CSCI435/CSCI935
Computer Vision: Algorithms & Systems

Photometry and Colorimetry

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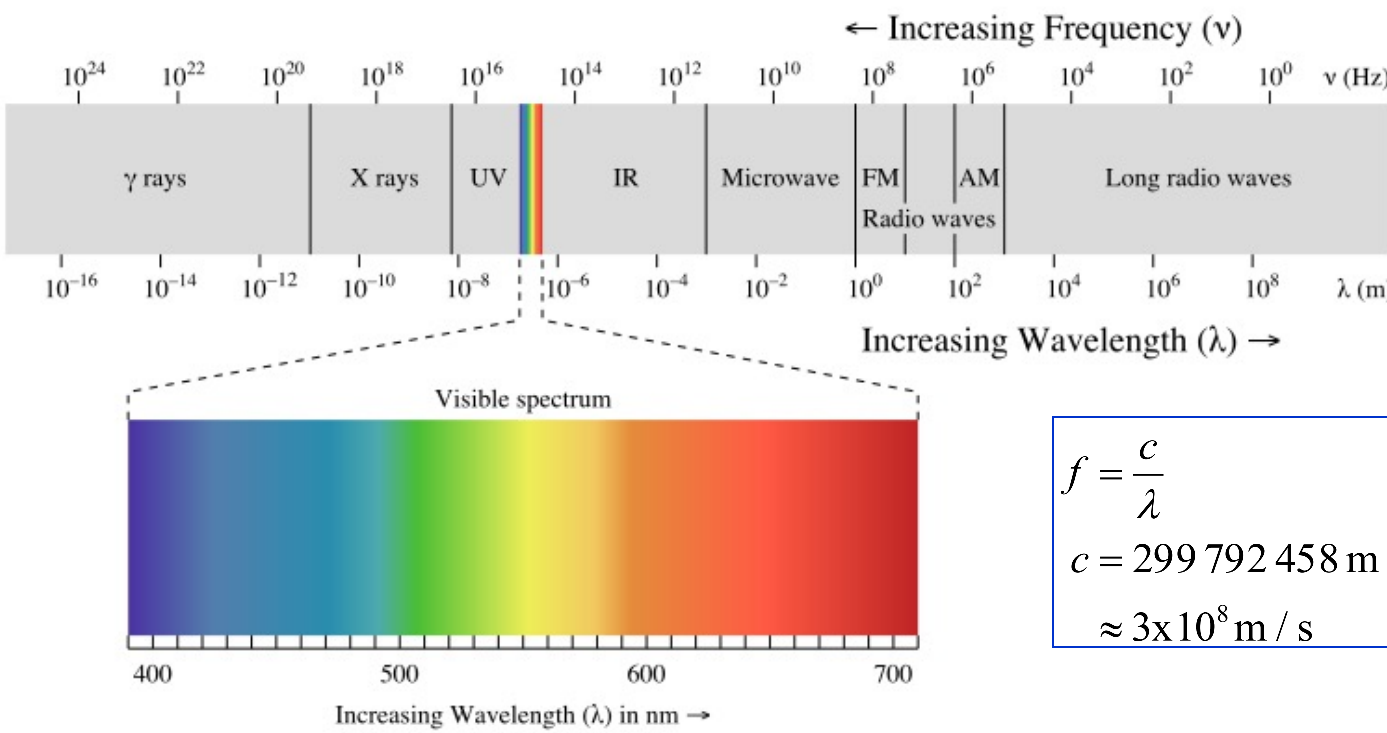
What is Light?



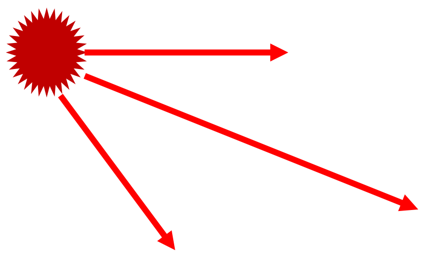
$$f = \frac{c}{\lambda}$$

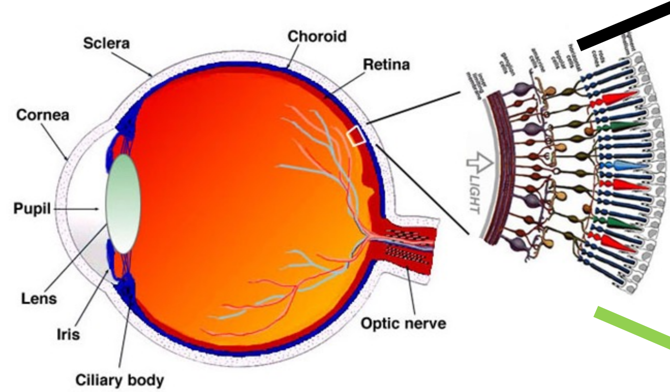
$$c = 299\,792\,458 \text{ m/s}$$

$$\approx 3\text{x}10^{8} \text{ m/s}$$

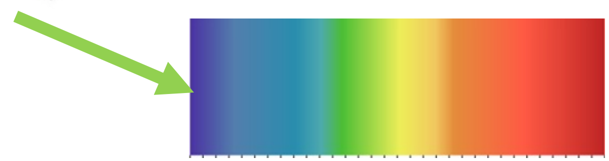
- Light is electromagnetic radiation that travels as electromagnetic waves
- There is no fundamental difference between light and radio waves

Radiometry, Photometry & Colorimetry





Photometry



Colorimetry

Radiometry

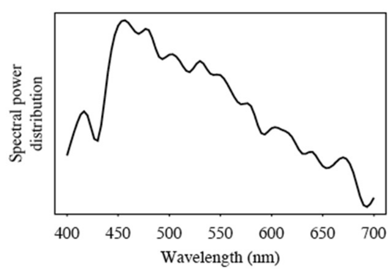


Fig. 4.2: Spectral power distribution of daylight.

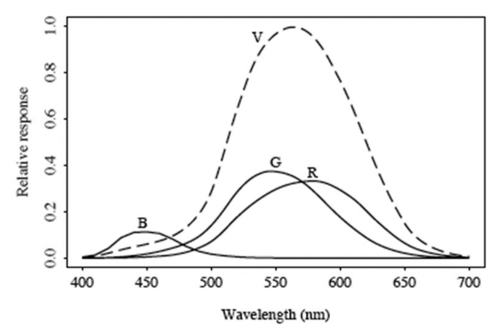


Image Formation

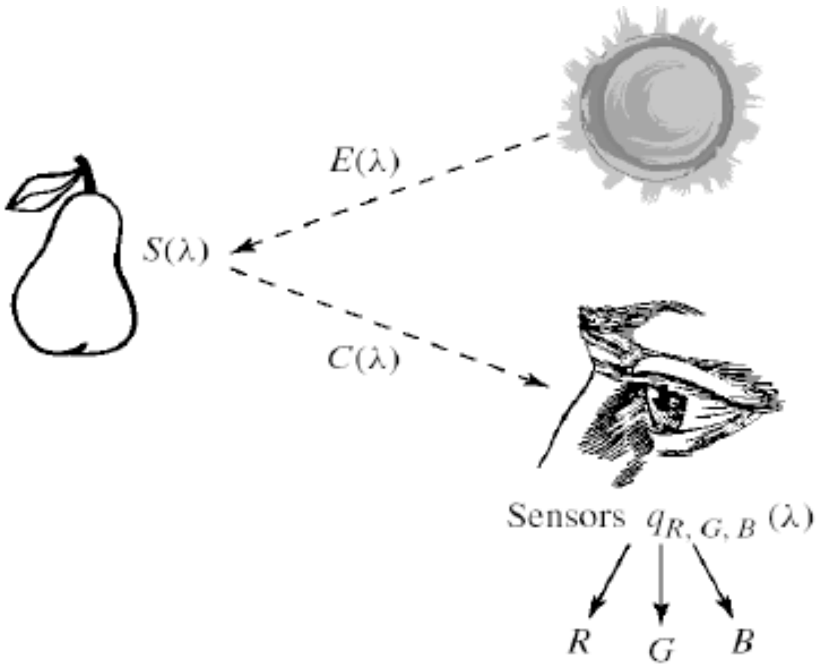


Fig. 4.5: Image formation model.

- Surfaces reflect different amounts of light at different wavelengths, and dark surfaces reflect less energy than light surfaces.

$$C(\lambda) = E(\lambda)\,S(\lambda).$$

Typical Outdoor Light

- Fig. 4.2 shows the relative power in each wavelength interval for typical outdoor light on a sunny day. This type of curve is called a Spectral Power Distribution (SPD) or a **spectrum**.

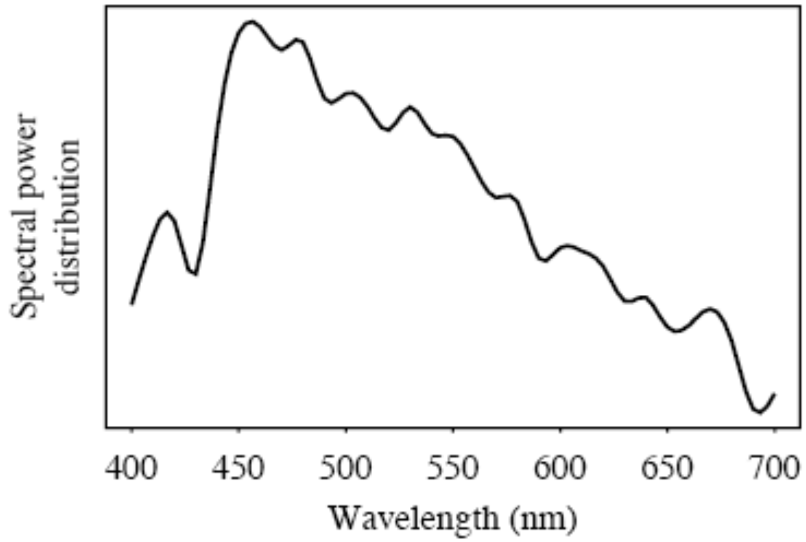
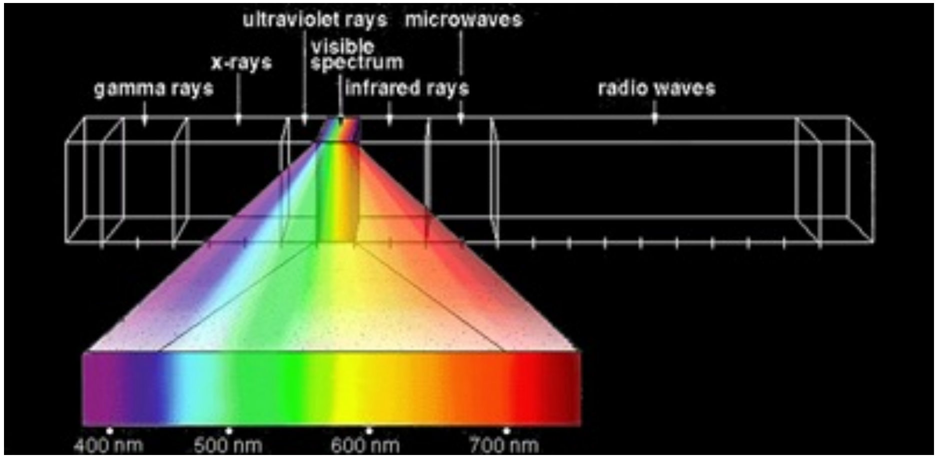


Fig. 4.2: Spectral power distribution of daylight.

Outdoor light is a mixture of waves with various wavelengths

What is Color?

- Color is a subjective sensation produced in the brain when the eyes are exposed to light
- Colour is characterized by the wavelength content of the light
  - Laser light consists of a single wavelength: e.g., a ruby laser produces a bright-red beam.
  - Short wavelengths produce a blue sensation, long wavelengths produce a red one



Receptors

- Human eyes have two types of receptors
  - Rods
    - night vision
    - cannot distinguish color
  - Cones
    - color vision
    - comes in three different sorts that respond to three different groups of wavelengths of light (*tristimulus theory*)

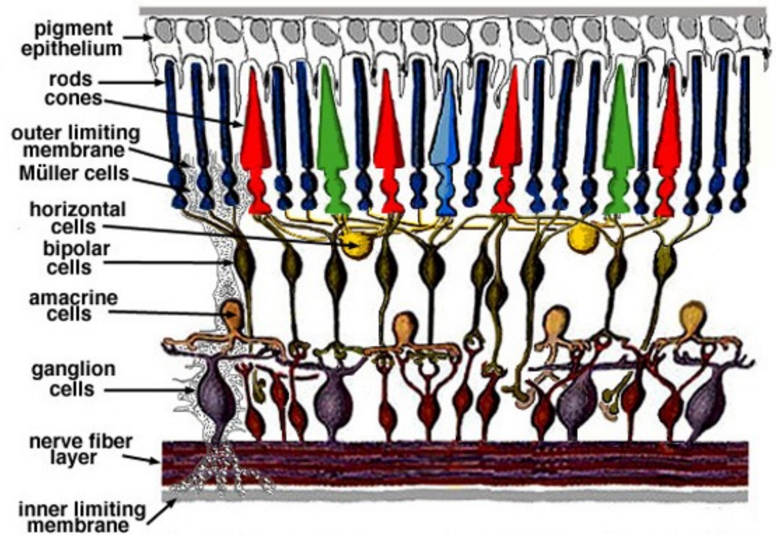
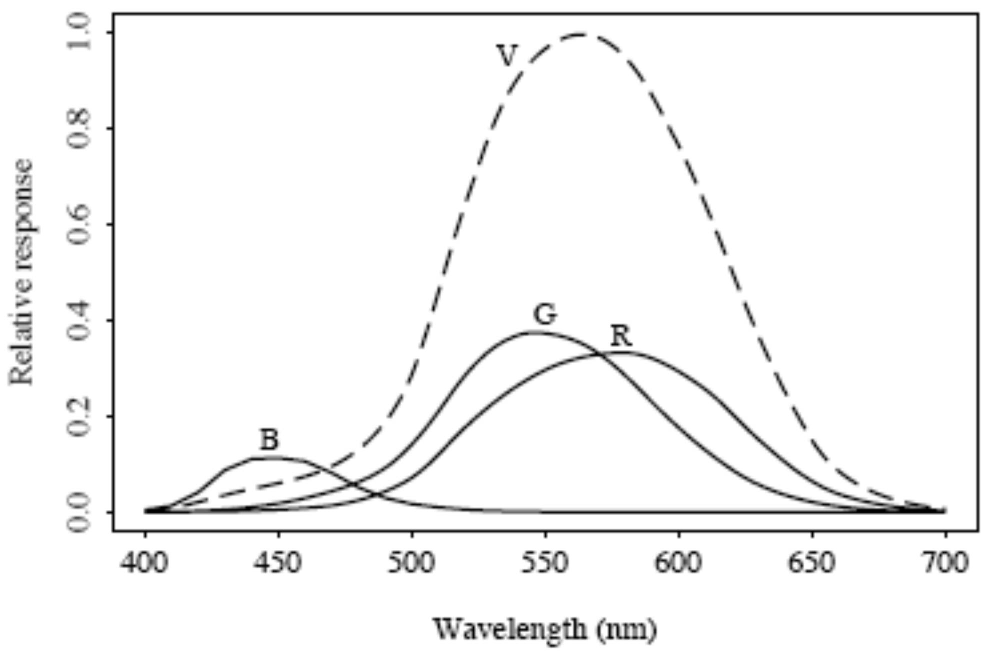


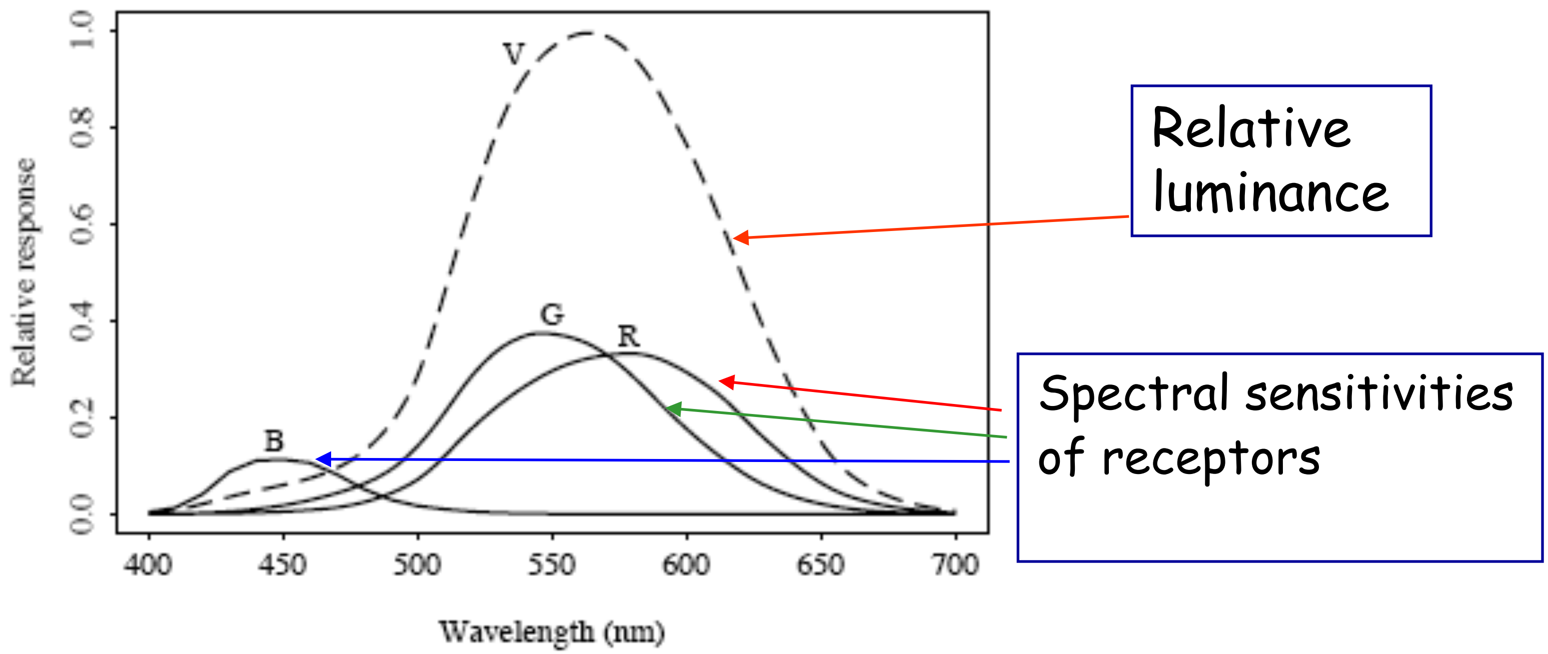
Fig. 2. Simple diagram of the organization of the retina.

Sensitivity of Receptors

- The eye is most sensitive to light in the middle of the visible spectrum.
  - The sensitivity of our *receptors* is also a function of wavelength



Luminance or Intensity



$$L = \int C(\lambda)V(\lambda)d\lambda$$

Perceptual brightness is not the same as luminance L

Weber's Law

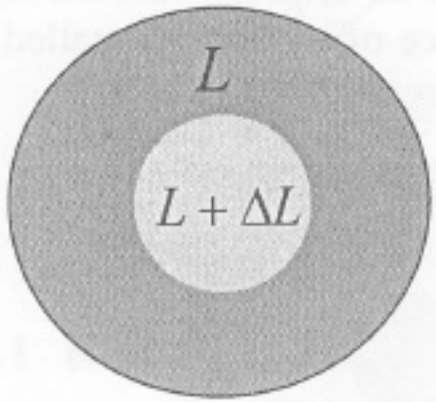


Figure 3.6. Contrast and luminance

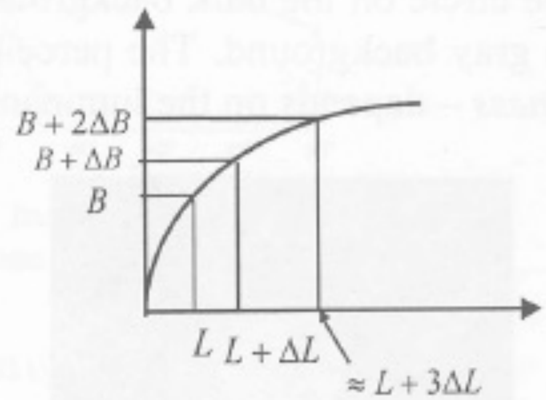


Figure 3.7. Brightness (B) and luminance (L)

- If ΔL is zero, the two regions are indistinguishable.
- If we slowly increase ΔL from zero. For a certain value of ΔL, the contrast of the two region will just be noticeable.
- Let this value be denoted as ΔL_N

Weber's Law…

- Weber-Fechner found that the ratio between ΔL_N and L is a constant (Weber's Law)

$$\frac{\Delta L_N}{L} = k$$

- k is about 0.02

- Weber's law also leads to the logarithmic relationship between the brightness and luminance

$$B = c \log L + d$$

Color Perception Of Objects

- Given three spectral sensitivity functions $q_R(\lambda)$, $q_G(\lambda)$ and $q_B(\lambda)$

  Illuminance perceived by the receptors can be calculated as

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

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

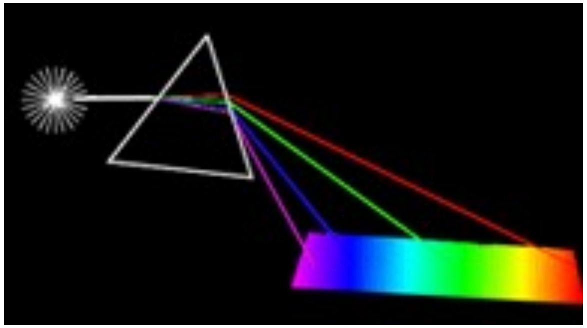
$$B = \int E(\lambda)\, S(\lambda)\, q_B(\lambda)\, d\lambda$$

Regardless how complex the spectrum $\boldsymbol{E(\lambda)}$ is, it is perceived as the tristimulus $\boldsymbol{R, G, B}$

Color Representation

- The *tristimulus theory* suggests that any color can be represented as three values R, G and B

- These three components
  - are called ***primary colors***
  - form ***color space***



RGB color space

- Color Primaries
  - Red
  - Green
  - Blue
- Any color can be represented or reproduced as a linear combination of R, G and B
- How much R, G and B needed for a particular color?
  - Color matching experiments using colorimeter

Red+Green+Blue=White

Colorimeter Experiment

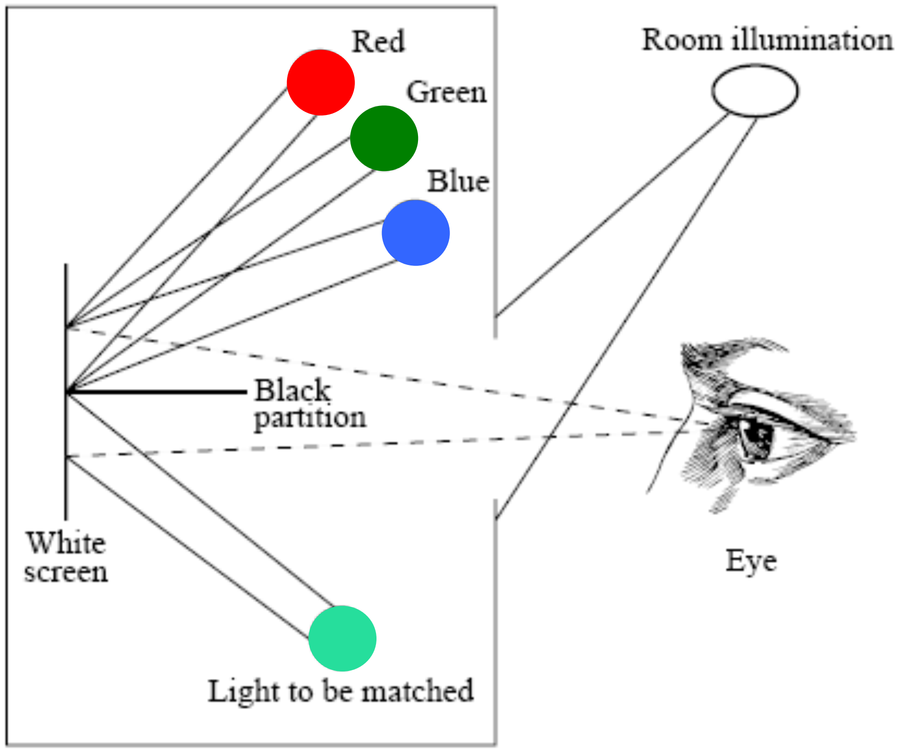
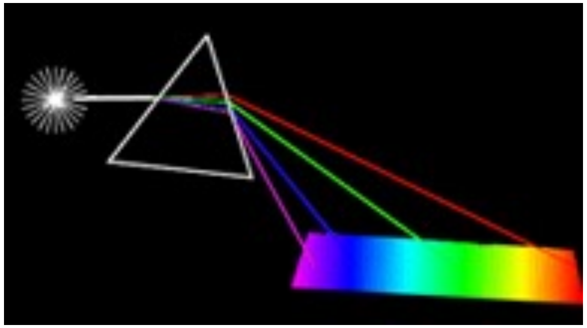
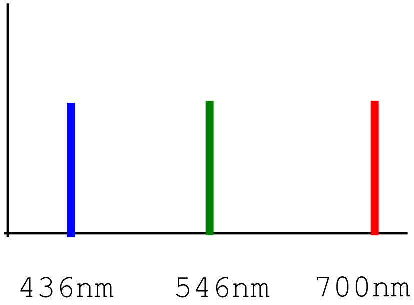


Fig. 4.8: Colorimeter experiment.

What Red, Green and Blue are?

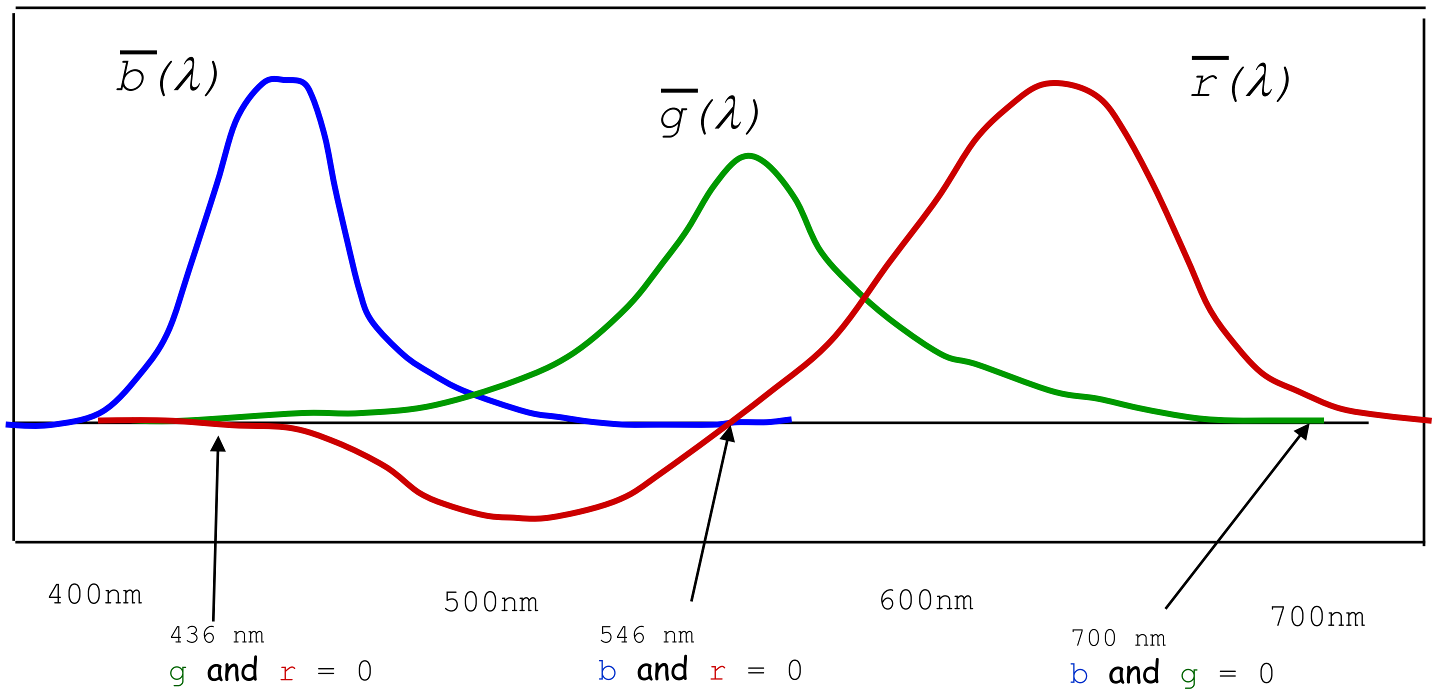




Red, Green and Blue stimuli standardised by CIE

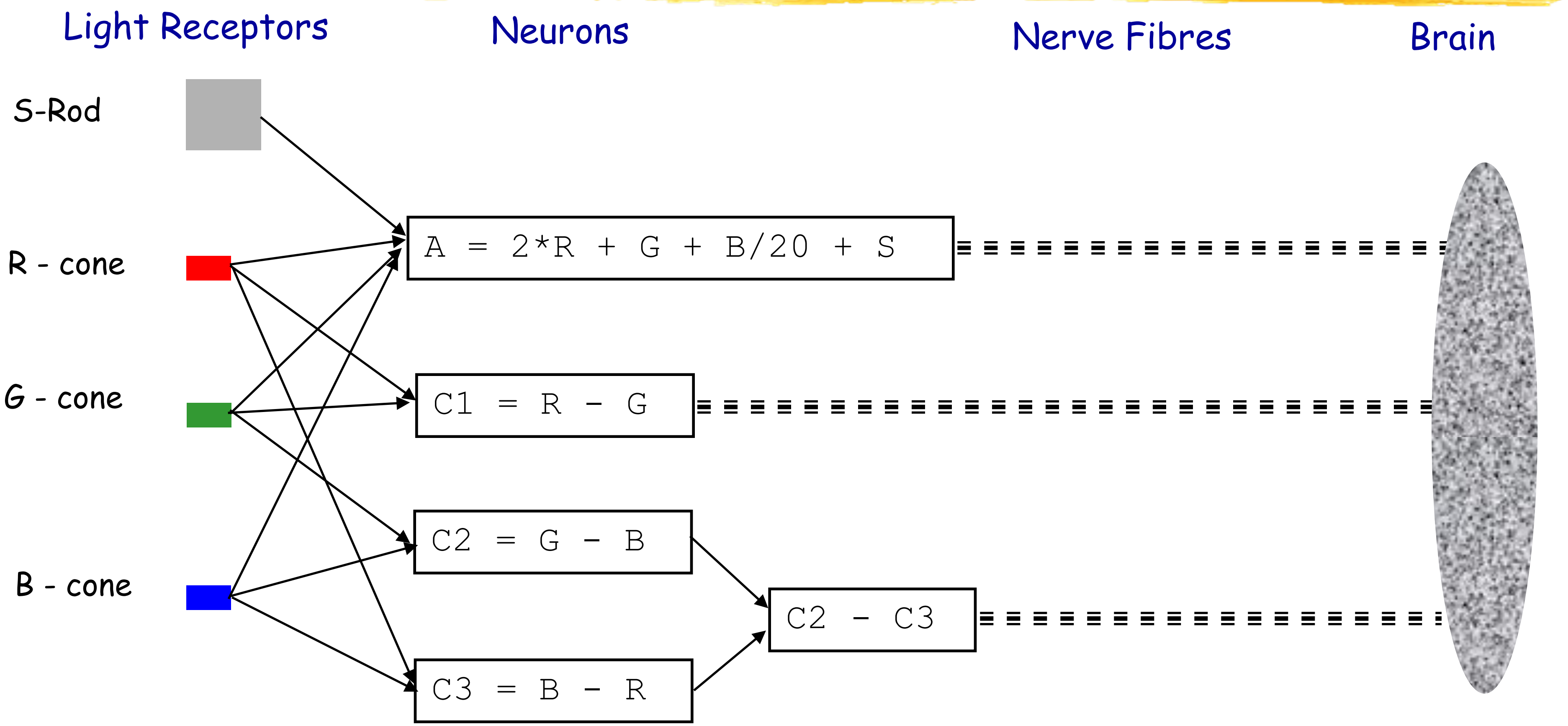
CIE Color Matching Functions

- In 1931 CIE (Commission Internationale de L'Eclarirage) run experiments to measure matching functions $b(\lambda)$, $g(\lambda)$ and $r(\lambda)$



The measured colour matching functions $\overline{b}(\lambda)$, $\overline{g}(\lambda)$ and $\overline{r}(\lambda)$ differ from spectral sensitivity of receptors $q_R(\lambda)$, $q_G(\lambda)$ and $q_B(\lambda)$

Visual Data Transmission



Shape of colour matching functions depends on spectral sensitivity of receptors, neuron processing and brain

Major Conclusions

1. Some of the colour matching functions have negative values. As a result, physical devices (TV, displays, etc) cannot reproduce some colours

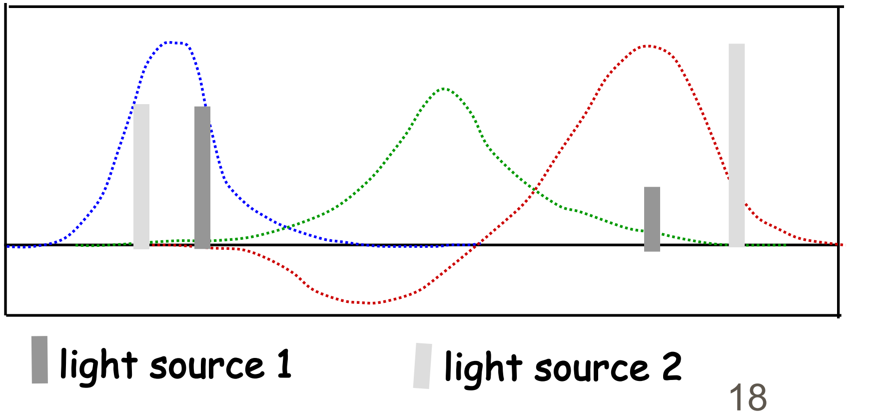
2. If a TV, or a display uses R, G, B emission with parameters different from those standardised by CIE, the colour matching functions have to be corrected

3. Integrated stimulation of cones may create identical r, g, b from light sources with different spectrums. Different light sources (in terms of their spectral composition) which visually look identical are called metameric

$$r = \int S_1(\lambda)\,\bar{r}(\lambda)\,d\lambda = \int S_2(\lambda)\,\bar{r}(\lambda)\,d\lambda$$

$$g = \int S_1(\lambda)\,\bar{g}(\lambda)\,d\lambda = \int S_2(\lambda)\,\bar{g}(\lambda)\,d\lambda$$

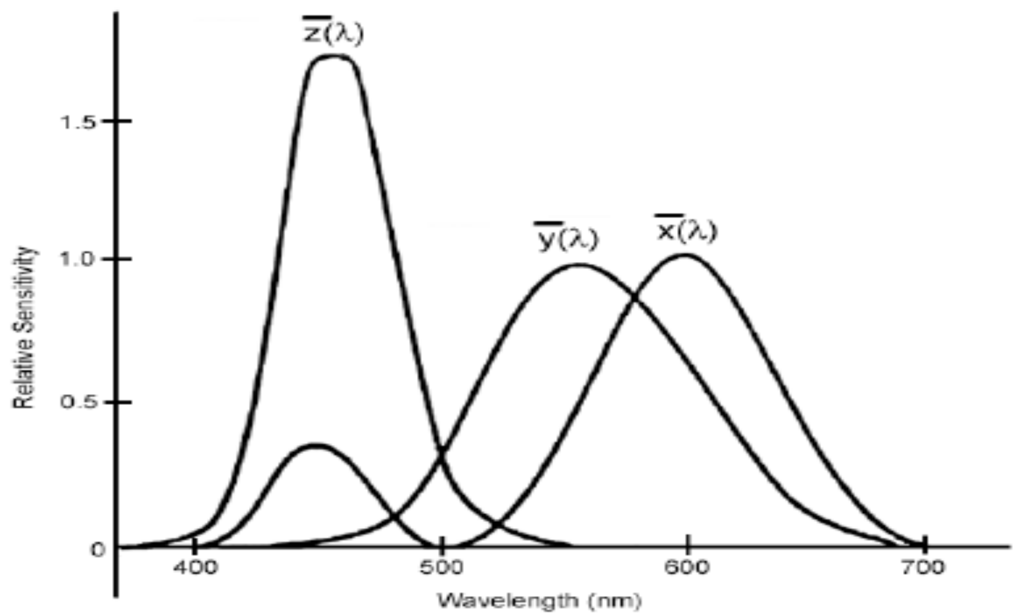
$$b = \int S_1(\lambda)\,\bar{b}(\lambda)\,d\lambda = \int S_2(\lambda)\,\bar{b}(\lambda)\,d\lambda$$



CIE XYZ Color Matching Functions

Derived from $b(\lambda)$, $g(\lambda)$ and $r(\lambda)$ **to eliminate negative values**

`[X Y Z] = [r g b]*`**T** where **T** is 3x3 transformation matrix



Any colour can be represented using positive XYZ primaries

However, X Y Z primaries are not real

CIE XYZ can only be used for theoretical analysis

Fig. 4.10: CIE standard XYZ color-matching functions $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$.

CIE Chromaticity

- We go to 2D by factoring out the magnitude of vectors (X, Y, Z); we could divide by $\sqrt{X^2 + Y^2 + Z^2}$, but instead we divide by the sum $X + Y + Z$ to make the **chromaticity**:

$$\begin{aligned} x &= X/(X+Y+Z) \\ y &= Y/(X+Y+Z) \\ z &= Z/(X+Y+Z) \end{aligned} \tag{4.7}$$

- This effectively means that one value out of the set (x, y, z) is redundant since we have

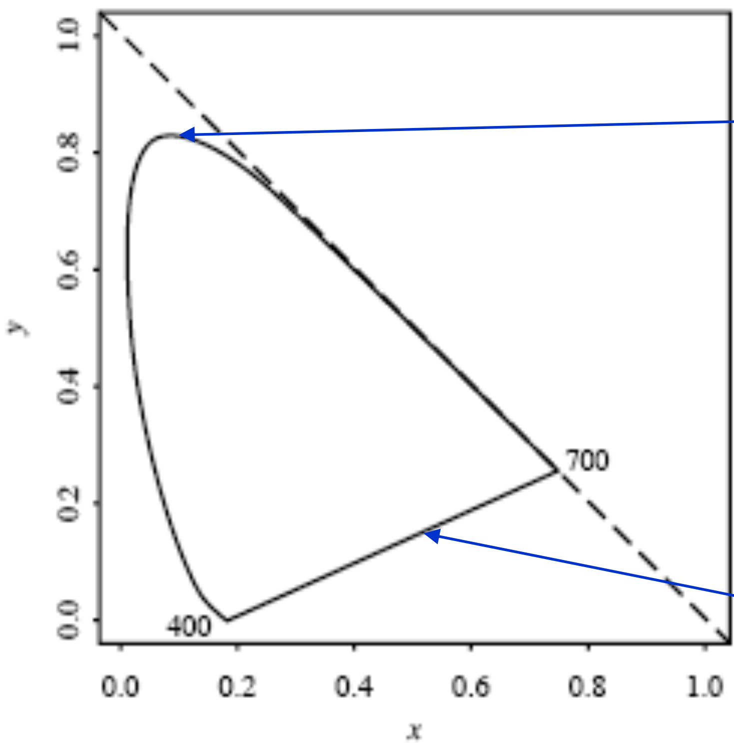
$$x + y + z = \frac{X+Y+Z}{X+Y+Z} \equiv 1 \tag{4.8}$$

so that

$$z = 1 - x - y \tag{4.9}$$

Values x, y are called chromaticity coordinates

CIE Chromaticity Diagram



Spectrum locus:
Pure colors

The third component z is calculated

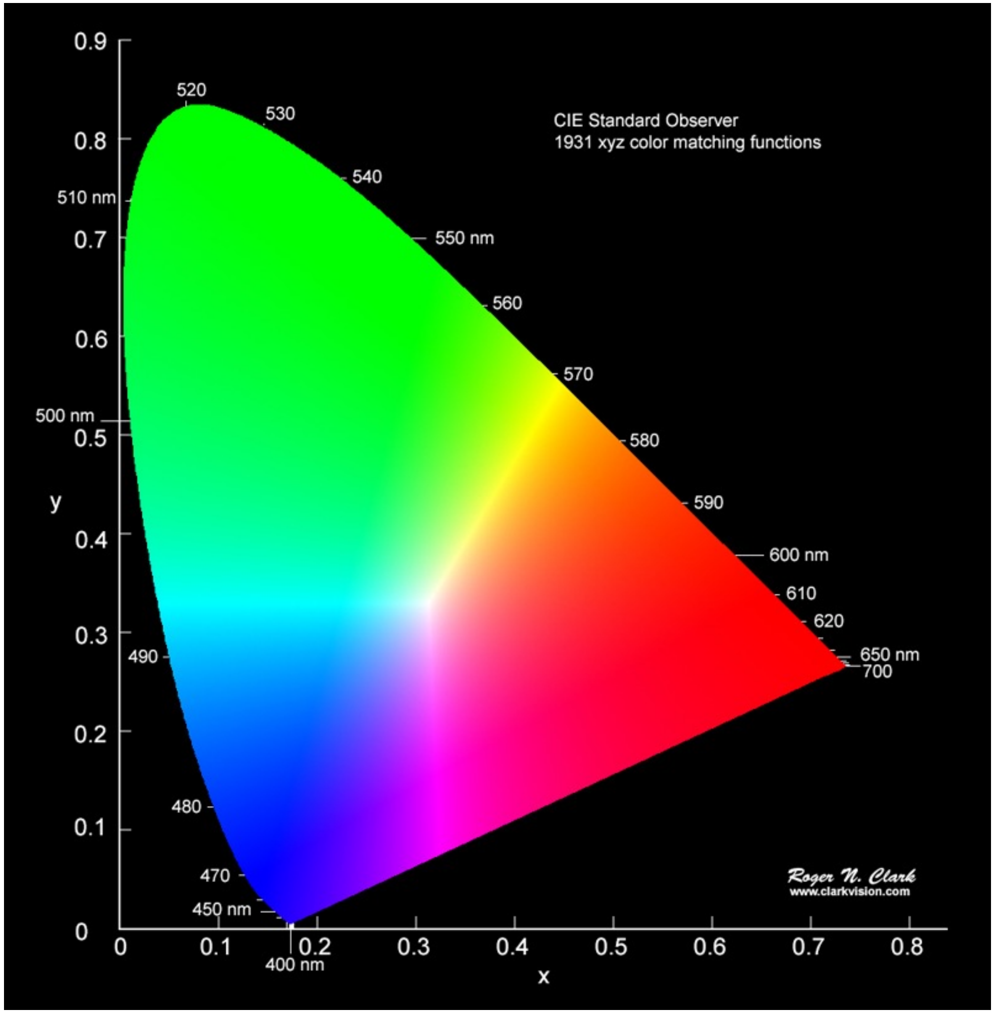
z = 1 - x - y

Line of purple

Fig. 4.11: CIE chromaticity diagram.

All real colours lie inside the spectrum locus

CIE Chromaticity Diagram



Colour Mixtures

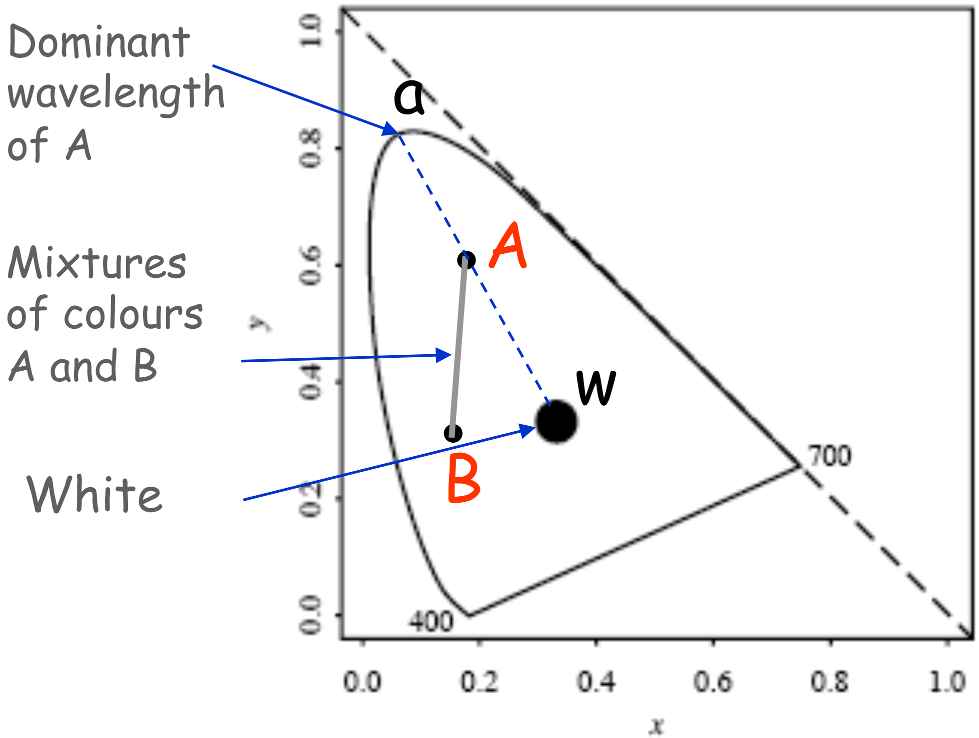


Fig. 4.11: CIE chromaticity diagram

Grassmann's Law:

If colours A(Xa, Ya, Za) and B(Xb, Yb, Zb) are mixed to obtain colour C(Xc, Yc, Zc)

$$X_c = \alpha X_a + (1-\alpha) X_b$$

$$Y_c = \alpha Y_a + (1-\alpha) Y_b$$

$$Z_c = \alpha Z_a + (1-\alpha) Z_b$$

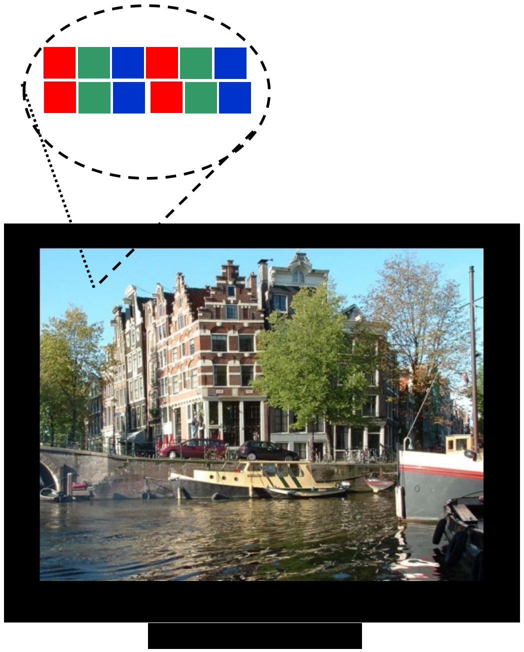
Chromaticity coordinates (*x,y,z*) are obtained as a liner weighted sum of components (equation of a straight line)

Colour purity of *A*:

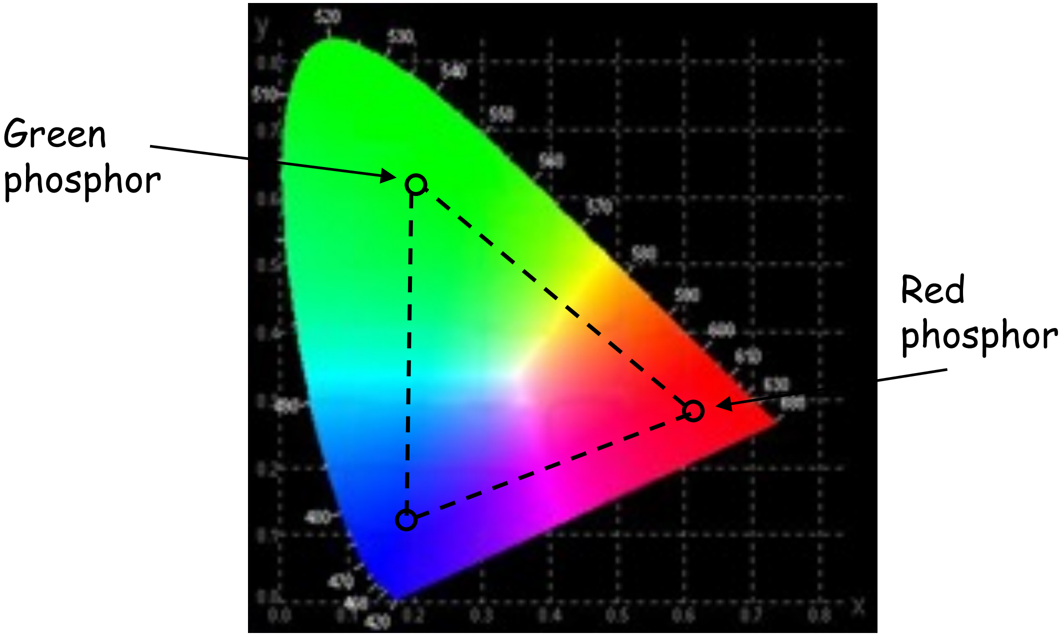
$$P_a = \text{length}(WA)/\text{length}(Wa)$$

Gamut

- Gamut is a range of colors that a device can produce



TV and monitors use 3-colour lite emission screens



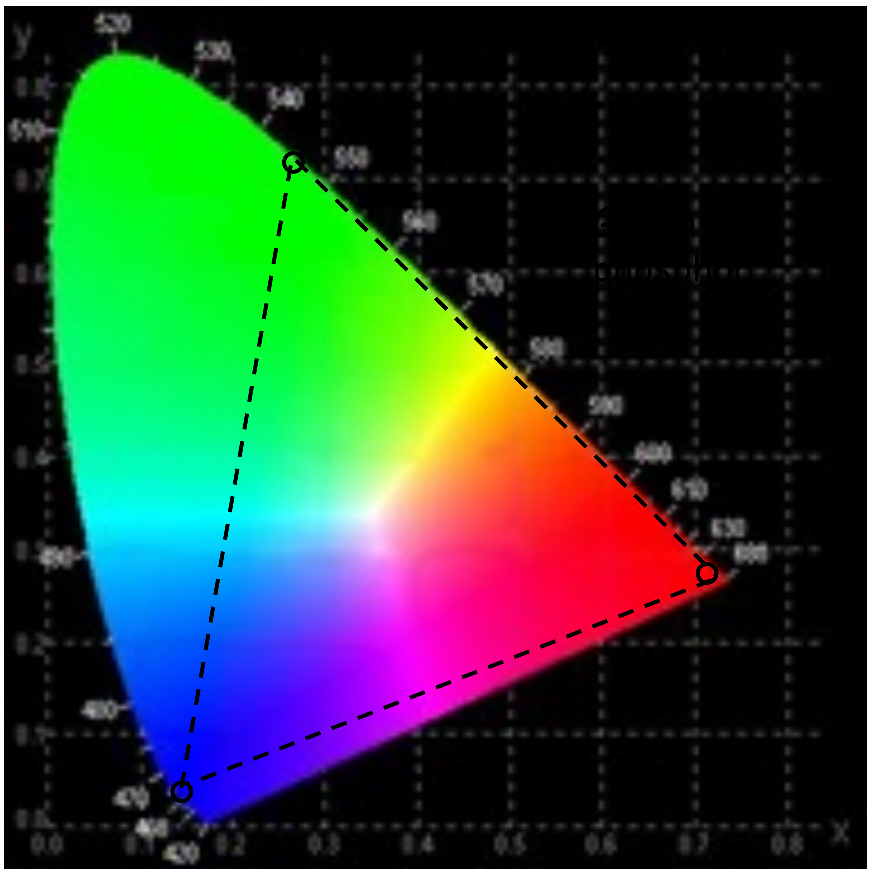
Only colours limited by the triangle can be reproduced

Note: B, G, R is the correct order that corresponds to the wavelength **436nm, 546nm and 700nm**

In the recording, it was R, G, B

Gamut

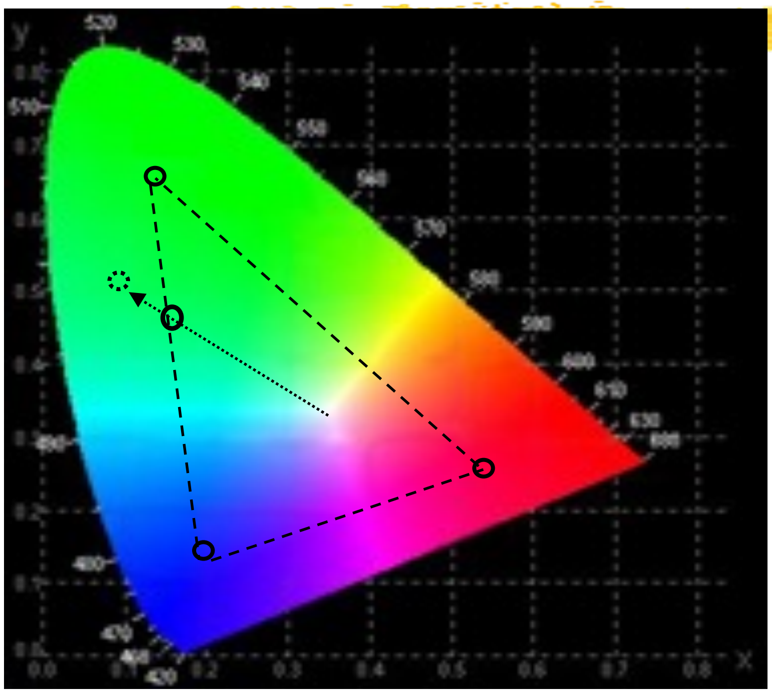
- Gamut for B, G, R primaries 436nm, 546nm and 700nm



- Only colours limited by the triangle can be reproduced
- If other primaries are used, the chromaticity diagram will have different coordinates for the same colours. However, this diagram will not be CIE Standard compliant
- Chromaticity coordinates of a colour in terms of any second set of primaries can be calculated from the coordinates that correspond to the first set of primaries.

Thus, CIE Chromaticity Diagram provides a device independent model for colour analysis

Out of Gamut Colors



An out-of-gamut colour is approximated by an in-gamut one

Although different TV standards specify different sets of primaries, all of them can be expressed in XYZ coordinates

Table 4.1: Chromaticities and White Points of Monitor Specifications

System	Red		Green		Blue		White Point	
	x_r	y_r	x_g	y_g	x_b	y_b	x_W	y_W
NTSC	0.67	0.33	0.21	0.71	0.14	0.08	0.3101	0.3162
SMPTE	0.630	0.340	0.310	0.595	0.155	0.070	0.3127	0.3291
EBU	0.64	0.33	0.29	0.60	0.15	0.06	0.3127	0.3291

Colour Transformations

- Given the tristimulus values R_1 G_1 B_1 of a colour in terms of the first set of primaries, how to get the tristimulus values R_2 G_2 B_2 of the same colour in terms of the second set of primaries
- In general: $$\begin{bmatrix} R2 \\ G2 \\ B2 \end{bmatrix} = \mathbf{M} * \mathbf{T} * \begin{bmatrix} R1 \\ G1 \\ B1 \end{bmatrix}$$

where **T** is 3x3 matrix that converts RGB into CIE XYZ colour space

M is a 3x3 matrix that converts CIE XYZ into RGB colour space of the second set of primaries

- Two 3x3 matrixes can be multiplied to produce **C** $= \mathbf{M} * \mathbf{T}$

Colour Transformations

- *Example:* PAL TV System specifies primaries which are different from CIE primaries.

1. Given a colour A in CIE XYZ Colour Space, how to get its RGB components in PAL primaries colour space?

$$\begin{bmatrix} R_A \\ G_A \\ B_A \end{bmatrix} = \begin{bmatrix} 2.57 & -1.02 & 0.98 \\ -1.17 & 1.98 & -0.25 \\ -0.40 & 0.04 & 1.18 \end{bmatrix} * \begin{bmatrix} X_A \\ Y_A \\ Z_A \end{bmatrix}$$

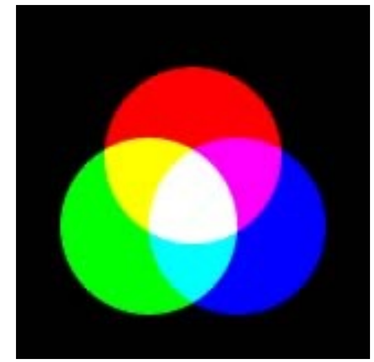
2. Given a colour A in PAL primaries colour space, how to get its CIE XYZ Colour coordinates?

$$\begin{bmatrix} X_A \\ Y_A \\ Z_A \end{bmatrix} = \begin{bmatrix} 0.51 & 0.27 & 0.02 \\ 0.32 & 0.67 & 0.12 \\ 0.16 & 0.07 & 0.85 \end{bmatrix} * \begin{bmatrix} R_A \\ G_A \\ B_A \end{bmatrix}$$

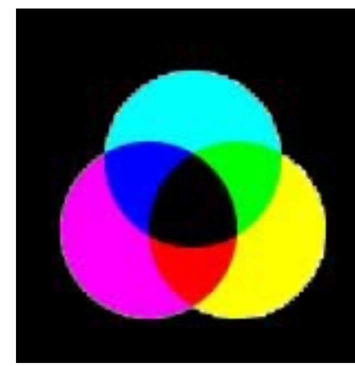
Additive and Subtractive Colour Models

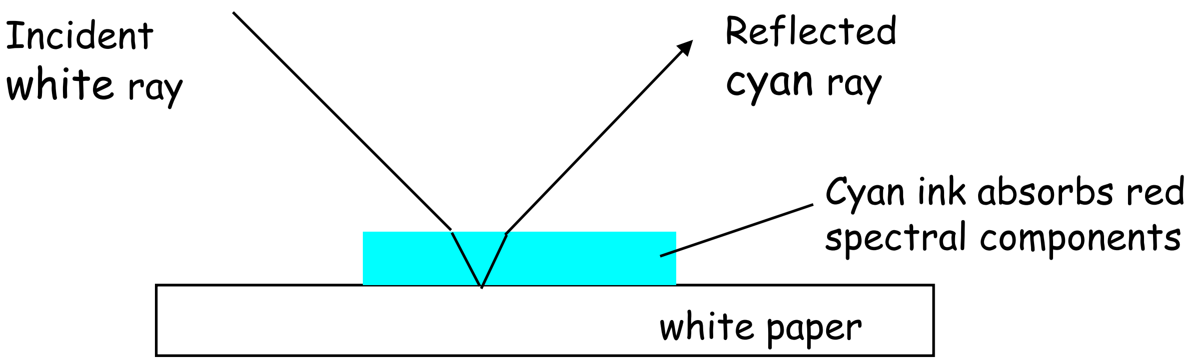
- R, G, B colour model describes intensities of components which are *emitted* to produce a given color. Components are added together

  (TV tubes, LCD and Plasma screens)



- Printed images use completely different model for colour rendering. Colour components a subtracted from white light





$$C = W - R$$
$$M = W - G$$
$$Y = W - B$$

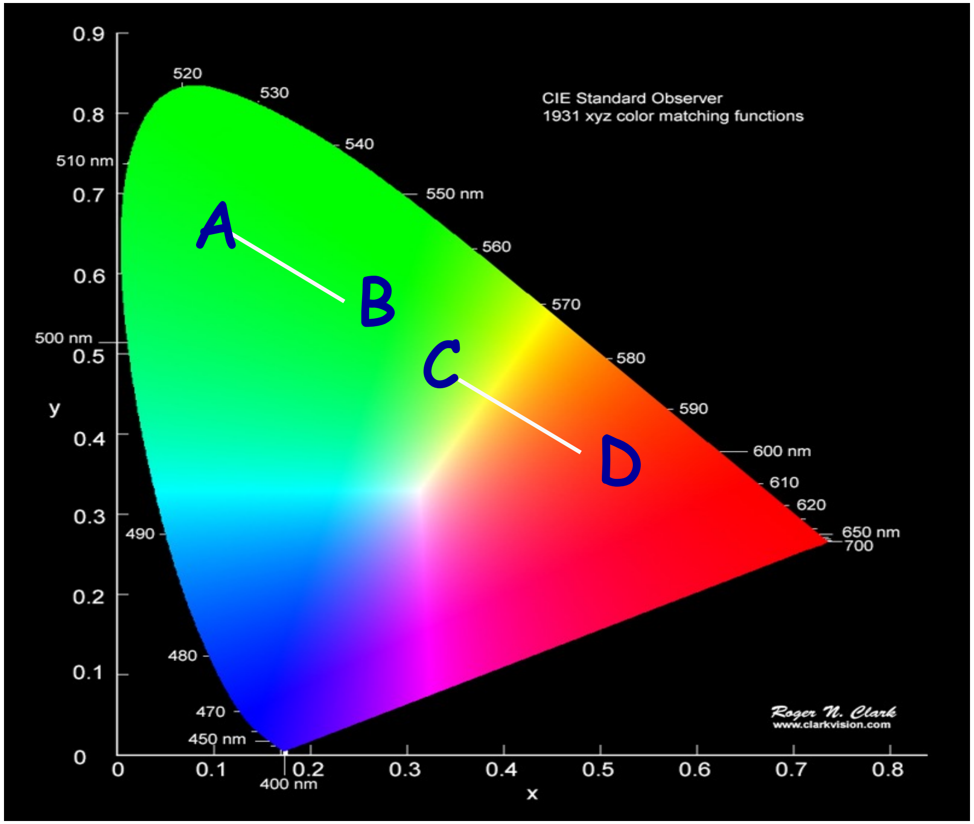
Non-perceptual uniformity

- In many applications, such as colour image processing, we need to evaluate colour differences.

- Many colour spaces including CIE-xy do not make this task easy
  - The magnitude of the difference in x,y coordinates does not related to the perceptual difference in colour

Non-perceptual uniformity of CIE-xy

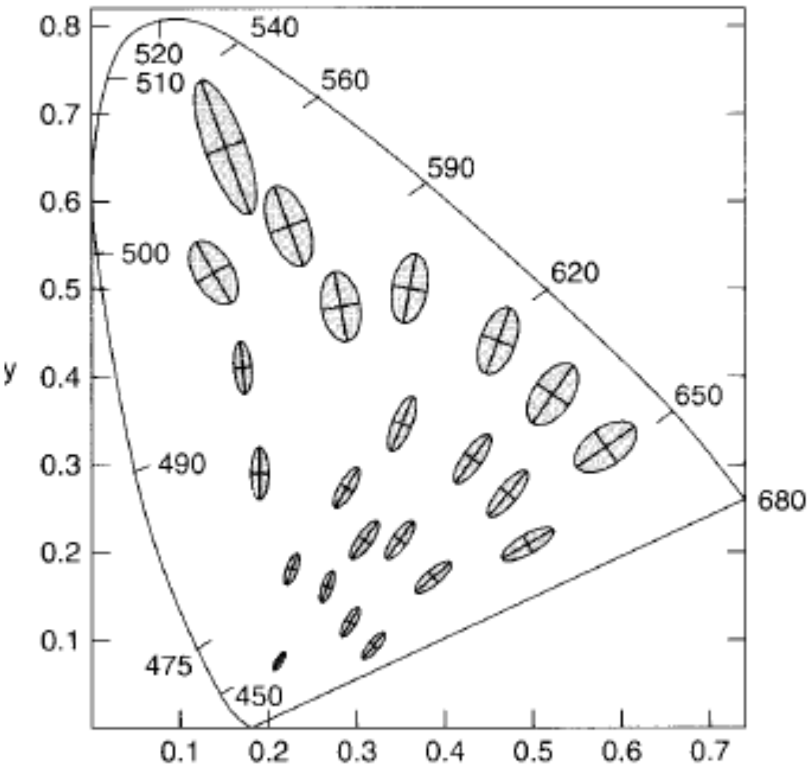
y

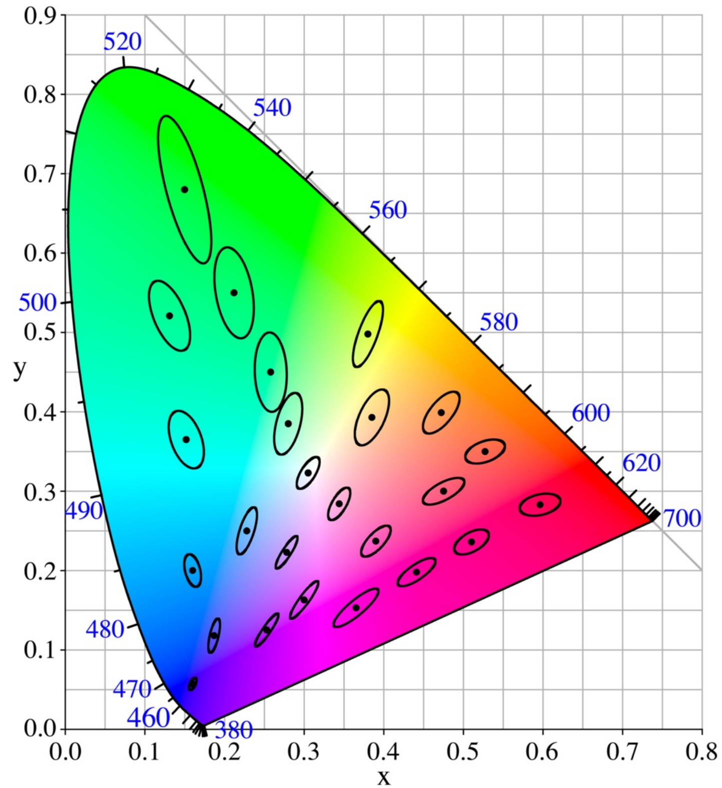


x

d(A,B) = d(C,D)

MacAdam Ellipses





All points in each ellipse would be perceived as the same colour as the centre of the ellipse

CIELab Color Model

- Analogy to the case of luminance and brightness
  - CIE XYZ quantifies the actual colors, not the perceived colors.
  - The perceived color difference of two colors can be quite different from the difference of their XYZ values
- CIE Lab color model intends to quantify differences perceived in color
  - **L** is the luminance or lightness component
  - **a** is the green to red component
  - **b** is the blue to yellow component

CIE Lab Calulation

- CIELAB:

$$\Delta E = \sqrt{(L*)^2 + (a*)^2 + (b*)^2}$$

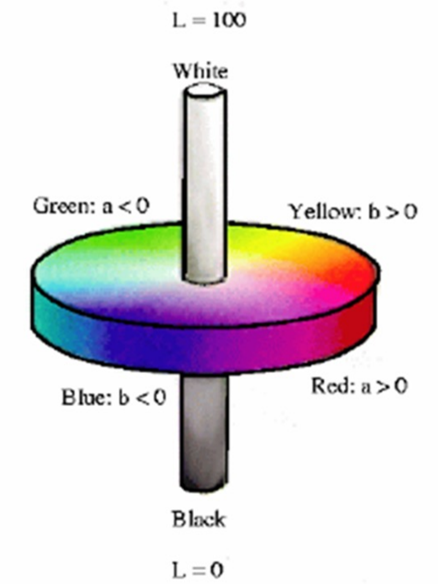
$$L^* = 116\left(\frac{Y}{Y_n}\right)^{(1/3)} - 16$$

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

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

with X_n, Y_n, Z_n the XYZ values of the white point. Auxiliary definitions are:

$$\text{chroma} = c^* = \sqrt{(a^*)^2 + (b^*)^2}\,,\ \text{hue angle} = h^* = \arctan\frac{b^*}{a^*}$$



CIELab model

HSB Color Space

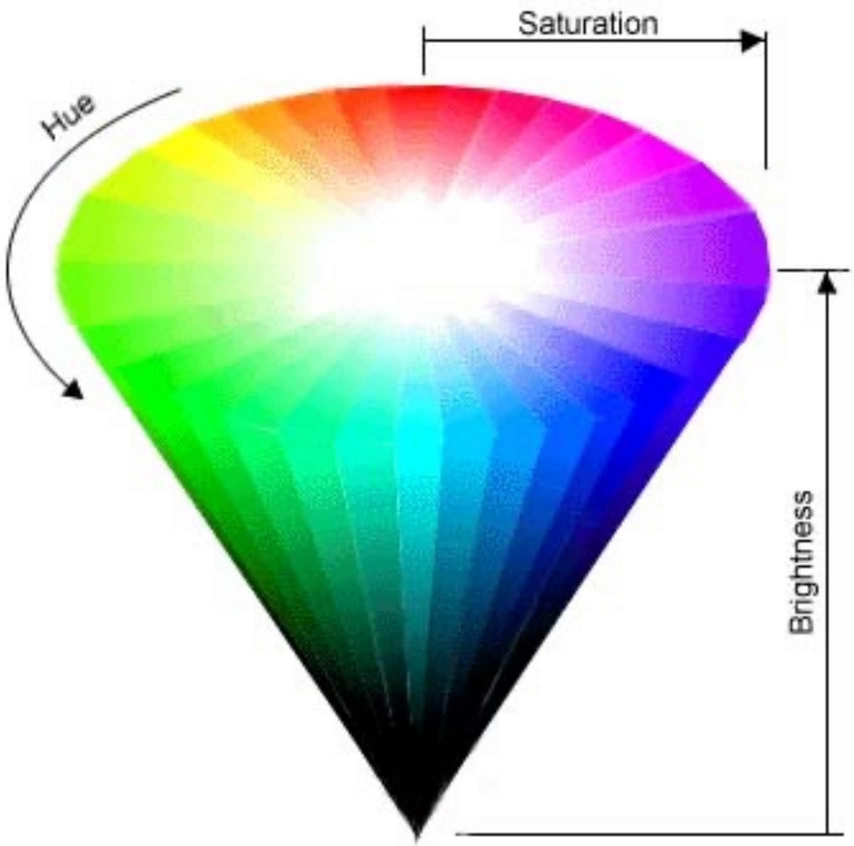
Describe the perceptual attributes of a color

- Hue, Saturation and Brightness
  - **Hue** is the wavelength at which most of the energy of the light is concentrated (the *dominant wavelength*)
  - **Saturation** is a measure of the purity of a color

    A hue can be "diluted" by mixing a pure colour with white. The dominant wavelength remains the same, but the presence of other hues makes the color paler
  - **Brightness** is a measure of how light or dark it is
    - A color's appearance will be modified by the intensity of the light. Less light intensity makes it appear darker

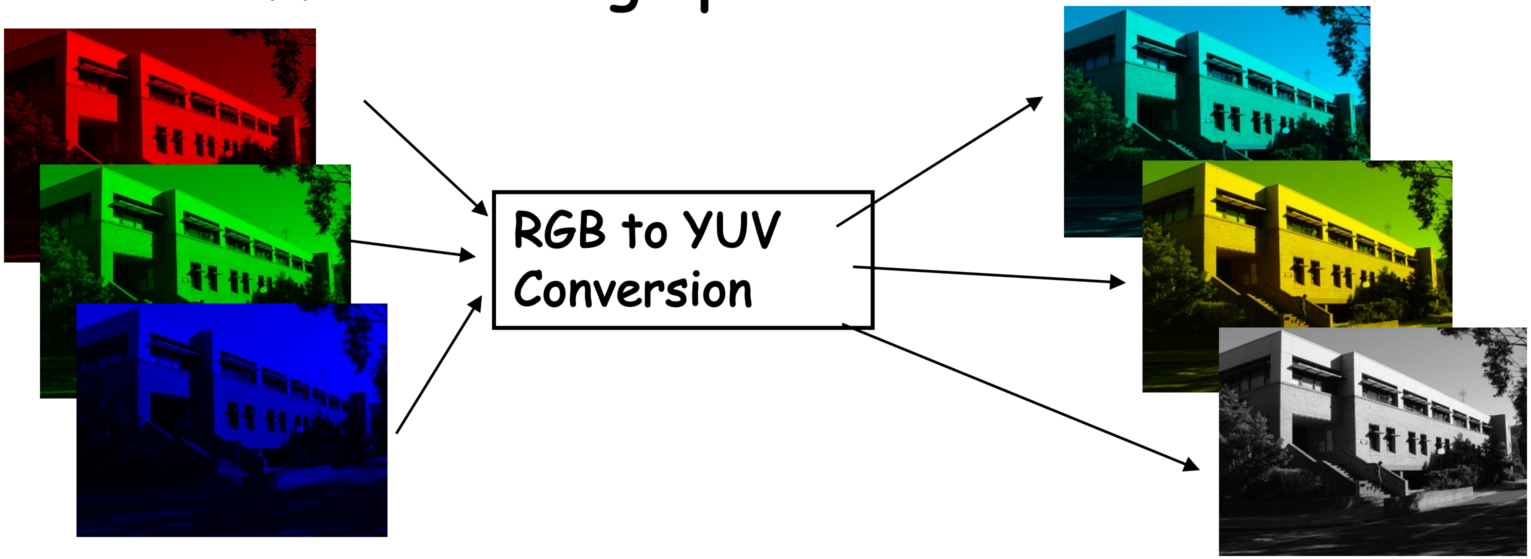
HSB Color Space

- **Hue** is the actual colour. It is measured in angular degrees around the cone starting and ending at red = 0 or 360 (so yellow = 60, green = 120, etc.).
- **Saturation** is the purity of the colour, measured in percent from the centre of the cone (0) to the surface (100). At 0% saturation, hue is meaningless.
- **Brightness** is measured in percent from black (0) to white (100). At 0% brightness, both hue and saturation are meaningless.



YUV Colour Space

- The human vision is more sensitive to variation in perceived image brightness rather than to variation of any colour component separately
- Some operations can be more efficiently performed in YUV colour space where brightness and colour are stored in different image planes



YUV Colour Space (ITU.BT-601)

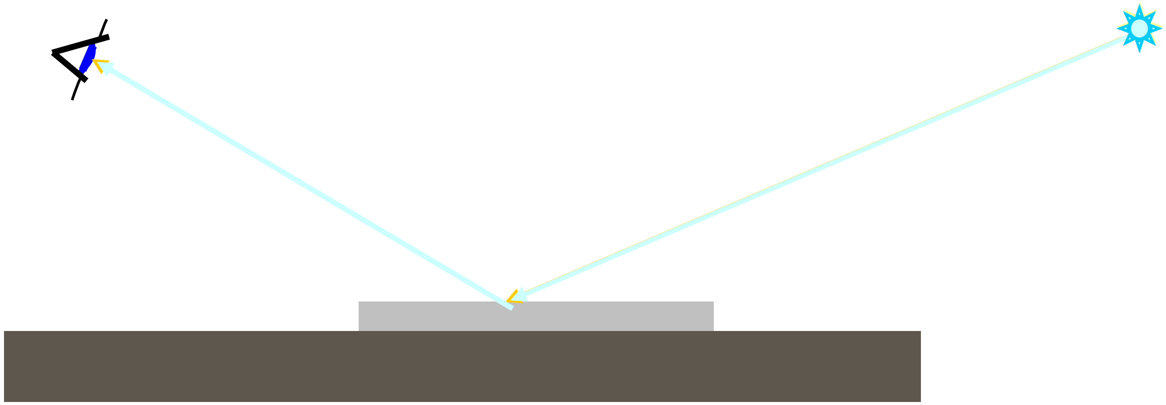
- RGB to YUV colour space conversion is a matrix operation

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.30 & 0.59 & 0.114 \\ -0.17 & -0.33 & 0.5 \\ 0.5 & -0.42 & -0.08 \end{bmatrix} * \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

- YUV image can be converted back to RGB

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1.0 & 0.0 & 1.4 \\ 1.0 & -0.34 & -0.71 \\ 1.0 & 1.77 & 0.0 \end{bmatrix} * \begin{bmatrix} Y \\ U \\ V \end{bmatrix}$$

Colour Constancy



$$r_1 = \int S_1(\lambda)\,\bar{r}(\lambda)\,d\lambda$$

$$g_1 = \int S_1(\lambda)\,\bar{g}(\lambda)\,d\lambda$$

$$b_1 = \int S_1(\lambda)\,\bar{b}(\lambda)\,d\lambda$$

$$r_2 = \int S_2(\lambda)\,\bar{r}(\lambda)\,d\lambda$$

$$g_2 = \int S_2(\lambda)\,\bar{g}(\lambda)\,d\lambda$$

$$b_2 = \int S_2(\lambda)\,\bar{b}(\lambda)\,d\lambda$$

According to the formulas, if two sources of light have different spectrums, a white object should change its colour

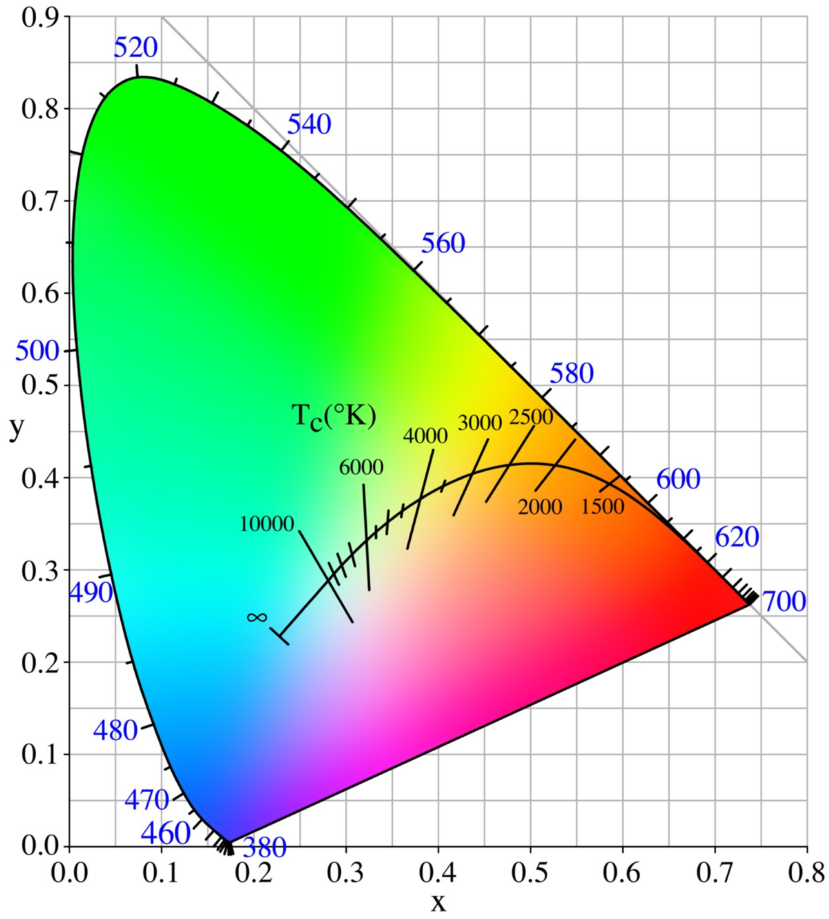
However. the perceived color of objects remains relatively constant under varying illumination conditions

The mechanism of adaptation of the human vision to illumination conditions is still not fully understood

Colour Temperature

- **Color temperature** is a characteristic of visible light, a simple way to measure the spectral (hue) of the light.
- It is determined by comparing its chromaticity with that of an ideal black-body radiator.
- The temperature (usually measured in kelvin (T(K) = T(°C) + 273.15)) at which the heated black-body radiator matches the color of the light source is that source's color temperature; for a black body source.
  - 2700-3600 are recommended for most general indoor lighting

Color Temperature



References

David Forsyth, Jean Ponce, *Computer Vision A Modern Approach, 2nd edition*

Chapters 2 and 3

OpenCV 4.6.0 - References

- Basic Operations on Images
- Arithmetic Operations on Images

- Colour Space Conversions