Color in Image and Video

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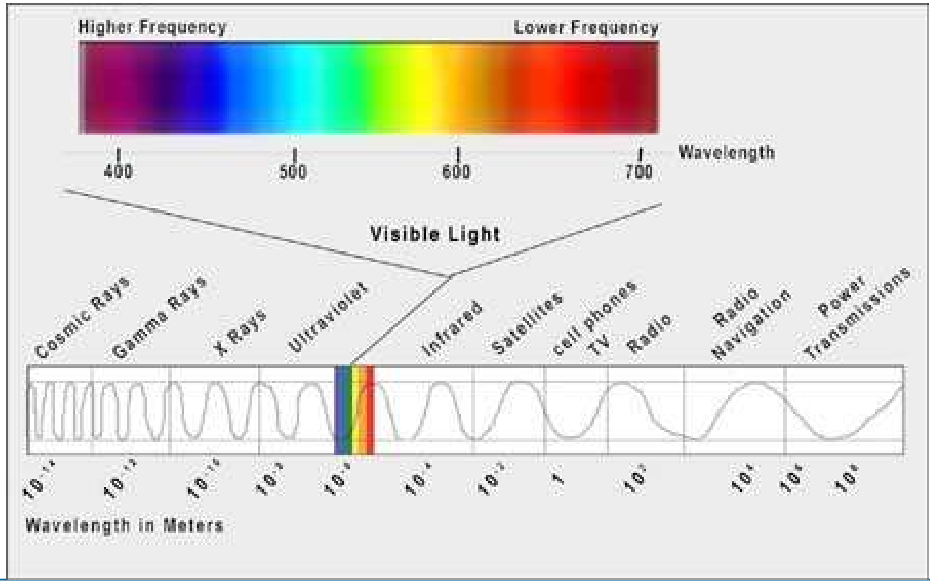
1. Color Science
2. Color Models in Images
3. Color Models in Video

1. Color Science

- Light and Spectra
- Gamma Correction
- Color-Matching Functions
- L*a*B*(CIELAB) Color Model
- CMY(CMYK)
- HSV
- Other Color Models

1.1 Light and Spectra

- Light is an electromagnetic wave, its color characterized by the wavelength
  - Laser Light -- a single wavelength
  - Most light sources -- Contributions over many wavelengths
  - Short wave – Blue, Long wave -- Red
  - Visible light in the range： 400-700nm (Nanometer, 10^{-9} M)



1.1 Light and Spectra

- **Spectrophotometer:** device used to measure visible light, by reflecting light from a diffraction grating (a ruled surface) that spreads out the different wavelengths.

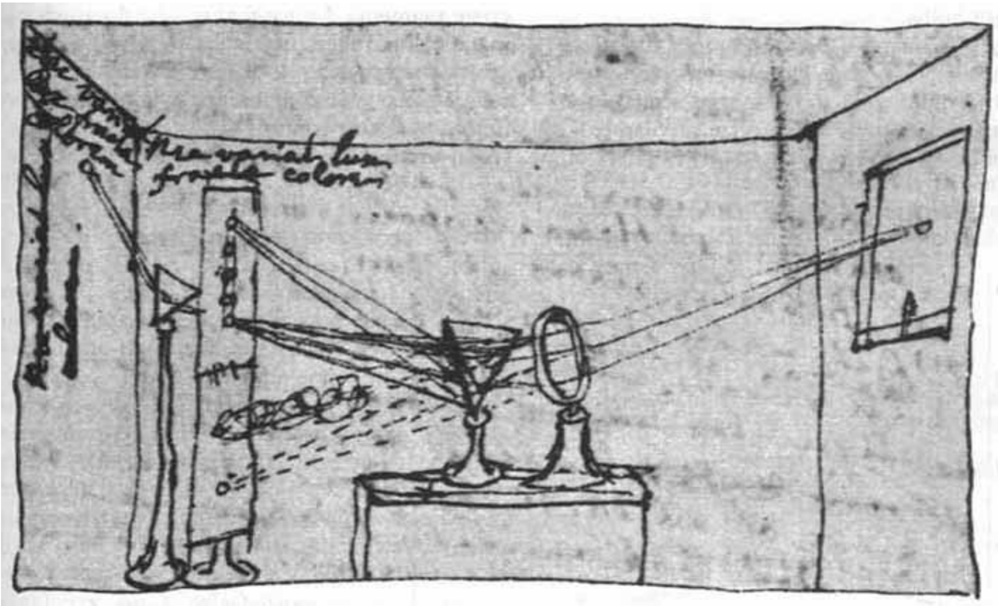
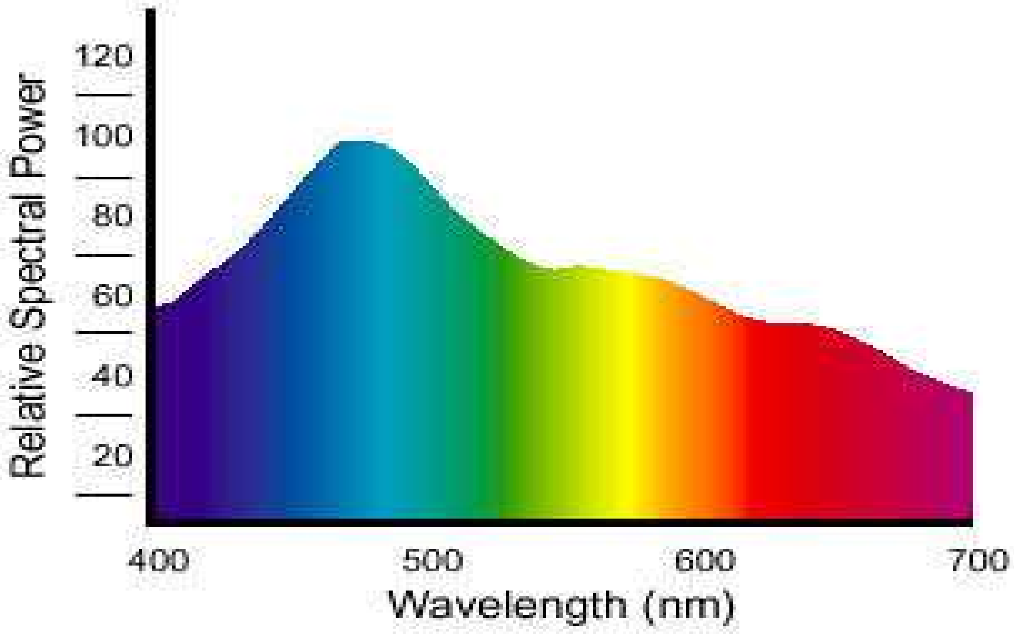


Fig. 4.1: Sir Isaac Newton's experiments.

1.1 Light and Spectra

- Spectral Power Distribution (SPD)
  - The relative power in each wavelength interval
  - The symbol for wavelength is λ. This curve is called E(λ).



Spectral Power Distribution of Daylight

1.1 Light and Spectra

- Human Vision
  - Works like a camera
  - Lens focusing an image onto the retina

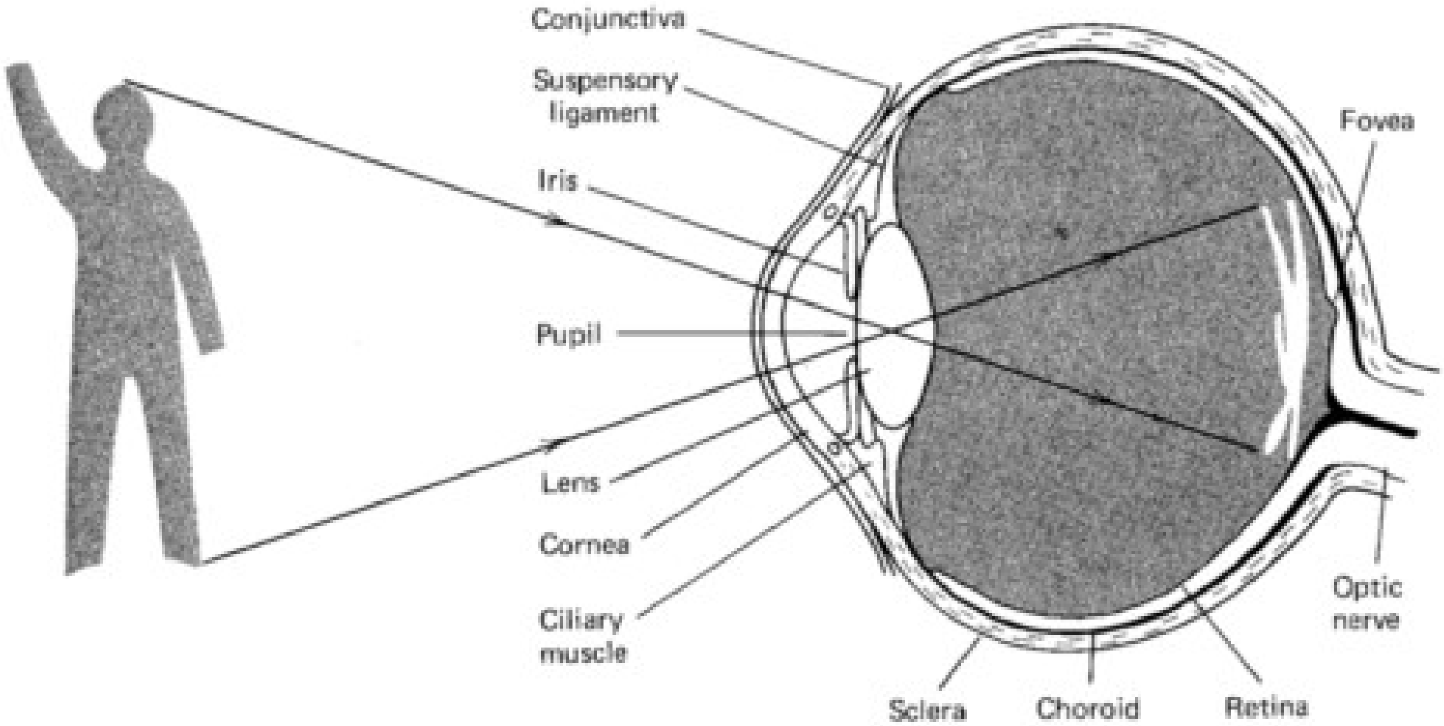
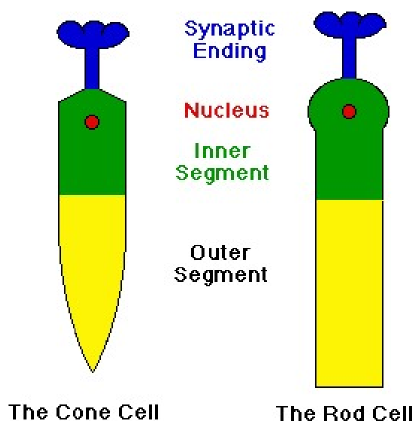


Fig. 1. Human retina as seen through an opthalmoscope.

1.1 Light and Spectra

- Human Vision (Conti.)
  - The retina – Rods and Cones
  - The rods come into play when light levels are low and produce a image in shades of gray.
  - For higher light levels, the cones each produce a signal. the three kinds of cones are most sensitive to red (R), green (G), and blue (B) light.



Rods and Cones

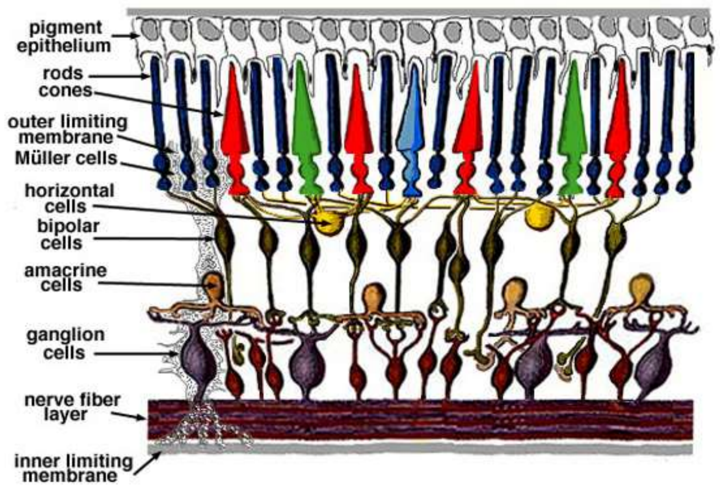
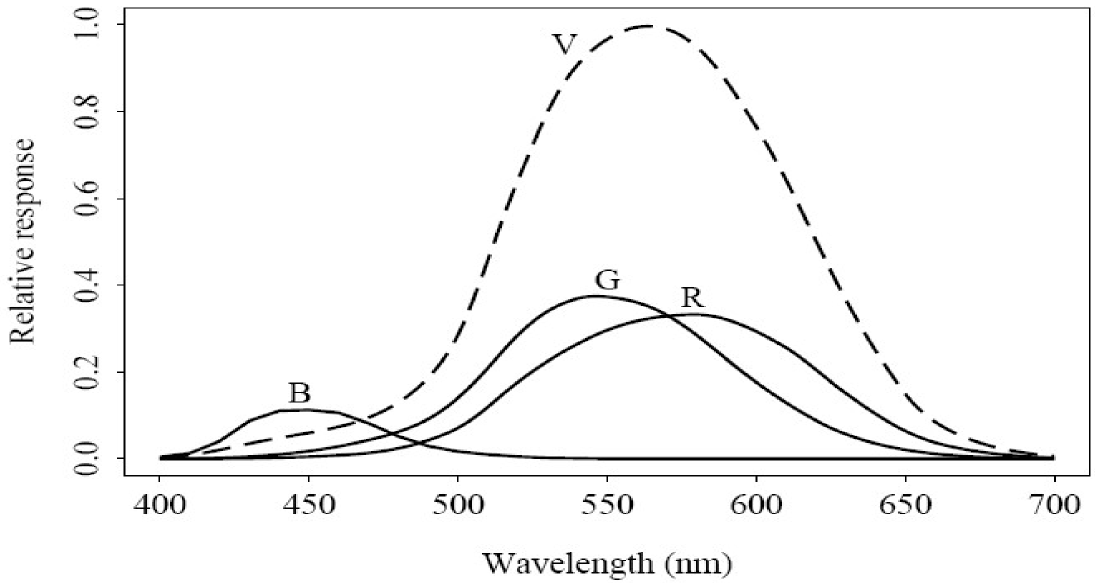


Fig. 2. Simple diagram of the organization of the retina.

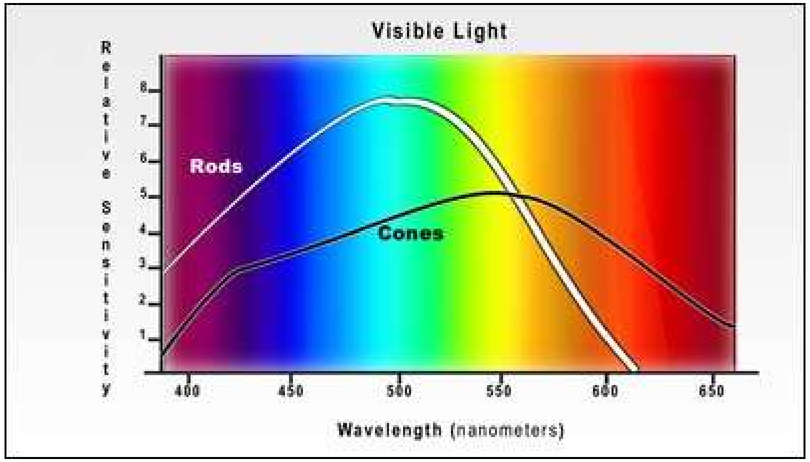
1.1 Light and Spectra

- Spectral Sensitivity of the Eye
  - Most Sensitive to the middle of the visible spectrum
  - The sensitivity of our receptors is also a function of wavelength
  - Luminous-efficiency function showing the overall sensitivity
  - The Blue receptor sensitivity is not shown to scale because it is much smaller than the curves for Red or Green

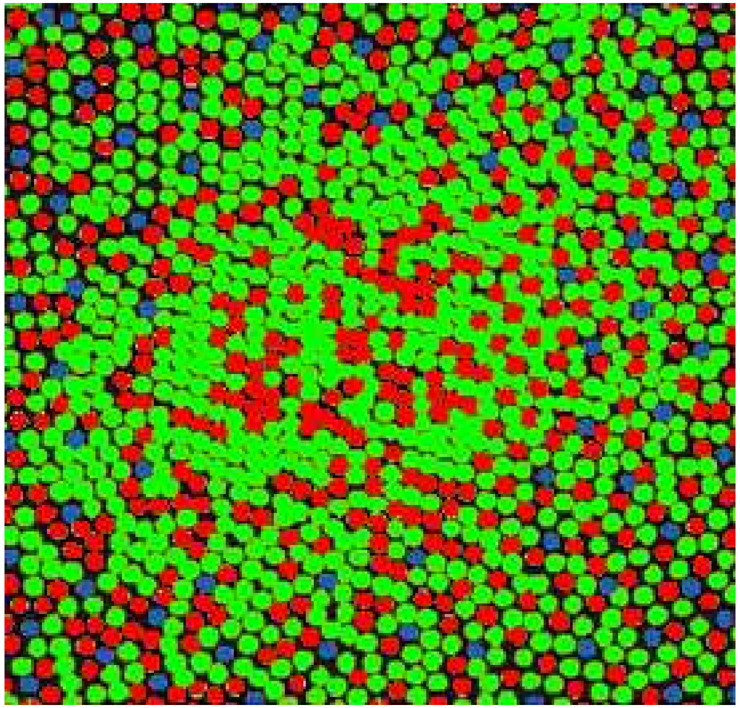


1.1 Light and Spectra

- ☐ Spectral Sensitivity of the Eye (Conti.)
  - Rods – broad range wavelengths, perception of Black-White
  - About 6 million cones – color R:G:B=40:20:1



Spectral Sensitivity of Rods and Cones



Response in the eye to the falling light

1.1 Light and Spectra

- These spectral sensitivity functions are usually denoted by letters other than "R,G,B"; here let's use a vector function $q(\lambda)$, with components

$$q(\lambda) = (q_R(\lambda), q_G(\lambda), q_B(\lambda))^T \tag{4.1}$$

- The response in each color channel in the eye is proportional to the number of neurons firing.

We can succinctly write down this idea in the form of an integral:

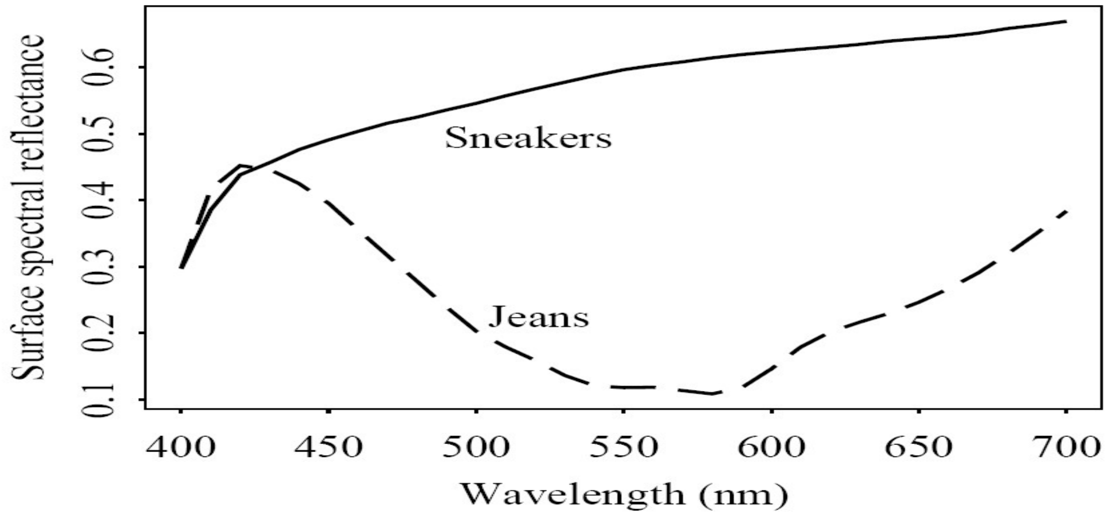
$$R = \int E(\lambda)\, q_R(\lambda)\, d\lambda$$

$$G = \int E(\lambda)\, q_G(\lambda)\, d\lambda$$

$$B = \int E(\lambda)\, q_B(\lambda)\, d\lambda \tag{4.2}$$

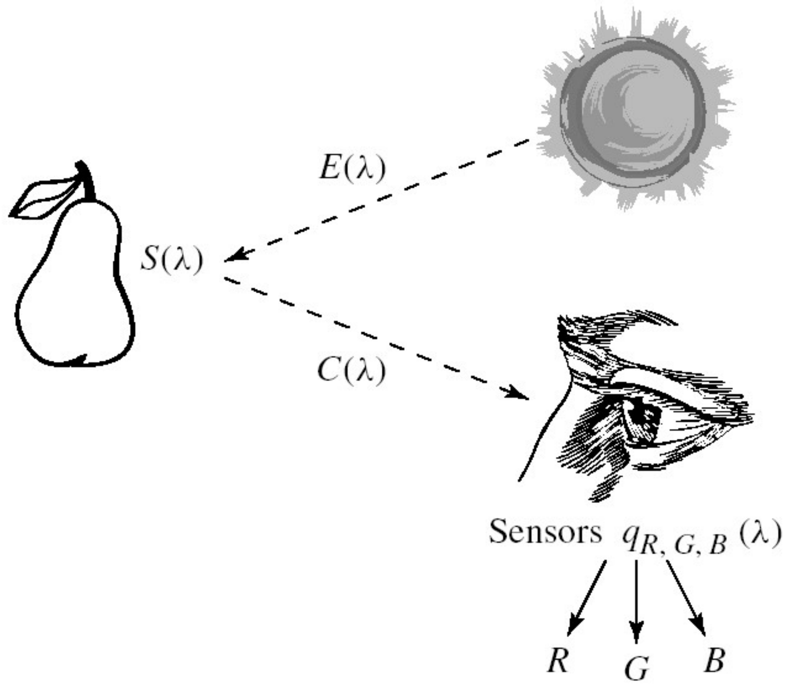
1.1 Light and Spectra

- Image Formation
  - Surfaces reflect different amounts of light at different wavelengths, and dark surfaces reflect less energy than light surfaces.
  - Fig. 4.4 shows the surface spectral reflectance from (1) orange sneakers and (2) faded blue jeans. The reflectance function is denoted $S(\lambda)$.



1.1 Light and Spectra

- Image formation is thus:
  - Light from the illuminant with SPD $E(\lambda)$ impinges on a surface, with surface spectral reflectance function $S(\lambda)$, is reflected, and then is filtered by the eye's cone functions $q\ (\lambda)$.



1.1 Light and Spectra

- The function C(λ) is called the color signal and consists of the product of E(λ), the illuminant, times S(λ), the reflectance: C(λ) = E(λ) S(λ).

- The equations that take into account the image formation model are:

$$R = \int E(\lambda)\, S(\lambda)\, q_R(\lambda)\, d\lambda$$

$$G = \int E(\lambda)\, S(\lambda)\, q_G(\lambda)\, d\lambda$$

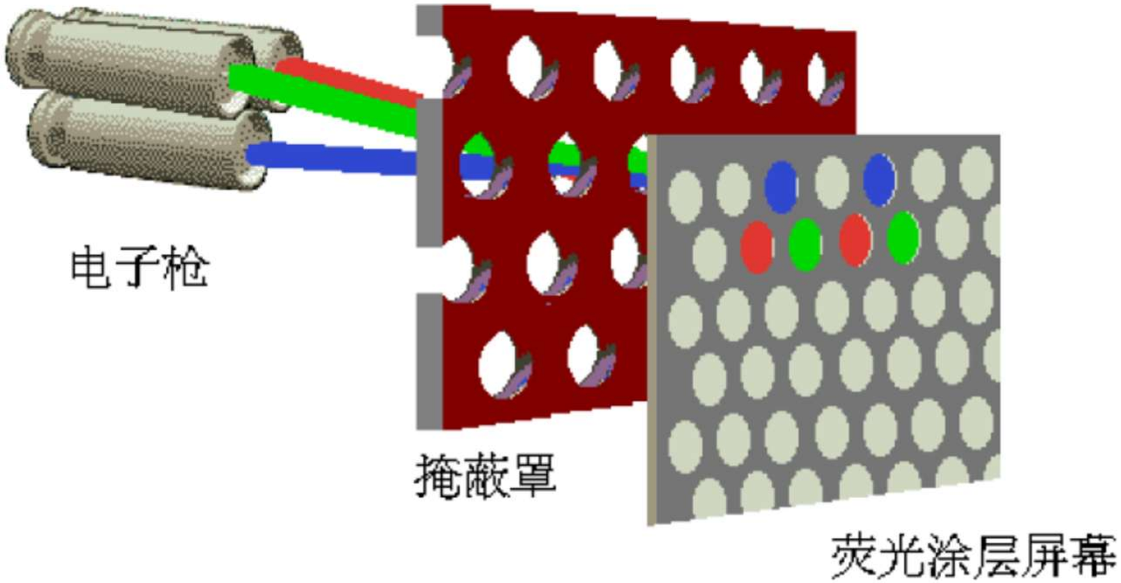
$$B = \int E(\lambda)\, S(\lambda)\, q_B(\lambda)\, d\lambda$$

1.1 Light and Spectra

- Camera System
  - Camera systems are made in a similar fashion; a studio quality camera has three signals produced at each pixel location (corresponding to a retinal position).
  - Analog signals are converted to digital, truncated to integers, and stored. If the precision used is 8-bit, then the maximum value for any of R,G,B is 255, and the minimum is 0.

1.2 Gamma Correction

- CRT Display
  - Convert RGB number back to analog (voltage), driving the electron gun in CRT (cathode ray tube)
  - !! Light linearly related to the voltage

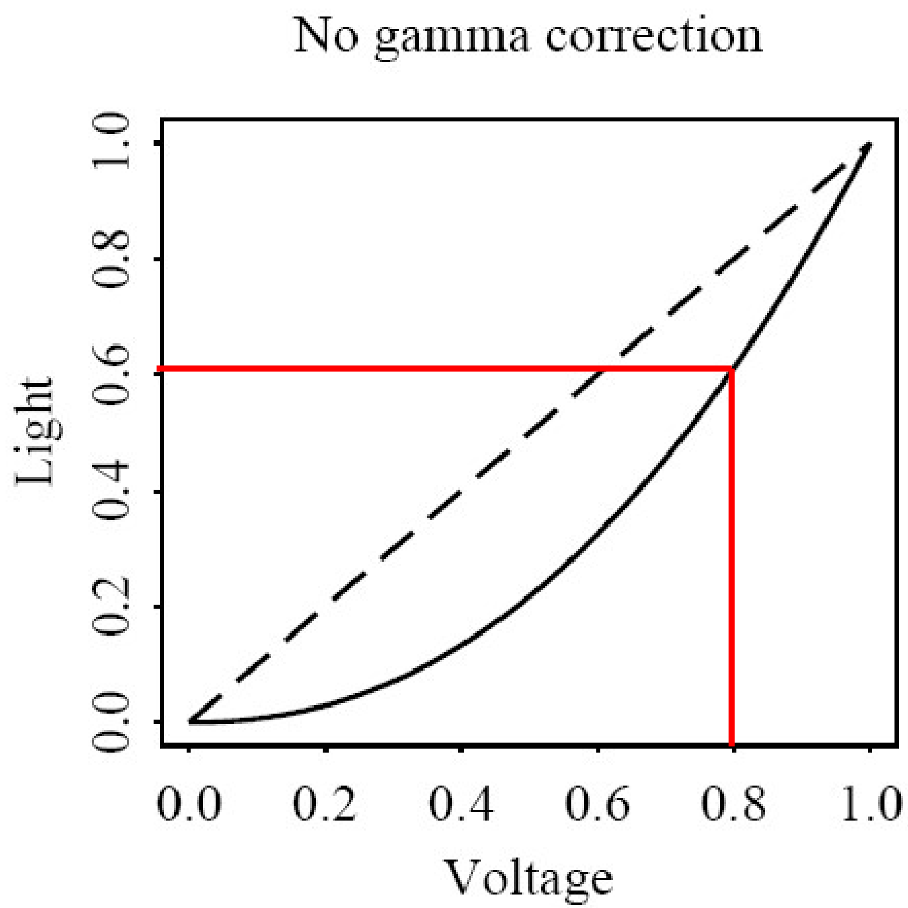


1.2 Gamma Correction

- CRT's light not linear to the driving voltage
  - Proportional to the voltage raised to a power

    $R \to R^{\gamma}$

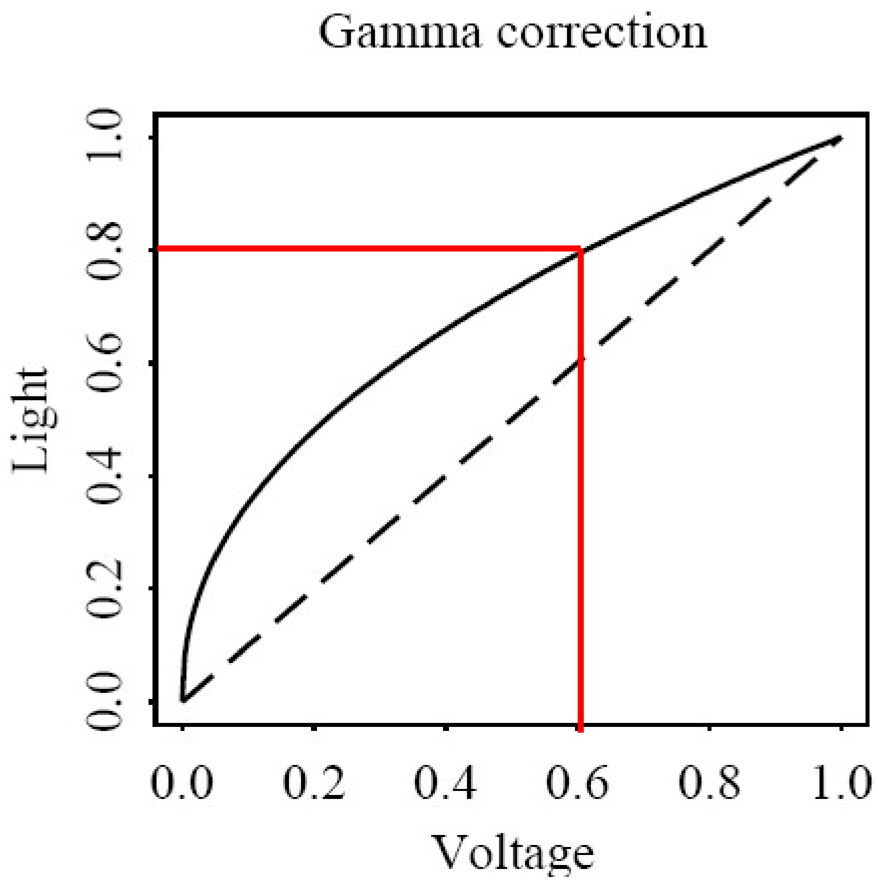
  - The power called "gamma", with the symbol γ. The value of gamma is around 2.2.



1.2 Gamma Correction

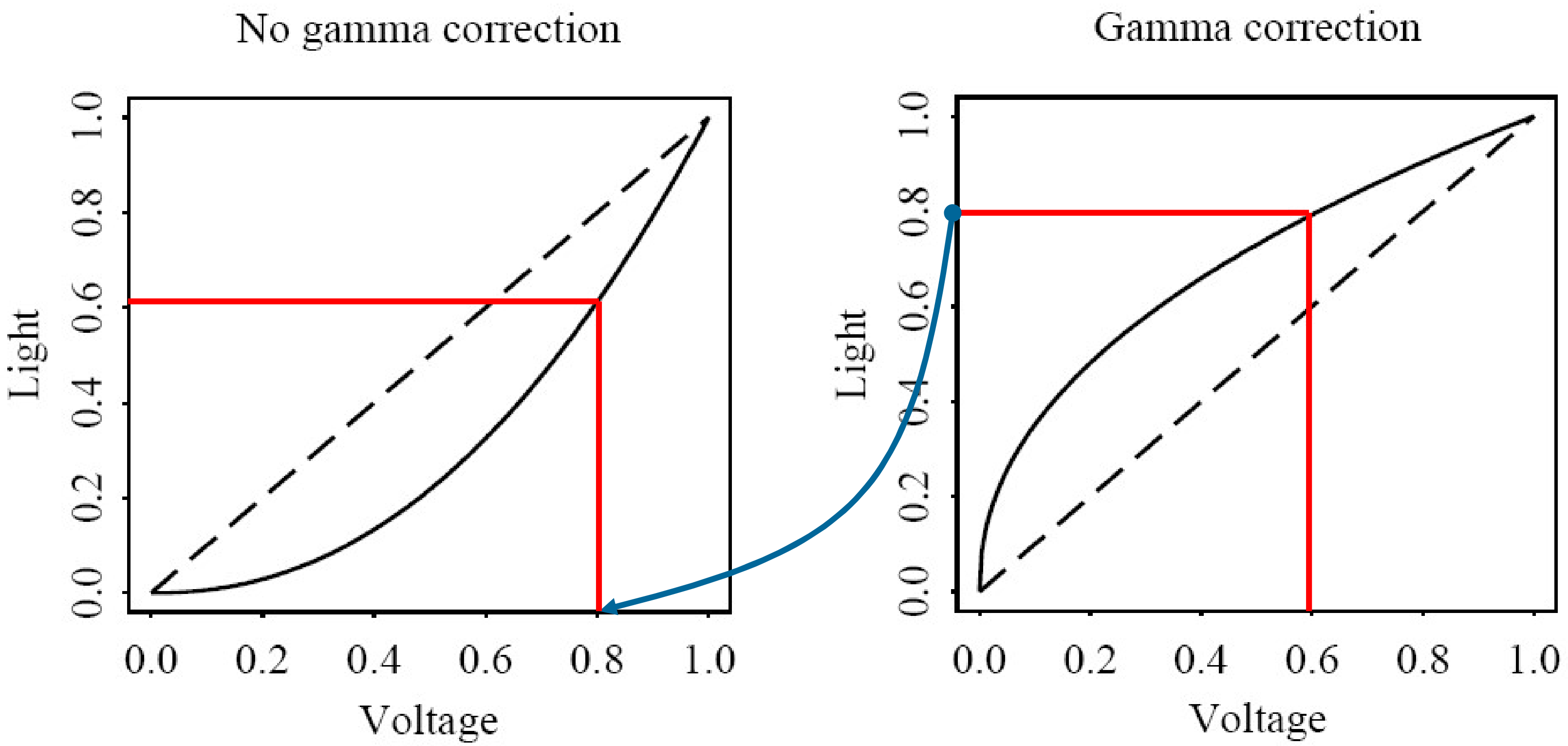
- Signal "Gamma Corrected" before transmission,
  - It is customary to append a prime to signals that are **gamma-corrected** by raising to the power $(1/\gamma)$ before transmission. Thus we arrive at **linear signals**:

$$R \rightarrow R' = R^{1/\gamma} => (R')^{\gamma} \rightarrow R$$



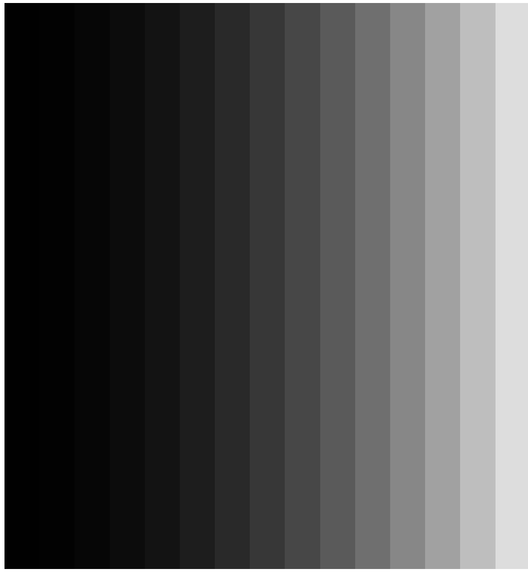
1.2 Gamma Correction

- Voltage normalized to maximum 1

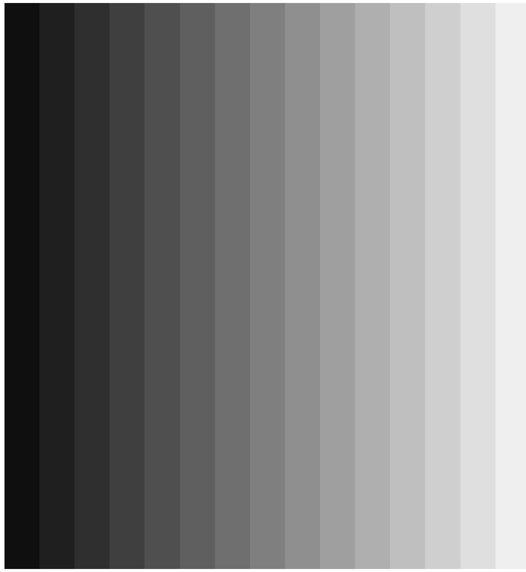


1.2 Gamma Correction

- Gamma Correction Effect
  - Example – Display of ramp from 0 to 255



With no gamma Correction



Applying gamma correction

1.2 Gamma Correction

Original image

After gamma correction

1.2 Gamma Correction

- Camera transfer function: One practical method
  - R→R' = a × $R^{1/\gamma}$ + b, with special care at the origin

$$V_{out} = \begin{cases} 4.5 \times Vin & \text{Vin} < 0.018 \\ 1.099 \times (Vin - 0.099) & \text{Vin} >= 0.018 \end{cases}$$

  - Recommended by SMPTE（The Society of Motion Picture and Television）as standard SMPTE-170

- Why a gamma of 2.2？（NTSC）
  - Actual be close to 2.8 (About = 1.25 * 2.2)
- An issue related to gamma Correction
  - What intensity level – what bit pattern in the pixel values
  - Most sensitive to ratios of level rather than absolute intensities

1.3 Color-Matching Functions

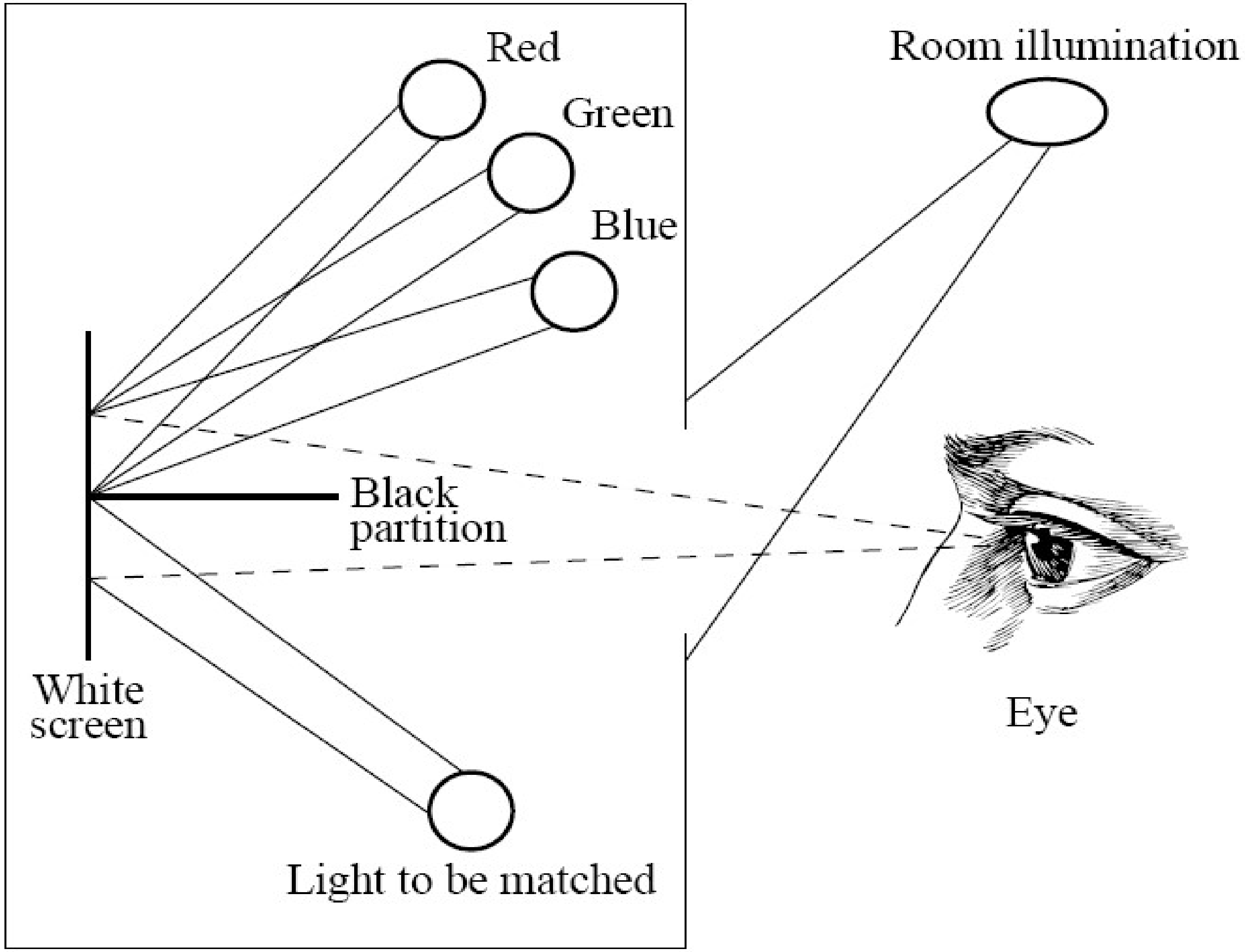
- Even without knowing the eye-sensitivity curves of Fig.4.3, a technique evolved in psychology for matching a combination of basic R, G, and B lights to a given shade.

- The particular set of three basic lights used in an experiment are called the set of **color primaries**.

- To match a given color, a subject is asked to separately adjust the brightness of the three primaries using a set of controls until the resulting spot of light most closely matches the desired color.

- The basic situation is shown in Fig.4.8. A device for carrying out such an experiment is called a **colorimeter**.

1.3 Color-Matching Functions



Red: 700nm
Green: 546.1nm
Blue: 435.8nm

Fig. 4.8: colorimeter experiment.

1.3 Color-Matching Functions

- The amounts of R, G, and B the subject selects to match each single-wavelength light forms the *color-matching curves*. These are denoted $\bar{r}(\lambda), \bar{g}(\lambda), \bar{b}(\lambda)$ and are shown in Fig. 4.9.

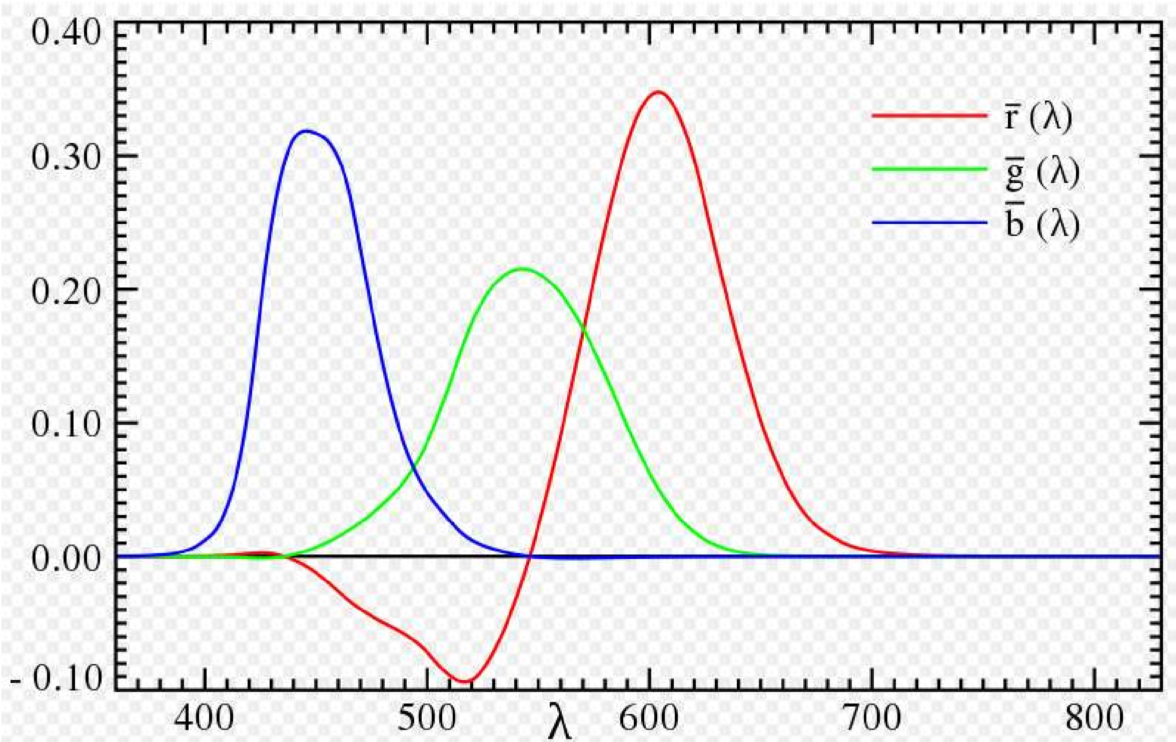


Fig. 4.9: CIE RGB color-matching functions

1.3 Color-Matching Functions

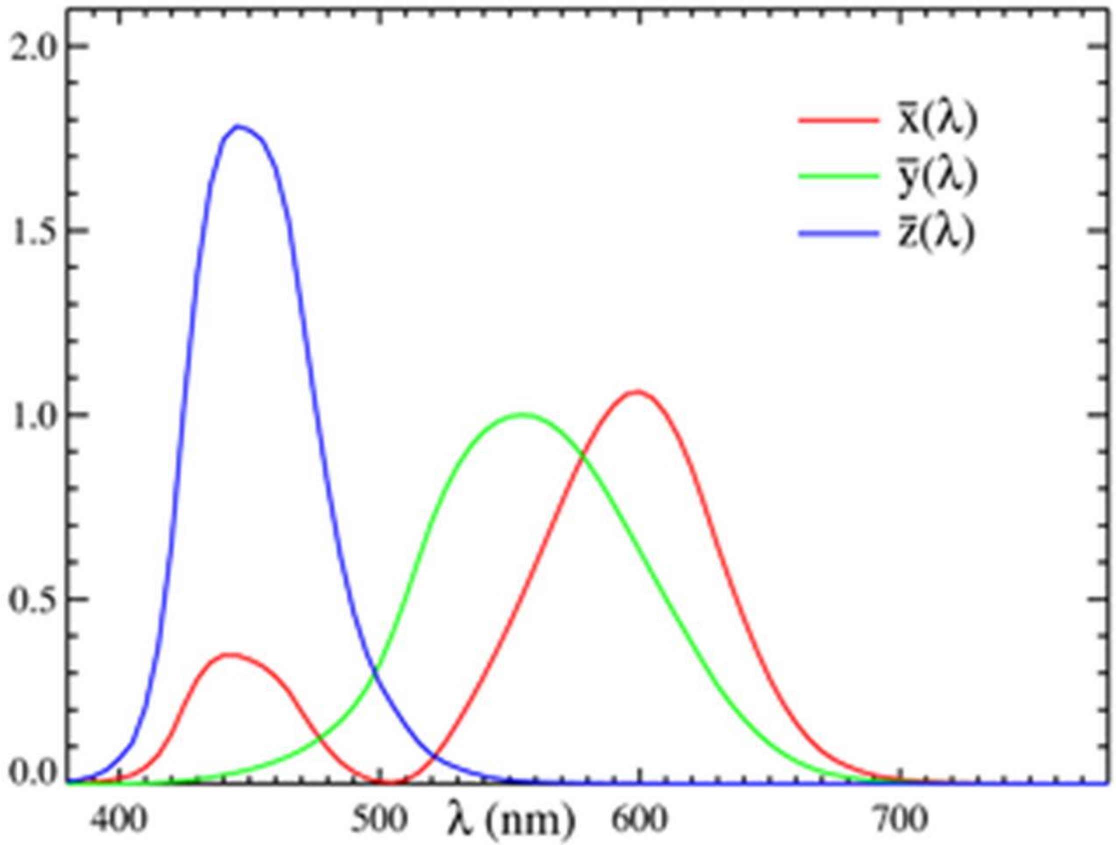
- Since the $\bar{r}(\lambda)$ color-matching curve has a negative lobe, a set of fictitious primaries were devised that lead to color-matching functions with only positives values.

(a) The resulting curves are shown in Fig. 4.10; these are usually referred to as the color-matching functions.

(b) They are a 3 $\times$ 3 matrix away from $\bar{r}, \bar{g}, \bar{b}$ curves, and are denoted $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$.

(c) The matrix is chosen such that the middle standard color-matching function $\bar{y}(\lambda)$ exactly equals the luminous-efficiency curve $V(\lambda)$ shown in Fig. 4.3.

1.3 Color-Matching Functions



$$X = \int E(\lambda)\,\overline{x}(\lambda)\,d\lambda$$

$$Y = \int E(\lambda)\,\overline{y}(\lambda)\,d\lambda$$

$$Z = \int E(\lambda)\,\overline{z}(\lambda)\,d\lambda$$

CIE standard color-matching functions: CIE XYZ Color Space

XYZ to RGB Transform

- Now the 3×3 transform matrix from XYZ to RGB is taken to be

$$T = M\,D \tag{4.15}$$

even for points other than the white point:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = T \begin{bmatrix} R \\ G \\ B \end{bmatrix} \tag{4.16}$$

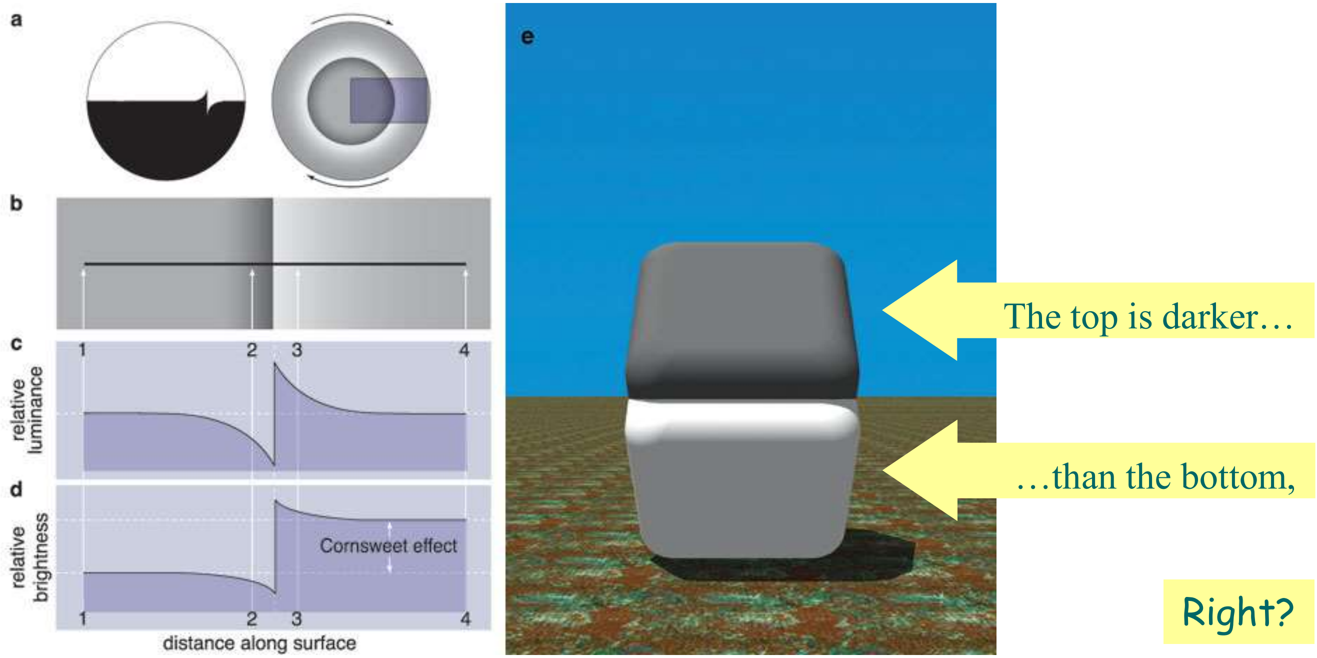
- For the SMPTE specification, we arrive at:

$$T = \begin{bmatrix} 0.3935 & 0.3653 & 0.1916 \\ 0.2124 & 0.7011 & 0.0866 \\ 0.0187 & 0.1119 & 0.9582 \end{bmatrix} \tag{4.17}$$

- Written out, this reads:

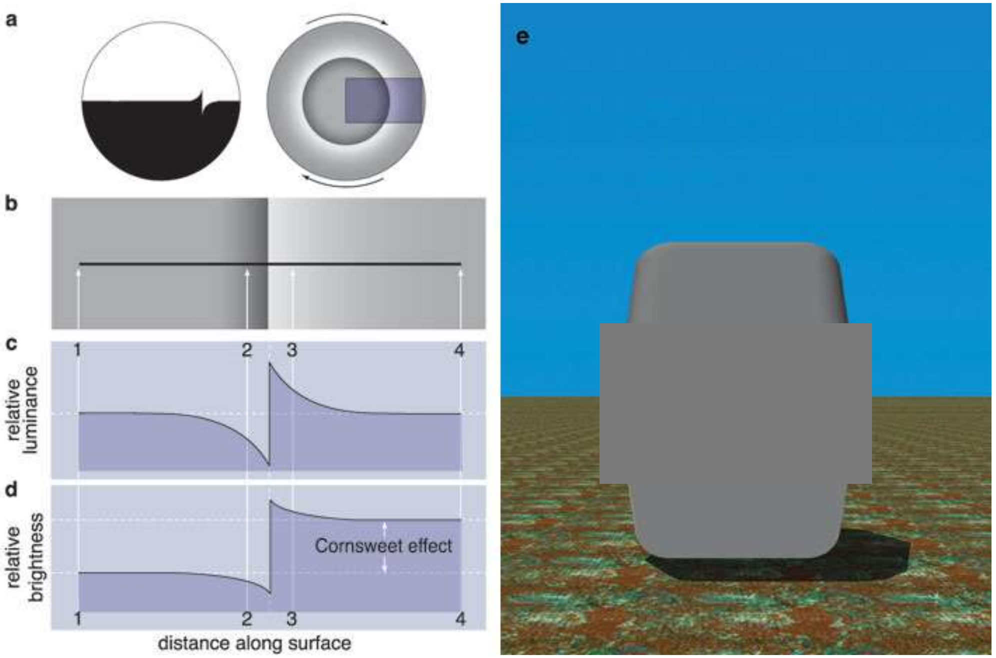
$$\begin{aligned} X &= 0.3935 \cdot R + 0.3653 \cdot G + 0.1916 \cdot B \\ Y &= 0.2124 \cdot R + 0.7011 \cdot G + 0.0866 \cdot B \\ Z &= 0.0187 \cdot R + 0.1119 \cdot G + 0.9582 \cdot B \end{aligned} \tag{4.18}$$

Color Perception: the Cornsweet Effect



Dale Purves, R. Beau Lotto, Surajit Nundy, "Why We See What We Do", *American Scientist*, Volume 90, No. 3, May-June 2002

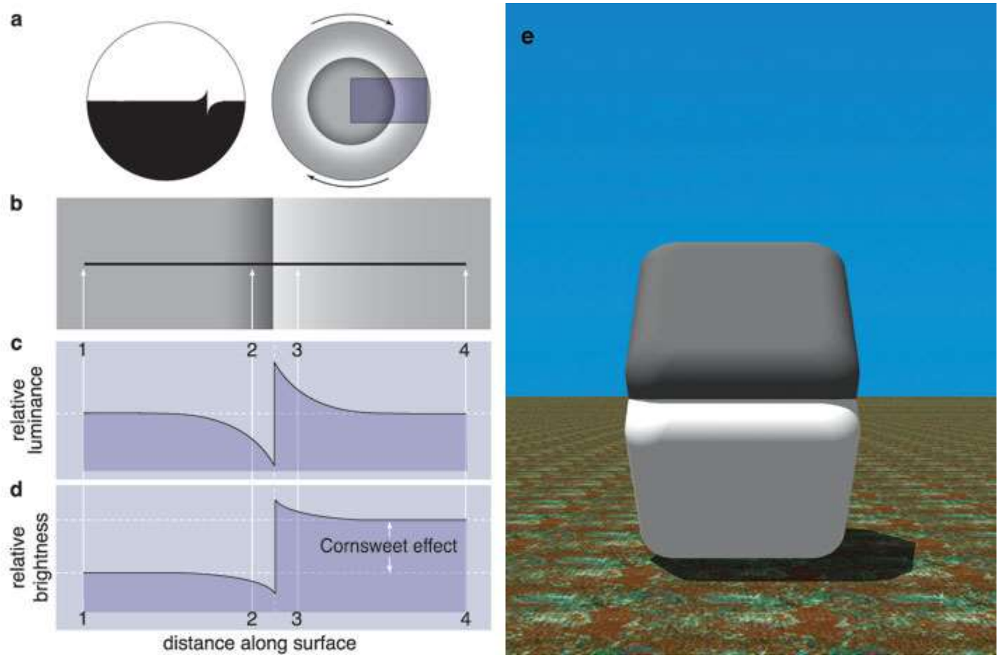
Color Perception: the Cornsweet Effect



Wrong!

Dale Purves, R. Beau Lotto, Surajit Nundy, "Why We See What We Do",
American Scientist, Volume 90, No. 3, May-June 2002

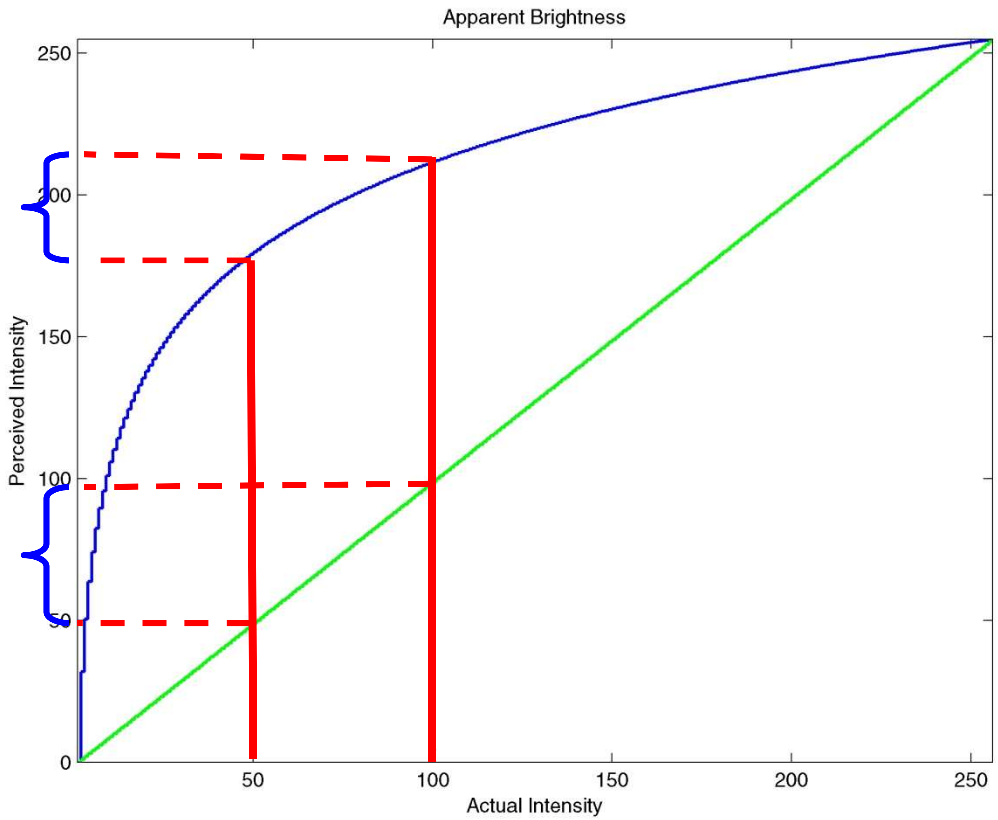
Color Perception: the Cornsweet Effect



Dale Purves, R. Beau Lotto, Surajit Nundy, "Why We See What We Do",
American Scientist, Volume 90, No. 3, May-June 2002

Brightness Perception

The linear slope of the intensity change is perceived as logarithmic.



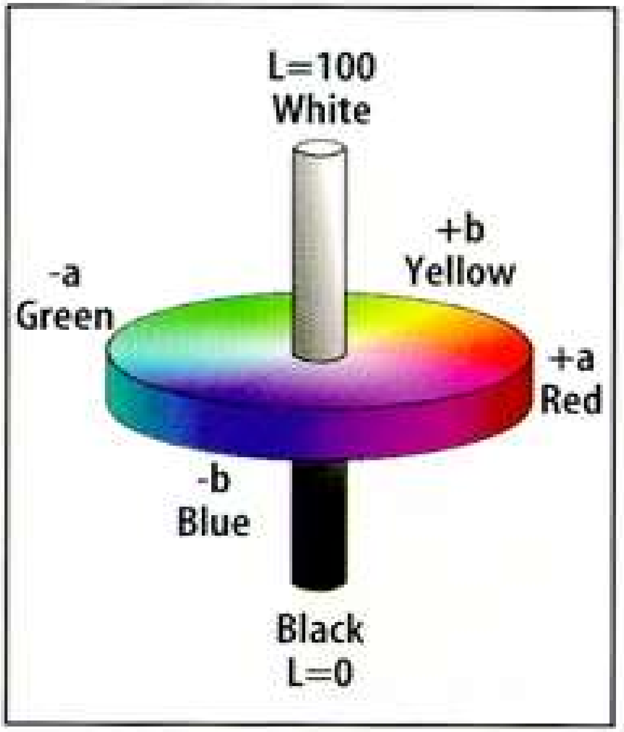
The green curve is the actual intensity; the blue curve is the perceived intensity.

1.4 L*a*b*(CIELAB) Color Model

- Weber's Law （From psychology）
  - The more there is of a quantity， the more changes there must be to perceive a difference
  - Changes are about equally perceived if the ratio of the change is the same
    - A logarithmic approximation
    - 50->100, 100%
    - 100->150, 50%

1.5 L*a*b*(CIELAB) Color Model

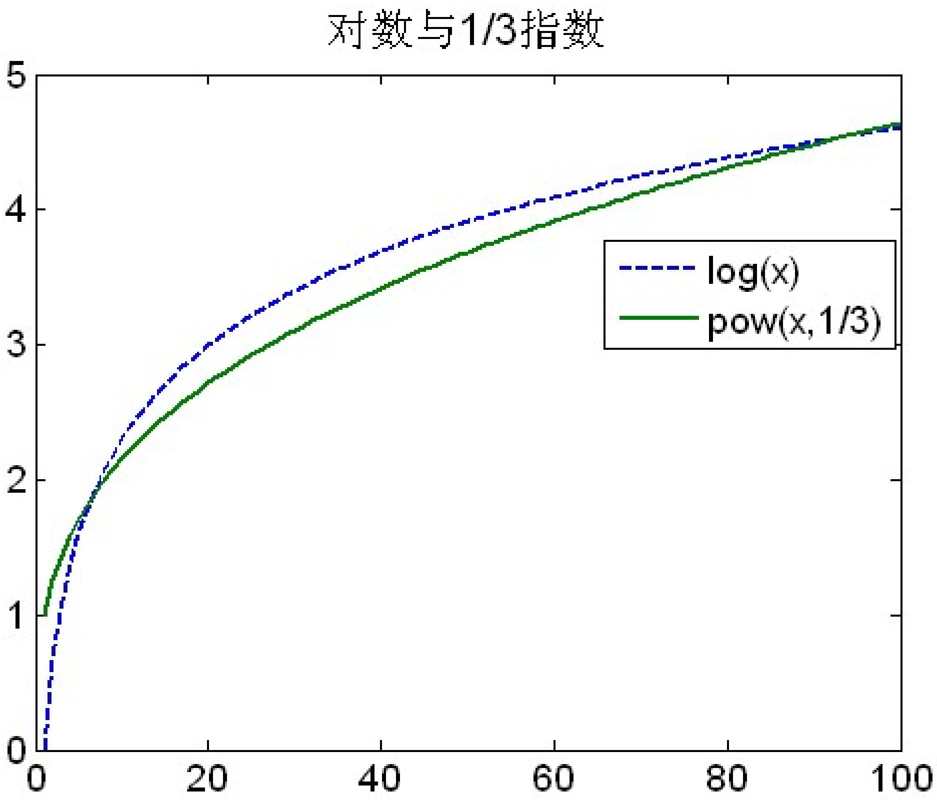
- CIE – Human vision: CIELAB space, called L*a*b*
  - Three value – Luminance, Colorfulness and Hue
  - Using Power law of 1/3 – instead of logarithm



Lab model

1.3 L*a*b*(CIELAB) Color Model

- Logarithm close to the power law of 1/3



1.3 L*a*b*(CIELAB) Color Model

- The color difference is defined as

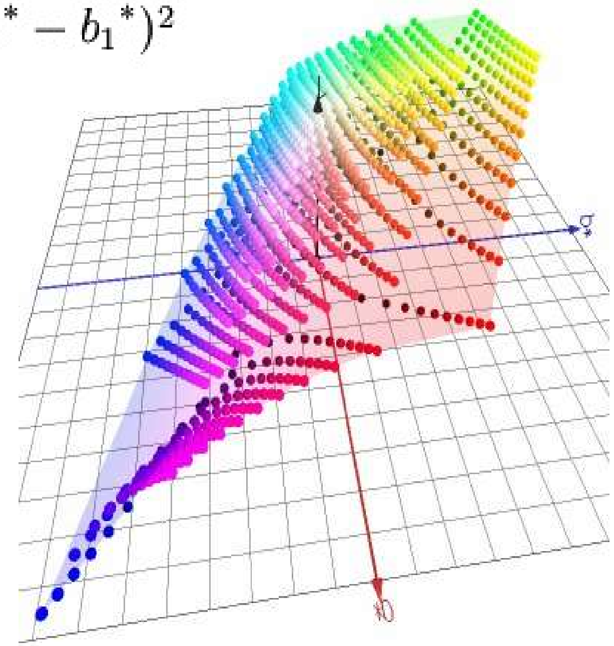
$$\Delta E^*_{ab} = \sqrt{(L_2{}^* - L_1{}^*)^2 + (a_2{}^* - a_1{}^*)^2 + (b_2{}^* - b_1{}^*)^2}$$

where,

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

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

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

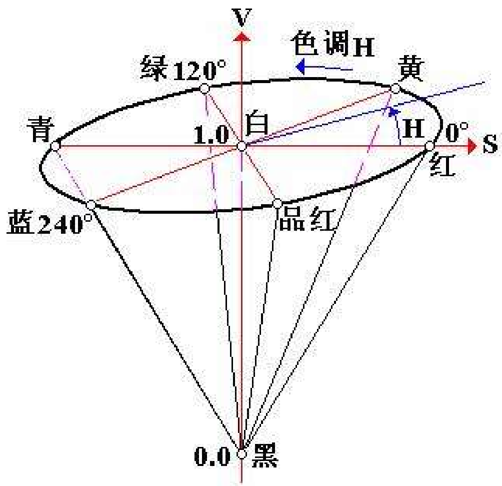


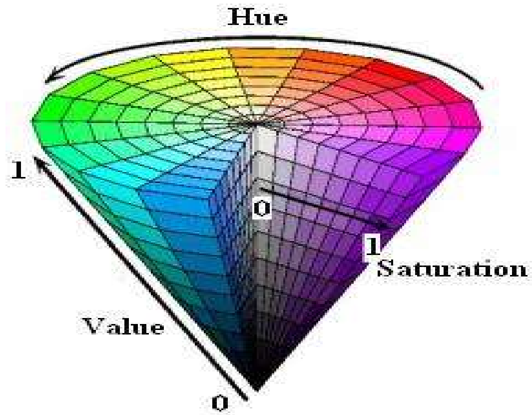
L*a*b* space

With Xn, Yn, Zn the XYZ value of the white point

1.4 Other color models

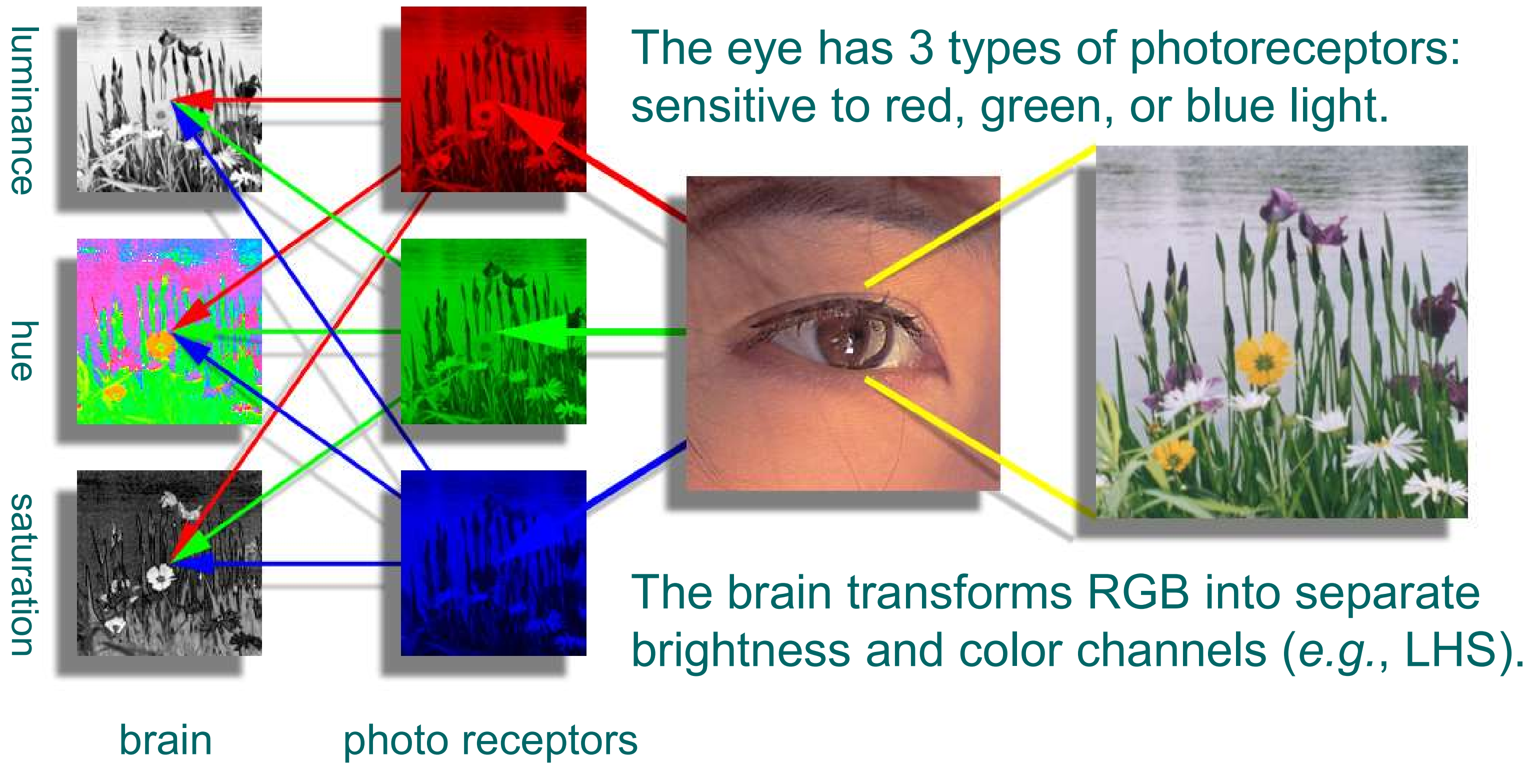
- HSL(HSB) – Hue, Saturation, Lightness/Brightness.
- HSV --Hue Saturation Value
- HIS -- Hue, Saturation and Intensity
- HCI -- C= Chroma
- HVC -- V = value
- HSD -- D=Darkness
- CMY
- …





1.4 Other color models

In the Brain: from RGB to LHS

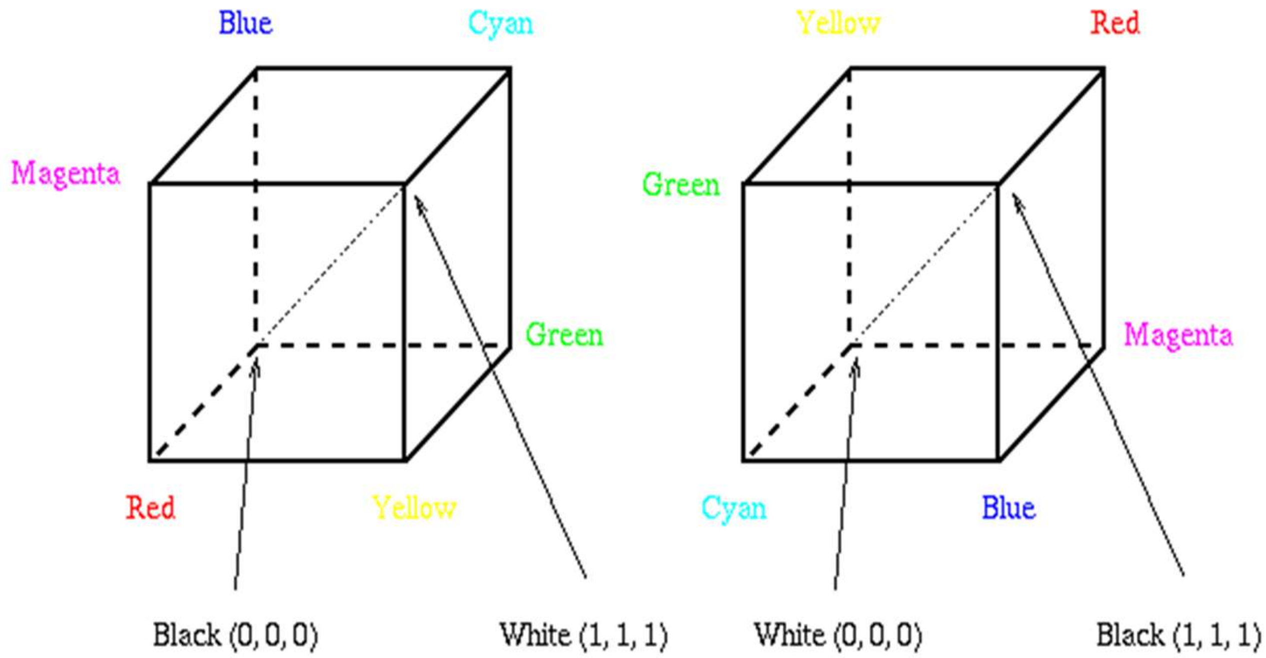


2. Color Models in Images

- RGB color model for CRT Display
- CMY color model
- Transformation from RBG to CMY
- CMYK color system

2.1 RGB model for CRT display

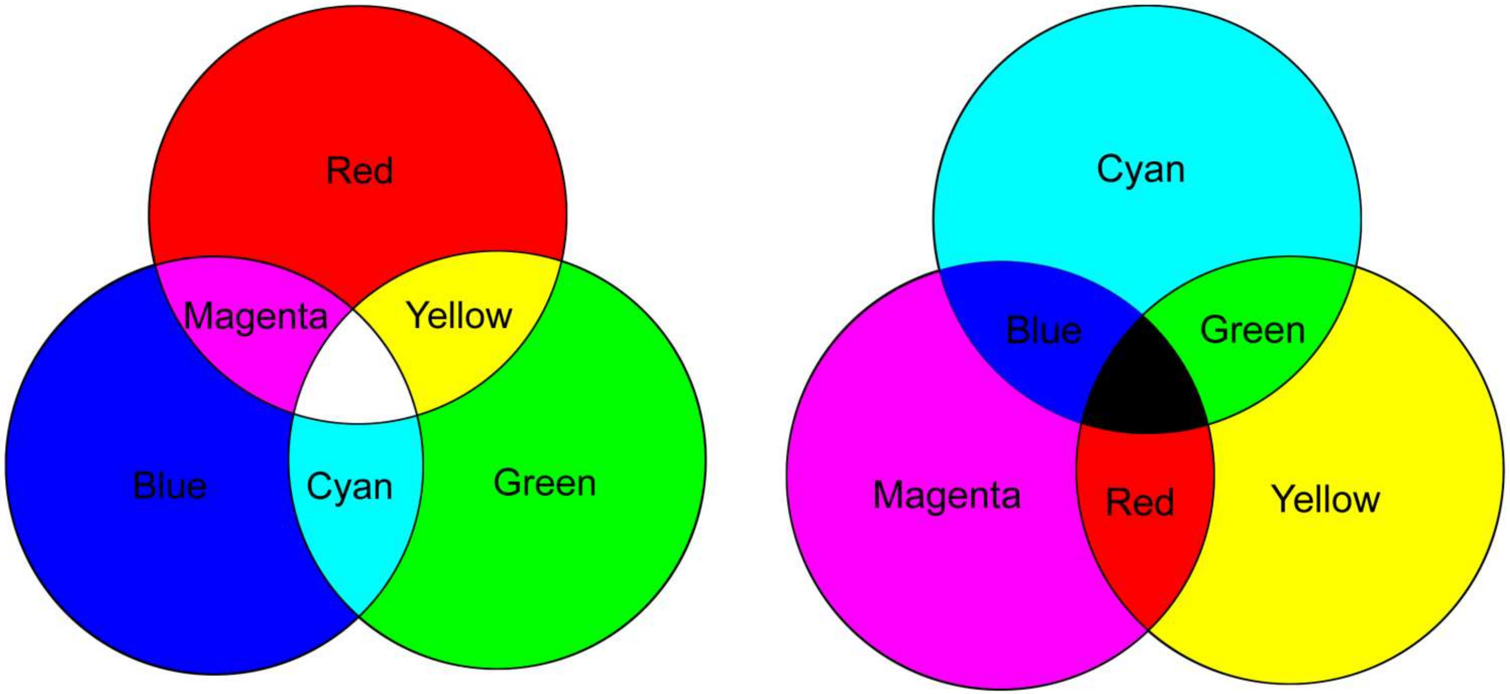
- Store integers proportional to intensity in frame buffer
- Gamma Correction



The RGB Cube

The CMY Cube

2.2 Subtractive Color: CMY



Additive and subtractive color

RGB is additive color; CMYK is subtractive color

2.3 Transformation from RBG to CMY

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

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

The inverse transform

2.4 Under color Removal : CMYK

$$K \equiv \min\{\, C, M, Y \,\}$$

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

CMYK system get the “true” black by adding K component

3. Color Models in Video

- YUV Color Model
- YIQ Color Model
- YCbCr Color Model

3. Color Models in Video

- **Video Color Transforms**

  (a) Largely derive from older analog methods of coding color for TV. Luminance is separated from color information.

  (b) For example, a matrix transform method similar to Eq. (4.9) called YIQ is used to transmit TV signals in North America and Japan.

  (c) In Europe, video tape uses the PAL or SECAM codings, which are based on TV that uses a matrix transform called YUV.

  (d) Finally, digital video mostly uses a matrix transform called YCbCr that is closely related to YUV

3.1 YUV Color Model

- YUV – for PAL analog video, also CCIR 601 standard for digital video
  - $Y = 0.299R + 0.587G + 0.114B$
  - *Chrominance*(色度) as:

$$U = B - Y$$
$$V = R - Y$$

  - U = V = 0. No chrominance!

3.1 YUV Color Model

- After gamma correction (R', G', B')

$$U = B' - Y'$$

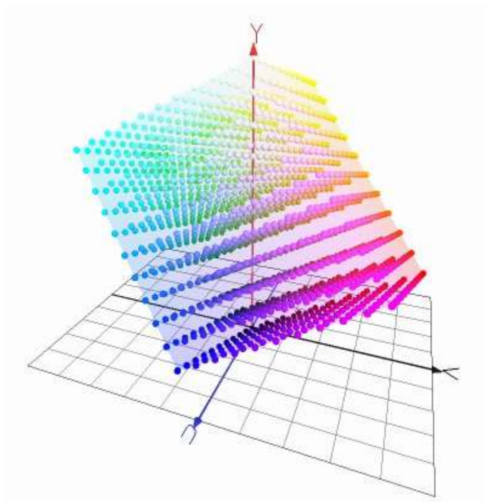
$$V = R' - Y'$$

$$\begin{bmatrix} Y' \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.144 \\ -0.299 & -0.587 & 0.886 \\ 0.701 & -0.587 & -0.114 \end{bmatrix} \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix}$$

- In PAL application

U = 0.492 (B' – Y')

V = 0.877 (R' – Y')



YUV space

3.1 YUV Color Model

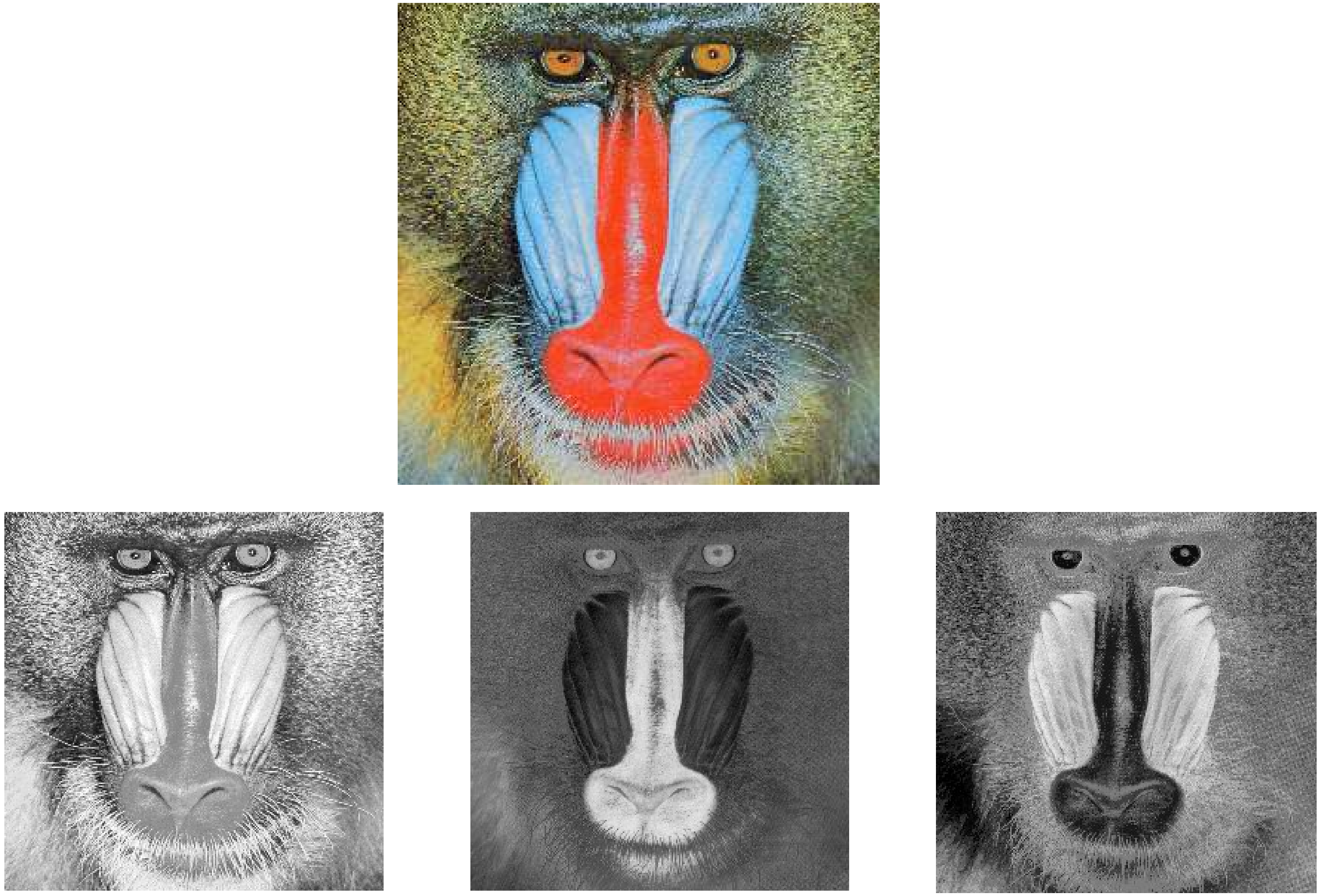


Fig. 4.18: Y ′UV decomposition of color image. Top image (a) is original color image; (b) is Y ′; (c,d) are (U, V)

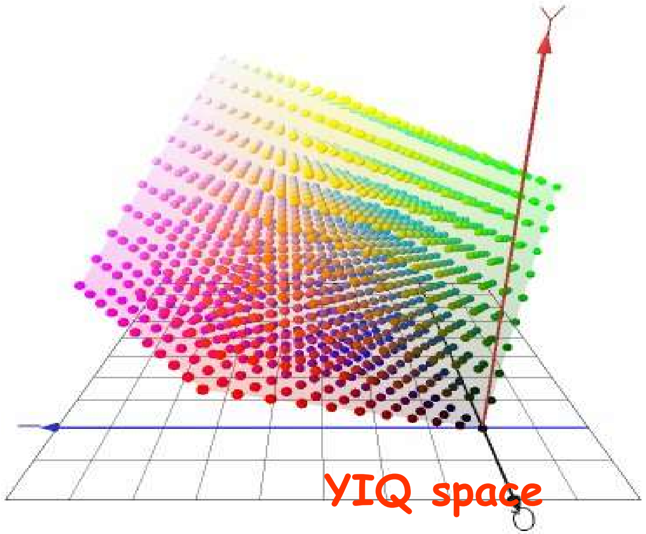
3.2 YIQ Color Model

- YIQ -- NTSC color TV broadcasting,
  - Adapt to black-white TV (only Y)
- U and V not capture the most-to-least hierarchy of human vision sensitivity
  - I and Q used in NTSC, instead of U,V.
- I -- orange-blue , Q -- purple-green
  - I and Q obtained by rotating R - Y and B – Y with 33°.

$$I = 0.877(R - Y)\cos 33 - 0.492(B - Y)\sin 33$$
$$Q = 0.877(R - Y)\sin 33 + 0.492(B - Y)\cos 33$$

3.2 YIQ color Model

- Leading to the follow equations:
  - $I = 0.736(R - Y) - 0.268(B - Y) = 0.596R - 0.275G - 0.321B$
  - $Q = 0.478(R - Y) + 0.413(B - Y) = 0.212R - 0.523G + 0.311B$
- Most sensitivity to Y, then to I, Least to Q
  - In NTSC Broadcasting, the bandwidth for each components as follows:
    - 4.2 MHz is allocated to Y
    - 1.5 MHz to I
    - 0.55 MHz to Q



3.2 YIQ color Model

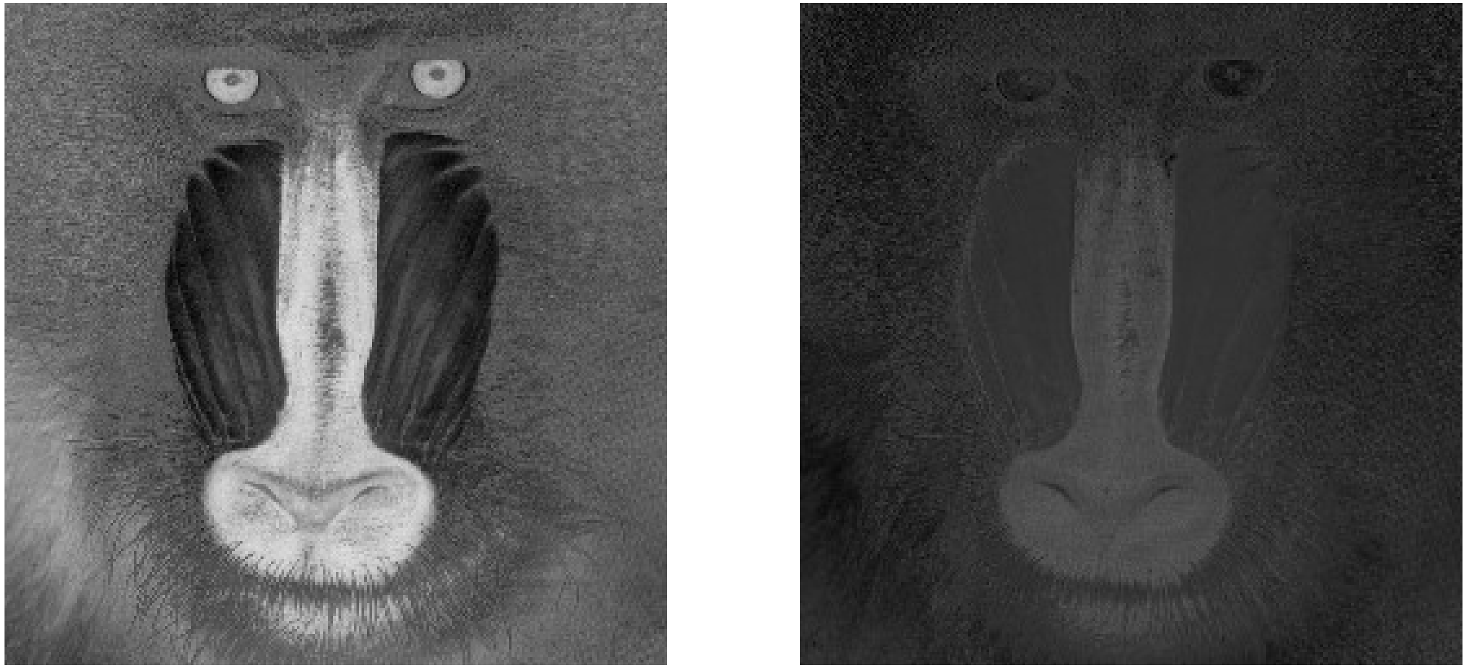


Fig.4.19: I and Q components of color image.

3.3 YCbCr Color Model

- YCbCr – ITU-R BT.601-4
- YCbCr model closely related to YUV
  - Cb = (B - Y) / 1.772 + 0.5
  - Cr = (R - Y) / 1.402 + 0.5

$$\begin{bmatrix} Y' \\ C_b \\ C_r \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ -0.168736 & -0.331264 & 0.5 \\ 0.5 & -0.418688 & -0.081312 \end{bmatrix} \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} + \begin{bmatrix} 0 \\ 0.5 \\ 0.5 \end{bmatrix}$$

- YCbCr is widely used in JPEG image compression and MPEG video compression.

The End

Thanks！

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