

Light and Color



Painting by Cheryl Yaney

Topics

Physics

- Spectrum
- Sources, filters, sensors

Perception

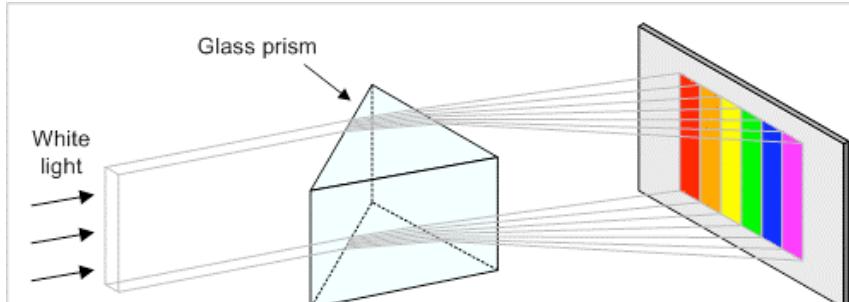
- Trichromatic theory
- Opponent theory
- Luminance and lightness

Art

- Color terms

Physics

Light



Newton's experiment for splitting white light into a spectrum

Image from Clive Maxfield

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Electromagnetic Spectrum

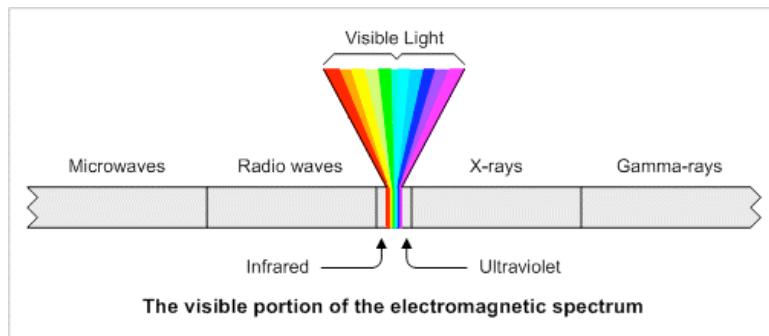


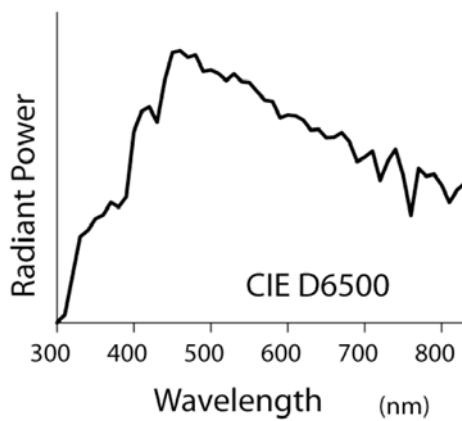
Image from Clive Maxfield

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Sources

Visible spectra power distribution

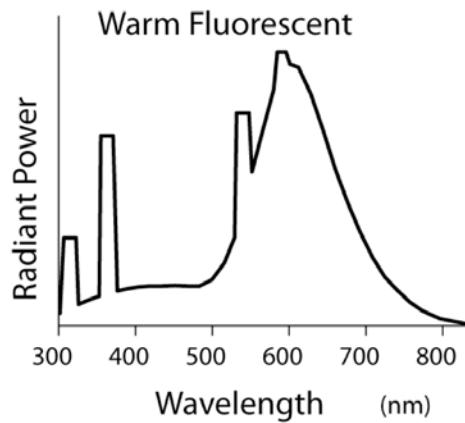


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Sources

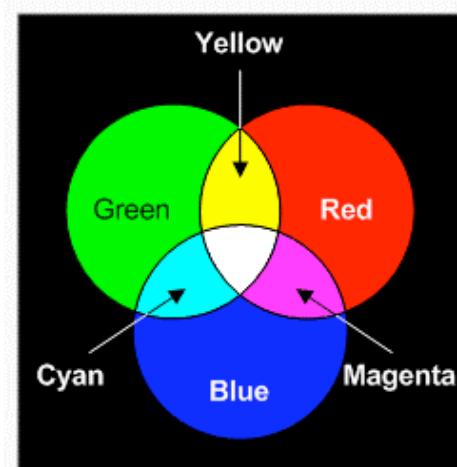
Visible spectra power distribution



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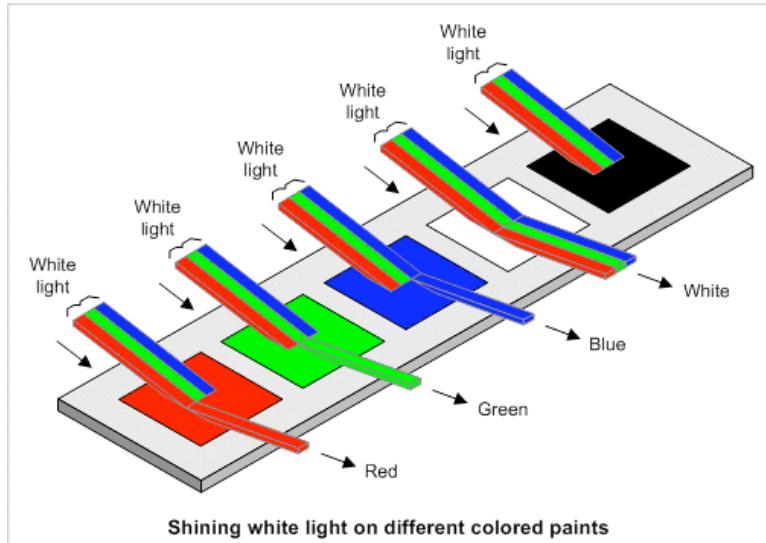
Adding Light



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Reflecting Light



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Light Operations

Add spectra

$$L(\lambda) = S_1(\lambda) + S_2(\lambda)$$

Multiply spectra (reflection and transmission)

$$L(\lambda) = T(\lambda)S(\lambda)$$

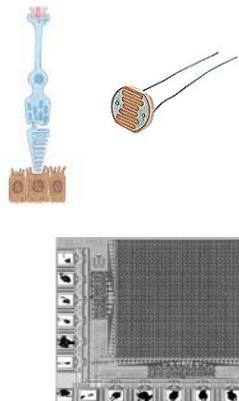
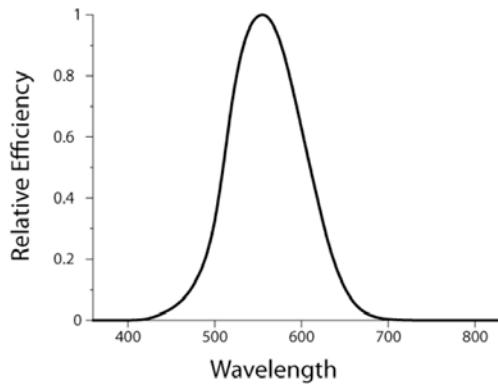
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Photon Detector

Measuring light

$$R = \int R(\lambda)L(\lambda) d\lambda$$



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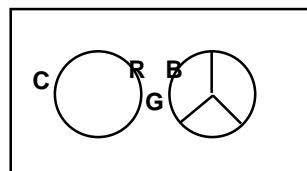
Perception

Color Matching

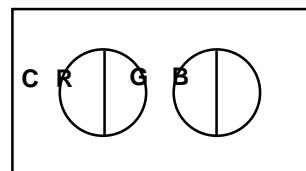
Adjust brightness of 3 primaries to “match” color

C - color to be matched

Lasers: R=700 nm, G=546 nm, B=435 nm



$$C = R + G + B$$



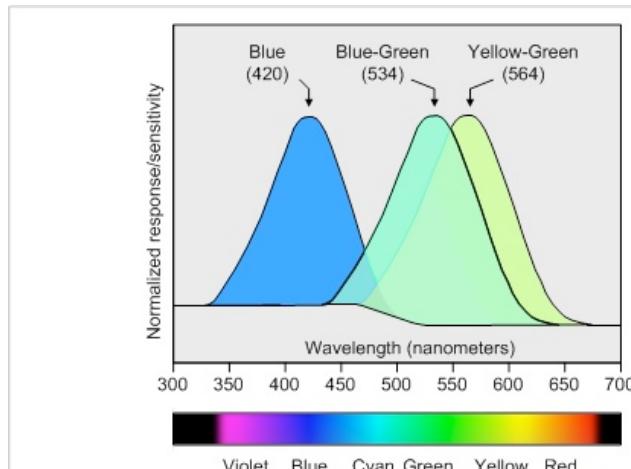
$$C + R = G + B$$

Therefore: humans have trichromatic color vision

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Three Cones/Pigments



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Cone Response

■ Three cones

$$\text{L (long)} \quad L = \int L(\lambda)E(\lambda) d\lambda$$

$$\text{M (medium)} \quad M = \int M(\lambda)E(\lambda) d\lambda$$

$$\text{S (short)} \quad S = \int S(\lambda)E(\lambda) d\lambda$$

■ Metamerism - Different spectra; same response

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Color Blindness

Dichromacy - missing pigment (genetic)

- Protanopia - missing L
- Deutanopia - missing M (red-green)
- Tritanopia - missing S



Normal



Deutanopia



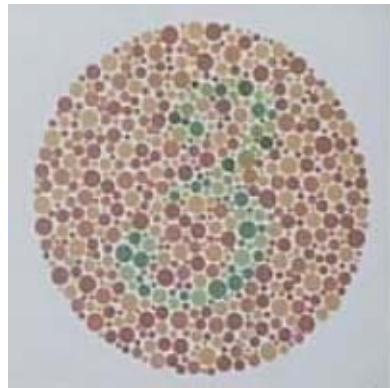
Tritanopia

www.vischeck.com

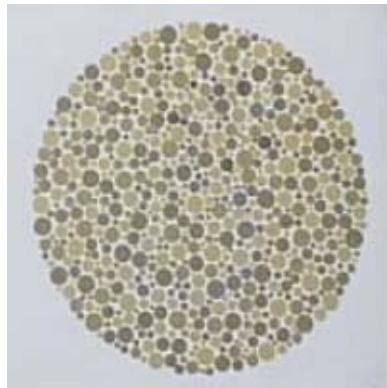
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Ishihara Test



Normal



Deutanopia

<http://www.toledo-bend.com/colorblind/Ishihara.html>

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Grassman's Laws

Color matching is linear!

- Scaling the color and the primaries by the same factor preserves the match**

$$2(C) = 2(R) + 2(G) + 2(B)$$

- To match a color formed by adding two colors, add the primaries for each color**

$$(C_1) + (C_2) = (R_1) + (R_2) + (G_1) + (G_2) + (B_1) + (B_2)$$

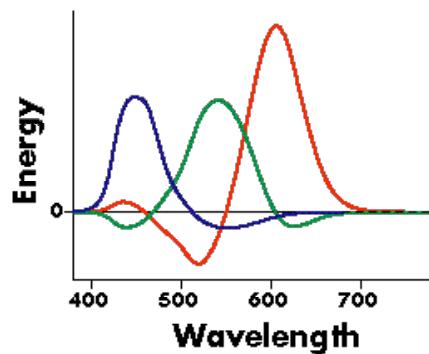
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Spectral Matching Functions

Spectral matching curves

Match each pure color in the visible spectrum (rainbow), and record the color coordinates as a function of wavelength



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Absolute Color Space

- Spectral locus
- Region inside locus
= All possible colors
= Human gamut

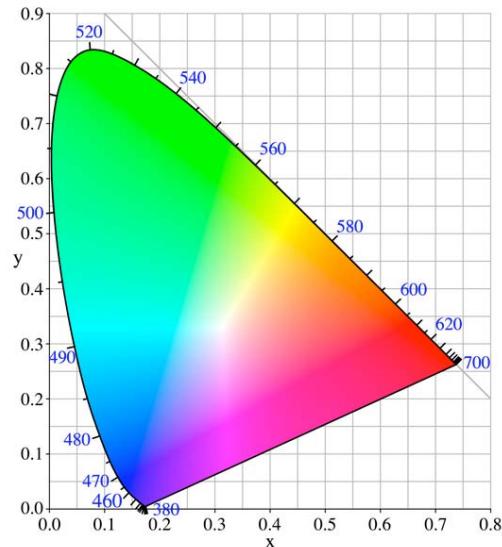
- CIEXYZ color space

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 2.77 & 1.75 & 1.13 \\ 1.00 & 4.59 & 0.06 \\ 0.00 & 0.57 & 5.59 \end{bmatrix} \begin{bmatrix} R_\lambda \\ G_\lambda \\ B_\lambda \end{bmatrix}$$

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CIE Chromaticity Coordinates



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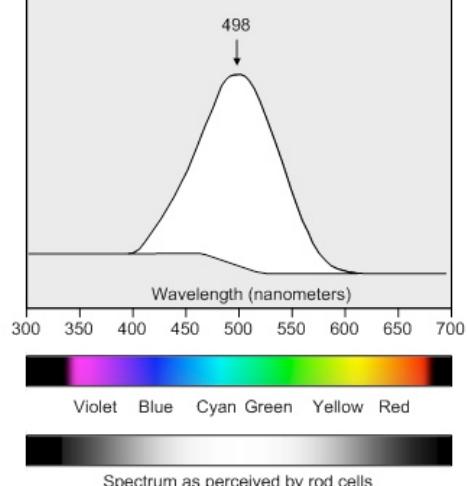
$$x = X/(X+Y+Z)$$

$$y = Y/(X+Y+Z)$$

$$z = Z/(X+Y+Z)$$

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Rod

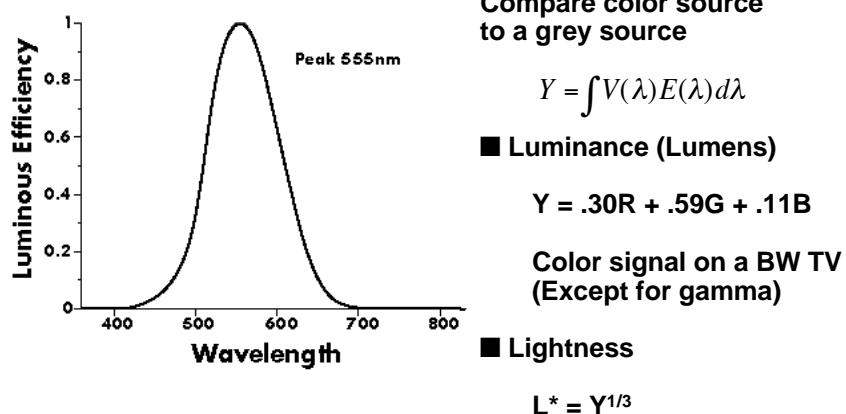


Humans also have rod cells (black, white, shades of gray)

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Luminance and Lightness



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Light Measurement

Radiometry

- Units: Watts = Joules/Second

Photometry

- Units: Lumens

Colorimetry

- CIEXYZ

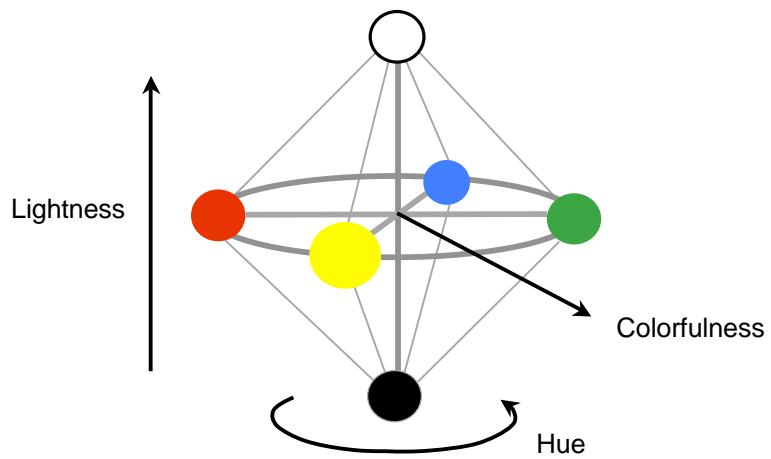
- CIELAB

- ...

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Perceptual Organization



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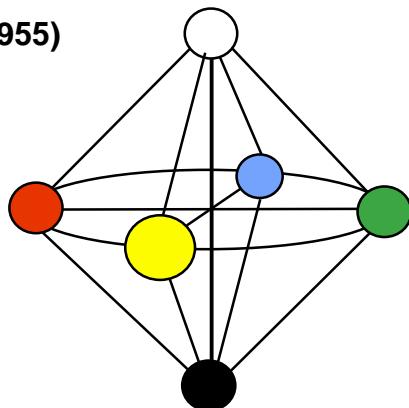
Opponent Color

History

- Herring (1878)
- Jameson & Hurvich (1955)

Experiments

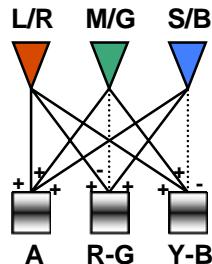
- No Rish-G or Bish-Y
- Color afterimages



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Early Visual Processing



$$A = R + G + B$$

$$(Y - B) = R + G - B$$

$$(R - G) = R - G$$

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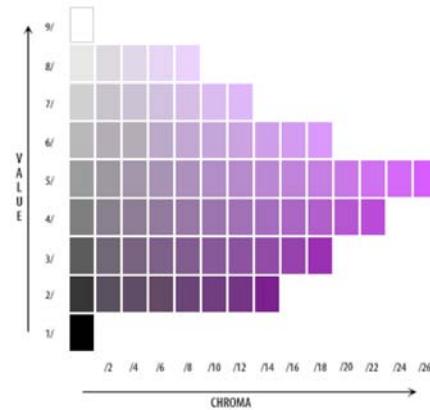
Munsell Color Space

■ Book of painted chips

■ Perceptually uniform



Hue



Chroma vs. Value

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CIELAB

$$L^* = 116 \left[\left(\frac{Y}{Y_n} \right)^{1/3} - \frac{16}{116} \right]$$

$$a^* = 500 \left[\left(\frac{X}{X_n} \right)^{1/3} - \left(\frac{Y}{Y_n} \right)^{1/3} \right]$$

$$b^* = 200 \left[\left(\frac{Y}{Y_n} \right)^{1/3} - \left(\frac{Z}{Z_n} \right)^{1/3} \right]$$

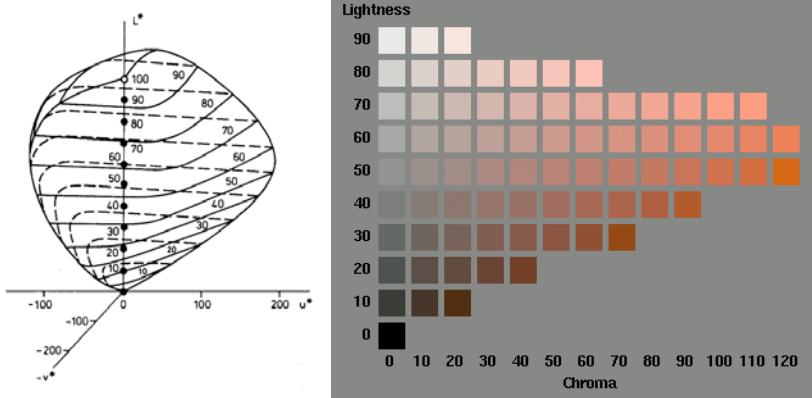
X_n, Y_n, Z_n are the tristimulus values of the reference white.

Color “distance”: $\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2}$

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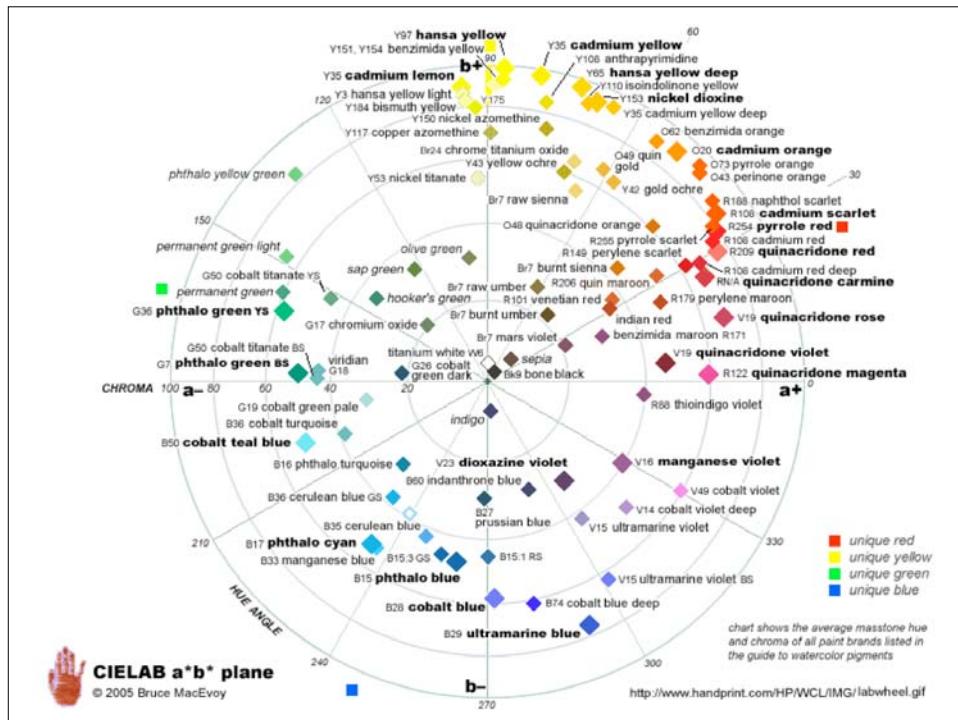
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CIELAB



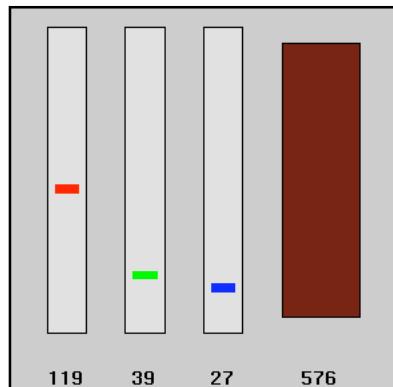
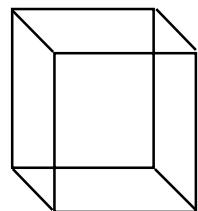
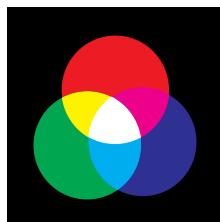
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Art

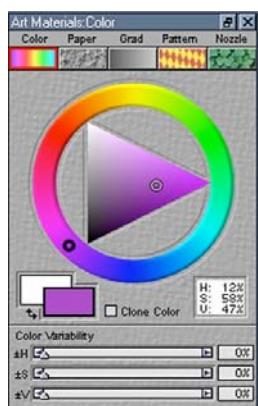
Color Cube



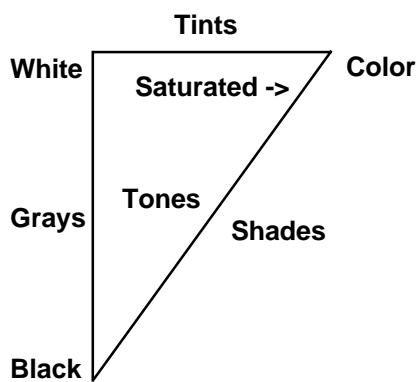
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Intuitive Color Spaces



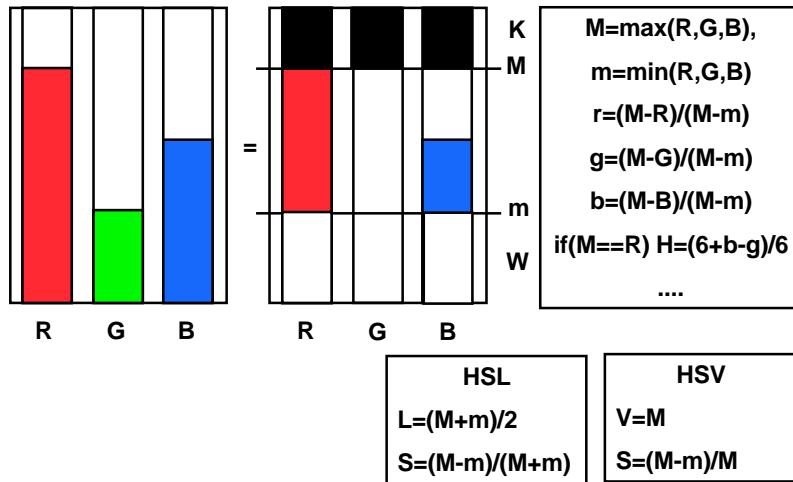
MetaDesign Color Picker



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HSV and HSL



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