Forming Color Images

Image Manipulation and Computational Photography
CS294-69 Fall 2011
Maneesh Agrawala

[Some slides from James Hays , Derek Hoiem, Alexei Efros and Fredo Durand]

Forming Color Images

Sergey Prokudin-Gorsky 1909, 1915
http://www.flickr.com/photos/prokudin-gorsky/

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Cool Educational Applets

From Marc Levoy, Andrew Adams et al.

http://graphics.stanford.edu/courses/cs178-10/applets/

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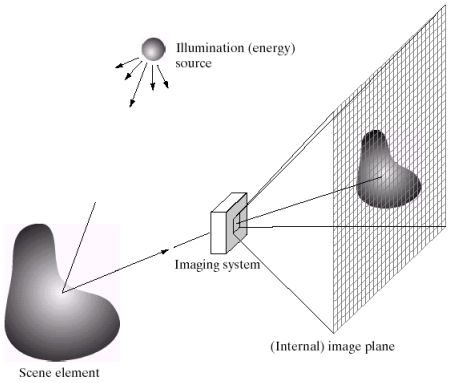
Etymology

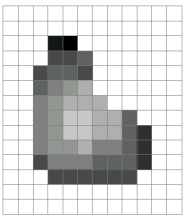
PHOTOGRAPHY

light

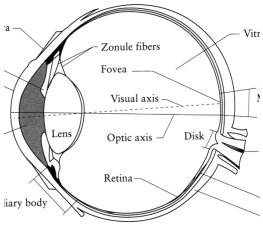
drawing / writing

Image Formation





Camera



The Eye

Topics

Light and the Eye

Color Spaces

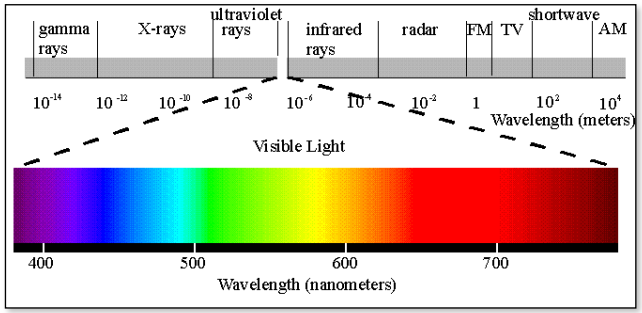
Color Sensing in Cameras

Demosiacing

Light and the Eye

What is Light?

Radiation in a particular range of wavelengths

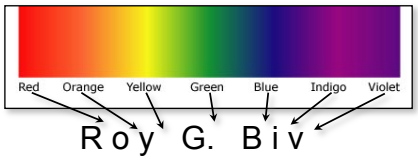


Why do we only see these wavelengths?

Spectral Colors

Light at a single frequency

Bright and distinct in appearance



Reproduction only, not a real spectral color!

Other Colors

Most colors we see are a mix light of several wavelengths

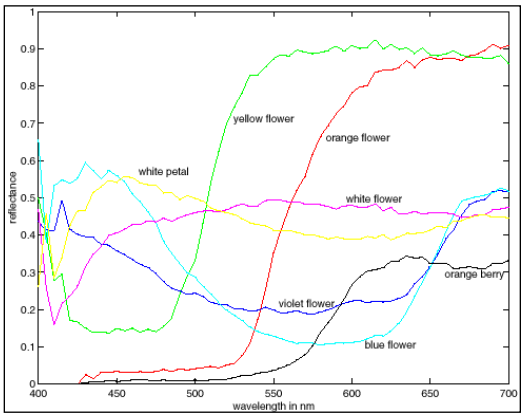


Image from David Forsyth

Curves describe spectral composition $\Phi(\lambda)$ of stimulus

Other Colors

Most colors we see are a mix light of several wavelengths

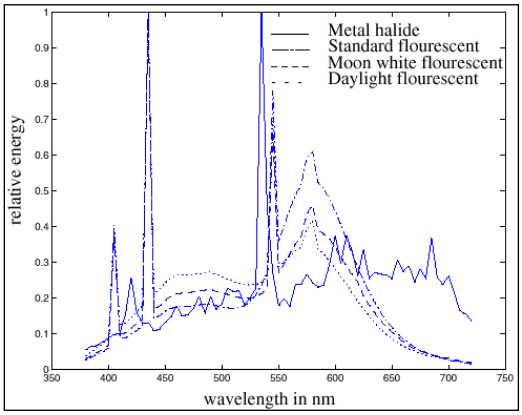
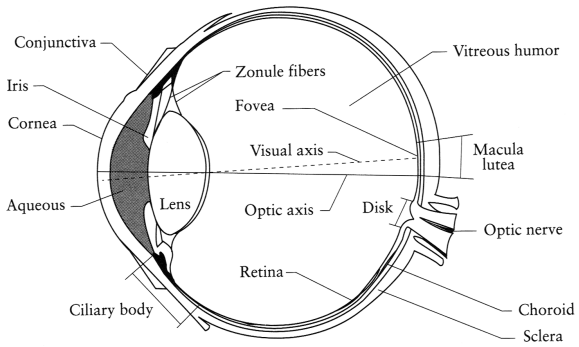


Image from David Forsyth

Curves describe spectral composition $\Phi(\lambda)$ of stimulus

The Eye

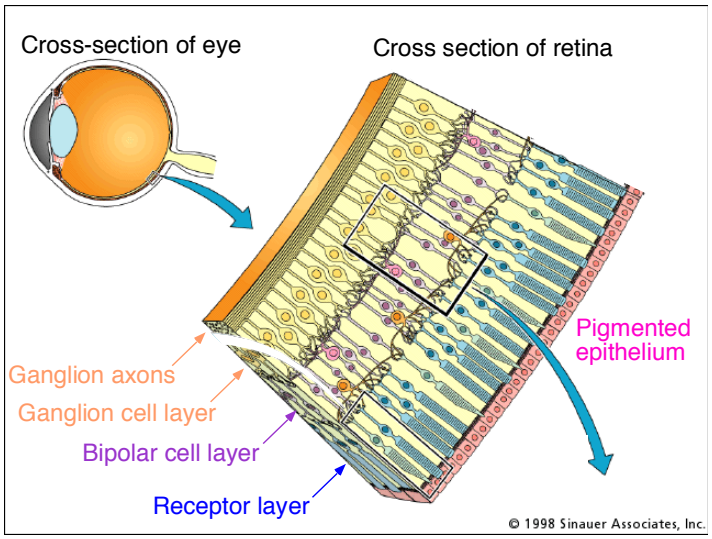


The human eye is a camera!

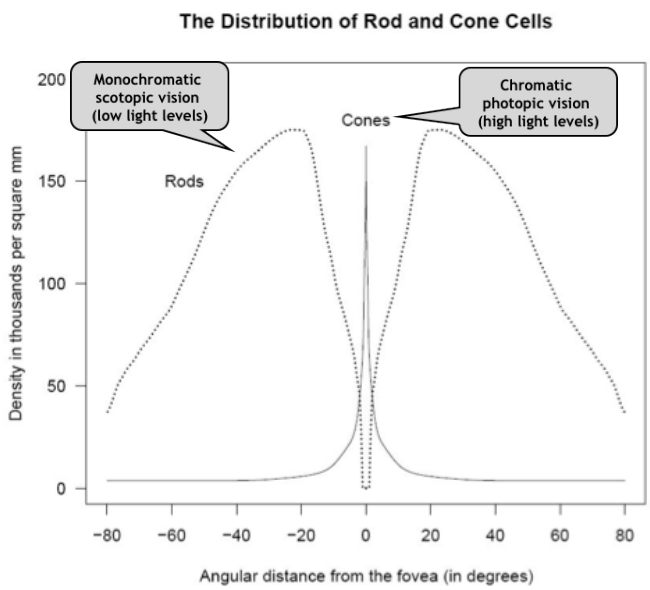
- **Iris** - colored annulus with radial muscles
- **Pupil** - the hole (aperture) whose size is controlled by the iris
- What's the "film"?
  - photoreceptor cells (rods and cones) in the **retina**

Slide by Steve Seitz

The Retina



Eyes as Sensors



Rods and Cones

The human eye contains cells that sense light

Rods
- No color (sort of)
- Spread over the retina
- More sensitive

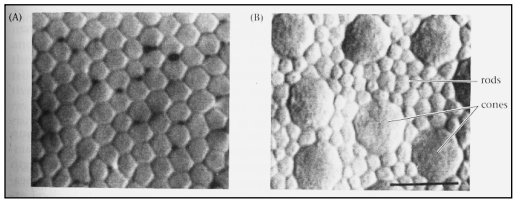
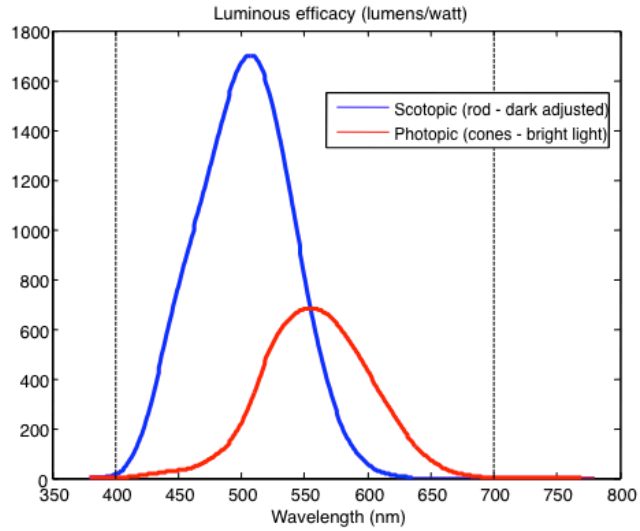


Image from Stephen Chenney

Cones
- Three types of cones
- Each sensitive to different frequency distribution
- Concentrated in fovea (center of the retina)
- Less sensitive

Rods vs Cones



Cones

Each type of cone responds to different range of wavelengths

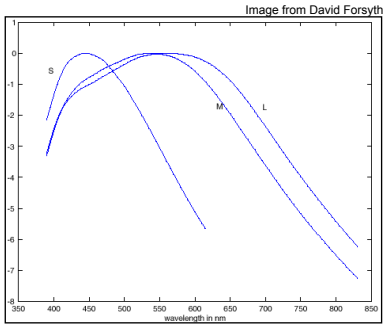
- Long, medium, short
- Ratio: L10/M40/S1

Also called by color

- Red, green, blue
- Misleading:

"Red" does not mean only your red cones are firing…

Image from David Forsyth



Note: Rod response peaks between S&M

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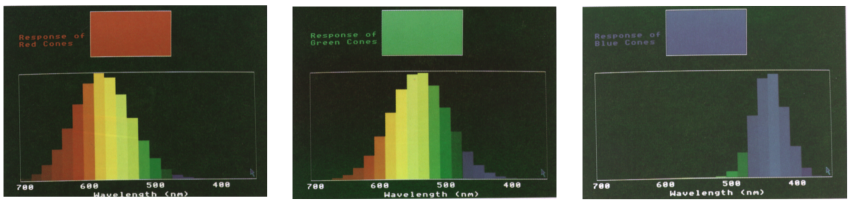
Cones



Images from David Forsyth

"Red" and "green" cones respond to more than just red and green wavelengths...

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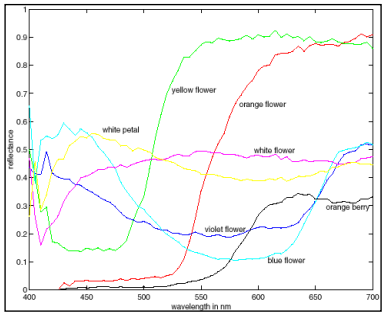
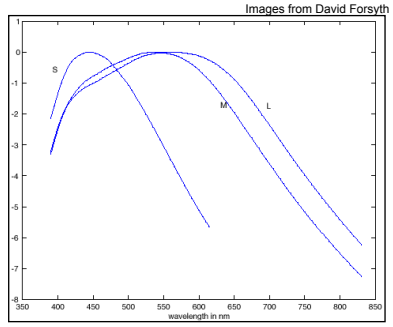
Cones

Cone response given by a convolution integral :

Images from David Forsyth





$$L = \int \Phi(\lambda) L(\lambda) \mathrm{d}\lambda$$

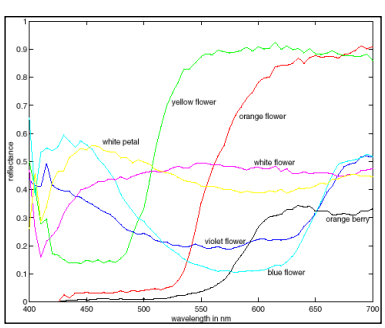
$$M = \int \Phi(\lambda) M(\lambda) \mathrm{d}\lambda$$

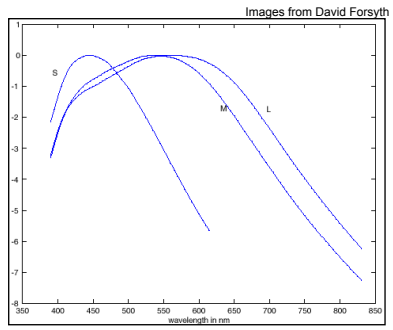
$$S = \int \Phi(\lambda) S(\lambda) \mathrm{d}\lambda$$

Cones

Response integral is continuous version of dot prod.

Images from David Forsyth





$$L = \int \Phi(\lambda) L(\lambda) \mathrm{d}\lambda$$

$$M = \int \Phi(\lambda) M(\lambda) \mathrm{d}\lambda$$

$$S = \int \Phi(\lambda) S(\lambda) \mathrm{d}\lambda$$

$$\begin{pmatrix} L(\lambda_1) & \dots & L(\lambda_N) \\ M(\lambda_1) & \dots & M(\lambda_N) \\ S(\lambda_1) & \dots & S(\lambda_N) \end{pmatrix} \begin{pmatrix} \phi(\lambda_1) \\ \vdots \\ \phi(\lambda_N) \end{pmatrix}$$

Trichromaticity

Eye records color by 3 measurements

We can "fool" it with combination of 3 signals

So display devices (monitors, printers, etc.) can generate perceivable colors as mix of 3 primaries

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Cone Responses are Linear

Response to stimulus Φ_1 is (L_1, M_1, S_1)

Response to stimulus Φ_2 is (L_2, M_2, S_2)

Then response to $\Phi_1 + \Phi_2$ is $(L_1 + L_2, M_1 + M2, S_1 + S_2)$

Response to $n\Phi_1$ is (nL_1, nM_2, nS_1)

System that obeys superposition and scaling is called a **linear system**

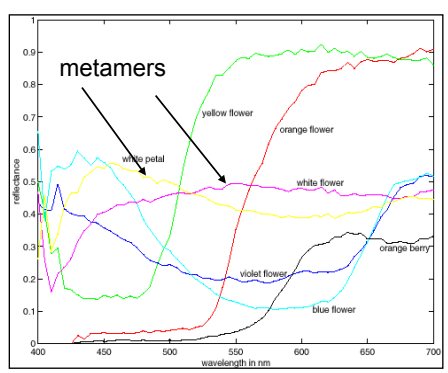
Cones and Metamers

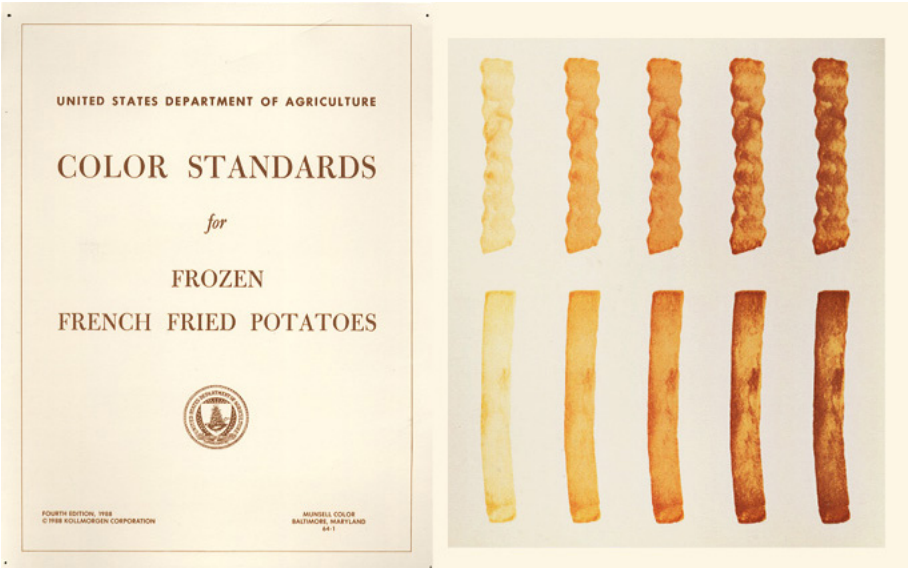
Cone response is an integral

$$L = \int \Phi(\lambda)L(\lambda)\mathrm{d}\lambda \quad M = \int \Phi(\lambda)M(\lambda)\mathrm{d}\lambda \quad S = \int \Phi(\lambda)S(\lambda)\mathrm{d}\lambda$$

Metamers: Different light input $\Phi_1(\lambda), \Phi_2(\lambda)$ produce same L, M, S cone response

- Different spectra look the same
- Useful for measuring color





Slide from Bill Freeman

Standard Color Spaces

We need a principled representation of color

Many possible definition

- Including cone response (LMS)
- Unfortunately not really used,
  (because not known at the time)

Good news: Color vision is linear and 3-dimensional

So any representation based on color matching can be obtained using 3x3 matrix

- There are also non-linear color spaces (e.g. Hue Saturation Value, Lab)

Additive Mixing

Given three primaries we agree on p_1, p_2, p_3

Match generic input light with $\Phi = \alpha p_1 + \beta p_2 + \gamma p_3$

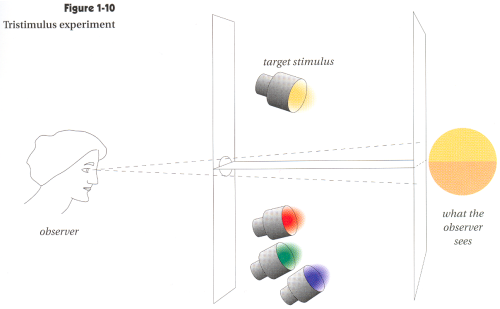
Negative not realizable, but can add primary to test light

Color now described by $\alpha,\ \beta,\ \gamma$

Example p_1, p_2, p_3

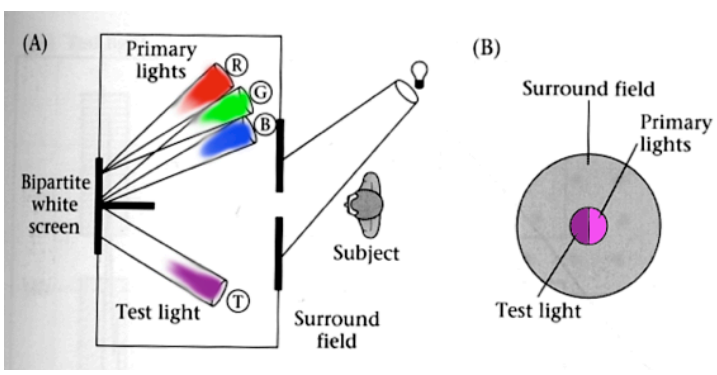
computer monitor [RGB]

Figure 1-10
Tristimulus experiment



The observer adjusts the intensities of the red, green, and blue lamps until they match the target stimulus on the split screen.

Additive Color Matching



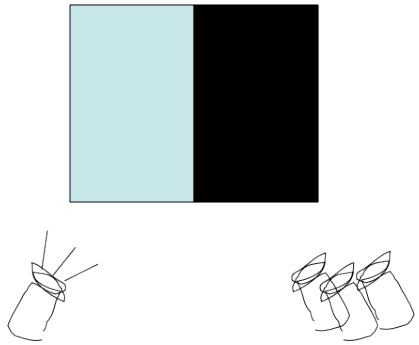
Show test light spectrum on left

Mix 3 "primaries" on right until they match and record 3 values

The primaries need not be RGB

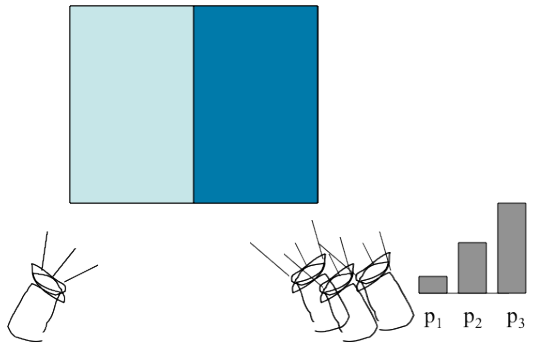
What do we get if we do this for each spectral color (400 to 700 nm)?

Experiment 1



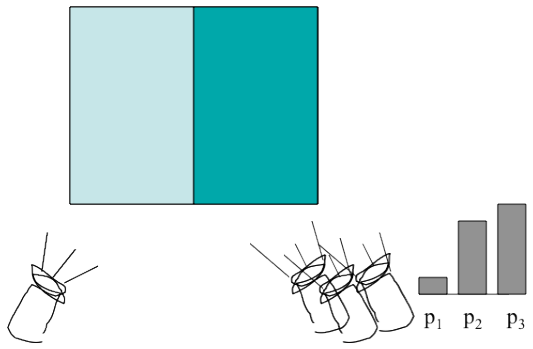
Slide from Durand and Freeman 06

Experiment 1



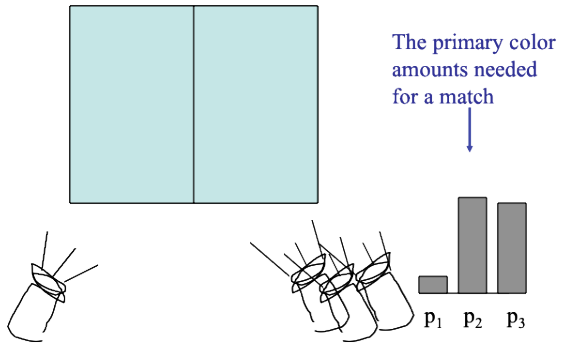
Slide from Durand and Freeman 06

Experiment 1



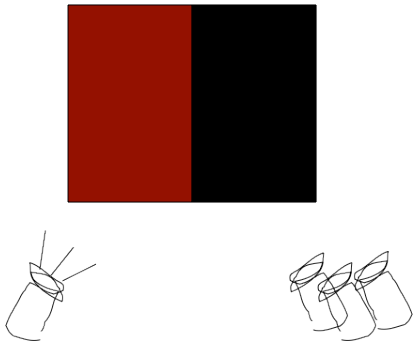
Slide from Durand and Freeman 06

Experiment 1



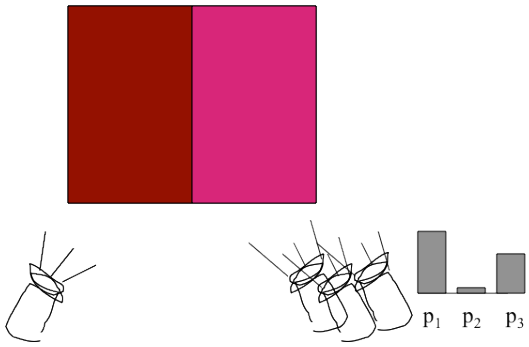
Slide from Durand and Freeman 06

Experiment 2



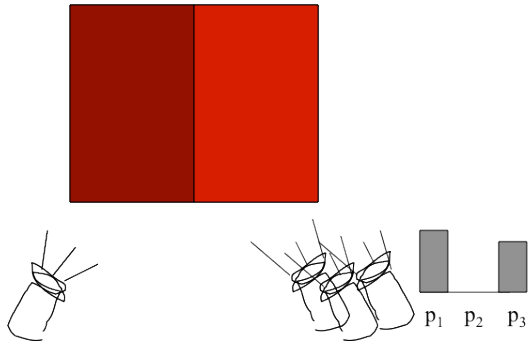
Slide from Durand and Freeman 06

Experiment 2



Slide from Durand and Freeman 06

Experiment 2

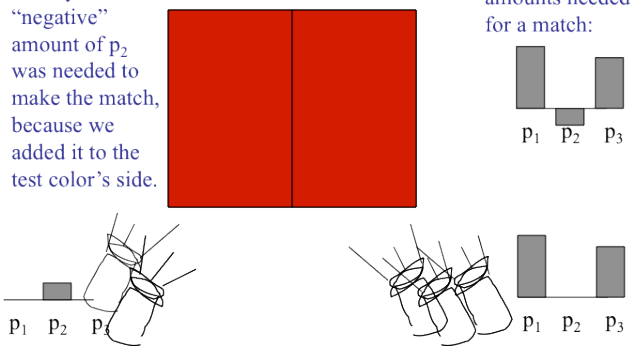


Slide from Durand and Freeman 06

Experiment 2

We say a "negative" amount of p_2 was needed to make the match, because we added it to the test color's side.

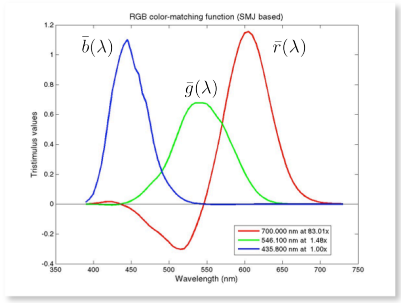
The primary color amounts needed for a match:



Slide from Durand and Freeman 06

Color Matching Functions

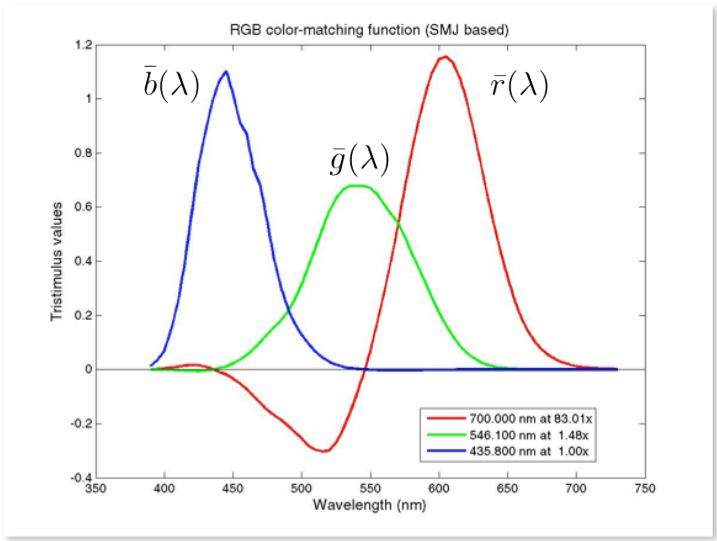
Compute amount of each primary required to produce spectral colors of each wavelength 400-700nm



Meaning: Spectral color λ can be reproduced with

$\bar{b}(\lambda)$ amount of blue primary
$\bar{g}(\lambda)$ amount of green primary
$\bar{r}(\lambda)$ amount of red primary

Color Matching Functions

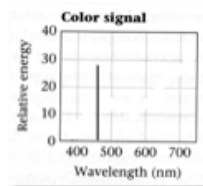


Input wavelengths are CIE 1931 spectral (monochromatic) primaries

Using Color Matching Functions

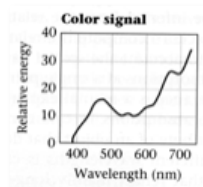
For a spectral light of wavelength λ_i
we know the amount of each primary necessary to match it:

$$\bar{r}(\lambda_i), \bar{g}(\lambda_i), \bar{b}(\lambda_i)$$



Given a new light input signal

$$\Phi = \begin{pmatrix} \phi(\lambda_1) \\ \vdots \\ \phi(\lambda_N) \end{pmatrix}$$



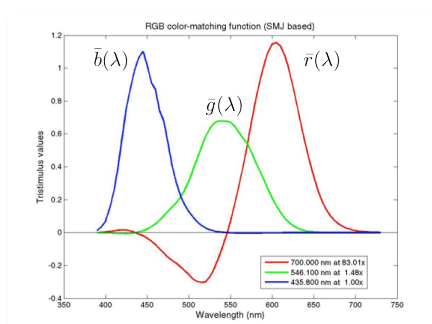
Compute the primaries necessary to match it

Using Color Matching Functions

Given color match. functions in matrix form and new light

$$C = \begin{pmatrix} \bar{r}(\lambda_1) & \dots & \bar{r}(\lambda_N) \\ \bar{g}(\lambda_1) & \dots & \bar{g}(\lambda_N) \\ \bar{b}(\lambda_1) & \dots & \bar{b}(\lambda_N) \end{pmatrix}$$

$$\Phi = \begin{pmatrix} \phi(\lambda_1) \\ \vdots \\ \phi(\lambda_N) \end{pmatrix}$$

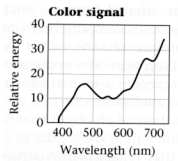


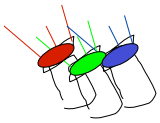
amount of each primary necessary to match is given by $C\Phi$
a metamer of Φ

Fully specifies color perceived by humans …

But what about negative primaries?

Could Compute Match for Any 3 Primaries





Why would you want to?:

- To paint Kodak carton with the Kodak yellow color.
- To match skin color in a photograph printed on an ink jet printer to their true skin color.
- To match colors in the world, with those on a monitor, or those in print, etc.

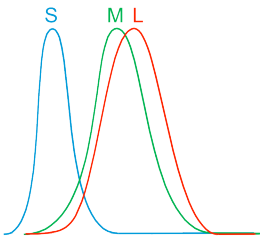
Relation to Cone Curves

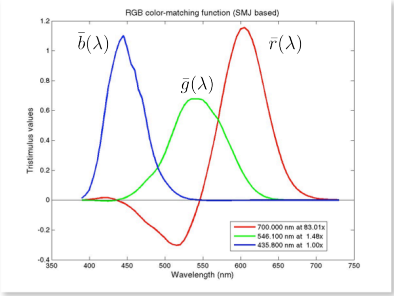
Project to the same subspace

- b, g, and r are linear combinations of S, M and L

Related by 3x3 matrix

- In fact any set of primaries for which we have color matching curves is related by 3x3 matrix due to linearity (**how?**)





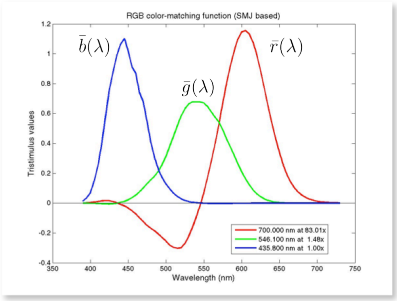
How to Build Measurement Device?

How to Build Measurement Device?

Idea:

- Start with light sensor sensitive to all wavelengths
- Use three filters with spectra b, r, g
- measure 3 numbers

This is pretty much what the eyes do!

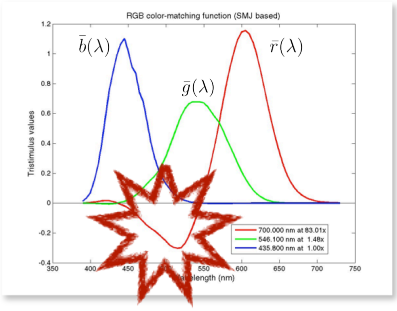


Problem

Idea:

- Start with light sensor sensitive to all wavelength
- Use three filters with spectra b, r, g
- measure 3 numbers

For CIE primaries need negative values



Solution

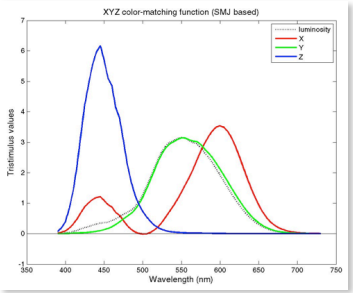
Too obvious:

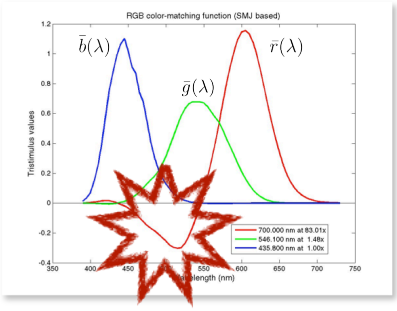
Use cone response!

- But unknown at the time

New set of tristimulus curves

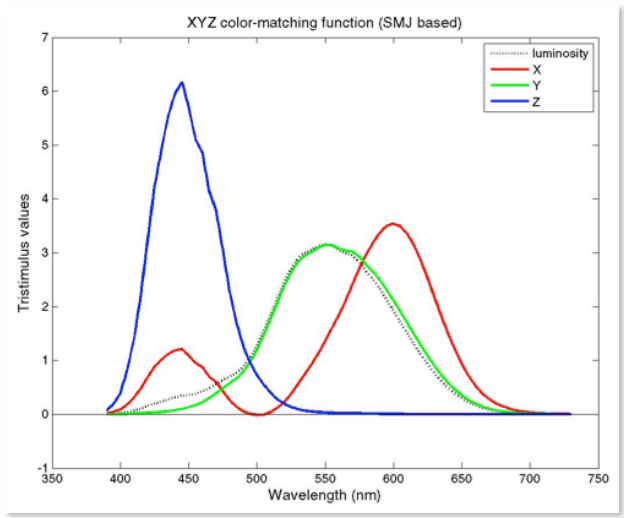
- linear combinations of b, g, r
- pretty much add enough b and g until r is positive





CIE XYZ

Imaginary set of color primaries with positive values, X, Y, Z



Conversion between XYZ and RGB

RGB space created with a different set of primaries

- So 3x3 transform foes the trick

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} 3.24 & -1.54 & -0.50 \\ -0.97 & 1.88 & 0.04 \\ 0.06 & -0.20 & 1.06 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0.41 & 0.36 & 0.18 \\ 0.21 & 0.72 & 0.07 \\ 0.02 & 0.12 & 0.95 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

Rescaled XYZ to xyz

Rescale X, Y, and Z to remove luminance, leaving chromaticity:

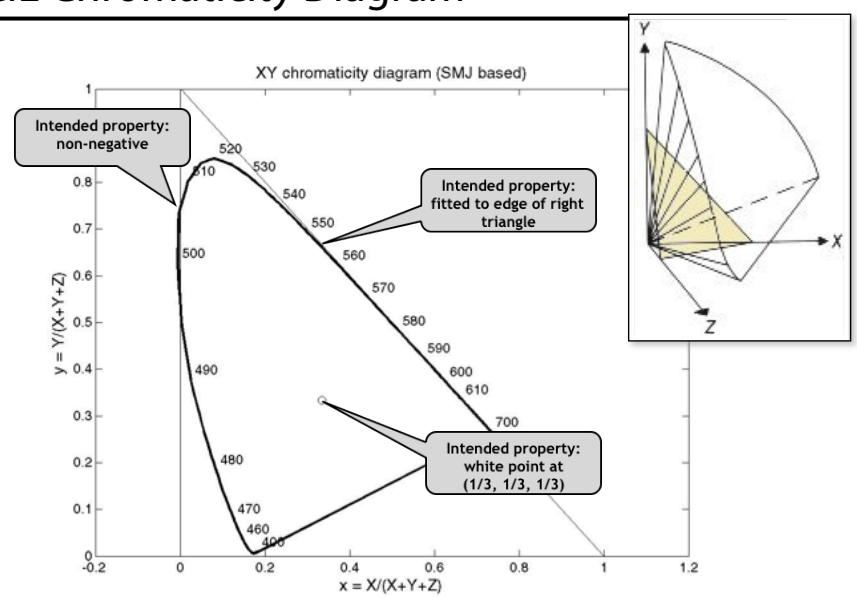
$$x = X / (X+Y+Z)$$
$$y = Y / (X+Y+Z)$$
$$z = Z / (X+Y+Z)$$

$$x+y+z = 1$$

Because the sum of the chromaticity values x, y, and z is always 1.0, a plot of any two of them loses no information

Such a plot is a chromaticity diagram

CIE Chromaticity Diagram



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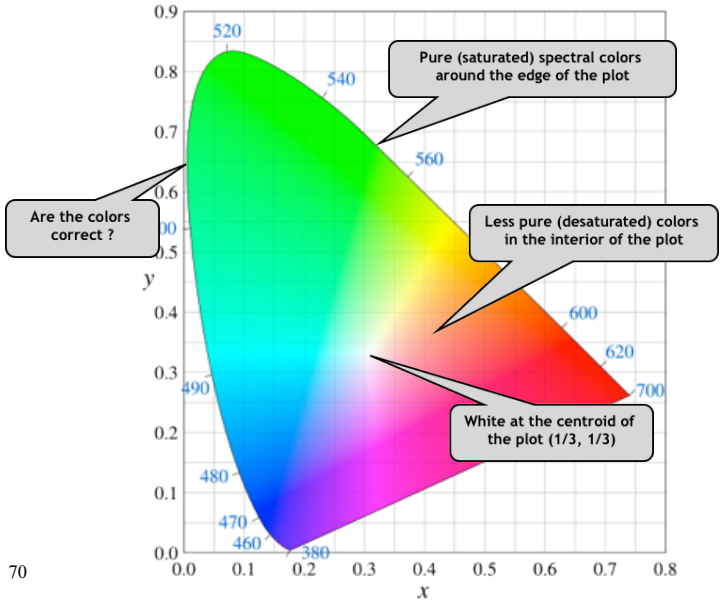
CIE Chromaticity Diagram



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Gamut

Gamut is the chromaticities generated by a set of primaries

Because everything we've done is linear, interpolation between chromaticities on a chromaticity plot is also linear

Thus the gamut is the convex hull of the primary chromaticities

What is the gamut of the CIE 1931 primaries?

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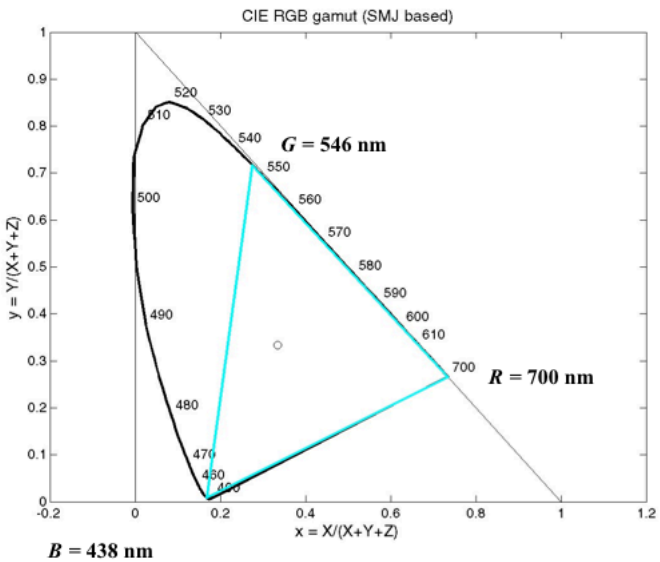
CIE 1931 RGB Gamut



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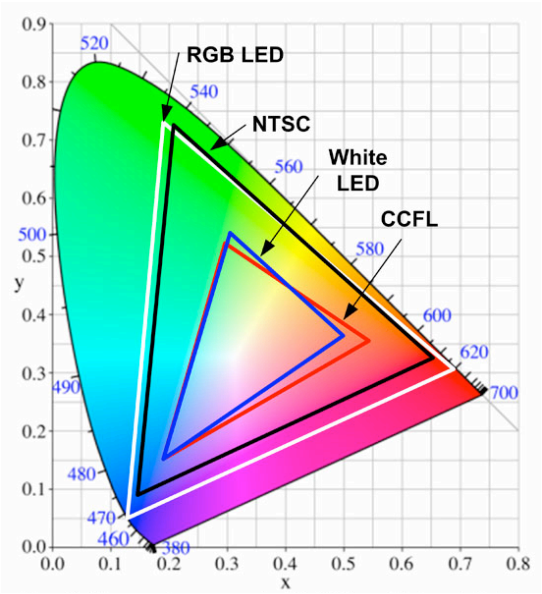
Other Gamuts (LCDs and NTSC)



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Color Sensing in Cameras

Color Sampling

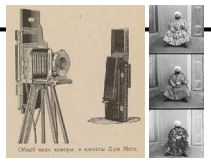
Problem: a photosite can record only one number

We need 3 numbers for color

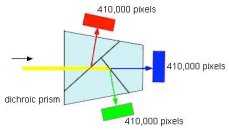
What can we do?

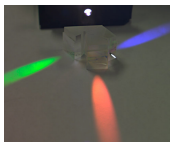
Approaches

Scan 3 times
(temporal multiplexing)



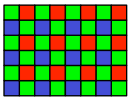
Use 3 detectors
(3-ccd camera)

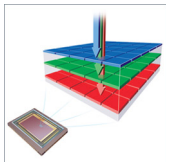




Use offset color samples (spatial multiplexing)
Multiplex in depth (Tripack film, Foveon)
Interferences (Lipmann)

Dicklyon at the English Wikipedia project.





Temporal multiplexing

Examples:

- Drum scanners
- Flat-bed scanners
- Maxwell,
  Russian photographs from 1900's

Pros:

- 3 real values per pixel
- Can use a single sensor

Cons

- Only for static scenes, slow

3-chip

High-end 3-ccd video cameras

Use separation prisms

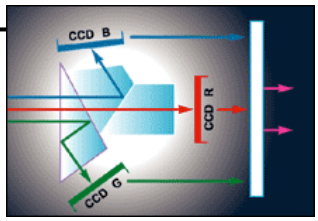
- prisms that split wavelengths

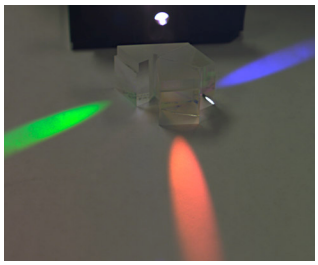
Pros

- 3 real values per pixel
- Little photon loss

Cons

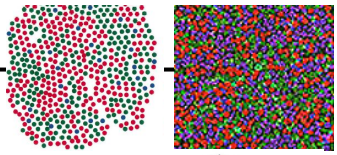
- costly (needs 3 sensors)
- space





Dicklyon at the English Wikipedia project.

Spatial Multiplexing

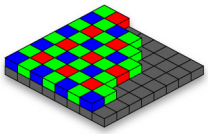


Human eye (cone mosaic)

Older color film (Autochrome)

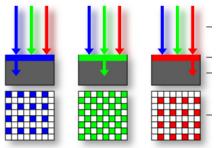
Bayer mosaic or CFA (color filter array)

Most still cameras, most cheap camcorder, some high-end video cameras (e.g. RED)



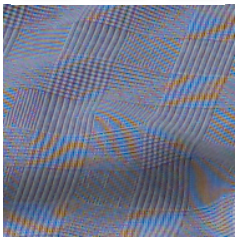
Pros

- single sensor
- well mastered technology, high resolution



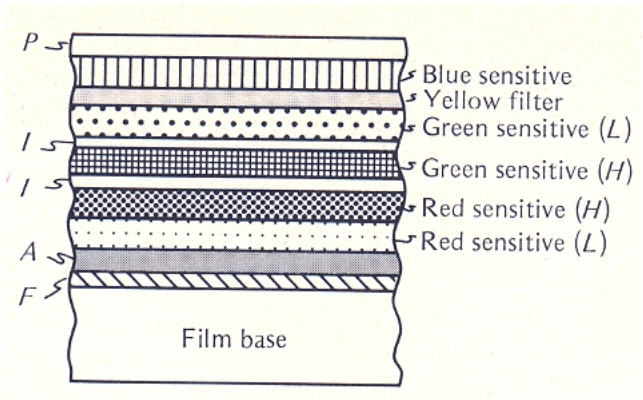
Cons

- needs interpolation, color jaggies
- requires antialiasing filter (reduces sharpness)
- loss of light



Depth multiplexing

Good old color film (tripack)



Depth Multiplexing (Foveon X3 sensor)

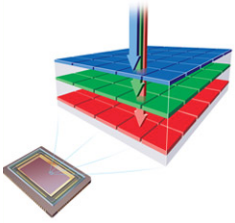
Leverage difference in absorption per wavelength

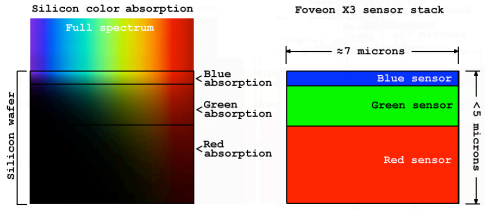
Pros

- 3 real numbers per pixel
- Less light loss

Cons

- Requires more color processing (3 numbers must be multiplied by matrix to get RGB)
- Nosier (because of color processing and shallow blue layer)
- Lower resolution these days

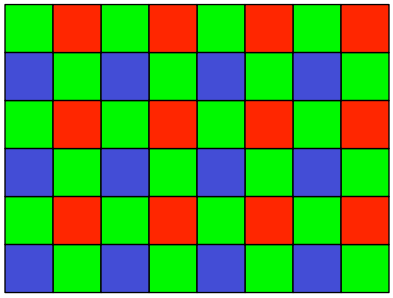




Demoaicing

Bayer RGB Mosaic

Each photosite has a different color filter

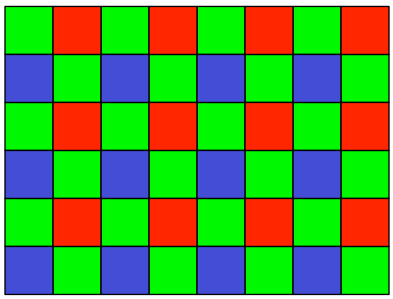


Note that which one is the upper left color is arbitrary and depends on the camera

Bayer RGB mosaic

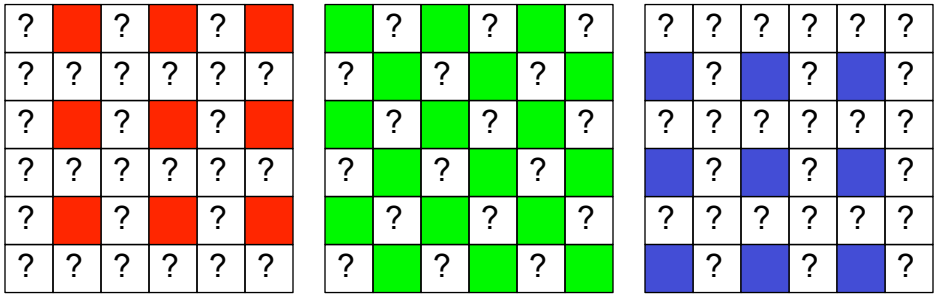
Why more green?

- Have 3 channels and square lattices don't like odd numbers
- It's the spectrum "in the middle"
- More important to human perception of luminance



Demosaicing

Interpolate missing values



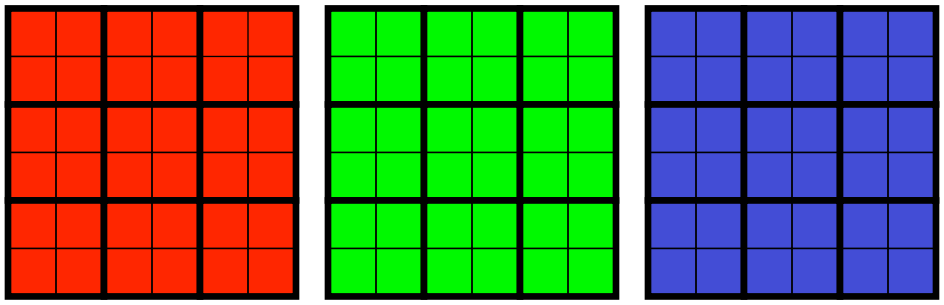
Demosaicing

Simplest solution: downsample!

- Nearest-neighbor reconstruction

Problem: resolution loss

- And megapixels are so important for marketing!



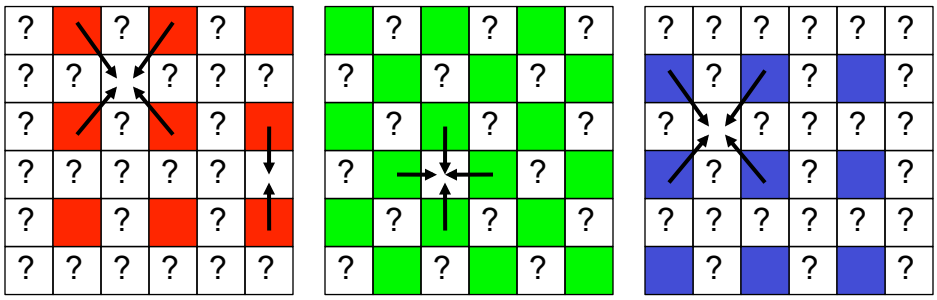
Linear Interpolation

Average of the 4 or 2 nearest neighbors

- Linear (tent) kernel

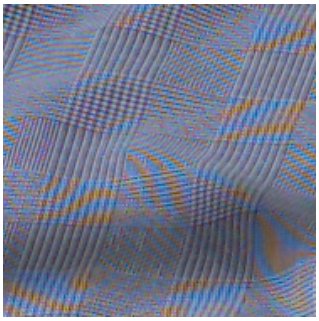
Smoother kernels also possible

- (e.g. bicubic) but need wider support



Errors in Demosaicing

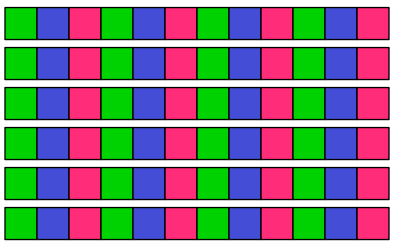
Color fringes or jaggies



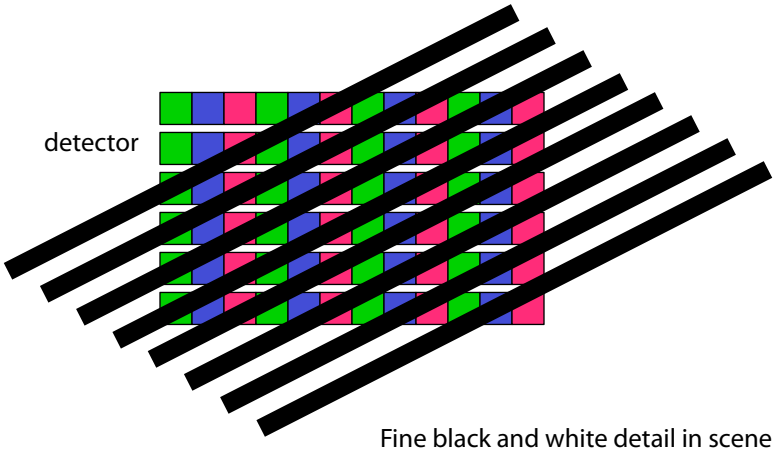
Cause of Color Moire

detector

(simplified for visualization)



Cause of Color Moire



Fine black and white detail in scene
mis-interpreted as color information.

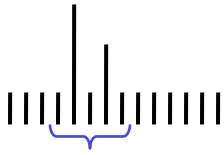
Median Demosiacing

The color fringe artifacts are places where chrominance changes abruptly and only temporarily.

Median Filter

Replace each pixel by the median over N pixels (5 pixels, for these examples).

In:



5-pixel neighborhood

Out:

Spike noise is removed

In:

Out:

Monotonic edges remain unchanged

Degraded image

Radius 1 median filter

Radius 2 median filter

YCbCr Color Space

One of many "decorrelated" or opponent color spaces

- used in JPEG, TV
- a little too focused on 8-bit but oh well

Y: luminance

Cb: blue-yellow difference

Cr: green-red difference

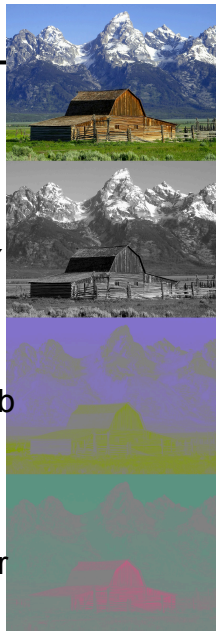
e.g.

$Y = 16 + 1/256 * (65.738 * R + 129.057 * G + 25.064 * B)$

$Cb = 128 + 1/256 * (- 37.945 * R - 74.494 * G + 112.439 * B)$

$Cr = 128 + 1/256 * (112.439 * R - 94.154 * G - 18.285 * B)$

Just remember it's linear



Median Color Interpolation

Apply naive interpolation

Convert to YCbCr

- throw away luminance Y

Median filter Cr & Cb

- independently for simplicity
- vector-median if you're hard core

At each pixel, reconstruct R, G, and B from sensor value + Cr & Cb

Per-pixel Reconstruction

For each pixel we have

- One of either R, G, or B (sensor data)
- 2 chrominance numbers Cr & Cb (after median)

We want three numbers R, G, and B

We know

- Cb = 128 + 1/256 * (- 37.945 * R - 74.494 * G + 112.439 * B)
- Cr = 128 + 1/256 * (112.439 * R - 94.154 * G - 18.285 * B)

Think you can do it?

Recombining Filtered Colors

Linear interpolation

Median filter interpolation

Summary

Spectrum: Infinite dimensional – value at every wavelength

Cones: Project spectrum according to L,M,S responses into 3 values

Metamers: Different spectra, same responses

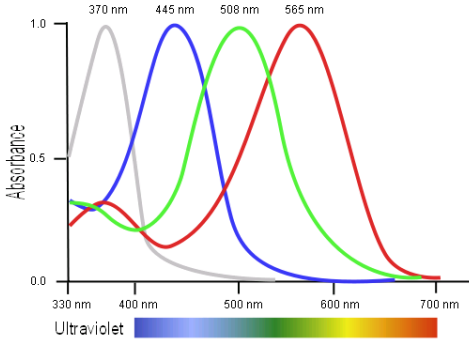
Color Matching: Reponses are linear so can convert to any color space using 3x3 matrix

Sensing Color: Spatial multiplexing via Bayer mosaic most common … but requires **demosaicing**

Tetrachromatism

Most birds, and many other animals, have cones for ultraviolet light.

Some humans, mostly female, seem to have slight tetrachromatism.



Bird cone responses