

CS534: Introduction to Computer Vision  
Color in Digital Images

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## Outlines

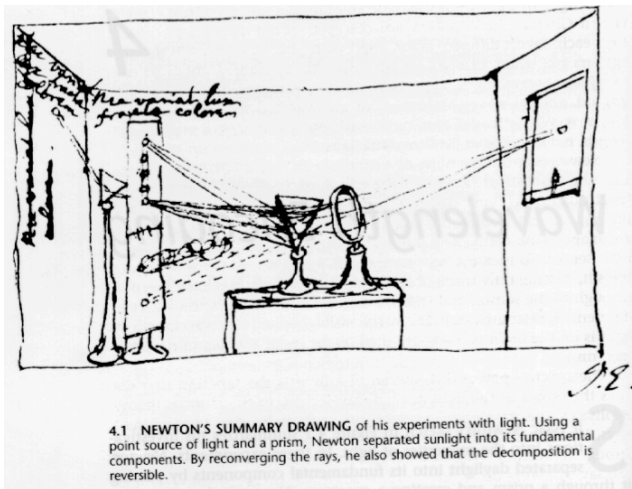
- Color Perception
- RGB color space
- HSV and HLS
- Color Models for TV and Video
- Colorimetric Color Spaces
  
- Sources:
  - Burger and Burge “Digital Image Processing” Chapter 12

## 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



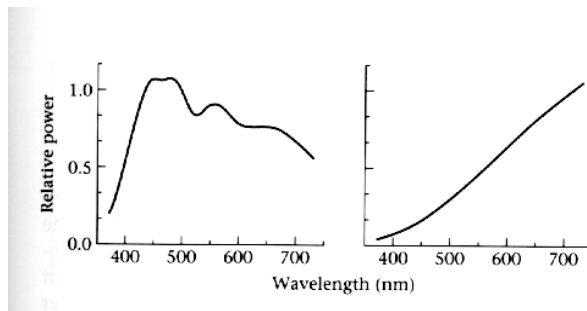
## Complications of color

- 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

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

\* - viewed in isolation

## Complications of color

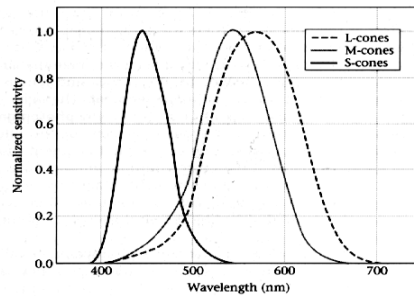


**4.4 THE SPECTRAL POWER DISTRIBUTION** of two important light sources are shown: (left) blue skylight and (right) a tungsten bulb.

## Cones and color – color perception

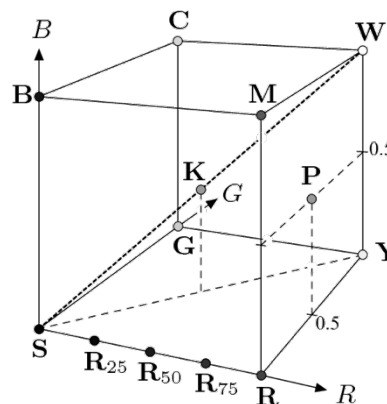
- Three different types of cones
  - they differ in their sensitivity to different wavelengths of light (blue-violet, green, yellow-red)

**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.

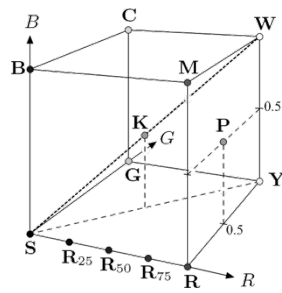


## RGB color images

- 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

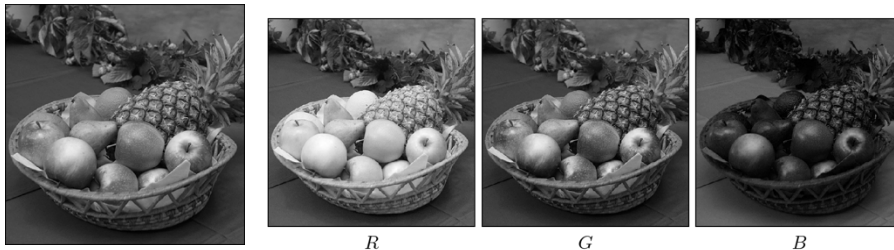


$$C_i = (R_i, G_i, B_i)$$



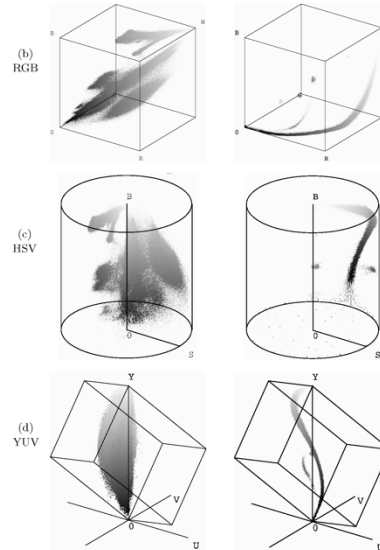
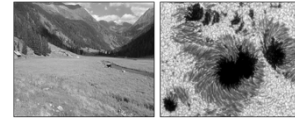
		RGB Value		
Point	Color	R	G	B
<b>S</b>	Black	0.00	0.00	0.00
<b>R</b>	Red	1.00	0.00	0.00
<b>Y</b>	Yellow	1.00	1.00	0.00
<b>G</b>	Green	0.00	1.00	0.00
<b>C</b>	Cyan	0.00	1.00	1.00
<b>B</b>	Blue	0.00	0.00	1.00
<b>M</b>	Magenta	1.00	0.00	1.00
<b>W</b>	White	1.00	1.00	1.00
<b>K</b>	50% Gray	0.50	0.50	0.50
<b>R<sub>75</sub></b>	75% Red	0.75	0.00	0.00
<b>R<sub>50</sub></b>	50% Red	0.50	0.00	0.00
<b>R<sub>25</sub></b>	25% Red	0.25	0.00	0.00
<b>P</b>	Pink	1.00	0.50	0.50

- It is hard to determine the color of a pixel from knowing its 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<sub>b</sub>C<sub>r</sub>
- Color spaces for printing:
  - CMY, CMYK
- Colorimetric Color Spaces:
  - CIE XYZ
  - CIE L\*a\*b\*

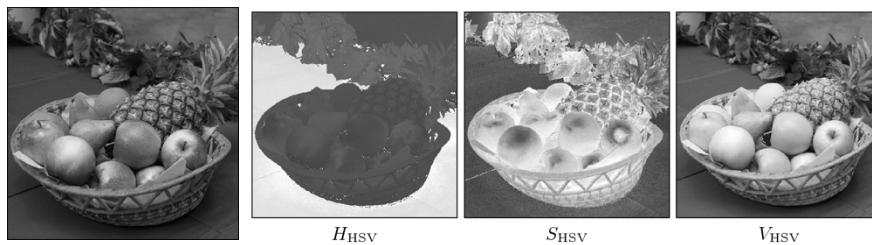
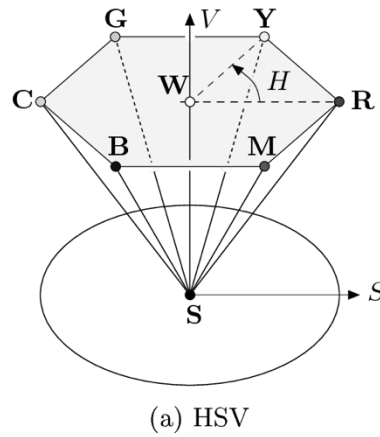


- Three important concepts:
  - Hue
  - Saturation
  - Luminance



## HSV color space

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



## RGB to HSV

- Easier represented as a cylinder.

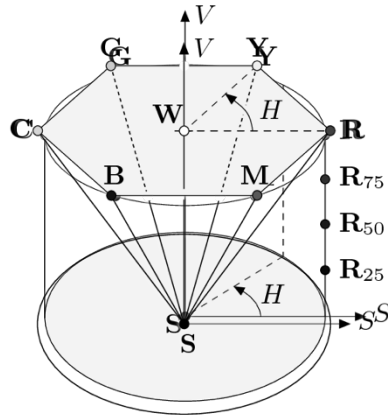
$$C_{\text{high}} = \max(R, G, B), \quad C_{\text{low}} = \min(R, G, B), \\ C_{\text{rng}} = C_{\text{high}} - C_{\text{low}}$$

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

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

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

$$H' = \begin{cases} B' - G' & \text{if } R = C_{\text{high}} \\ R' - B' + 2 & \text{if } G = C_{\text{high}} \\ G' - R' + 4 & \text{if } B = C_{\text{high}} \end{cases}$$



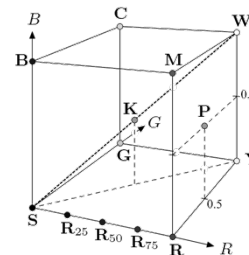
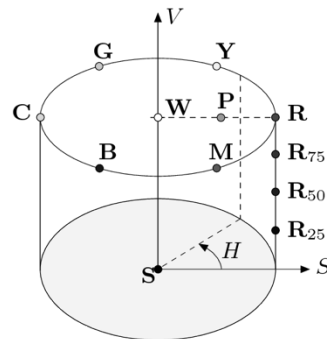
(a) HSV

$$H_{\text{HSV}} = \frac{1}{6} \cdot \begin{cases} (H' + 6) & \text{for } H' < 0 \\ H' & \text{otherwise} \end{cases}$$

## RGB to HSV

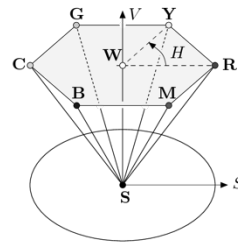
RGB/HSV Values

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

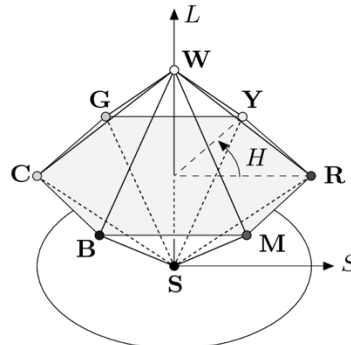


## HLS color space

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



(a) HSV



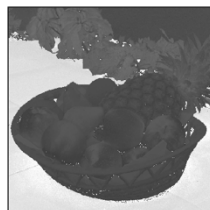
(b) HLS

## RGB to HLS

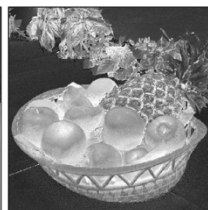
$$H_{\text{HLS}} = H_{\text{HSV}}$$

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

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



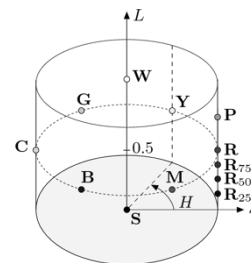
$H_{\text{HLS}}$



$S_{\text{HLS}}$

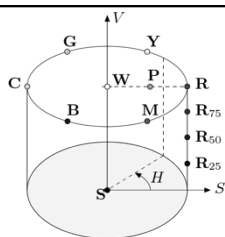
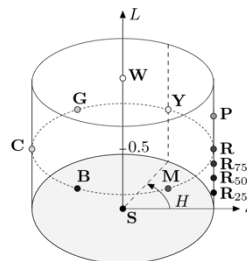


$L_{\text{HLS}}$



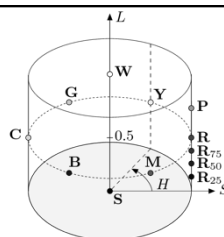
RGB/HLS Values

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



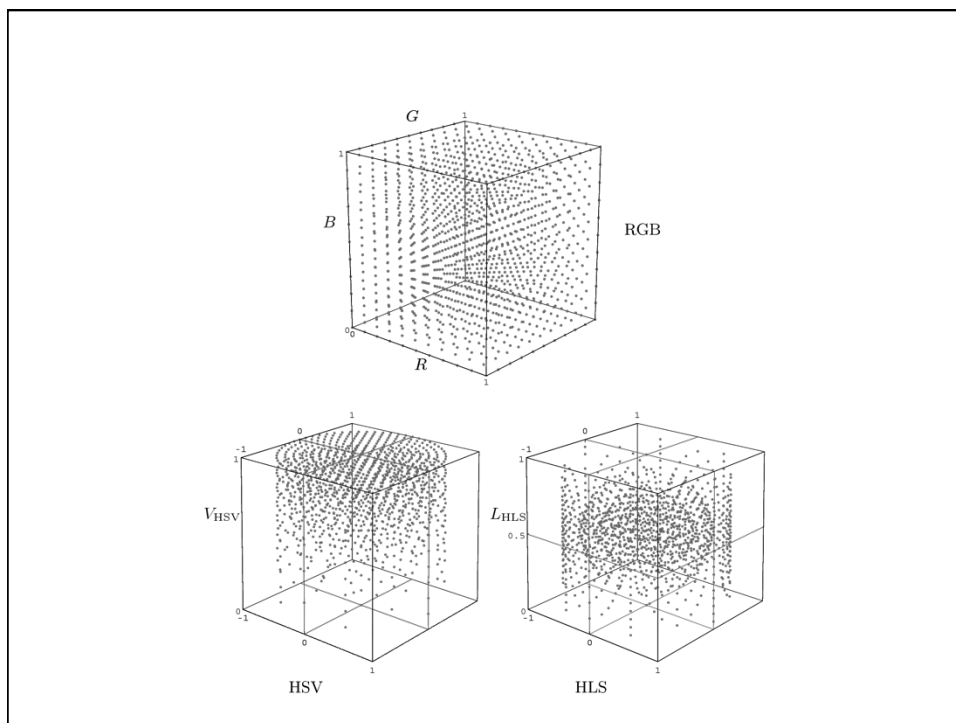
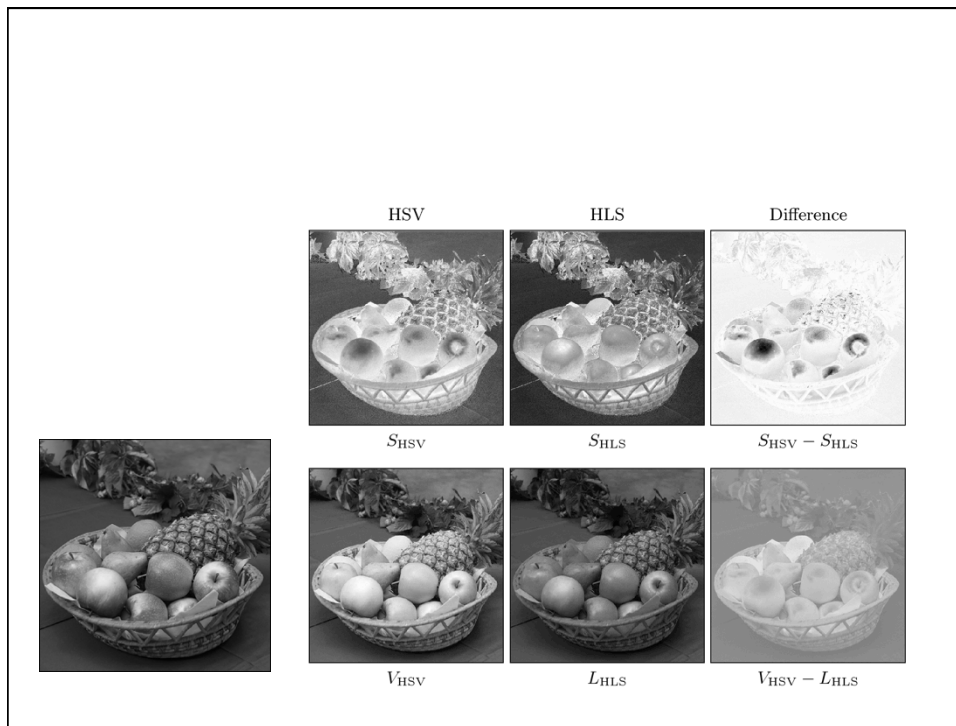
RGB/HSV Values

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



RGB/HLS Values

Pt.	Color	R	G	B	H	S	L
<b>S</b>	Black	0.00	0.00	0.00	—	0.00	0.00
<b>R</b>	Red	1.00	0.00	0.00	0	1.00	0.50
<b>Y</b>	Yellow	1.00	1.00	0.00	1/6	1.00	0.50
<b>G</b>	Green	0.00	1.00	0.00	2/6	1.00	0.50
<b>C</b>	Cyan	0.00	1.00	1.00	3/6	1.00	0.50
<b>B</b>	Blue	0.00	0.00	1.00	4/6	1.00	0.50
<b>M</b>	Magenta	1.00	0.00	1.00	5/6	1.00	0.50
<b>W</b>	White	1.00	1.00	1.00	—	0.00	1.00
<b>R<sub>75</sub></b>	75% Red	0.75	0.00	0.00	0	1.00	0.375
<b>R<sub>50</sub></b>	50% Red	0.50	0.00	0.00	0	1.00	0.250
<b>R<sub>25</sub></b>	25% Red	0.25	0.00	0.00	0	1.00	0.125
<b>P</b>	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:

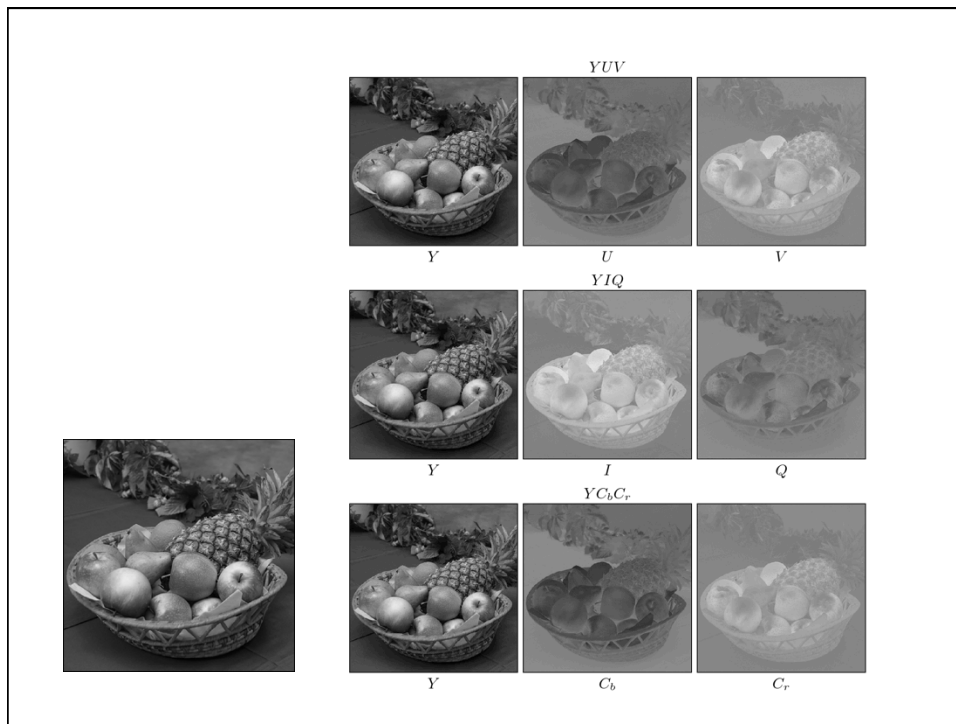
$$Y = 0.299 \cdot R + 0.587 \cdot G + 0.114 \cdot B$$

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

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

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

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



## YIQ and YCbCr

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

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

- YCbCr:  $Y = w_R \cdot R + (1 - w_B - w_R) \cdot G + w_B \cdot B$

$$C_b = \frac{0.5}{1 - w_B} \cdot (B - Y)$$

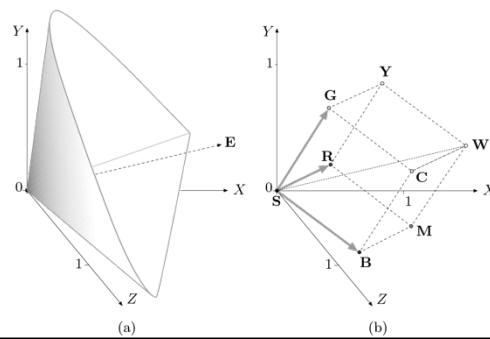
$$C_r = \frac{0.5}{1 - w_R} \cdot (R - Y)$$

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

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

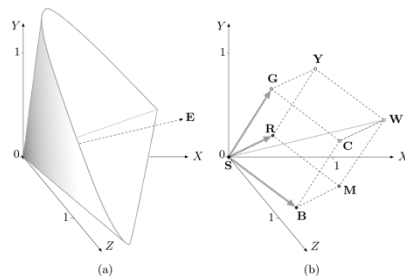
## Colorimetric Color Spaces

- Goal: measure colors independent of devices
- A calibrated device-independent color system
- CIE color spaces: CIE (Commission Internationale d'Eclairage - International Commission on Illumination).
- CIE XYZ, CIE  $x,y$ , CIE  $L^*a^*b^*$

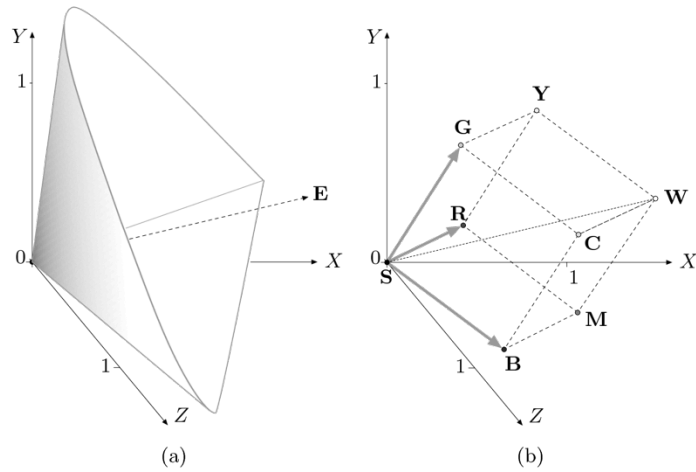


## CIE XYZ

- 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



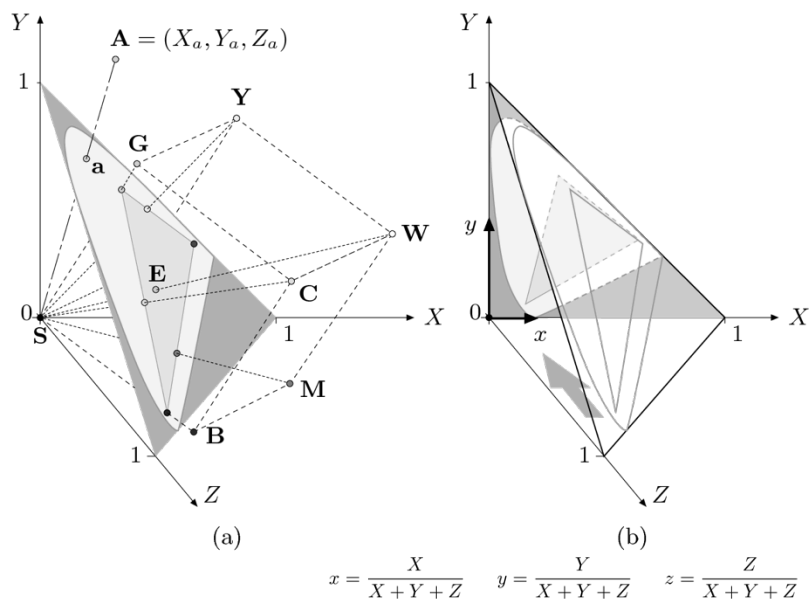
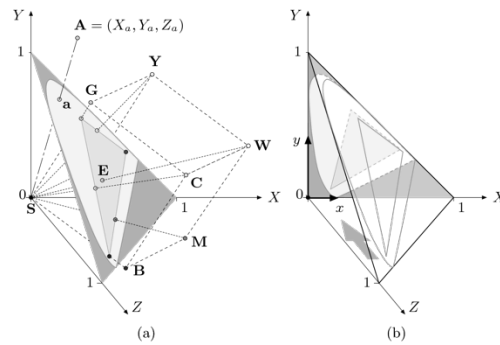
## RGB (linear) to CIE XYZ - a linear transformation

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

## CIE x,y chromaticity

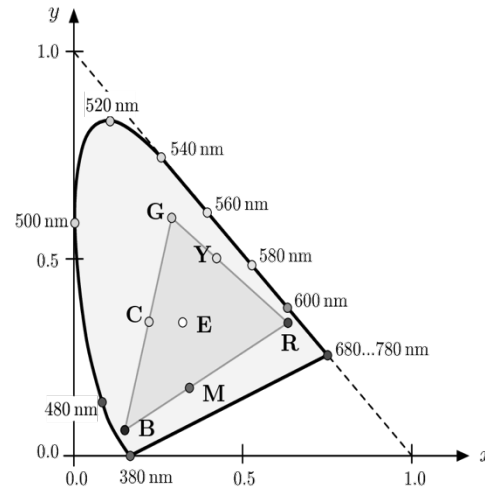
- How to separate the color hue from the luminance
- A central projection (through S) to the plane  $X + Y + Z = 1$ 

$$x = \frac{X}{X+Y+Z} \quad y = \frac{Y}{X+Y+Z} \quad z = \frac{Z}{X+Y+Z}$$
- Then, project to the XY plane (use only the  $x,y$  - drop  $z$ )



## CIE-xy chromaticity diagram

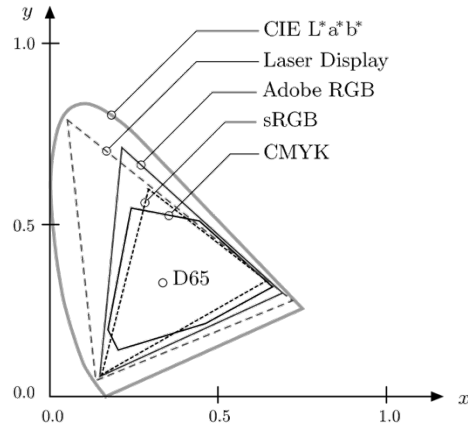
- Horseshoe-shaped
- The outer boundary represents monochromatic (spectrally pure), maximally saturated colors.
- Neutral point (E) where  $x=y=1/3$ , ( $X=Y=Z=1$ )
- Saturation falls off towards E
- Complementary colors?



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

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

- 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

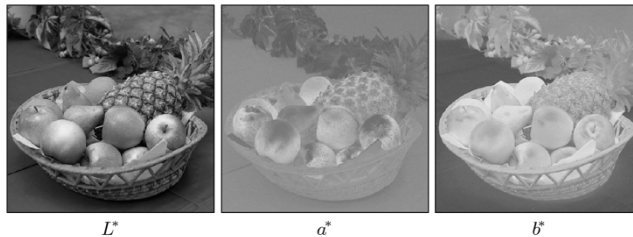
## CIE L\*a\*b\*

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

$$L^* = 116 \cdot Y' - 16 \quad X' = f_1\left(\frac{X}{X_{\text{ref}}}\right) \quad Y' = f_1\left(\frac{Y}{Y_{\text{ref}}}\right) \quad Z' = f_1\left(\frac{Z}{Z_{\text{ref}}}\right)$$

$$a^* = 500 \cdot (X' - Y') \quad f_1(c) = \begin{cases} c^{\frac{1}{3}} & \text{for } c > 0.008856 \\ 7.787 \cdot c + \frac{16}{116} & \text{for } c \leq 0.008856 \end{cases}$$

$$b^* = 200 \cdot (Y' - Z')$$



$$\text{ColorDist}_{\text{Lab}}(\mathbf{C}_1, \mathbf{C}_2) = \|\mathbf{C}_1 - \mathbf{C}_2\|$$

$$= \sqrt{(L_1^* - L_2^*)^2 + (a_1^* - a_2^*)^2 + (b_1^* - b_2^*)^2}$$

## 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):

$$C = 1 - R$$

$$M = 1 - G$$

$$Y = 1 - B$$

## 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

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

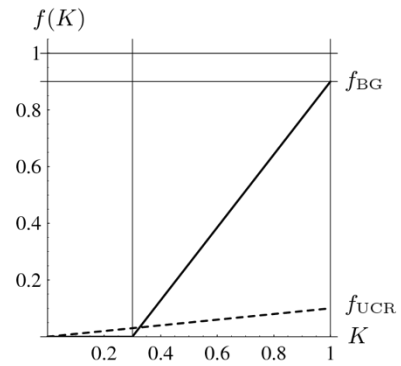
- Version 2

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

$$K' = K$$

- Version 3

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



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

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

