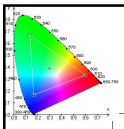

Digital Image Processing (DIP)

ImProc website:
https://my.eurecom.fr/jcms/p0_2027226/en/improc

Introduction to Colorimetry

Nov. 13, 2018

We can confirm **#TheDress** is blue and black!
We should know! http://bit.ly/1arLYRe

#THE DRESS *NOW BACK IN STOCK*

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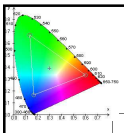

The Internet lost its collective mind Thursday over the color of a dress originally posted by a Tumblr user.

swiked: guys please help me - is this dress white and gold (about 72%), or blue and black? Me and my friends can't agree and …

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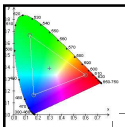


Introduction

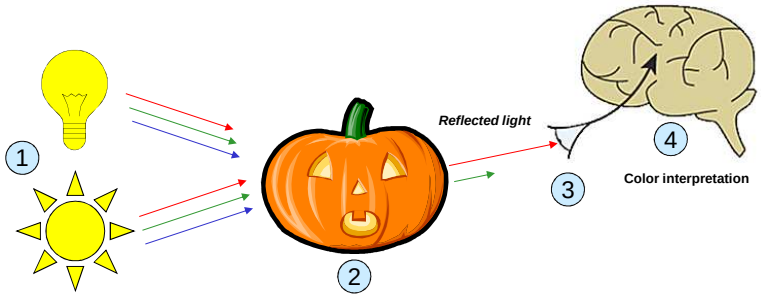
Color perception of an object depends on:

1) Illumination source (ex: sunlight, incandescent bulb, fluorescent bulb, etc.)

2) The characteristic that an object absorbs light from certain wavelengths and reflects light from others

3) Characteristics of the human eyes

4) Human brain → Color interpretation



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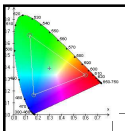
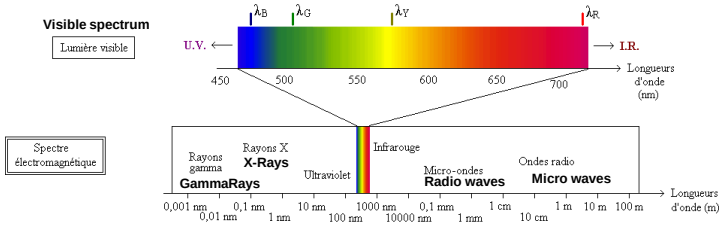


Light

Light is electromagnetic (EM) radiation.

The human eye is only sensitive to EM radiation at wavelengths that range roughly between 780 nanometers and 380 nanometers (less than 1% of the total EM radiation emitted by the sun).

The visible spectrum contains numerous colors that are distinguished by wavelength and amplitude; wavelength determines color and amplitude determines brightness.



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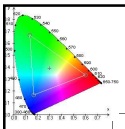
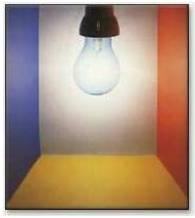


Light sources

Light comes from a variety of sources. Because color depends on the reflection of light from an object, the nature of the light source is of the utmost importance.

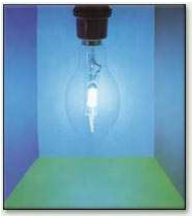
The most common means to produce light are:

- Incandescence (sun, candle, filament light bulb)
- Gas discharge (sodium, mercury, and xenon lamps)
- Photoluminescence (florescent lighting tube)
- Chemical reactions (producing light but no heat)



Daylight bulb

Sodium lamp (low pressure)



Mercury lamp

Sodium lamp (high pressure)

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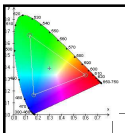
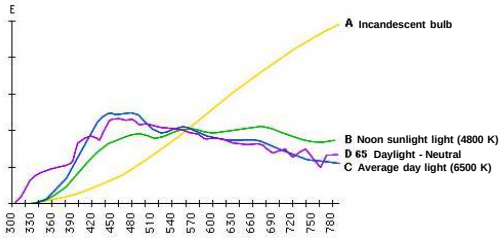
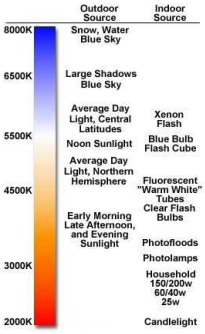


Illuminants

Light sources (physical emitter of radiation), or illuminants (specification for a potential light source), are primarily characterized by their color temperature and spectral power distribution



Color temperature of a light source can be defined as the temperature of a black body in degrees Kelvin having the same color appearance.



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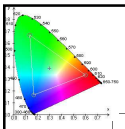
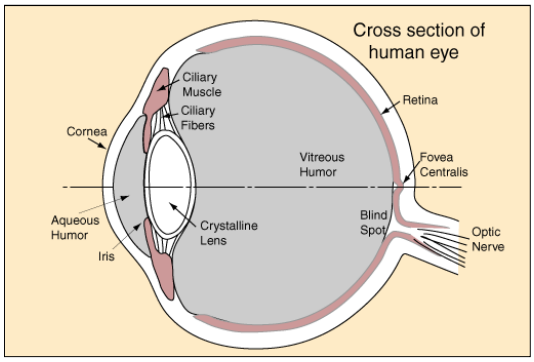


Human eye



Retina: the membrane on the inner wall of the eyeball which receives the image from the lens and converts it into nerve impulses.

Fovea: the center of the retina and the region of highest visual acuity and cone cell density.

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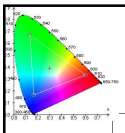
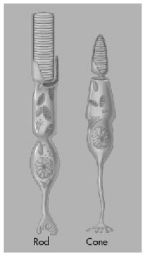
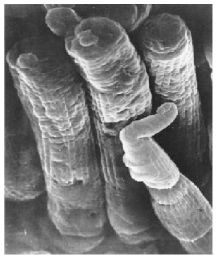


Photosensitive cells

2 photosensitive cell types in retina

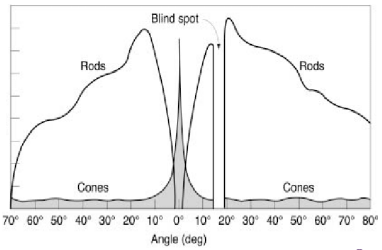
- RODS: sensitive to brightness / luminance (scotopic vision)
  ~ 120 million rods
- CONES: sensitive to color / frequency (photopic vision)
  ~ 5 million cones





Cellular distribution not uniform

- Cones predominate at the fovea
- Rods dominate at periphery of vision



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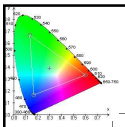
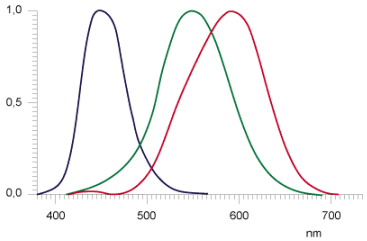


Cone facts

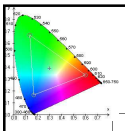
Overall sensitivity peaks in the green

Color vision is provide by 3 types of cone width different colored light absorptions, lossely called red (L) 64%, green (M) 32% and blue cones (S) 4% (no blue cones in the center of the retina)

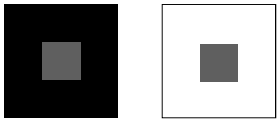
Sensation of whole spectrum of colors provided by exciting differently the 3 cone types



Metamers: different light spectrum that produce the same color perception.



Color illusions



Lightness contrast

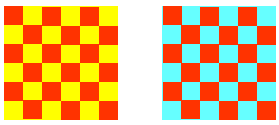
If the surrounding color is darker, the central square appears lighter; if the surrounding color is lighter, the central square appears darker.

Saturation contrast

The central square appears bright and strong against the gray; it looks dust against saturated colors.

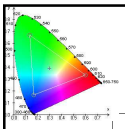
Hue contrast

The central square appears blue on the left because the surrounding color is green; and green on the right because the surrounding color is blue.



Complementary contrast

The red checker appears brighter on the right (on the cyan, its complementary color), that on the left.



Color blindness

Normal vision

Pronatope (L-Cone def.)

Deuteratope (M-Cone def.)

Tritanope (S-Cone def.)

Classification	Incidence (%)	
	Males	Females
Anomalous Trichromacy	**6.3**	**0.37**
Protanomaly (L-cone defect)	1.3	0.02
Deuteranomaly (M-cone defect)	5.0	0.35
Tritanomaly (S-cone defect)	0.0001	0.0001
Dichromacy	**2.4**	**0.03**
Protanopia (L-cone absent)	1.3	0.02
Deuteranopia (M-cone absent)	1.2	0.01
Tritanopia (S-cone absent)	0.001	0.03
Rod Monochromacy (no cones)	**0.00001**	**0.00001**

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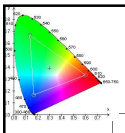
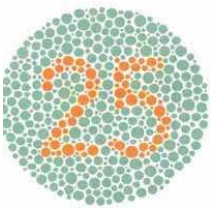
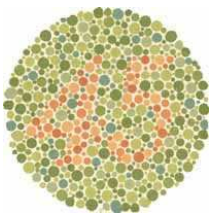


Ishihara test for color blindness



25



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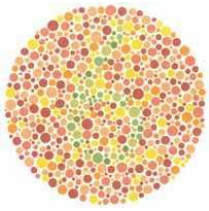

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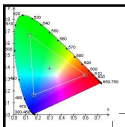
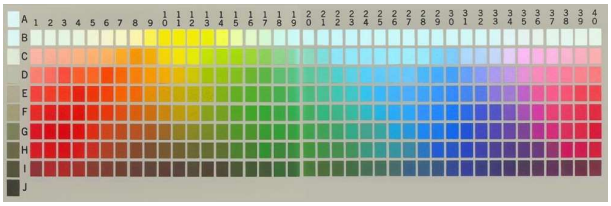


Color naming

- **Color Naming**: attaching labels to color. Perceptual categories are constructed through language
- Name the following colors:



- 11 **culture colors** (Berlin & Kay,1969) : black, white, red, green , yellow, blue, brown, purple, pink, orange, gray

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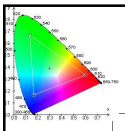


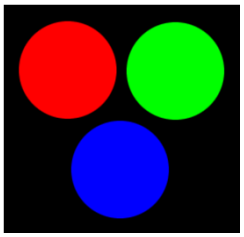
Additive color mixing

Primary colors: red, green, and blue

Secondary colors: yellow, cyan, magenta

Starting with a black background and adding lights to create color (other colors can be created by varying the intensities of red, blue, and green).

Used in television, cameras, computer graphics, etc.



Grassman's laws:

- Law 1: Any color C can be matched by a linear combination of three other colors (*e.g.* primary colors)

$$C = r_c(\mathbf{R}) + g_c(\mathbf{G}) + b_c(\mathbf{B})$$

- Law 2: A mixture of two colors (C_1 and C_2) can be matched by linearly adding theirs components

$$C_3 = C_1 + C_2 = [r_1+r_2](\mathbf{R}) + [g_1+g_2](\mathbf{G}) + [b_1+b_2](\mathbf{B})$$

- Law 3: Proportionality

$$k.C = k.r_c(\mathbf{R}) + k.g_c(\mathbf{G}) + k.b_c(\mathbf{B})$$

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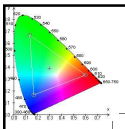


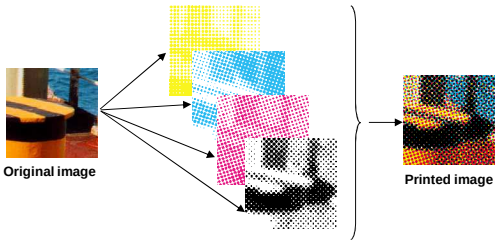
Subtractive color mixing

Primary colors: yellow, cyan, magenta

Secondary colors: red, green, and blue

Starting with white and subtracting cyan, magenta, and yellow pigments to create black.

Used in printing and photography.
Printers often include the fourth component, black ink, to improve the color gamut (by increasing the density range), improving blacks and saving money



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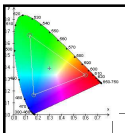
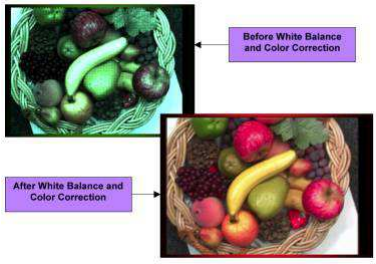


White Balance, Bayer Interpolation

A white object will have equal value of reflectivity for each primary color, i.e. R = G = B



$G'=R'a=bB'$

Source: www.siliconimaging.com

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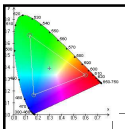
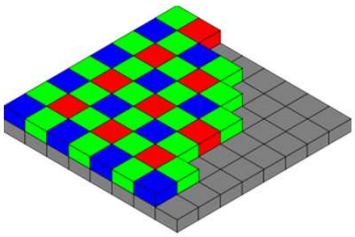


White Balance, Bayer Interpolation

Its particular arrangement of color filters is used in most single-chip digital image sensors used in digital cameras, camcorders, and scanners to create a color image.



R and B values are interpolated from the (2 or 4) nearest neighbors of the same color.

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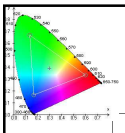

Color models

Color models are used to classify colors and to qualify them according to such attributes as hue, saturation, chroma, lightness, or brightness.

There are three manners to classify the colors:

- According to a visual approach: Munsell, Chevreul, Ostwald
- According to a physical approach: **RGB**, HSV, CIE XYZ, etc.
- According to a physical and psychometrical approach: CIE Lab, CIE Luv, etc.

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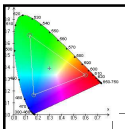
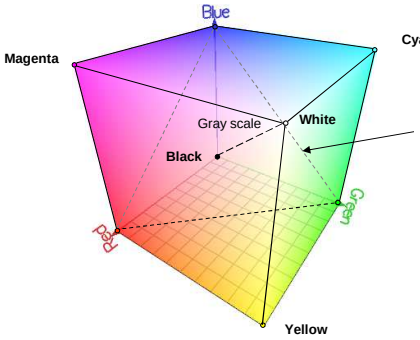
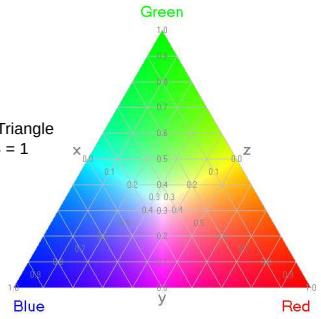


RGB color model

RGB color space can be represented as a cube:



Maxwell's Triangle
R+G+B = 1



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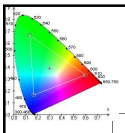

Problems with RGB

Only a small range of potential perceivable colors.

It is not easy to determine how much of R, G and B to use to make a give color.

RGB = (? , ? , ?)

Perceptually non-linear:

- Two points a certain distance apart in one part of the space may be perceptually different.
- Two other points, the same distance apart in another part of the space, may be perceptually the same.

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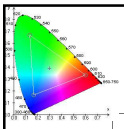

Colormaking attributes

Color scientists around the middle of the 19th century had discovered that three colormaking attributes, hue, lightness and chroma, provide the best description of conscious color judgments.

Hue corresponds to the common definition of colour, e.g. "red", "orange", "violet" etc.

Lightness or value is determined by the total quantity of light reaching the eye. It is the perceptual response (nonlinear) to luminance.

Chroma or saturation is the intensity or purity of hue. An intense or highly chromatic color looks very luminous, while a color with low chroma looks dull.

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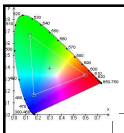

Munsell color system (1/2)

Henry Munsell, an artist, wanted to create a "rational way to describe color" that would use decimal notation instead of color names.

Munsell modeled his system as an orb around whose equator runs a band of colors:

- The central column represents the color **value** (dark to light from bottom to top, represented by the notation 1/ to 9/).
- Each arm radiating out from the central column represents the color **hue** (five basic colors: red (R), yellow (Y), green (G), blue (B), and purple (P), with a second dimension between each color).
- Along each arm from the central column to its outer limit, the intensity of color saturation is expressed as the color **chroma** (dull to bright, represented by the notation /1 to /26).

  NB: chroma is not uniform for every hue at every value.

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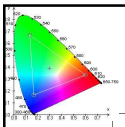
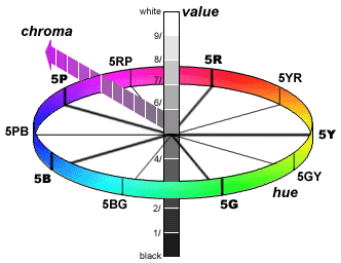
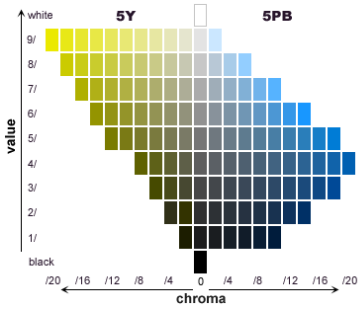


Munsell color system (2/2)



Munsell color wheel



Sample pages of Munsell's book

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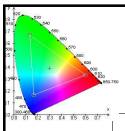


HSV / HLS color models

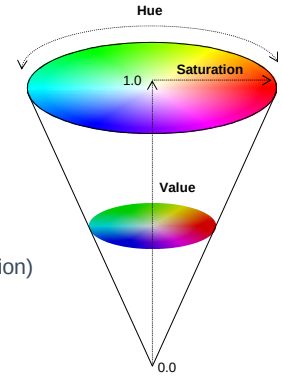
HSV: Hue, Saturation, Value

Transformation of RGB space that can describe colors in terms more natural to an artist.

HLS: Hue, Lightness, Saturation

Analogous to HSV (double cone representation)

Value ≠ Lightness
(equal to the square root of the luminance).



HSV color space

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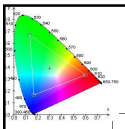
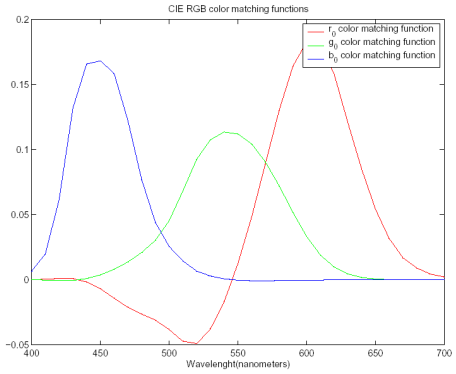


RBG color model

Color expressed in RGB color space is a mixture of 3 primary colors: red, green and blue.

RGB color matching functions r_0, g_0, b_0



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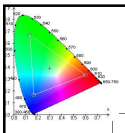
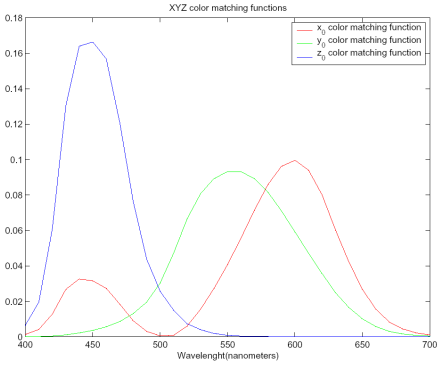


CIE XYZ color model

Defined in 1931 by the CIE (Commission International de l'Eclairage) to describe the full space of perceptible colors

Defined X, Y, and Z primaries (hypothetical lights) to replace red, green and blue primaries



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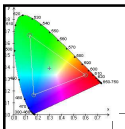

XYZ RGB

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

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

Many points in XYZ do not correspond to visible colors.
XYZ is more standardized
XYZ can reproduce all colors with positive values
XYZ is not realizable physically

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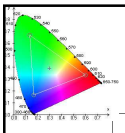
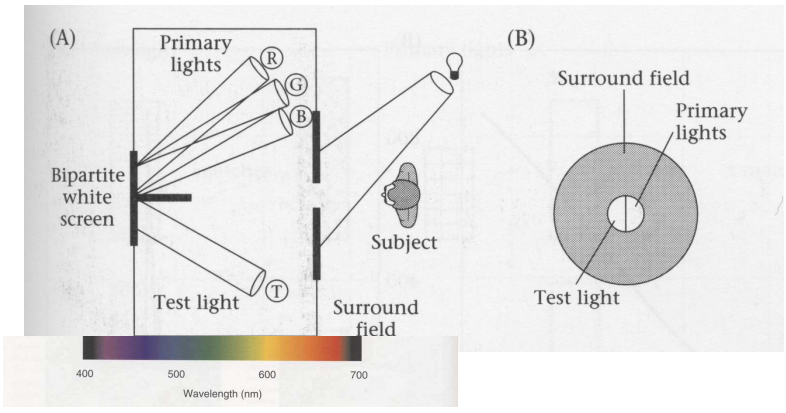


Color Matching



Some colors cannot be produced using only positively weighted primaries
Solution: add light on the other side!

$$C = r_c(\mathbf{R}) + g_c(\mathbf{G}) + b_c(\mathbf{B})$$

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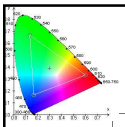
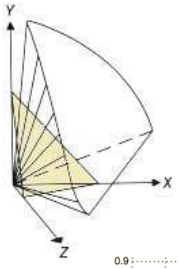
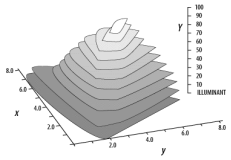


CIE chromaticity diagram (1931)

CIE xyY color space

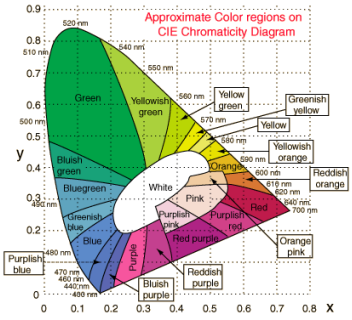
$$\begin{cases} x = \dfrac{X}{X+Y+Z} \\ y = \dfrac{Y}{X+Y+Z} \\ z = \dfrac{Z}{X+Y+Z} \end{cases} \qquad x+y+z$$





x, y: chromaticity coordinates

Y: brightness



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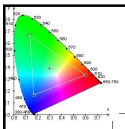
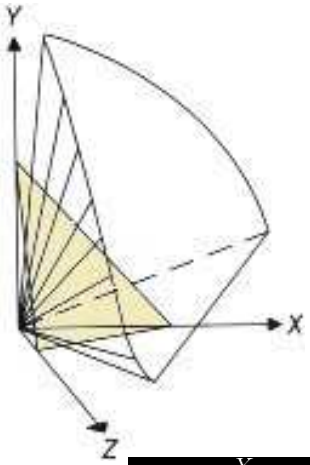
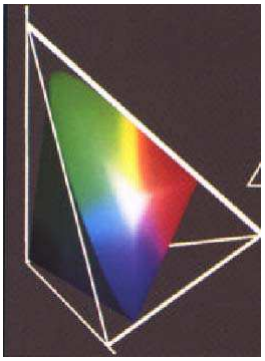
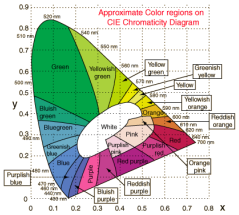


CIE XYZ







xyY

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

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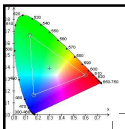
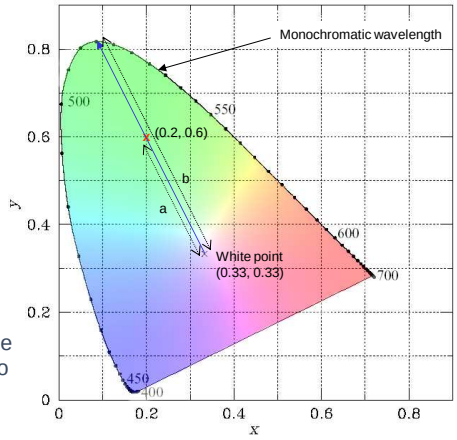


Dominant wavelength

- White point at (0.33, 0.33)
- $(x, y) = (0.2, 0.6)$
- Draw line from white point through point
- Extend it to boundary

  ⇨ $\lambda_D = 512\text{nm}$
- Purity (saturation): percentage of distance from white point to edge

  ⇨ purity = a/b ≈ 55%



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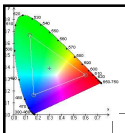
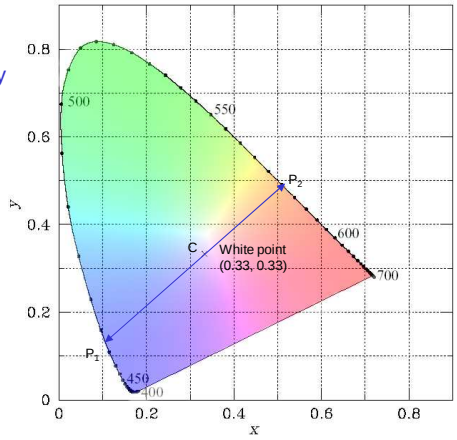


Complementary wavelength

- White point at (0.33, 0.33)
- P_1 and P_2 are complementary
- Line passes through white point
- The colors on segment CP_1 are complementary to the colors on segment CP_2



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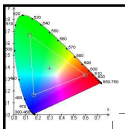


Additive color mixing

Two color mixing:

$$P = \alpha P_1 + \beta P_2$$

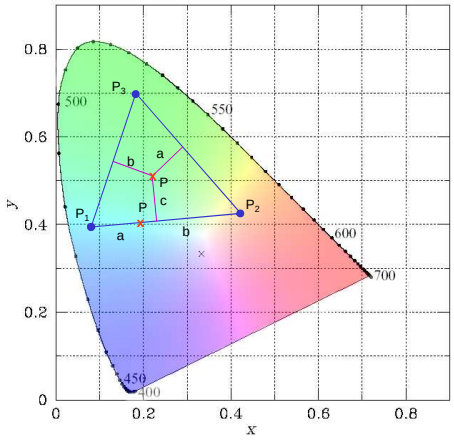
$$\alpha = \frac{a}{a+b}, \quad \beta = \frac{b}{a+b}$$

Three color mixing:

$$P = \alpha P_1 + \beta P_2 + \gamma P_3$$

$$\alpha = \frac{a}{a+b+c}, \quad \beta = \frac{b}{a+b+c}$$

$$\gamma = \frac{c}{a+b+c}$$



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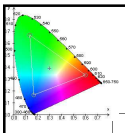
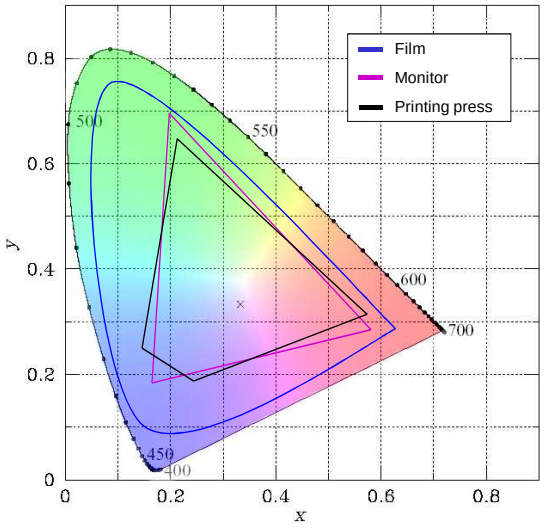


Examples of color gamuts



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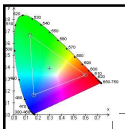
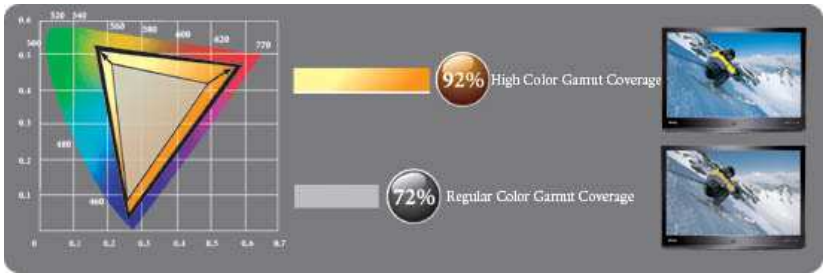


Gamut Coverage



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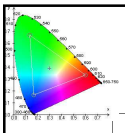


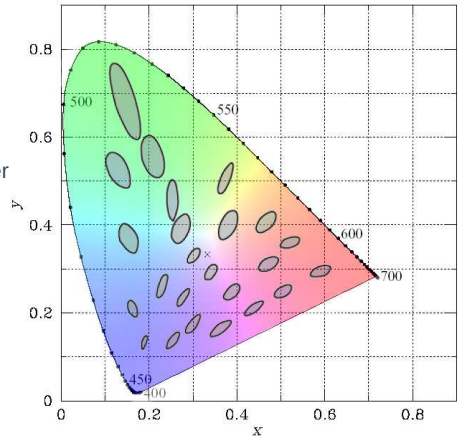
Mac Adam's ellipses

Ellipse = minimum perceivable color differences.

Color lying just outside the ellipse is just noticeably different (JND) from the center of the ellipse.

The scales of the chromaticity diagram are not uniform.

CIE 1976 uniform chromaticity scale (UCS) diagram



The ellipses are plotted 10 times their actual size

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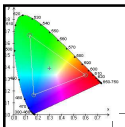


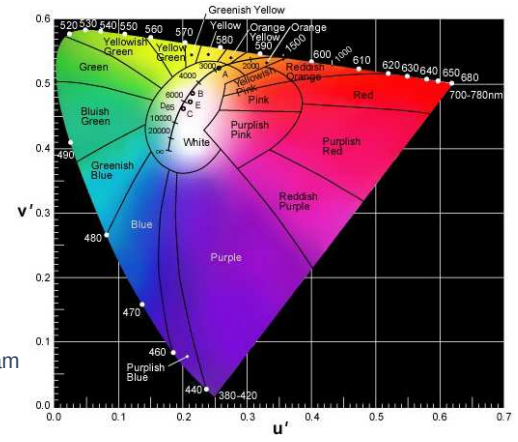
CIE 1976 USC diagram

The chromaticity coordinates (u', v') are given by:

$$u' = \frac{4X}{X+15Y+3Z}$$

$$v' = \frac{9Y}{X+15Y+3Z}$$

The 1976 chromaticity diagram is more uniform than the (x, y) diagram.



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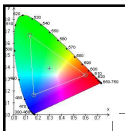
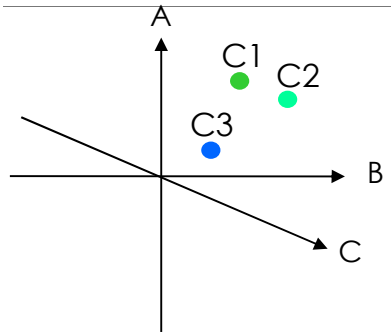


Perceptual uniform color model



Perceptual distance

Measuring the perceptual similarity among colors: C1 is more similar to C2 than to C3

Measurable distance

Measuring the metric distance in the color space: i.e. Euclidean distance

- Does the perceptual distance match with the measurable distance among colors?

  d(C1C2)<d(C1,C3)?

- Color models whose metric is representative of the perceptual distance are perceptually uniform

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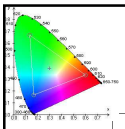
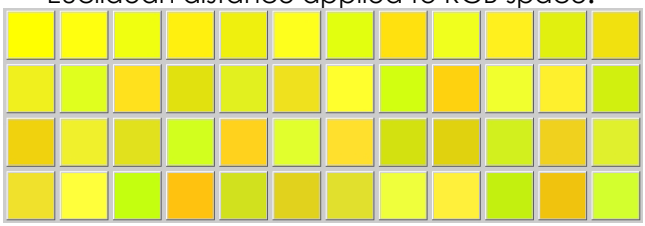
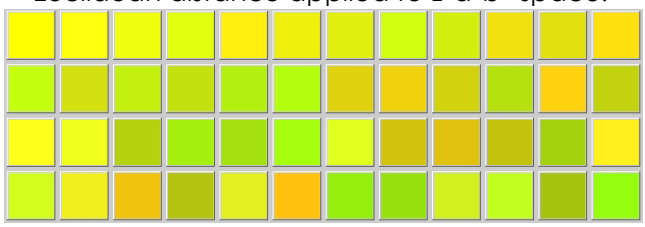


Non perceptually uniform color models

Euclidean distance applied to RGB space.



Euclidean distance applied to L*a*b* space.



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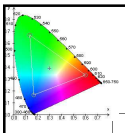
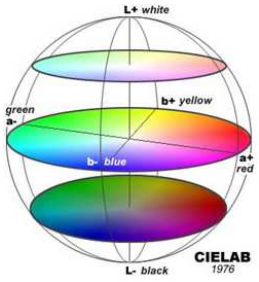


Lab color space



CIE Lab was introduced un 1976

- L^* is luminosity
- a^* is red/green axis
- b^* is yellow/blue axis

Mathematically described space and a perceptually uniform color space.

Given white = (X_n, Y_n, Z_n)

$L^* = 116\,(Y/Y_n)^{1/3} - 16$ when $Y/Y_n > 0.008856$
$L^* = 903.292\,(Y/Y_n)$ when $Y/Y_n \leq 0.008856$
$a^* = 500\,(f(X/X_n) - f(Z/Z_n))$
$b^* = 200\,(f(X/X_n) - f(Z/Z_n))$

where $f(t) = t^{1/3}$ when $Y/Y_n > 0.008856$
else $f(t) = 7.87t + 16/116$

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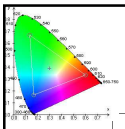

YIQ color model

Used by US commercial color TV broadcasting (used by NTSC standard).

Y: encodes luminance
I, Q: encode color (chromaticity)

For black and white TV, only the Y channel is used (we do not need to broadcast separate signals for B/W TV).

People are more sensitive to the illuminance difference, so we can use more bits (bandwidth) to encode Y and less bits to encode I and Q.

$$\begin{pmatrix} Y \\ I \\ Q \end{pmatrix} = \begin{pmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.273 & -0.322 \\ 0.212 & -0.522 & 0.315 \end{pmatrix} \cdot \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

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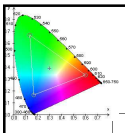

YCrCb color model (or YUV)

Initially, for PAL analog video, it is now also used in CCIR 601 standard for digital video.

Y = 0.299R + 0.587G + 0.114B
Cr = R - Y
Cb = B - Y

Scaled and filtered versions of the B-Y and R-Y color difference signals are used to modulate the PAL subcarrier in the U and V axes respectively.

U = 0.492 (B - Y)
V = 0.877 (R - Y)

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

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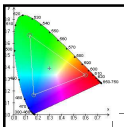

True color image

24 bits color image

Red channel

Green channel

Blue channel

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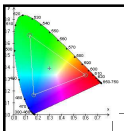
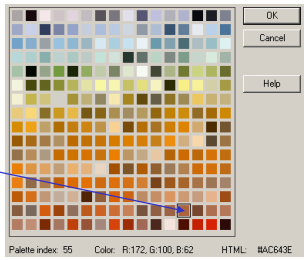


Look-up table

8 bits color image

Pixel value
= index



Color map / Look-up table

Each pixel value is an index to the look-up table (or color map).

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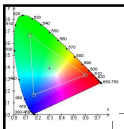

Color FAQ - Frequently Asked Questions Color

Applets of interest

The Chromaticity Diagram and Gamut Applet

The Color Spaces Conversion Applet

The Color Matching Game Applet

Main page: Color spaces: http://www.cs.rit.edu/~ncs/color/

Color blindness:

you can test your color vision on-line.

How does the world look to someone who is color deficient. (Why are you colorblind)

http://vischeck.com/runVischeck.php3 (simulateur)