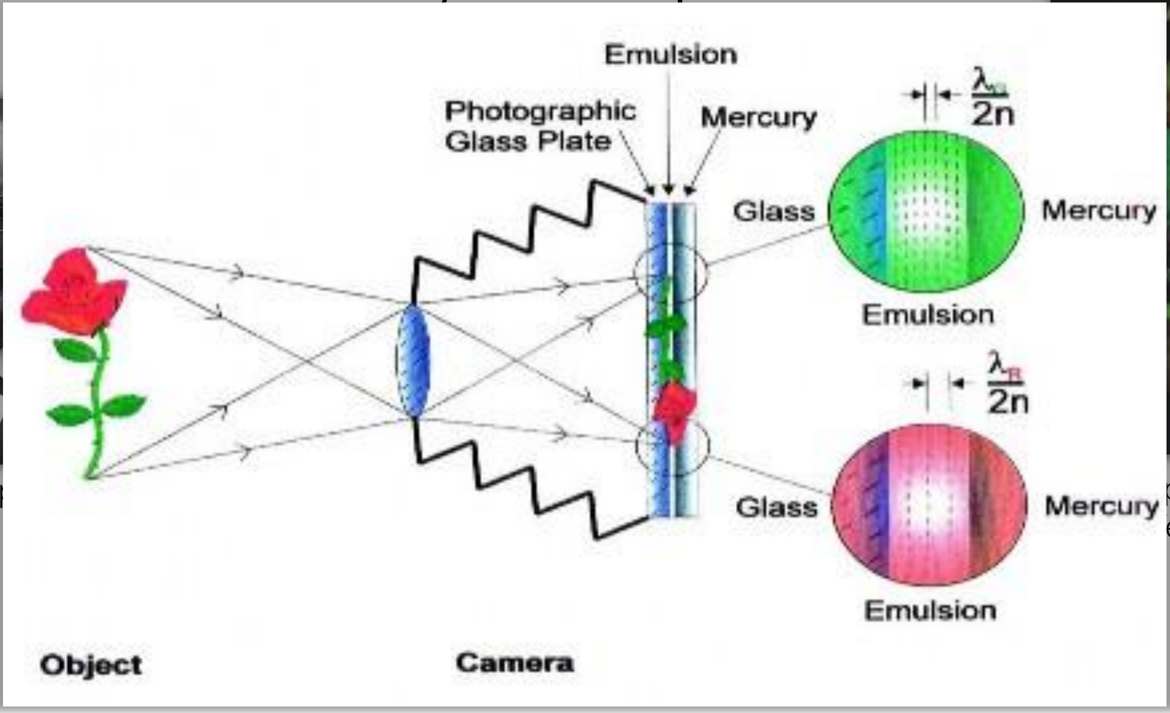
  = volume emulsion capturing interference
- today, this process is most similar to volume holography!
- also invented integral imaging (will hear more…)

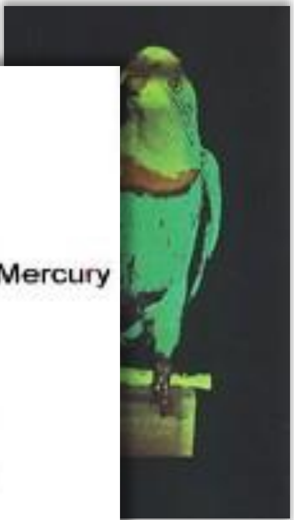
Lippmann's stuffed parrot

More Ways to Capture Color



Gabriel Lip

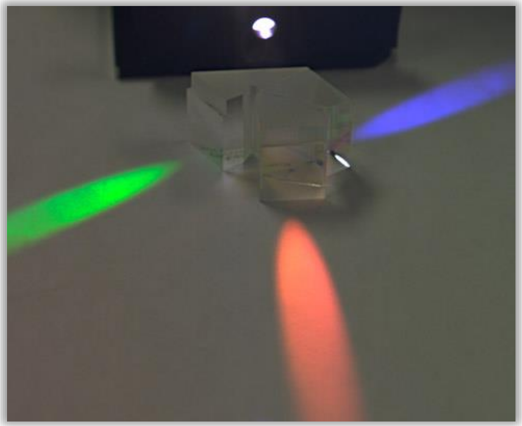


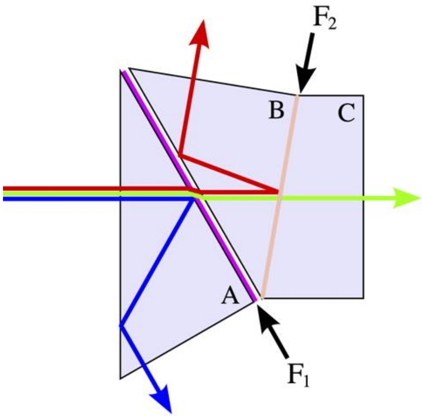


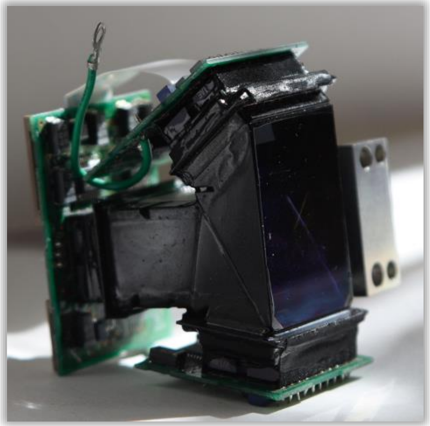
pmann’s
ed parrot

Three-CCD Camera

beam splitter prism

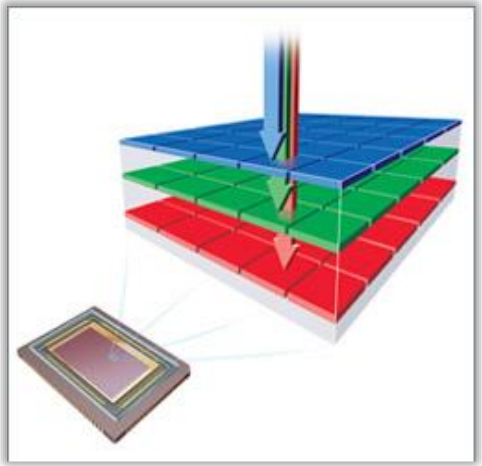




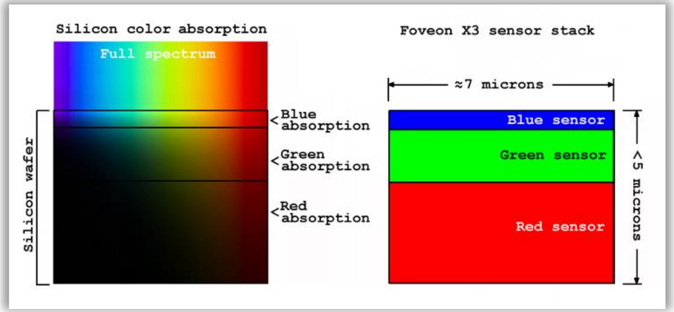


Philips / wikipedia

Stacked Sensor



Foveon X3

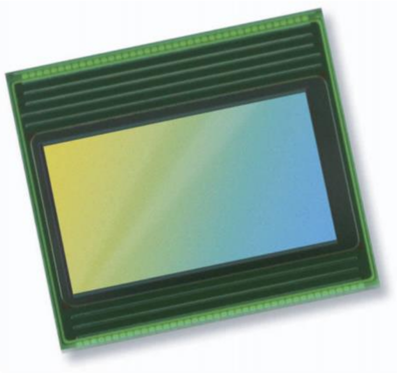


Sigma SD9

Other Wavelengths

- OmniVision:

  RGB + near IR!



Product Specifications

Part Number	**OV4682-G04A**
Resolution	4MP
Chroma	Color
Analog / Digital	Digital
Power Requirement	Active: 163 mA (261 mW) Standby: 1 mA XSHUTDOWN: <10 µA
Temperature Range	Operating: -30°C to +85°C junction temperature Stable image: 0°C to +60°C junction temperature
Output Format	10-bit RAW data
Optical Format	1/3"
Frame Rate	Full @ 90 fps 1080p @ 120 fps 672x380: 330 fps 720p @ 180 fps
Pixel Size	2.0 µm
Image Area	5440 x 3072 µm
Package	COB
Package Dimensions	6600 x 5800 µm
Product Brief	Product Brief

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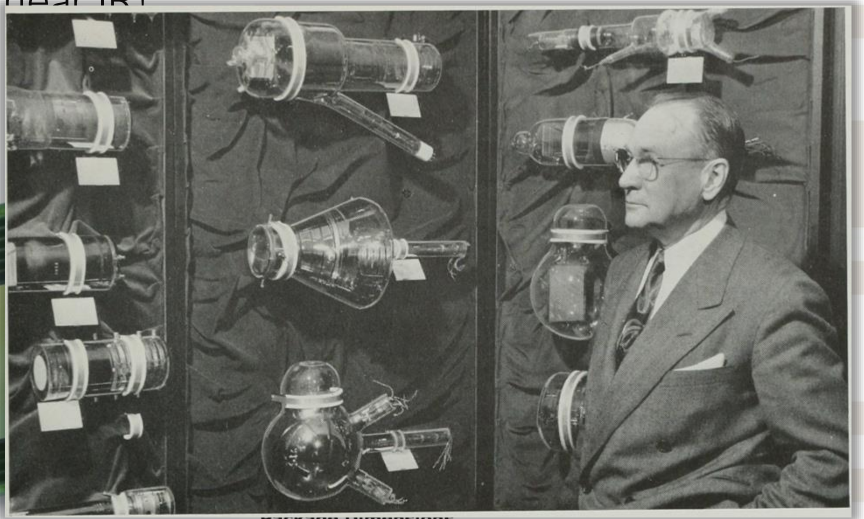

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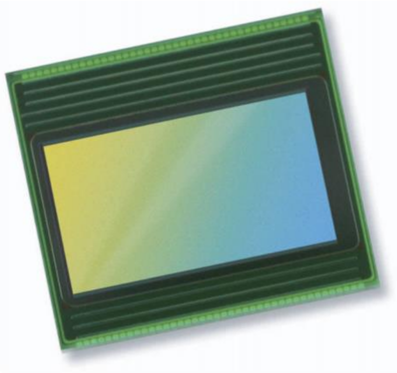

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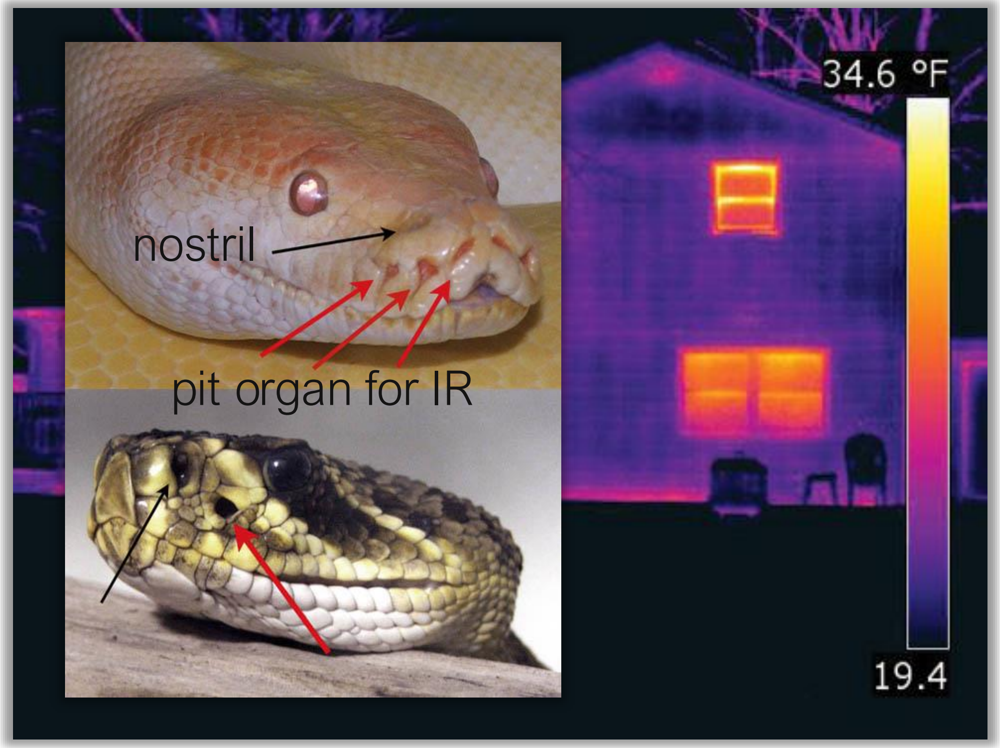
Other Wavelengths

FLIR Systems

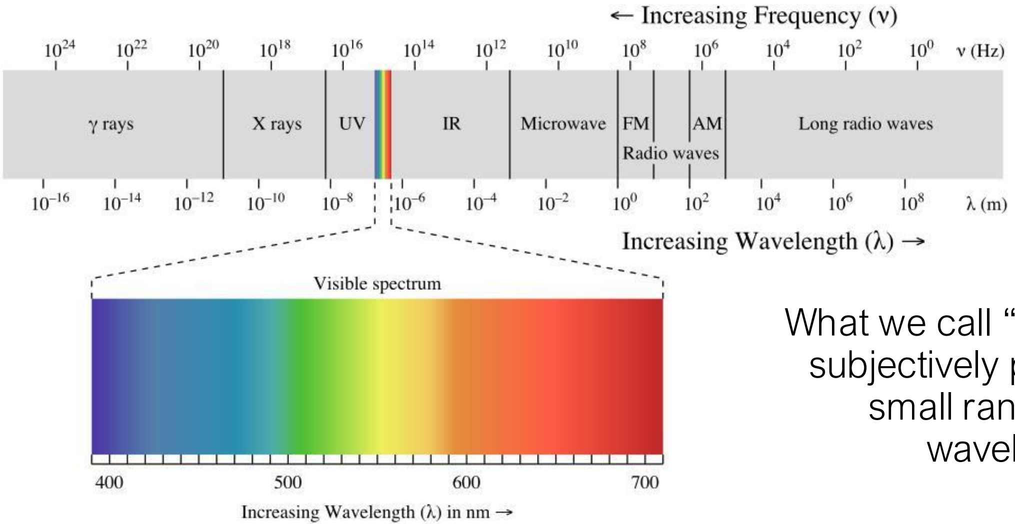
- thermal IR
- often use Germanium optics (transparent IR)

- sensors don't use silicon: indium, mercury, lead, etc.



Color is an artifact of human perception

- “Color” is not an objective physical property of light (electromagnetic radiation).
- Instead, light is characterized by its wavelength.



electromagnetic spectrum

What we call “color” is how we subjectively perceive a very small range of these wavelengths.

Spectral Sensitivity Function (SSF)

- Any light sensor (digital or not) has different sensitivity to different wavelengths.
- This is described by the sensor's spectral sensitivity function $f(\lambda)$
- When measuring light of some SPD $\Phi(\lambda)$ the sensor produces a scalar response:

light SPD sensor SSF

sensor response $\longrightarrow$ $$R = \int_\lambda \Phi(\lambda) f(\lambda) d\lambda$$

Weighted combination of light's SPD: light contributes more at wavelengths where the sensor has higher sensitivity.

Spectral Sensitivity Function of Human Eye

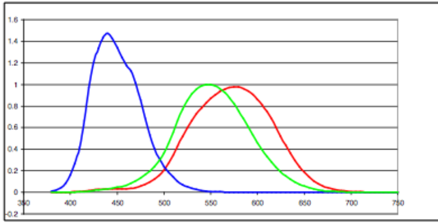
- The human eye is a collection of light sensors called cone cells.
- There are three types of cells with different spectral sensitivity functions.
- Human color perception is three-dimensional (tristimulus color).

"short" $$S = \int_\lambda \Phi(\lambda) S(\lambda) d\lambda$$

"medium" $$M = \int_\lambda \Phi(\lambda) M(\lambda) d\lambda$$

"long" $$L = \int_\lambda \Phi(\lambda) L(\lambda) d\lambda$$

$k_s(\lambda)$ $k_m(\lambda)$ $k_l(\lambda)$

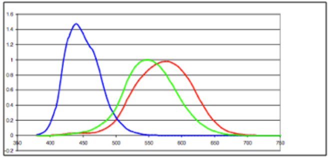


LMS senstivity functions

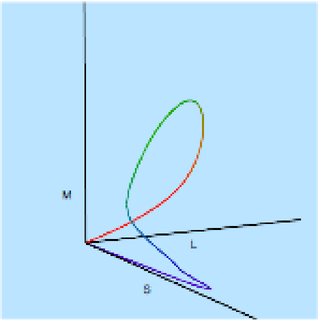
The retinal color space

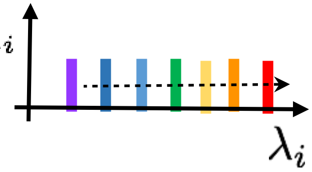
$$\mathbf{c}(\ell_{\lambda_i}) = (c_s, c_m, c_l)$$

$k_s(\lambda)$ $k_m(\lambda)$ $k_l(\lambda)$



LMS senstivity functions





“pure beam” (laser)

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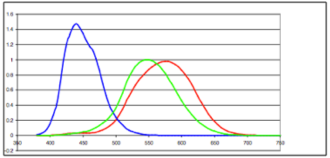

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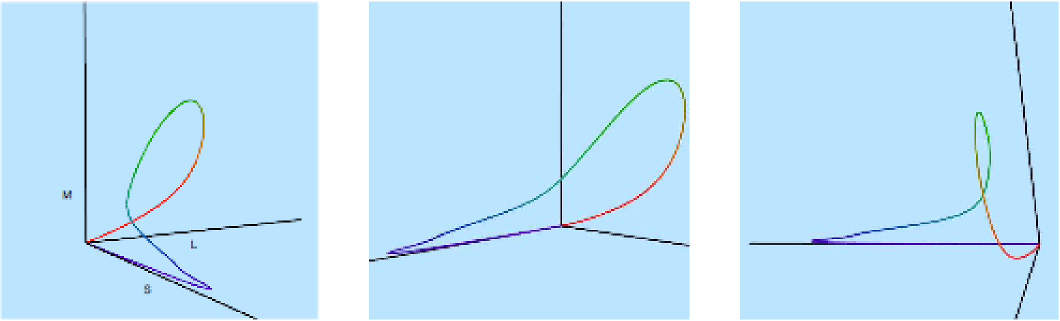
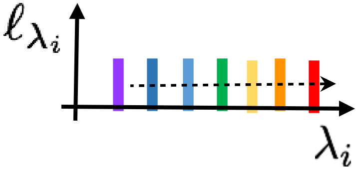




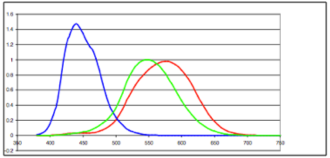
“pure beam” (laser)

- “lasso curve”
- contained in positive octant
- parameterized by wavelength
- starts and ends at origin ← why?
- never comes close to M axis ← why?

The retinal color space

$$\mathbf{c}(\ell_{\lambda_i}) = (c_s, c_m, c_l)$$

$k_s(\lambda)$ $k_m(\lambda)$ $k_l(\lambda)$



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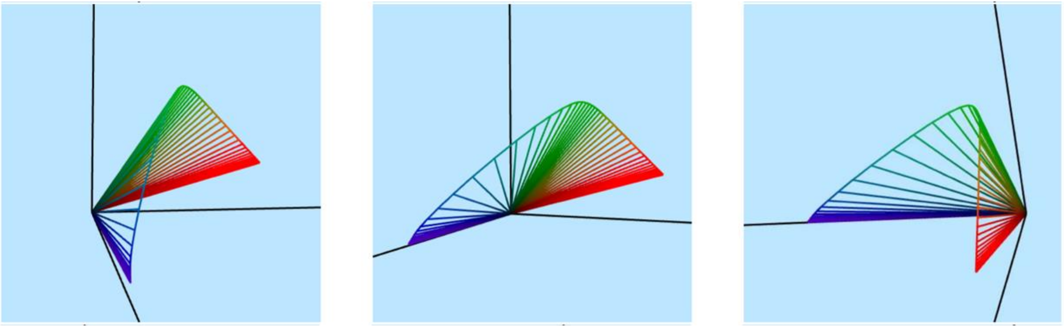
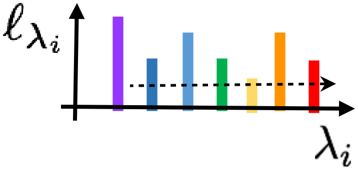




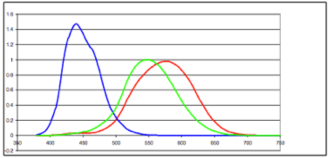
“pure beam” (laser)

if we also consider variations in the strength of the laser this “lasso” turns into (convex!) radial cone with a “horse-shoe shaped” radial cross-section

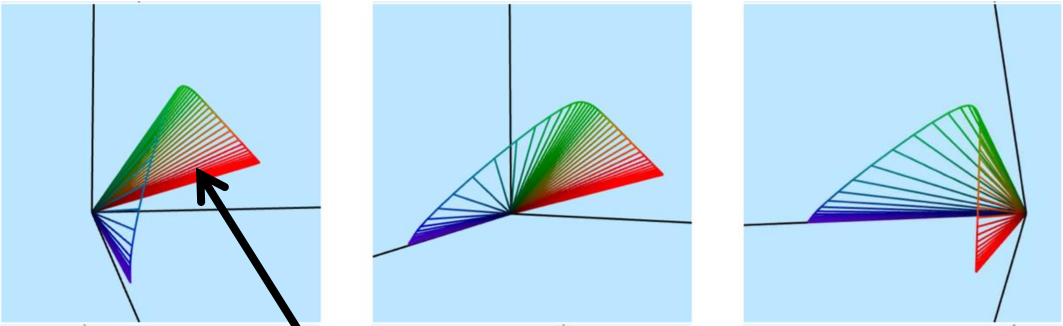
The retinal color space

$$\mathbf{c}(\ell_{\lambda_i}) = (c_s, c_m, c_l)$$

$k_s(\lambda)$ $k_m(\lambda)$ $k_l(\lambda)$

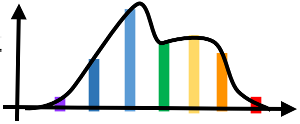


LMS senstivity functions



colors of mixed beams are <u>at the interior</u> of the convex cone with boundary the surface produced by monochromatic lights

ℓ_{λ_i}



λ_i

"mixed beam"

= convex combination of pure colors

The retinal color space

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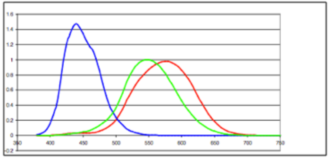
$k_s(\lambda)$ $k_m(\lambda)$ $k_l(\lambda)$



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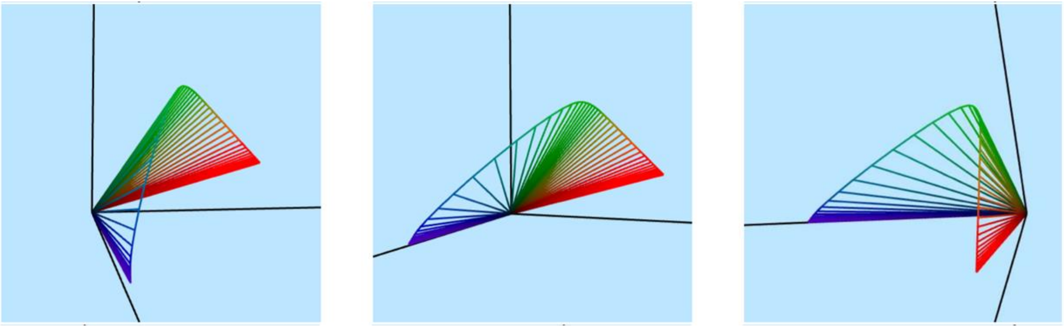
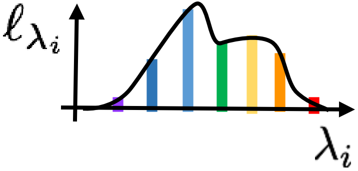


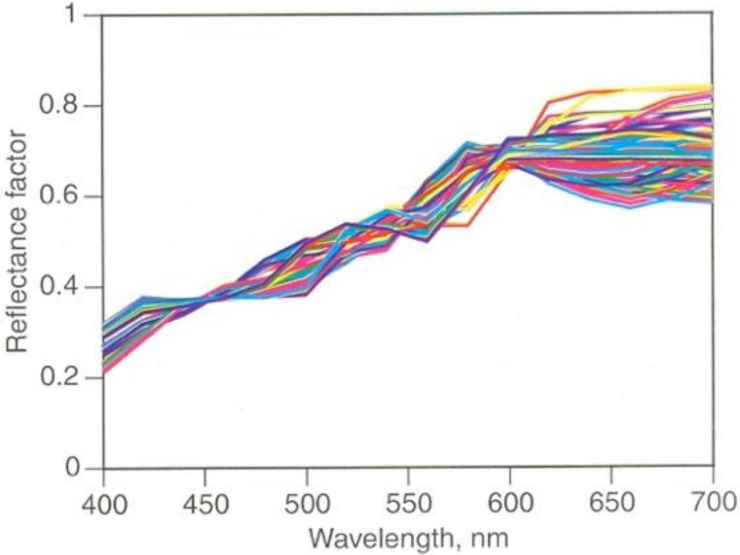


“mixed beam”

= convex combination of pure colors

- distinct mixed beams can produce the same retinal color
- these beams are called metamers

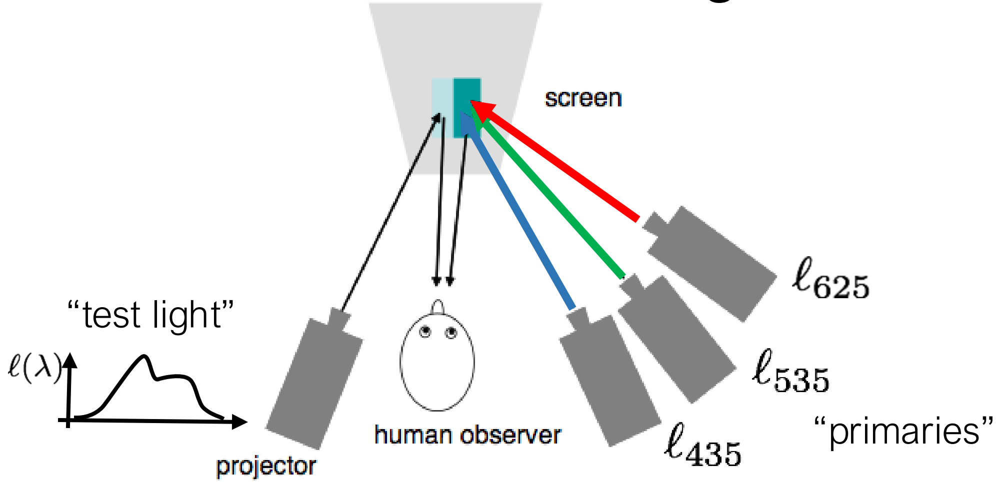
There is an infinity of metamers



Ensemble of spectral reflectance curves corresponding to three chromatic-pigment recipes all matching a tan material when viewed by an average observer under daylight illumination. [Based on Berns (1988b).]

Color matching

CIE color matching

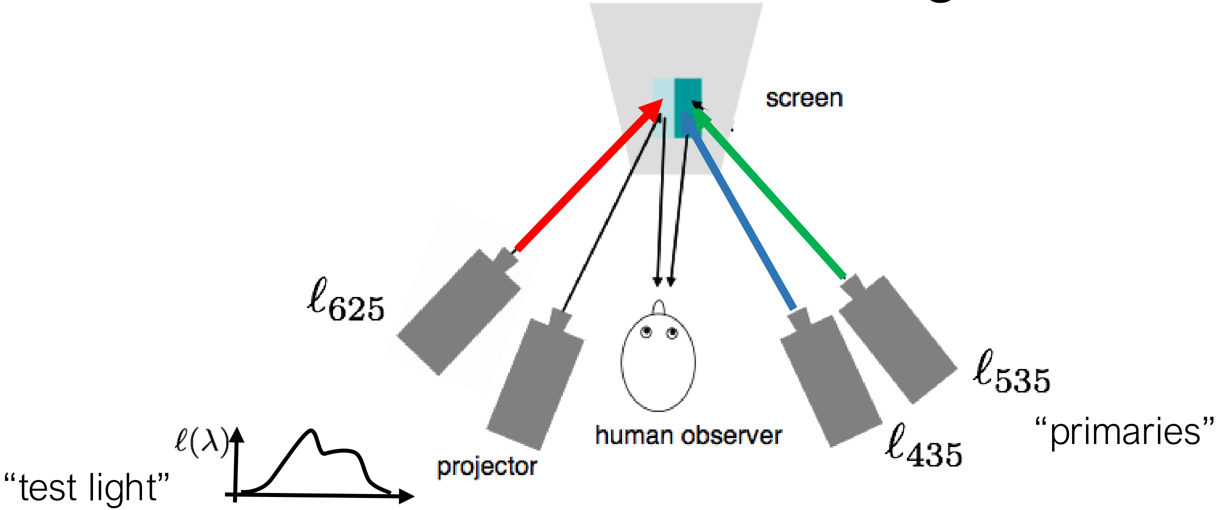


Adjust the strengths of the primaries until they re-produce the test color. Then:

$$\mathbf{c}(\ell(\lambda)) = \alpha\mathbf{c}(\ell_{435}) + \beta\mathbf{c}(\ell_{535}) + \gamma\mathbf{c}(\ell_{625})$$

equality symbol means "has the same retinal color as" or "is metameric to"

CIE color matching

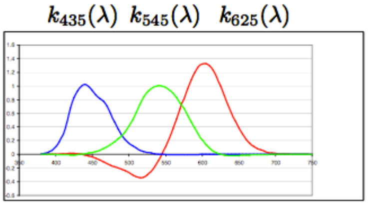


To match some test colors, you need to add some primary beam on the left (same as "subtracting light" from the right)

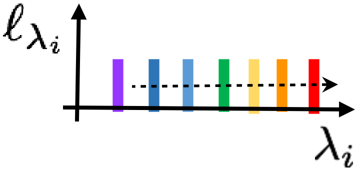
$$\mathbf{c}(\ell(\lambda)) + \gamma\mathbf{c}(\ell_{625}) = \alpha\mathbf{c}(\ell_{435}) + \beta\mathbf{c}(\ell_{535})$$

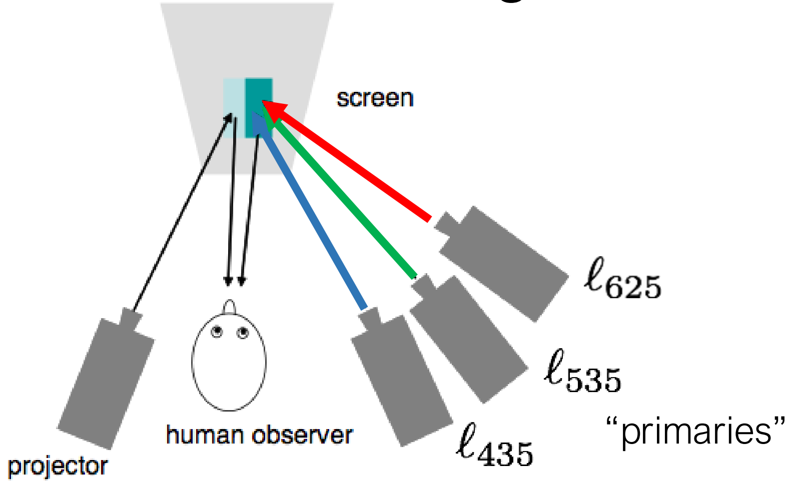
$$\longrightarrow \mathbf{c}(\ell(\lambda)) = \alpha\mathbf{c}(\ell_{435}) + \beta\mathbf{c}(\ell_{535}) - \gamma\mathbf{c}(\ell_{625})$$

CIE color matching



Matching experiment matching functions



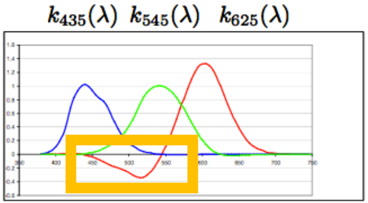


Repeat this matching experiments for pure test beams at wavelengths λ_i and keep track of the coefficients (negative or positive) required to reproduce each pure test beam.

$$\mathbf{c}(\lambda_i) = k_{435}(\lambda)\mathbf{c}(\ell_{435}) + k_{535}(\lambda)\mathbf{c}(\ell_{535}) + k_{625}(\lambda)\mathbf{c}(\ell_{625})$$

CIE color matching

note the negative values



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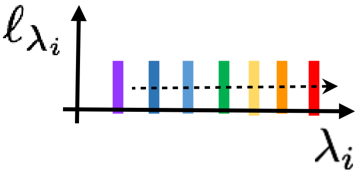

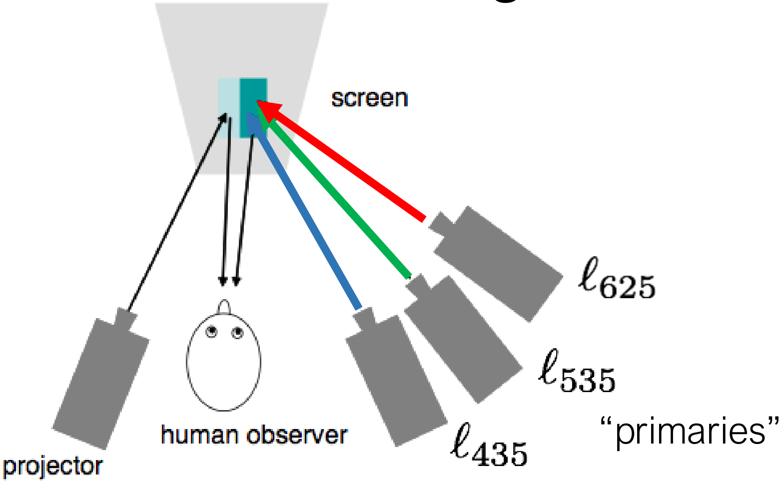

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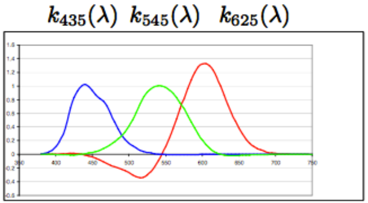

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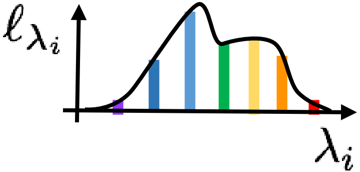
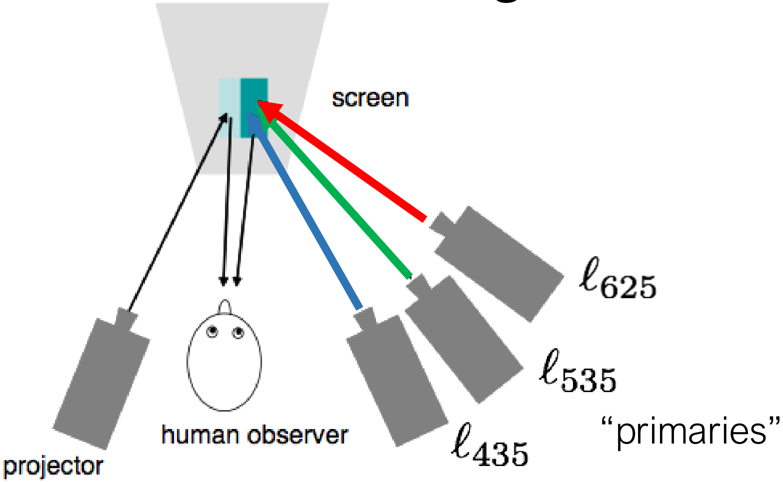
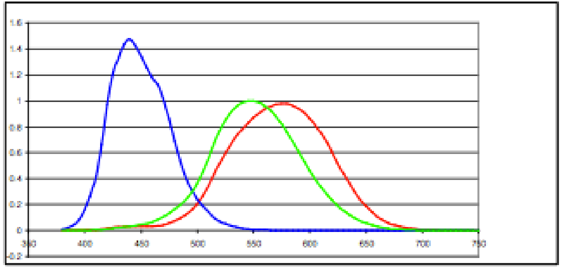




What about “mixed beams”?

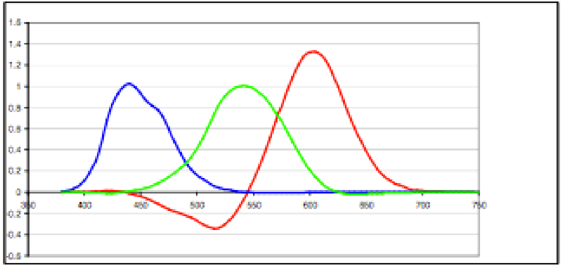
Two views of retinal color

$k_s(\lambda)$ $k_m(\lambda)$ $k_l(\lambda)$



LMS senstivity functions

$k_{435}(\lambda)$ $k_{545}(\lambda)$ $k_{625}(\lambda)$



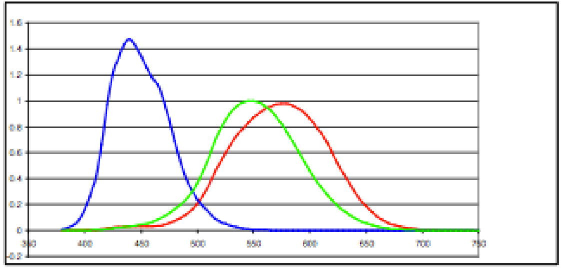
Matching experiment matching functions

<u>Analytic:</u> Retinal color is produced by analyzing spectral power distributions using the color sensitivity functions.

<u>Synthetic:</u> Retinal color is produced by synthesizing color primaries using the color matching functions.

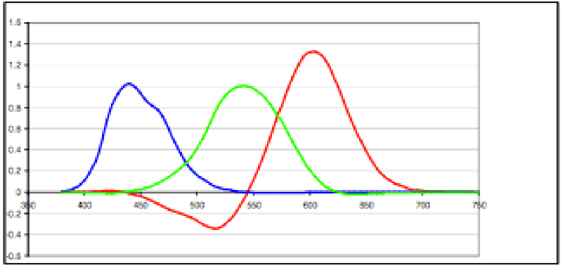
Two views of retinal color

$k_s(\lambda)\ \ k_m(\lambda)\ \ k_l(\lambda)$



LMS senstivity functions

$k_{435}(\lambda)\ \ k_{545}(\lambda)\ \ k_{625}(\lambda)$

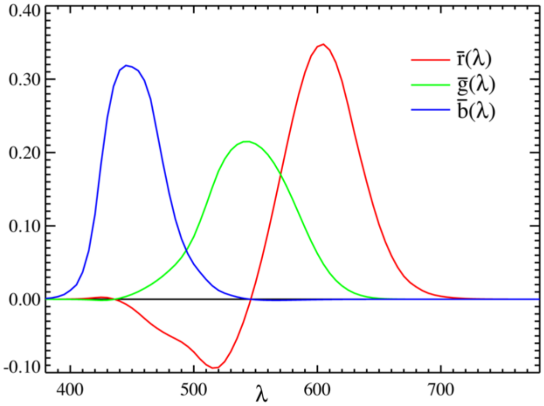


Matching experiment matching functions

<u>Analytic:</u> Retinal color is produced by analyzing spectral power distributions using the color sensitivity functions.

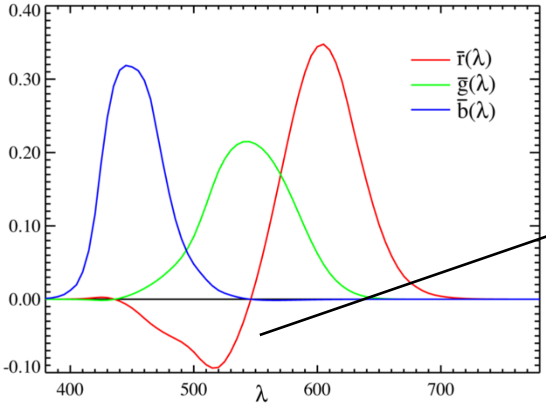
<u>Synthetic:</u> Retinal color is produced by synthesizing color primaries using the color matching functions.

<u>The two views are equivalent:</u> Color matching functions are also color sensitivity functions. For each set of color sensitivity functions, there are corresponding color primaries.



CIE RGB colorspace

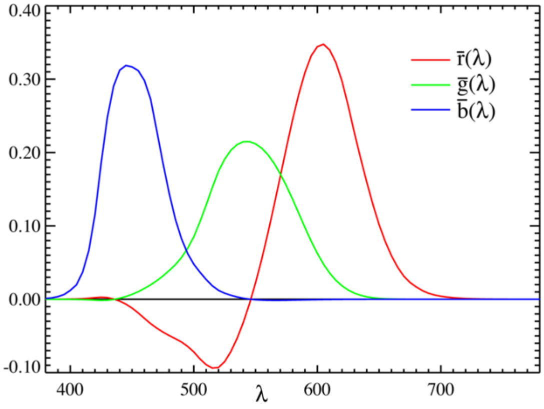
Created by the International Commission on Illumination in 1931 based on color matching experiments from 12 people!

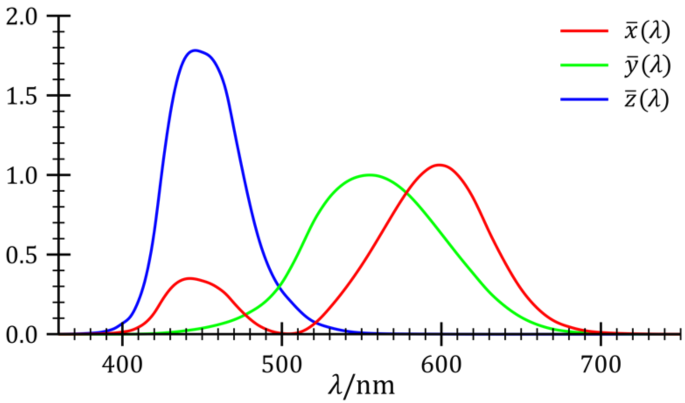


Negative values are not physical since we cannot subtract light

CIE RGB colorspace

Created by the International Commission on Illumination in 1931 based on color matching experiments from 12 people!



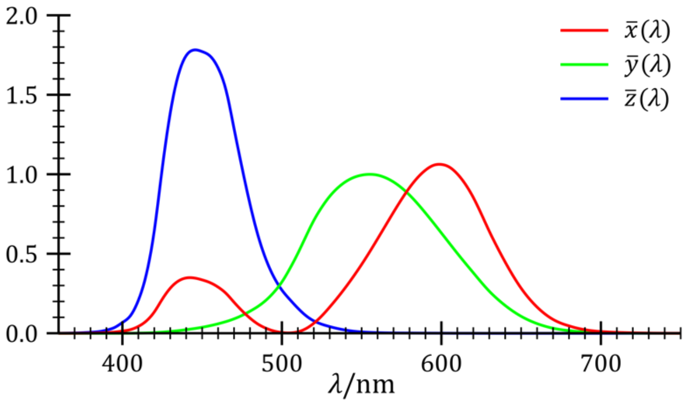


CIE RGB colorspace

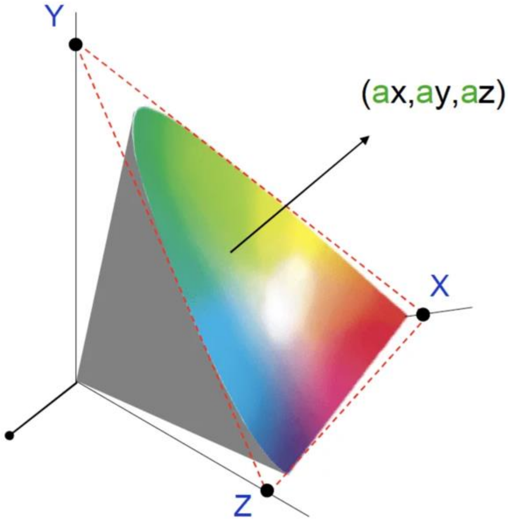
CIE XYZ colorspace

Created by the International Commission on Illumination in 1931 based on color matching experiments from 12 people!

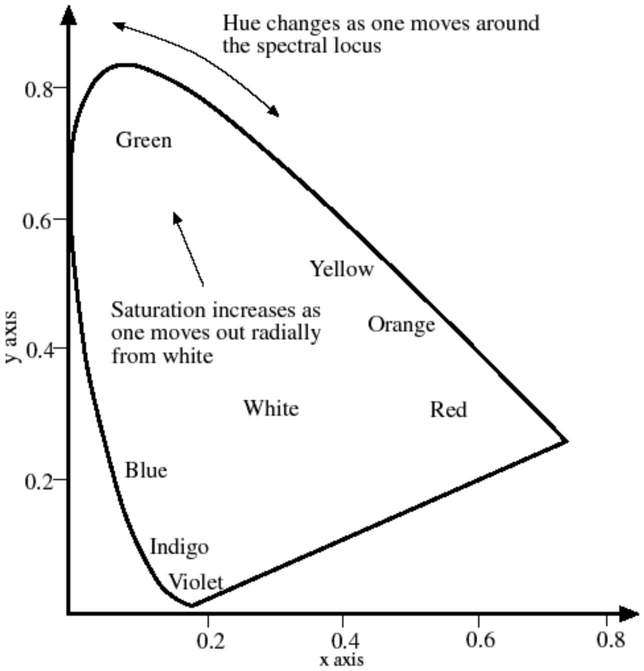
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$



CIE XYZ colorspace



CIE xy (chromaticity)



$$x = \frac{X}{X+Y+Z}$$

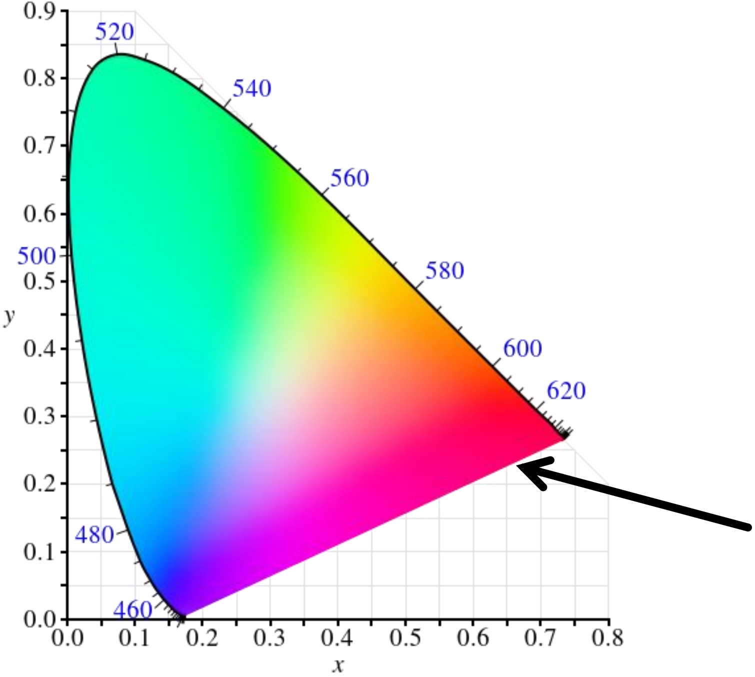
$$y = \frac{Y}{X+Y+Z}$$

$$(X, Y, Z) \longleftrightarrow (\underbrace{x, y}_{\text{chromaticity}}, Y)$$

luminance/brightness

Perspective projection of 3D retinal color space to two dimensions.

CIE xy (chromaticity)



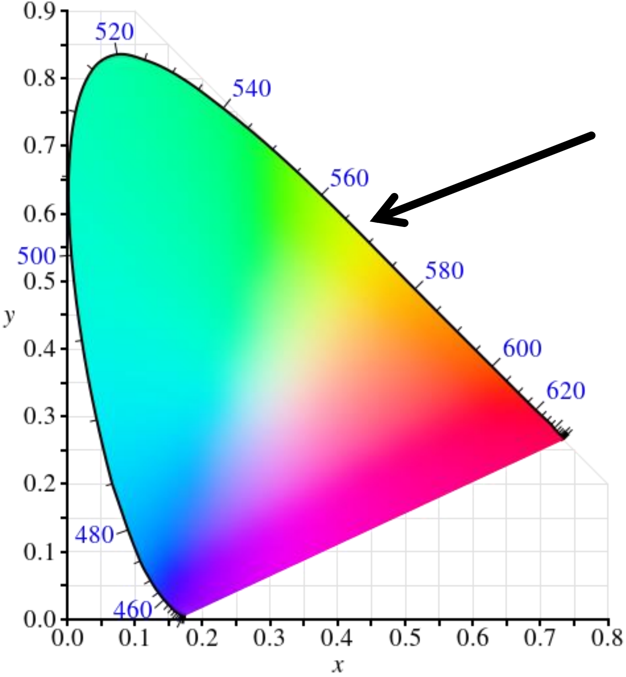
$$x = \frac{X}{X+Y+Z}$$

$$y = \frac{Y}{X+Y+Z}$$

$$(X, Y, Z) \longleftrightarrow (x, y, Y)$$

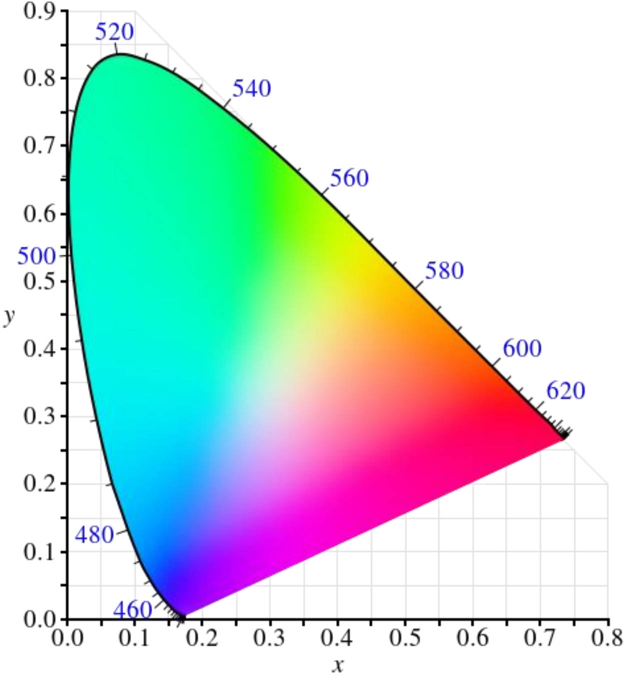
Note: These colors can be extremely misleading depending on the file origin and the display you are using

CIE xy (chromaticity)



What does the boundary of the chromaticity diagram correspond to?

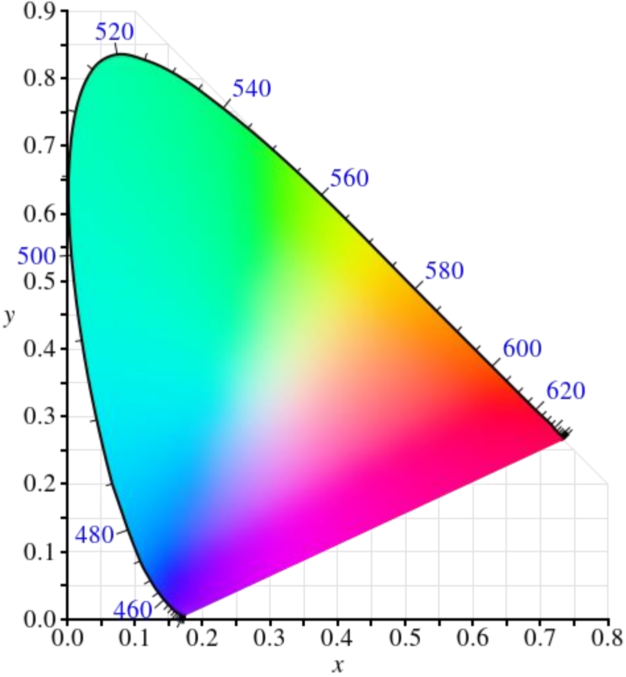
Color gamuts



We can compare color spaces by looking at what parts of the chromaticity space they can reproduce with their primaries.

But why would a color space not be able to reproduce all of the chromaticity space?

Color gamuts

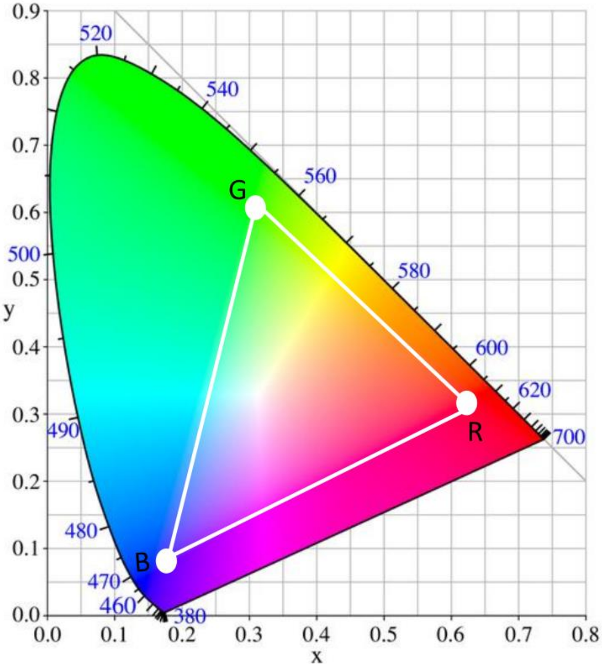


We can compare color spaces by looking at what parts of the chromaticity space they can reproduce with their primaries.

But why would a color space not be able to reproduce all of the chromaticity space?

- Many colors require negative weights to be reproduced, which are not realizable.

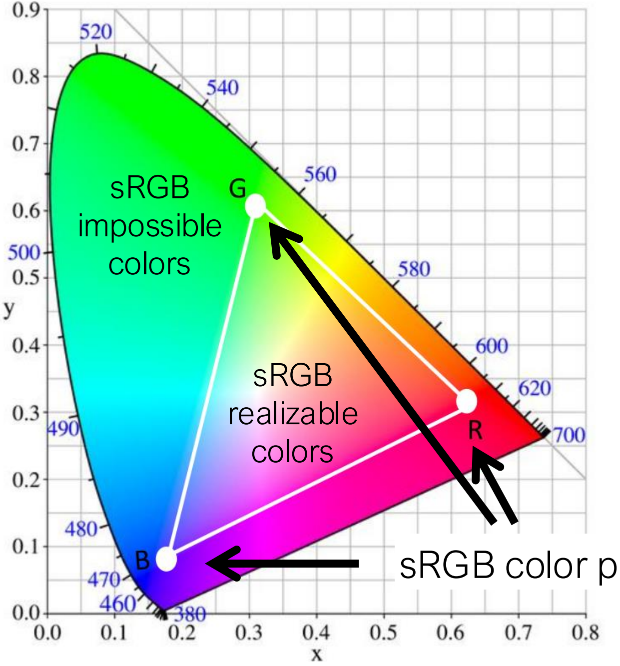
Color gamuts



sRGB color gamut:

- What are the three triangle corners?
- What is the interior of the triangle?
- What is the exterior of the triangle?

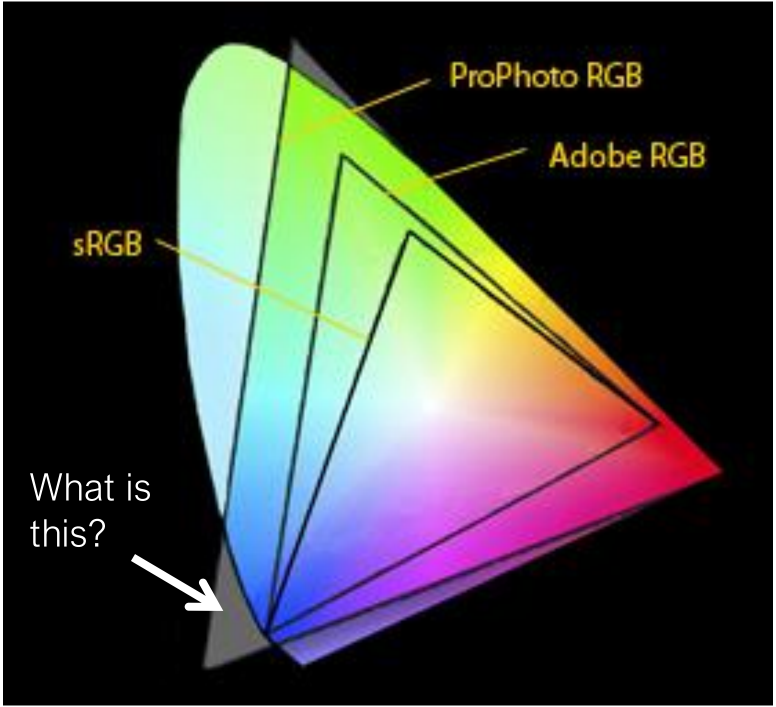
Color gamuts



sRGB color gamut

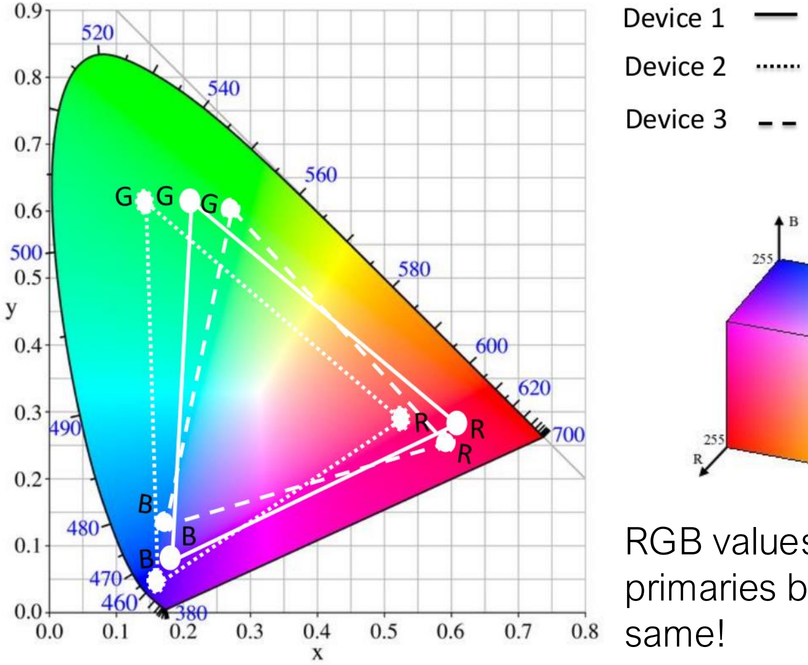
sRGB color primaries

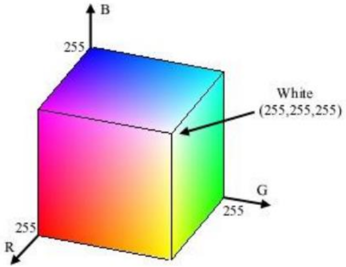
Color gamuts



Gamuts of various common industrial RGB spaces

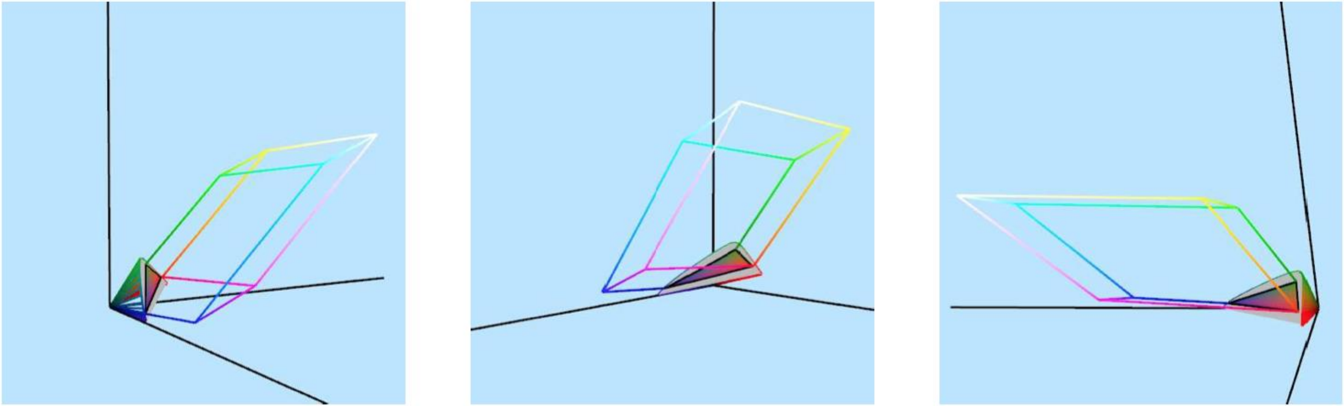
The problem with RGBs visualized in chromaticity space





RGB values have no meaning if the primaries between devices are not the same!

Chromaticity diagrams can be misleading



Different gamuts may compare very differently when seen in full 3D retinal color space.

Some take-home messages about color spaces

Analytic: Retinal color is three numbers formed by taking the dot product of a power spectral distribution with three color matching/sensitivity functions.

Synthetic: Retinal color is three numbers formed by assigning weights to three color primaries to match the perception of a power spectral distribution.

Some take-home messages about color spaces

<u>Fundamental problem:</u> Analysis spectrum (camera, eyes) cannot be the same as synthesis one (display) - impossible to encode all possible colors without something becoming negative

- CIE XYZ only needs positive coordinates, but need primaries with negative light.
- sRGB must use physical (non-negative) primaries, but needs negative coordinates for some colors.

Some take-home messages about color spaces

Problem with current practice: Many different RGB color spaces used by different devices, without clarity of what exactly space a set of RGB color values are in.

- Huge problem for color reproduction from one device to another.
- there are standards (like sRGB), but consumer displays are not calibrated—so you cannot really conclude that images are color accurate

camera processing pipeline

Review: Photons to RAW Image

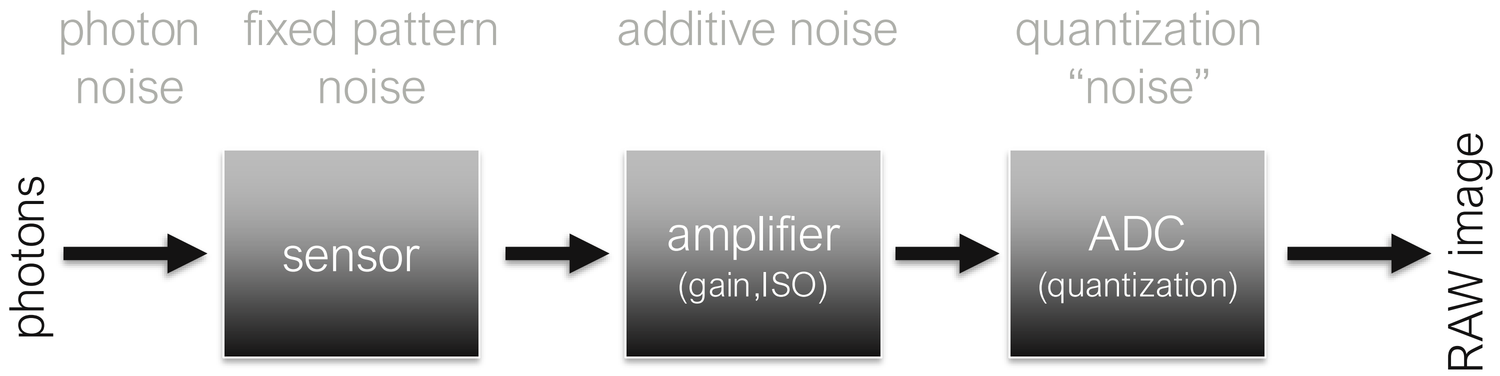
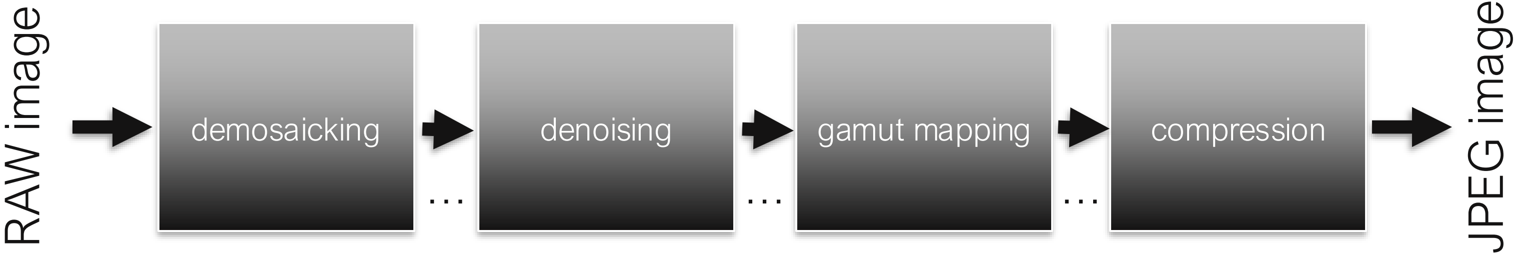


Image Processing Pipeline



also:

- dead pixel removal
- dark frame subtraction (fixed pattern / thermal noise removal)
- lens blur / vignetting / distortion correction
- sharpening / edge enhancement

Image Processing Pipeline

RAW image
(dcraw –D)

JPEG image

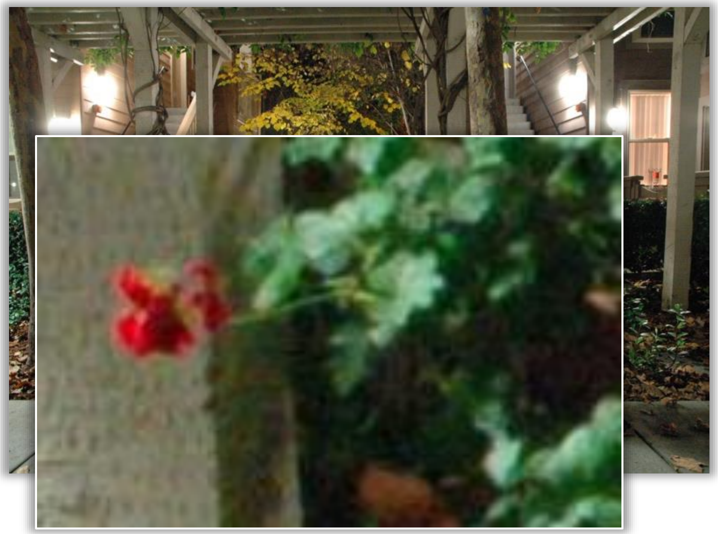
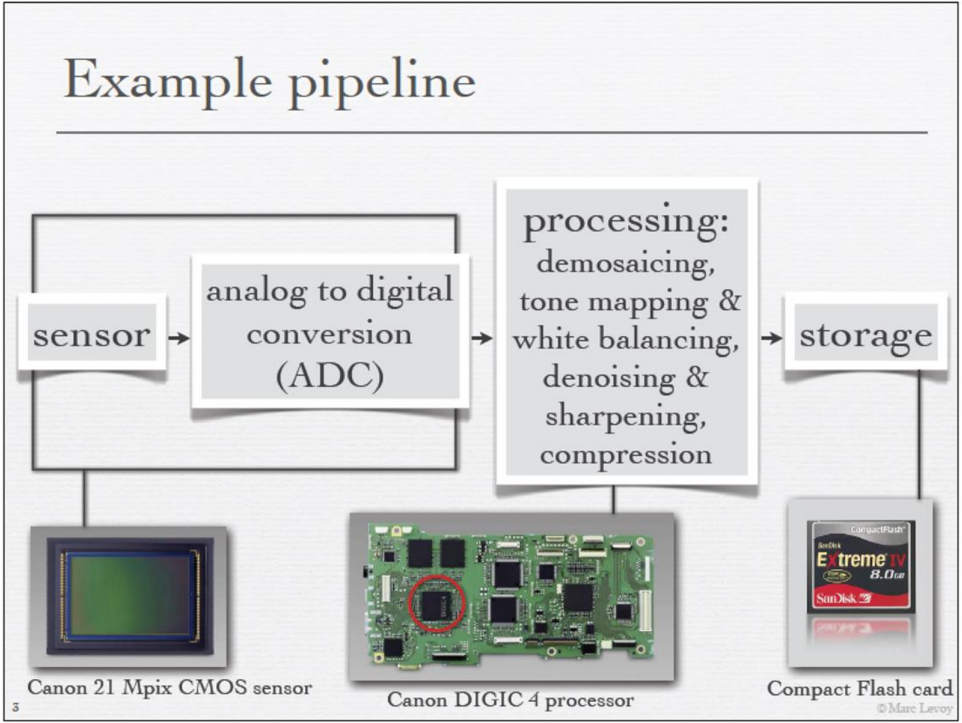


Image Processing Pipeline

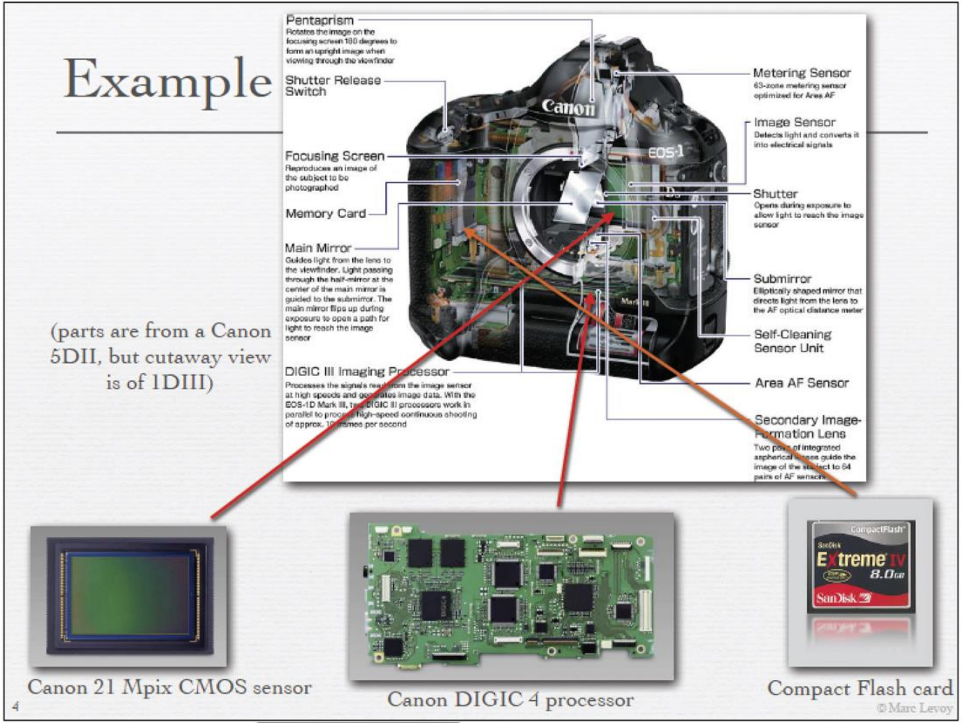
- demosaicking
- denoising
- digital autoexposure
- white balancing
- linear 10/12 bit to 8 bit gamma
- compression

Image Processing Pipeline



Marc Levoy, CS 448

Image Processing Pipeline



Marc Levoy, CS 448

Exif Meta Data

exchangeable image file format

Filename - night_nikon.JPG
Make - NIKON CORPORATION
Model - NIKON D70s
Orientation - Top left
XResolution - 300
YResolution - 300
ResolutionUnit - Inch
Software - Ver.1.00
DateTime - 2005:09:01 12:16:43
YCbCrPositioning - Co-Sited
ExifOffset - 216
ExposureTime - 10 seconds
FNumber - 13.00
ExposureProgram - Manual control
ExifVersion - 0221
DateTimeOriginal - 2005:09:01 12:16:43
DateTimeDigitized - 2005:09:01 12:16:43
ComponentsConfiguration - YCbCr
CompressedBitsPerPixel - 1 (bits/pixel)
ExposureBiasValue - 0.50
MaxApertureValue - F 3.48
MeteringMode - Center weighted average
LightSource - Auto
Flash - Not fired
FocalLength - 18.00 mm
UserComment - (c) Gordon Wetzstein
SubsecTime - 00
SubsecTimeOriginal - 00
SubsecTimeDigitized - 00
FlashPixVersion - 0100
ColorSpace - sRGB
ExifImageWidth - 3008
ExifImageHeight - 2000
InteroperabilityOffset - 29230
SensingMethod - One-chip color area sensor
FileSource - Other
SceneType - Other
CustomRendered - Custom process
ExposureMode - Manual
White Balance - Auto
DigitalZoomRatio - 1 x
FocalLengthIn35mmFilm - 27 mm
SceneCaptureType - Portrait
GainControl - Low gain up
Contrast - Normal
Saturation - Normal
Sharpness - Soft
SubjectDistanceRange - Unknown

Maker Note (Vendor): -
Data version - 0210 (808595760)
ISO Setting - 1600
Image Quality - BASIC
White Balance - AUTO
Image Sharpening - MED.L
Focus Mode - MANUAL
Flash Setting - NORMAL
Flash Mode -
White Balance Adjustment - 0
Exposure Adjustment - 1.7
Thumbnail IFD offset - 1430
Flash Compensation - 67072
ISO 2 - 1600
Tone Compensation - AUTO
Lens type - AF-D G
Lens - 618
Flash Used - Not fired
AF Focus Position - Center
Bracketing - 131072
Color Mode - MODE1a
Light Type - NORMAL
Hue Adjustment - 0
Noise Reduction - FPNR
Total pictures - 22346
Optimization - PORTRAIT

Thumbnail: -
Compression - 6 (JPG)
XResolution - 300
YResolution - 300
ResolutionUnit - Inch
JpegIFOffset - 29368
JpegIFByteCount - 8393
YCbCrPositioning - Co-Sited

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MaxApertureValue - F 3.48
MeteringMode - Center weighted average
LightSource - Auto
Flash - Not fired
FocalLength - 18.00 mm
UserComment - (c) Gordon Wetzstein
SubsecTime - 00
SubsecTimeOriginal - 00
SubsecTimeDigitized - 00
FlashPixVersion - 0100
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Demosaicking (CFA Interpolation)

RAW

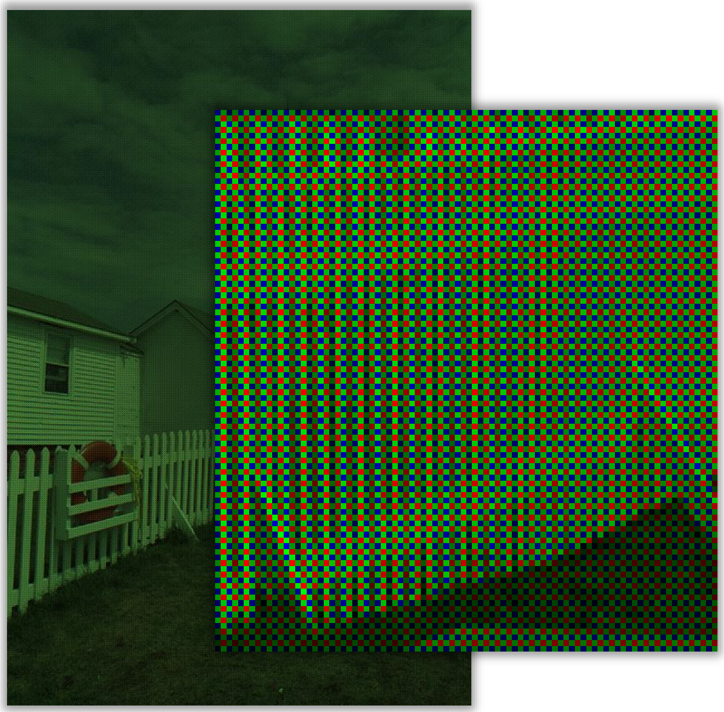
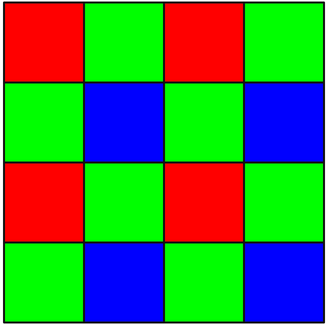


image from Kodac dataset



Bayer CFA

Demosaicking (CFA Interpolation)

RAW

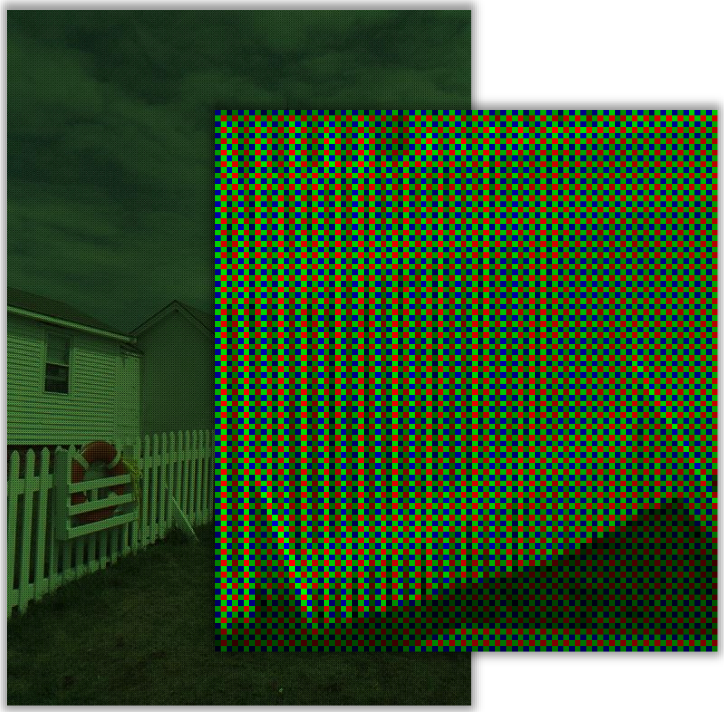
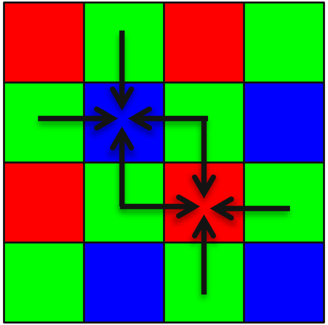


image from Kodac dataset

linear interpolation green channel

$$\hat{g}_{lin}(x,y) = \frac{1}{4} \sum_{(m,n)} g(x+m, y+n)$$

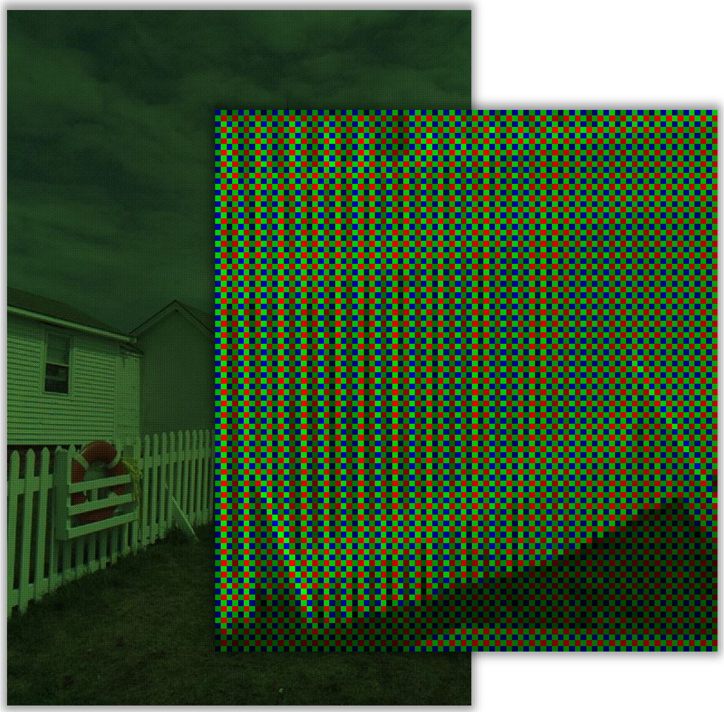
$$(m,n) = \{(0,-1),(0,1),(-1,0),(1,0)\}$$



Bayer CFA

Demosaicking (CFA Interpolation)

RAW



linear interpolation

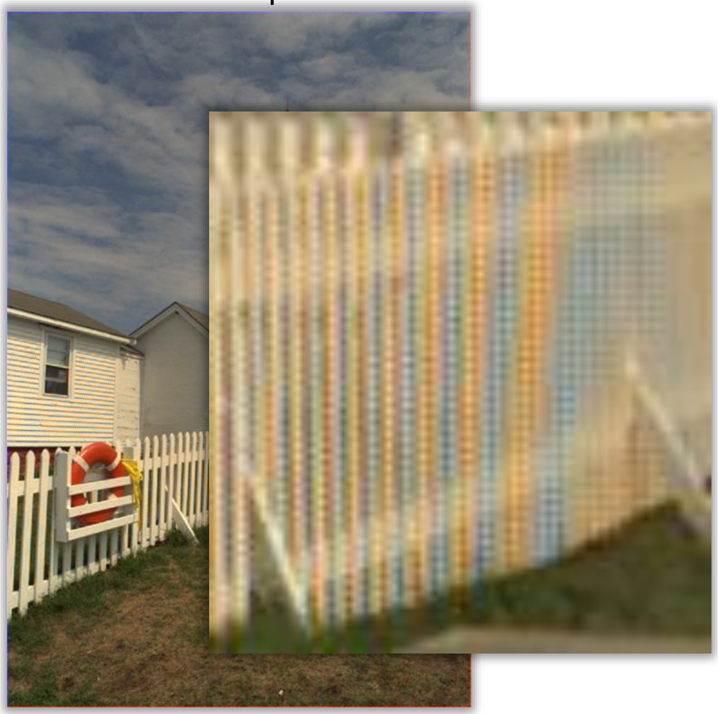
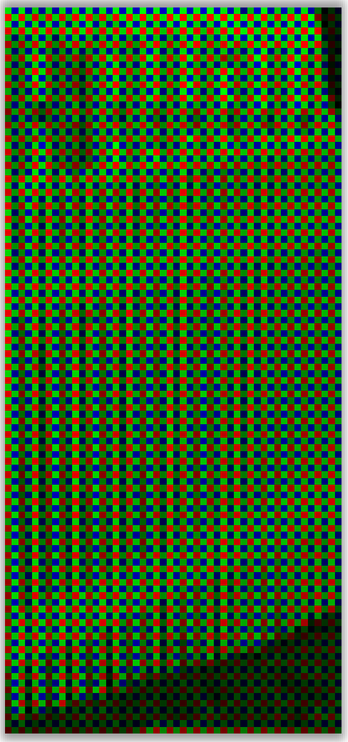


image from Kodac dataset

Demosaicking (CFA Interpolation)

original

RAW



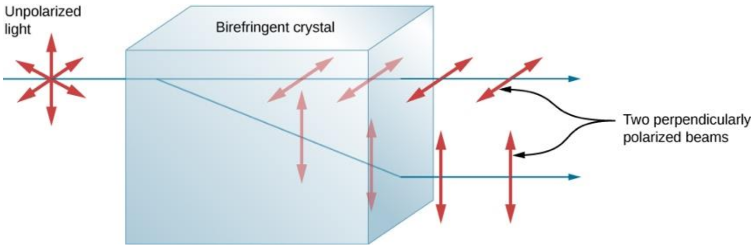
demosaicked

image from Kodac dataset

Quick aside: optical low-pass filter

- Sensors often have a separate glass sheet in front of them acting as an optical low-pass filter (OLPF, also known as optical anti-aliasing filter).
- The OLPF is typically implemented as two birefringent layers, combined with the infrared filter.
- The two layers split 1 ray into 4 rays, implementing a 4-tap discrete convolution filter kernel.

birefringence in a calcite crystal



birefringence ray diagram

Quick aside: optical low-pass filter

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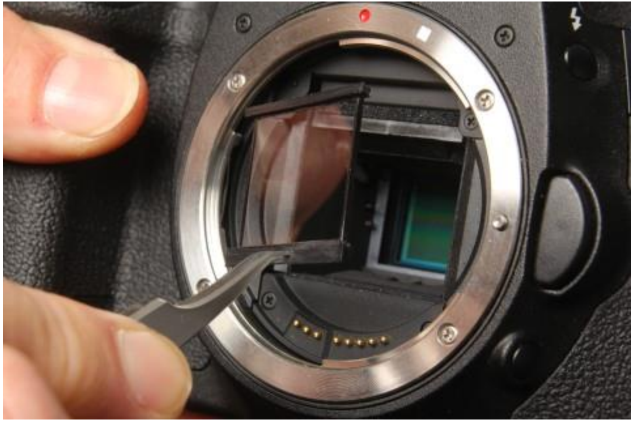


- However, the OLPF means you also lose resolution.
- Photographers often hack their cameras to remove the OLPF, to avoid the loss of resolution ("hot rodding").
- Camera manufacturers offer camera versions with and without an OLPF.

Quick aside: optical low-pass filter

Example where OLPF is needed

without OLPF

with OLPF

Quick aside: optical low-pass filter

Example where OLPF is unnecessary

without OLPF

with OLPF

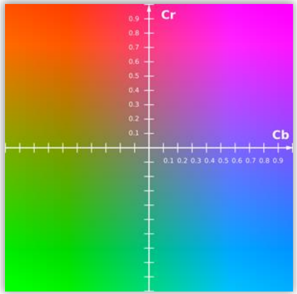
Quick aside: optical low-pass filter

Identical camera model with and without an OLPF (no need for customization).

Nikon D800

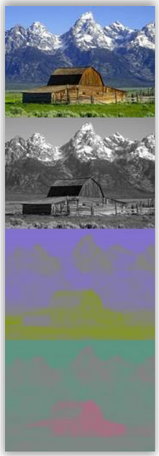
Nikon D800E

Demosaicing – Low-pass Chroma



- sampling problem (despite optical AA filter): (too) high-frequency red/blue information

- simple solution: low-pass filter chrominance – humans are most sensitive to “sharpness” in luminance:
  1. apply naïve interpolation
  2. convert to Y’CbCr (related to YUV)
  3. median filter chroma channels: Cb & Cr
  4. convert back to RGB

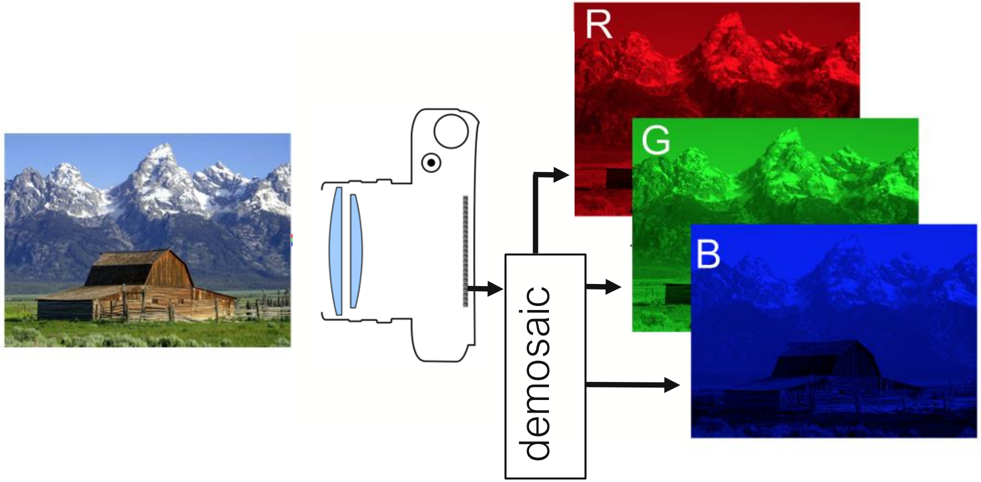


Y’

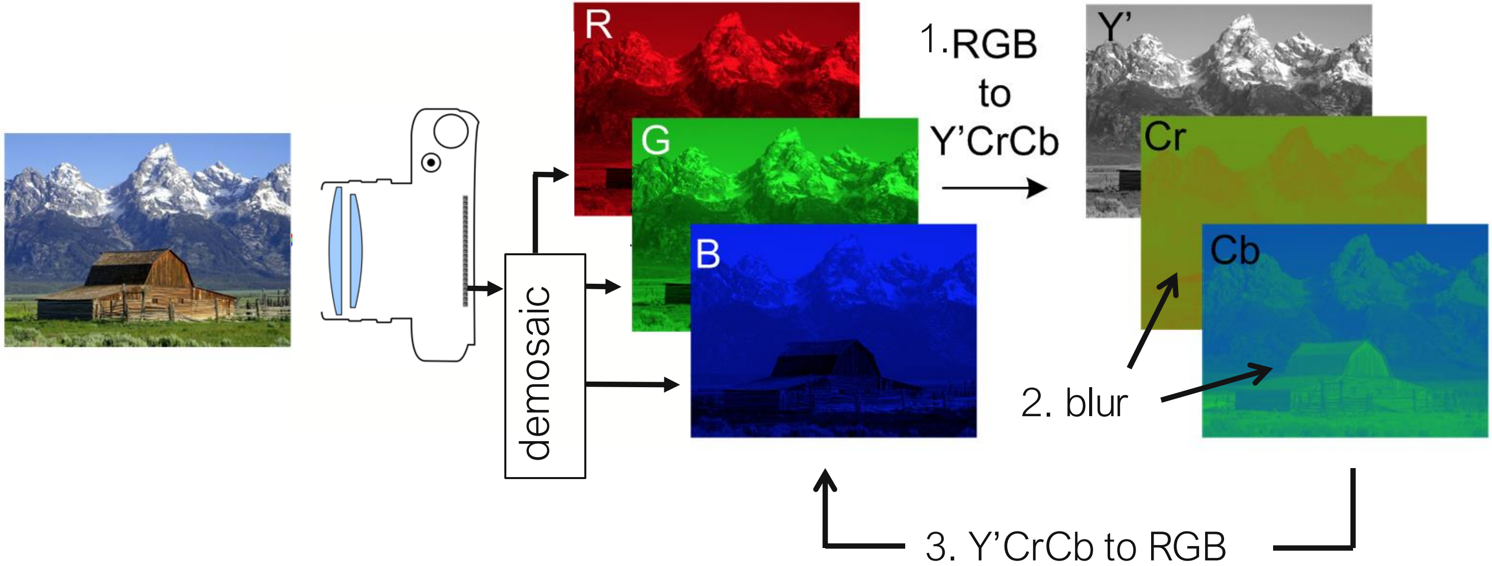
Cb

Cr

Demosaicing – Low-pass Chroma



Demosaicing – Low-pass Chroma



Demosaicing – Low-pass Chroma

RGB to Y'CrCb:

$$\begin{bmatrix} Y' \\ Cb \\ Cr \end{bmatrix} = \left(\underbrace{\begin{bmatrix} 65.48 & 128.55 & 24.87 \\ -37.80 & -74.20 & 112.00 \\ 112.00 & -93.79 & -18.21 \end{bmatrix}}_{M} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \right) \cdot \frac{257}{65535} + \begin{bmatrix} 16 \\ 128 \\ 128 \end{bmatrix}$$

Y'CrCb to RGB:

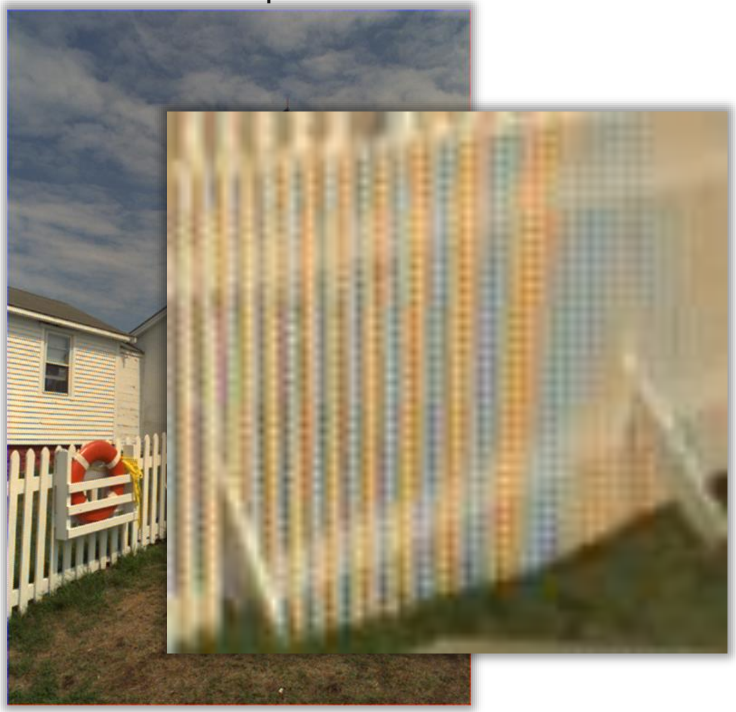
$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = M^{-1} \left(\begin{bmatrix} Y' \\ Cb \\ Cr \end{bmatrix} - \begin{bmatrix} 16 \\ 128 \\ 128 \end{bmatrix} \right) \cdot \frac{65535}{257}$$

Matlab functions: *rgb2ycbcr()* and *ycbcr2rgb()*

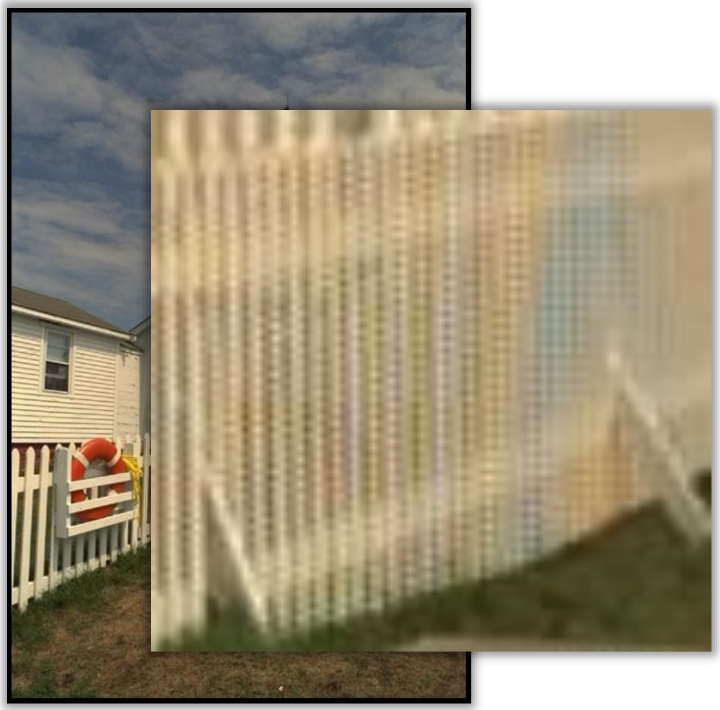
Pixel values for above equations between 0 and 255!

Demosaicing – Low-pass Chroma

linear interpolation

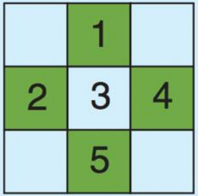


chrominance filtered



Demosaicing – Edge-Directed Interpolation

- intuitive approach: consider 3x3 neighborhood
- example: recover missing green pixel



1. Calculate horizontal gradient $\Delta H = |G2 - G4|$
2. Calculate vertical gradient $\Delta V = |G1 - G5|$
3. If $\Delta H > \Delta V$,

   $G3 = (G1 + G5)/2$

   Else if $\Delta H < \Delta V$,

   $G3 = (G2 + G4)/2$

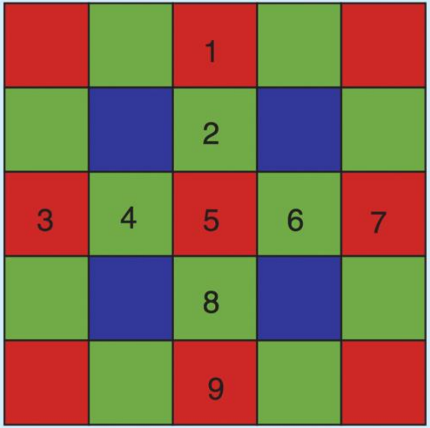
   Else

   $G3 = (G1 + G5 + G2 + G4)/4$

from Gunturk et al. 2005

Demosaicing – Edge-Directed Interpolation

- better: consider 5x5 neighborhood
- example: recover missing green pixel on red pixel



1. Calculate horizontal gradient $\Delta H = |(R3 + R7)/2 - R5|$
2. Calculate vertical gradient $\Delta V = |(R1 + R9)/2 - R5|$
3. If $\Delta H > \Delta V$,

   $G5 = (G2 + G8)/2$

   Else if $\Delta H < \Delta V$,

   $G5 = (G4 + G6)/2$

   Else

   $G5 = (G2 + G8 + G4 + G6)/4$

from Gunturk et al. 2005

Demosaicing – Edge-Directed Interpolation

- insights so far:
    - larger pixel neighborhood may be better, but also more costly
    - using gradient information (edges) may be advantageous, even if that info comes from other color channels!
    - nonlinear method is okay, but not great – linear would be best!

- Malvar et al. 2004 – what's the best linear filter for 5x5 neighborhood?
- this is implemented in Matlab function *demosaic()* and part of HW2

Demosaicing- Malvar et al. 2004

- interpolate G at R pixels: $$\hat{g}(x,y) = \hat{g}_{lin}(x,y) + \alpha\Delta_R(x,y)$$

  red gradient: $$\Delta_R(x,y) = r(x,y) - \frac{1}{4}\sum_{(m,n)} r(x+m, y+n)$$

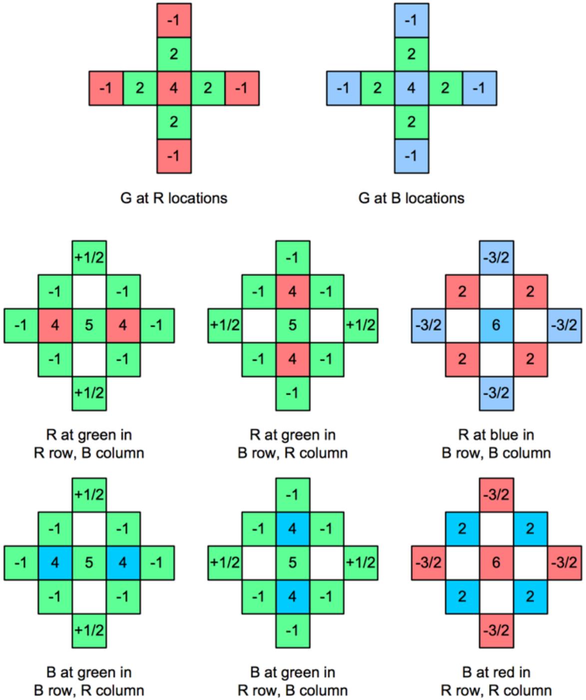
  $$(m,n) = \{(0,-2),(0,2),(-2,0),(2,0)\}$$

- interpolate R at G pixels: $$\hat{r}(x,y) = \hat{r}_{lin}(x,y) + \beta\Delta_G(x,y)$$
- interpolate R at B pixels: $$\hat{r}(x,y) = \hat{r}_{lin}(x,y) + \gamma\Delta_B(x,y)$$

- gain parameters optimized from Kodak dataset: $\alpha = 1/2,\ \beta = 5/8,\ \gamma = 3/4$

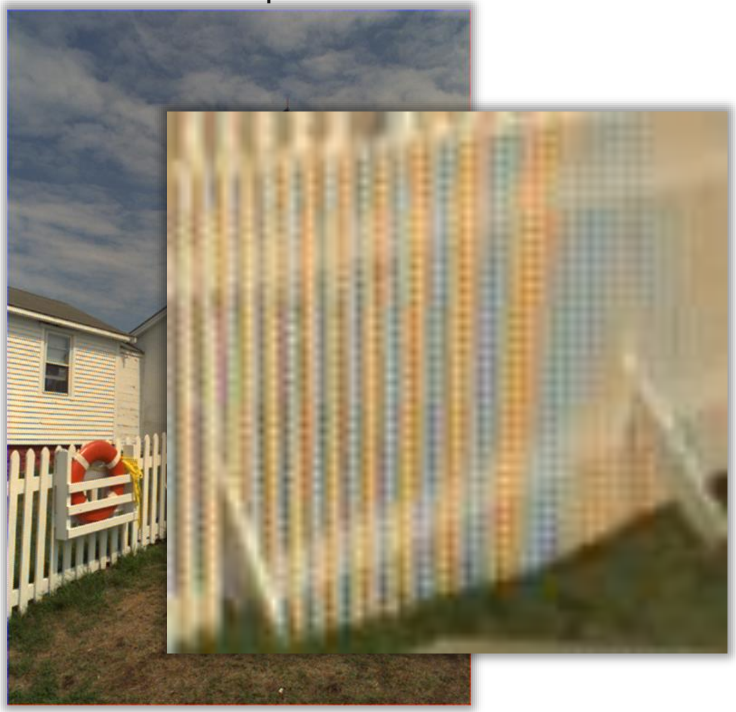
Demosaicing - Malvar et al. 2004

- write out math to get linear filters:
- use normalized filters in practice, i.e. scale numbers by sum of filter

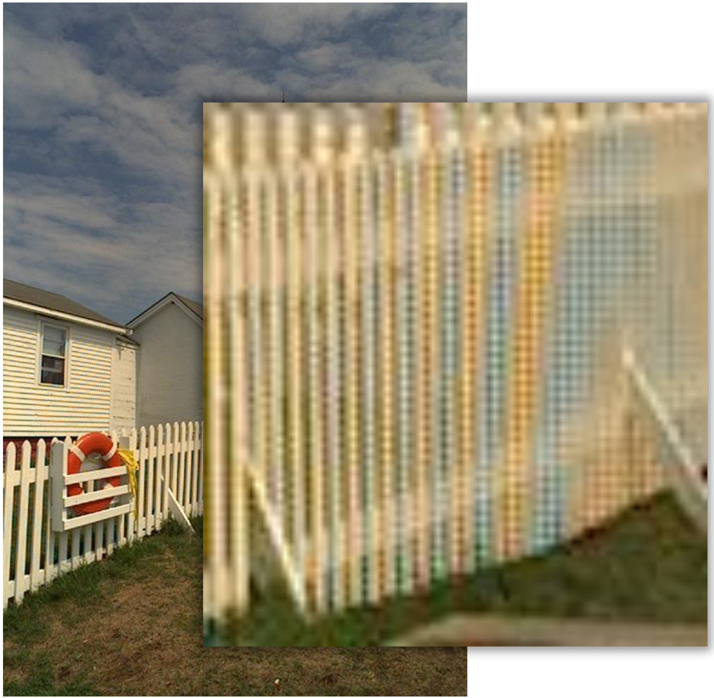


Demosaicing - Malvar et al. 2004

linear interpolation



Malvar et al.



Deblurring / Deconvolution

common sources:

out-of-focus blur

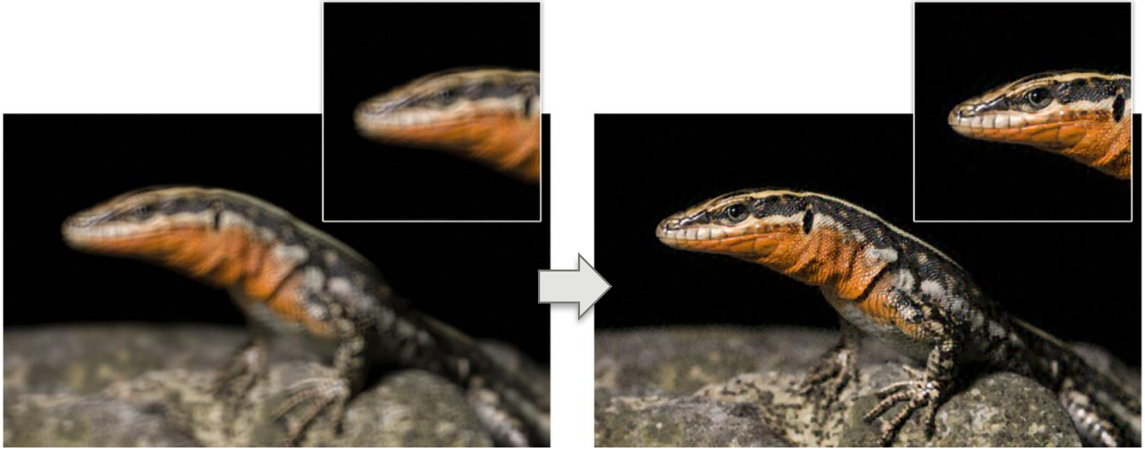
geometric distortion

spherical aberration

chromatic aberration

coma

from Heide et al. 2016



Blurred input image

Deblurred / deconvolved image

Denoising

noisy image

(Gaussian iid noise, σ=0.2)

- problem: have noisy image, want to remove noise but retain high-frequency detail

Denoising – Most General Approach

$$i_{denoised}(x) = \frac{1}{\sum_{\text{all pixels } x'} w(x, x')} \sum_{\text{all pixels } x'} i_{noisy}(x') \cdot w(x, x')$$

- many (not all) denoising techniques work like this
- idea: average a number of similar pixels to reduce noise
- question/difference in approach: how similar are two noisy pixels?

Denoising – Most General Approach

$$i_{denoised}(x) = \frac{1}{\sum_{\text{all pixels } x'} w(x, x')} \sum_{\text{all pixels } x'} i_{noisy}(x') \cdot w(x, x')$$

1. Local, linear smoothing
2. Local, nonlinear filtering
3. Anisotropic diffusion
4. Non-local methods

Denoising – 1. Local, Linear Smoothing

$$i_{denoised}(x) = \frac{1}{\sum_{\text{all pixels } x'} w(x, x')} \sum_{\text{all pixels } x'} i_{noisy}(x') \cdot w(x, x')$$

$$w(x, x') = \exp\left(- \frac{\left\| x' - x \right\|^2}{2\sigma^2} \right)$$

- naïve approach: average in <u>local</u> neighborhood, e.g. using a Gaussian low-pass filter

Denoising – 2. Local, Nonlinear Filtering

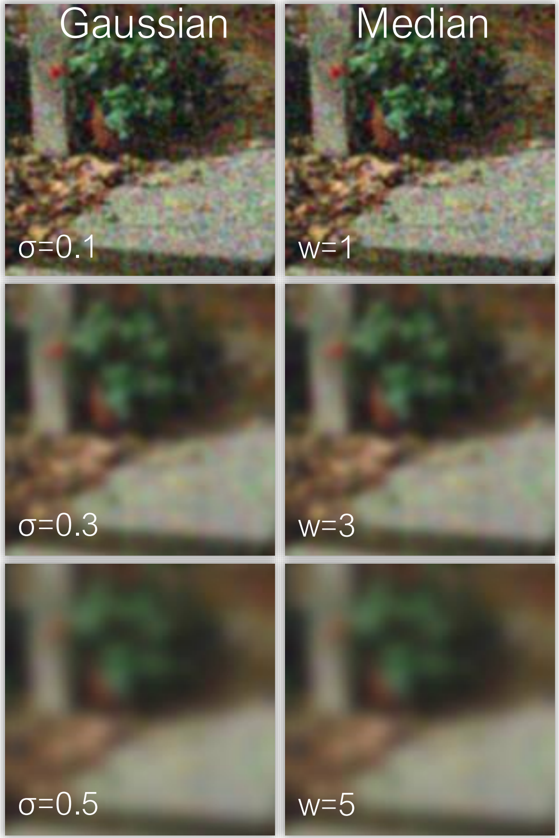
$$i_{denoised}(x) = median\left(W\left(i_{noisy}, x\right)\right)$$

small window of image i_{noisy} centered at x

- almost as naïve: use median filter in <u>local</u> neighborhood

Denoising

noisy image (Gaussian, σ=0.2)



Denoising – 3. Bilateral Filtering

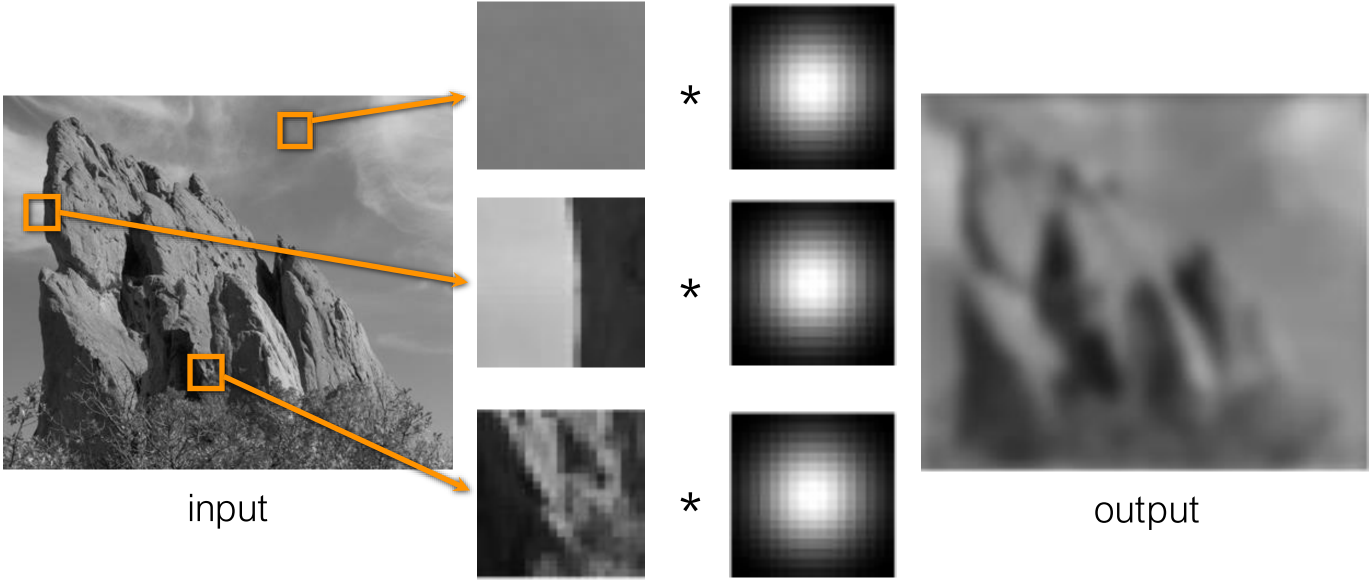
original

Gaussian filtering

bilateral filtering

Denoising – 3. Bilateral Filtering

Gaussian kernel

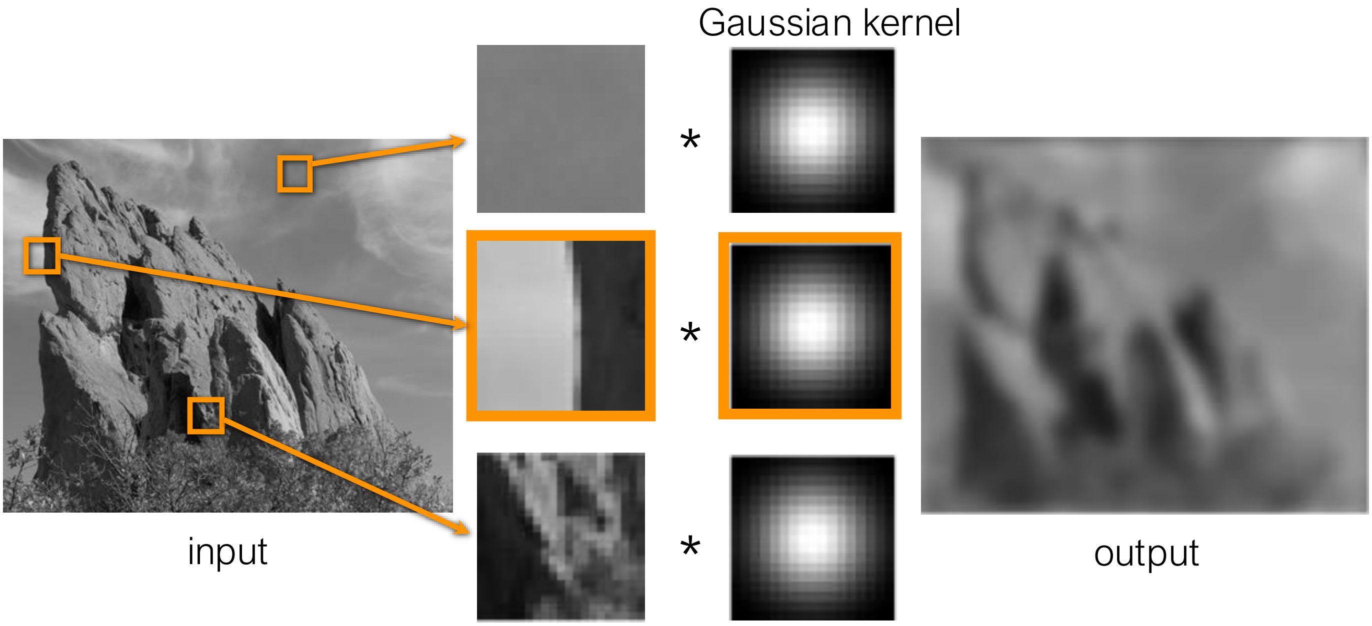


input

output

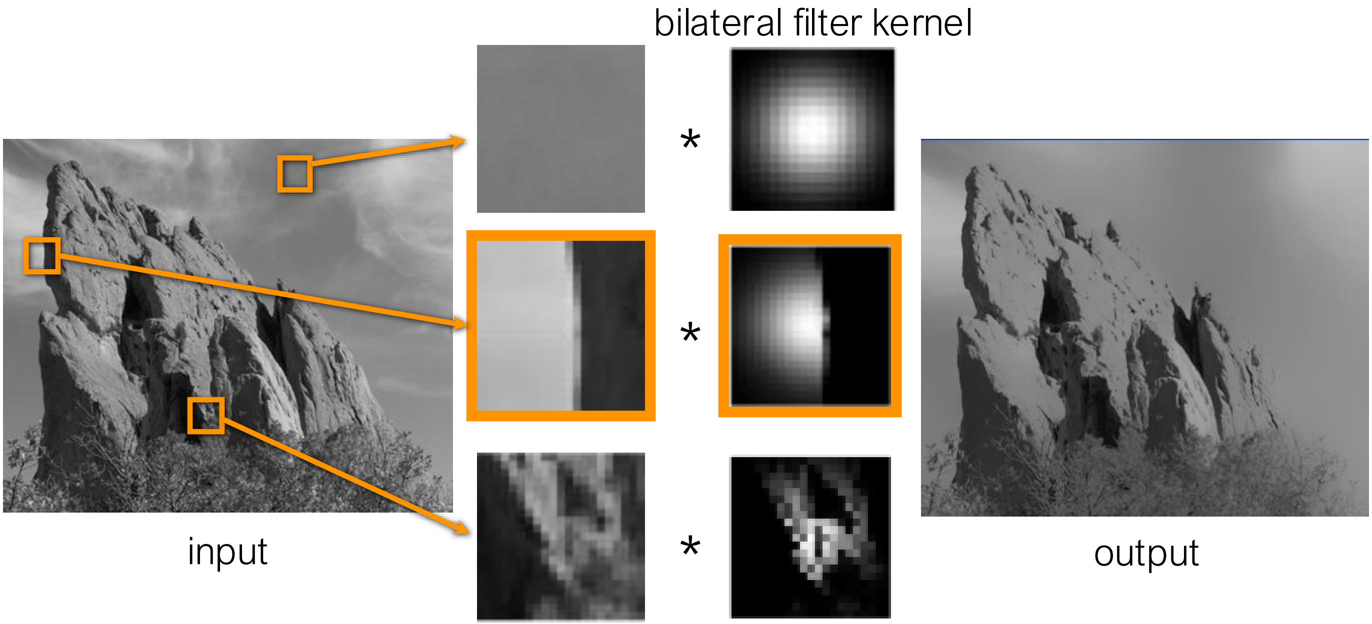
Why is the output so blurry?

Denoising – 3. Bilateral Filtering



Blur kernel averages across edges

Denoising – 3. Bilateral Filtering



Do not blur if there is an edge! How does it do that?

Denoising – 3. Bilateral Filtering

$$i_{denoised}(x) = \frac{1}{\sum_{\text{all pixels } x'} w(x,x')} \sum_{\text{all pixels } x'} i_{noisy}(x') \cdot w(x,x')$$

spatial distance — distance of intensities

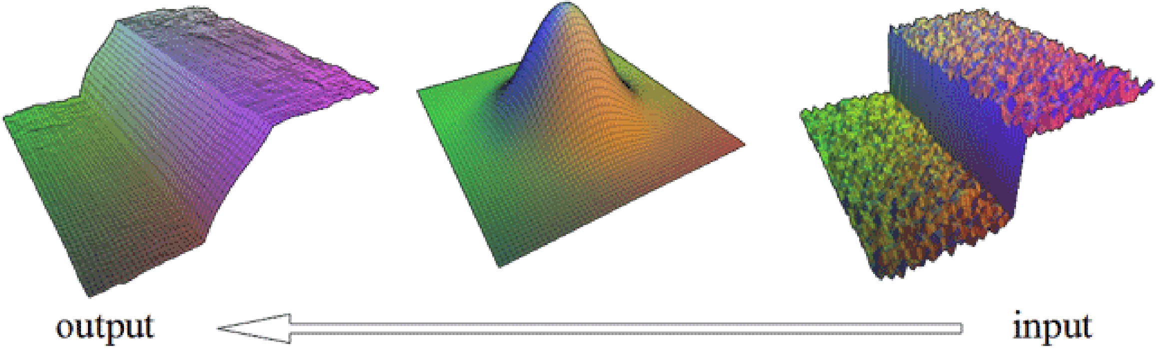
$$w(x,x') = \boxed{\exp\left(-\frac{\left\|x' - x\right\|^2}{2\sigma^2}\right)} \cdot \boxed{\exp\left(-\frac{\left\|i_{noisy}(x') - i_{noisy}(x)\right\|^2}{2\sigma_i^2}\right)}$$

- more clever: average in <u>local</u> neighborhood, but only average similar intensities!

Denoising – Gaussian Filter

J: filtered output (is blurred)
f: Gaussian convolution kernel
I: step function & noise

$$J(x) = \sum_{\xi} f(x,\xi)\, I(\xi)$$

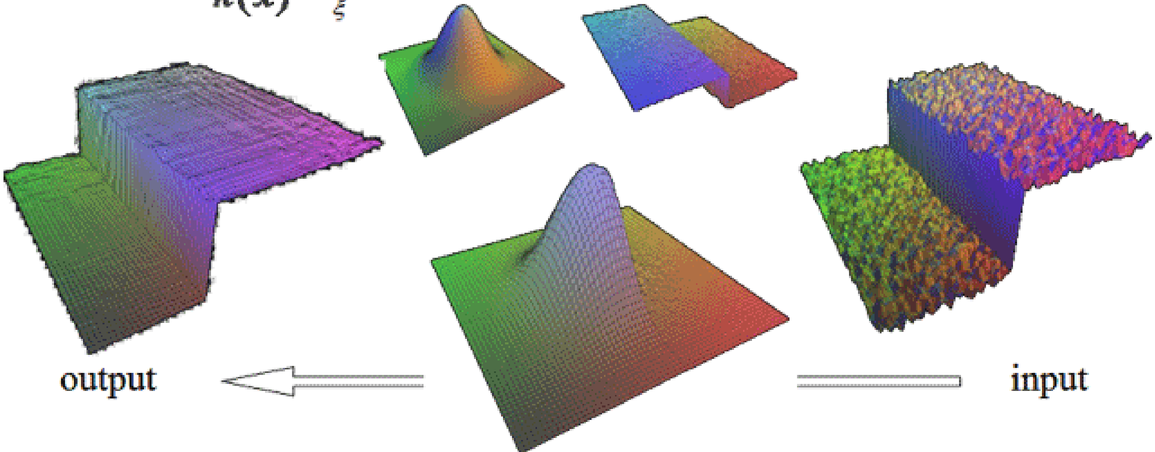


Denoising – Bilateral Filter

J: filtered output (is not blurred)
f: Gaussian convolution kernel
I: noisy image (step function & noise)

difference in intensity as scale!

$$J(x) = \frac{1}{k(x)} \sum_{\xi} f(x,\xi) \quad g(I(\xi) - I(x)) \quad I(\xi)$$



Tomasi & Manduchi, 1998

Denoising – Bilateral Filter

original image

bilateral filter = “edge-aware smoothing”

Denoising – Bilateral Filter

noisy image

bilateral filter = “edge-aware smoothing”

Exploring the bilateral filter parameter space

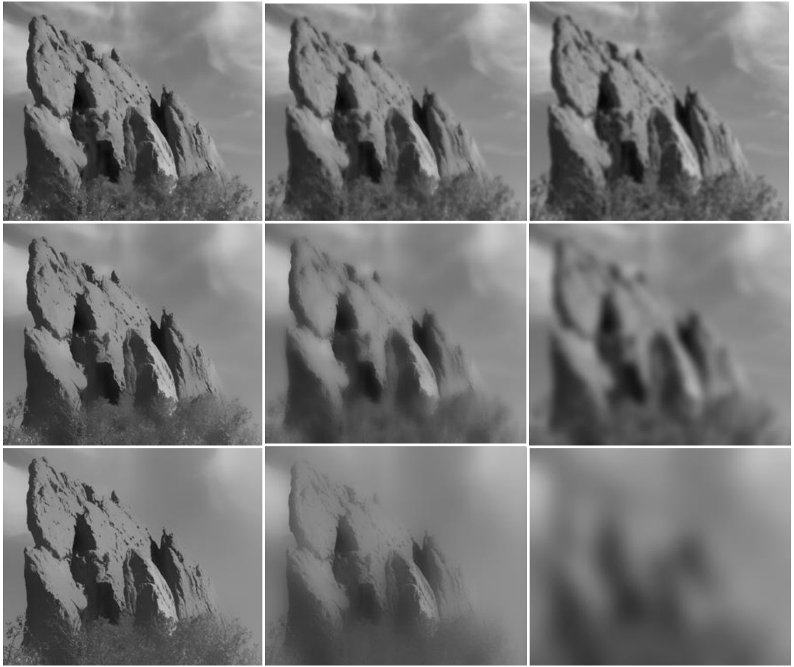
input

$\sigma_r = 0.1$ | $\sigma_r = 0.25$ | $\sigma_r = 8$ (Gaussian blur)

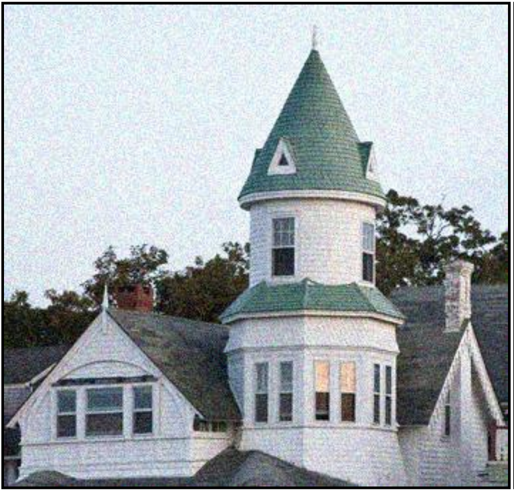
$\sigma_s = 2$

$\sigma_s = 6$

$\sigma_s = 18$



Denoising



noisy input

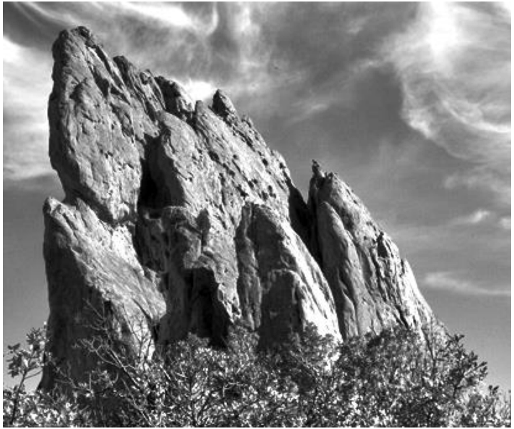
bilateral filtering

median filtering

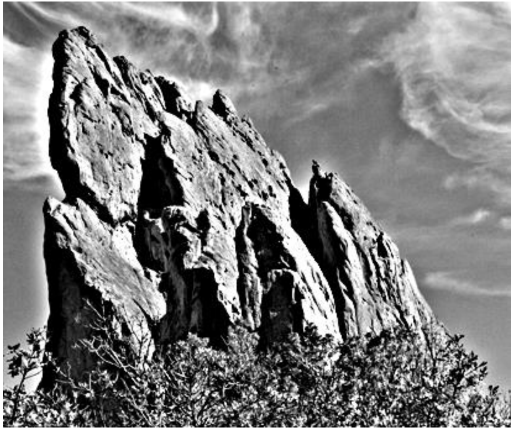
Contrast enhancement

How would you use Gaussian or bilateral filtering for sharpening?

input



sharpening based on bilateral filtering



sharpening based on Gaussian filtering

Photo retouching

Photo retouching

original

digital pore removal (aka bilateral filtering)

Before

After

Close-up comparison

original

digital pore removal (aka bilateral filtering)

Cartoonization

input

cartoon rendition

Cartoonization

How would you create this effect?

Cartoonization

edges from bilaterally filtered image

+

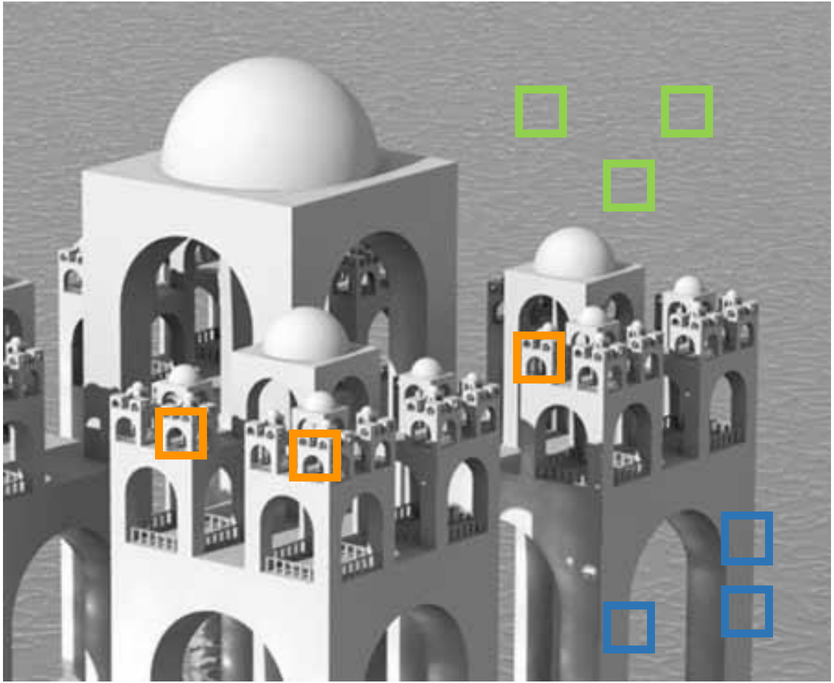
bilaterally filtered image

=

cartoon rendition

Note: image cartoonization and abstraction are very active research areas.

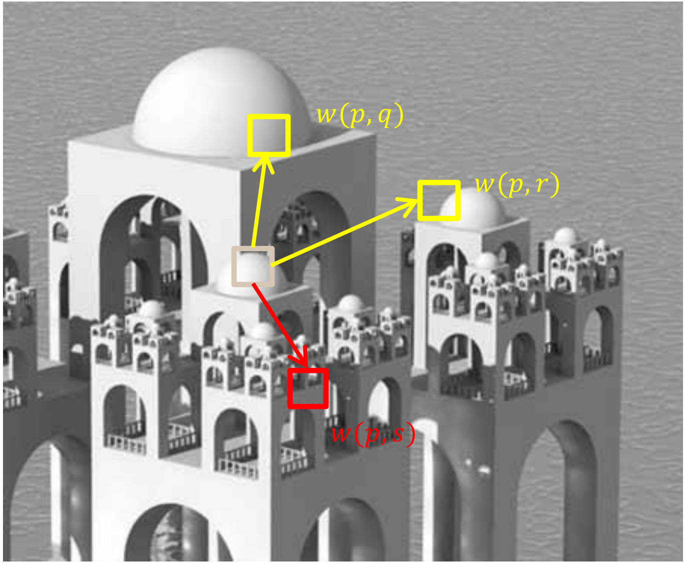
Denoising – 4. Non-local Means



Denoising – 4. Non-local Means

- define distance between global image patches
- average distant pixels with similar neighborhood!

$$i_{denoised}(x) = \sum_{\text{all pixels } x'} i_{noisy}(x') \cdot w(x, x')$$



[Buades 2005]

Denoising – 4. Non-local Means

$$i_{denoised}(x) = \frac{1}{\sum_{\text{all pixels } x'} w(x, x')} \sum_{\text{all pixels } x'} i_{noisy}(x') \cdot w(x, x')$$

$$w(x, x') = \exp\left(- \frac{\left\| W\left(i_{noisy}, x'\right) - W\left(i_{noisy}, x\right) \right\|^2}{2\sigma^2} \right)$$

[Buades 2005]

- very powerful approach: exploit self-similarity in image; average pixels with a similar neighborhood, but don't need to be close → non-local

Denoising – 4. Non-local Means

[Buades 2005]

Everything put together

Gaussian filtering

Smooths everything nearby (even edges)
Only depends on spatial distance

Bilateral filtering

Smooths ‘close’ pixels in space and intensity
Depends on spatial and intensity distance

Non-local means

Smooths similar patches no matter how far away
Only depends on intensity distance

Denoising – Other Non-local Method BM3D

- find similar image patches and group them in 3D blocks

- apply collaborative filter on all of them:
  - DCT-transform each 3D block
  - threshold transform coefficients
  - inverse transform 3D block

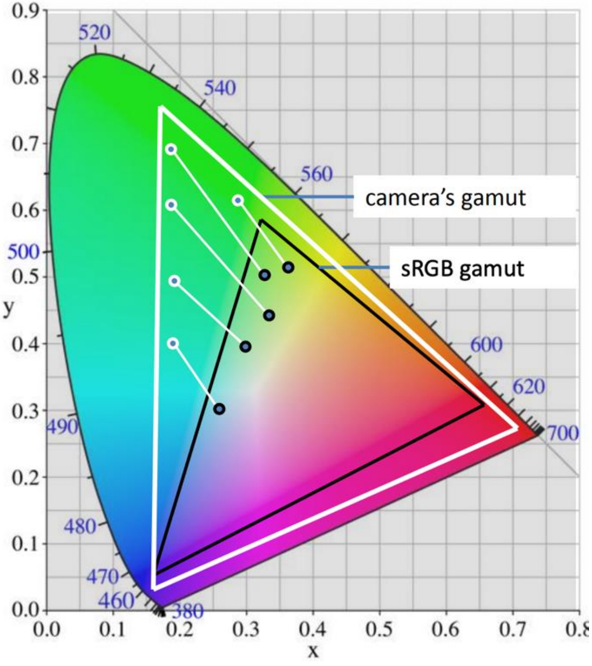
[Dabov 2006]

Denoising

- many methods for denoising (check Buades 2005):
    - filtering wavelet or other coefficients
    - total variation denoising
    - patch-based or convolutional sparse coding …

- state of the art: non-local methods, in particular BM3D

Gamut Mapping



Need to map from camera gamut to standard gamut (sRGB).

Different ways of projecting the colors lead to different camera modes (e.g., vivid, portrait, landscape, etc.).

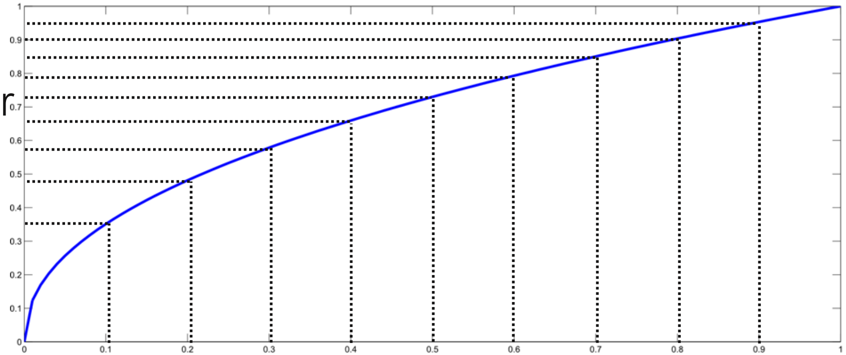
Internally, we transform from camera XYZ->CIE XYZ and eventually sRGB

Gamma Correction

- from linear 10/12 bit to 8 bit (save space)
- perceptual linearity for optimal encoding with specific bit depth
- sensitivity to luminance is roughly γ=2.2

perceptually linear

spacing!

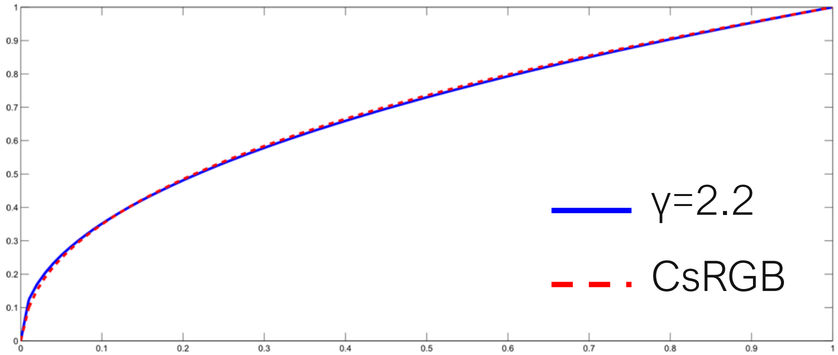


Gamma Correction in sRGB

- standard 8 bit color space of most images, e.g. jpeg
- roughly equivalent to γ=2.2

$$C_{sRGB} = \begin{cases} \boxed{12.92\,C_{linear} \quad C_{linear} \le 0.0031308} & \text{linear} \\ \boxed{(1+a)C_{linear}^{1/2.4} - a \quad C_{linear} > 0.0031308} & \text{gamma} \end{cases}$$

$$a = 0.055$$



Compression – JPEG (joint photographic experts group)

jpeg – ps quality 0

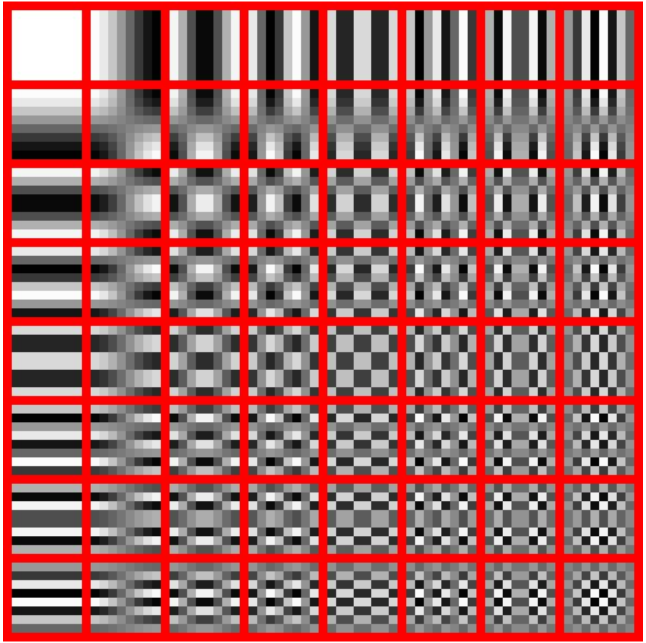
jpeg – ps quality 2

original

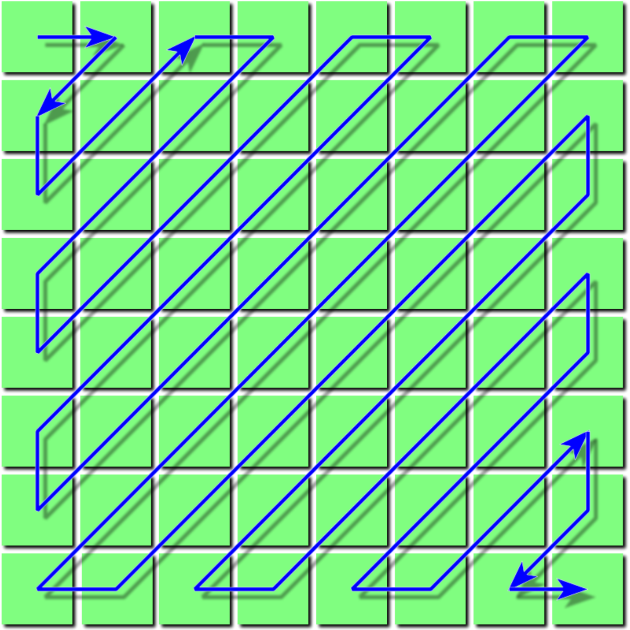
Compression – JPEG (joint photographic expert group)

1. transform to YCbCr
2. downsample chroma components Cb & Cr
   - 4:4:4 – no downsampling
   - 4:2:2 – reduction by factor 2 horizontally
   - 4:2:0 – reduction by factor 2 both horizontally and vertically
3. split into blocks of 8x8 pixels
4. discrete cosine transform (DCT) of each block & component
5. quantize coefficients
6. entropy coding (run length encoding – lossless compression)

Compression – JPEG (joint photographic expert group)

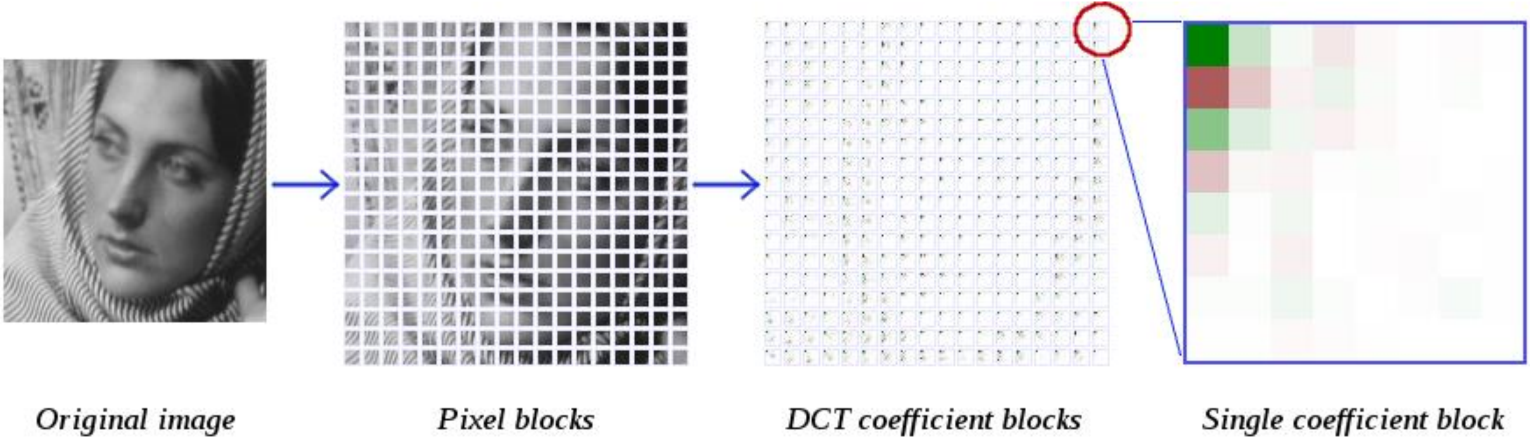

wikipedia

DCT basis functions



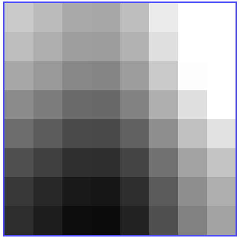
RLE of “same frequency” coefficients

Compression – JPEG (joint photographic expert group)



http://xiph.org/~xiphmont/demo/daala/demo1.shtml

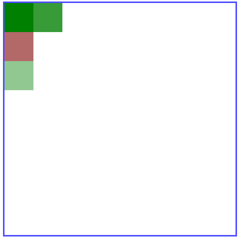
Compression – JPEG (joint photographic expert group)



Original pixel data

114	108	100	99	109	129	152	166
109	102	95	94	104	124	146	161
99	93	85	84	94	114	137	151
86	80	72	71	82	102	124	138
73	66	58	57	68	88	110	125
60	53	46	45	55	75	97	112
50	43	36	35	45	65	88	102
45	38	31	30	40	60	82	97

DCT →

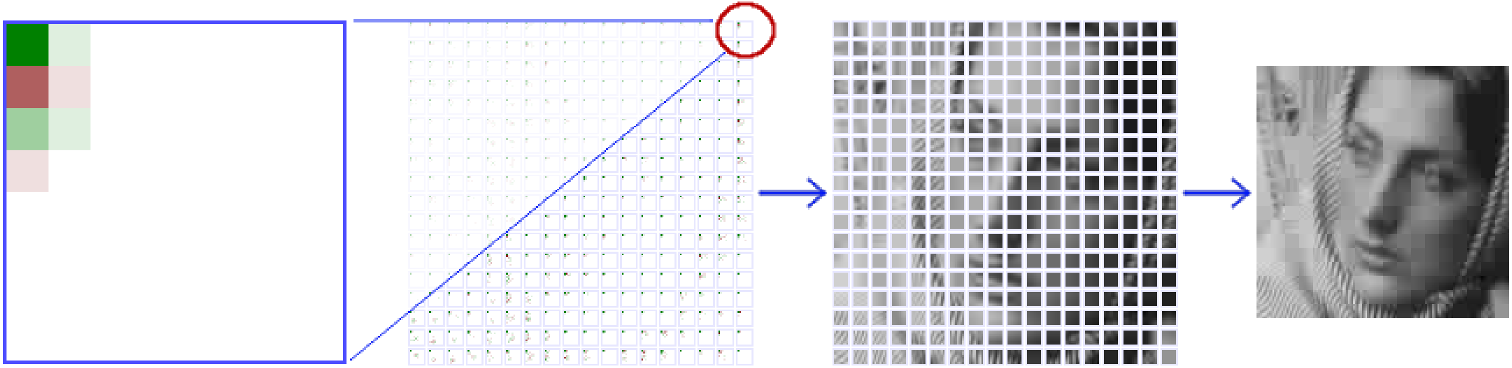


DCT coefficient data

700	200	0	0	0	0	0	0
-150	0	0	0	0	0	0	0
110	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

http://xiph.org/~xiphmont/demo/daala/demo1.shtml

Compression – JPEG (joint photographic expert group)

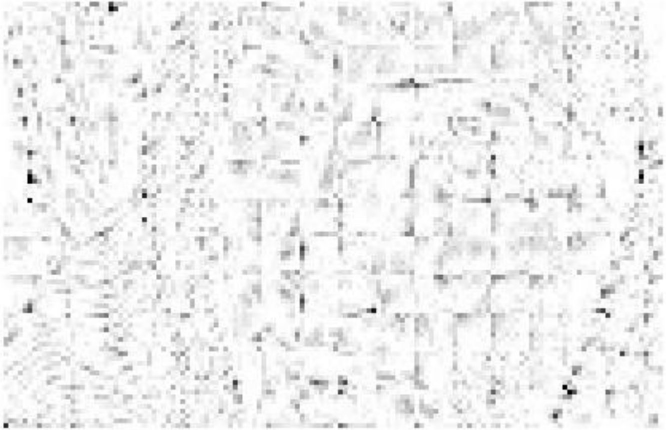


Single quantized block *Quantized coefficient blocks* *Reconstructed pixel blocks* *Reconstructed image*

http://xiph.org/~xiphmont/demo/daala/demo1.shtml

Compression – JPEG (joint photographic expert group)

Closeup of reconstructed image



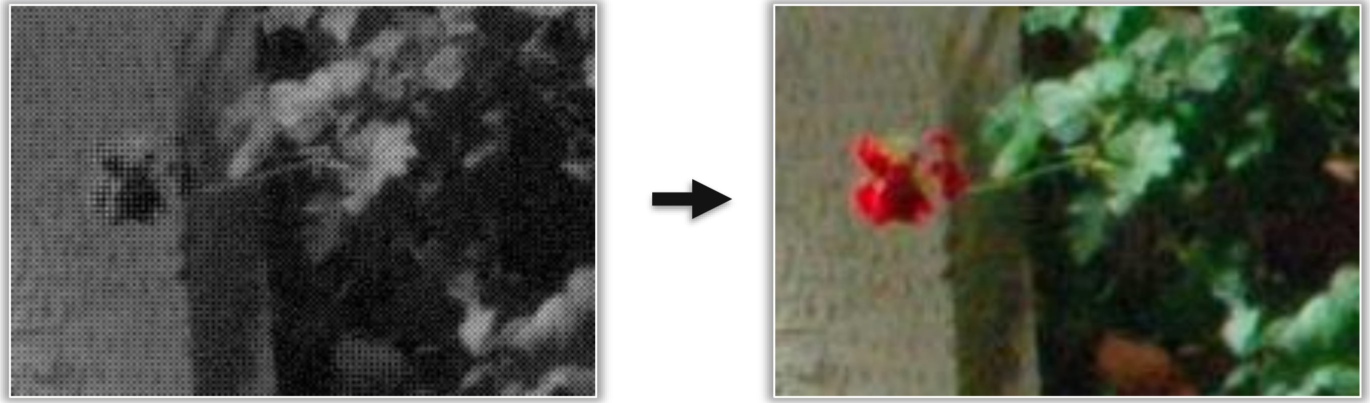
Normalized error distribution within each block

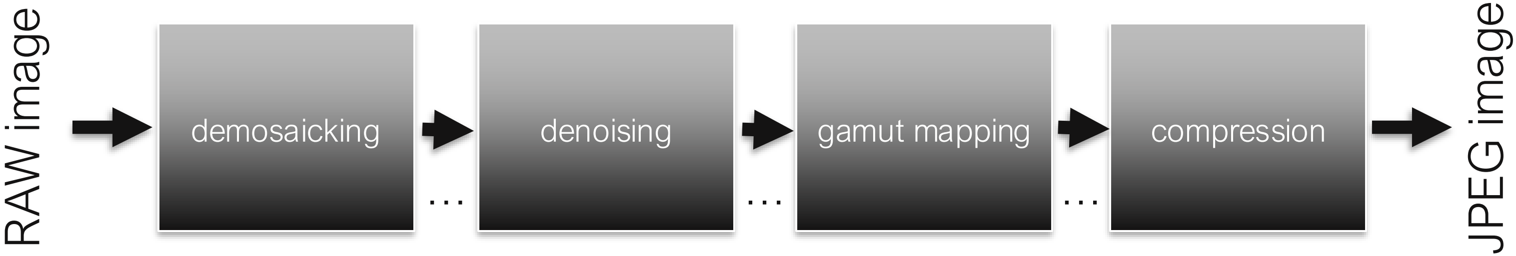
http://xiph.org/~xiphmont/demo/daala/demo1.shtml

Compression – JPEG (joint photographic experts group)

jpeg – ps quality 0 | jpeg – ps quality 2 | original

Image Processing Pipeline





Homework 2

- calculate and plot depth of field of different cameras
- implement a simple image processing pipeline in Python and explore demosaicking, denoising, etc.

Next: Math Review

- sampling
- filtering
- deconvolution
- sparse image priors
- …

References and Further Reading

Denoising

- S. Paris, P. Kornprobst, J. Tumblin, F. Durand "A Gentle Introduction to Bilateral Filtering and its Applications", SIGGRAPH 2007 course notes
- Buades, Morel, "A non-local algorithm for image denoising", CVPR 2005
- Dabov, Foi, Katkovnik, Egiazarian, "Image denoising by sparse 3D transform-domain collaborative filtering", IEEE Trans. Im. Proc. 2007

Demosaicking

- Malvar, He, Cutler, "High-quality Linear Interpolation for Demosaicking of Bayer-patterned Color Images", Proc. ICASSP 2004
- Gunturk, Glotzbach, Alltunbasak, Schafer, "Demosaicking: Color Filter Array Interpolation", IEEE Signal Processing Magazine 2005

Plenoptic function

- E. Adelson, J. Bergen "The Plenoptic Function and Elements of Early Vision", Computational Models of Visual Processing, 1991
- G. Wetzstein, I. Ihrke, W. Heidrich "On Plenoptic Multiplexing and Reconstruction", Int. Journal on Computer Vision, 2013

Other, potentially interesting work

- F. Heide, S. Diamond, M. Niessner, J. Ragan-Kelly, W. Heidrich, G. Wetzstein, "ProxImaL: Efficient Image Optimization using Proximal Algorithms", ACM SIGGRAPH 2016
- Kodac dataset (especially good and standard for demosaicking): http://r0k.us/graphics/kodak/