Chapter 4
Color in Image and Video

Presented By
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Agenda

4.1 Color Science

4.2 Color Models in Images

4.3 Color Models in Video
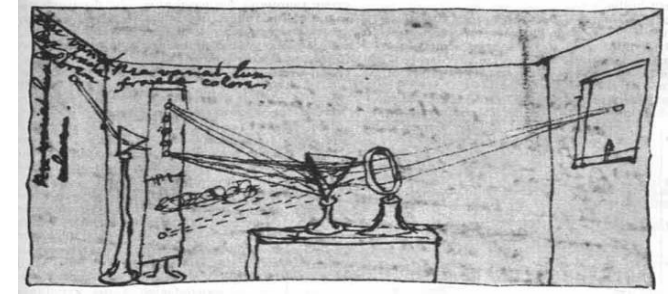
4.1 Color Science

Light and Spectra

- Light is an electromagnetic wave. Its color is characterized by the **wavelength content of the light.**

   a) **Laser light** consists of **a single wavelength**: e.g., a ruby laser produces a bright, scarlet-red beam.

   b) However, **humans cannot detect all light**, just contributions that fall in the "visible wavelengths".

   c) **Short wavelengths** →a **blue** sensation,
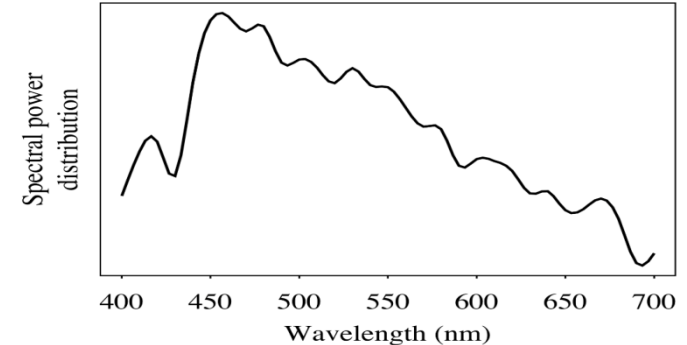
   d) **long wavelengths** →produce a **red** sensation.
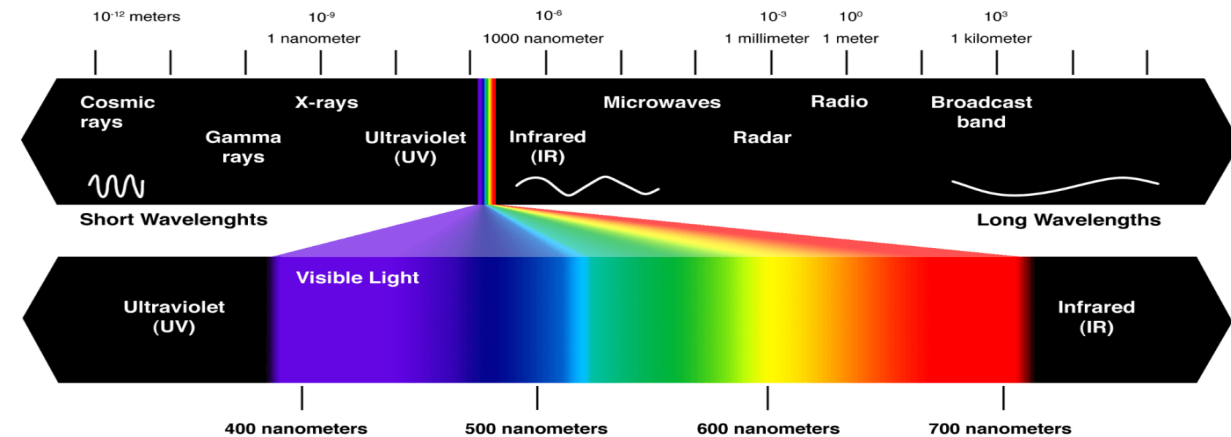
visible wavelengths

4.1 Color Science cont.

Fig. 4.1: Sir Isaac Newton's experiments.
By permission of the Warden and Fellows, New College, Oxford.

- Figure 4.1 shows the phenomenon that white light contains all the colors of a rainbow.

- Visible light is an electromagnetic wave in the **range 400 nm to 700 nm (where nm stands for nanometer, 10^{-9} meters).**

- 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)*** التوزيع الطيفي للطاقة or a spectrum .

- The symbol for wavelength is *λ **Lambda*** . This curve is called ***E(λ).***

Fig. 4.2: Spectral power distribution of daylight.

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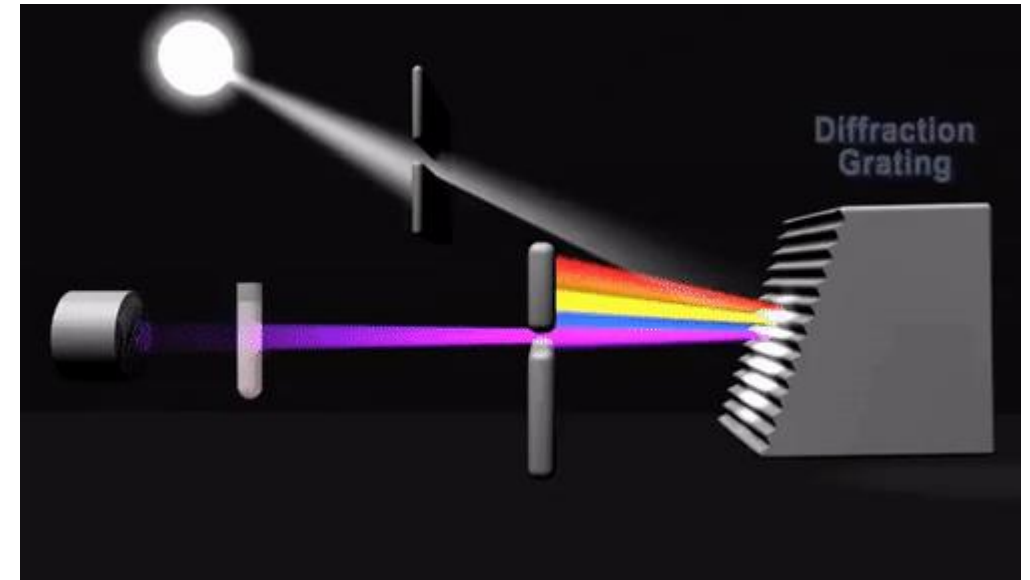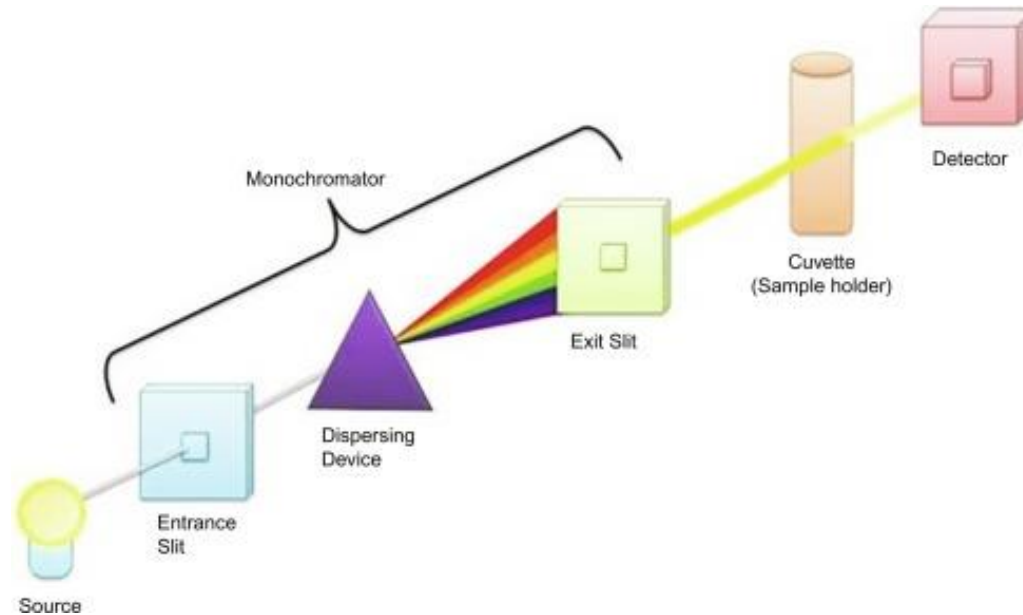
- **Spectrophotometer** مقياس الطيف الضوئي: device used to measure visible light, by reflecting light from a diffraction grating (a ruled surface) that spreads out the different wavelengths.

Dr. Samaa Shohieb Ref. Li, Drew, & Liu   © Springer 2021

4.1 Color Science cont.
4.1.2 Human Vision

- The **eye** works like a **camera**,

  - the lens focusing an image **onto the retina** (upside-down and left-right reversed).

- The **retina** consists of an *array* of *rods* +**three kinds of cones**.

- The **rods** come into play when **light levels are low**

  - When you are in a dark place

  - and produce a image in **shades of gray** ("all cats are gray at night!").

- 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.

- It seems likely that the brain makes use of differences **R-G, G-B, and B-R,** as well as combining all of R, G, and B into a high-light-level achromatic channel.
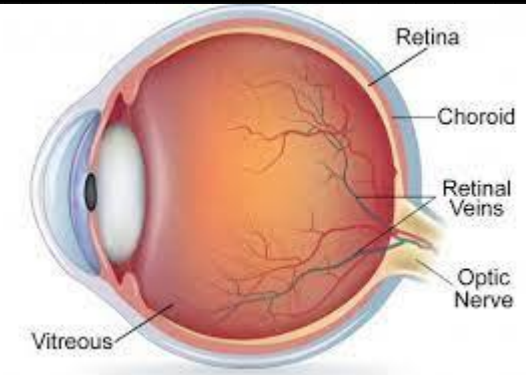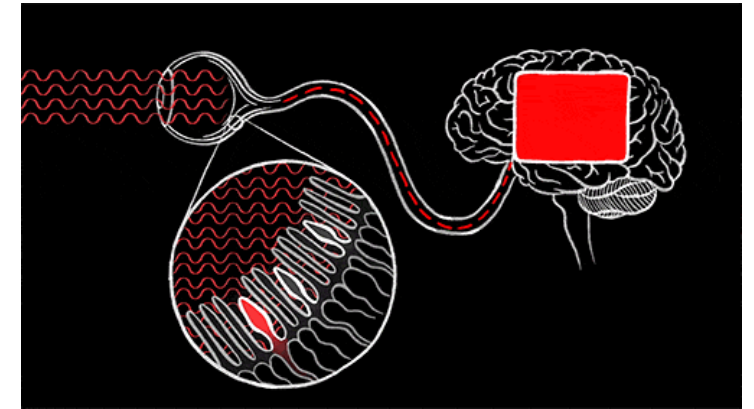
4.1.3 Spectral Sensitivity of the Eye

- 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 (Fig. 4.3).
- The Blue receptor sensitivity is not shown to scale because it **is much smaller** than the curves for **Red or Green** — Blue is a late addition, in human evolution.
  - Statistically, Blue is the favourite color of humans, regardless of nationality
  - perhaps for this reason: **Blue is a latecomer in the new versions of human** →a bit surprising!
- Fig. 4.3 shows the overall sensitivity as a dashed line — this important curve is called the **luminous-efficiency function** V(λ)**.**
  - is formed as the sum of the response curves for Red, Green, and Blue.
  - Our l**uminous-efficiency** is bigger at the middle
  - The eye has about ***6 million cones***, but the proportions of R, G, and B cones are different ***is approximately 2R+G+B/20***.
 - ***Ratios about (40:20:1)***
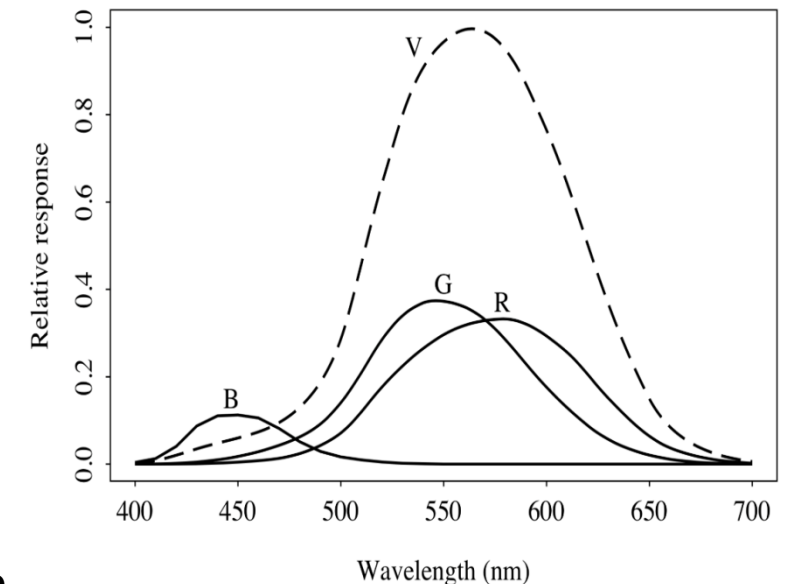
**Fig. 4.3: R,G, and B cones, and Luminous Efficiency curve V(λ).**

4.1.4 Image Formation

- Surfaces **reflect different amounts** of light at different wavelengths,

- **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 $S(\lambda)$.

- **Image formation is thus:**

  - **_Light_** from the illuminant with **_Spectral Power Distribution (SPD)_** $E(\lambda)$

  1. Impinges تصطدم on a surface,

     - each surface has a **surface spectral reflectance function $S(\lambda)$,**

  2. is reflected,

  3. and then is **filtered by the eye's cone** functions **$q(\lambda)$.**

  − The function **$C(\lambda)$** = the color signal

  - consists of the product of :

     $E(\lambda)$, the illuminant, times $S(\lambda)$, the reflectance:

     $$C(\lambda) = E(\lambda) * S(\lambda).$$
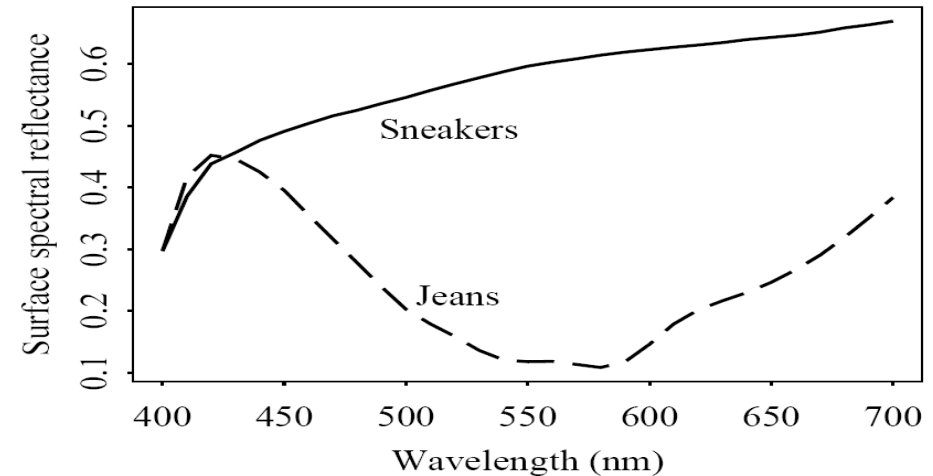
Fig. 4.4: Surface spectral reflectance functions S(λ) for objects.
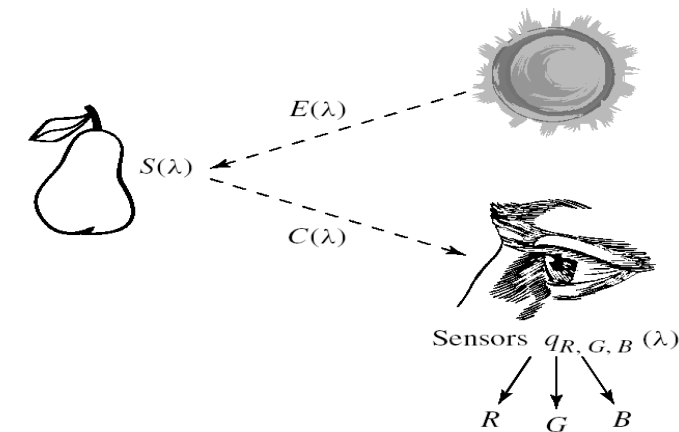
Fig. 4.5: Image formation model.

4.1.5 Camera Systems

- Camera systems are made *in a similar fashion*;
- **a studio quality camera has <u>three signals produced</u> at each pixel location** (<u>corresponding to a retinal position</u>).
  - **Analog signals are converted →to digital**,
  - truncated to integers,
  - and **stored**.
- If the precision used is **8**-bit, for any of *R,G,B* is
  - **max=255**
  - **min=0**
- Light entering the eye of the computer user
  - emitted by the screen
  - the screen = a self-luminous source.

4.1.6 Gamma Correction

- The light emitted is in fact roughly

  - ❑ ***Proportional*** **to** the **voltage** *raised to a power*, called **gamma**, with **_symbol γ_**.

  - ❑ The value of gamma is γ =~2.2.

  - ❑ So it **lowers MORE FROM the LOW voltage** values➔ we can't differentiate between the degrees of the dark columns (fig 4.7 a)

- Append a prime to signals that are **gamma-corrected**

  - ❑ By raising to the power (1/γ) before transmission.
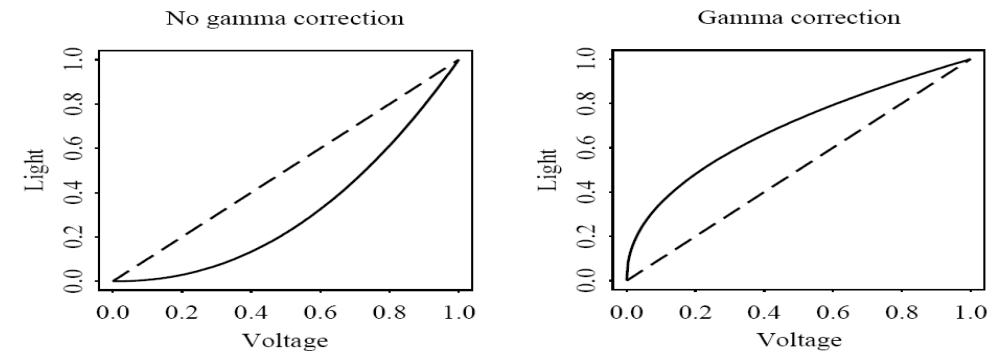
  - ❑ Thus we arrive at **linear signals**

Fig. 4.6: (a) Effect of CRT (mimicked by an actual modern display) on light emitted from screen (voltage is normalized to range 0..1). (b) Gamma correction of signal.
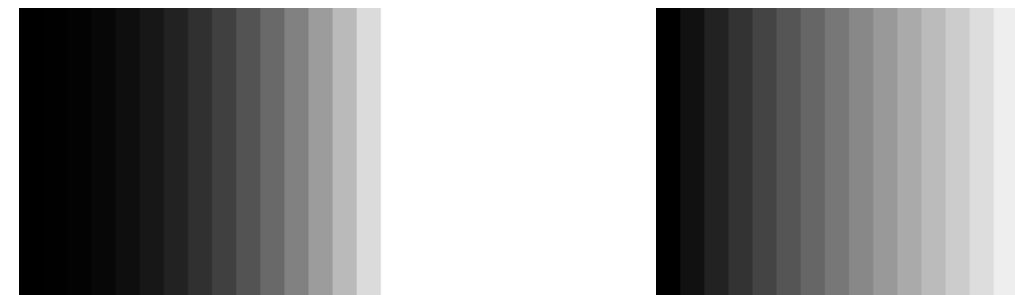
Fig. 4.7: (a) Display of ramp from 0 to 255, with no gamma correction. (b) Image with gamma correction applied.

4.1.7 Color-Matching Function

- 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 (**_Person_**) 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 ➔ a device for carrying out such an experiment is called a **colorimeter**.
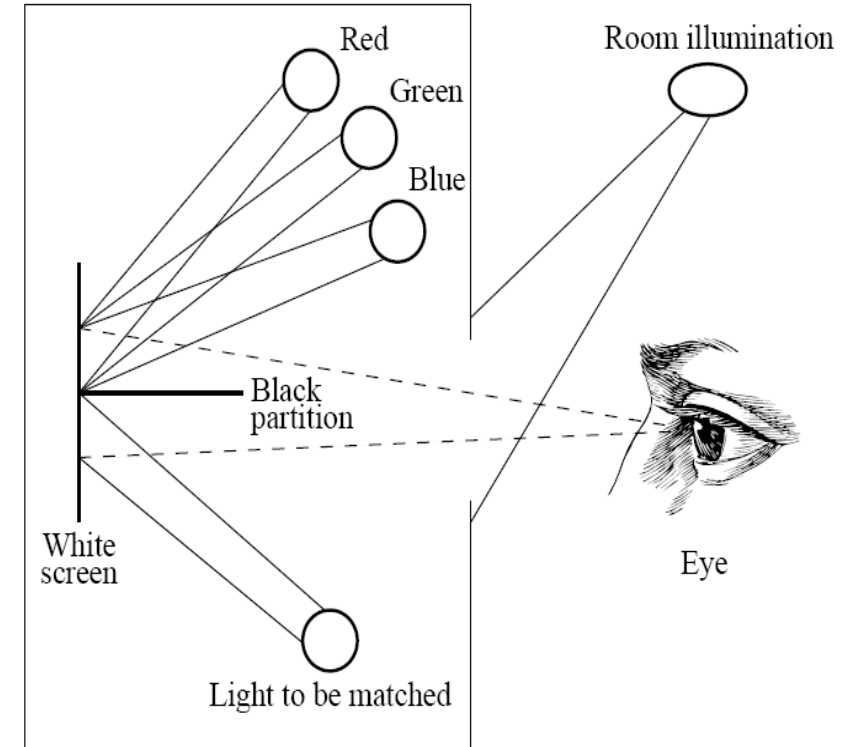
Fig. 4.8: Colorimeter experiment.

4.1.8 CIE Chromaticity Diagram

- International Commission on Illumination / commission international de l'éclairage الهيئه الدولية للاضاءه

- The amounts of R, G, and B the subject selects to match each single-wavelength light forms the color-matching curves ➔ **CIE RGB color-matching functions**.

- These are denoted $\overline{r}(\lambda), \overline{g}(\lambda), \overline{b}(\lambda)$

- **Problem:**

  - Since the color-matching R curve has a negative lobe, HOW CAN I PUT ANEGATIVE RED COLOR➔ **NOT** applicable

- **Solution** ➔ select fictitious primaries ➔They are a 3 × 3 matrix away from $\overline{r}, \overline{g}, \overline{b}$ curves, ➔ called **_CIE standard XYZ_** and are denoted $\overline{x}(\lambda), \overline{y}(\lambda), \overline{z}(\lambda)$

  - The matrix is chosen such that the middle standard color-matching function exactly equals the luminous-efficiency curve V(λ) shown in Fig. 4.3.
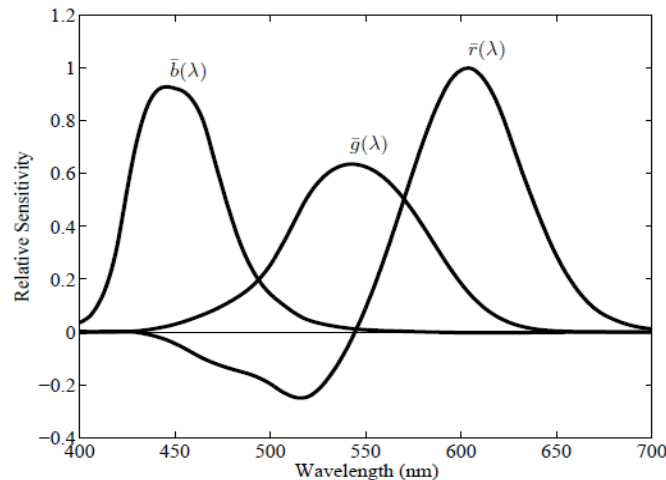
Fig. 4.9: CIE RGB color-matching functions $\overline{r}(\lambda), \overline{g}(\lambda), \overline{b}(\lambda)$
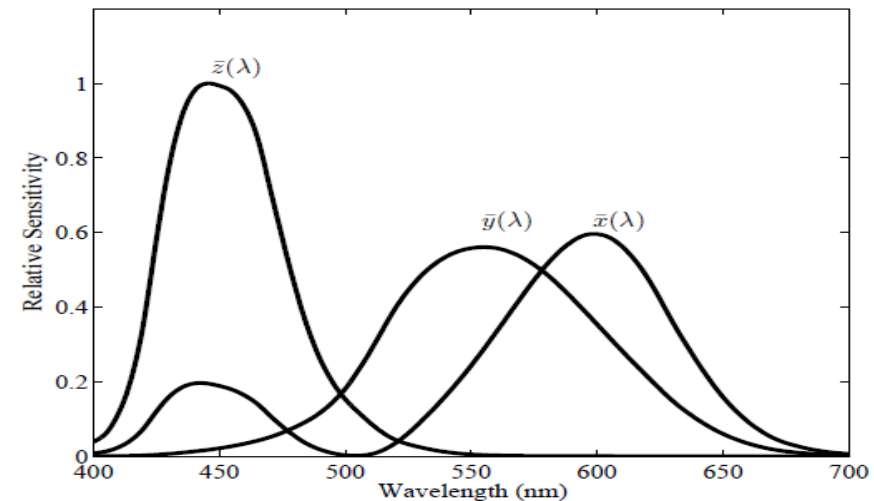
Fig. 4.10: CIE standard XYZ color- $\overline{x}(\lambda), \overline{y}(\lambda), \overline{z}(\lambda)$ matching functions

4.1.8 CIE Chromaticity Diagram

- We want to convert the 3D CIE standard XYZ 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**:

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

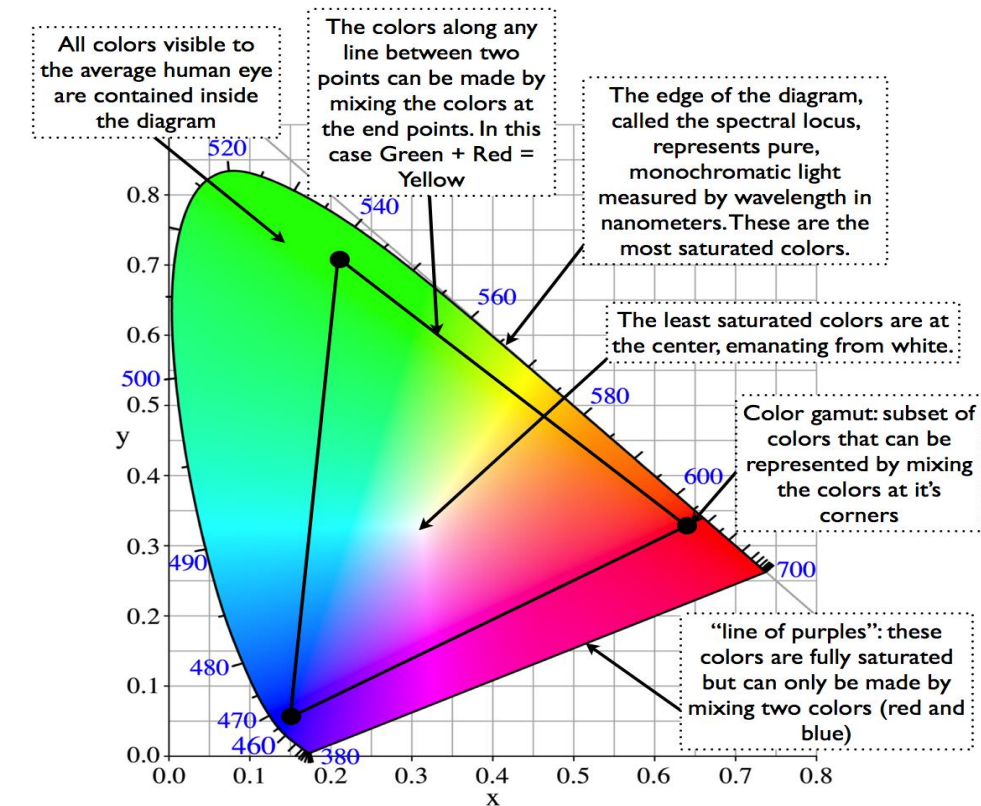- This effectively means that one value out of the set (x, y, z) is redundant since we have

$$x + y + z = \frac{X+Y+Z}{X+Y+Z} \equiv 1 \qquad (4.7)$$

$$(4.8)$$

So that

$$Z = 1 - x - y \qquad (4.9)$$

- Effectively, we are projecting each vector (X, Y, Z) onto the plane connecting points (1, 0, 0), (0, 1, 0), and (0, 0, 1).

- Fig. 4.11 shows the locus of points for monochromatic light

All colors visible to the average human eye are contained inside the diagram

The colors along any line between two points can be made by mixing the colors at the end points. In this case Green + Red = Yellow

The edge of the diagram, called the spectral locus, represents pure, monochromatic light measured by wavelength in nanometers. These are the most saturated colors.

The least saturated colors are at the center, emanating from white.

Color gamut: subset of colors that can be represented by mixing the colors at it's corners

"line of purples": these colors are fully saturated but can only be made by mixing two colors (red and blue)

Anatomy of a CIE Chromaticity Diagram

4.1.10 Out-of-Gamut colors

- For any (x, y) pair we wish to find that RGB triple giving the specified (x, y, z): We form the z values for the phosphors, via $z = 1 - x - y$

- We combine nonzero values of R, G, and B via

$$\begin{bmatrix} x_r & x_g & x_b \\ y_r & y_g & y_b \\ z_r & z_g & z_b \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

What do we do if any of the *RGB* numbers is negative ➔; color, visible to humans, but is out-of-gamut for our display

- – *Solution 1*: simply use the closest in-gamut color available, intersection on the boundary of the triangle from white point to the point

- – *Solution 2*: select the closest **complementary** color.
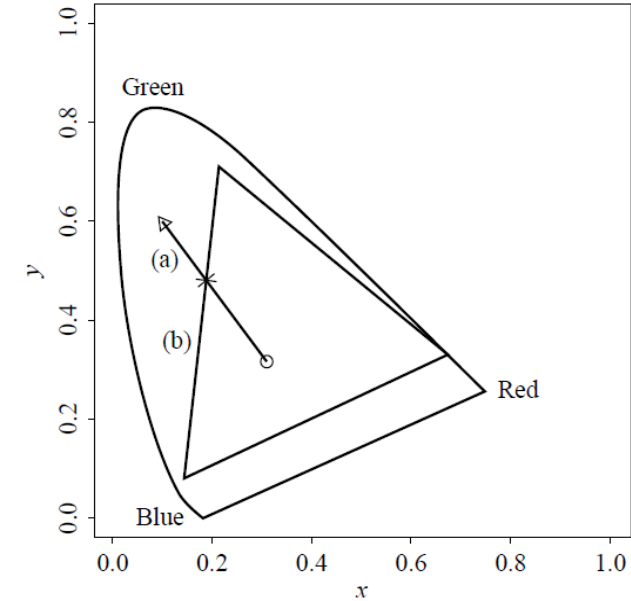
Fig. 4.13: Approximating an out-of-gamut color by an in-gamut one. The out-of-gamut color shown by a triangle is approximated by the intersection of the line (labeled (a)) from that color to the white point with the boundary (labeled (b)) of the device color gamut.

4.1.14 L*a*b* (CIELAB) color Model

- **Weber's Law:**
  - Equally-perceived differences are proportional to magnitude.
- The more there is of a quantity, the more change there must be to perceive a difference.
- A rule of thumb
  - equally-perceived changes **must be relative**
  - changes are about **equally perceived** if the ratio of the **change is the same,** whether for dark or bright lights, etc.
- Mathematically,
  - with intensity I, change is equally perceived so long as the change $\frac{\Delta I}{I}$ is a constant.
- Ex in sound :
  - If it's quiet, we can hear a small change in sound.
  - If there is a lot of noise, to experience the same difference the change has to be of the same proportion.
- For human vision, the CIE arrived at a different version of this kind of rule — CIELAB space. What is being quantified in this space is differences perceived in color and brightness.

- Fig. 4.14 shows a cutaway into a 3D solid of the coordinate space associated with this color difference metric.

L = 100
White

Green: a < 0

Yellow: b > 0

Red: a > 0

Blue: b < 0

Black
L = 0
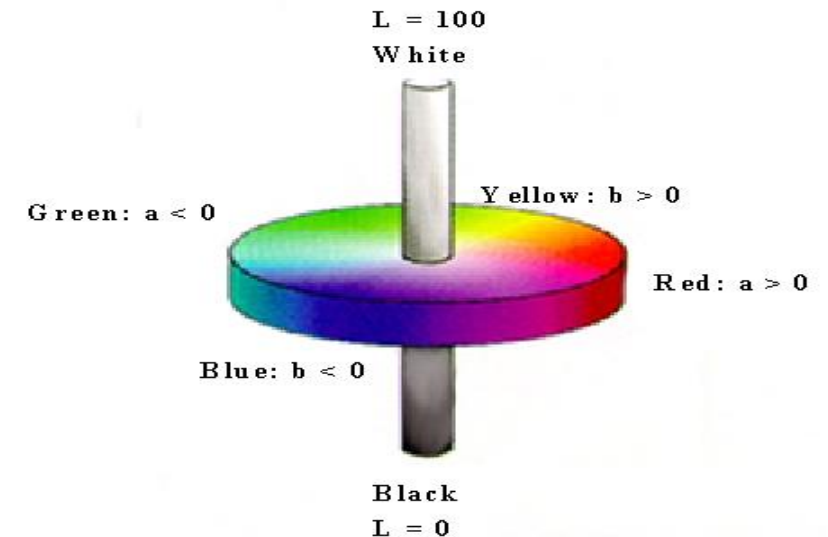
4.1.14 L*a*b* (CIELAB) color Model

• CIELA

$$\Delta E = \sqrt{(L_1^* - L_2^*)^2 + (a_1^* - a_2^*)^2 + (b_1^* - b_2^*)^2}$$
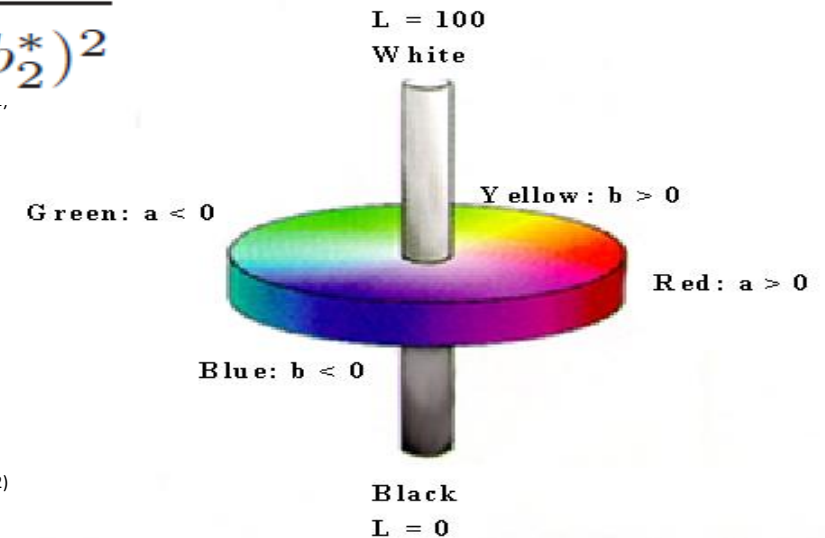
$$L^* = 116\left(\frac{Y}{Y_n}\right)^{(1/3)} - 16$$

$$a^* = 500\left[\left(\frac{X}{X_n}\right)^{1/3} - \left(\frac{Y}{Y_n}\right)^{1/3}\right] \qquad (4.22)$$

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

•   **Fig. 4.14:** CIELAB model.

with X_n, Y_n, Z_n the XYZ values of the white point.

•   Auxiliary definitions are:

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

4.1.15 More Color Coordinate Schemes

- Beware: gamma correction or not is usually ignored.

- Schemes include:
  a) CMY — Cyan (C), Magenta (M) and Yellow (Y) color model;

  b) HSL — Hue, Saturation and Lightness;

  c) HSV — Hue, Saturation and Value;

  d) HSI — Hue, Saturation and Intensity;

  e) HCI — C=Chroma;

  f) HVC — V=Value;

  g) HSD — D=Darkness.

4.2 Color Models in Images

- Colors models and spaces used for stored, displayed, and printed images.

- **RGB Color Model for Displays**

  ✓ We expect to be able to use 8 bits per color channel for color that is accurate enough.

  ✓ However, in fact we have to use about 12 bits per channel to avoid an aliasing effect in dark image areas — contour bands that result **from gamma correction**.

  ✓ For images produced from computer graphics,

    ❑ we store integers proportional to intensity in the frame buffer.

    ❑ So should have a gamma correction Lookup Table ***LUT*** between the frame buffer and the display.

  ✓ If gamma correction is applied to floats

    ❑ before quantizing to integers,

    ❑ before storage in the frame buffer,

    ❑ then in fact we can use only 8 bits per channel.

4.2.2 Multi-sensor Cameras

1. **More accurate color** can be achieved by using cameras with **more than 3 sensors, = more than 3color filters.**

2. One way of doing this is by using **a rotating filter**.

    –   Can remove the near-infrared filter typically placed in a camera,

    –   so as to extend the camera's sensitivity into the infrared

RGB + Near-Infrared → Combination: smooths skin

4.2.3 Camera-Dependant Colour : HSV

1. Besides R,G,B, two other camera-dependent color spaces are commonly used: HSV and sRGB.

2. **_HSV_**: **H** stands for hue درجه اللون; **S** stands for 'saturation' of a color; **V** stands for 'value', meaning brightness.

   – Assuming R,G,B are in 0..255 are KNOWN, ➔ <u>**We can get the HSV**</u>

$$
\begin{aligned}
M &= \max\{R, G, B\} \\
m &= \min\{R, G, B\} \\
V &= M \\
S &= \begin{cases} 0 & \text{if } V = 0 \\ \left(V - m\right)/V & \text{if } V > 0 \end{cases} \\
H &= \begin{cases} 0 & \text{if } S = 0 \\ 60(G - B)/(M - m) & \text{if } (M = R \text{ and } G \geq B) \\ 60(G - B)/(M - m) + 360 & \text{if } (M = R \text{ and } G < B) \\ 60(B - R)/(M - m) + 120 & \text{if } M = G \\ 60(R - G)/(M - m) + 240 & \text{if } M = B \end{cases}
\end{aligned}
\tag{4.24}
$$

4.2.3 Camera-dependant Colour : sRGB

3. **sRGB** (standard RGB):

- Tied to the color space of a particular reference display device

- Adopted as a reference color space on the web

- With each color channel I in (R,G,B) normalized into the range $[0, 1])$): for $I = R,G,B$, we apply a function to take gamma-corrected I' back into "linear" I:

- When white is $(R,G,B) = (1, 1, 1)$, the XYZ is that **of standard light D65 /100**: $(X, Y,Z) = (0.9505, 1.0000, 1.0890)$.

- The **sRGB** standard also specifies a colorimetric transform to go from such linear **sRGB** values i to CIEXYZ values:

(4.25)

What the human perceives $\longrightarrow$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0.4124 & 0.3576 & 0.1805 \\ 0.2126 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9505 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

$\longleftarrow$ *What can be displayed over the most of devices*

4.2.4 Subtractive color: CMY color model

- So far, we have effectively been **dealing only** with **additive color**.

- Namely, when 2 light beams impinge on a target, **their colors add**

  - (when 2 phosphors on an older CRT screen are turned on, their colors add)

- But for **printing** ➜ *__ink deposited on paper,__* the opposite situation holds:

  - yellow ink = white illumination - blue,

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

  - reflects red and green; it appears yellow.

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


The RGB Cube   The CMY Cube
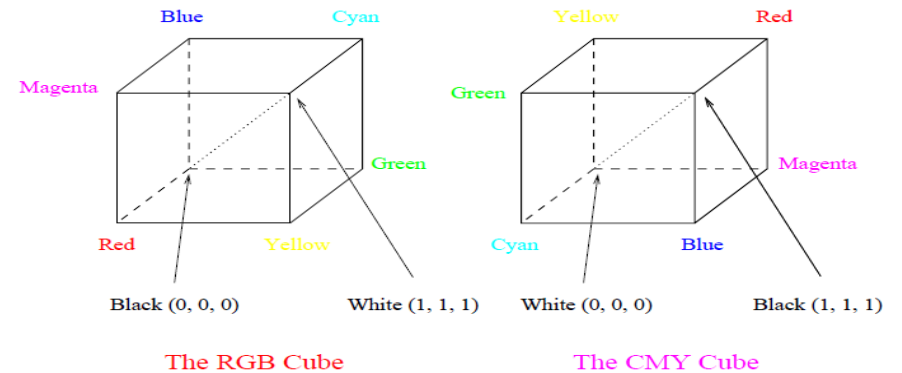
4.2.6 Undercolor Removal: CMYK System

- **Undercolor removal**: Sharper and cheaper printer it looses ink to use the colors in order to get BLACK COLOR
  - colors:
    1. calculate that part of the CMY
    2. mix that would be black,
    3. remove it from the color proportions,
    4. and add it back as real black (relatively inexpensive ink).

- The new specification of inks is thus:

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

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} \Rightarrow \begin{bmatrix} C - K \\ M - K \\ Y - K \end{bmatrix}$$
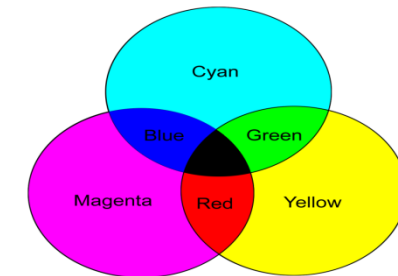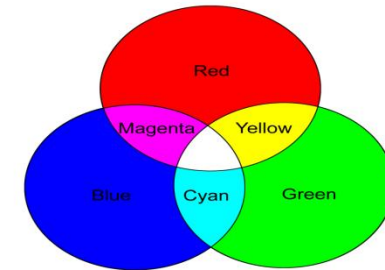
Fig. 4.16: Additive and subtractive color.
(a): RGB is used to specify **additive color**.
(b): CMY is used to specify **subtractive color**

4.3 Color Models in Video
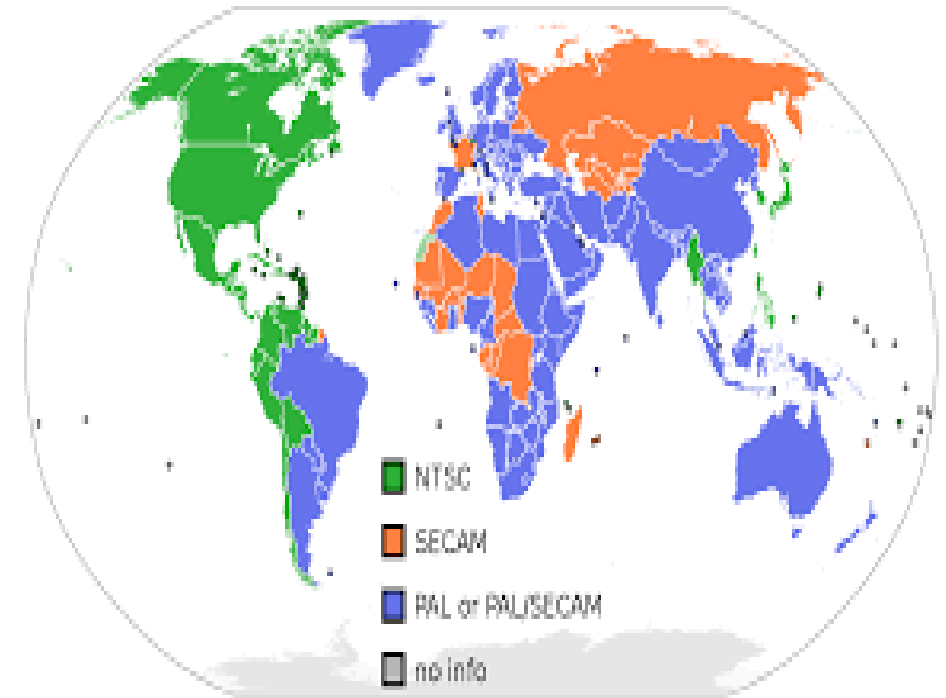
• **Video Color Transforms**

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

- a matrix transform method

• 2 Majors analog models

  ❑ **NTSC➔YIQ** is used to transmit TV signals in **North America and Japan**.

  ❑ In Europe, video tape uses the **PAL or SECAM** codings, ➔ **YUV**.

• digital video

  ❑ uses a matrix transform called **YCbCr** that is **closely related to YUV**

NTSC
SECAM
PAL or PAL/SECAM
no info

THANK YOU