Unit 2-2. Color

CS 3570
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Content

- Color Science
- Human Vision
- Image Formation
- Color Matching
- Color Spaces
  - RGB
  - CMYK
  - HSV
  - YUV
  - YIQ
  - YCbCr

Color Science

- Light and Spectra

- Light is an electromagnetic wave in the range 400 nm to 700 nm. Its color is characterized by the wavelength content of the light.
  - Laser light consists of a single wavelength: e.g., a ruby laser produces a bright, scarlet-red beam.
  - Most light sources produce contributions over many wavelengths.
  - However, humans cannot detect all light, just contributions that fall in the "visible wavelengths".
  - Short wavelengths produce a blue sensation, long wavelengths produce a red one.

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

Spectral Power Distribution

- 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.
- The symbol for wavelength is λ. This curve is called $E(\lambda)$.

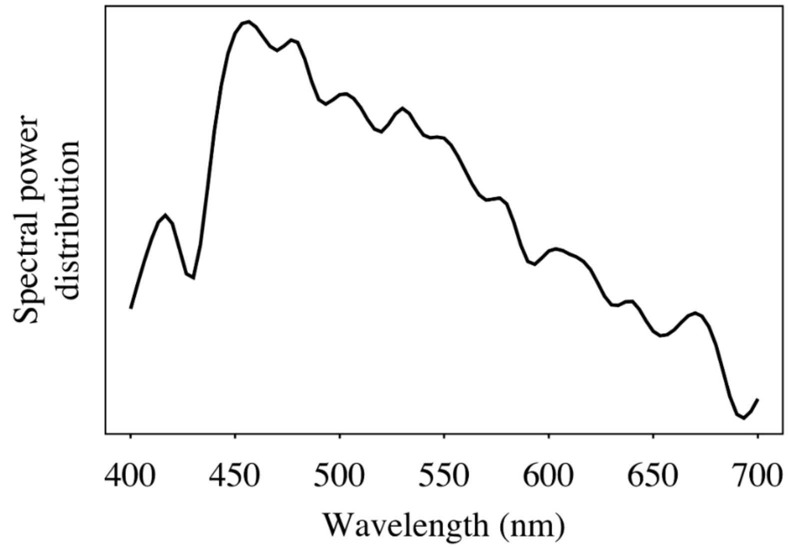
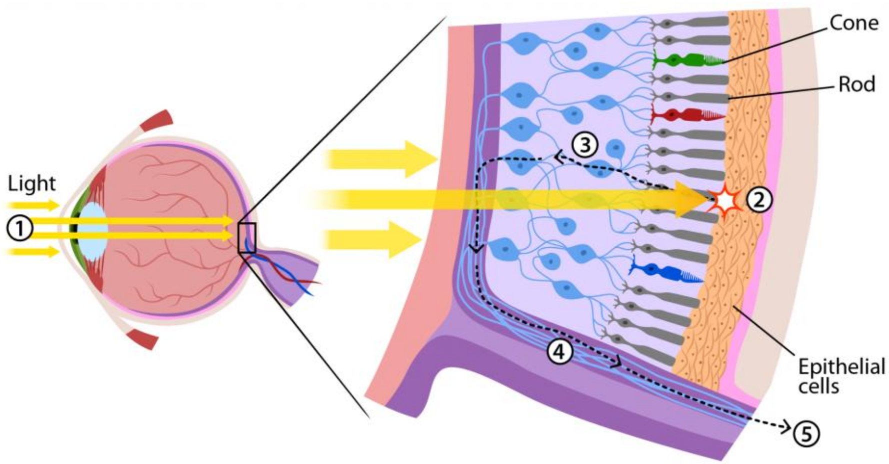


Fig. 4.2: Spectral power distribution of daylight.

Human Vision

- The eye works like a camera, with the lens focusing an image onto the retina (upside-down and left-right reversed).
- The retina consists of an array of rods and three kinds of cones.
- The rods come into play when light levels are low and produce an image in shades of gray.
- For higher light levels, the cones each produce a signal. Because of their differing pigments, the three kinds of cones are most sensitive to red (R), green (G), and blue (B) light.

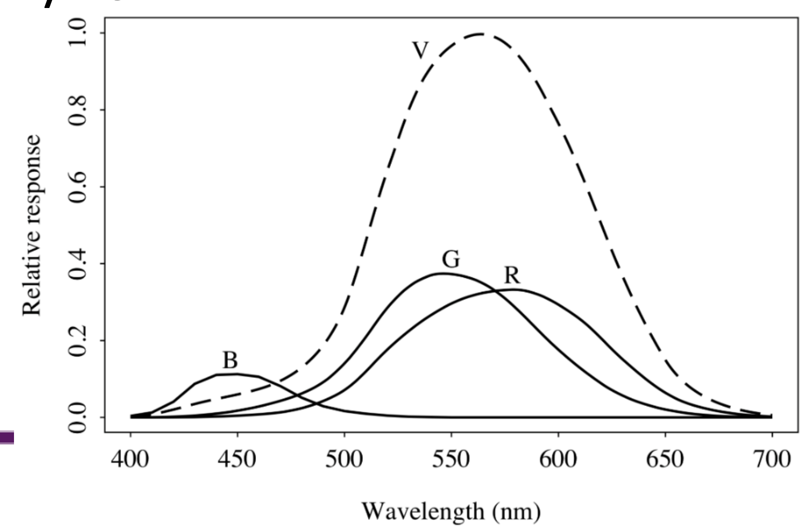


Spectral Sensitivity of the Eye

- 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.
- 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 evolution.
  - Statistically, Blue is the favourite color of humans, regardless of nationality — perhaps for this reason: Blue is a latecomer and thus is a bit surprising!

Spectral Sensitivity of the Eye

- Fig. 4.3 shows the overall sensitivity as a dashed line — this important curve is called the luminous-efficiency function.
  - It is usually denoted $V(\lambda)$ and is formed as the sum of the response curves for Red, Green, and Blue.
- The rod sensitivity curve looks like the luminous-efficiency function $V(\lambda)$ but is shifted to the red end of the spectrum.
- The achromatic channel produced by the cones is approximately proportional to 2R+G+B/20.



Spectral Sensitivity Function

- 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

$$q(\lambda) = (q_R(\lambda), q_G(\lambda), q_B(\lambda))$$

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

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

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

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

Image Formation

- Surfaces reflect different amounts of light at different wavelengths, and dark surfaces reflect less energy than light surfaces.
- Here shows the **surface spectral reflectance** from (1) orange sneakers and (2) faded blue jeans. The reflectance function is denoted S(λ).

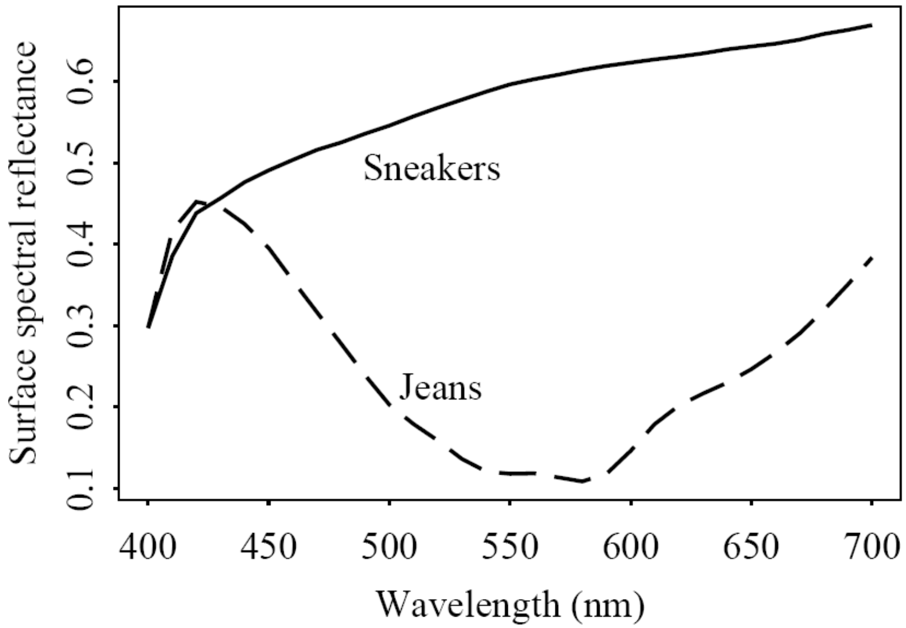


Image Formation Model

- Image formation is thus:
  - Light from the illuminant with SPD E(λ) impinges on a surface, with surface spectral reflectance function S(λ), is reflected, and then is filtered by the eye's cone functions q(λ).
  - The function C(λ) is called the color signal and consists of the product of E(λ), the illuminant, times S(λ), the reflectance:

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

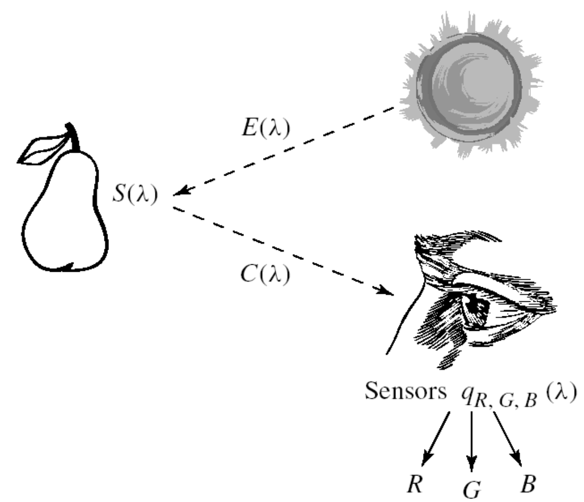


Image Formation Model

- The following equations take into account the image formation model:

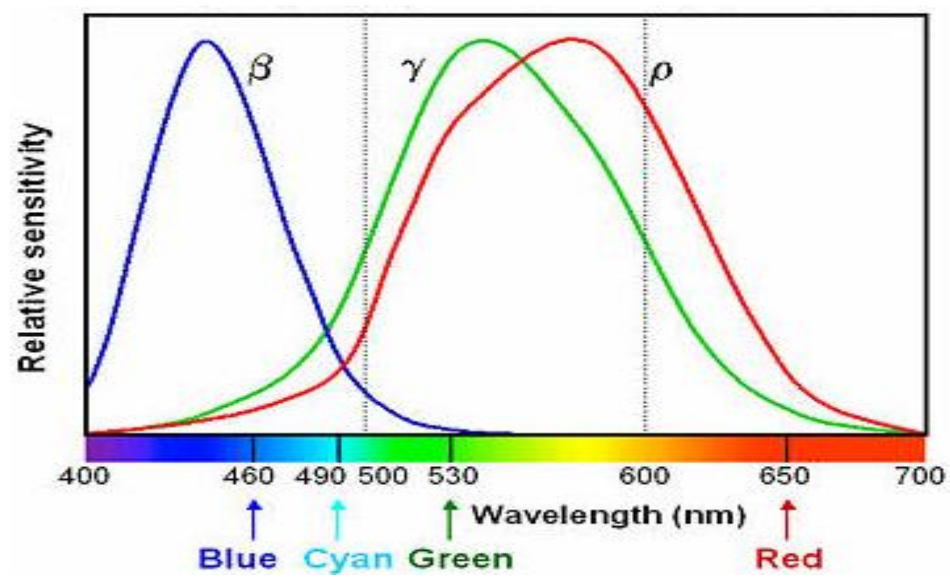
$$R = \int E(\lambda)\, S(\lambda)\, q_R(\lambda)\, d\lambda$$

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

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

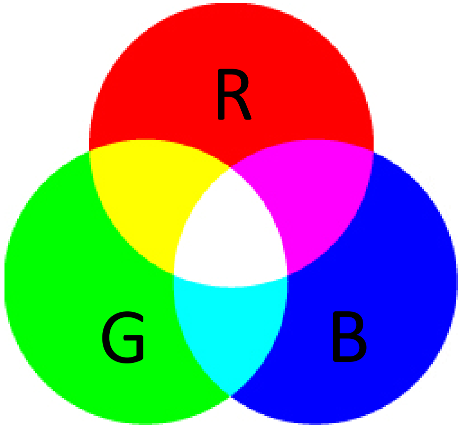
Color

- Color is composed of electromagnetic waves
  - The wavelength of visible color fall between approximately 370 and 780 nanometers.
- Three Characteristics of colors
  - Hue (essential color): *dominant wavelength*
  - Saturation (color purity)
  - Luminance (lightness)
- Color model
  - RGB color model
  - CMY color model
  - HSV color model
  - YIQ color model



RGB color mode

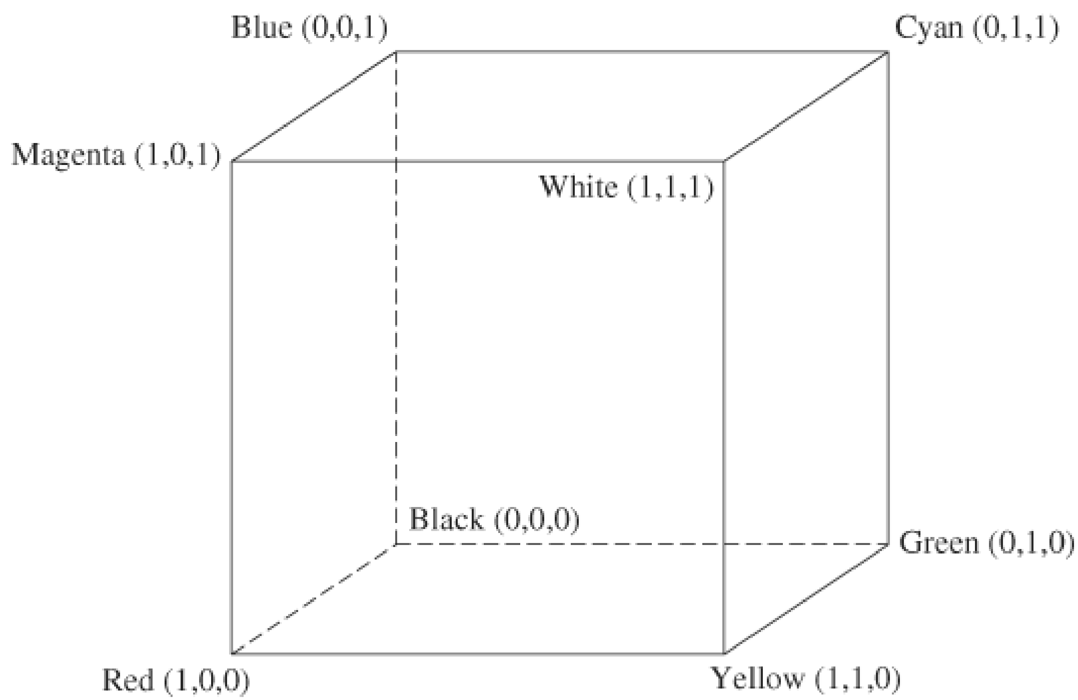
- Additive color mixing
- Combinations of three primary colors. No one of them can be created as a combination of the other two
  - Red
  - Green
  - Blue



- $C = rR + gG + bB$
  - *R, G, B*: constant values based on the wavelengths
  - *r, g, b*: the relative amounts. The values r, g, b are referred to as the values of the **RGB color components** (color channels)

RGB color cube

- R, G, and B correspond to three axes in 3D space
- Normalize the relative amount of R,G and B in a color. Each value varies between 0 and 1.



RGB color to grayscale

- The conversion of RGB color to grayscale
  - In RGB color (R, G, B)
  - In grayscale (L, L, L)

$$L = 0.299R + 0.587G + 0.114B$$

- Since all three color components are equal in a gray pixel, only one of the three values needs to be stored. Thus a 24-bit RGB pixel can be stored as an 8-bit grayscale pixel.

Image from google

RGB color model – advantage & disadvantage

- Advantage
  - The human eye perceives color
  - The computer monitor can be engineered to display color
- Disadvantage
  - There exist visible colors that can’t be represented with positive value for each of the red, green and blue components
  - It is necessary to “subtract out” some of the red, green, or blue in the combined beams to match the pure color

Subtractive color: CMY color model

For printing purpose, instead of red, green, and blue primaries, we need primaries that amount to minus-red, minus-green, and minus-blue. I.e., we need to *subtract* R, or G, or B.

These subtractive color primaries are Cyan (*C*), Magenta (*M*) and Yellow (*Y*) inks.

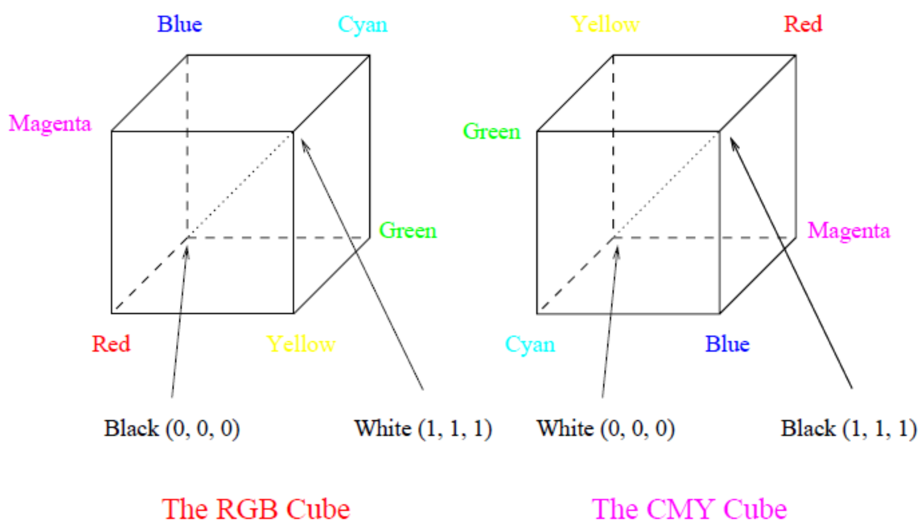
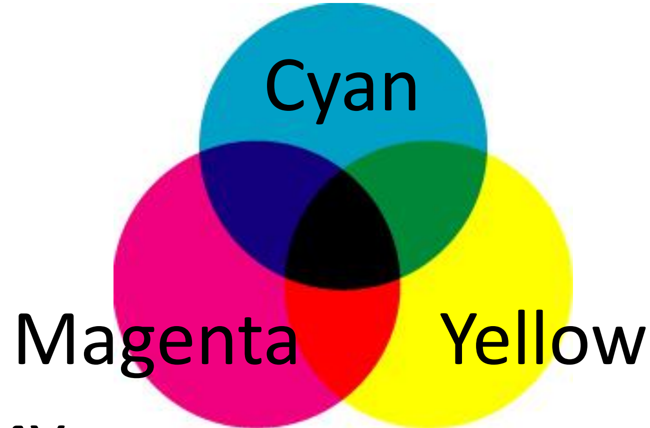


Fig. 4.15: RGB and CMY color cubes.

CMY color model

- Subtractive color mixing
- Commonly used in printing
- It has three primaries
  - Cyan, Magenta, Yellow



- Conversion between RGB and CMY color models
  - C = 1 – R, M = 1-G, Y = 1 – B
- CMYK model
  - In CMY color mode, the maximum amount of three primary should combine to black, but in fact producing a dark brown
  - Add a pure black -> K
  - K = min(C, M, Y), C_{new} = C – K, M_{new} = M – K, Y_{new} = Y - K

Transformation from RGB to CMY

- Simplest model we can invent to specify what ink density to lay down on paper, to make a certain desired RGB color:

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix} \tag{4.27}$$

- Then the inverse transform is:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} C \\ M \\ Y \end{bmatrix} \tag{4.28}$$

Undercolor Removal: CMYK System

- **Undercolor removal**: Sharper and cheaper printer colors: calculate that part of the CMY mix that would be black, remove it from the color proportions, and add it back as real black (relatively inexpensive ink).

- The new specification of inks is thus:

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

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} \Rightarrow \begin{bmatrix} C-K \\ M-K \\ Y-K \end{bmatrix} \qquad (4.29)$$

- Color combinations that result from combining primary colors available in the two situations, additive color and subtractive color.

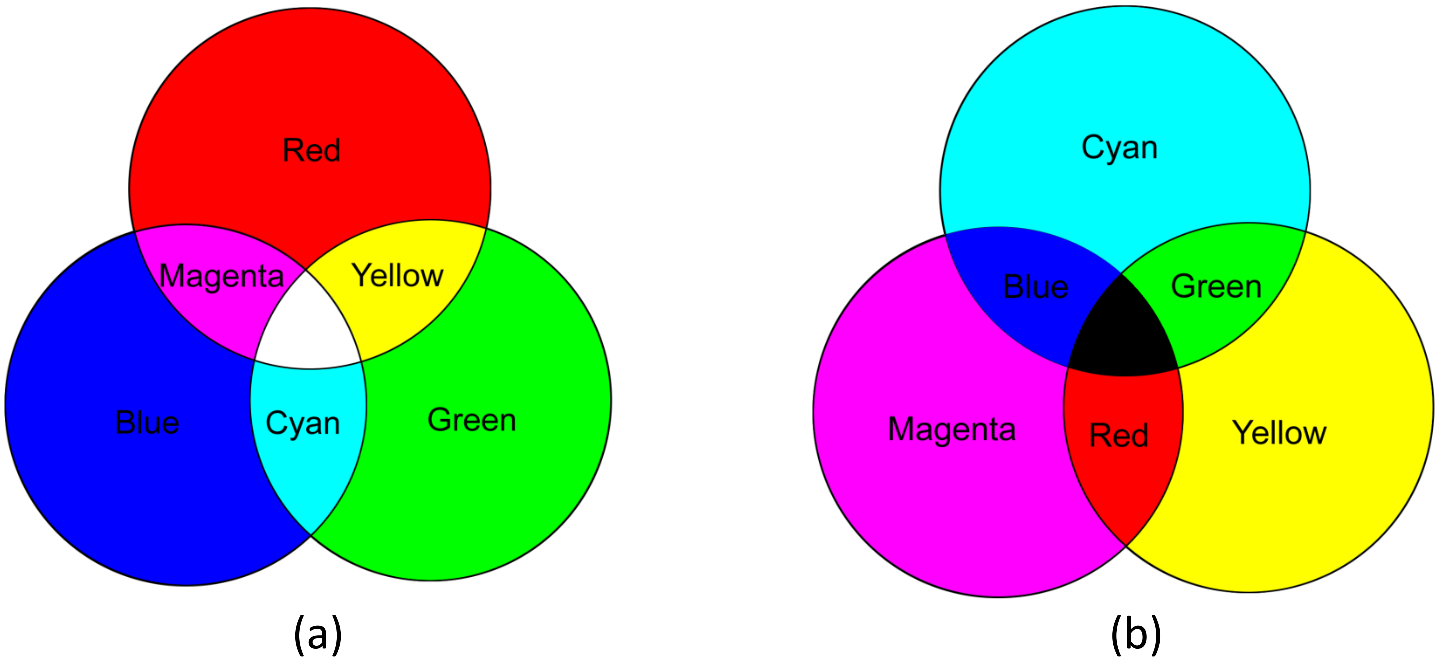
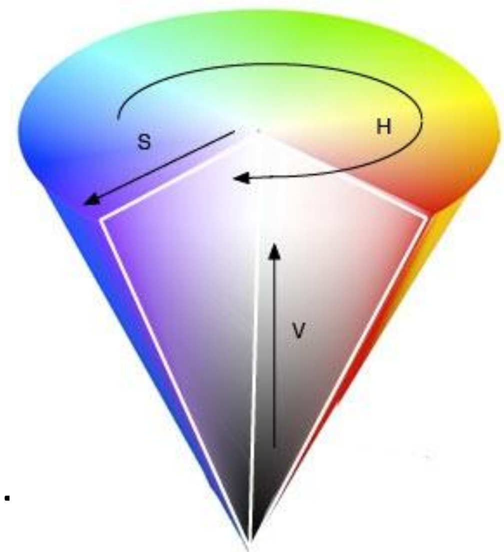


Fig. 4.16: Additive and subtractive color.

(a): RGB is used to specify additive color. (b): CMY is used to specify subtractive color

HSV Color Model

- Represent color by three terms
  - Hue, the color type (such as red, blue, or yellow)
    - ✓ Ranges from 0-360 (but normalized to 0-100% in some applications)
  - Saturation, the "vibrancy" of the color
    - ✓ Ranges from 0-100%
    - ✓ The lower the saturation of a color,
    - ✓ the more “grayness”
  - Value, the brightness of the color
    - ✓ Ranges from 0-100%
- Also called HSB(hue, saturation and brigh



HSV Color Model

- Besides R,G,B, another camera-dependent color space is commonly used: HSV
- **HSV**: H stands for hue; S stands for 'saturation' of a color; V stands for 'value', meaning brightness. Assuming R,G,B are in [0..255],

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

RGB to HSV

ALGORITHM 2.3 - RGB TO HSV

```
/* Input: r, g, and b, each real numbers in the range [0 . . . 1].
Output: h, a real number in the range of [0 . . . 360),
except if s = 0, in which case h is undefined.
s and v are real numbers in the range of [0 . . . 1].*/
{
  max = maximum(r,g,b)
  min = minimum(r,g,b)
  v = max
  if max ≠ 0 then s = (max − min)/max
  else s = 0
  if s == 0 then h = undefined
  else {
    diff = max − min
    if r == max then h = (g − b) / diff
    else if g == max then h = 2 + (b − r) / diff
    else if b == max then h = 4 + (r − g) / diff
    h = h * 60
    if h < 0 then h = h + 360
  }
}
```

Color Models in Video

- Video Color Transforms
  - Largely derive from older analog methods of coding color for TV. Luminance is separated from color information.
  - For example, a matrix transform method called YIQ is used to transmit TV signals in North America and Japan.
  - This coding also makes its way into VHS video tape coding in these countries since video tape technologies also use YIQ.
  - In Europe, video tape uses the PAL or SECAM codings, which are based on TV that uses a matrix transform called YUV.
  - Finally, digital video mostly uses a matrix transform called YCbCr that is closely related to YUV

YUV Color Model

(a) YUV codes a luminance signal (for gamma-corrected signals) equal to Y ′ in Eq. (4.20). the "luma".

(b) **Chrominance** refers to the difference between a color and a reference white at the same luminance. → use color differences *U*, *V*:

$$U = B' - Y', \qquad V = R' - Y' \tag{4.30}$$

From Eq. (4.20),

$$\begin{bmatrix} Y' \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ -0.299 & -0.587 & 0.886 \\ 0.701 & -0.587 & -0.114 \end{bmatrix} \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} \tag{4.31}$$

(c) For gray, *R′* = *G′* = *B′*, the luminance *Y′* equals to that gray, since 0.299+0.587+0.114 = 1.0. For a gray image, the chrominance (*U*, *V*) is zero.

YUV Color Model

(d) In the actual implementation *U* and *V* are rescaled to have a more convenient maximum and minimum.

(e) For dealing with composite video, it turns out to be convenient to contain the composite signal magnitude $Y' \pm \sqrt{U^2 + V^2}$ within the range −1/3 to +4/3. So *U* and *V* are rescaled:

$$U = 0.492111\,(B' - Y')$$
$$V = 0.877283\,(R' - Y') \qquad (4.32)$$

The chrominance signal = the composite signal *C*:

$$C = U \cdot \cos(\omega t) + V \cdot \sin(\omega t) \qquad (4.35)$$

(f) *U* is approximately from blue (*U* > 0) to yellow (*U* < 0) in the RGB cube; V is approximately from red (*V* > 0) to cyan (*V* < 0).

YUV Color Model

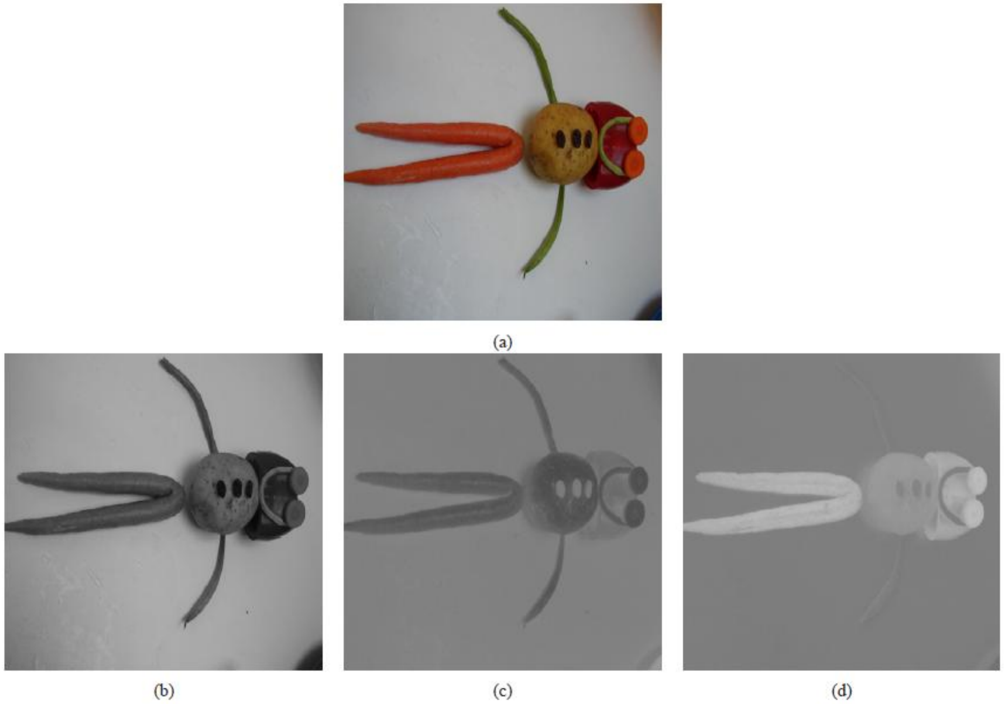


Fig. 4.18: Y ′UV decomposition of color image. Top image (a) is original color image; (b) is Y ′; (c,d) are (U, V)

YIQ color model

- It captures the luminance information in one value and puts the color (chrominance) information in the other two values
  - Luminance component: Y
  - Chrominance components: I, Q
- Convert RGB to YIQ

$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & 0.275 & 0.321 \\ 0.212 & 0.523 & 0.311 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

- Translate YIQ to RGB → Invert the matrix
- YIQ color model is used in U.S. commercial television broadcasting
- Advantage in color/black and white broadcasting

YIQ Color Model

- YIQ is used in NTSC color TV broadcasting. Again, gray pixels generate zero (I, *Q*) chrominance signal.

(a) I and *Q* are a rotated version of *U* and *V* .

(b) *Y ′* in YIQ is the same as in YUV; *U* and *V* are rotated by 33°:

$$I = 0.492111(R' - Y') \cos 33° - 0.877283(B' - Y') \sin 33°$$

$$Q = 0.492111(R' - Y') \sin 33° + 0.877283(B' - Y') \cos 33° \qquad (4.36)$$

(c) This leads to the following matrix transform:

$$\begin{bmatrix} Y' \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.595879 & -0.274133 & -0.321746 \\ 0.211205 & -0.523083 & 0.311878 \end{bmatrix} = \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} \qquad (4.37)$$

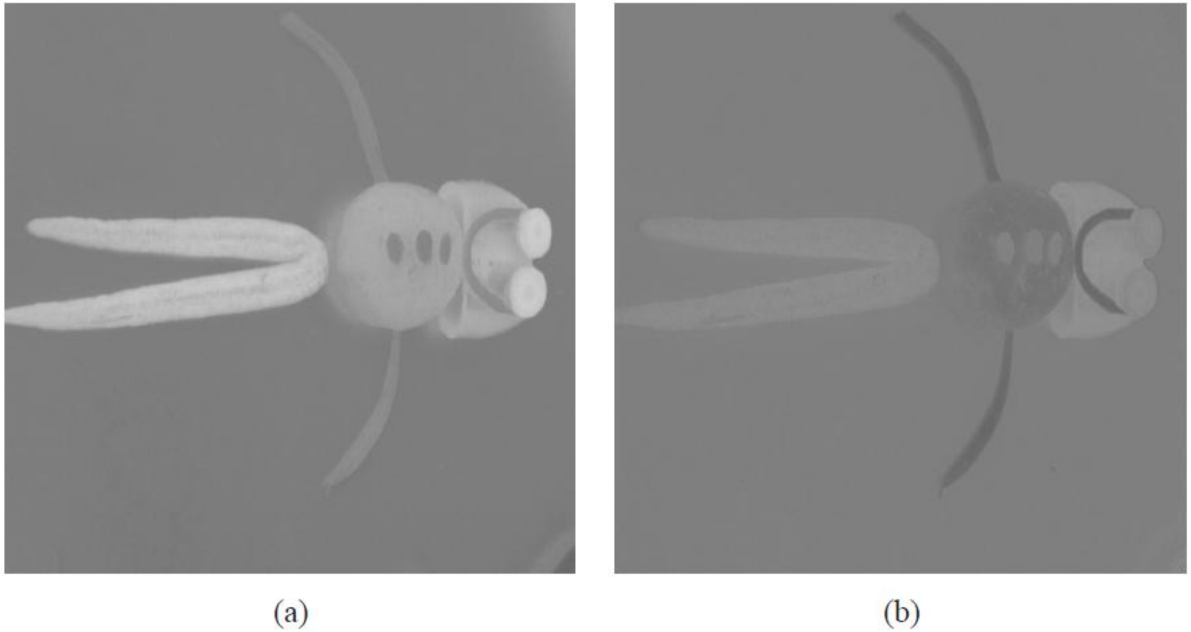


Fig.4.19: (a) I, and (b) *Q* components of color image.

YCbCr Color Model

- The Rec. 601 standard for digital video uses another color space, YC_bC_r , often simply written YCbCr — closely related to the YUV transform.

  a) YUV is changed by scaling such that C_b is U, but with a coefficient of 0.5 multiplying B'. In some software systems, C_b and C_r are also shifted such that values are between 0 and 1.

  b) This makes the equations as follows:

$$
\begin{aligned}
C_b &= ((B' - Y')/1.772) + 0.5 \\
C_r &= ((R' - Y')/1.402) + 0.5
\end{aligned} \tag{4.39}
$$

  c) Written out:

$$
\begin{bmatrix} Y' \\ C_b \\ C_r \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ -0.168736 & -0.331264 & 0.5 \\ 0.5 & -0.418688 & -0.081312 \end{bmatrix} \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} + \begin{bmatrix} 0 \\ 0.5 \\ 0.5 \end{bmatrix} \tag{4.40}
$$

- d) In practice, however, Recommendation 601 specifies 8-bit coding, with a maximum Y′ value of only 219, and a minimum of +16. Cb and Cr have a range of ±112 and offset of +128. If R′, G′, B′ are floats in [0..+1], then we obtain Y ′, Cb, Cr in [0..255] via the transform:

$$\begin{bmatrix} Y' \\ C_b \\ C_r \end{bmatrix} = \begin{bmatrix} 65.481 & 128.553 & 24.966 \\ -37.797 & -74.203 & 112 \\ 112 & -93.786 & -18.214 \end{bmatrix} \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} + \begin{bmatrix} 16 \\ 128 \\ 128 \end{bmatrix} \qquad (4.41)$$

- e) The YCbCr transform is used in JPEG image compression and MPEG video compression.

Summary

- Image formation model
- Light and color in spectral domain
- Color models for different applications
- Human visual system – human perception
- Image compression performs quantization on a chosen color space to remove redundancy in images and minimize distortion for human visual system