Color

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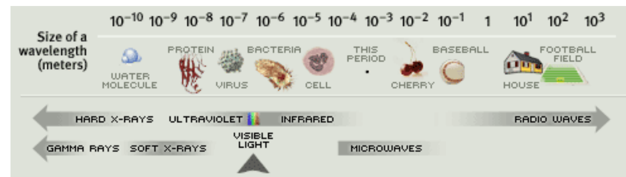
Adapted from Andy van Dam (Brown)
CSE 457
Autumn 2011

Spectrum and Color

- Physical - Mixture of wavelengths
- Perception - Color



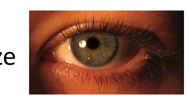
380nm/violet – 740nm/red

High Level Points

- Color is perceptual; spectral distributions are physical
- Elementary school was a simplification
- The eye is logarithmic

Dynamic Range

- Ratio of maximum to minimum light intensities
- Eye overall 10^9:1
  - Adaptation by changing pupil size
  - 10,000:1 at any moment



Display Media	Dynamic Range
Apple 30" HD Display	700 : 1
CRT	50-200 : 1
Photographic prints	100 : 1
Photographic slides	1000 : 1
Coated paper printed in B/W	100 : 1
Coated paper printed in color	50 : 1
Newsprint printed in B/W	10 : 1

[Dynamic range not the same as gamut]

Perceived Brightness

- Relationship between perceived brightness S and intensity I is non-linear
- S = C * log(I)
- Efficiently use 256 intensity values

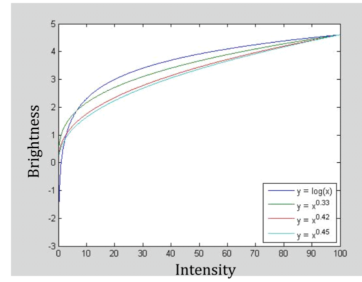
$$\frac{I_{j+1}}{I_j} = \frac{I_j}{I_{j-1}} = r$$

$$I_0 = I_0 \quad I_1 = rI_0 \quad \ldots \quad I_{255} = r^{255} I_0$$

$$r = \left(\frac{1}{I_0}\right)^{\frac{1}{255}}$$

Power Law

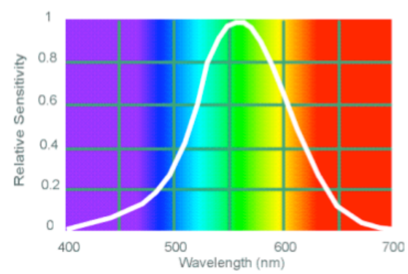
- Log function based on subjective human judgments
- Stevens' power law approximates the log well $S = c * I^{0.4}$



Screen Non-linearity: Gamma

- $I = k \bullet V^{\gamma}$
- Mac gamma: 1.8, PC: 2.5

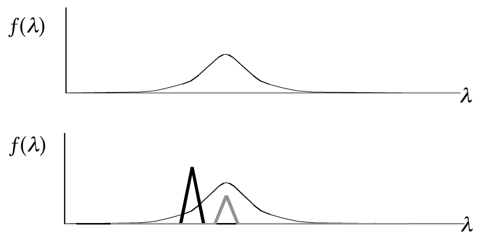
Luminous Efficiency



Perceived brightness of monochromatic light relative to 550nm

Metamers

One receptor response curve

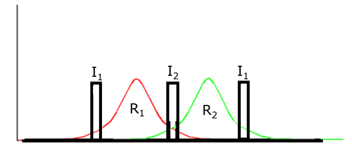


Response of receptor: $\int_{400nm}^{700nm} I(\lambda) f(\lambda)\, \mathrm{d}x$

Both frequency distributions produce the same response

Metamers

- Consider a creature with two receptors (R1, R2)



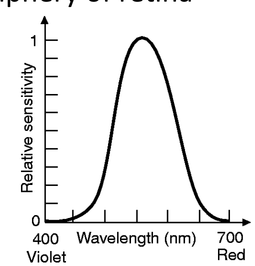
- Both I_1 and I_2 produce the same response in R_1 and R_2
- In principle an infinite number of frequency distributions can produce the same response.

Three Layers of Preception

- Receptors in retina
  - Rods, three types of cones (tristimulus theory)
  - Note: receptors each respond to wide range of frequencies, not just RGB
- Opponent channels
  - Blue-yellow, red-green, black-white
- Opponent cells
  - Spatial (context) effects, e.g., simultaneous contrast, lateral inhibition

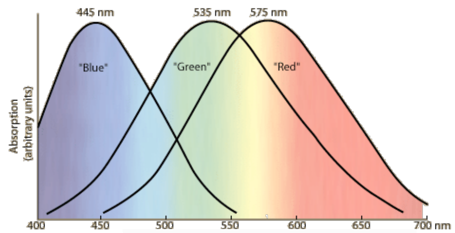
Rods

- See grays
- Work in low light
- Around periphery of retina

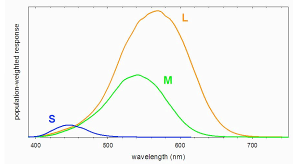


Cones

Not really RGB
Long, Medium, Short

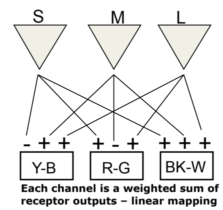


Many more long cones,
fewer medium, fewest short

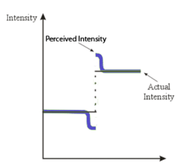


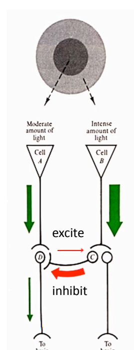
Hering's Chromatic Opponent Channels

- Additional processing
  - Cones feed into higher up neurons that correspond to opponent processes: red-green and yellow-blue
  - A color is never reddish-greenish or bluish-yellowish



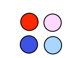
Lateral Inhibition / Mach Banding





Nature provides for contrast enhancement at boundaries between regions: edge detection. This is caused by lateral inhibition.

Describing Color

- Talked about intensity
- Hue: Which color
- Saturation: How pure the color is 
- Distinguish between around 7 million colors
  - Determined by Just Noticeable Differences (JND)
  - JND smaller near center of visible range of light

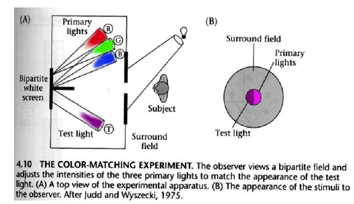
- Three terms implies 3 dimensional space

Naming Color

- How do you compare colors?
- PANTONE® Matching System in printing industry
- Munsell color-order system
  - hue, value/lightness, chroma (saturation)
  - equal perceived distances between neighbors

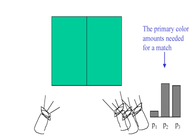
Color Matching

- Need a way to precisely describe colors
- Choose three primaries (RGB), try and match T

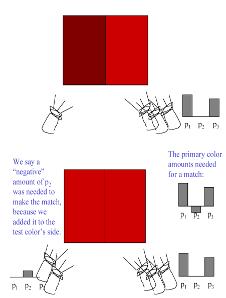


Color Matching

- Three primaries can't match all colors
- Adding a light to the test side lets you match all colors
- Can be thought of as -R

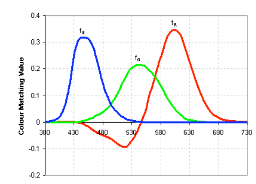


http://www.maelabs.ucsd.edu/mae152/handouts/12

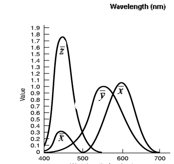


CIE Color Space

- Negative primary is awkward



- X, Y, Z replace red, green blue
- Y chosen so that y_λ matches luminous efficiency function



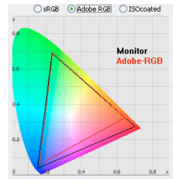
The mathematical color matching functions x_λ y_λ, and z_λ for the 1931 CIE X, Y, and Z primaries. They are defined tabularly at 1 nm intervals for color samples that subtend 2° field of view on retina

RGB in CIE

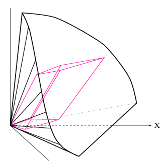
- Easily convert RGB <-> XYZ

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.412453 & 0.357520 & 0.180423 \\ 0.212671 & 0.715160 & 0.072169 \\ 0.019334 & 0.119193 & 0.950227 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

- Visible gamut has irregular shape in CIE based on response curves



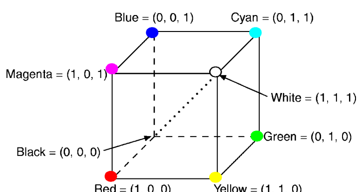
- RGB cube (right) distorted from projection



Color Spaces

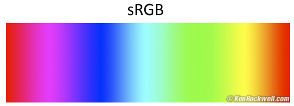
- Programming for monitors easier in space defined by monitor : RGB space (RGB pixels for both CRT's and flat panels)
- Printers use CMY (cyan, magenta, yellow) for color printing :CMY(K) space
- Six-primary-color projection system: 6-color IRODORI space
- User-friendliness: Hue, Saturation, Value is easier than RGB
- Need perceptual uniformity in the space? Munsell or CIELab

RGB Color Model



- RGB color gamut
  - differs from one monitor to another
  - differs by company too:
    - Adobe RGB - larger space
    - sRGB (HP/Microsoft) - fewer colors, but allocated bit depth better and more than enough for most on-screen and Web uses

sRGB



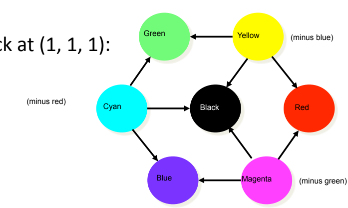
Adobe RGB

CMYK

- Used in most printers
  - Color ink is expensive, mix of inks dries slower
- Cyan, magenta, and yellow are complements of red, green , and blue
- Subtractive primaries: Color subtracted from white
- Subset is unit cube
  - White is at origin, black at (1, 1, 1):

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

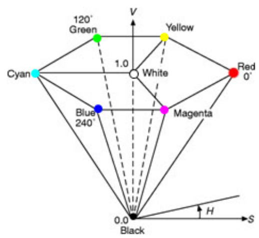
K = min(C, M, Y)



subtractive primaries (cyan, magenta, yellow) and their mixtures

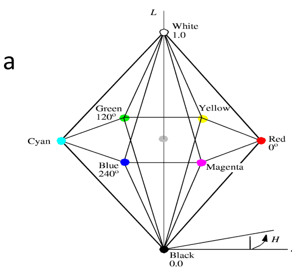
HSV

- Hue, saturation, value (kind of brightness)
- Polar coordinates



HLS

- Hue, lightness, saturation
- Easier to think of white as a point
- Maximally saturated hues at S=1, L = 0.5



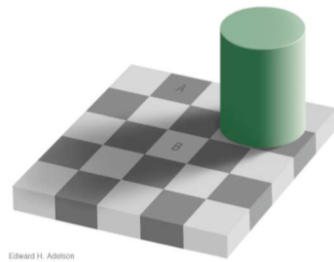
Perceptual Uniformity

- Equal changes in color values are not perceived as equal (RGB, CMYK, HSV, HLS)
- CIE Lab introduced in 1976
  - L: luminosity
  - a: red/green axis
  - b: yellow/blue axis
- Color space dependent on white value

Interpolating Colors

- RGB is easy
  red = (1, 0, 0), green = (0, 1, 0)
  midpoint = (0.5, 0.5, 0)
  RGB_to_HSV = (60º, 1, 0.5)
- HSV is less obvious
  red = (0º, 1, 1); green = (120º, 1, 1)
  midpoint = (60º, 1, 1)

Context



Is A lighter or darker than B?

Context

These rectangles have the same pixel values

Quick UI Implications

- 1 in 10 men are color blind
  – Mostly: Red / Green
  – Rare: Yellow / Blue
  – Very Rare: No color
- Test UIs for color blind (approximation)
  – http://colorfilter.wickline.org/