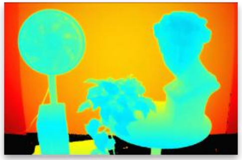
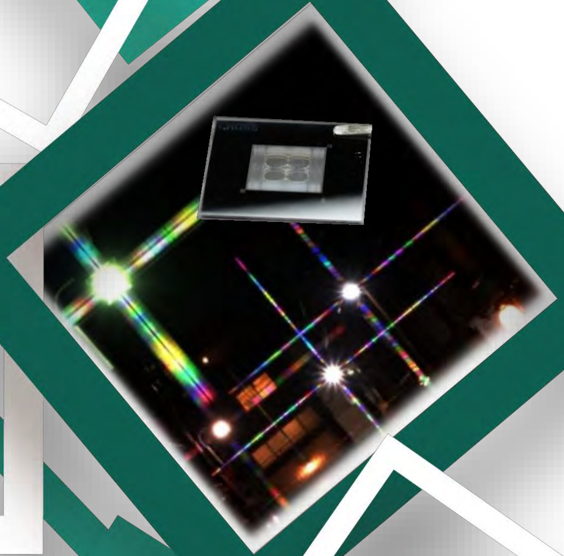


GAMES 204

Computational Imaging

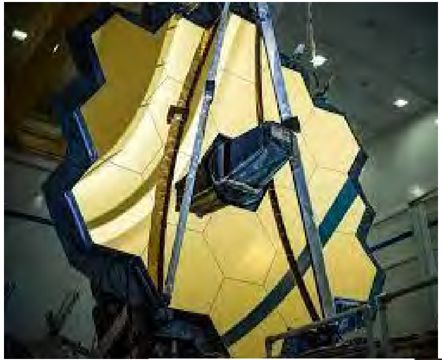
Lecture 03： Color and Human Visual System II

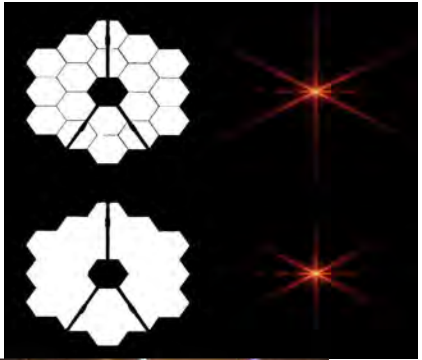
Qilin Sun（孙启霖）

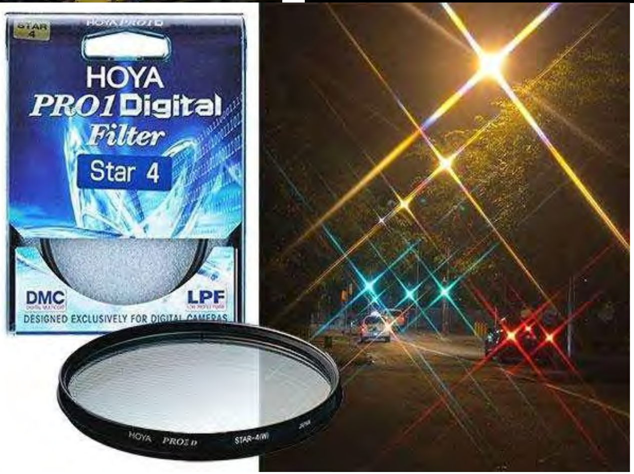
香港中文大学（深圳）

点昀技术（Point Spread Technology）

Webb Telescope







Credit@知乎：太空僧

Todays Topic

- Color Space
  - RGB
  - HSV
  - YCbCr
  - CIE LAB
- Displays Reproducing Color
- Color Reproduction
  - Linear Algebra
  - Pseudo-Geometric Interpretation
- Bayer Filter and Sensor Perception

Slide credits

Many of these slides were adapted from:

Wolfgang Heidrich(KAUST)

Ren Ng(Uc Bakery)

Kris Kitani, Ioannis Gkioulekas (15-463, 15-663, 15-862).

Fredo Durand (MIT).

Marc Leovy, Gordon Wetzstein (Stanford).

CS559-Computer Graphics

Color Space

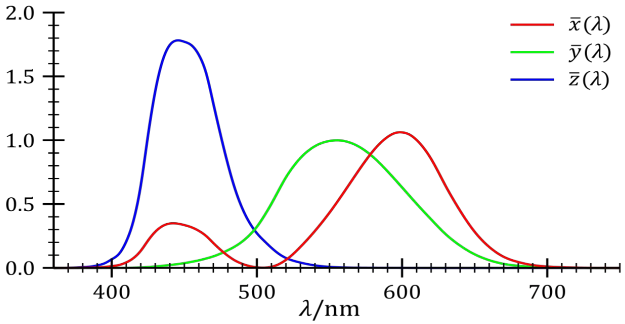
Color Spaces

- Use three numbers(dims) to specify a color:
  - Device dependent color space (e.g. RGB)
  - Device independent color space (e.g. CIE1931)
- E.g.: color space defined by a display
  - Define colors by what R, G, B scalar values will produce them on your monitor
    - Output spectra s = rR + gG + bB for some display primary spectra r, g, b
  - Device dependent (depends on gamma, phosphors, gains, ...)
    - The R,G,B on my display is different from what you see!
  - Also leaves out some colors (limited gamut), e.g. vivid yellow

A "Universal" Color Space: CIE XYZ

- Imaginary set of standard color primaries X, Y, Z
- Designed such that
  - X, Y, Z span all observable colors
  - Matching functions are strictly positive
  - Y is luminance (brightness absent color)
- "Imaginary" because the spectrum of the X,Y,Z primaries corresponding to these color matching functions are negative at some wavelengths

CIE XYZ color matching functions



For any spectrum Φ(λ), can express spectrum as weighted combination of primaries. Weights (X,Y,Z) given by:

$$X = k \int_\lambda \Phi(\lambda)\overline{x}(\lambda)d\lambda$$

$$Y = k \int_\lambda \Phi(\lambda)\overline{y}(\lambda)d\lambda$$

$$Z = k \int_\lambda \Phi(\lambda)\overline{z}(\lambda)d\lambda$$

Careful: these graphs are color matching curves, not spectra!

Change of Basis

- By definition, all observable monochromatic spectra are positive points in XYZ space, so can convert a color's representation (in space defined by realizable primaries like RGB) to XYZ via a linear transform:X, Y, Z span all observable colors
  - Consider display with 3 primaries (primaries need not be monochromatic light)
  - Compute XYZ coords of light emitted by display when providing it (1,0,0), (0,1,0), (0,0,1)
  - Light generated by display is linear combination of these vectors (non-negative weights)"

$$\begin{aligned}
\text{color of R primary ([1,0,0] on display)} &= R_x\mathbf{X} + R_y\mathbf{Y} + R_z\mathbf{Z} \\
\text{color of G primary ([0,1,0] on display)} &= G_x\mathbf{X} + G_y\mathbf{Y} + G_z\mathbf{Z} \\
\text{color of B primary ([0,1,0] on display)} &= B_x\mathbf{X} + B_y\mathbf{Y} + B_z\mathbf{Z}
\end{aligned}
\Rightarrow
\underbrace{\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}}_{\text{XYZ representation}} = \begin{bmatrix} R_x & G_x & B_x \\ R_y & G_y & B_y \\ R_z & G_z & B_z \end{bmatrix} \underbrace{\begin{bmatrix} R \\ G \\ B \end{bmatrix}}_{\text{color in space of display primaries}}$$

- E.g., Converting from CIE RGB to CIE XYZ:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \frac{1}{0.17697} \begin{bmatrix} 0.49 & 0.31 & 0.20 \\ 0.17687 & 0.81240 & 0.01063 \\ 0.00 & 0.01 & 0.99 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Brightness

- The color matching experiments measure how a human observer perceives color. The goal was to match the perceived color of one spectrum with a new spectrum (a metamer) formed via the combination of three primaries

- We can also ask the question, given lights with two different colors but equal power, how bright do the lights look?

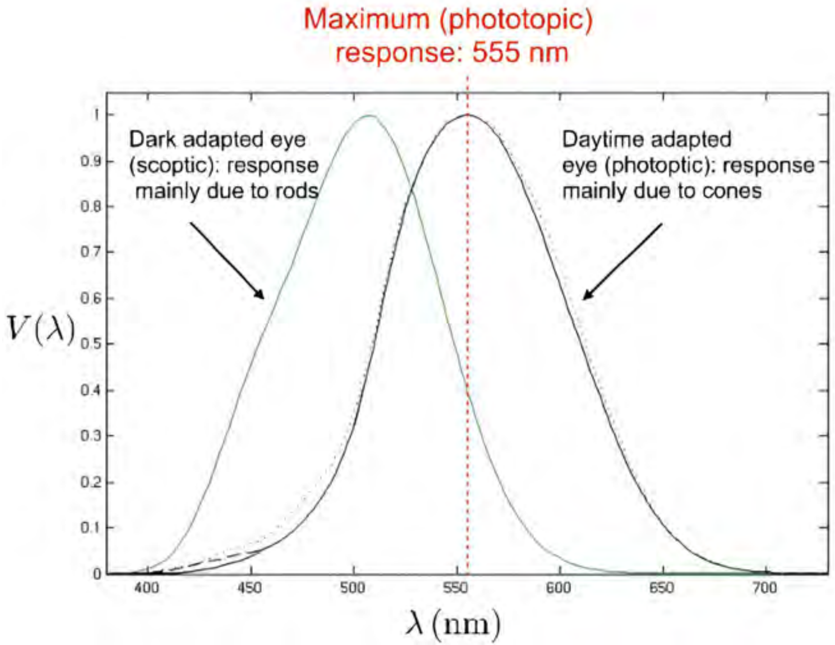
Luminance (Brightness)

- Product of radiance and the eye's luminous efficiency

$$Y = \int \Phi(\lambda) V(\lambda)\, \mathrm{d}\lambda$$

- Luminous efficiency is measure of how bright light at a given wavelength is perceived by a human (due to the eye's response to light at that wavelength)

- How to measure the eye's response curve V (λ)?
  - Adjust power of monochromatic light source of wavelength until it matches the brightness of reference 555 nm source (photopic case)
  - Notice: the sensitivity of photopic eye is maximized at ~ 555 nm

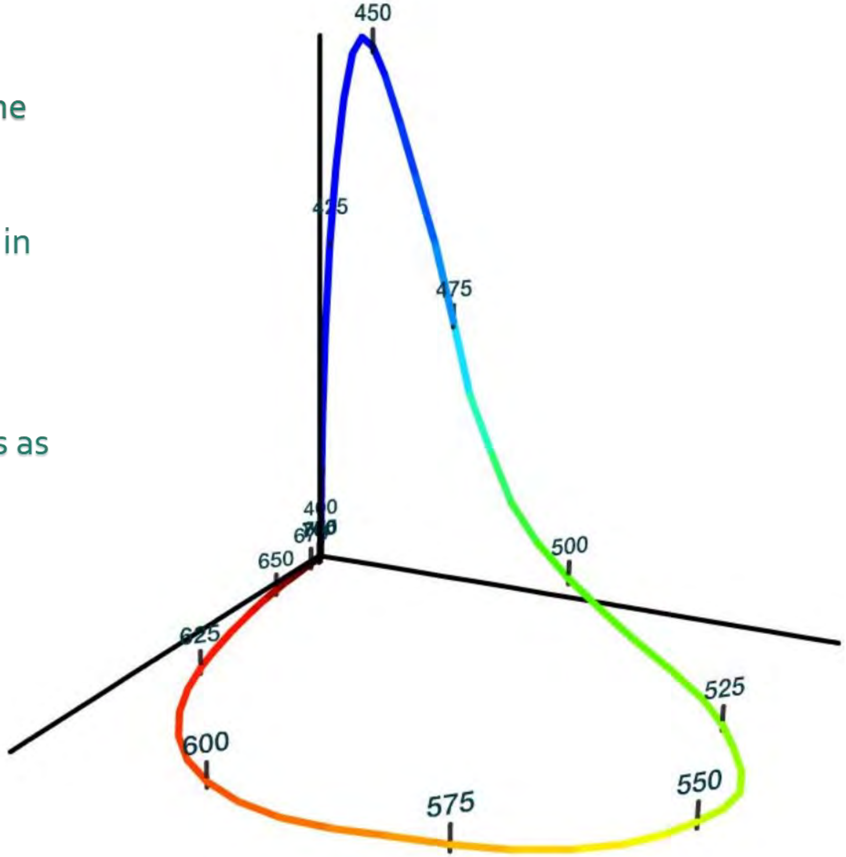


Recall： Retinal Cone Cell Response (L, M, S in 3D)

Visualization of "spectral locus" of human cone cells' response to monochromatic light (light with energy in a single wavelength) as points in 3D space.

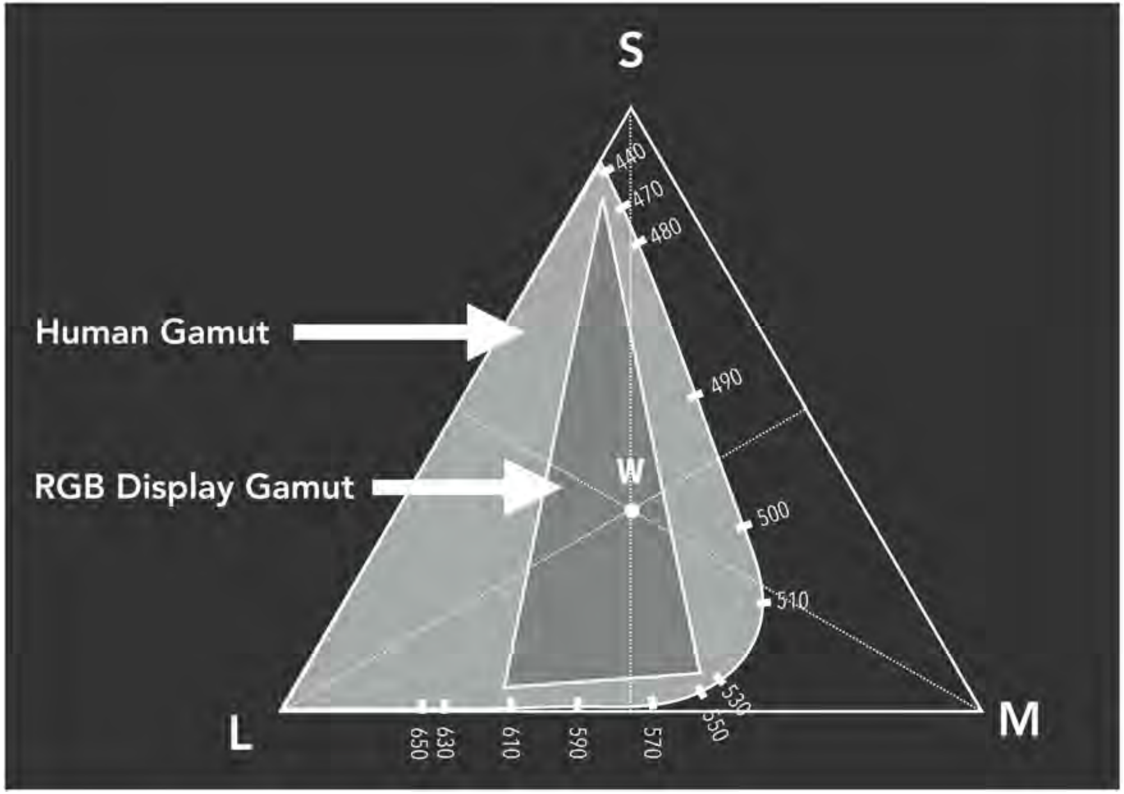
This is a plot of the S, M, L response functions as a point in 3D space.

Space of all possible responses are positive linear combinations of points on this curve.



Slides Credit: Marc Leovy

Chromaticity Diagram (Maxwellian)



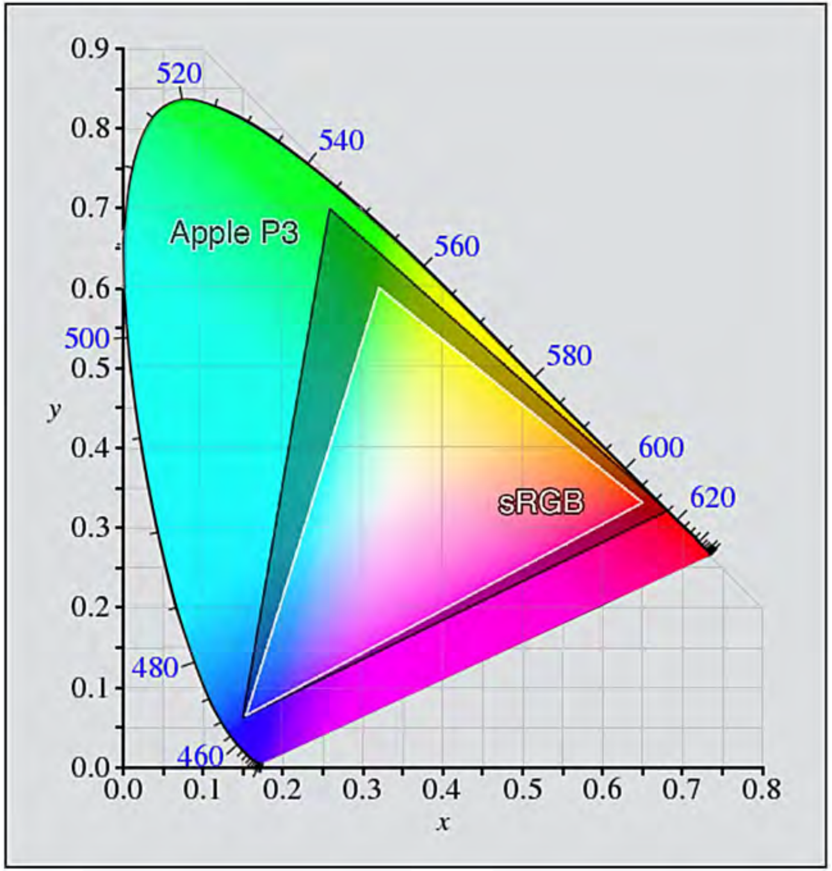
Perspective projection of spectral locus
looking diagonally down at origin from (1,1,1)

Chromaticity Diagram (CIE 1931 xy)

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 1.9121 & -1.1121 & 0.2019 \\ 0.3709 & 0.6291 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} L \\ M \\ S \end{bmatrix}$$

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

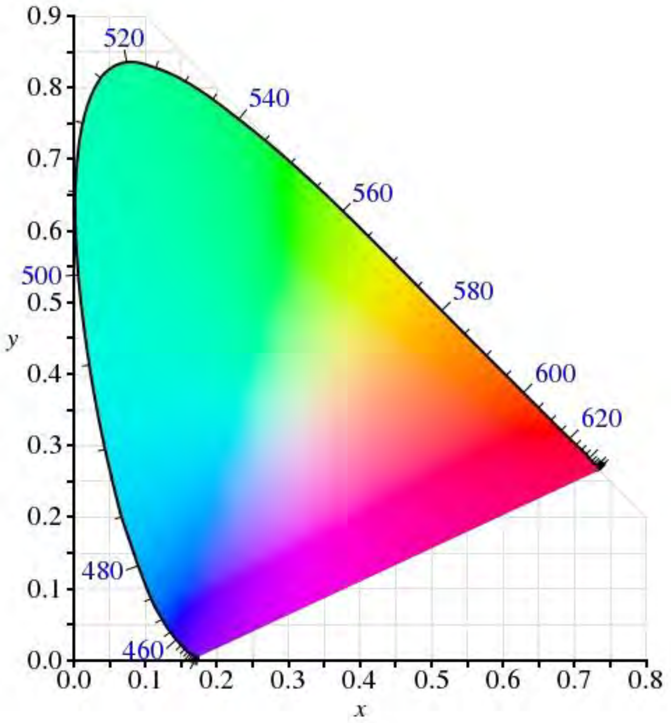
$$y = \frac{Y}{|X| + |Y| + |Z|}$$



Separating Luminance, Chromaticity

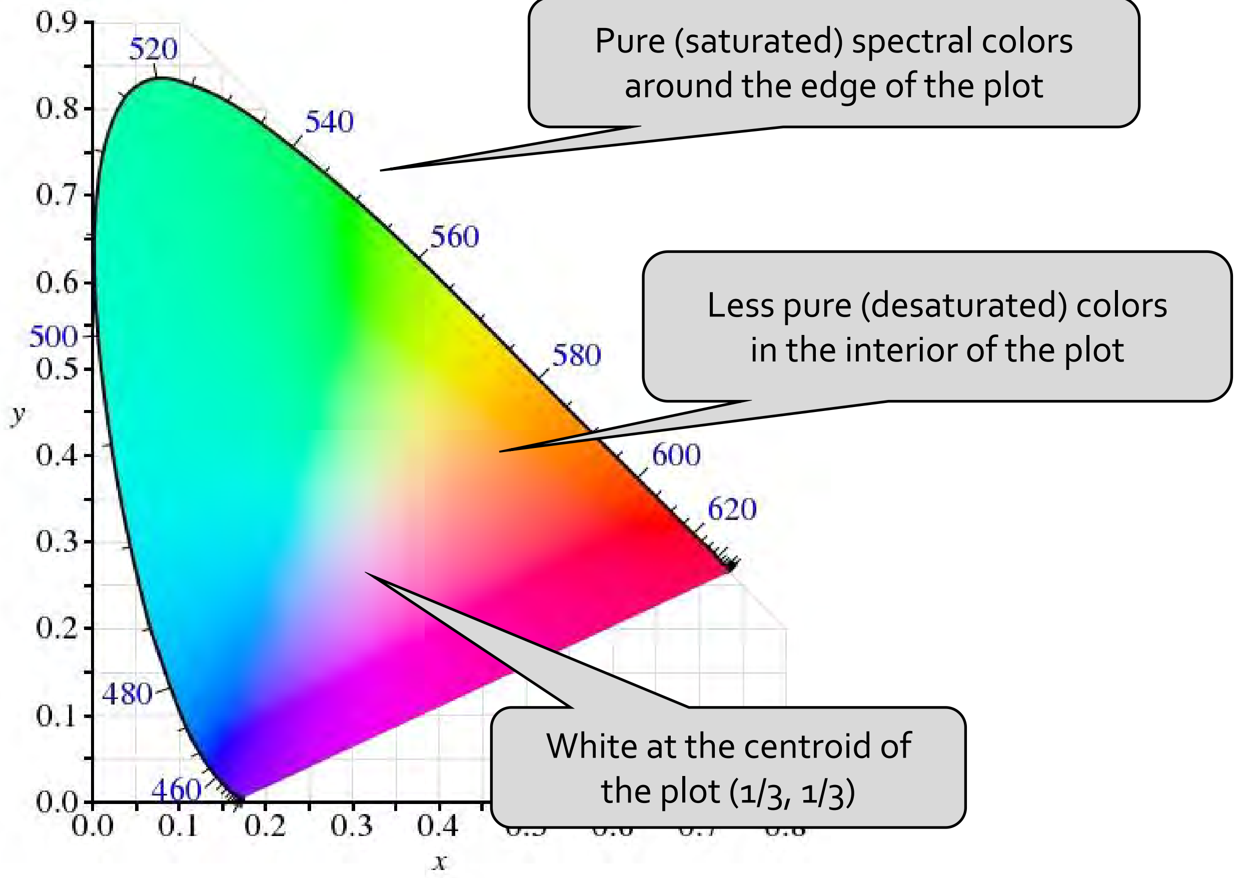
- Luminance: Y
- Chromaticity: x, y, z, defined as

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



- Since x + y + z = 1, we only need to record two of the three
- Usually choose x and y, leading to (x, y, Y) coords

CIE Chromaticity Diagram



Color Gamut

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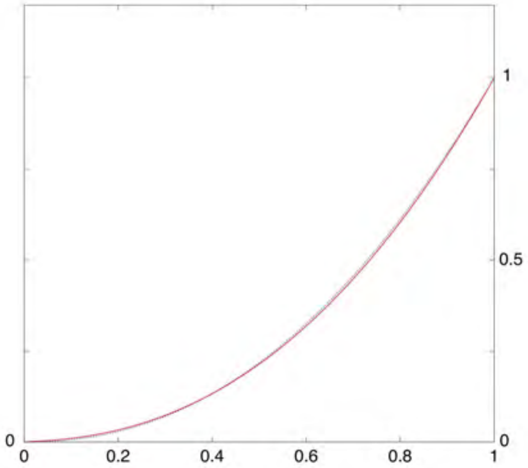
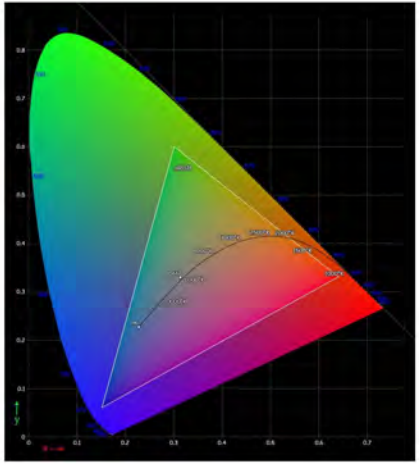
Standard Color Spaces

- Standardized RGB (sRGB)
  - Makes a particular monitor's primaries the RGB standard
  - Other color devices simulate that monitor by calibration
  - sRGB is usable as an interchange space; widely adopted today
  - Gamut is still limited

sRGB Color Space

- CIE 1934 captured all possible human-visible colors
- sRGB (roughly) subset of colors available on displays, printers, ...
- Nonlinear relationship between stored RGB values & intensity
  - Makes better use of limited set of numerical values





Comparing sRGB and Wide Gamut P3 Color Spaces

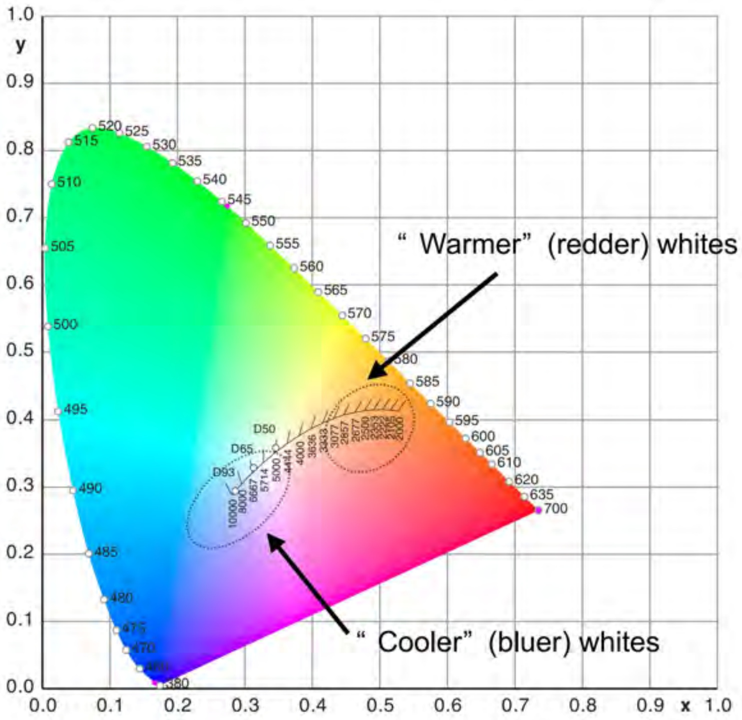
- Interactive Color Space Comparison:
  - Needs a wide-gamut physical display
  - I can see differences clearly on my MacBook Pro 2017

Credit: https://webkit.org/blog-files/color-gamut/comparison.html

What is White?

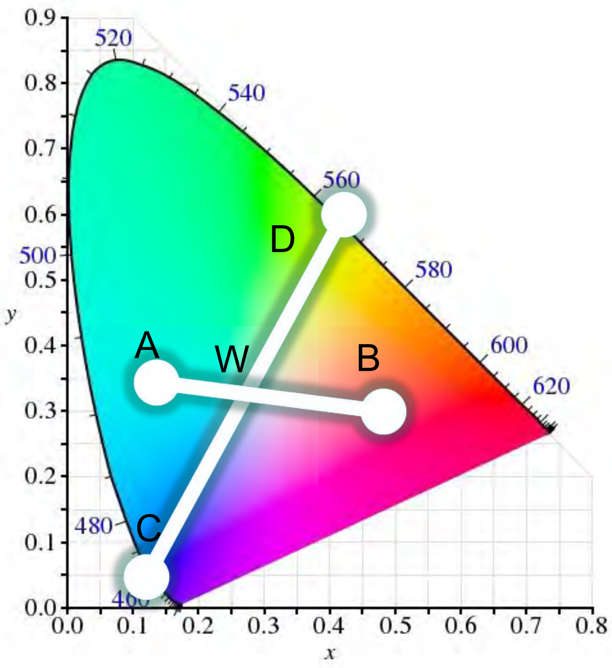
- "White point" of a display is the X,Y,Z color space vale of the point (1,1,1) in the color space defined by the display's primaries

"Warmth" of white light is often described by how chromaticity coordinates of (1,1,1) on display relate to that of spectrum emitted by black-body radiator of given temperature.



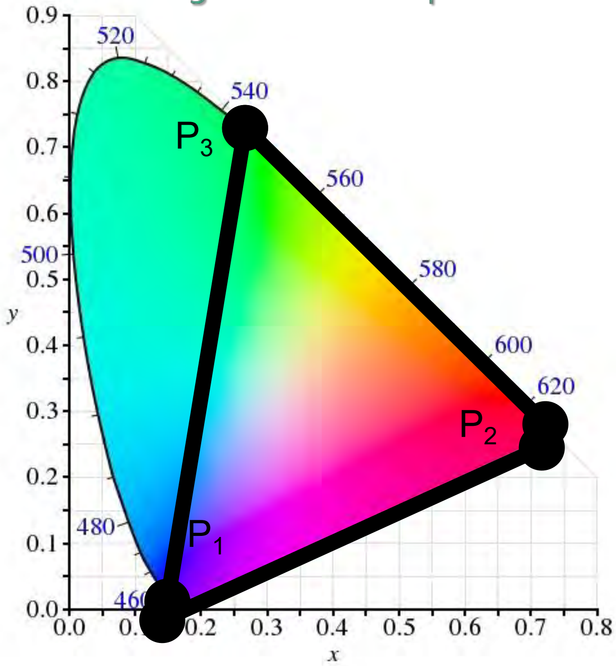
Uses of Chromaticity Diagram

Complementary colors are colors that can be mixed to form a designated white.



A and B and C and D are complementary with respect to reference white W

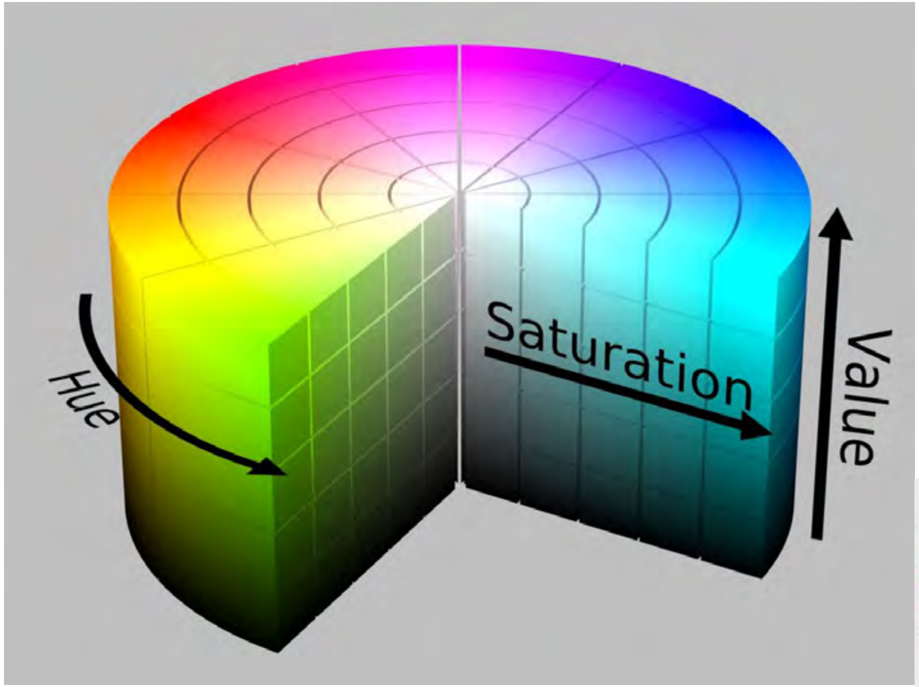
Demonstrate colors that fall out-of-gamut for a given choice of primaries

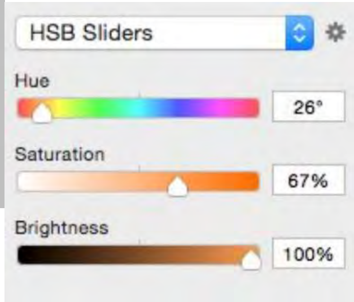


A display with primaries with chromacities P_1, P_2, P_3 can create colors that are combinations of these primaries (colors that fall within the triangle)

HSV (Hue, Saturation, Value)

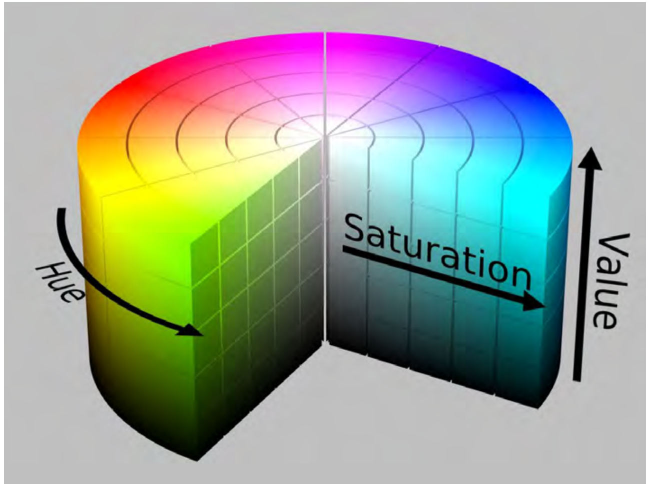
Axes of space correspond to natural notions of "characteristics" of color



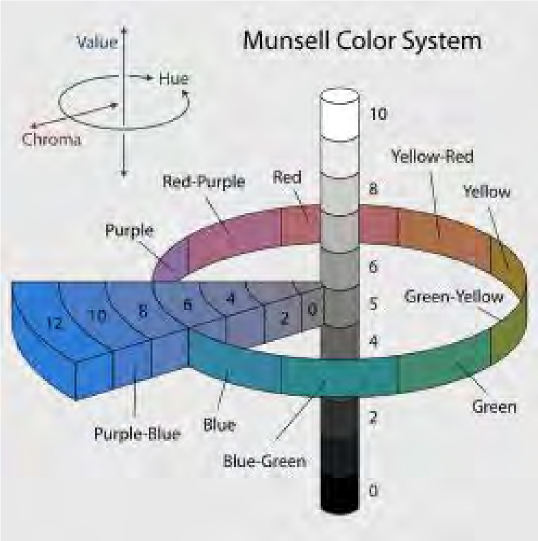


Perceptual Dimensions of Color

- Hue
  - The "kind" of color, regardless of attributes
  - Colorimetric correlate: dominant wavelength
  - Artist's correlate: the chosen pigment color
- Saturation
  - The "colorfulness"
  - Colorimetric correlate: purity
  - Artist's correlate: fraction of paint from the colored tube
- Value
  - The overall amount of light
  - Colorimetric correlate: luminance
  - Artist's correlate: tints are lighter, shades are darker



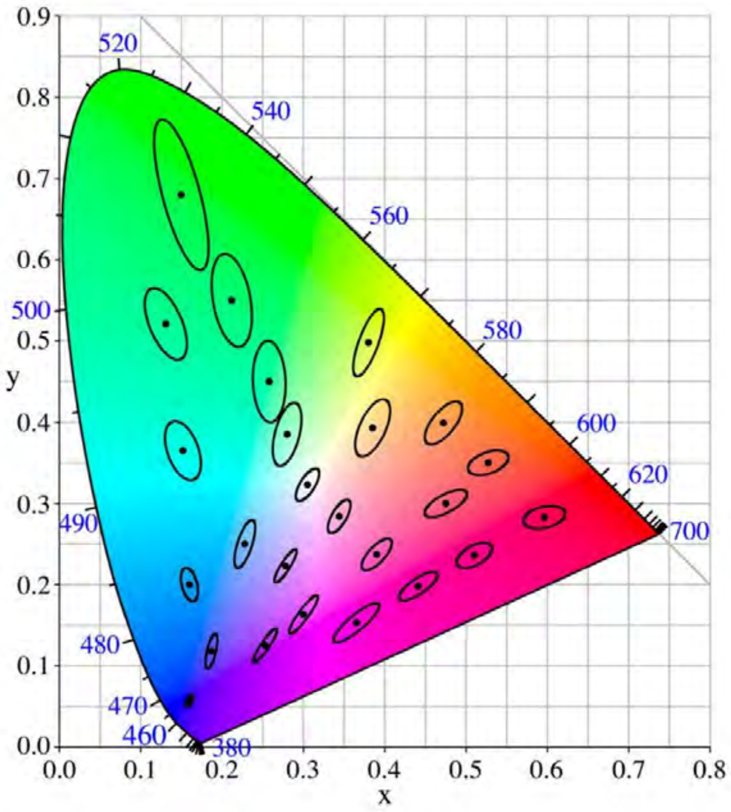
Munsell Book of Color



The Munsell color system, showing: a circle of hues at value 5 chroma 6; the neutral values from 0 to 10; and the chromas of purple-blue (5PB) at value 5.

Swatch identified by three numbers: hue, value (lightness), and chroma (color purity)

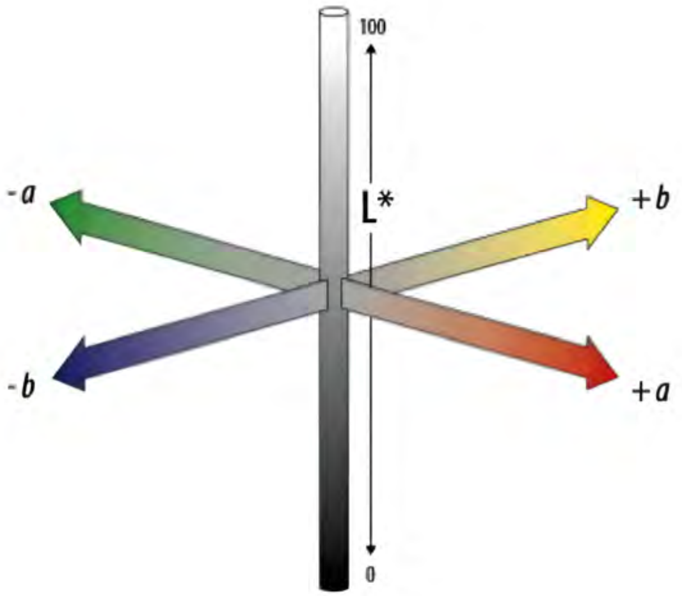
Perceptual Non-uniformity



- In the xy chromaticity diagram at left, **MacAdam ellipses** show regions of perceptually equivalent color (ellipses enlarged 10x)
- Must non-linearly warp the diagram to achieve uniform perceptual distances

CIELAB Space (L*a*b*)

- A commonly used color space that strives for perceptual uniformity
  - L* is lightness
  - a* and b* are color-opponent pairs
    - a* is red-green, and b* is blue-yellow
  - A gamma transform is used for warping because perceived brightness is proportiona to scene intensity γ, where *γ ≈ 1⁄3*



CIELAB

CIEXYZ --> CIELAB

$$L^\star = 116\, f\left(\frac{Y}{Y_\mathrm{n}}\right) - 16$$

$$a^\star = 500\left(f\left(\frac{X}{X_\mathrm{n}}\right) - f\left(\frac{Y}{Y_\mathrm{n}}\right)\right)$$

$$b^\star = 200\left(f\left(\frac{Y}{Y_\mathrm{n}}\right) - f\left(\frac{Z}{Z_\mathrm{n}}\right)\right)$$

where

$$f(t) = \begin{cases} \sqrt[3]{t} & \text{if } t > \delta^3 \\ \dfrac{t}{3\delta^2} + \dfrac{4}{29} & \text{otherwise} \end{cases}$$

$$\delta = \frac{6}{29}$$

CIELAB --> CIEXYZ

$$X = X_\mathrm{n} f^{-1}\left(\frac{L^\star + 16}{116} + \frac{a^\star}{500}\right)$$

$$Y = Y_\mathrm{n} f^{-1}\left(\frac{L^\star + 16}{116}\right)$$

$$Z = Z_\mathrm{n} f^{-1}\left(\frac{L^\star + 16}{116} - \frac{b^\star}{200}\right)$$

where

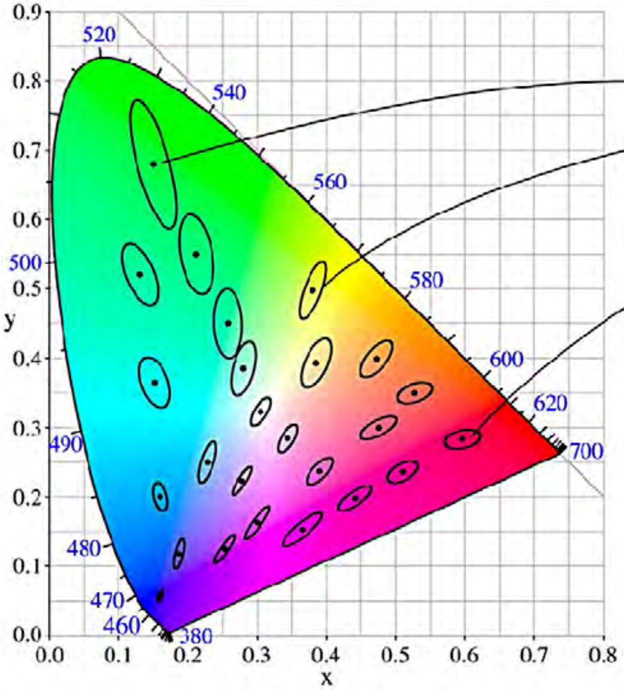
$$f^{-1}(t) = \begin{cases} t^3 & \text{if } t > \delta \\ 3\delta^2\left(t - \frac{4}{29}\right) & \text{otherwise} \end{cases}$$

and where $\delta = 6/29$.

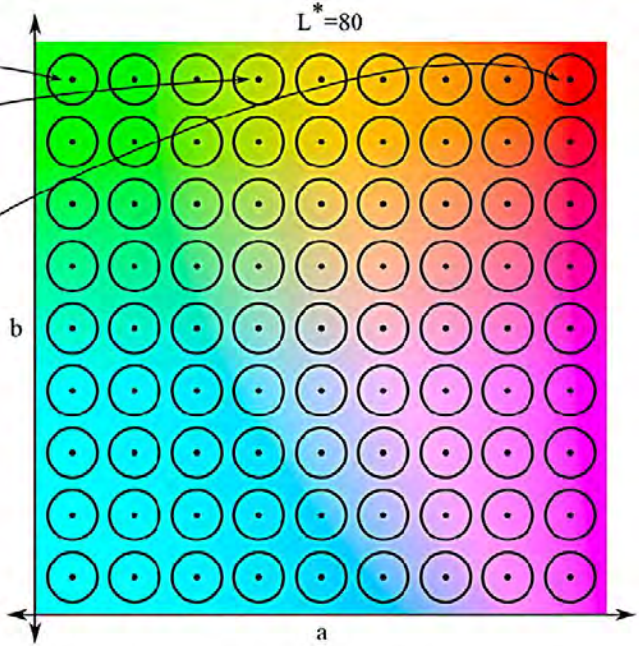
X_n, Y_n and Z_n are the CIEXYZ coordinates of the reference white point.

Credit: Wikipedia

Goal of CIELAB Is Perceptual Uniformity for Human Gamut



CIE 1931

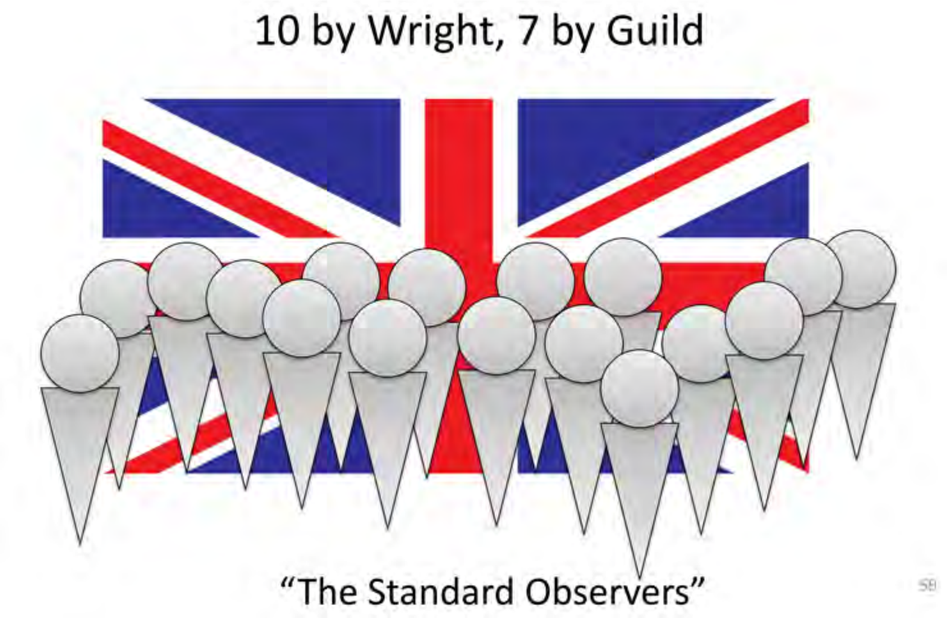


CIELAB (CIE 1976 L*,a*,b*)

https://iovs.arvojournals.org/article.aspx?articleid=2187751

香港中文大學(深圳) The Chinese University of Hong Kong, Shenzhen 点昀 POINT SPREAD

CIE 1931 (RGB and XYZ) is Based on 17 "Standard Observers"



Slide credit: M.S. Brown (see acknowledgments)

Opponent Color Theory

- There's a good neurological basis for the color space dimensions in CIE LAB
  - The brain seems to encode color early on using three axes:
    - white — black, red — green, yellow — blue
  - One piece of evidence: you can have a light green, a dark green, a yellow-green, or a blue_x0002_green, but you can't have a reddish green (just doesn't make sense)
    - Thus red is the opponent to green
  - Another piece of evidence: afterimages (following slides)

Opponent Color Theory

Credit: PetaPixel

Opponent Color Theory

Credit: PetaPixel

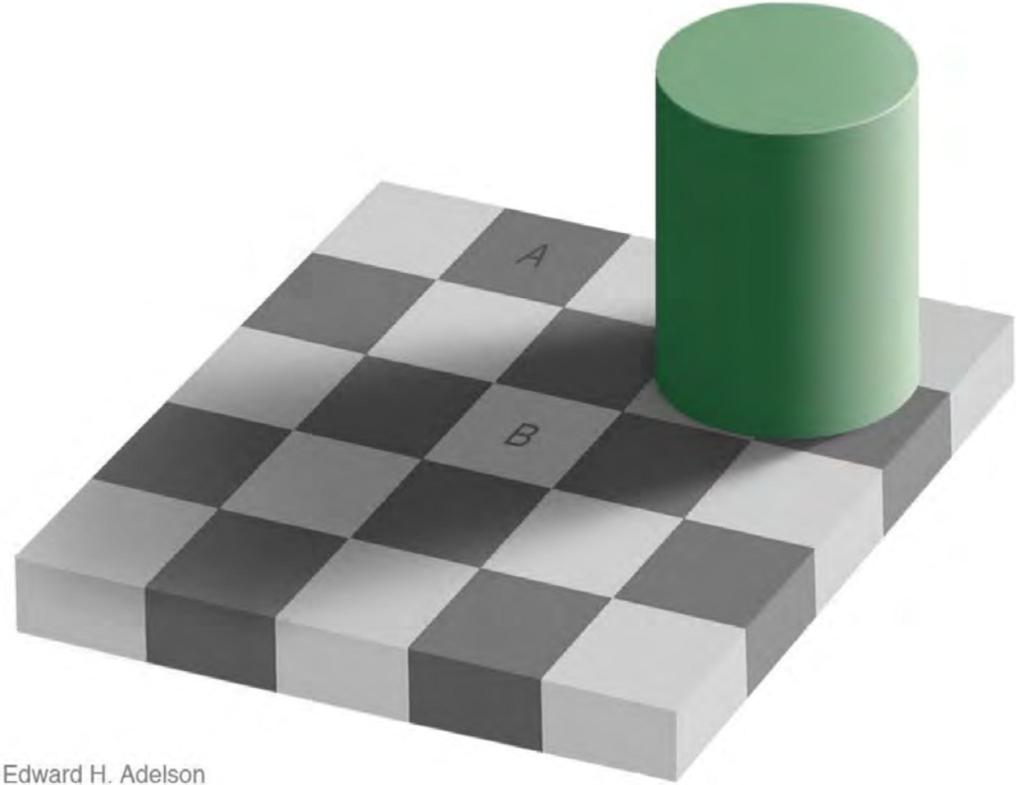
Opponent Color Theory

Opponent Color Theory

Even simple judgments – such as lightness - depend on brain processing

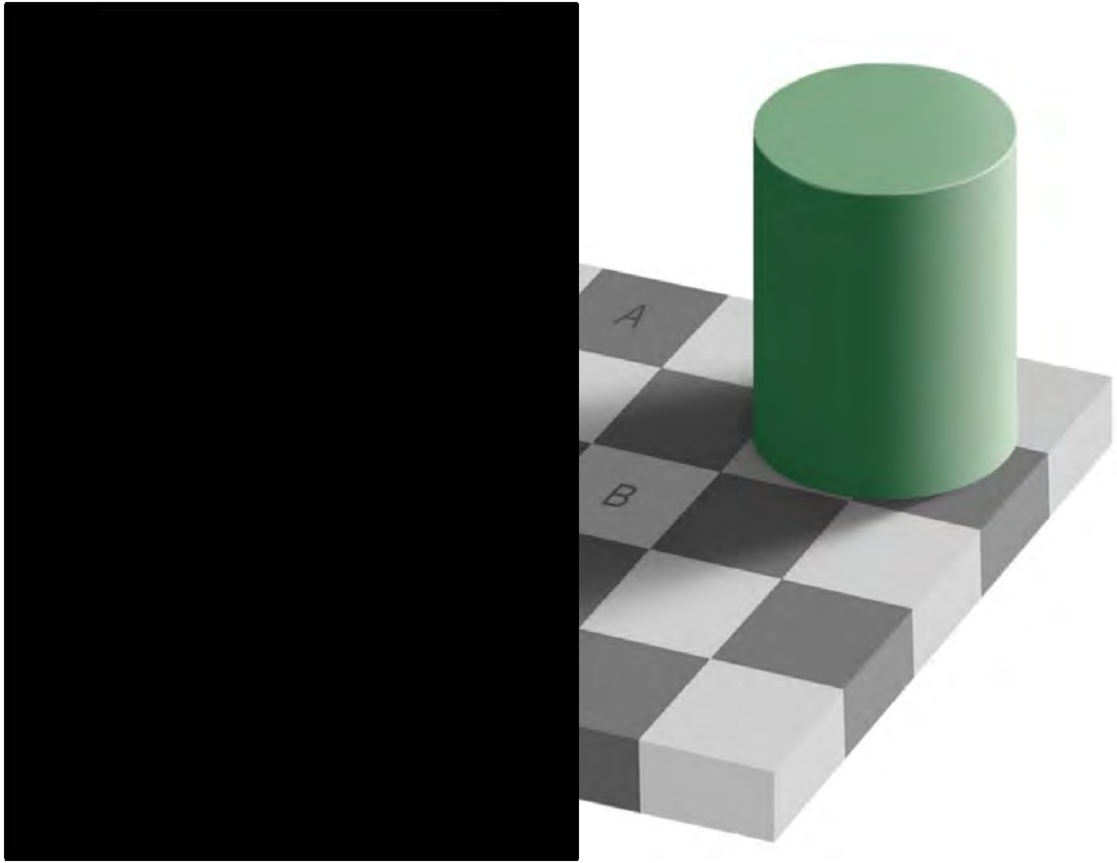
(Anderson and Winawer, Nature, 2005)

Everything is Relative

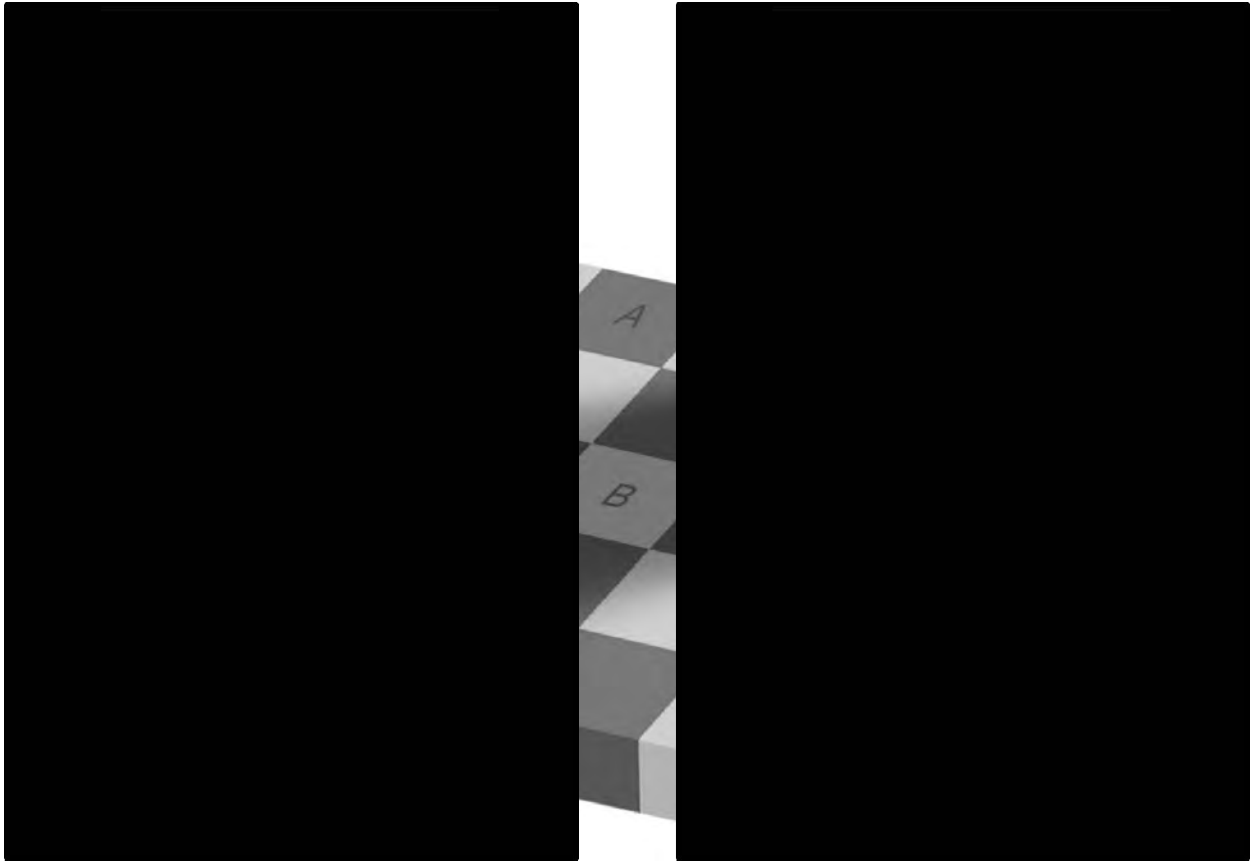


Edward H. Adelson

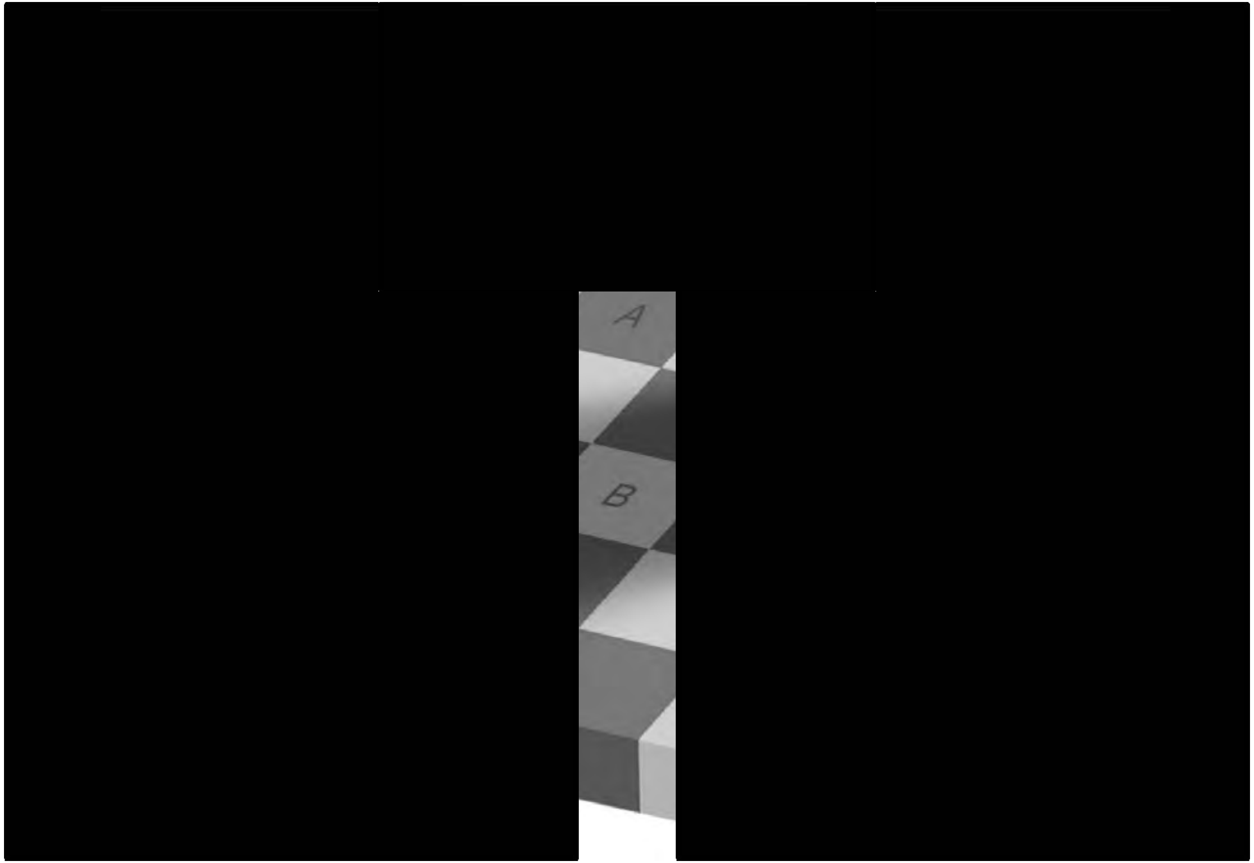
Everything is Relative



Everything is Relative



Everything is Relative



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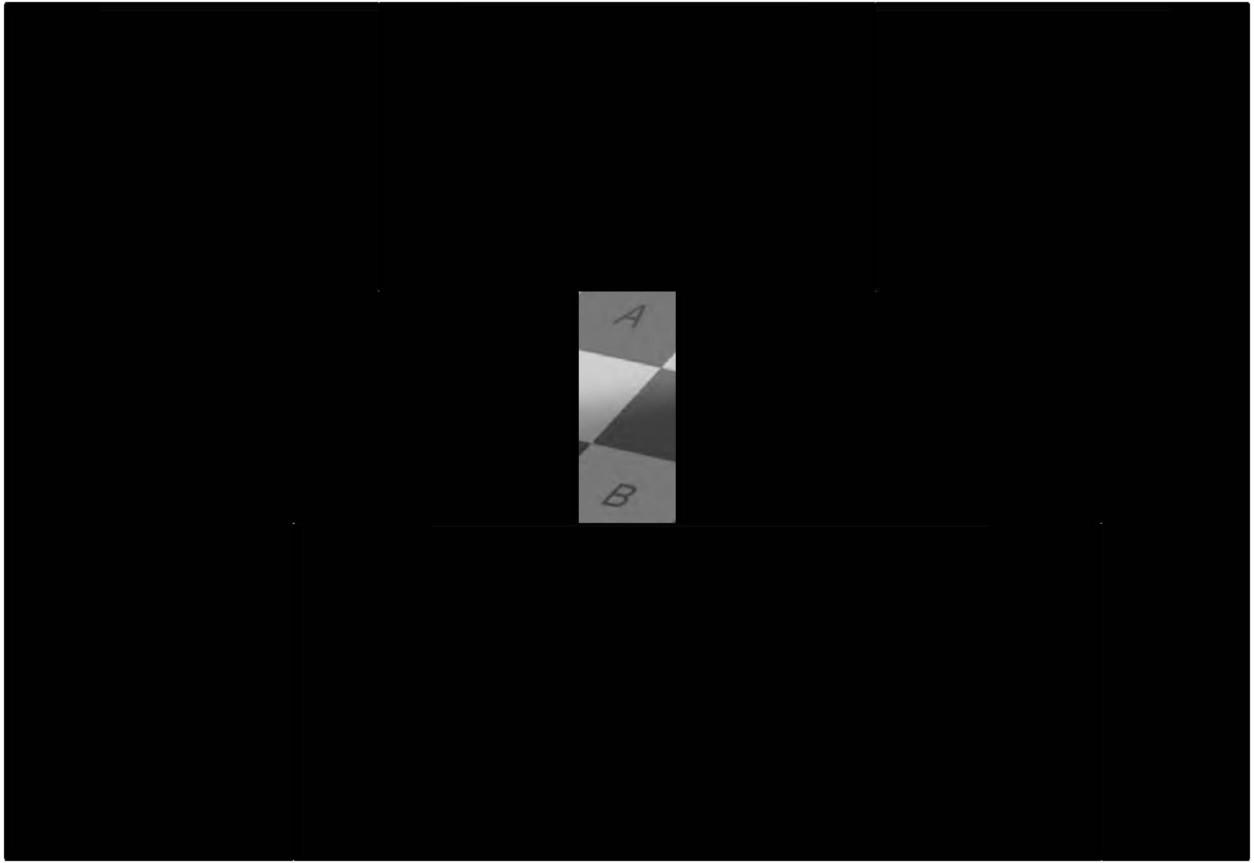
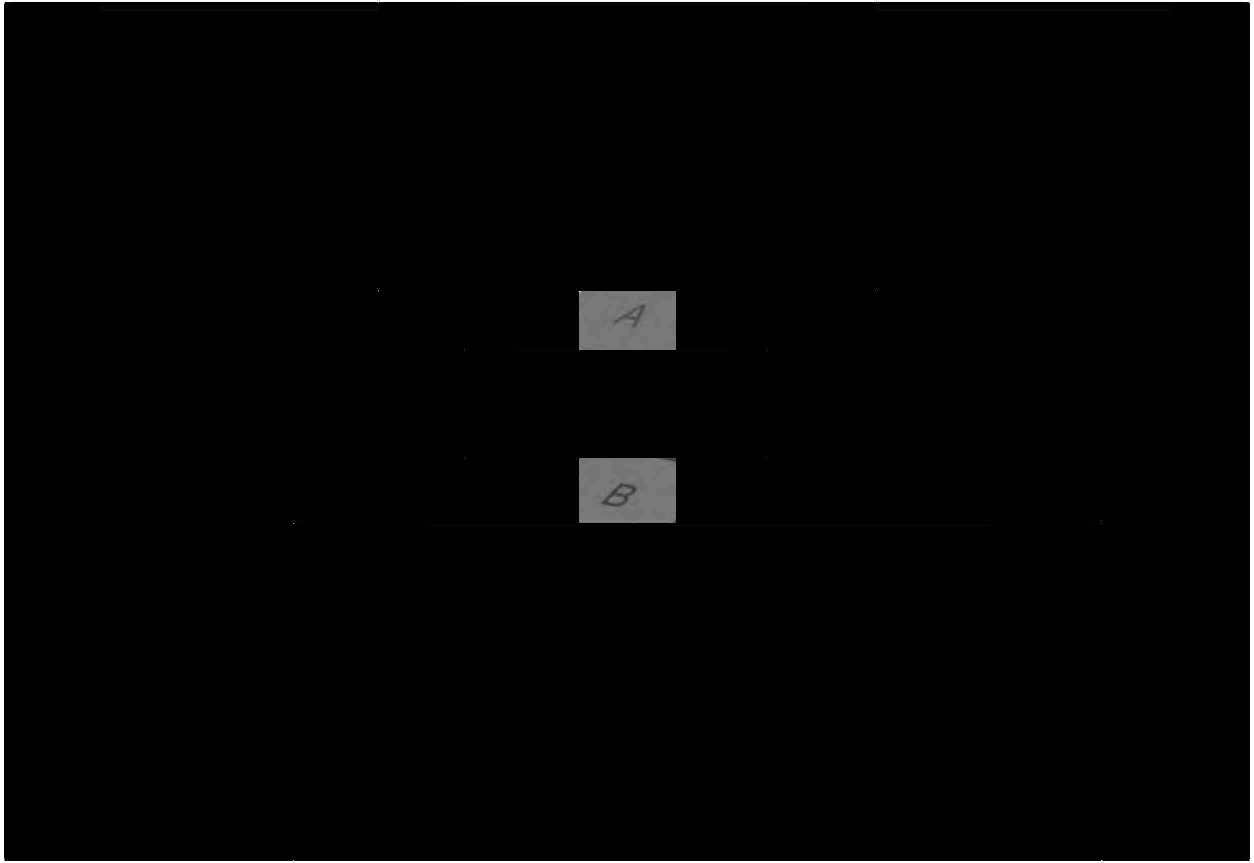
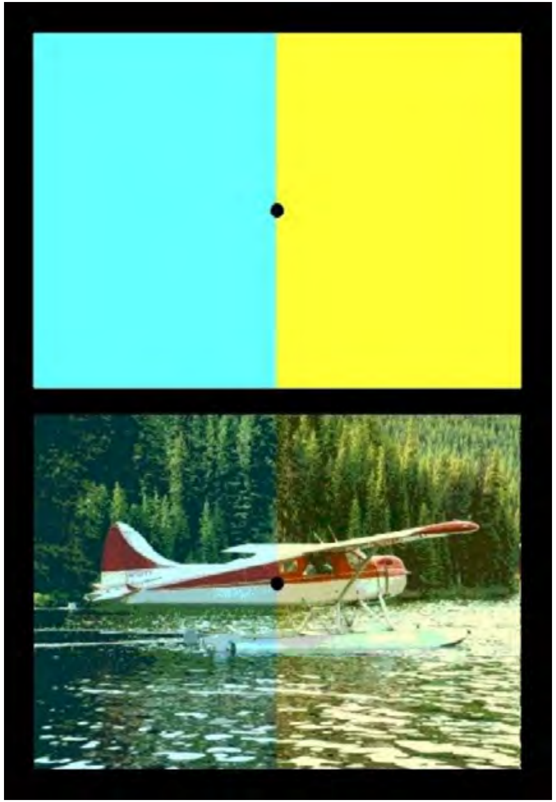


Everything is Relative

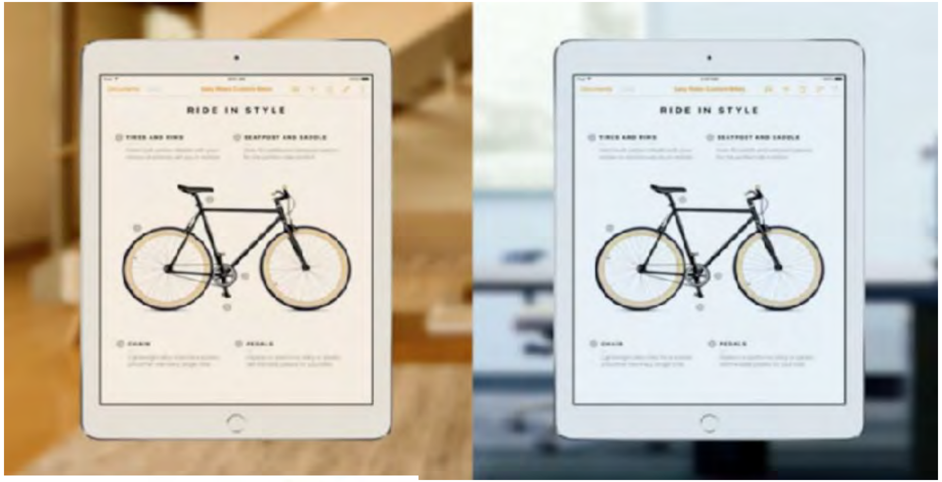


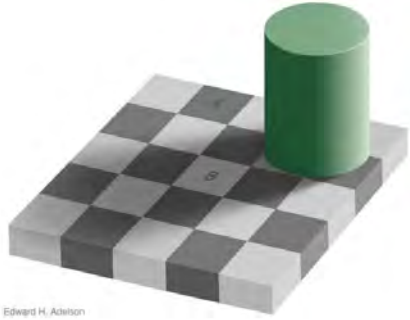
Visual Adaptation



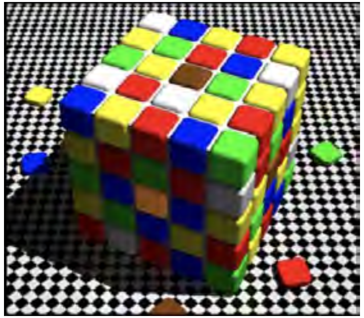
Chromatic adaptation

Apple True Tone



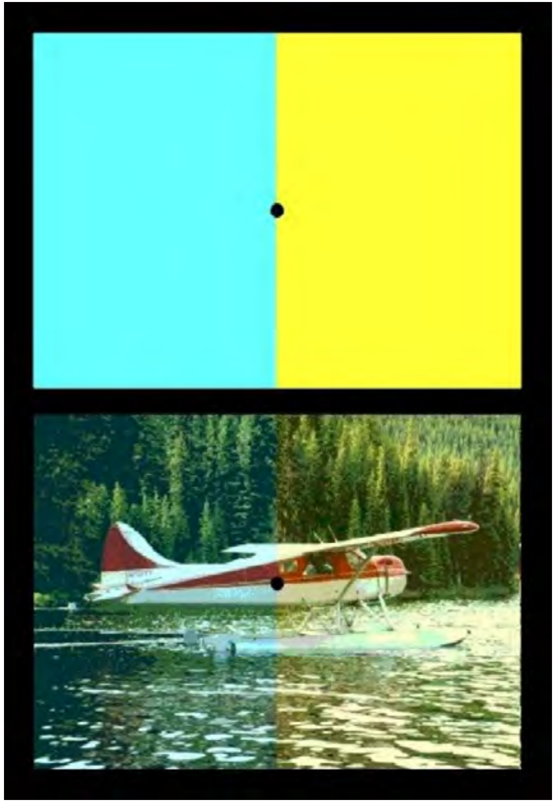


Adelson



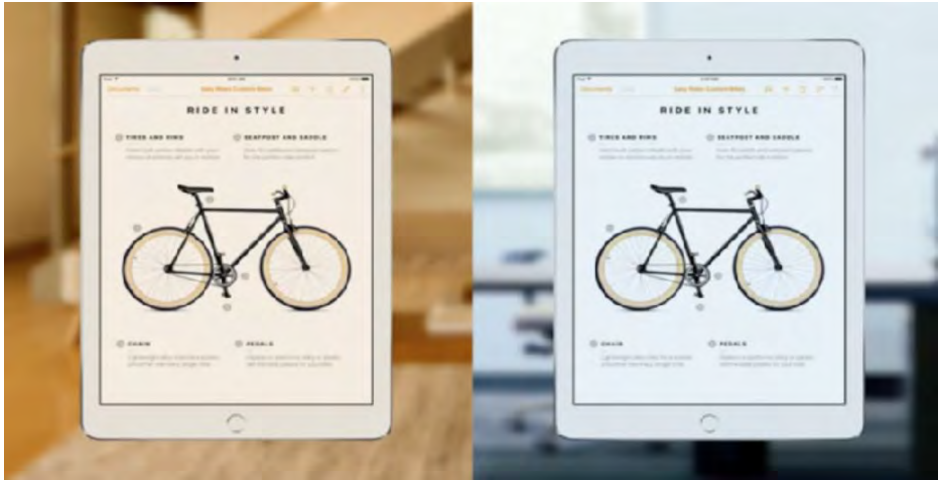
Lotto

Visual Adaptation



Chromatic adaptation

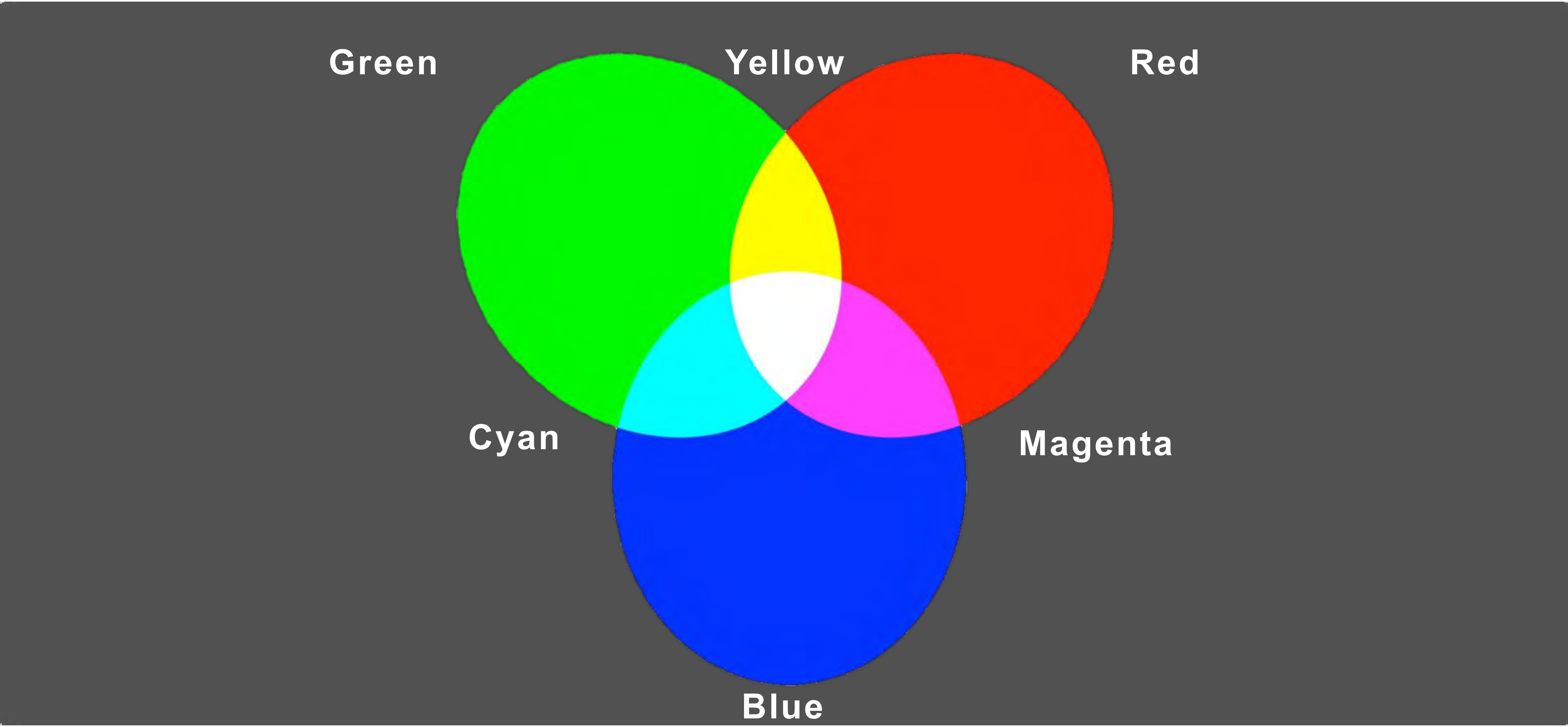
Apple True Tone



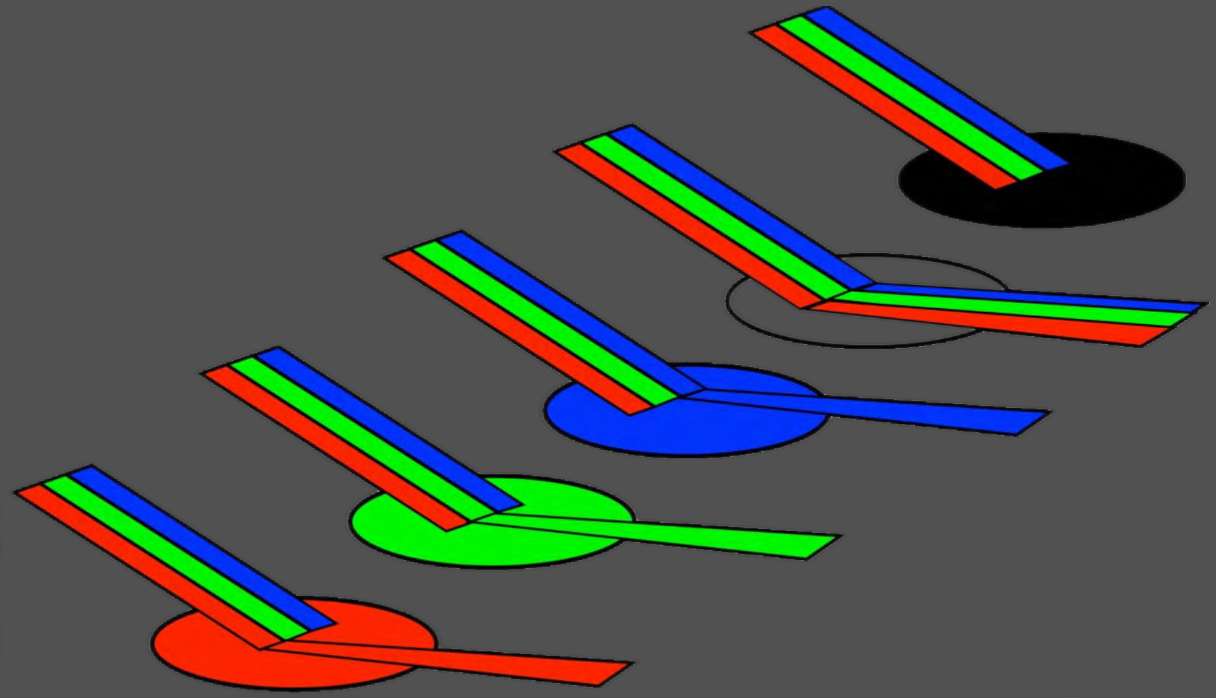
Adelson

Lotto

Adding Light Energy



Subtracting Light Energy



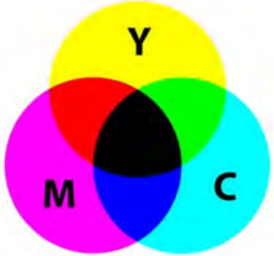
shining white light on various colored pigments

Subtractive Color

- Produce desired spectrum by subtracting from white light (usually via absorption by pigments)
- Photographic media (slides, prints) work this way
- Leads to C, M, Y (cyan, magenta, yellow) as primaries
- Approximately, 1 – R, 1 – G, 1 – B

Subtractive Color Space

- Up to this point, we've described color in terms of superposition of primaries. (addition of primaries)
  - Good description of color formed by mixing light from multiple light sources (e.g., displays)
- When describing color of reflected light, each mixed primary contributes to absorption of light (requires a subtractive color space)
  - Describes how to form colors by mixing inks (e.g., printing)



CMYK adds 4th component (K=black) as using a single black ink gives better black (and is more ink ecient) than mixing CMY primaries

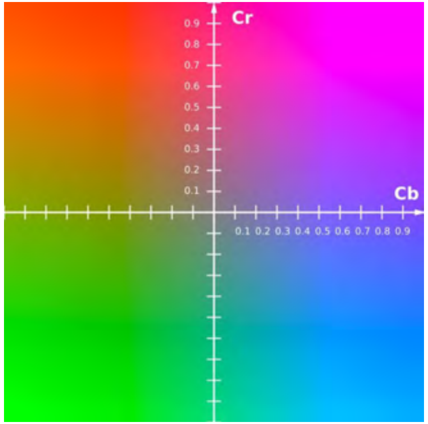
CMY Representation

(0,0,0) is white (1,1,1) is black

CMYK Representation

Y'CbCr Color Space

- Y' = luma: perceived luminance (non-linear)
- Cb = blue-yellow deviation from gray
- Cr = red-cyan deviation from gray



Non-linear RGB (primed notation indicates perceptual (non-linear) space)

Conversion from R'G'B' to Y'CbCr:

$$Y' = 16 + \frac{65.738 \cdot R'_D}{256} + \frac{129.057 \cdot G'_D}{256} + \frac{25.064 \cdot B'_D}{256}$$

$$C_B = 128 + \frac{-37.945 \cdot R'_D}{256} - \frac{74.494 \cdot G'_D}{256} + \frac{112.439 \cdot B'_D}{256}$$

$$C_R = 128 + \frac{112.439 \cdot R'_D}{256} - \frac{94.154 \cdot G'_D}{256} - \frac{18.285 \cdot B'_D}{256}$$

Y'

Cb

Cr

Chroma subsampling

- Y'CbCr is an efficient representation for storage (and transmission) because Y' can be stored at higher resolution than
- CbCr without significant loss in perceived visual quality

Y'_{00} Cb_{00} Cr_{00}	Y'_{10}	Y'_{20} Cb_{20} Cr_{20}	Y'_{30}
Y'_{01} Cb_{01} Cr_{01}	Y'_{11}	Y'_{21} Cb_{21} Cr_{21}	Y'_{31}

4:2:2 representation:

Store Y' at full resolution

Store Cb, Cr at full vertical resolution,

but only half horizontal resolution

X:Y:Z notation:

X = width of block

Y = number of chroma samples in "rst row

Z = number of chroma samples in second row

Y'_{00} Cb_{00} Cr_{00}	Y'_{10}	Y'_{20} Cb_{20} Cr_{20}	Y'_{30}
Y'_{01}	Y'_{11}	Y'_{21}	Y'_{31}

4:2:0 representation:

Store Y' at full resolution

Store Cb, Cr at half resolution in both dimensions

Real-world 4:2:0 examples:

most JPG images and H.264 video

Color Conversion

- Given a color specifed in one model/space (e.g., sRGB), try to find corresponding color in another model (e.g., CMYK)
- In a perfect world: want to match output spectrum
- Even matching perception of color would be terrifc (metamers)
- In reality: may not always be possible!
  - Depends on the gamut of the output device
  - E.g., VR headset vs. inkjet printer
- Complicated task!
- Lots of standards & software
  - ICC Profles
  - Adobe Color Management, …

Gamma Correction

Old CRT display:

- Image contains value X
- CRT display converts digital signal to an electron beam voltage V(x) (linear relationship)
- Electron beam voltage converted to light: (non-linear relationship)

$$Y \propto V^{\gamma} \qquad \gamma \approx 2.5$$

- So if pixels store Y, what will the display's output look like?
- Fix: pixels sent to display must store:

$$Y^{1/2.5} = Y^{0.4}$$

(non-linear correction for CRT display)

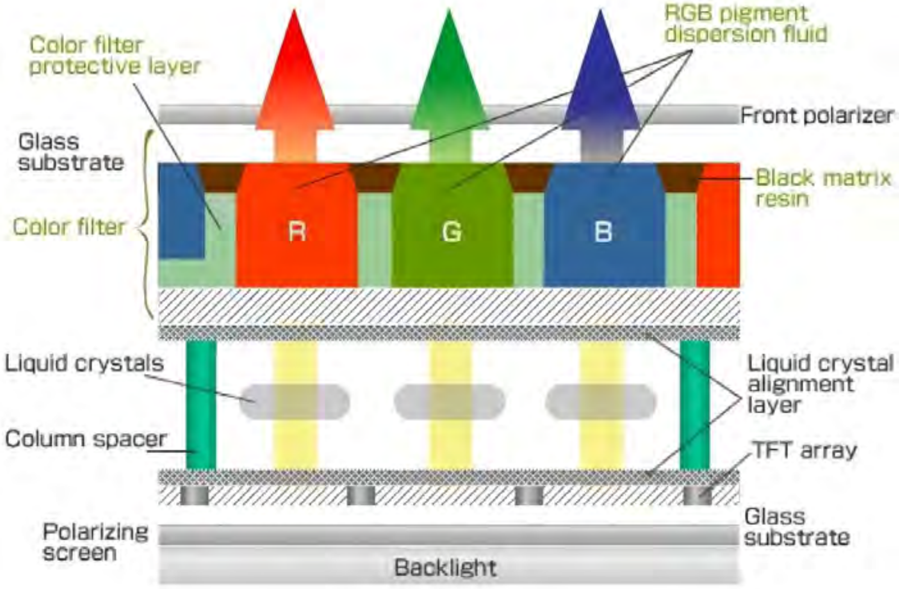
(Doesn't apply to modern LCD displays, whose luminance output is linearly proportional to input; DOES still apply to other devices, like sensors, etc.)

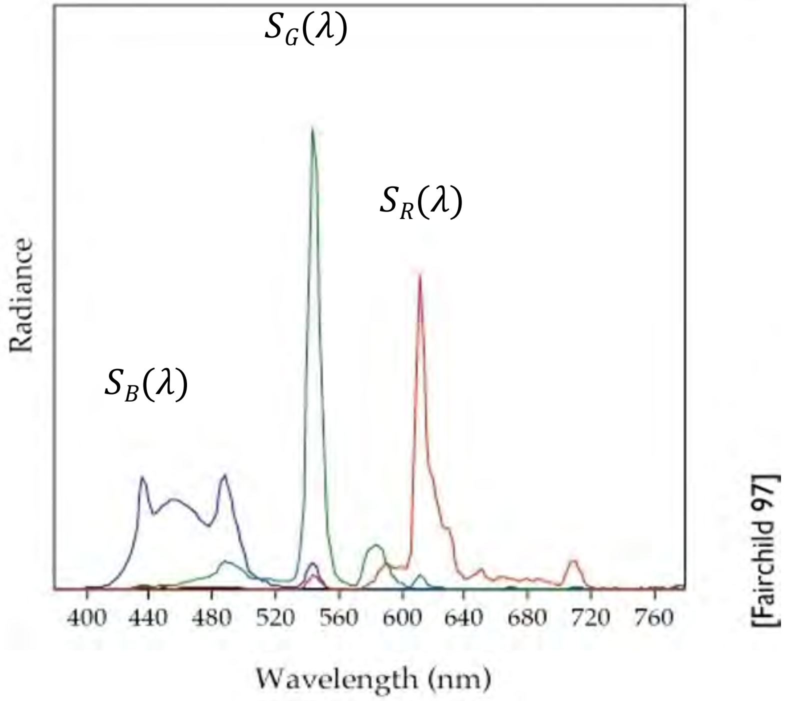
Observed display output | Desired display output

Credit:http://creativebits.org/mac_os_x/windows_vs_mac_monitor_gamma

Displays Reproducing Color

Color LCD display





Spectrum of display primaries (the curves) is determined by
display backlight and **LCD color filters**

Displays Reproducing Color (Additive Color)

- Given a set of primary lights, each with its own spectral distribution (e.g. R,G,B display pixels):

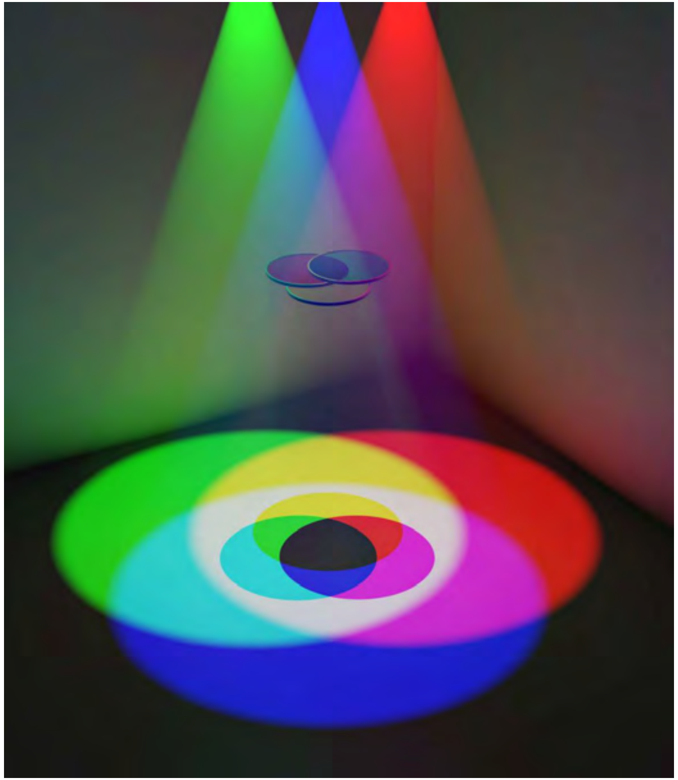
$$s_R(\lambda),\ s_G(\lambda),\ s_B(\lambda)$$

- Adjust the brightness of these lights and add them together:

$$R\, s_R(\lambda) + G\, s_G(\lambda) + B\, s_B(\lambda)$$

- The color is now described by the scalar values:

$$R,\ G,\ B$$



Color Reproduction

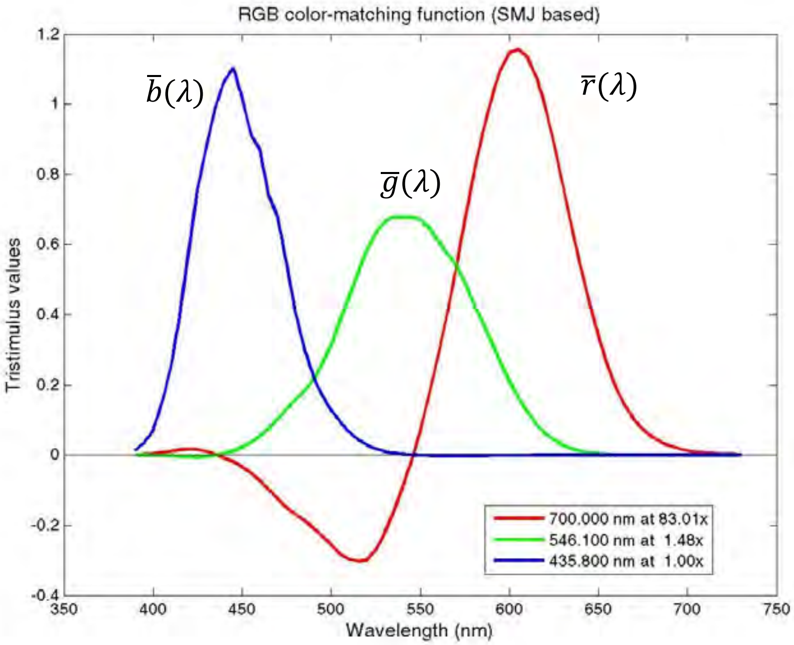
Color Reproduction with Matching Functions

- For any spectrum s, the perceived color is matched by the following formulas for scaling the CIE RGB primaries

$$R_{\text{CIE RGB}} = \int_\lambda s(\lambda)\bar{r}(\lambda)\, d\lambda$$

$$G_{\text{CIE RGB}} = \int_\lambda s(\lambda)\bar{g}(\lambda)\, d\lambda$$

$$B_{\text{CIE RGB}} = \int_\lambda s(\lambda)\bar{b}(\lambda)\, d\lambda$$



Careful: these graphs are color matching curves, not response curves or primary spectra!

Color Reproduction with Matching Functions

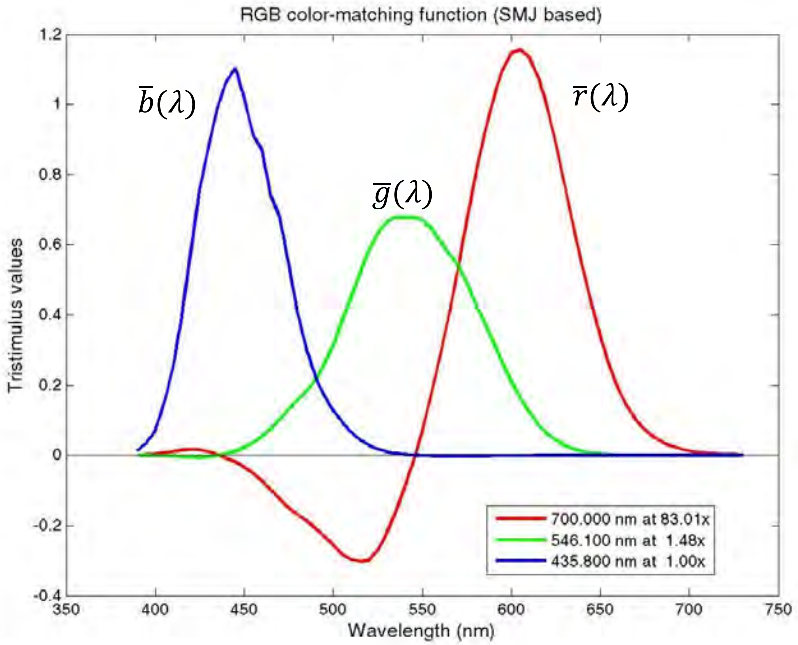
- For any spectrum s, the perceived color is matched by the following formulas for scaling the CIE RGB primaries

Written as vector dot products:

$$R_{\text{CIE RGB}} = s \cdot \bar{r}$$
$$G_{\text{CIE RGB}} = s \cdot \bar{g}$$
$$B_{\text{CIE RGB}} = s \cdot \bar{b}$$

Matrix formulation:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix}_{\text{CIE RGB}} = \begin{bmatrix} - & \bar{r} & - \\ - & \bar{g} & - \\ - & \bar{b} & - \end{bmatrix} \begin{bmatrix} | \\ s \\ | \end{bmatrix}$$

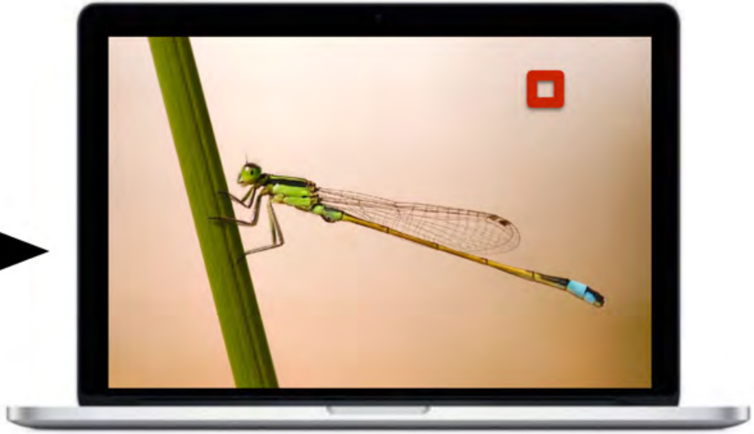


Careful: these graphs are color matching curves, not response curves or primary spectra!

Color Reproduction Problem

- Goal: at each pixel, choose R, G, B values for display so that the output color matches the appearance of the target color in the real world.

Target spectrum
(what is seen in real world)



Display outputs spectrum

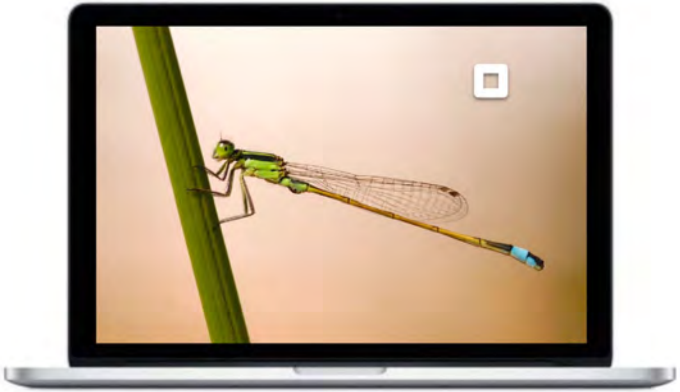
$$R\,s_R(\lambda) + G\,s_G(\lambda) + B\,s_B(\lambda)$$

Color Reproduction as Linear Algebra

- Spectrum produced by display given values R,G,B:

$$s_{\text{disp}}(\lambda) = R\, s_R(\lambda) + G\, s_G(\lambda) + B\, s_B(\lambda)$$

$$\Longrightarrow \begin{bmatrix} | \\ s_{\text{disp}} \\ | \end{bmatrix} = \begin{bmatrix} | & | & | \\ s_R & s_G & s_B \\ | & | & | \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$



Color Reproduction as Linear Algebra

- What color do we perceive when we look at the display?

$$\begin{bmatrix} S \\ M \\ L \end{bmatrix}_{\text{disp}} = \begin{bmatrix} — & r_S & — \\ — & r_M & — \\ — & r_L & — \end{bmatrix} \begin{bmatrix} | \\ s_{\text{disp}} \\ | \end{bmatrix}$$

$$= \begin{bmatrix} — & r_S & — \\ — & r_M & — \\ — & r_L & — \end{bmatrix} \begin{bmatrix} | & | & | \\ s_R & s_G & s_B \\ | & | & | \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

We want this displayed spectrum to be a metamer for the real-world target spectrum

Color Reproduction as Linear Algebra

- Color perceived for display spectra with values R,G,B

$$\begin{bmatrix} S \\ M \\ L \end{bmatrix}_{\text{disp}} = \begin{bmatrix} \text{—} & r_S & \text{—} \\ \text{—} & r_M & \text{—} \\ \text{—} & r_L & \text{—} \end{bmatrix} \begin{bmatrix} | & | & | \\ s_R & s_G & s_B \\ | & | & | \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

- Color perceived for real scene spectra, s

$$\begin{bmatrix} S \\ M \\ L \end{bmatrix}_{\text{real}} = \begin{bmatrix} \text{—} & r_S & \text{—} \\ \text{—} & r_M & \text{—} \\ \text{—} & r_L & \text{—} \end{bmatrix} \begin{bmatrix} | \\ s \\ | \end{bmatrix}$$

- How do we reproduce the color of s?
- Set these lines equal and solve for R,G,B as a function of s!

Color Reproduction as Linear Algebra

➢ Solution:

$$\begin{bmatrix} \text{—} & r_S & \text{—} \\ \text{—} & r_M & \text{—} \\ \text{—} & r_L & \text{—} \end{bmatrix} \begin{bmatrix} | & | & | \\ s_R & s_G & s_B \\ | & | & | \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} \text{—} & r_S & \text{—} \\ \text{—} & r_M & \text{—} \\ \text{—} & r_L & \text{—} \end{bmatrix} \begin{bmatrix} | \\ s \\ | \end{bmatrix}$$

$$\Longrightarrow \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \left(\begin{bmatrix} \text{—} & r_S & \text{—} \\ \text{—} & r_M & \text{—} \\ \text{—} & r_L & \text{—} \end{bmatrix} \begin{bmatrix} | & | & | \\ s_R & s_G & s_B \\ | & | & | \end{bmatrix} \right)^{-1} \begin{bmatrix} \text{—} & r_S & \text{—} \\ \text{—} & r_M & \text{—} \\ \text{—} & r_L & \text{—} \end{bmatrix} \begin{bmatrix} | \\ s \\ | \end{bmatrix}$$

Color Reproduction as Linear Algebra

- Solution (from #1):

$$\underbrace{\begin{bmatrix} R \\ G \\ B \end{bmatrix}}_{1\text{x}3} = \left(\underbrace{\underset{\text{Nx3}}{\begin{bmatrix} — & r_S & — \\ — & r_M & — \\ — & r_L & — \end{bmatrix}} \underset{\text{3xN}}{\begin{bmatrix} | & | & | \\ s_R & s_G & s_B \\ | & | & | \end{bmatrix}}}_{3\text{x}3} \right)^{-1} \underbrace{\underset{\text{Nx3}}{\begin{bmatrix} — & r_S & — \\ — & r_M & — \\ — & r_L & — \end{bmatrix}} \underset{\text{1xN}}{\begin{bmatrix} | \\ s \\ | \end{bmatrix}}}_{1\text{x}3}$$

- Solution (from #2):

$$\underset{\text{1x3}}{RGB} = \underbrace{(\underset{\text{Nx3}}{\mathbf{M}_{SML}} \, \underset{\text{3xN}}{\mathbf{M}_{RGB}})^{-1} \underset{\text{Nx3}}{\mathbf{M}_{SML}}}_{\text{Nx3}} \, \underset{\text{1xN}}{s}$$

Color Reproduction as Linear Algebra

- Solution (from #3):

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \underbrace{\begin{bmatrix} r_S \cdot s_R & r_S \cdot s_G & r_S \cdot s_B \\ r_M \cdot s_R & r_M \cdot s_G & r_M \cdot s_B \\ r_L \cdot s_R & r_L \cdot s_G & r_L \cdot s_B \end{bmatrix}^{-1} \begin{bmatrix} - & r_S & - \\ - & r_M & - \\ - & r_L & - \end{bmatrix}}_{\text{Nx3}} \begin{bmatrix} | \\ s \\ | \end{bmatrix}$$

This Nx3 matrix contains, as row vectors,

"color matching functions"

associated with the primary lights s_R, s_G, s_B

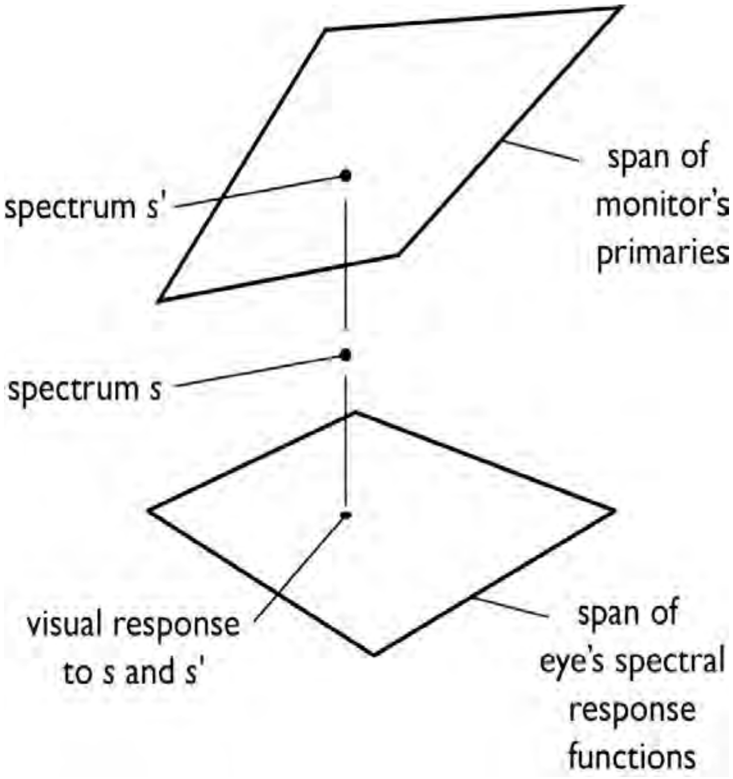
Color Reproduction Issue: No Negative Light

- R,G,B values must be positive
  - Display primaries can't emit negative light
  - But solution formulas can certainly produce negative R,G,B values
- What do negative R,G,B values mean?
  - Display can't physically reproduce the desired color
  - Desired color is outside the display's color gamut (more on this later)

Pseudo-Geometric Interpretation of Color Reproduction

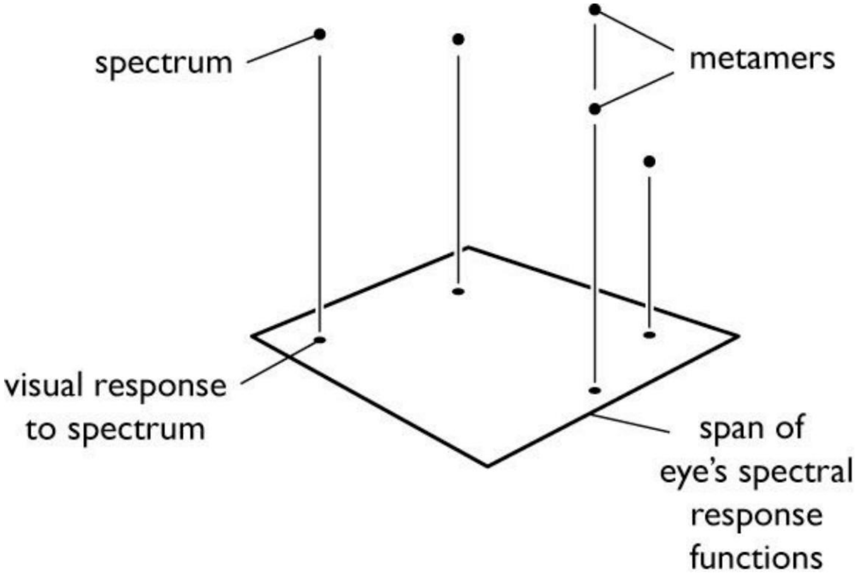
- The display can only produce a low dimensional subspace of all possible (linear combinations of display primaries)

- In color reproduction, for a given spectrum s (high dimensional), we want to choose a spectrum s' in the display's low-dimensional subspace, such that s' and s project to the same response in the low-dimensional subspace of the eye's SML response

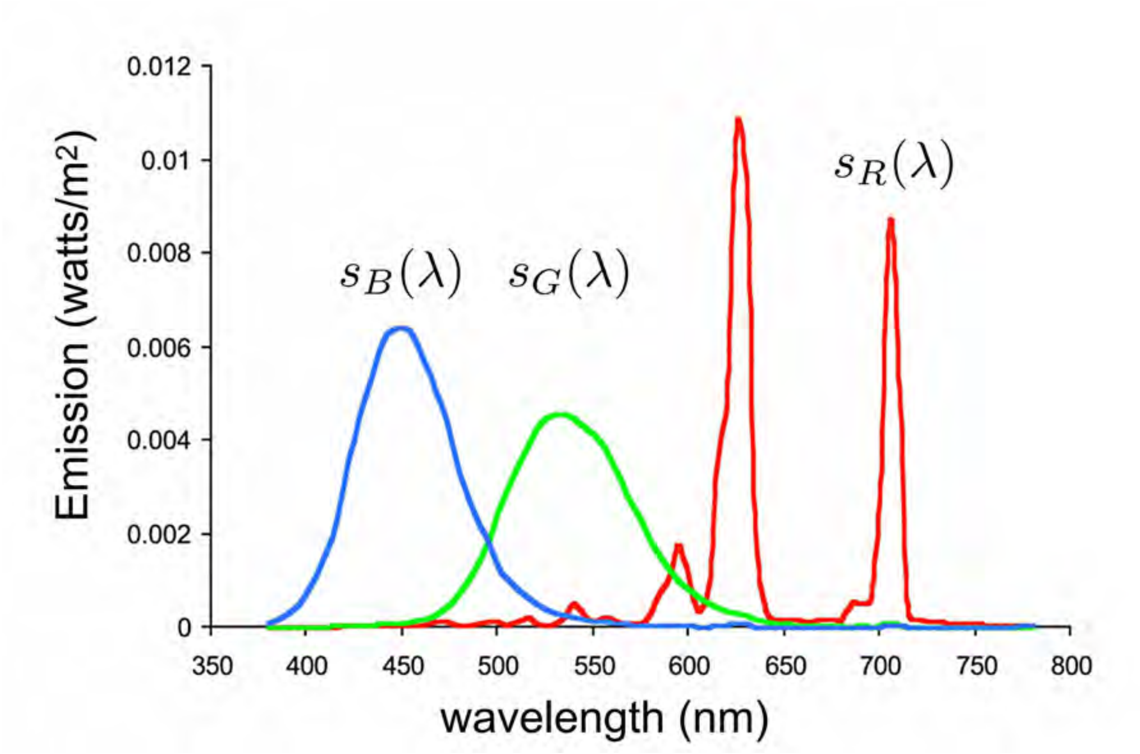


Pseudo-Geometric Interpretation

- We are projecting a high dimensional vector (wavelength spectrum function) onto a low-dimensional subspace (SML visual response)
- Differences that are perpendicular to the basis vectors of the low-dimensional space are not detectable

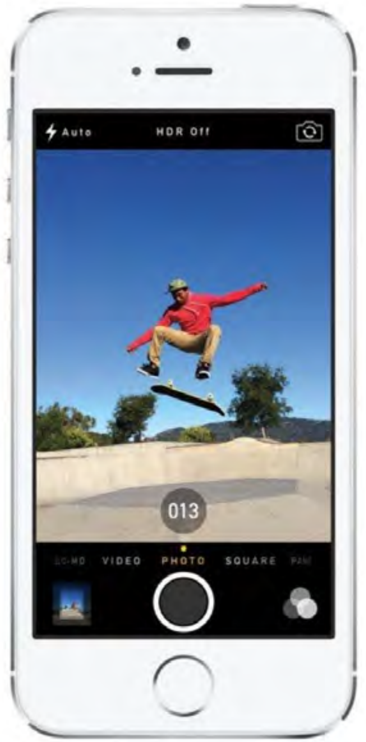


RGB Emission Spectra ("Color Primaries") for CRT Display

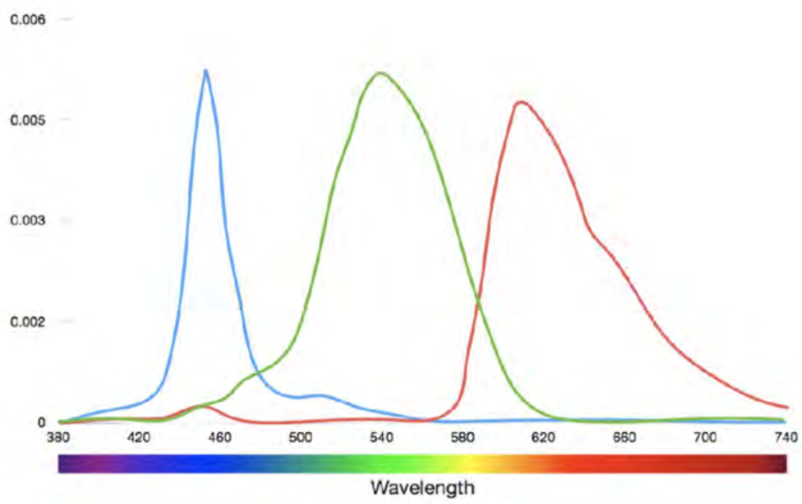


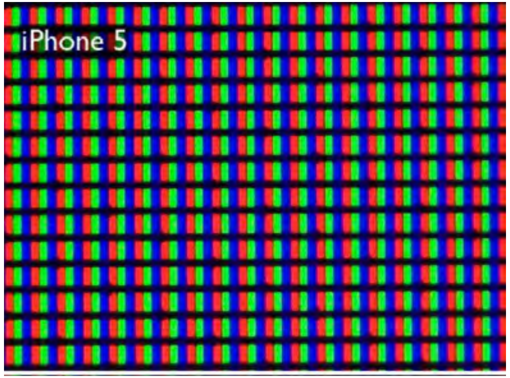
Curves determined by phosphor emission properties

RGB Emission Spectra ("Color Primaries") for Phone Display



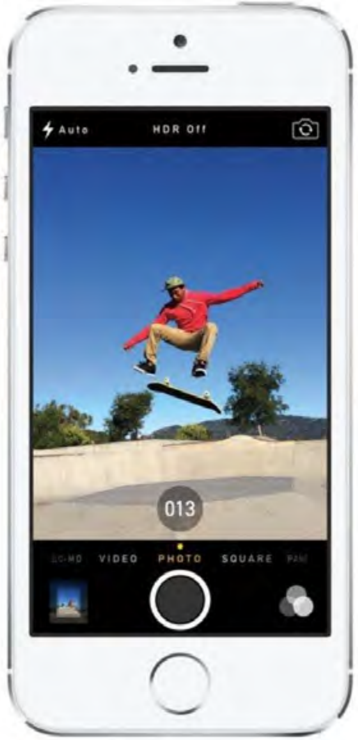
RGB pixel spectra (iPhone 5)



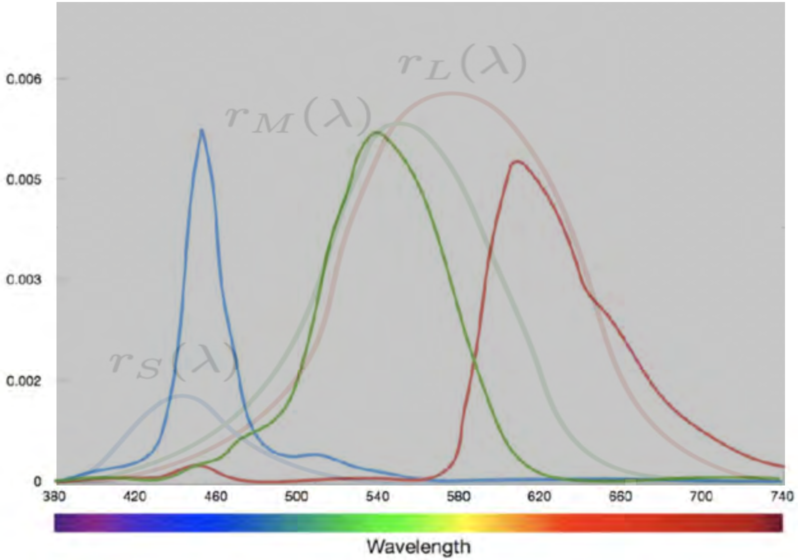


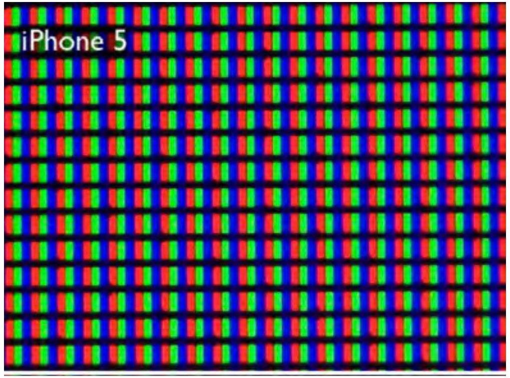
Credits: https://www.macrumors.com/roundup/iphone-5s/Yurek, https://dot-color.com/tag/color-2/page/2/Jones, https://prometheus.med.utah.edu/~bwjones/2012/09/iphone-5-display-vs-iphone-4-display/

RGB Emission Spectra ("Color Primaries") for Phone Display



RGB pixel spectra (iPhone 5)





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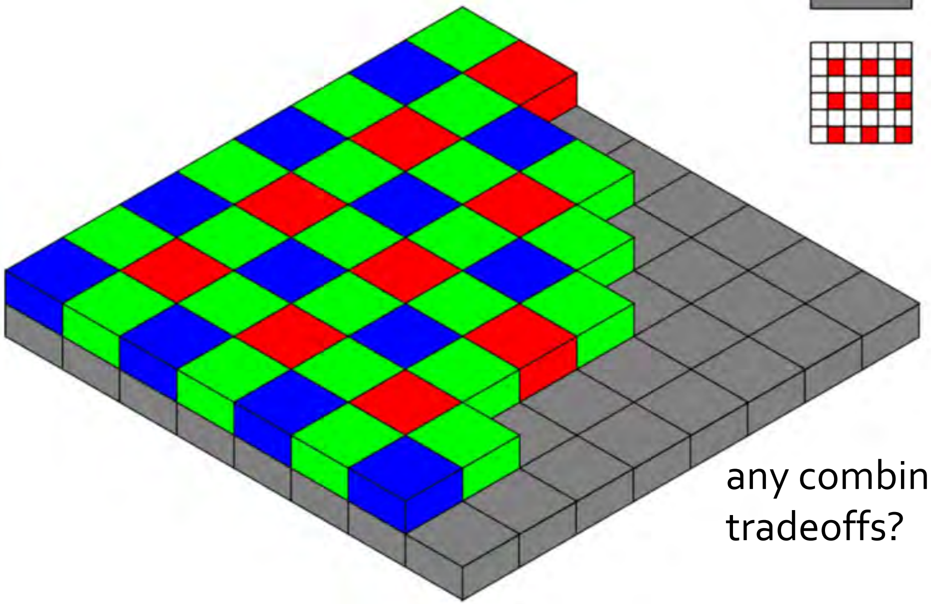
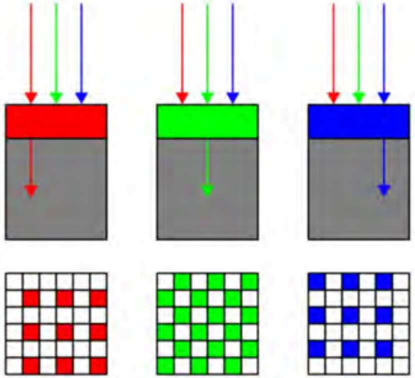
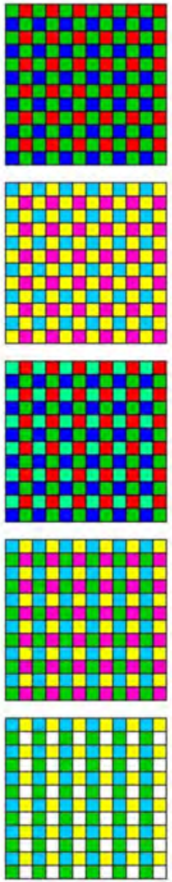
Bayer Filter and Sensor Perception

Sensors: Color Filter Arrays

Bayer pattern







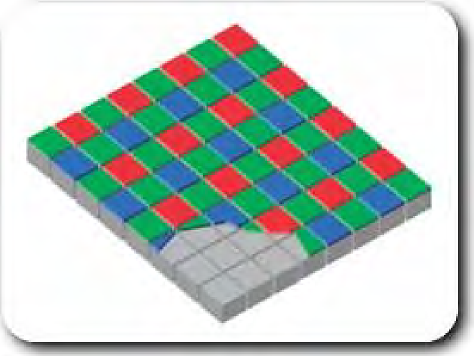
any combination possible
tradeoffs?

Credit: wikipedia

Sensors: Color Filter Arrays

Approach

- Pixels are covered by color filters
- Twice as many green pixels as red or blue ones
  - Interpreted as “intensity”
- Missing color values are interpolated for every pixel
  - More in later lecture
- Note: camera specs report the total number of pixels in a sensor
- I.e a image recorded by a 1-chip camera only consists of 1/3 measured values, 2/3 are interpolated



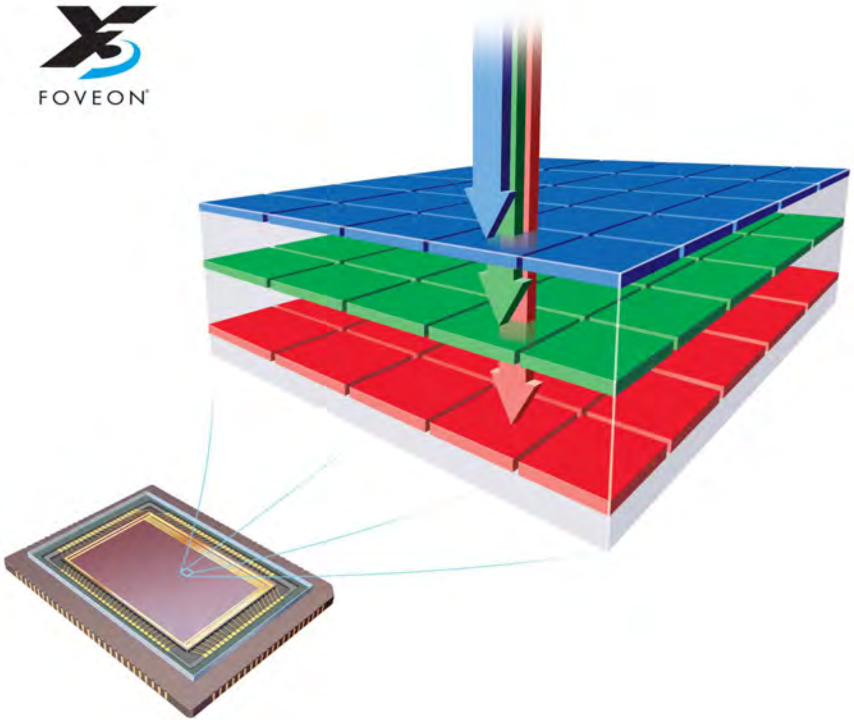
Sensors: “Direct Imaging Sensor”

Approach

- Layered RGB sensors
- All channels actually measure for every pixel

But

- Currently lower resolution
- Reportedly problems with color quality



Todays Topic

- Color Space
  - RGB
  - HSV
  - YCbCr
  - CIE LAB
- Displays Reproducing Color
- Color Reproduction
  - Linear Algebra
  - Pseudo-Geometric Interpretation
- Bayer Filter and Sensor Perception

GAMES 204

Thank You!

Qilin Sun（孙启霖）

香港中文大学（深圳）

点昀技术（Point Spread Technology）