COLOR APPEARANCE MODELS

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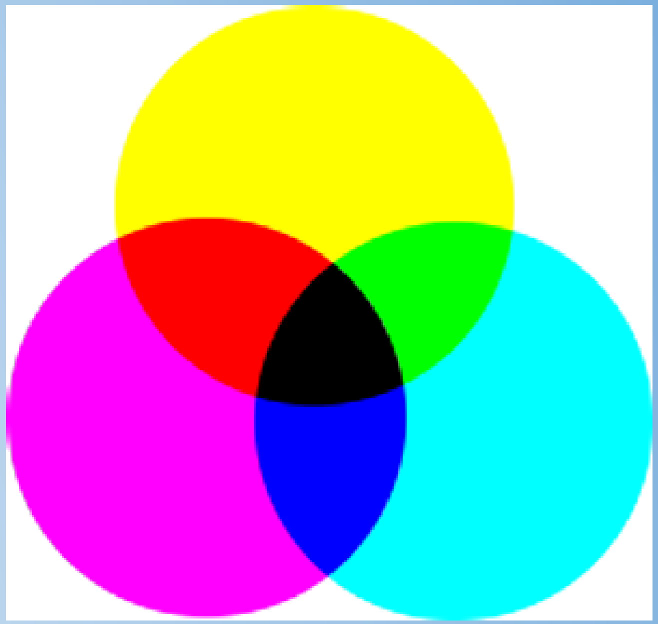

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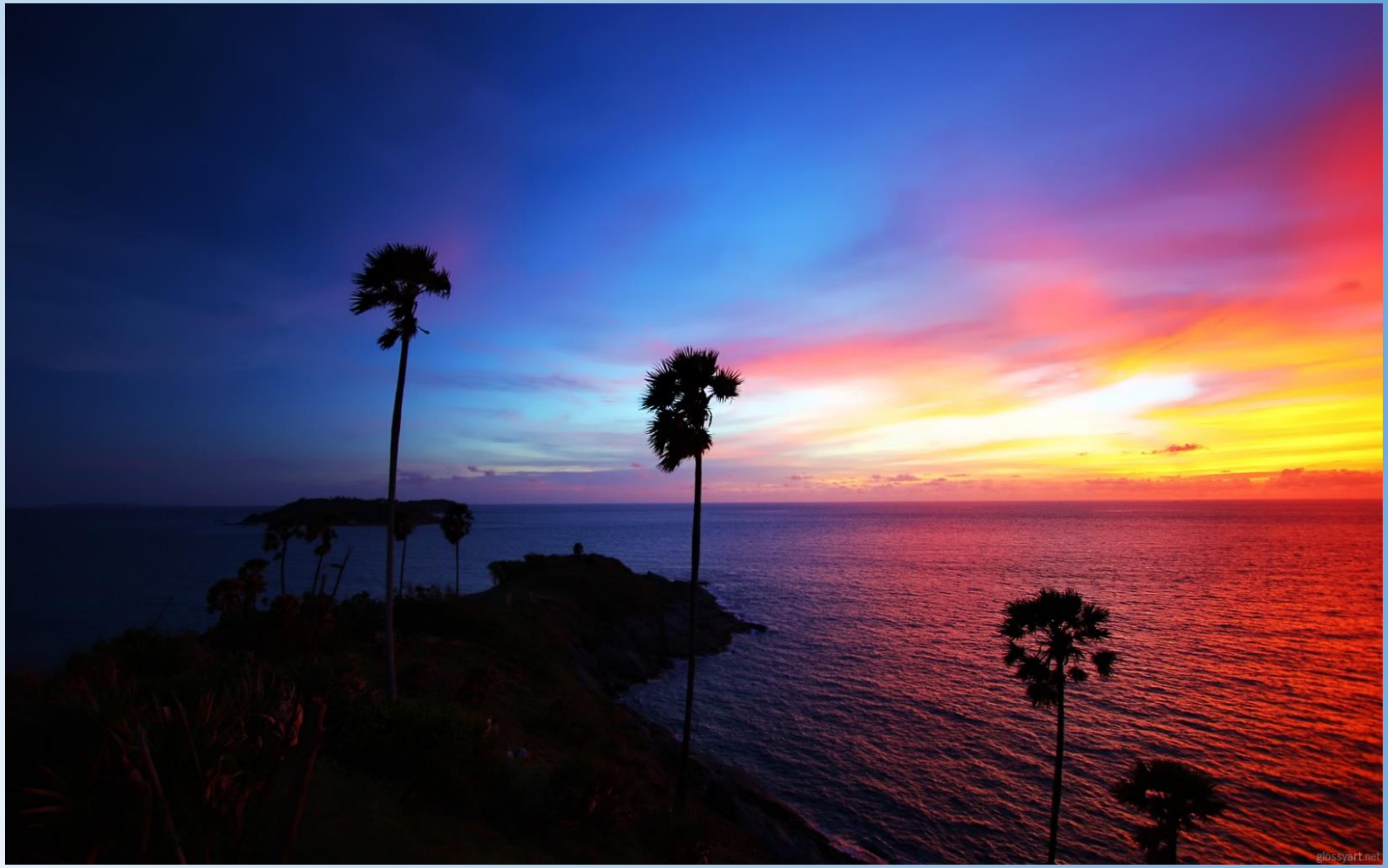
What is color ?

- An Attribute of visual sensation
- Cannot be defined without examples



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Rayleigh Scattering

- For small particles x<<1

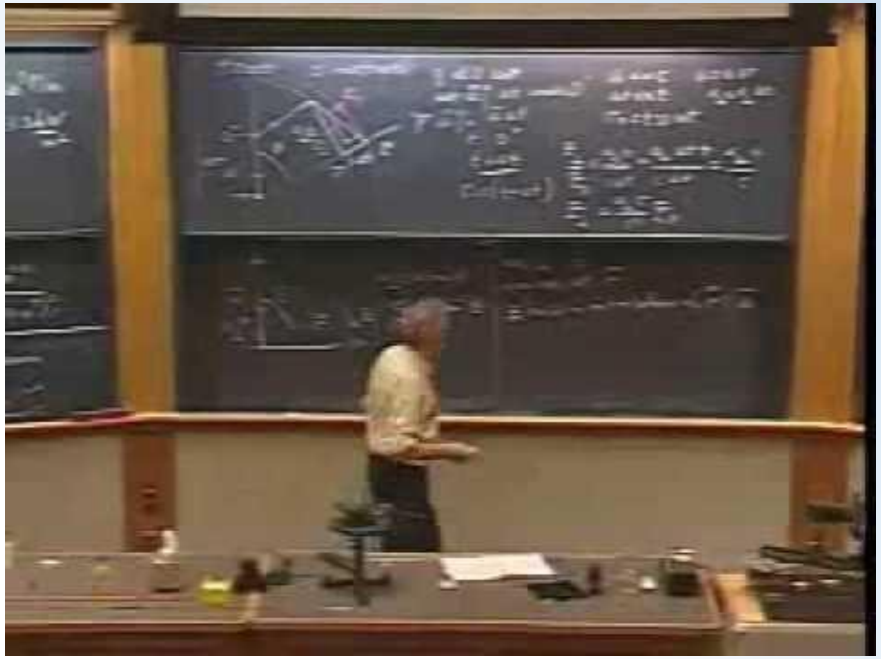
$$x = \frac{2\pi r}{\lambda}.$$

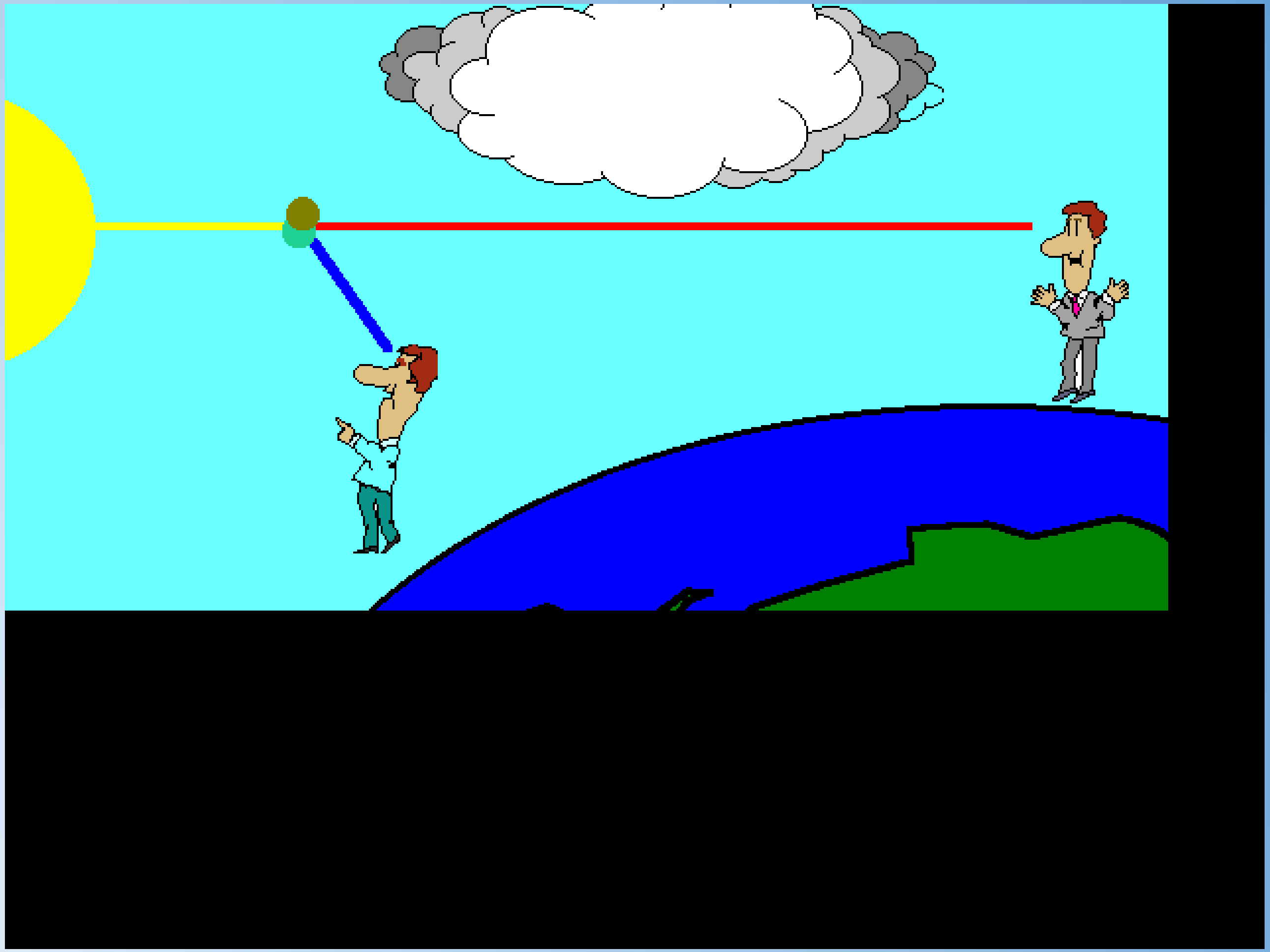
- Scattered rays

$$I = I_0 \frac{1+\cos^2\theta}{2R^2} \left(\frac{2\pi}{\lambda}\right)^4 \left(\frac{n^2-1}{n^2+2}\right)^2 \left(\frac{d}{2}\right)^6$$

- Lower wavelength, higher scattering

Rayleigh Scattering





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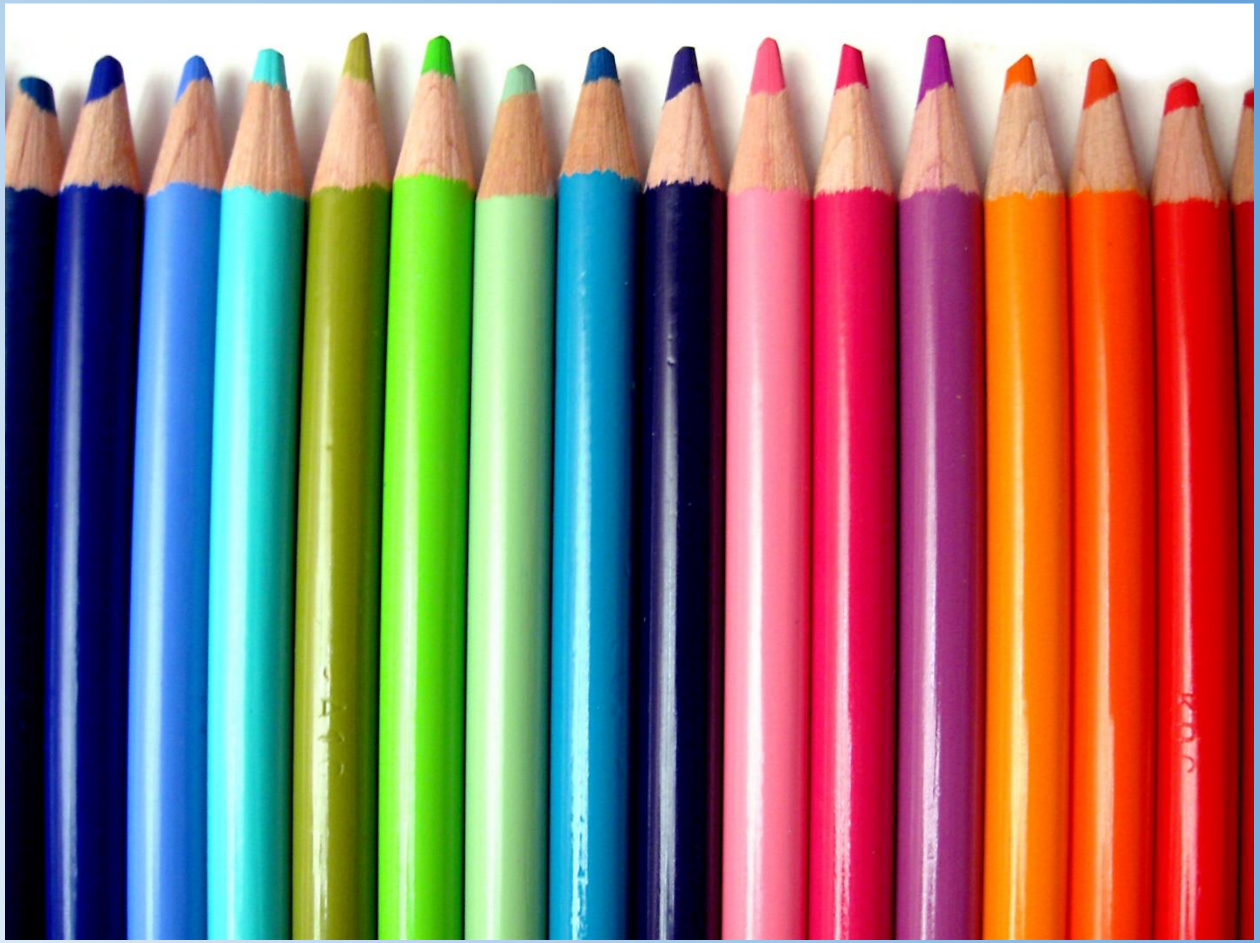
Color properties: Color

- Attribute of visual perception consisting of any combination of chromatic and achromatic content



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Color properties: Hue

- An area appears to be similar to one of the perceived colors:
- Red, Yellow, Green, Blue

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Color properties: Brightness and Lightness

- Brightness: An area appears to emit more or less light
- Lightness: The brightness of an area judged relative to brightness of a similarly illuminated white area

$$Lightness = \frac{Brightness}{Brightness\ (White)}$$

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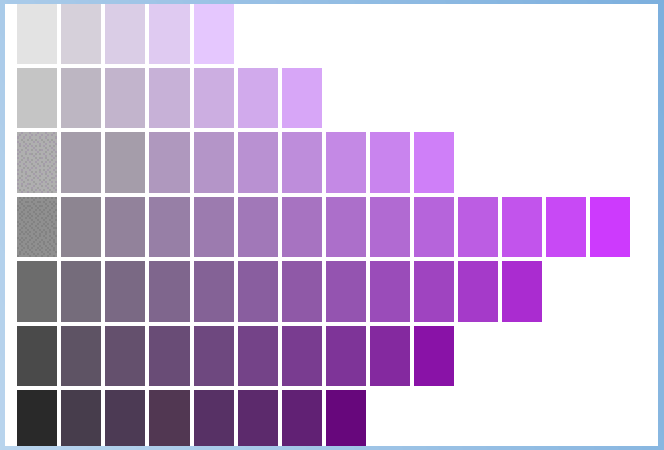
Color properties: Colorfulness and Chroma

- Colorfulness: An area appears to be more or less chromatic
- Chroma: The colorfulness of an area judged as a proportion of the brightness of similarly illuminated white



$$Chroma = \frac{Colorfulness}{Brightness\ (White)}$$

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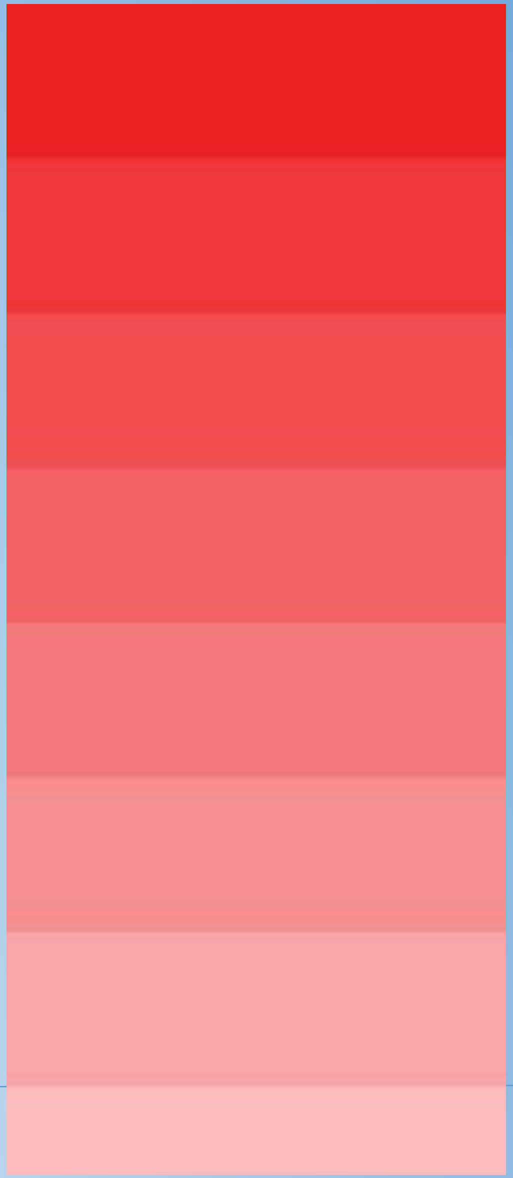
Color properties: Saturation

- Colorfulness of an area judged to its brightness

$$Saturation = \frac{Chroma}{Lightness}$$

$$Saturation = \frac{Colorfulness}{Brightness\ (White)} \times \frac{Brightness\ (White)}{Brightness}$$

$$Saturation = \frac{Colofulness}{Brightness}$$



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Color properties:

- Brightness
- Lightness
- Colorfulness
- Chroma
- Hue

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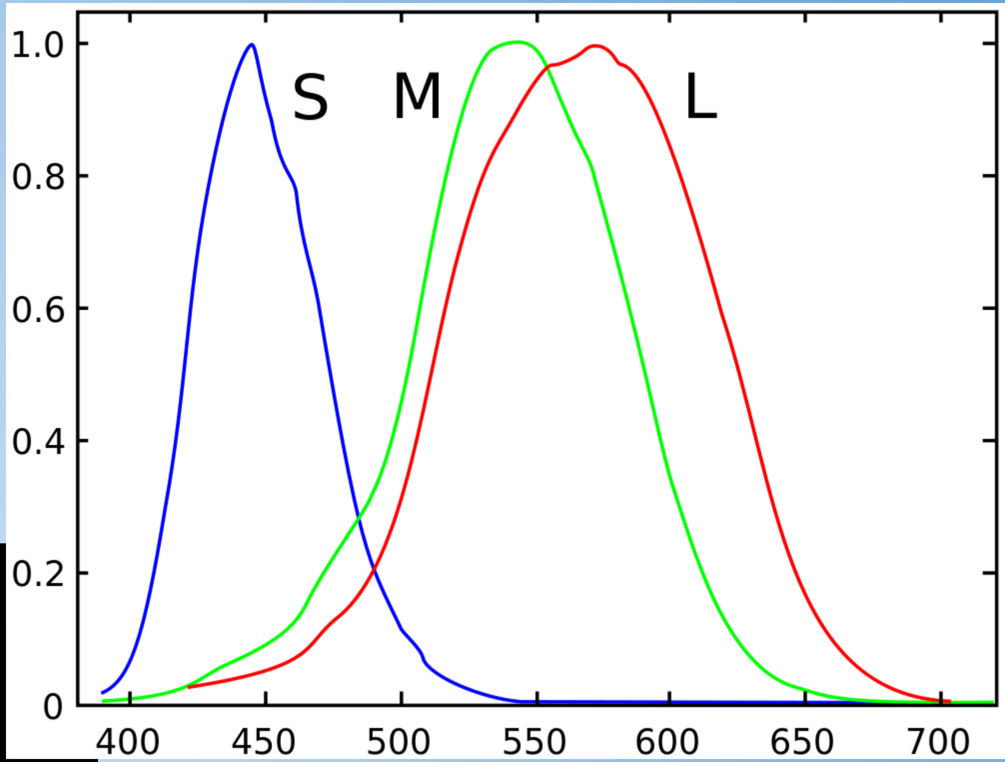
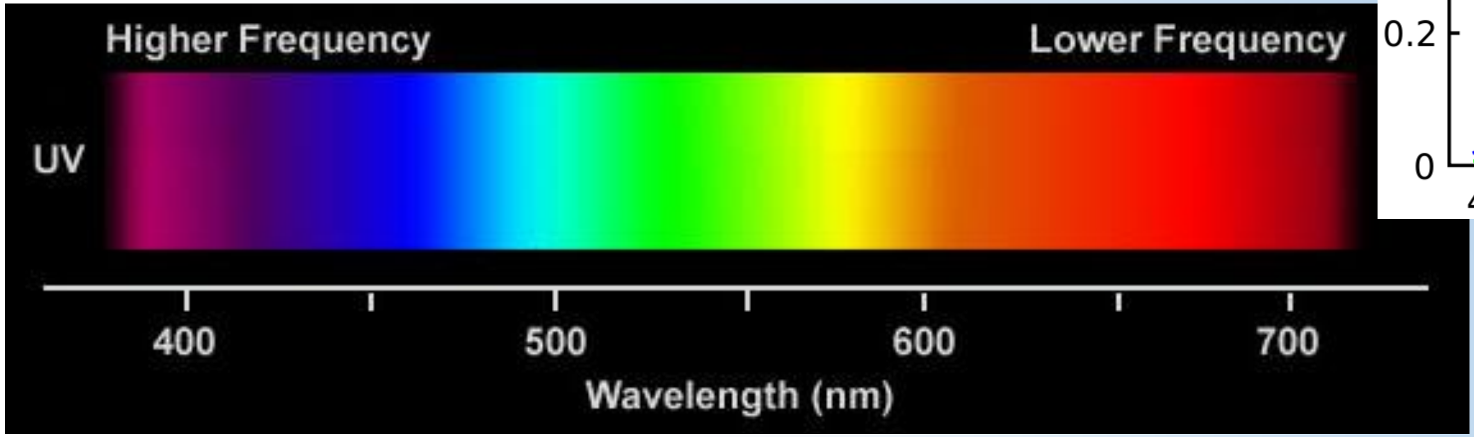
Human Color Perception:

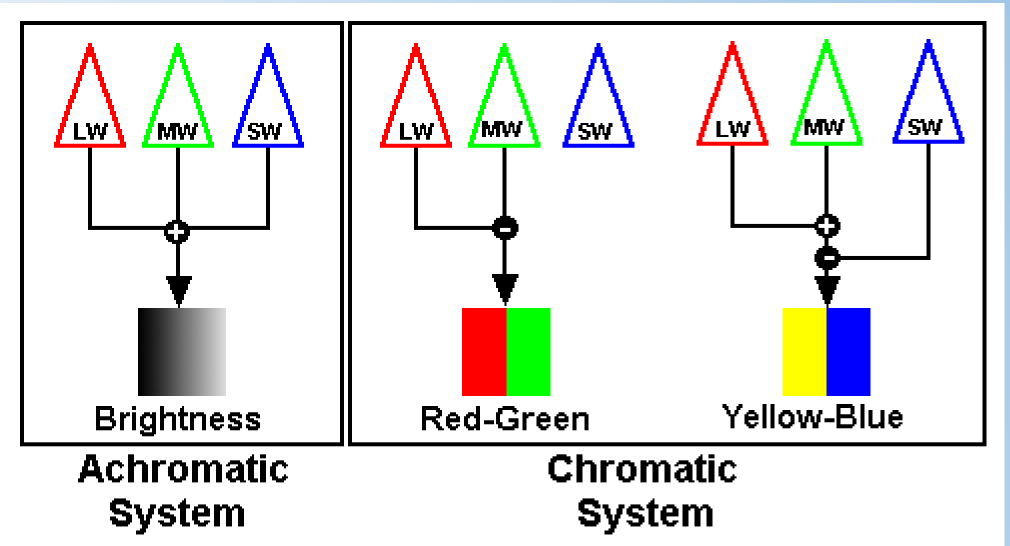
- Color spectrum
- Cone responses (L, M, S)



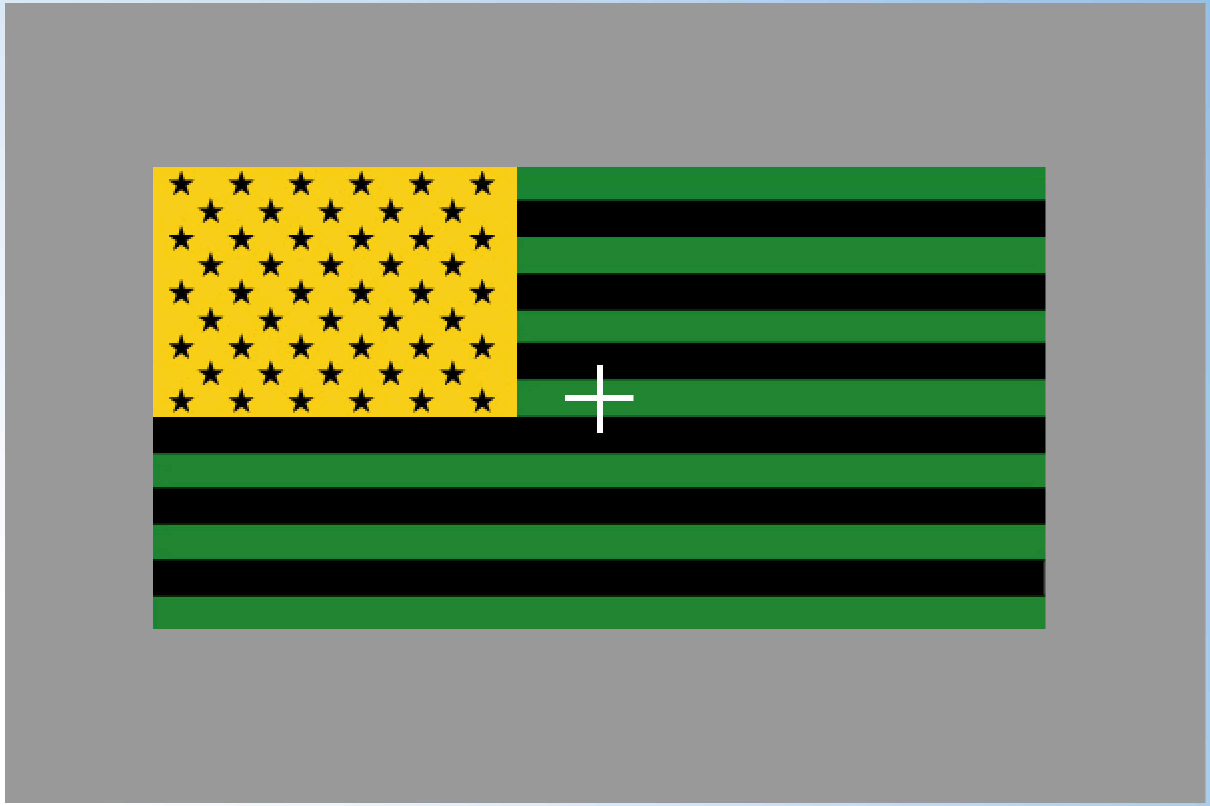


Opponent Color Theory:

- Primary colors are encoded before sending to brain

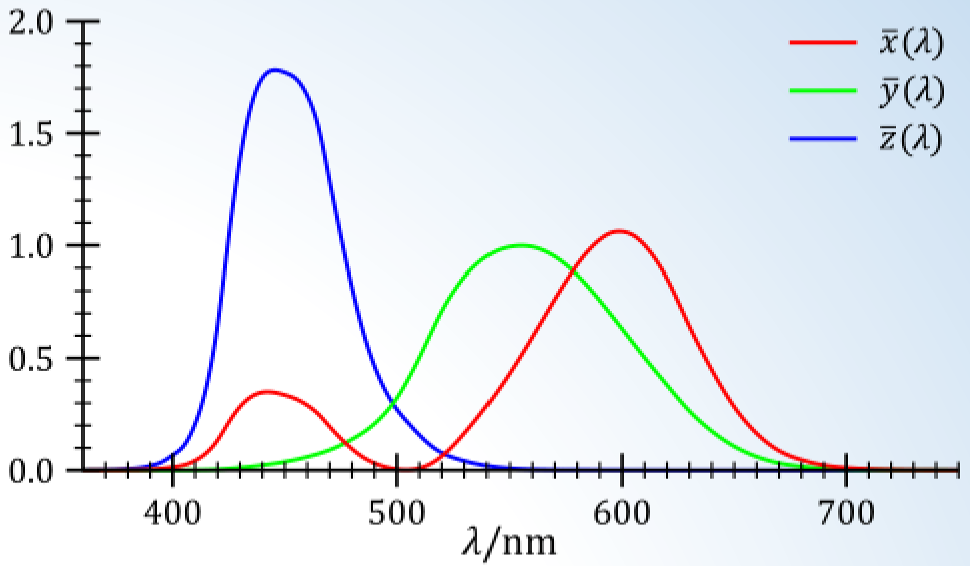


US Flag afterimage:



US Flag afterimage:

CIE 1937 XYZ matching functions:



$$X = \int_{380}^{780} I(\lambda)\,\overline{x}(\lambda)\,d\lambda$$
$$Y = \int_{380}^{780} I(\lambda)\,\overline{y}(\lambda)\,d\lambda$$
$$Z = \int_{380}^{780} I(\lambda)\,\overline{z}(\lambda)\,d\lambda$$

Color Appearance Phenomena: Simultaneous Contrast

- Darker background cause the gray ribbon appear lighter

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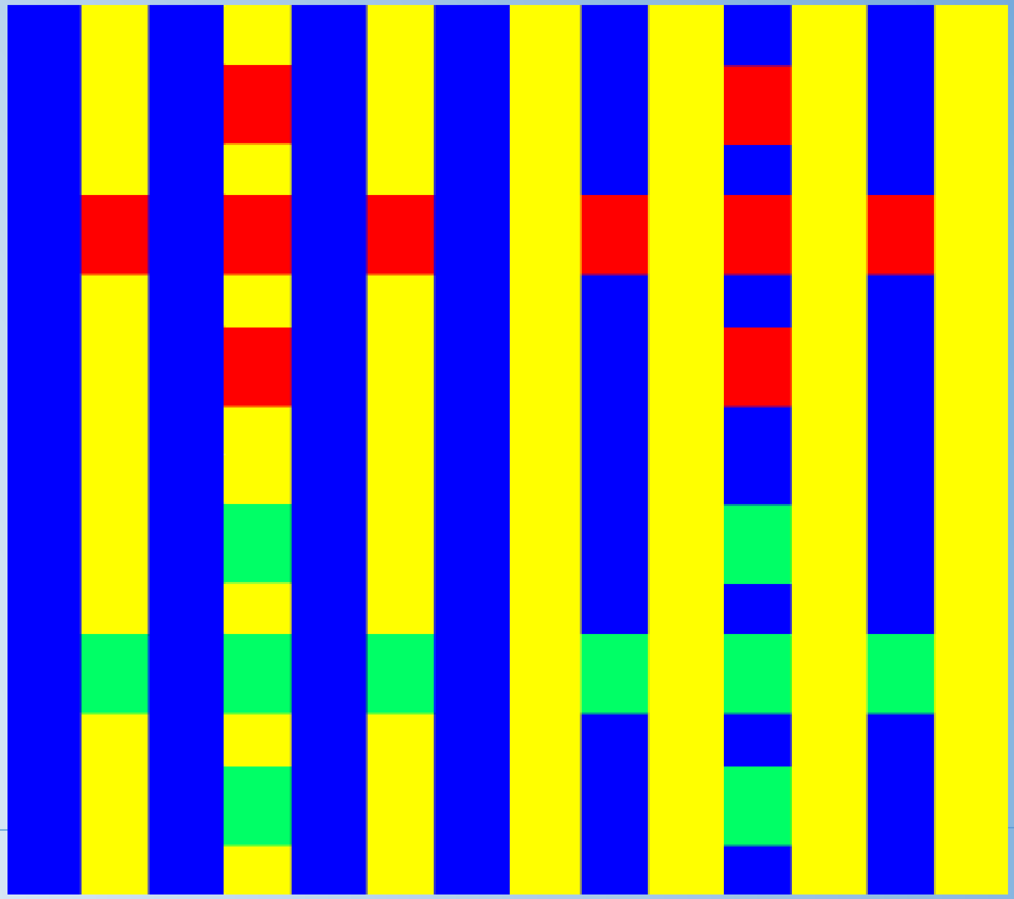
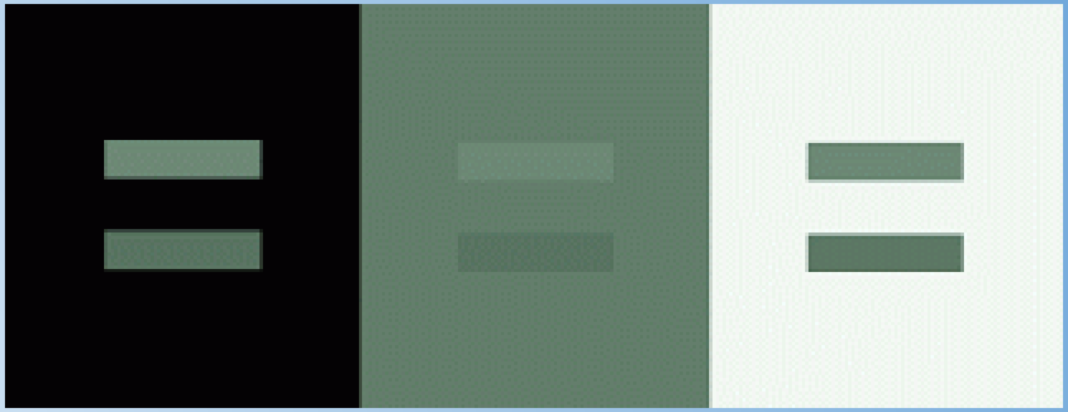
Color Appearance Phenomena: Simultaneous Contrast

- Robertson (1996)
- Darker background cause the gray ribbon appear lighter



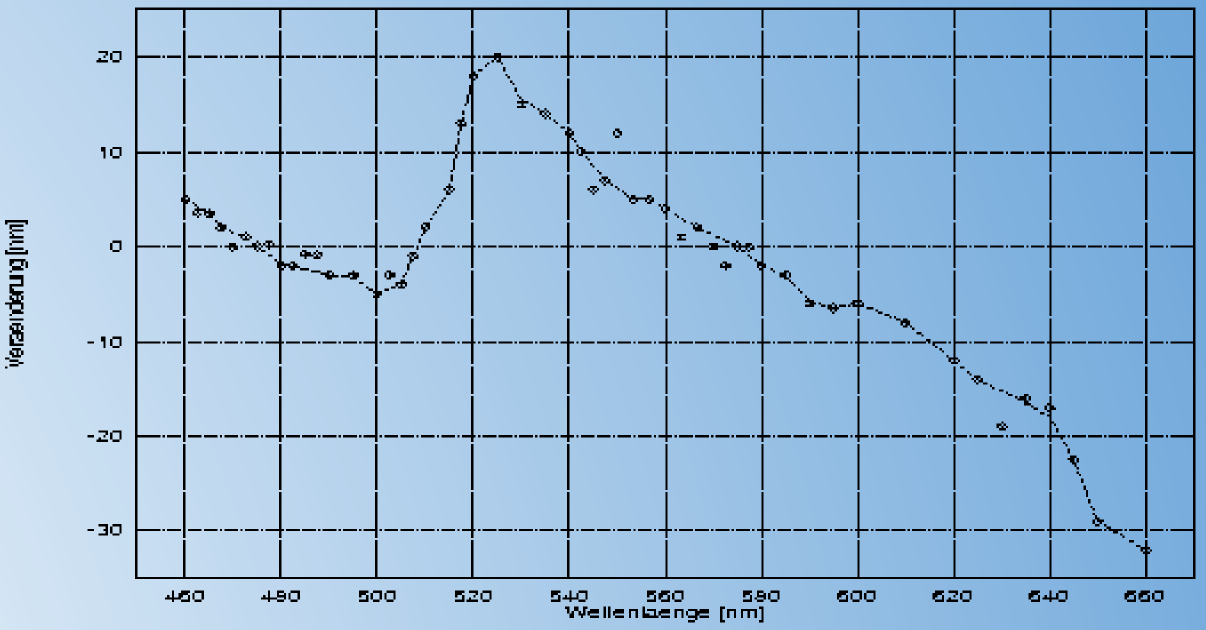
Color Appearance Phenomena: Crispening

- Increase in perceived magnitude of color differences when the background is similar in color



Color Appearance Phenomena: Bezold-Brucke Hue Shift

- Hue changes with luminance
- Wavelength shift required to maintain constant hue across a 10X reduction in luminance



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Color Appearance Phenomena:

- Hunt Effect: Colorfulness increases with luminance
- Stevens Effect: Contrast increases with luminance

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Color Appearance Phenomena: Helson-Judd effect

- Under strongly monochromatic illumination
- Samples lighter than the background exhibited Chroma of the same hue as the source
- Samples darker than background exhibited Chroma of the hue of the source's complement

Color Appearance Phenomena: Discounting-the-Illuminant

- Cognitive ability of observers to interpret the colors of objects based on illuminated environment in which the are viewed
- White objects appear white under tungsten light, fluorescent light, and daylight.

Color Appearance Model:

- Any model that includes predictors of at least the relative color-appearance attributes of lightness, chroma, and hue
- It must include at least some form of a chromatic-adaptation transform

Color Appearance Model:

- Transform of XYZ tri-stimulus values to cone responses
- Viewing environment (tri-stimulus of adaptation stimulus)

CIELAB:

- Stimulus XYZ
- Reference White X_n, Y_n, Z_n
- Results in L (luminance), a, and b (chrominance) parameters

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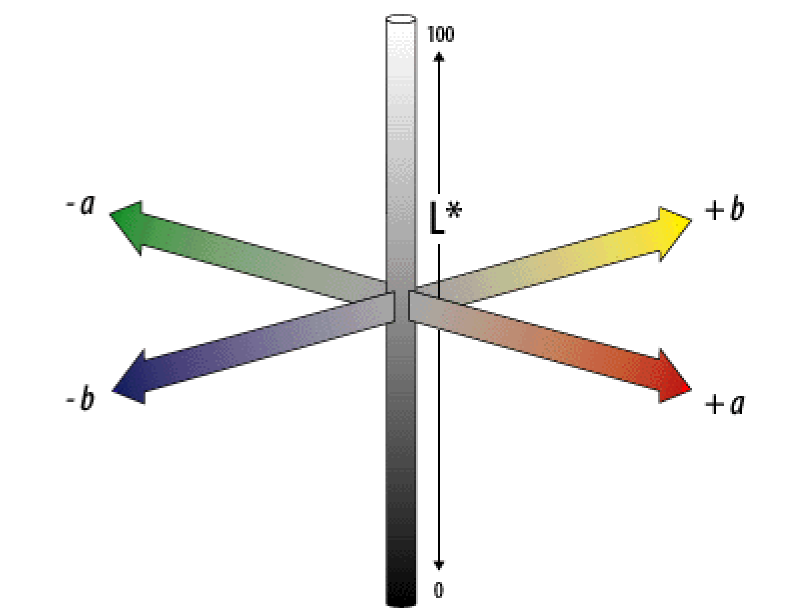
CIELAB:



- a: red-green
- b: yellow-blue
- $L = 116(Y/Y_n) - 16$
- $a = 500[f(X/X_n) - f(Y/Y_n)]$
- $b = 200[f(Y/Y_n) - f(Z/Z_n)$

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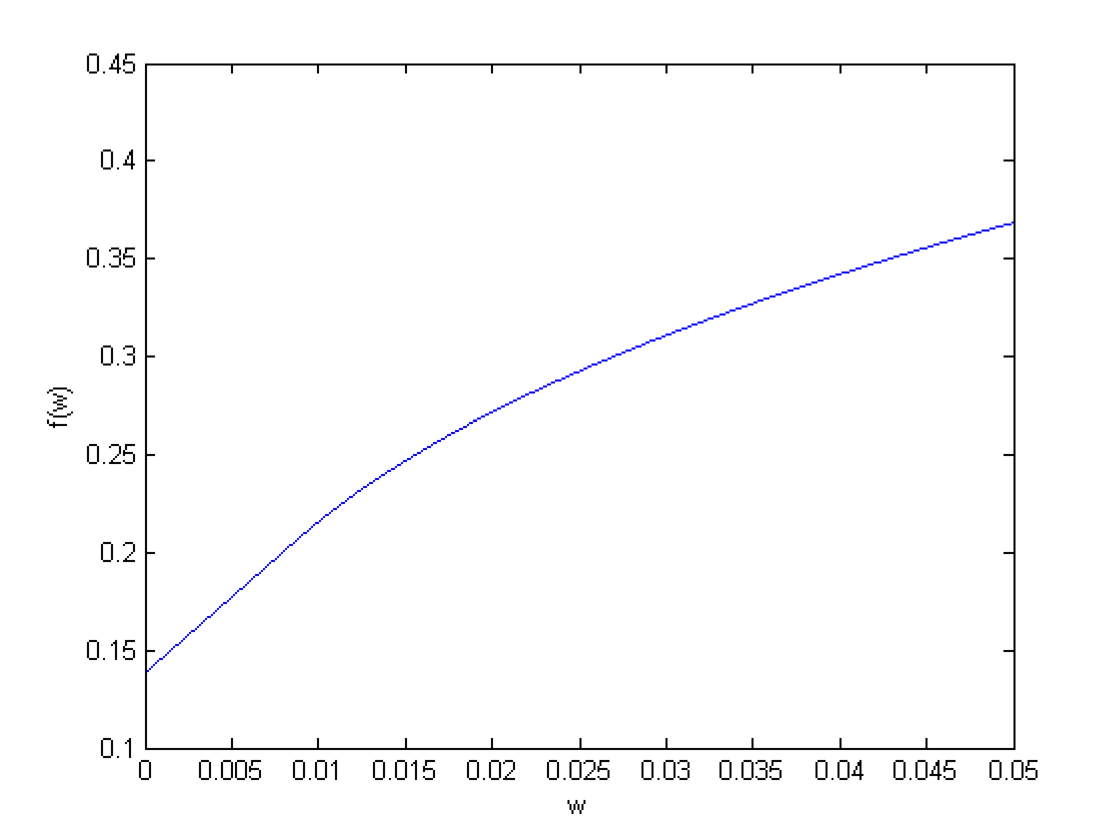
CIELAB:



- $f(\omega) = \begin{cases} \omega^{1/3} & \omega > 0.008856 \\ 7.787\omega + 16/116 & \omega \leq 0.008856 \end{cases}$

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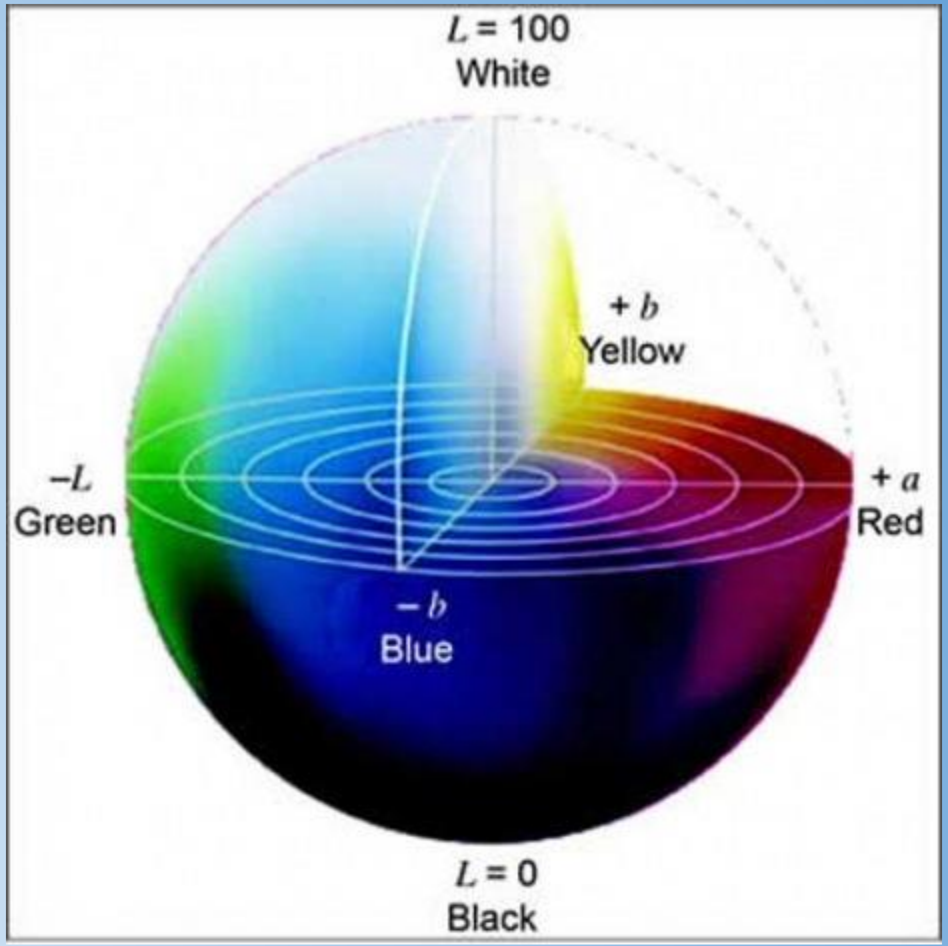
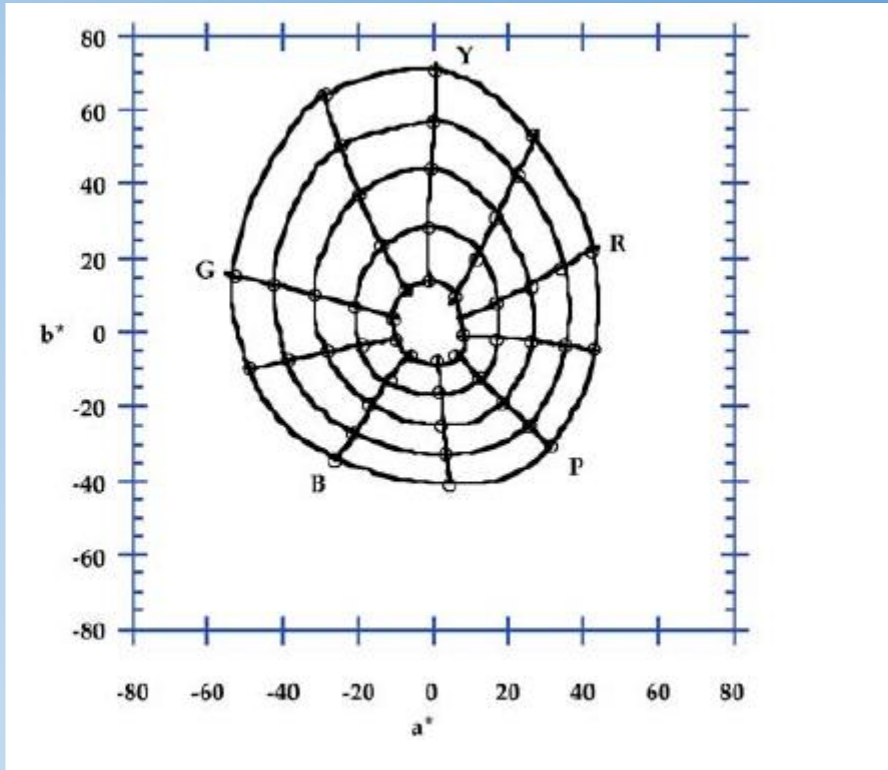
CIELAB:

- Chroma: $C_{ab} = \sqrt{a^2 + b^2}$
- Hue: $h_{ab} = \tan^{-1}(^{b}/_{a})$



CIELAB:

- Contours of constant Chroma and Hue
- Lines: constant Hue
- Circles: constant Chroma



CIELAB: Pros and Cons

- Not accurate von Kries adaptation transformation
- Incapable of predicting luminance-depending effects (Hunt and Stevens effect)
- Incorporate no background or surround dependency
- No modeling for discounting-the-illuminant

Nayatani et al:

- Luminance factor of achromatic background (Y_0)
- Color of the illumination (x_0, y_0)
- Test stimulus in (x, y, Y)
- Absolute luminance of the stimulus (E_0)
- Normalizing illuminance (E_{or})
- Noise term (n)

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Nayatani et al:

- Converting XYZ to intermediate values
- $\xi = (0.48105x_0 + 0.78841y_0 - 0.08081)/y_0$
- $\eta = (0.27200x_0 + 1.11962y_0 - 0.04570)/y_0$
- $\zeta = 0.91822(1 - x_0 - y_0)/y_0$

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Nayatani et al: adaptation model

$$\beta_1(R_o) = \frac{6.469 + 6.362 R_o^{0.4495}}{6.469 + R_o^{0.4495}}$$

$$\beta_1(G_o) = \frac{6.469 + 6.362 G_o^{0.4495}}{6.469 + G_o^{0.4495}}$$

$$\beta_2(B_o) = \frac{8.414 + 8.091 B_o^{0.5128}}{8.414 + B_o^{0.5128}} \times 0.7844$$

$$\beta_1(L_{or}) = \frac{6.469 + 6.362 L_{or}^{0.4495}}{6.469 + L_{or}^{0.4495}}$$

$$\begin{vmatrix} R \\ G \\ B \end{vmatrix} = \begin{vmatrix} 0.40024 & 0.70760 & -0.08081 \\ -0.22630 & 1.16532 & 0.04570 \\ 0.0 & 0.0 & 0.91822 \end{vmatrix} \begin{vmatrix} X \\ Y \\ Z \end{vmatrix}$$

$$e(R) = \begin{cases} 1.758 & R \geqslant 20\xi \\ 1.0 & R < 20\xi \end{cases}$$

$$e(G) = \begin{cases} 1.758 & G \geqslant 20\eta \\ 1.0 & G < 20\eta \end{cases}$$

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Nayatani et al: Opponent color dimension

Achromatic response

$$Q = \frac{41.69}{\beta_1(L_{or})}\left[\frac{2}{3}\beta_1(R_o)e(R)\log\frac{R+n}{20\xi+n} + \frac{1}{3}\beta_1(G_o)e(G)\log\frac{G+n}{20\eta+n}\right]$$

Chromatic response

$$t = \beta_1(R_o)\log\frac{R+n}{20\xi+n} - \frac{12}{11}\beta_1(G_o)\log\frac{G+n}{20\eta+n} + \frac{1}{11}\beta_2(B_o)\log\frac{B+n}{20\zeta+n}$$

$$p = \frac{1}{9}\beta_1(R_o)\log\frac{R+n}{20\xi+n} + \frac{1}{9}\beta_1(G_o)\log\frac{G+n}{20\eta+n} - \frac{2}{9}\beta_2(B_o)\log\frac{B+n}{20\zeta+n}$$

Nayatani et al: Pros and Cones

- Accounts for change in color appearance due to chromatic adaptation and luminance level (Stevens and Hunt effect)
- Predicts Helsun-Judd effect
- No chromatic or cognitive adaptation (von Kries and discounting-the-illuminant)
- Not incorporate rod vision

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Hunt Model:

- Heavily depends on surround relative luminance
- Transparencies projected in a dark room
- Television displays in a dim surround

Hunt Model:

- Chromaticity coordinates of the illuminant and the adapting field
- Chromaticity and luminance factors of the background, reference white and test sample

Hunt Model: adaptation model

$$\begin{vmatrix} \rho \\ \gamma \\ \beta \end{vmatrix} = \begin{vmatrix} 0.38971 & 0.68898 & -0.07868 \\ -0.22981 & 1.18340 & 0.04641 \\ 0.0 & 0.0 & 1.0 \end{vmatrix} \begin{vmatrix} X \\ Y \\ Z \end{vmatrix}$$

$$\rho_a = B_\rho[f_n(F_L F_\rho \rho/\rho_W) + \rho_D] + 1$$

$$\gamma_a = B_\gamma[f_n(F_L F_\gamma \gamma/\gamma_W) + \gamma_D] + 1$$

$$\beta_a = B_\beta[f_n(F_L F_\beta \beta/\beta_W) + \beta_D] + 1$$

- F_L: Luminance-level adaptation factor
- $F_\rho, F_\gamma,$ and F_β are chromatic adaptation factors
- $\rho_D, \gamma_D,$ and β_D are Helson-Judd effect factors
- $B_\rho, B_\gamma,$ and B_β are cone bleach factors

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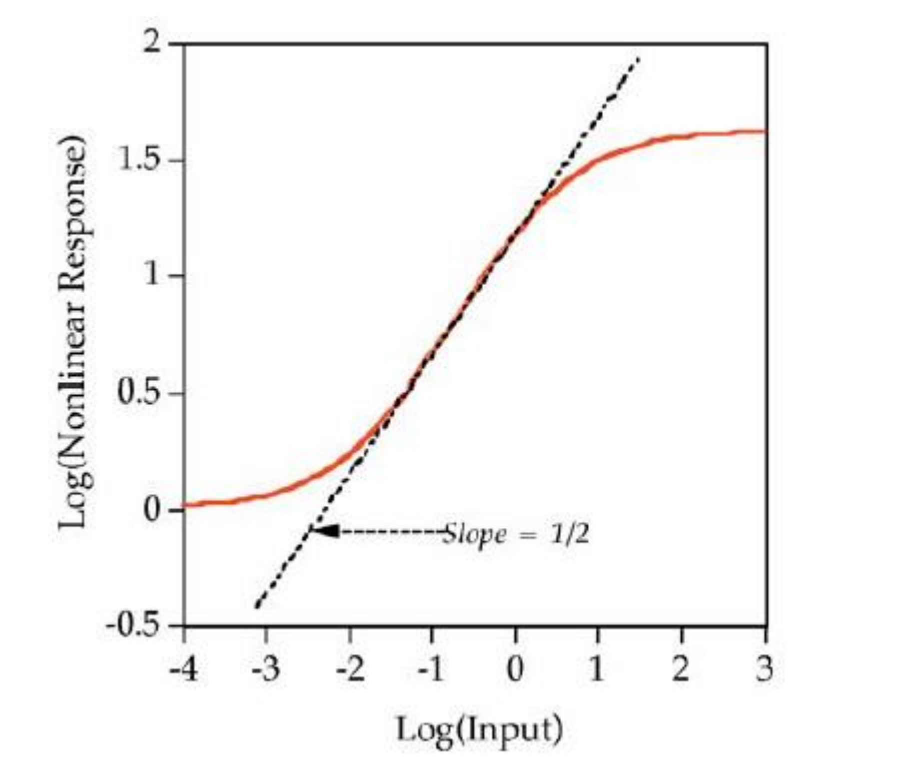
Hunt Model: adaptation model

$$f_n[I] = 40[I^{0.73}/(I^{0.73} + 2)]$$



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Hunt Model: Opponent color dimension

$$A_a = 2\rho_a + \gamma_a + (1/20)\beta_a - 3.05 + 1$$

$$C_1 = \rho_a - \gamma_a$$

$$C_2 = \gamma_a - \beta_a$$

$$C_3 = \beta_a - \rho_a$$

A: Achromatic post-adaptation signal

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Hunt Model: Pros and Cons

- Designed to predict the appearance of stimuli in a variety background and surround
- Predicts Hunt effect, Hue shift, Helson-Judd effect, Simultaneous constant, Stevens effect
- Predicts chromatic adaptation due to discounting-the-illuminant

Hunt Model: Pros and Cons

- It is very complex model
- Extreme poor result on incomplete input data
- Cannot be easily converted
- Expensive and difficult to implement

RLAB:

- XYZ of the test object
- X_n, Y_n, Z_n of the white point
- Absolute luminance of the white object in cd/m^2
- Relative luminance of the surround
- Is discounting-the-illuminant taking place?

RLAB:

$$\begin{vmatrix} X_{\text{ref}} \\ Y_{\text{ref}} \\ Z_{\text{ref}} \end{vmatrix} = \mathbf{RAM} \begin{vmatrix} X \\ Y \\ Z \end{vmatrix}$$

- M: Cone Response Transformation
- A: von Kries adaptation
- R: $A^{-1}M^{-1}$for reference viewing conditions

$$\mathbf{M} = \begin{vmatrix} 0.3897 & 0.6890 & -0.0787 \\ -0.2298 & 1.1834 & 0.0464 \\ 0.0 & 0.0 & 1.0000 \end{vmatrix}$$

$$\mathbf{A} = \begin{vmatrix} a_L & 0.0 & 0.0 \\ 0.0 & a_M & 0.0 \\ 0.0 & 0.0 & a_S \end{vmatrix}$$

$$\mathbf{R} = \begin{vmatrix} 1.9569 & -1.1882 & 0.2313 \\ 0.3612 & 0.6388 & 0.0 \\ 0.0 & 0.0 & 1.0000 \end{vmatrix}$$

RLAB: Opponent color dimension

- Analogous to CIELAB

$$L^R = 100(Y_{ref})^\sigma$$

$$a^R = 430[(X_{ref})^\sigma - (Y_{ref})^\sigma]$$

$$b^R = 170[(Y_{ref})^\sigma - (Z_{ref})^\sigma]$$

- Average surround $\sigma = 1/2.3$
- Dim surround $\sigma = 1/2.7$
- Dark surround $\sigma = 1/3.5$

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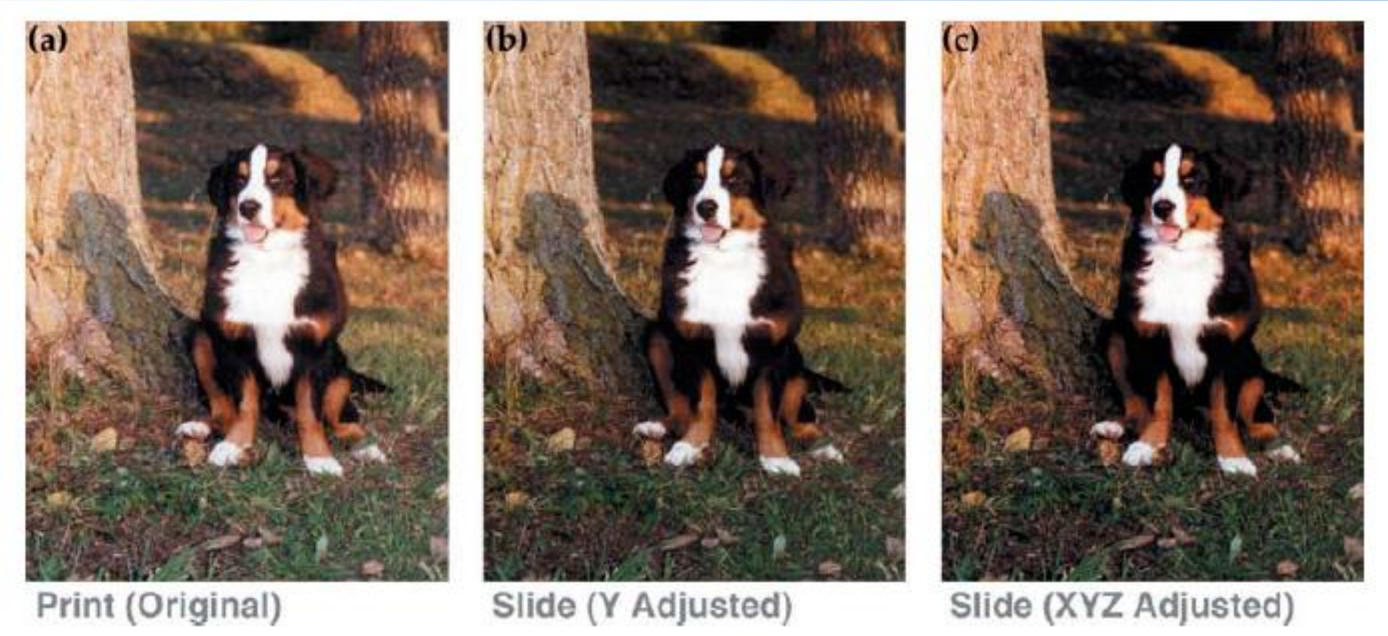
RLAB:

- Adaptation to dark surround



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RLAB: Pros and Cons

- Predicts discounting-the-illuminant
- Includes variable exponent for better contrast in different surroundings
- Not exhaustive in predicting color-appearance phenomena (Hunt, Helson-Judd, Stevens)
- Not over a wide range of luminance