Color

Multimedia Techniques & Applications

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Course Information (Update)

- **Teaching assistants:** 賴彥富
- **Final project policy:**
  - **3~5** students per group
  - The film has not to be long, but has **better** be interesting and high-quality
  - It is a plus if some techniques we taught in this course have been used
  - The final score is determined by the instructor, the TA, and all students

Outline

- Color science
- Tristimulus theory
- RGB color model
- Other color models
- User interface for color selection

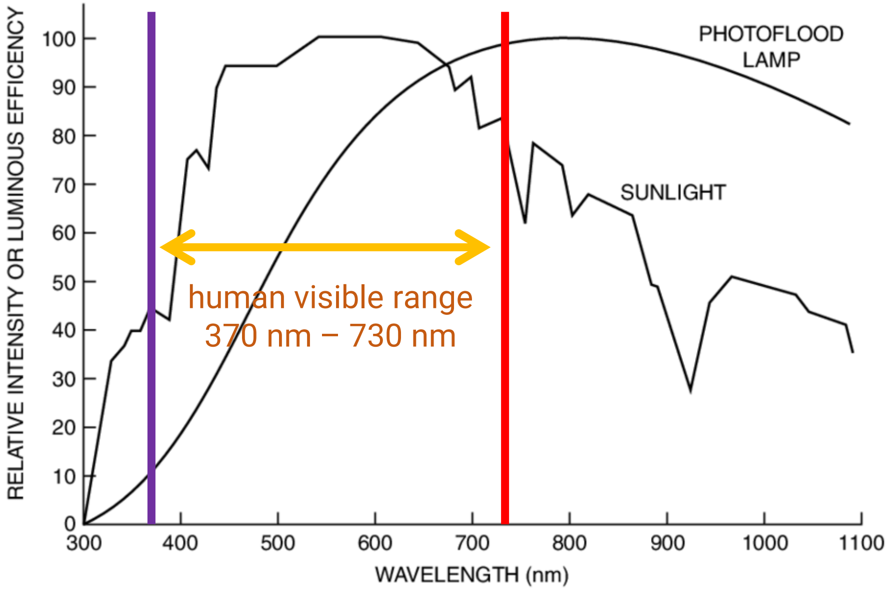
Color Science

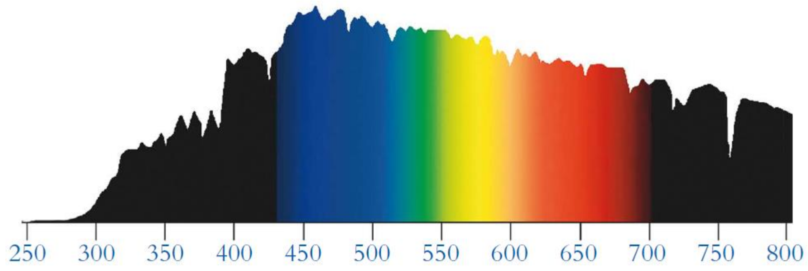
Color Science

- Color is a common experience for human, but being a rather complex phenomenon
- Color science is a topic that attempts to relate the **subjective sensation** of color to **measurable** and **reproducible** physical phenomena

Spectral Power Distribution

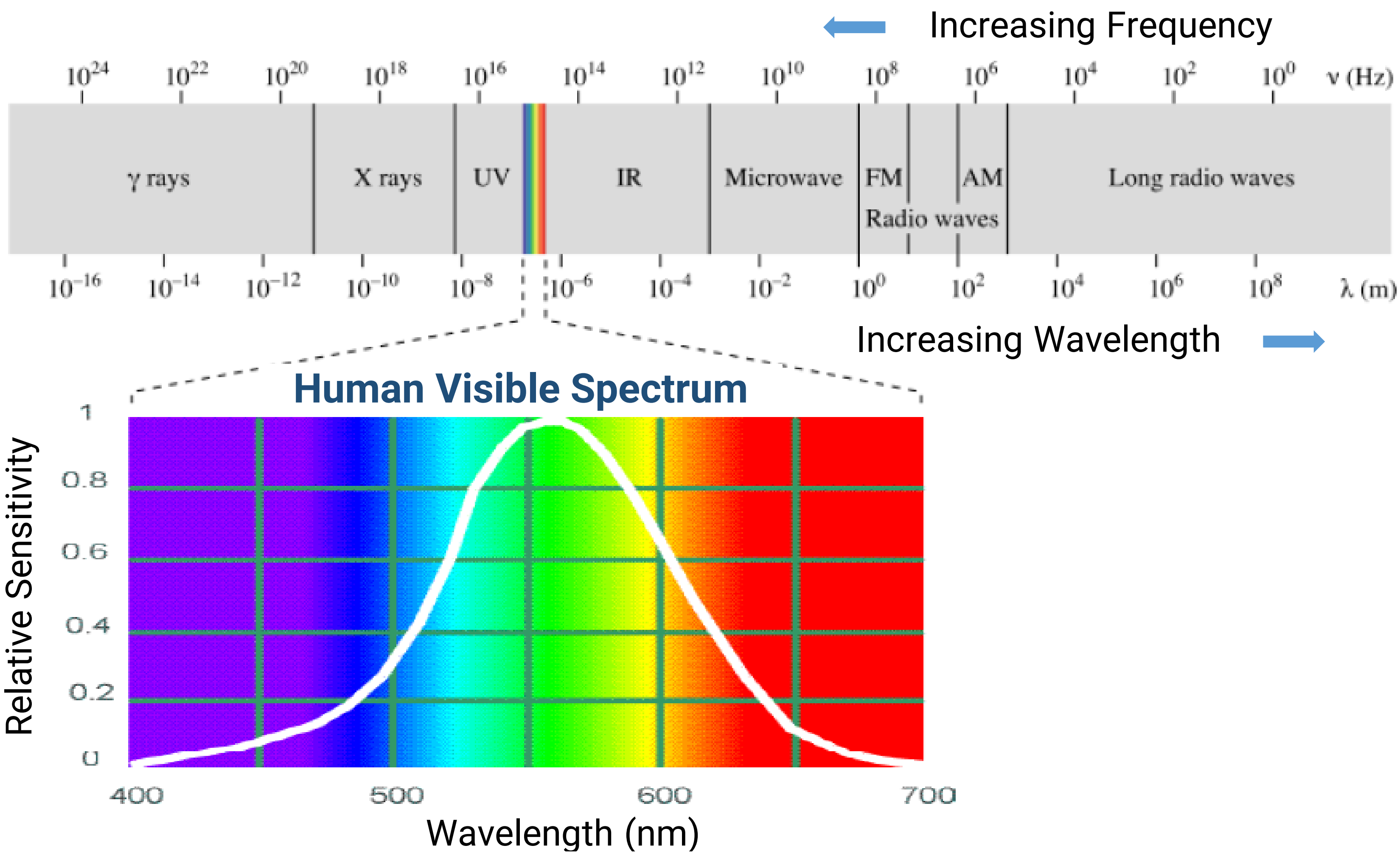
- Light is an electromagnetic wave, and we can measure its wavelength and intensity
- **Spectral power distribution (SPD)** is a description of how the intensity of light varies with its wavelength





SPD of daylight

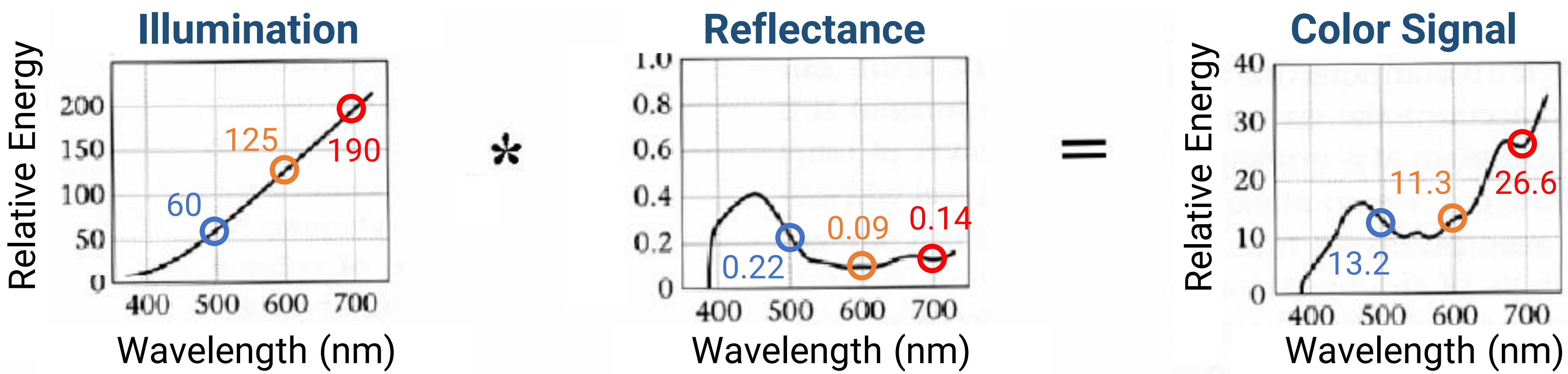
Spectral Power Distribution (cont.)



Human Luminance Sensitivity Function

Color

- Reflected color is the result of interaction of **light source spectrum** with **surface reflectance**



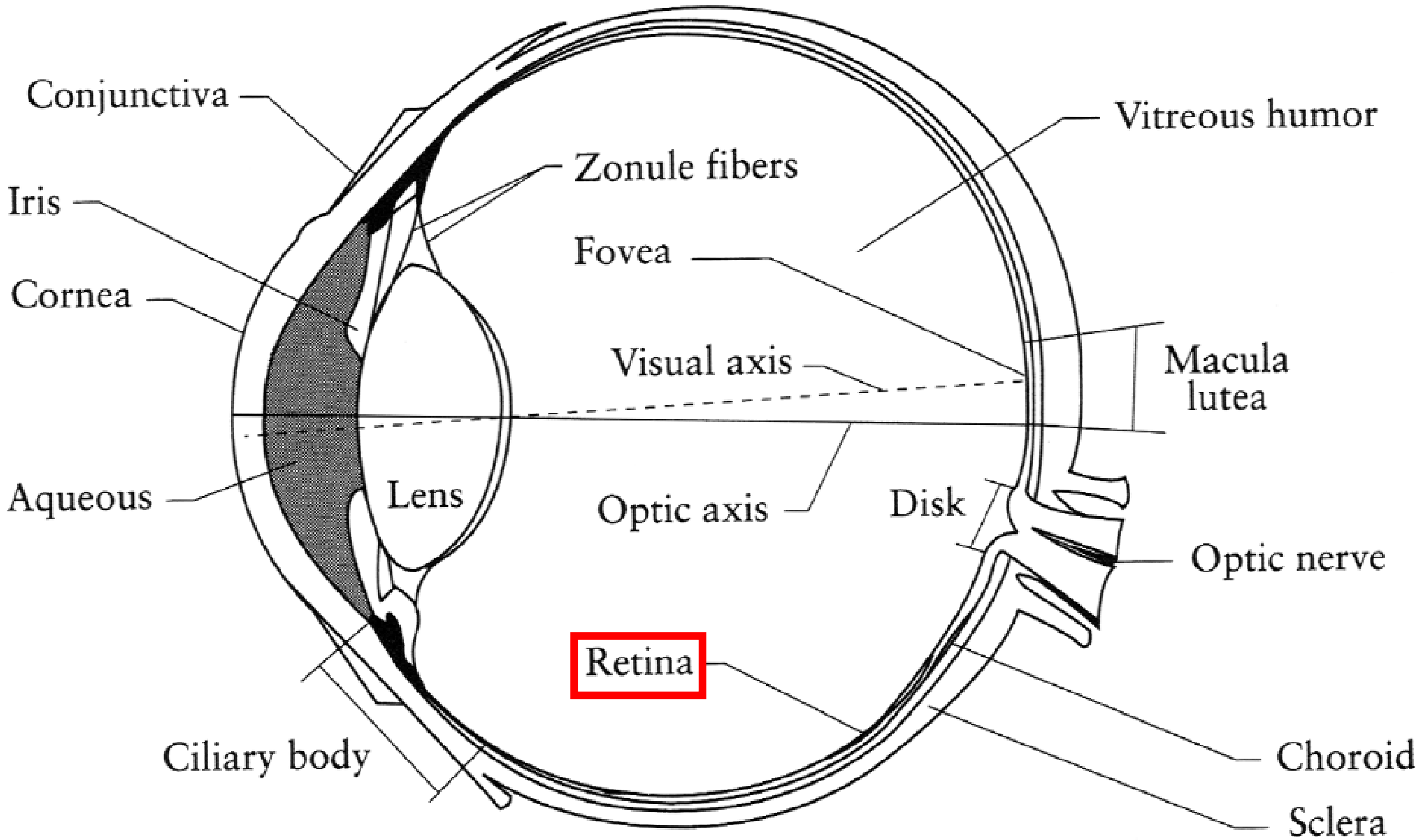
Tristimulus Theory

Tristimulus Theory

- SPDs are too cumbersome for representing the color in computer graphics
- Need a more compact, efficient, and accurate way to represent color signals
  - Find a proper basis functions to map the infinite-dimensional space of all possible SPDs to a **low-dimensional space of coefficients**
- We use **tristimulus theory**
  - All visible SPDs can be accurately represented with **three values**

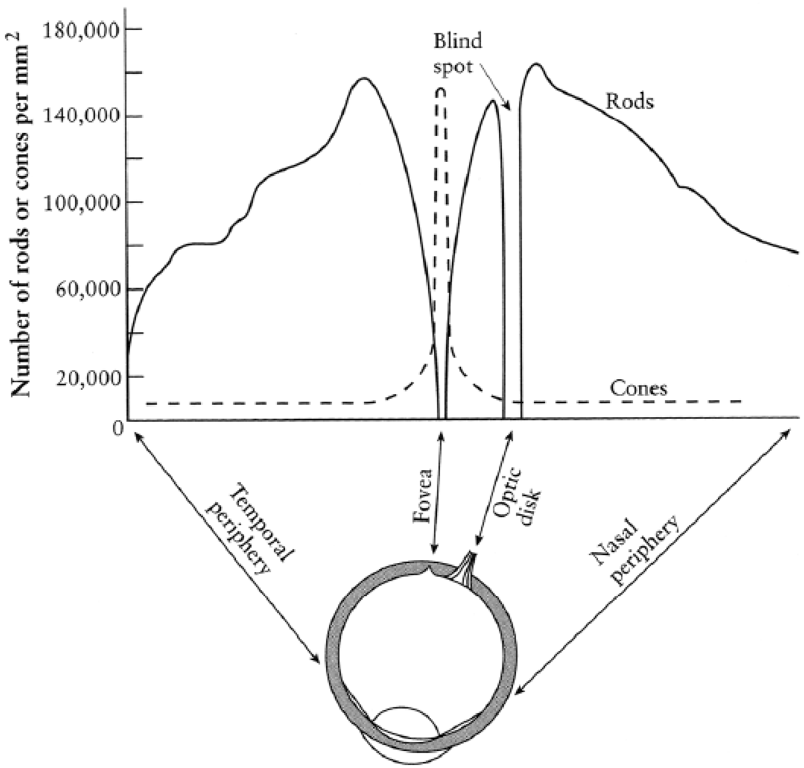
= Any color can be specified by just three values, giving the weights of each of three components

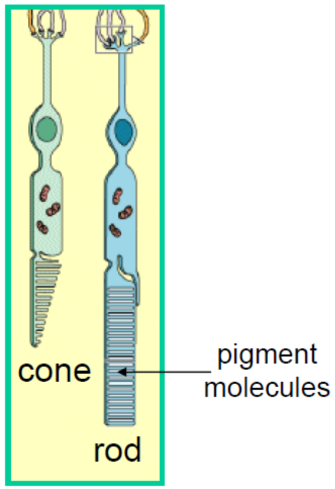
Human Eye

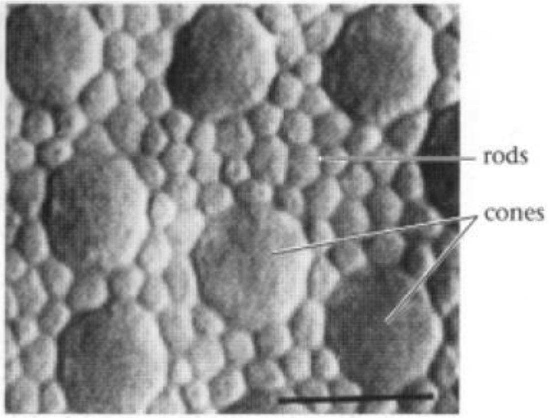

Conjunctiva
Iris
Cornea
Aqueous
Ciliary body
Zonule fibers
Fovea
Visual axis
Lens
Optic axis
Retina
Disk
Vitreous humor
Macula
lutea
Optic nerve
Choroid
Sclera

Rods and Cones

- Two types of cells on the retina: rods and cones
  - **Rods:** responsible for **intensity (125M)**
  - **Cones:** responsible for **color (6M~7M)**

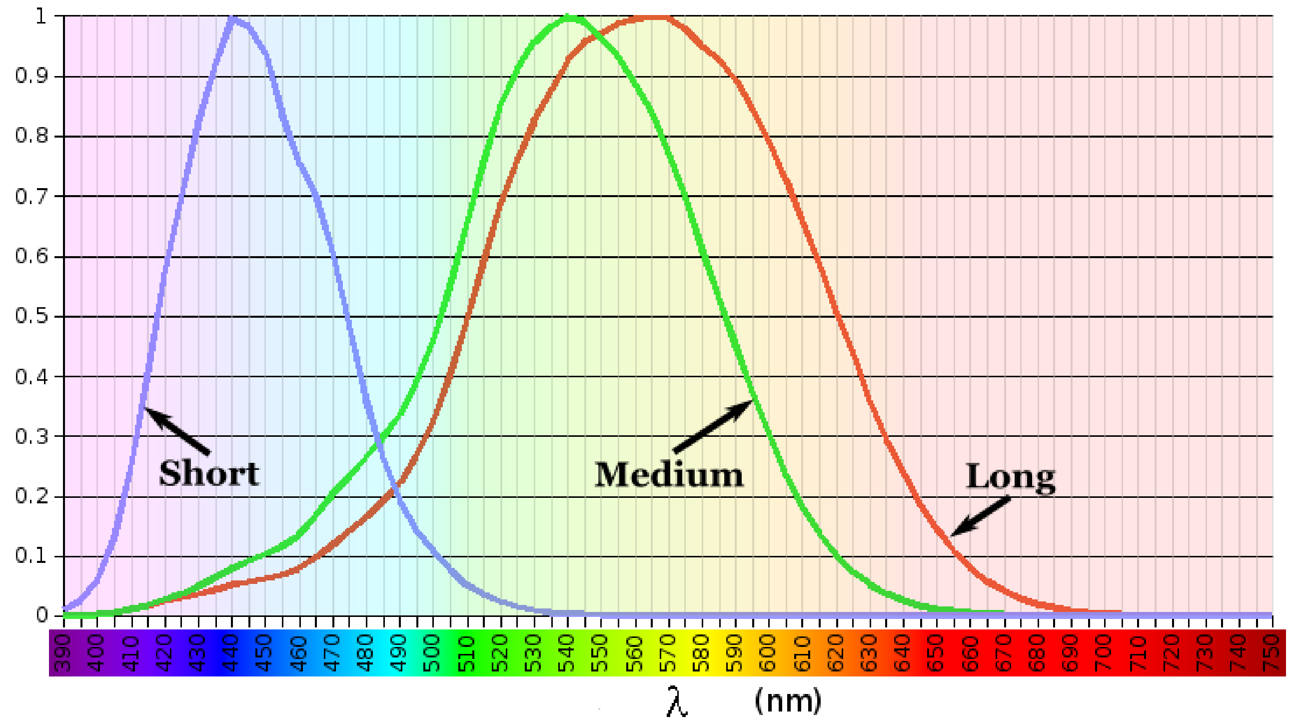






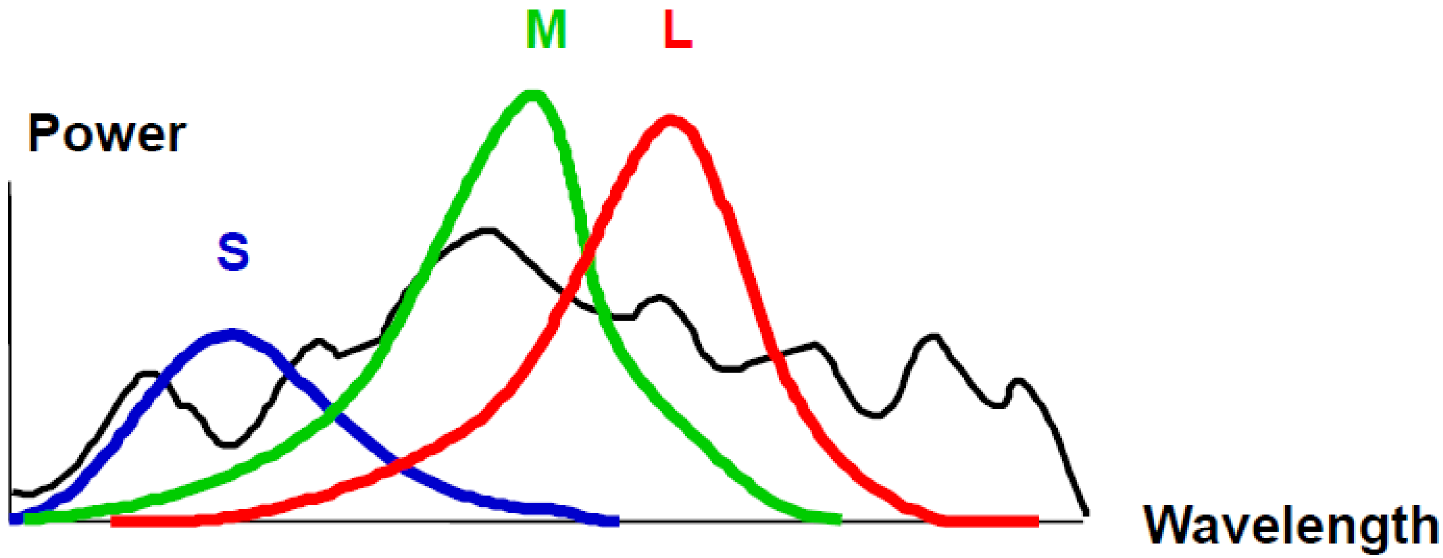
Three Types of Cone Cells

- L-cones: 564 nm (Long)
- M-cones: 534 nm (Medium)
- S-cones: 420 nm (Short)



Color Perception

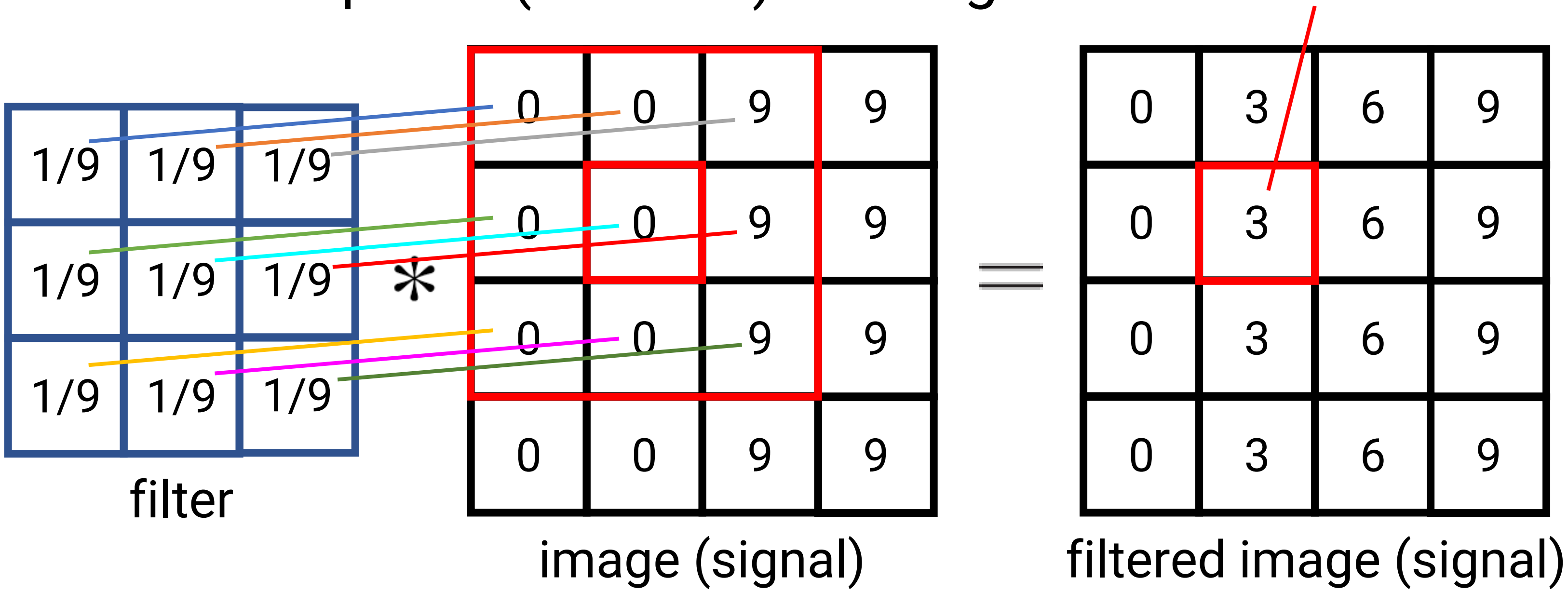
- Rods and cones act as **filters** on the spectrum
  - To get the output of a filter, multiply its response curve by the spectrum, integrate over all wavelengths
  - Each cone yields one number and we just got three numbers in total!

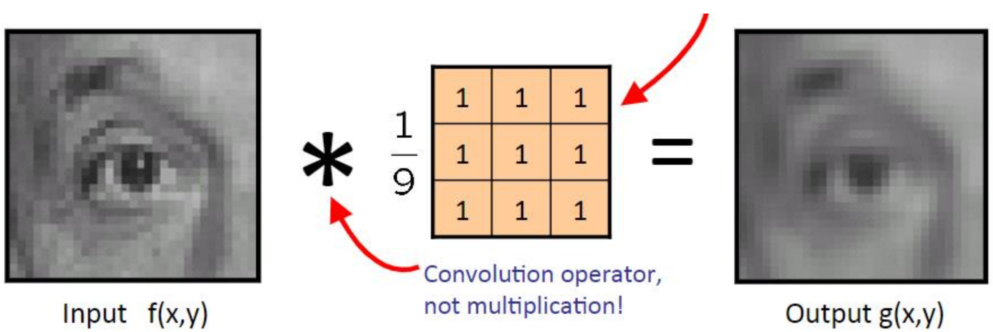


Color Perception (cont.)

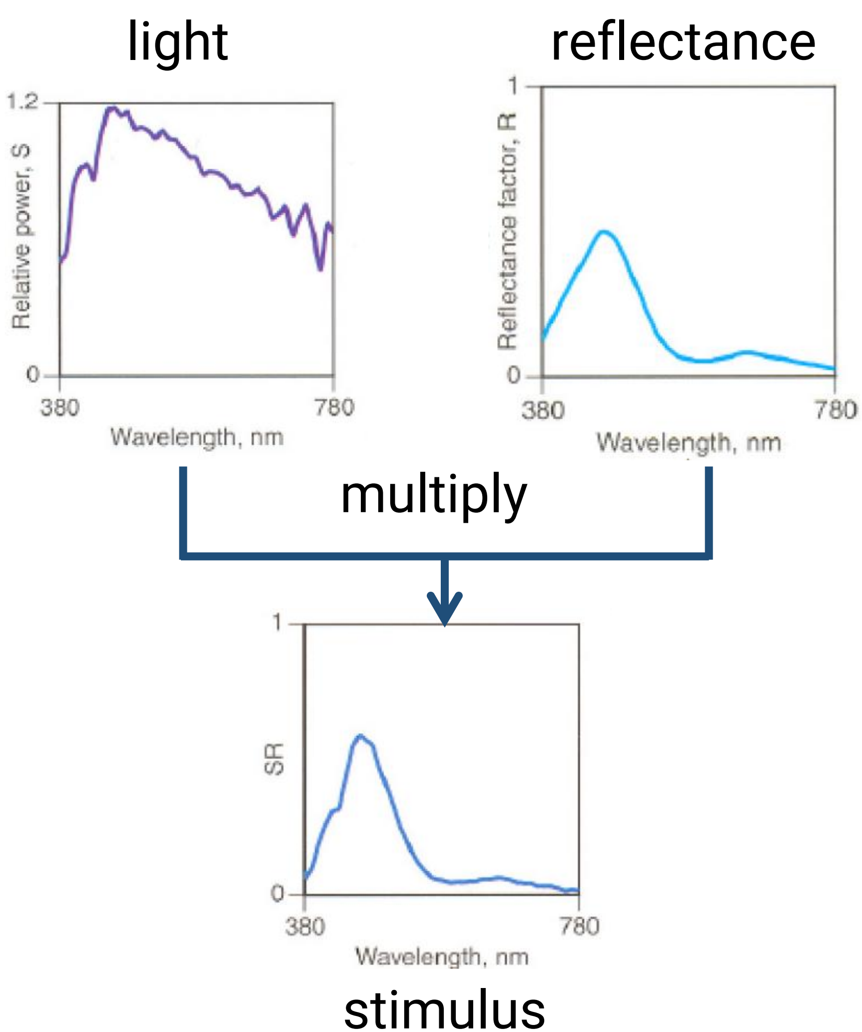
- An example of (discrete) filtering

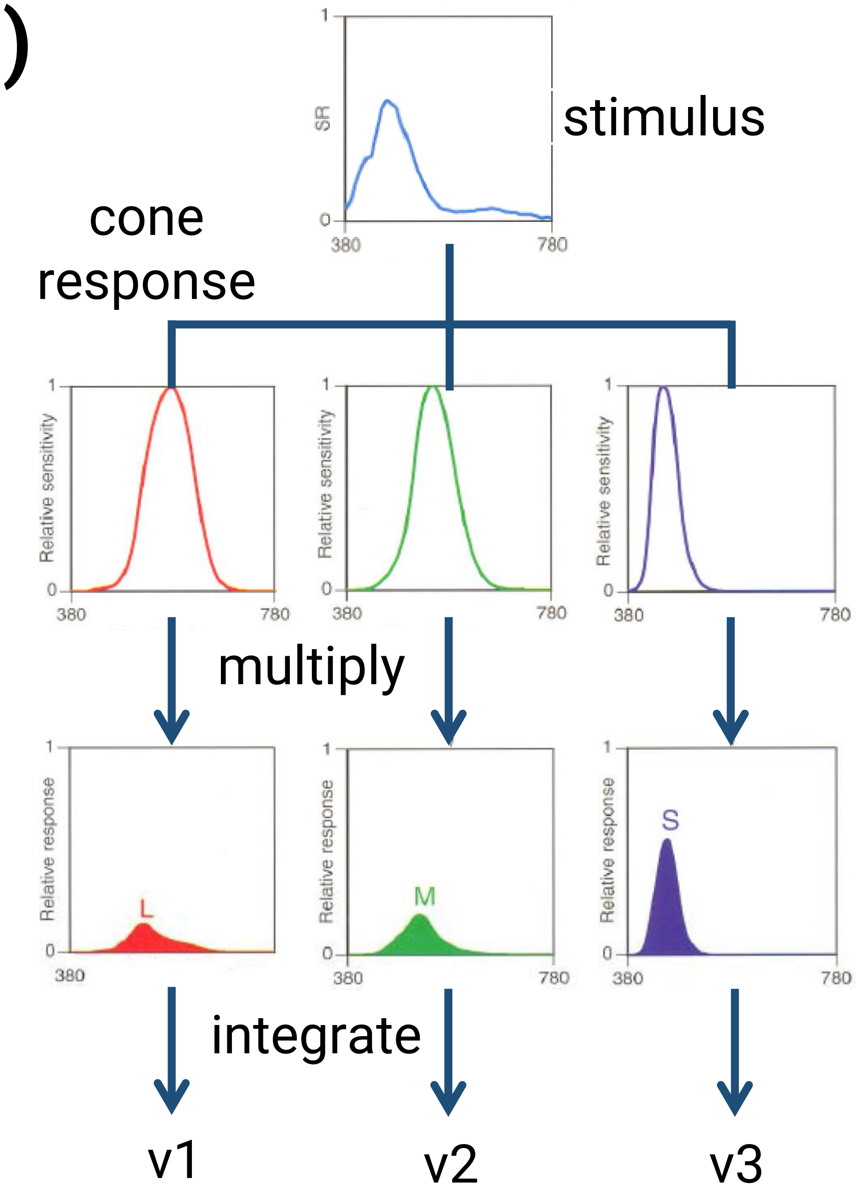
(1/9*0+1/9*0+1/9*0+
1/9*0+1/9*0+1/9*0+
1/9*9+1/9*9+1/9*9)





Color Perception (cont.)

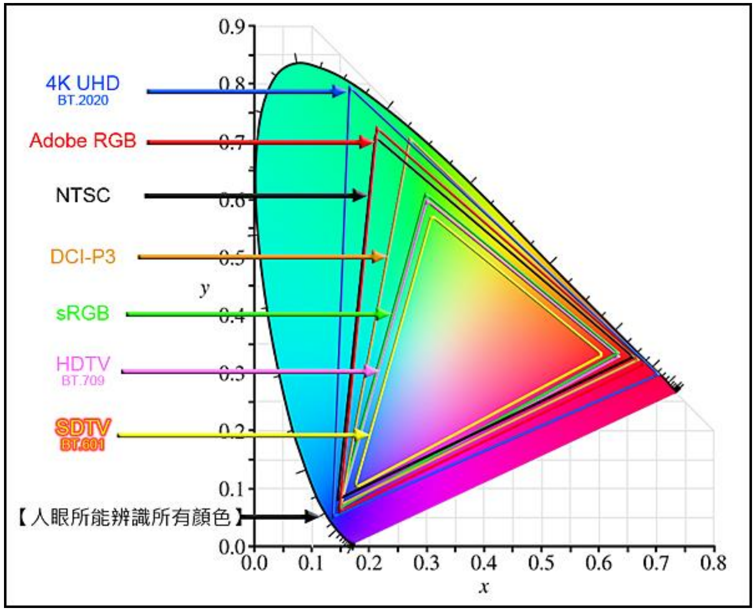




RGB Color Model

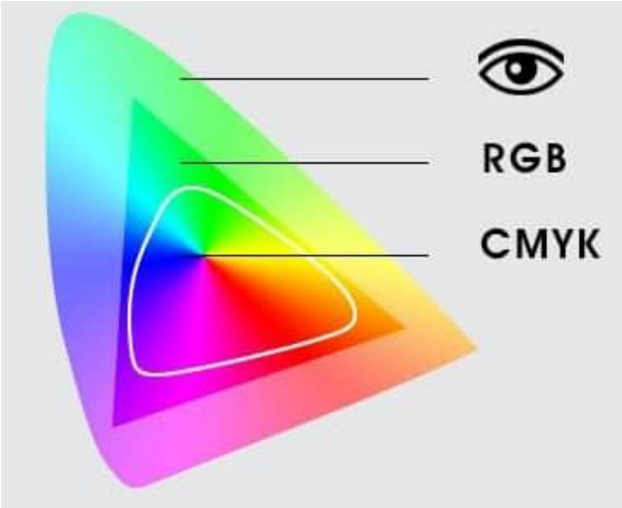
RGB Color Model

- The **tristimulus theory** and the **response curves of LMS cones** lead to the RGB model
  - Any color can be represented by three values, giving the proportions of red (R), green (G), and blue (B) light
  - However, no standard SPDs are defined for R, G, and B



RGB Color Gamut

- Although RGB model provides a good representation for color, it cannot represent all visible color of human eye
- RGB primaries do produce the **largest** gamut from simple addition of three primaries
- Red, green, and blue are called the **primary color** of light (additive mixing)



RGB Color Model Representation

- We can write a color with RGB model in the form of

  (r, g, b),

where r, g ,b are the **amounts (proportion of the pure light)** of red, green, and blue light making up the color

Red (100%, 0%, 0%)	Black (0%, 0%, 0%)	Cyan (0%, 100%, 100%)
Green (0%, 100%, 0%)	White (100%, 100%, 100%)	Magenta (100%, 0%, 100%)
Blue (0%, 0%, 100%)	Gray (50%, 50%, 50%)	Yellow (100%, 100%, 0%)

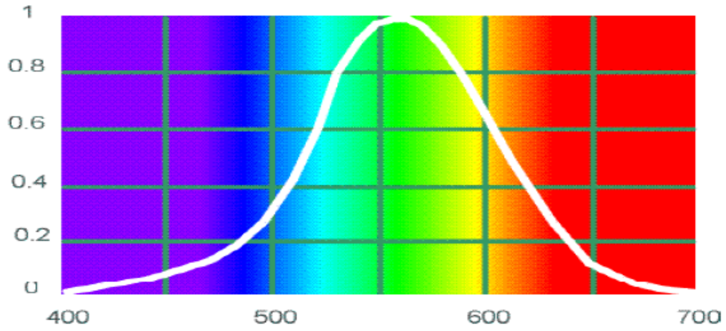
Color Depth

- In digital representation, we must choose the number of bits used for a color
- The most common choice is 8 bits (1 byte) for each primary color, making 24 bits (3 bytes) in total
  - The range of value falls within [0, 255], making a total 256 x 256 x 256 = 16777216 different colors **(24 bit color depth)**

Red (255, 0, 0)	Black (0, 0, 0)	Cyan (0, 255, 255)
Green (0, 255, 0)	White (255, 255, 255)	Magenta (255, 0, 255)
Blue (0, 0, 255)	Gray (127, 127, 127)	Yellow (255, 255, 0)

Color Depth (cont.)

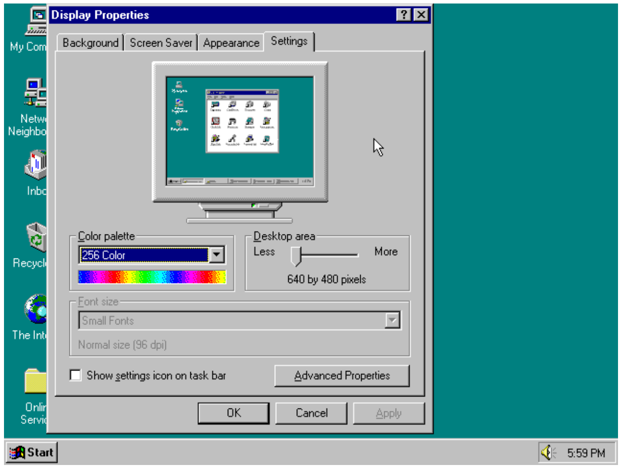
- Other possibilities
  - 1-bit color: two different colors (black or white)
  - 4-bit color: 16 different colors
  - 8-bit color: 256 different colors (earlier games or internet)
  - 16-bit color: 65536 different colors (5 bits for red and blue, 6 bits for green)

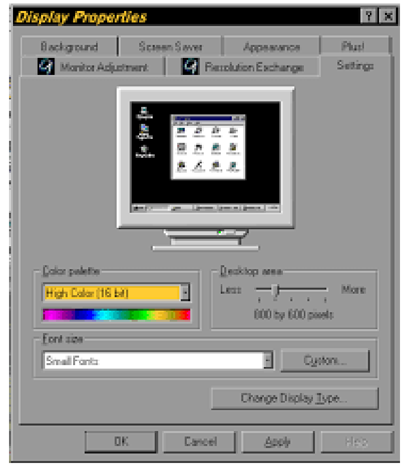


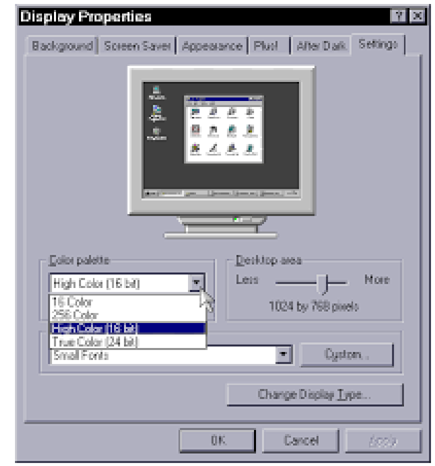
Human Luminance Sensitivity Function

  - 24-bit color: 16777216 different colors (sufficient for human eyes)

Color Depth (cont.)





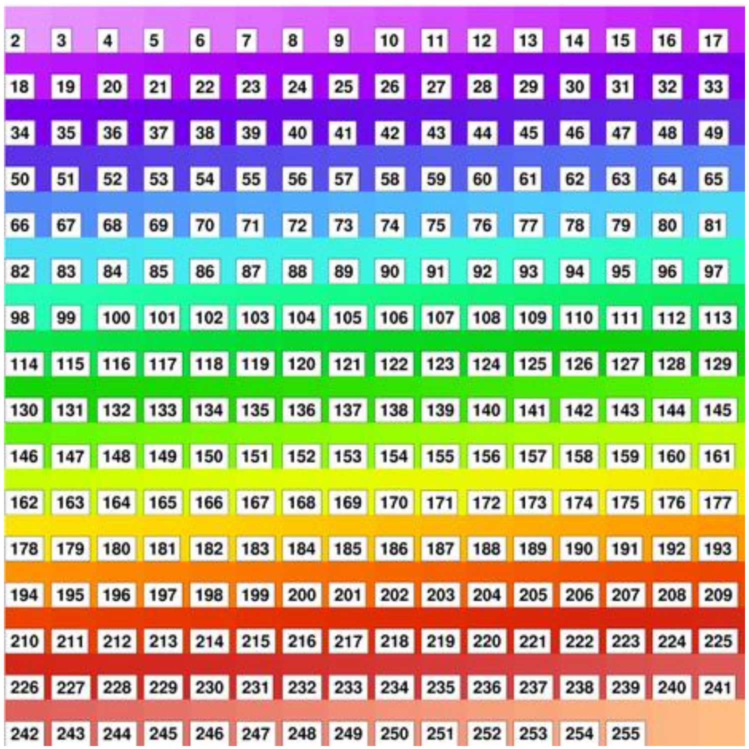


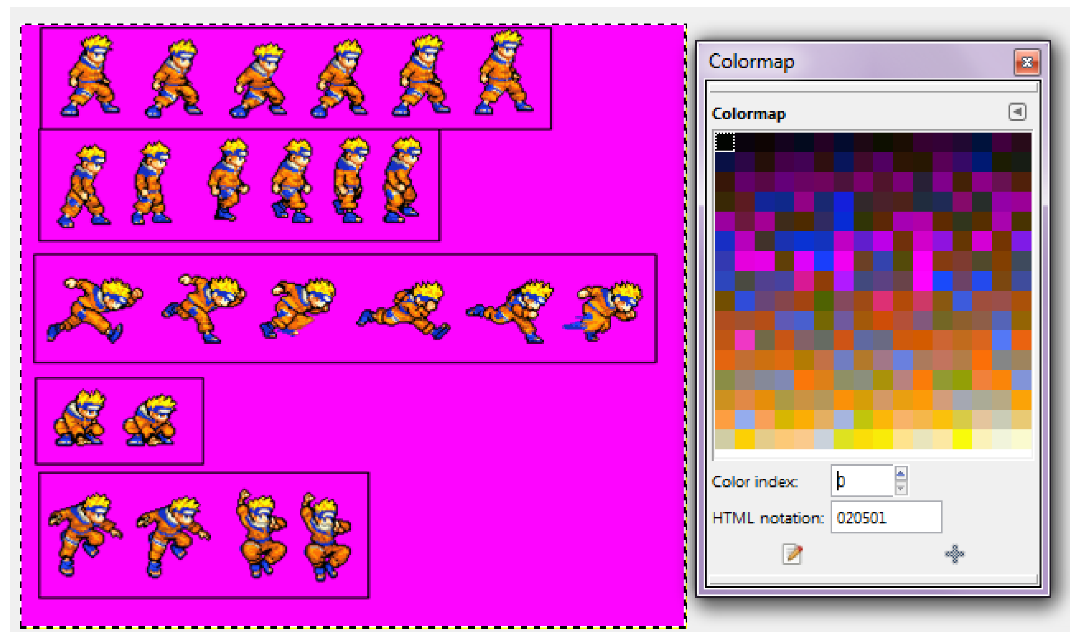
Game with 16 different colors (PC 98)

Game with 256 different colors

Indexed Color

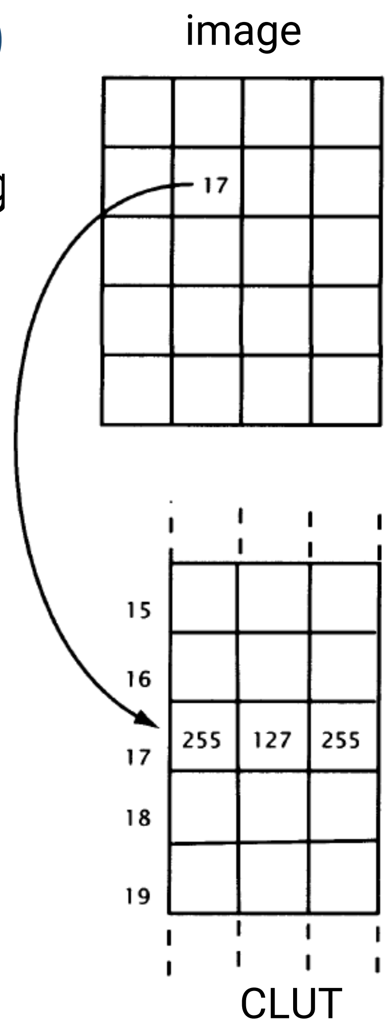
- For some applications, colors can also be stored or represented by an indexed table
- Using a **palette** of *N* specific colors with **each image**





Indexed Color (cont.)

- Implementation: **Color Lookup Table (CLUT)**
  - When an image is displayed, the graphics system looks up the color from the palette corresponding to each **single byte value stored at each pixel**
  - Need to load the correct palette
  - Use the default system palette if no palette is supplied (can have a bad look though)
  - Issue: what will happen if two images with different palette need to be displayed in a window?

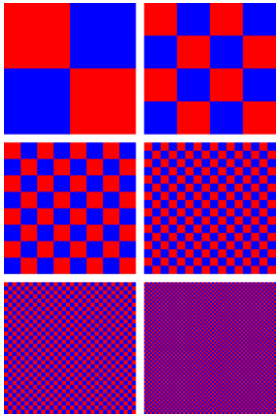


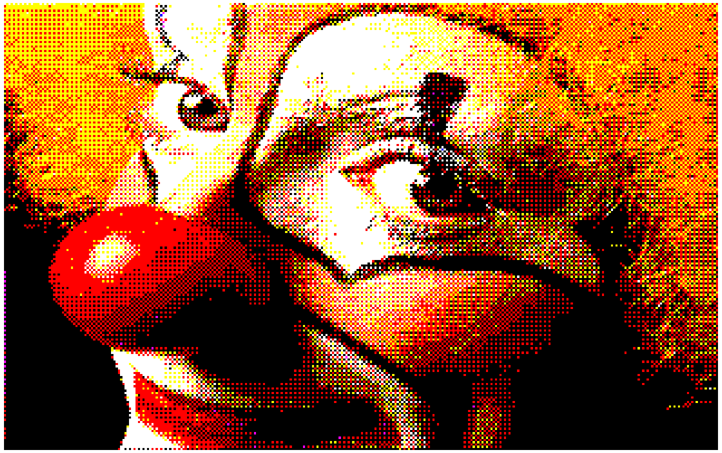
Indexed Color (cont.)

- Strategies for handling missing colors in CLUT
  - **Replace the color with the CLUT index of the nearest color**

$$(r', g', b') = \sqrt{(r' - r)^2 + (g' - g)^2 + (b' - b)^2}$$

  - **Dithering**
    - Areas of a single color are replaced by a pattern of dots of several different colors, in such a way that optical mixing in the eye produces a color close to the desired one





Other Color Models

CMYK

- **Cyan (C)**, **Magenta (M)**, **Yellow (Y)**, and Blac**k (K)**
- Subtraction of light

$$W = R + G + B$$

$$\boxed{C} = G + B = W - \boxed{R}$$

$$\boxed{M} = R + B = W - \boxed{G}$$

$$\boxed{Y} = R + G = W - \boxed{B}$$

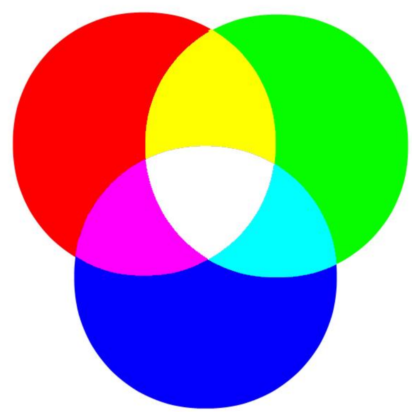
complementary color

Cyan
(0%, 100%, 100%)

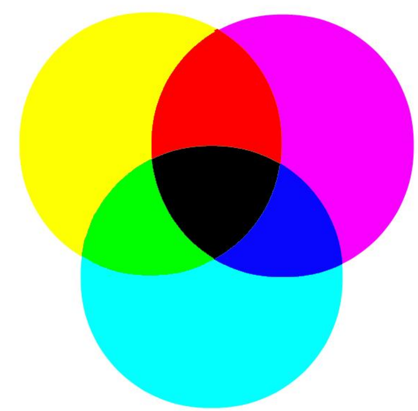
Magenta
(100%, 0%, 100%)

Yellow
(100%, 100%, 0%)

  - Appropriate to ink and paint (absorb lights)



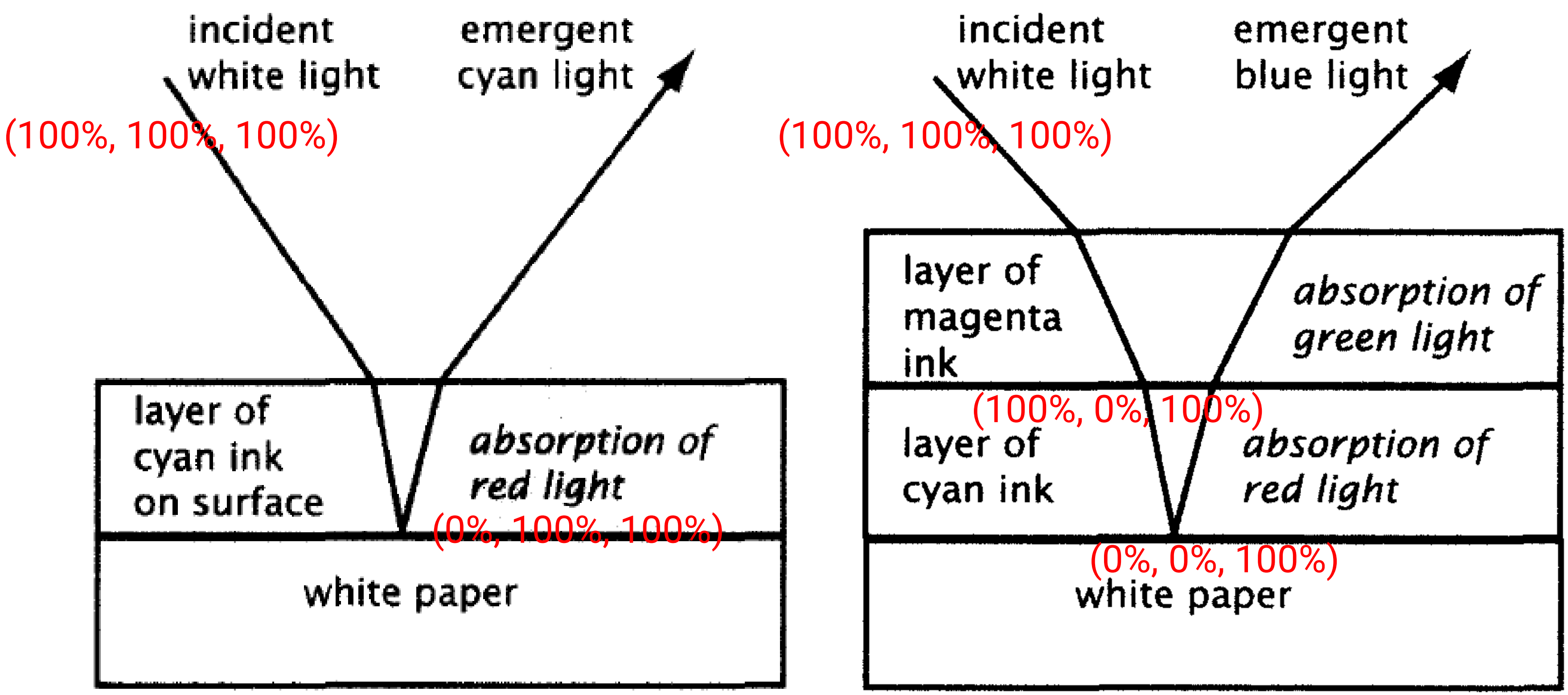
R + G + B = White



C + M + Y = K (Black)

CMYK (cont.)

- Effect of color ink



CMYK (cont.)

- In practice, it is not possible to manufacture **perfect inks** which absorb only light of precisely the complementary color
- As a result, the gamut of colors that can be printed using cyan, magenta, and yellow is not the same as the RGB gamut

  ➔ Ensure all the colors in your printed data are within the CMYK color gamut !

- Furthermore, apply CMY inks does not produce a very good black color
  - So augmented with the black color

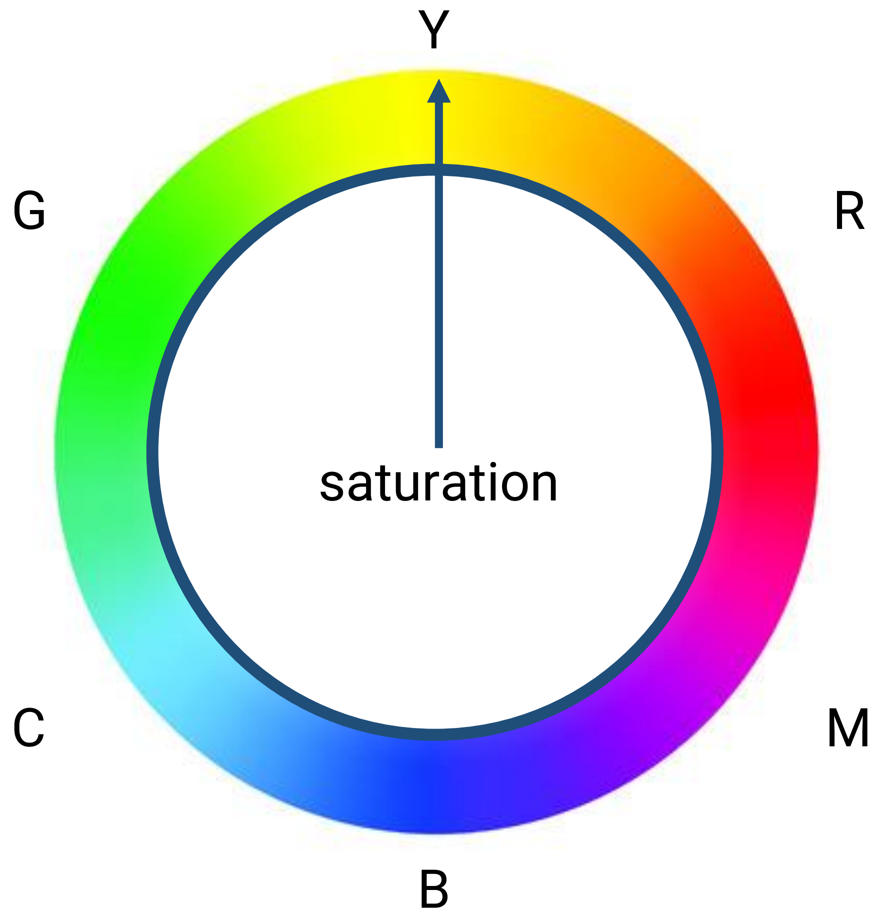
HSV

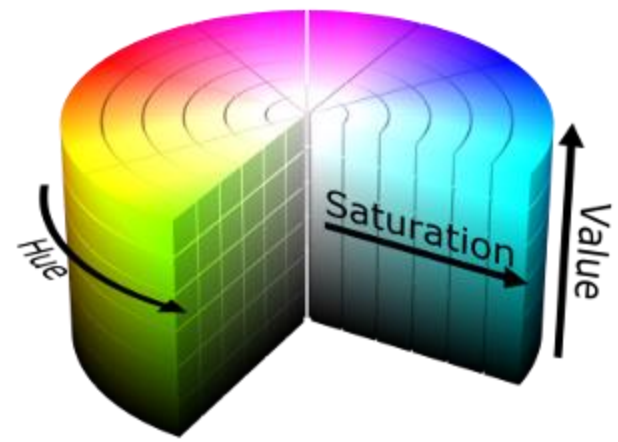
- Breaking a color down into its primary components make sense from a theoretical point of view, but does not correspond to the way we experience colors in the world
  - Ex: Cyan is a kind of blue (not green + blue)

- **HSV color models**
  - **Hue**: the dominant wavelength and the pure color of light
  - **Saturation**: a measure of a color’s purity
    - Saturated colors are pure hues
    - Saturation decreases as white is mixed in
  - **Brightness**: a measure of how light or dark a color is

HSV (cont.)

- Color wheel





Color Harmonization

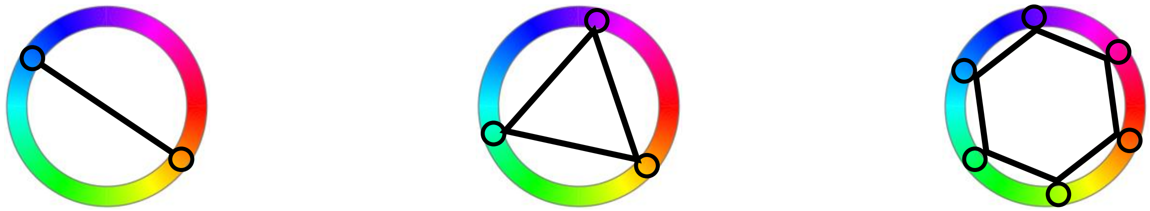
- Daniel et al., SIGGRAPH 2006

original image

harmonized image

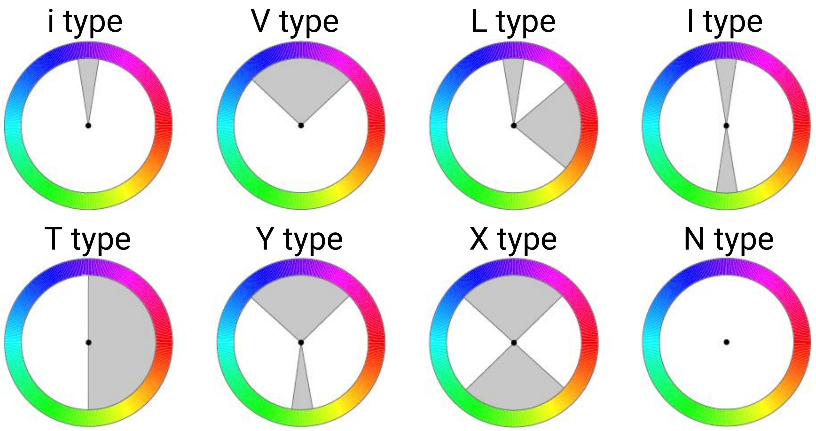
Background

- Itten [1960]: harmony means **relationships** on the **hue** wheel



2-color harmony: complementary colors
3-color harmony: equilateral triangle
N-color harmony: equilateral N-gon

- Matsuda [1995]: extensive empirical studies, derived **8 hue templates**

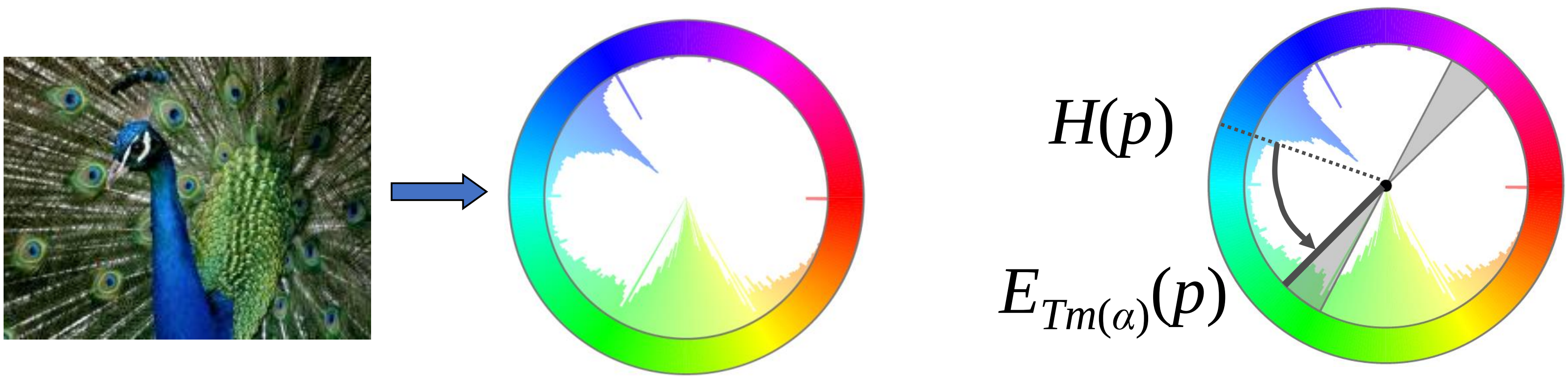


- The templates can be **arbitrarily rotated**

Harmonic Scheme and Harmonic Function

- **Harmonic scheme** is template type T_m + specific orientation α
- Define the **harmonic function**:
  - The harmony of image X w. r. t. harmonic scheme (T_m, α)

$$F\left(X,(T_m,\alpha)\right)=\sum_{p\in X}\left\|H(p)-E_{Tm(\alpha)}(p)\right\|\cdot S(p)$$

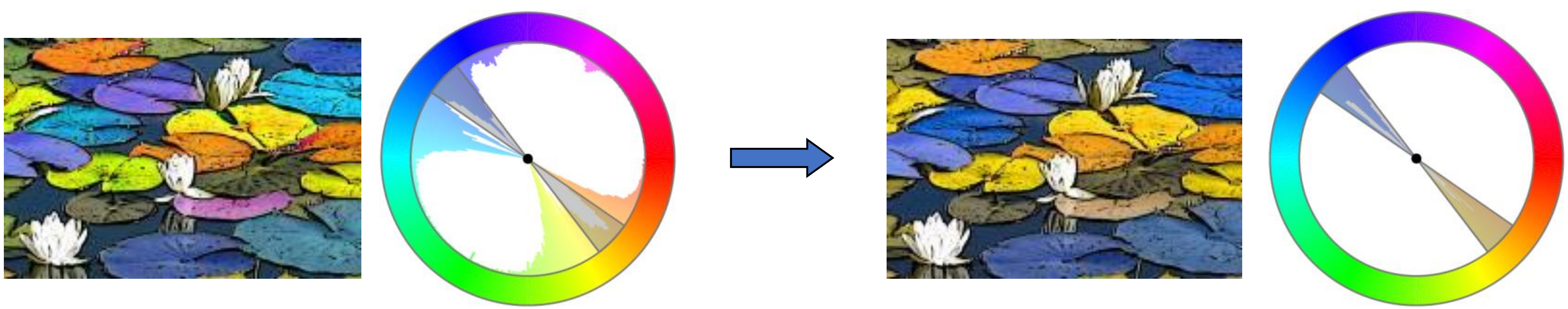


Harmonization

- **Best template**
  - Compute α that minimizes $F(X, (T_m, \alpha))$ for each template T_m using Brent's algorithm
  - The best-fitting harmonic scheme:

$$(T_{m_0}, \alpha_0) = \arg\min_{(m,\alpha)} F\left(X, (T_m, \alpha)\right)$$

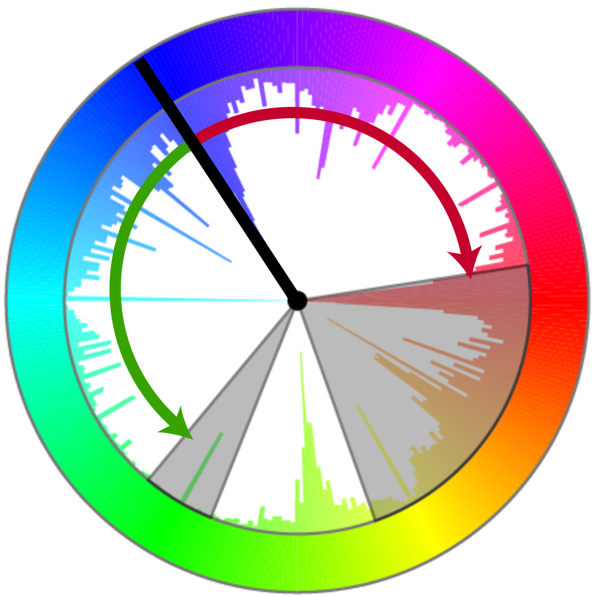
- **Harmonization**
  - Given (T_m, α) we shift the hues so that the hue histogram is contained in (T_m, α)



Color Harmonization (cont.)

- **Color coherence**
  - If we define $E_{Tm(\alpha)}(p)$ simply as the closest template sector to $H(p)$, we get coloring discontinuity

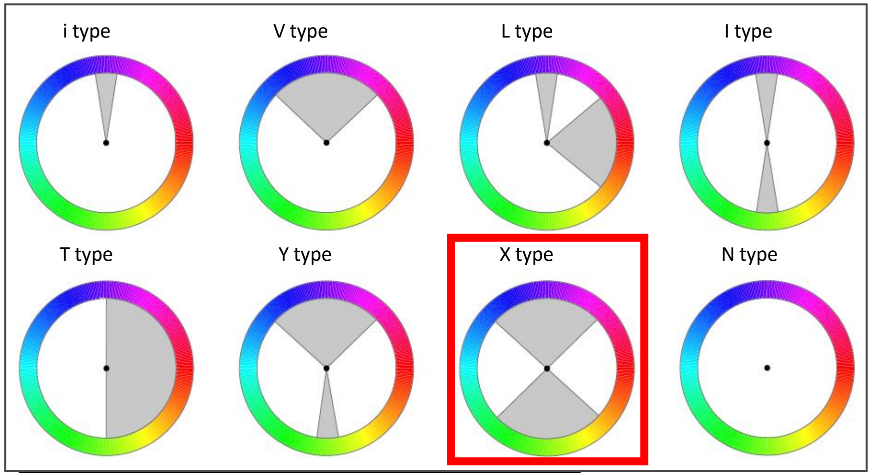
original image

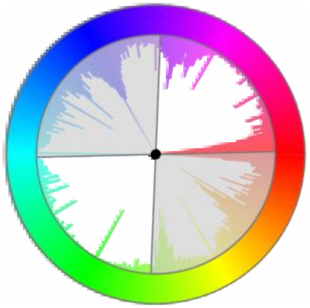


simple solution

add constraints

Color Harmonization Example





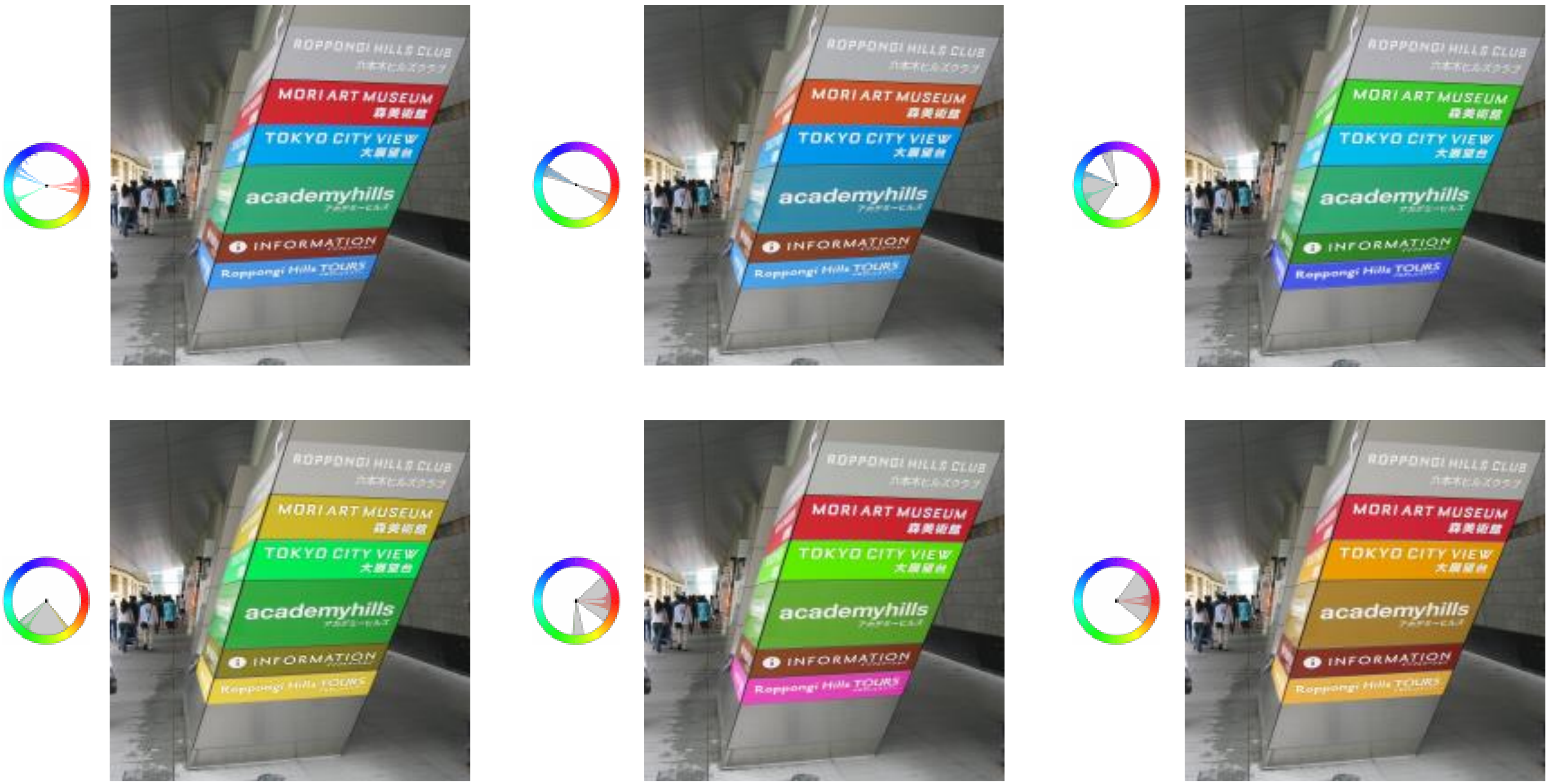
Hue histogram

Results

- Matching the colors coming from different sources

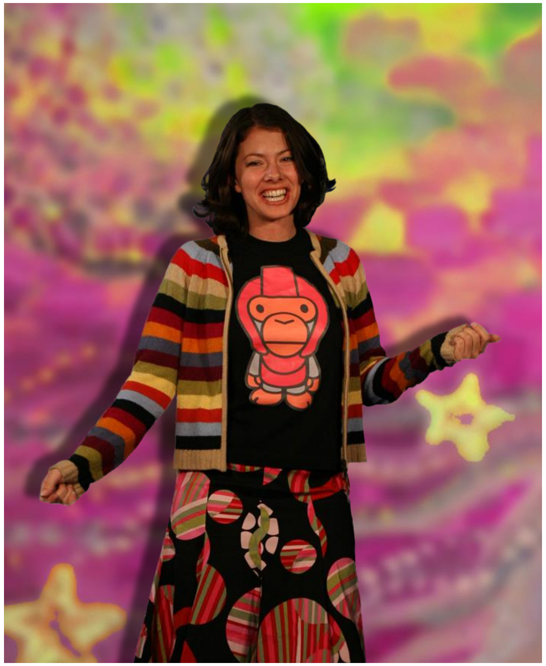
Results (cont.)

- Choosing colors



Results (cont.)

- Cut and paste

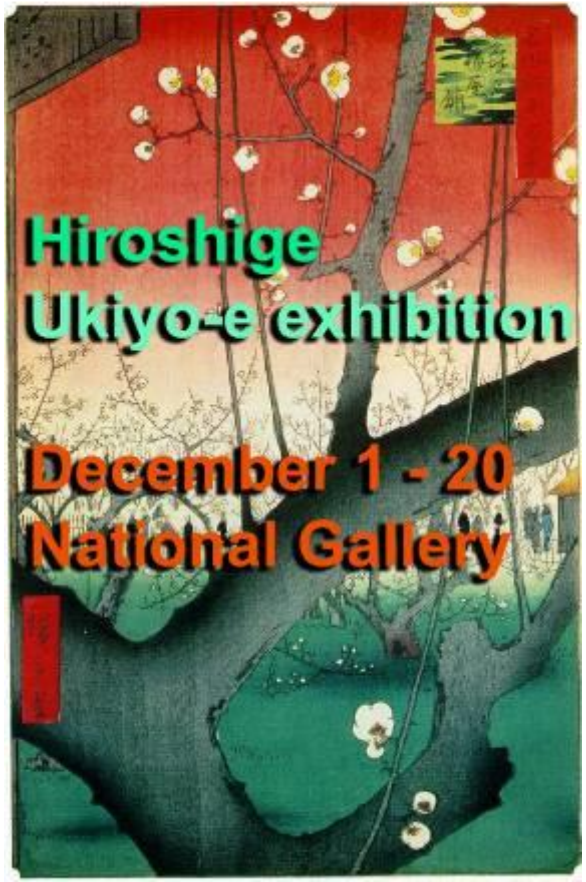

original

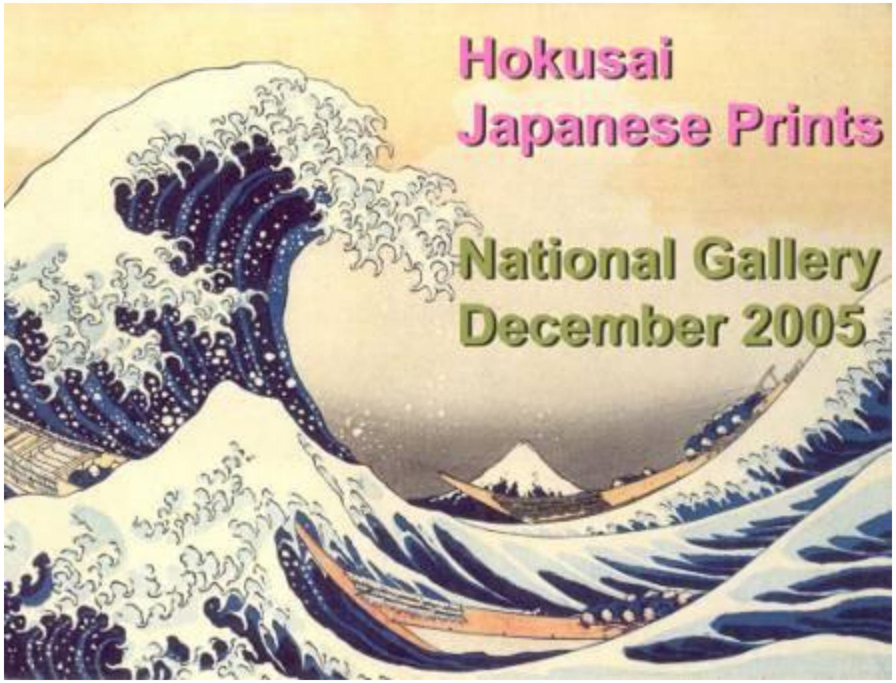

harmonized


harmonized

Results (cont.)

- Text over a poster





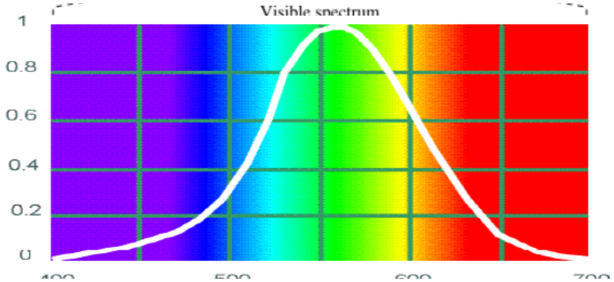
YUV

- It is usually useful to separate the brightness information of an image from its color
  - Ex: transmit color TV signals that would be compatible with older black and white receivers
  - It becomes possible to use less bandwidth for color transmission than the brightness

- Brightness calculation

$$Y = 0.2125\,R + 0.7154\,G + 0.0721\,B$$

luminance



Human Luminance Sensitivity Function

YUV (cont.)

- The red, green, and blue values can be reconstructed from luminance and any two of the primaries
- For technical reasons, the left two components are usually represented by **two difference values**

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

- YUV color model is useful for applications that require operations on the luminance channel
- YCbCr is a similar variant

RGB

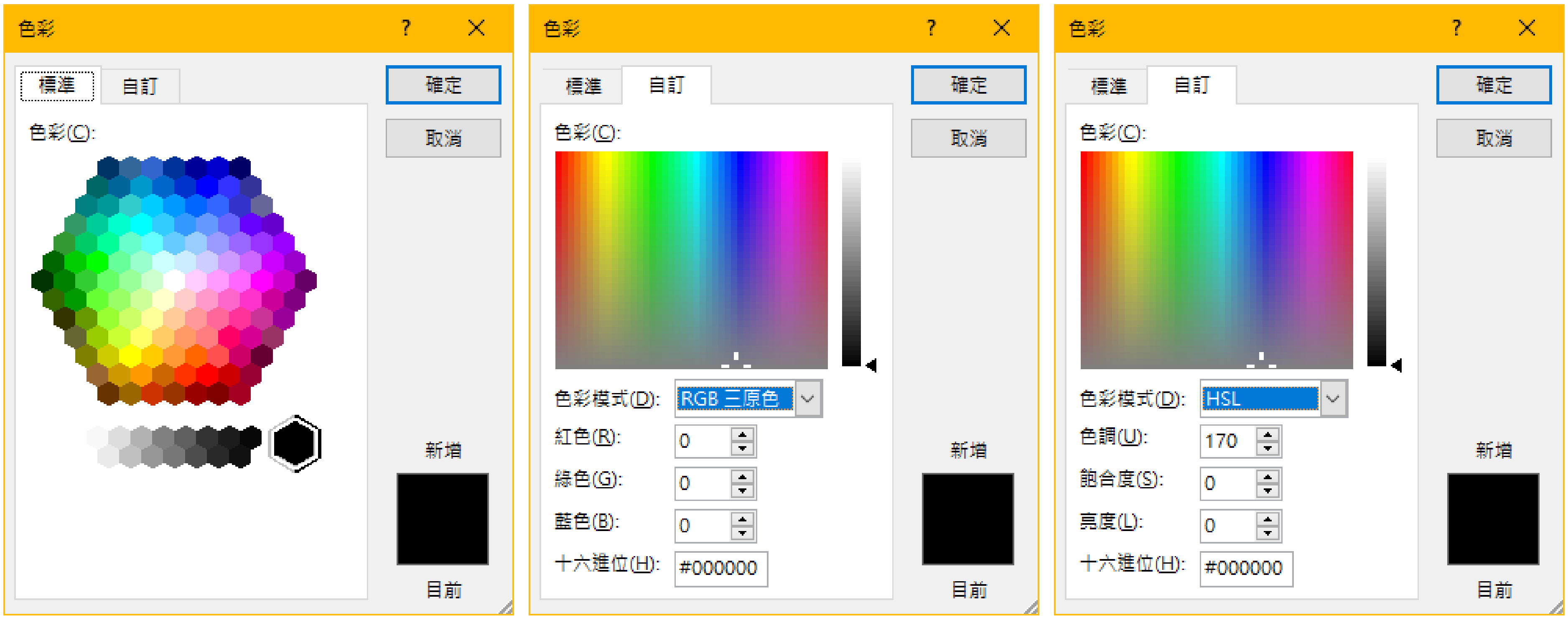
Y

Cb

Cr

User Interface for Color Selection

Example: Power Point



Example: Painter