CS534: Introduction to Computer Vision
Color in Digital Images

Ahmed Elgammal
Dept. of Computer Science
Rutgers University

Outlines

- Color Perception
- RGB color space
- HSV and HLS
- Color Models for TV and Video
- Colorimetric Color Spaces

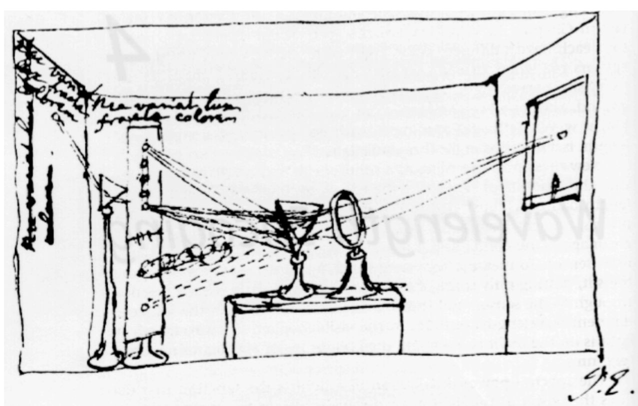
- Sources:
  - Burger and Burge “Digital Image Processing” Chapter 12

Color Perception

- Color perception is a fascinating and complicated phenomenon that has occupied the interest of scientist, psychologists, philosophers, and artists for hundreds of years.
- Color plays an important role in object recognition
- What is the best way to represent colors in the digital domain?
- Challenging problem: color constancy.

Complications of color

- Spectral composition of light
  - Newton's original prism experiment
  - light decomposed into its spectral components



4.1 **NEWTON'S SUMMARY DRAWING** of his experiments with light. Using a point source of light and a prism, Newton separated sunlight into its fundamental components. By reconverging the rays, he also showed that the decomposition is reversible.

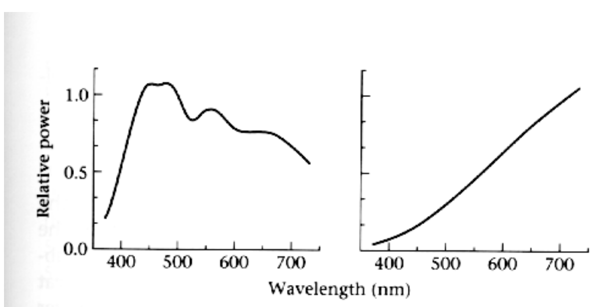
Complications of color

- Why does the prism separate the light into its spectral components?
  - prism bends different wavelengths of light by different amounts
    - refractive index is a function of wavelength
    - shorter wavelengths are refracted more strongly than longer wavelengths

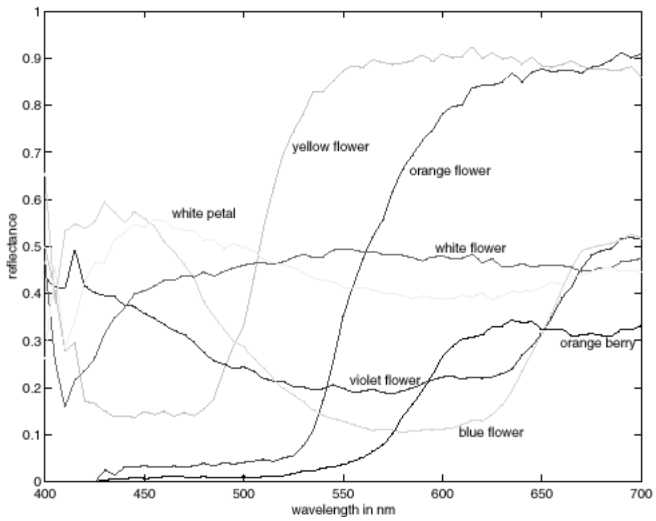
Wavelength	Color (*)
700	Red
610	Orange
580	Yellow
540	Green
480	Blue
400	Violet

* - viewed in isolation

Complications of color



4.4 THE SPECTRAL POWER DISTRIBUTION of two important light sources are shown: (left) blue skylight and (right) a tungsten bulb.



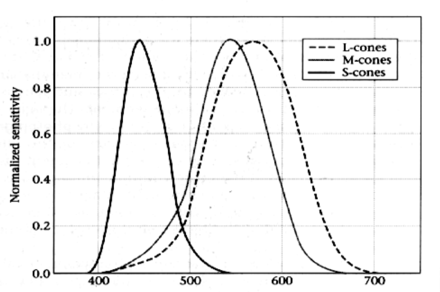
Spectral albedoes for several different leaves, with color names attached. Notice that different colours typically have different spectral albedo, but that different spectral albedoes may result in the same perceived color (compare

Computer Vision - A Modern Approach
Set: Color
Slides by D.A. Forsyth

Cones and color – color perception

- Three different types of cones
  - they differ in their sensitivity to different wavelengths of light (blue-violet, green, yellow-red)

3.3 SPECTRAL SENSITIVITIES OF THE L-, M-, AND S-CONES in the human eye. The measurements are based on a light source at the cornea, so that the wavelength loss due to the cornea, lens, and other inert pigments of the eye plays a role in determining the sensitivity. Source: Stockman and MacLeod, 1993.



Wavelength encoding

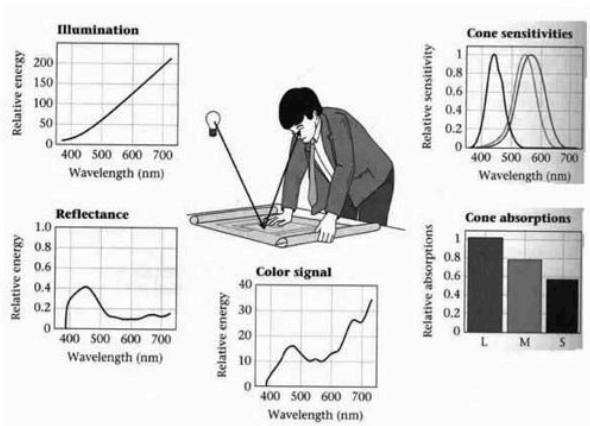
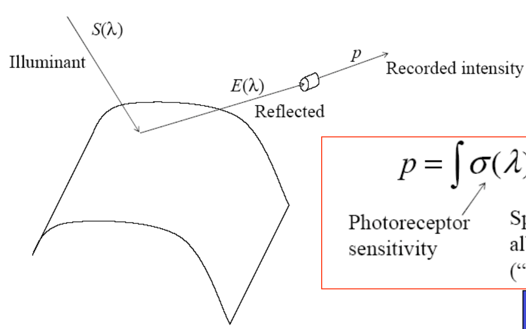


Figure from Rob Collins at Penn State



$$p = \int \sigma(\lambda)\rho(\lambda)S(\lambda)d\lambda$$

Photoreceptor sensitivity

Spectral albedo (“object color”)

Illuminant color

3 cones

COLOR!

$$p_S = \int \sigma_S(\lambda)E(\lambda)d\lambda$$

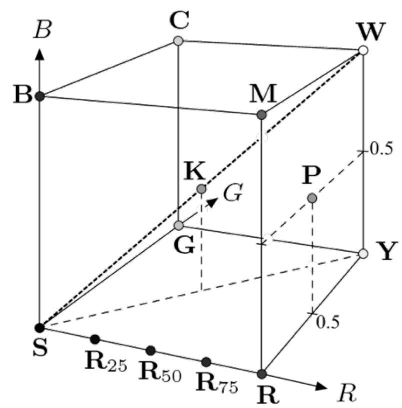
$$p_M = \int \sigma_M(\lambda)E(\lambda)d\lambda$$

$$p_L = \int \sigma_L(\lambda)E(\lambda)d\lambda$$

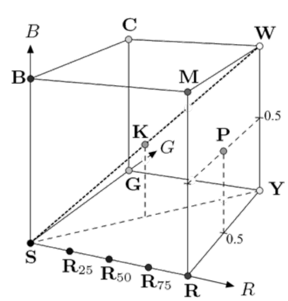
Figure from Rob Collins at Penn State

RGB color images

- Three primary colors: Red, Green, blue
- Widely used in transmission, representation, storage of color images.
- RGB is additive color system: add primary colored-light to form different colors

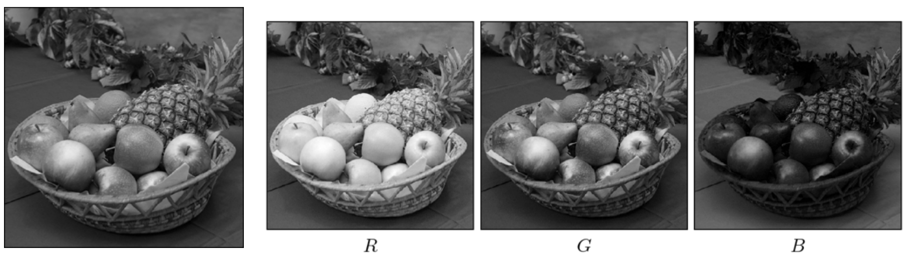


$$\mathbf{C}_i = (R_i, G_i, B_i)$$

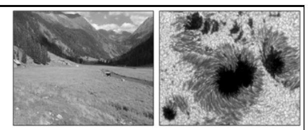


Point	Color	RGB Value R	G	B
S	Black	0.00	0.00	0.00
R	Red	1.00	0.00	0.00
Y	Yellow	1.00	1.00	0.00
G	Green	0.00	1.00	0.00
C	Cyan	0.00	1.00	1.00
B	Blue	0.00	0.00	1.00
M	Magenta	1.00	0.00	1.00
W	White	1.00	1.00	1.00
K	50% Gray	0.50	0.50	0.50
$\mathbf{R}_{75}$	75% Red	0.75	0.00	0.00
$\mathbf{R}_{50}$	50% Red	0.50	0.00	0.00
$\mathbf{R}_{25}$	25% Red	0.25	0.00	0.00
P	Pink	1.00	0.50	0.50

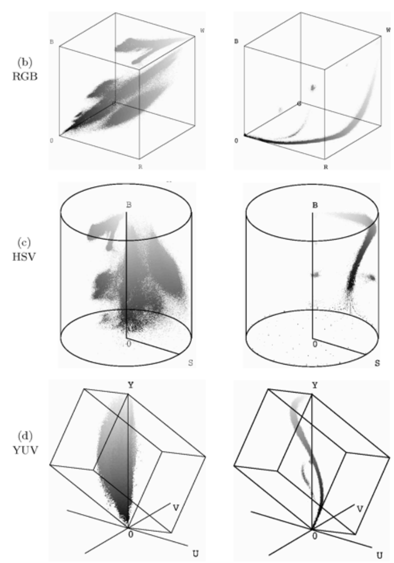
- It is hard to determine the color of a pixel from knowing it's R,G,B components
- RGB is not a perceptually uniform representation: measured distance in the RGB color space doesn't correspond to our perception of color.



Other Color Spaces



- HSV/HSB and HLS
- TV Color Spaces:
  - YUV, YIQ, YC_bC_r
- Color spaces for printing:
  - CMY, CMYK
- Colorimetric Color Spaces:
  - CIE XYZ
  - CIE L*a*b*



- Three important concepts:
  - Hue
  - Saturation
  - Luminance

From RGB to Grayscale

- How to compute luminance value Y from RGB

  $$Y = \mathrm{Avg}(R, G, B) = \frac{R+G+B}{3}$$

- We perceive red and green as being brighter than blue

  $$Y = \mathrm{Lum}(R, G, B) = w_R \cdot R + w_G \cdot G + w_B \cdot B$$

- For analog color TV signal

  $w_R = 0.299 \qquad w_G = 0.587 \qquad w_B = 0.114$

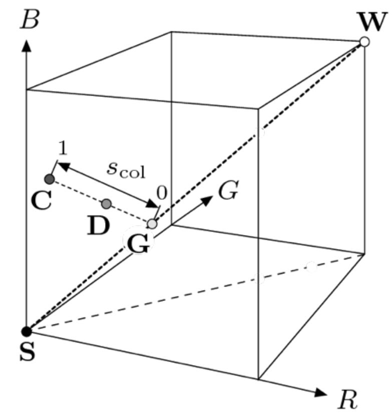
- For digital color encoding ITY-BT.709

  $w_R = 0.2125 \qquad w_G = 0.7154 \qquad w_B = 0.072$

R G B

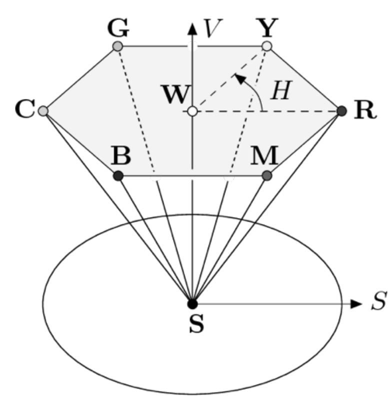
Desaturating Color Images

$$\begin{pmatrix} R_d \\ G_d \\ B_d \end{pmatrix} \leftarrow \begin{pmatrix} Y \\ Y \\ Y \end{pmatrix} + s_{\mathrm{col}} \cdot \begin{pmatrix} R-Y \\ G-Y \\ B-Y \end{pmatrix}$$

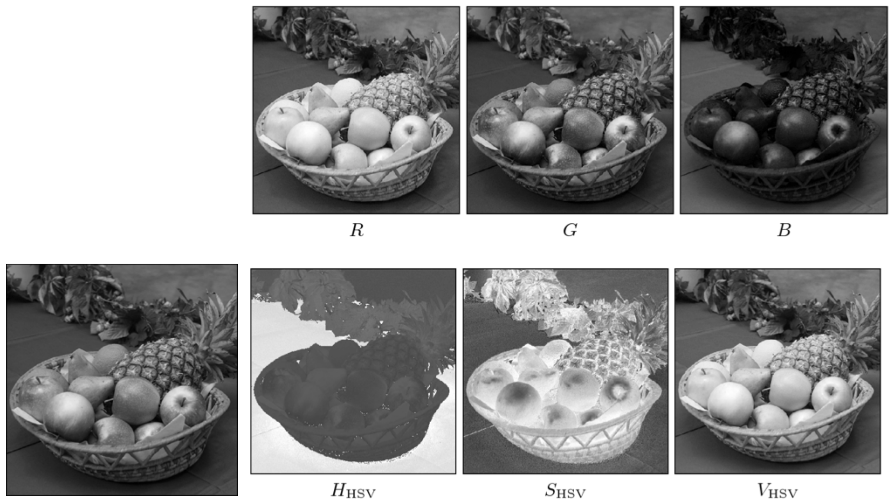


HSV color space

- Represent three components:
  - Hue
  - Saturation
  - Value (brightness)
- Also called HSB
- Upside-down six-sided pyramid



(a) HSV



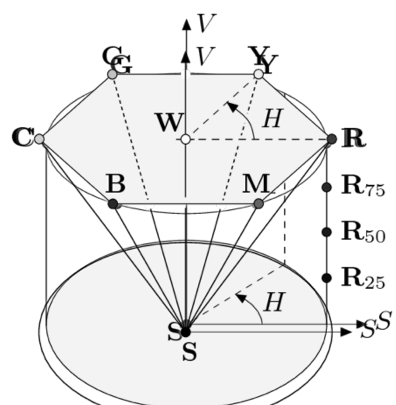
RGB to HSV

- Easier represented as a cylinder.

$$C_{\text{high}} = \max(R, G, B), \quad C_{\text{low}} = \min(R, G, B),$$
$$C_{\text{rng}} = C_{\text{high}} - C_{\text{low}}.$$

$$S_{\text{HSV}} = \begin{cases} \frac{C_{\text{rng}}}{C_{\text{high}}} & \text{for } C_{\text{high}} > 0 \\ 0 & \text{otherwise} \end{cases}$$

$$V_{\text{HSV}} = \frac{C_{\text{high}}}{C_{\text{max}}}$$



(a) HSV

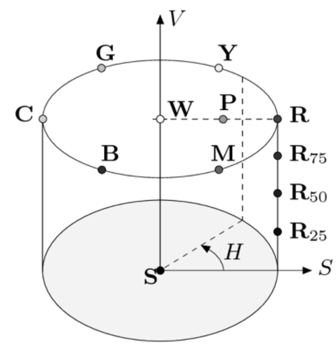
$$R' = \frac{C_{\text{high}} - R}{C_{\text{rng}}} \qquad G' = \frac{C_{\text{high}} - G}{C_{\text{rng}}} \qquad B' = \frac{C_{\text{high}} - B}{C_{\text{rng}}}$$

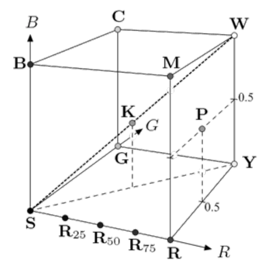
$$H' = \begin{cases} B' - G' & \text{if } R = C_{\text{high}} \\ R' - B' + 2 & \text{if } G = C_{\text{high}} \\ G' - R' + 4 & \text{if } B = C_{\text{high}} \end{cases} \qquad H_{\text{HSV}} = \frac{1}{6} \cdot \begin{cases} (H' + 6) & \text{for } H' < 0 \\ H' & \text{otherwise} \end{cases}$$

RGB to HSV

RGB/HSV Values

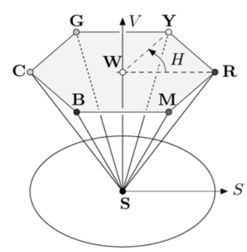
Pt.	Color	R	G	B	H	S	V
S	Black	0.00	0.00	0.00	—	0.00	0.00
R	Red	1.00	0.00	0.00	0	1.00	1.00
Y	Yellow	1.00	1.00	0.00	1/6	1.00	1.00
G	Green	0.00	1.00	0.00	2/6	1.00	1.00
C	Cyan	0.00	1.00	1.00	3/6	1.00	1.00
B	Blue	0.00	0.00	1.00	4/6	1.00	1.00
M	Magenta	1.00	0.00	1.00	5/6	1.00	1.00
W	White	1.00	1.00	1.00	—	0.00	1.00
$\mathbf{R}_{75}$	75% Red	0.75	0.00	0.00	0	1.00	0.75
$\mathbf{R}_{50}$	50% Red	0.50	0.00	0.00	0	1.00	0.50
$\mathbf{R}_{25}$	25% Red	0.25	0.00	0.00	0	1.00	0.25
P	Pink	1.00	0.50	0.50	0	0.5	1.00



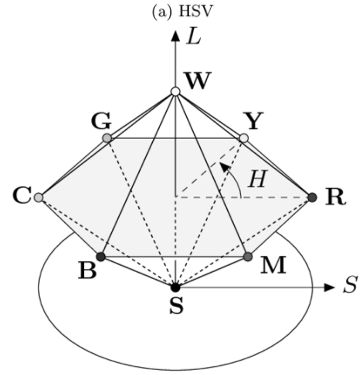


HLS color space

- Similar to HSV:
  - Hue
  - Luminance
  - Saturation
- Also called HSL
- Double pyramid representation (like a diamond)



(a) HSV



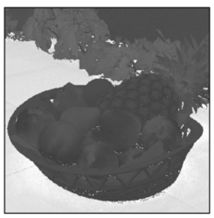
(b) HLS

RGB to HLS

$$H_{\mathrm{HLS}} = H_{\mathrm{HSV}}$$

$$L_{\mathrm{HLS}} = \frac{C_{\mathrm{high}} + C_{\mathrm{low}}}{2}$$

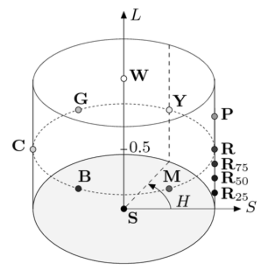
$$S_{\mathrm{HLS}} = \begin{cases} 0 & \text{for } L_{\mathrm{HLS}} = 0 \\ 0.5 \cdot \frac{C_{\mathrm{rng}}}{L_{\mathrm{HLS}}} & \text{for } 0 < L_{\mathrm{HLS}} \leq 0.5 \\ 0.5 \cdot \frac{C_{\mathrm{rng}}}{1 - L_{\mathrm{HLS}}} & \text{for } 0.5 < L_{\mathrm{HLS}} < 1 \\ 0 & \text{for } L_{\mathrm{HLS}} = 1 \end{cases}$$



H_{HLS}

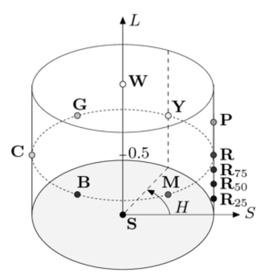
S_{HLS}

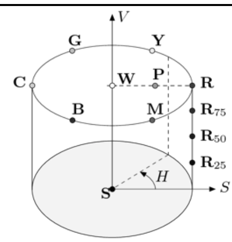
L_{HLS}

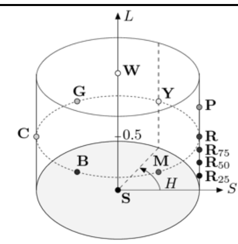


RGB/HLS Values

Pt.	Color	R	G	B	H	S	L
S	Black	0.00	0.00	0.00	—	0.00	0.00
R	Red	1.00	0.00	0.00	0	1.00	0.50
Y	Yellow	1.00	1.00	0.00	1/6	1.00	0.50
G	Green	0.00	1.00	0.00	2/6	1.00	0.50
C	Cyan	0.00	1.00	1.00	3/6	1.00	0.50
B	Blue	0.00	0.00	1.00	4/6	1.00	0.50
M	Magenta	1.00	0.00	1.00	5/6	1.00	0.50
W	White	1.00	1.00	1.00	—	0.00	1.00
$\mathbf{R}_{75}$	75% Red	0.75	0.00	0.00	0	1.00	0.375
$\mathbf{R}_{50}$	50% Red	0.50	0.00	0.00	0	1.00	0.250
$\mathbf{R}_{25}$	25% Red	0.25	0.00	0.00	0	1.00	0.125
P	Pink	1.00	0.50	0.50	0/6	1.00	0.75





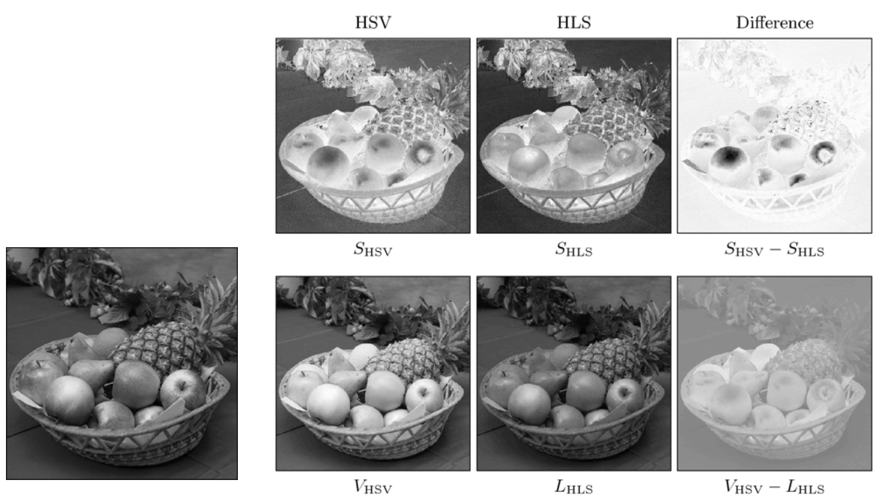


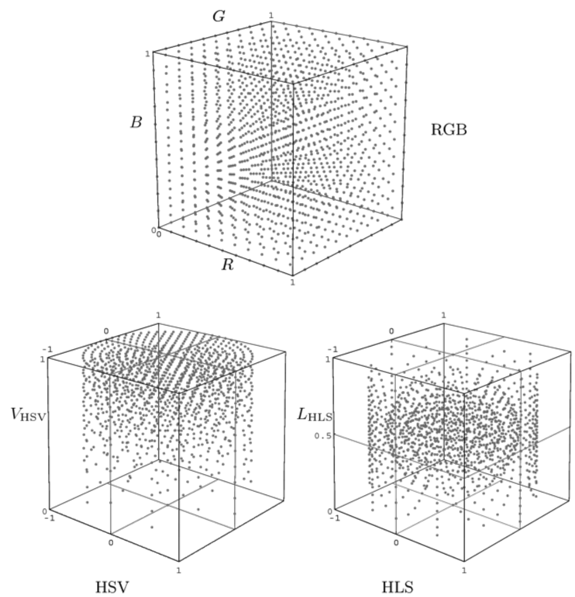
RGB/HSV Values

Pt.	Color	R	G	B	H	S	V
S	Black	0.00	0.00	0.00	—	0.00	0.00
R	Red	1.00	0.00	0.00	0	1.00	1.00
Y	Yellow	1.00	1.00	0.00	1/6	1.00	1.00
G	Green	0.00	1.00	0.00	2/6	1.00	1.00
C	Cyan	0.00	1.00	1.00	3/6	1.00	1.00
B	Blue	0.00	0.00	1.00	4/6	1.00	1.00
M	Magenta	1.00	0.00	1.00	5/6	1.00	1.00
W	White	1.00	1.00	1.00	—	0.00	1.00
$\mathbf{R}_{75}$	75% Red	0.75	0.00	0.00	0	1.00	0.75
$\mathbf{R}_{50}$	50% Red	0.50	0.00	0.00	0	1.00	0.50
$\mathbf{R}_{25}$	25% Red	0.25	0.00	0.00	0	1.00	0.25
P	Pink	1.00	0.50	0.50	0	0.5	1.00

RGB/HLS Values

Pt.	Color	R	G	B	H	S	L
S	Black	0.00	0.00	0.00	—	0.00	0.00
R	Red	1.00	0.00	0.00	0	1.00	0.50
Y	Yellow	1.00	1.00	0.00	1/6	1.00	0.50
G	Green	0.00	1.00	0.00	2/6	1.00	0.50
C	Cyan	0.00	1.00	1.00	3/6	1.00	0.50
B	Blue	0.00	0.00	1.00	4/6	1.00	0.50
M	Magenta	1.00	0.00	1.00	5/6	1.00	0.50
W	White	1.00	1.00	1.00	—	0.00	1.00
$\mathbf{R}_{75}$	75% Red	0.75	0.00	0.00	0	1.00	0.375
$\mathbf{R}_{50}$	50% Red	0.50	0.00	0.00	0	1.00	0.250
$\mathbf{R}_{25}$	25% Red	0.25	0.00	0.00	0	1.00	0.125
P	Pink	1.00	0.50	0.50	0/6	1.00	0.75





Color Models in TV and Video

- Part of the standards for recording, storage, transmission, and display of TV signals
- YIQ: used in analog NTSC systems. Also in VHS videotape coding. (N. America and Japan
- YUV: used in European TV standard (SECAM)
- YCbCr: a variation of YUV that is used in digital video and digital TV. Also in JPEG
- Common ideas:
  - A separate luminance component Y
  - Two chroma components
  - Encode color difference instead of absolute colors
  - More bandwidth for luminance than chroma components.
  - Linear transformation from RGB (a matrix multiplication for conversion.

YUV

- Luminance component:

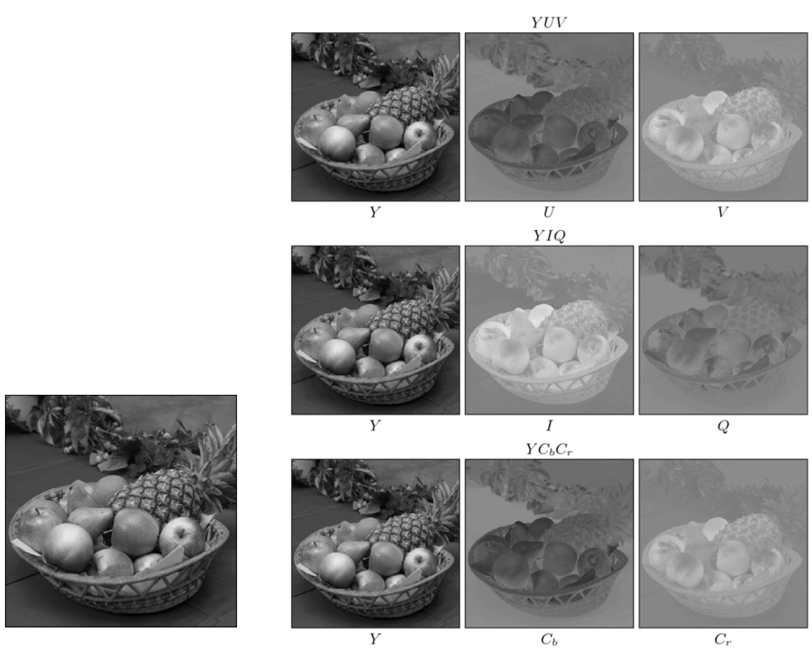
$$Y = 0.299 \cdot R + 0.587 \cdot G + 0.114 \cdot B$$

- Chroma components: based on differences between the luminance and the blue and red components:

$$U = 0.492 \cdot (B - Y) \qquad \text{and} \qquad V = 0.877 \cdot (R - Y)$$

$$\begin{pmatrix} Y \\ U \\ V \end{pmatrix} = \begin{pmatrix} 0.299 & 0.587 & 0.114 \\ -0.147 & -0.289 & 0.436 \\ 0.615 & -0.515 & -0.100 \end{pmatrix} \cdot \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} 1.000 & 0.000 & 1.140 \\ 1.000 & -0.395 & -0.581 \\ 1.000 & 2.032 & 0.000 \end{pmatrix} \cdot \begin{pmatrix} Y \\ U \\ V \end{pmatrix}$$



YIQ and YCbCr

- YIQ: similar to YUV (rotate and mirror the UV)

$$\begin{pmatrix} I \\ Q \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \cdot \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \cdot \begin{pmatrix} U \\ V \end{pmatrix}$$

- YC_bC_r:

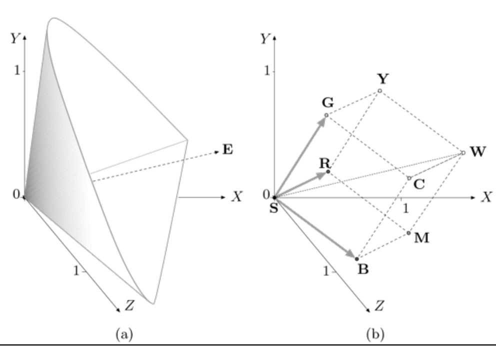
$$Y = w_R \cdot R + (1 - w_B - w_R) \cdot G + w_B \cdot B$$
$$C_b = \frac{0.5}{1 - w_B} \cdot (B - Y)$$
$$C_r = \frac{0.5}{1 - w_R} \cdot (R - Y)$$

- Setting the weights to w_B=0.299 and w_R=0.114

$$\begin{pmatrix} Y \\ C_b \\ C_r \end{pmatrix} = \begin{pmatrix} 0.299 & 0.587 & 0.114 \\ -0.169 & -0.331 & 0.500 \\ 0.500 & -0.419 & -0.081 \end{pmatrix} \cdot \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

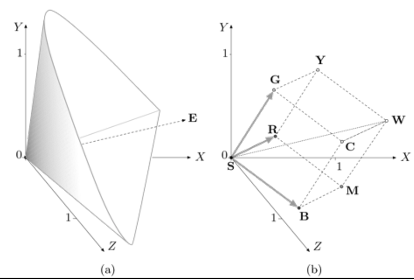
Colorimetric Color Spaces

- Goal: measure colors independent of devices
- A calibrated device-independent color system
- CIE color spaces: CIE (Commission Inernationale d'Eclairge - International commission on Illumination.
- CIE XYZ, CIE x,y, CIE L*a*b*

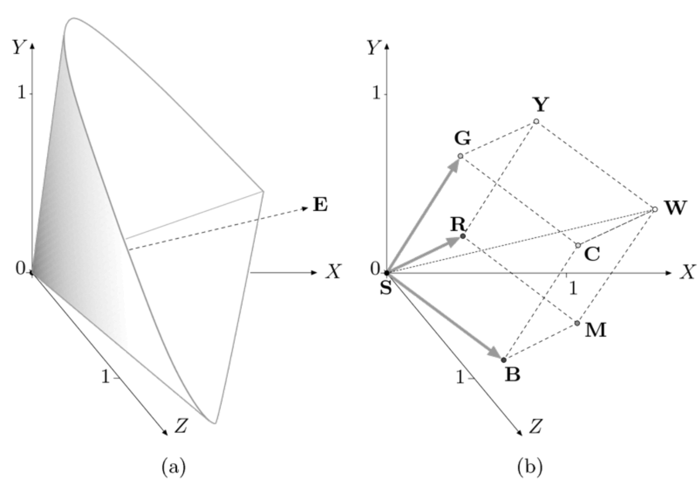


CIE XYZ

- Three imaginary primary colors X, Y, Z
- All the visible colors are summations of positive components.
- All visible colors lie inside a cone-shaped region, which doesn't include the X,Y, Z
- Y corresponds to the luminosity of the color (lightness)
- RGB cube is a distorted cube in the XYZ space.
- Linear transformation between RGB and XYZ
- Similar to RGB, the space is nonlinear wrt human color perception



CIE - XYZ



RGB (linear) to CIE XYZ - a linear transformation

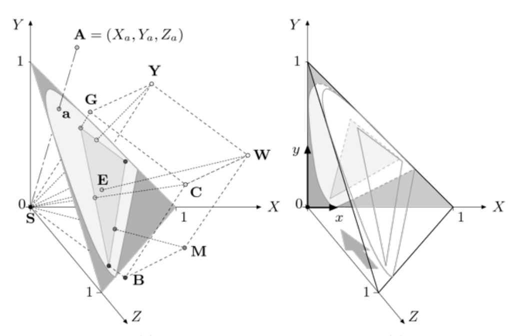
Pt.	Color	R	G	B	X	Y	Z	x	y
S	black	0.00	0.00	0.00	0.0000	0.0000	0.0000	0.3127	0.3290
R	red	1.00	0.00	0.00	0.4125	0.2127	0.0193	0.6400	0.3300
Y	yellow	1.00	1.00	0.00	0.7700	0.9278	0.1385	0.4193	0.5052
G	green	0.00	1.00	0.00	0.3576	0.7152	0.1192	0.3000	0.6000
C	cyan	0.00	1.00	1.00	0.5380	0.7873	1.0694	0.2247	0.3288
B	blue	0.00	0.00	1.00	0.1804	0.0722	0.9502	0.1500	0.0600
M	magenta	1.00	0.00	1.00	0.5929	0.2848	0.9696	0.3209	0.1542
W	white	1.00	1.00	1.00	0.9505	1.0000	1.0888	0.3127	0.3290

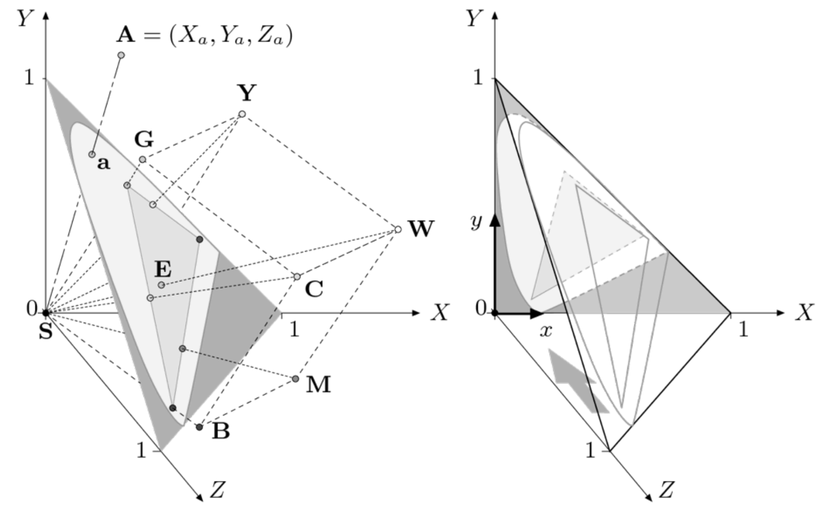
CIE x,y chromaticity

- How to separate the color hue from the luminance
- A central projection (through S) to the plane $X + Y + Z = 1$

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

- Then, project to the XY plane (use only the *x*,*y* - drop *z*)



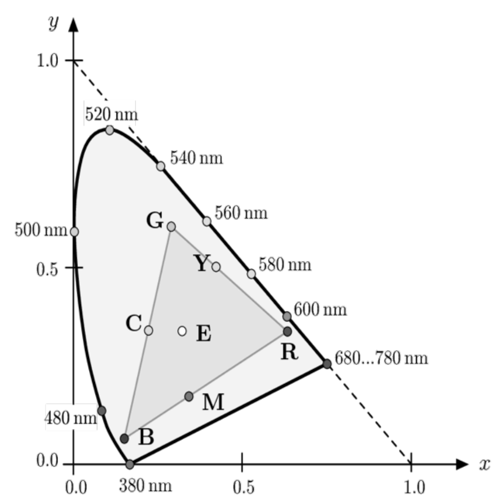


(a) (b)

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

CIE-xy chromaticity diagram

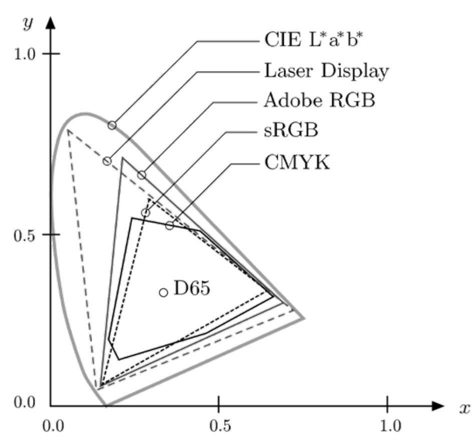
- Horseshoe-shaped
- The outer boundary represents monochromatic (spectrally pure), maximally saturated colors.
- Neutral point (E) where x=y=1/3, (X=Y=Z=1)
- Saturation falls off towards E
- Complementary colors?



- We cannot reconstruct the XYZ from xy only
- We can reconstruct the XYZ if we know x,y, and Y

$$X = x \cdot \frac{Y}{y} \qquad Z = z \cdot \frac{Y}{y} = (1 - x - y) \cdot \frac{Y}{y}$$

- Standard illuminants
  - D50: emulate direct sunlight illumination
  - D65:emulate overcast daylight illumination
- These are important reference points to transform between color spaces and devices
- Perception of color depends on the choice of the temperature of the ambient light
- Gamut: the set of all colors that can be handled by a certain media device or can be represented by a given color space.



Pt.	Temp.	X	Y	Z	x	y
D50	5000° K	0.964296	1.000000	0.825105	0.3457	0.3585
D65	6500° K	0.950456	1.000000	1.088754	0.3127	0.3290
E	5400° K	1	1	1	1/3	1/3

CIE L*a*b*

- XYZ is not perceptually uniform
- L*a*b* is a similar color space but more uniform
- Green-red, blue-yellow hue axis.

$$\begin{aligned} L^* &= 116 \cdot Y' - 16 \\ a^* &= 500 \cdot (X' - Y') \\ b^* &= 200 \cdot (Y' - Z') \end{aligned}$$

$$X' = f_1\left(\frac{X}{X_{\mathrm{ref}}}\right) \quad Y' = f_1\left(\frac{Y}{Y_{\mathrm{ref}}}\right) \quad Z' = f_1\left(\frac{Z}{Z_{\mathrm{ref}}}\right)$$

$$f_1(c) = \begin{cases} c^{\frac{1}{3}} & \text{for } c > 0.008856 \\ 7.787 \cdot c + \frac{16}{116} & \text{for } c \leq 0.008856 \end{cases}$$

L^* a^* b^*

$$\begin{aligned} \mathrm{ColorDist}_{\mathrm{Lab}}(\mathbf{C}_1, \mathbf{C}_2) &= \|\mathbf{C}_1 - \mathbf{C}_2\| \\ &= \sqrt{(L_1^* - L_2^*)^2 + (a_1^* - a_2^*)^2 + (b_1^* - b_2^*)^2} \end{aligned}$$

Color Models for Printing

- Subtractive color models: CMY and CMYK
- Color printing requires a minimum of three primary colors: traditionally: Cyan, Magenta, and Yello
- White: C=M=Y=0 (no ink)
- Black: C=M=Y=1 (complete subtraction of light)
- CMY from RGB (simplified):

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

CMYK

- In actual printing, CMY is not sufficient, we need a black ink as well. K component
- How to determine the amount of black ink?

$$K = \min(C, M, Y)$$

- The more the black the less the C, M, Y ink should be
- If C=M=Y, we only need black ink
- Different conversions are possible.
- Very complicated task in reality, which depends on the printer used

CMY to CMYK

- Version 1

$$\begin{pmatrix} C' \\ M' \\ Y' \\ K' \end{pmatrix} = \begin{pmatrix} C-K \\ M-K \\ Y-K \\ K \end{pmatrix}$$

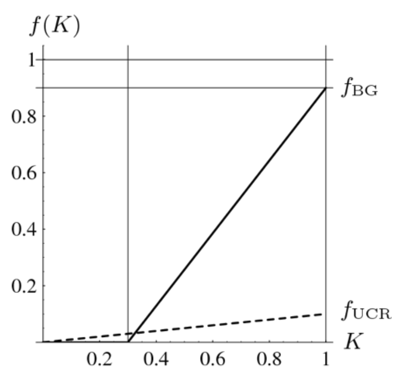
- Version 2

$$\begin{pmatrix} C' \\ M' \\ Y' \end{pmatrix} = \begin{pmatrix} C-K \\ M-K \\ Y-K \end{pmatrix} \cdot \begin{cases} \frac{1}{1-K} & \text{for } K < 1 \\ 1 & \text{otherwise} \end{cases}$$

$$K' = K$$

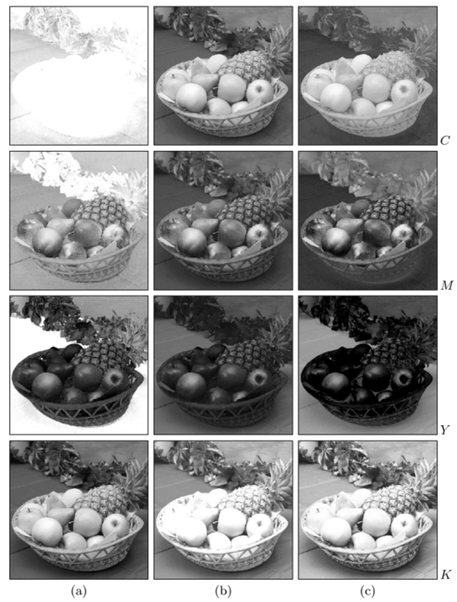
- Version 3

$$\begin{pmatrix} C' \\ M' \\ Y' \\ K' \end{pmatrix} = \begin{pmatrix} C - f_{\mathrm{UCR}}(K) \\ M - f_{\mathrm{UCR}}(K) \\ Y - f_{\mathrm{UCR}}(K) \\ f_{\mathrm{BG}}(K) \end{pmatrix}$$



$$f_{\mathrm{UCR}}(K) = s_K \cdot K$$

$$f_{\mathrm{BG}}(K) = \begin{cases} 0 & \text{for } K < K_0 \\ K_{\max} \cdot \frac{K-K_0}{1-K_0} & \text{for } K \geq K_0 \end{cases}$$


C
M
Y
K
(a)
(b)
(c)