TDS3651
Visual Information Processing

Color
Lecture 6

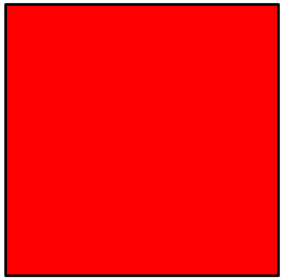
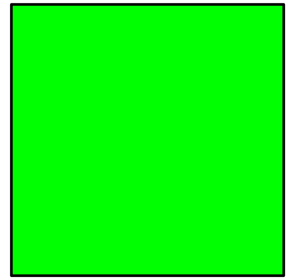
Faculty of Computing and Informatics
Multimedia University

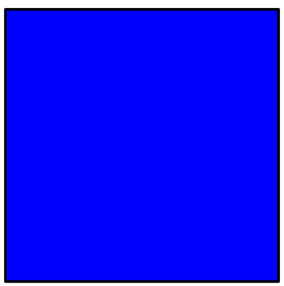
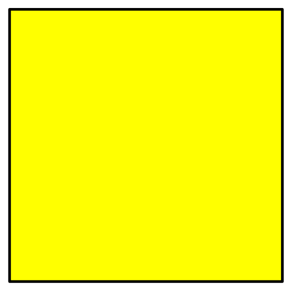
Previously created by John See, edited by Lai-Kuan, Wong, Yuen Peng, Loh
Some graphics and materials are taken from UTexas at Austin CS376 & CS381V notes, Stanford Uni’s CS131 notes and Gonzalez & Wood’s DIP textbook

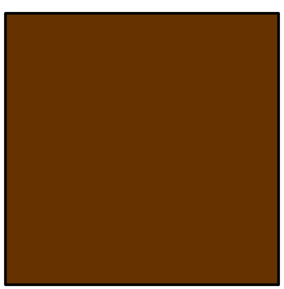
Lecture Outline

- Color – Fundamental concepts
- Human color perception
- Color spaces/models
- Using color information

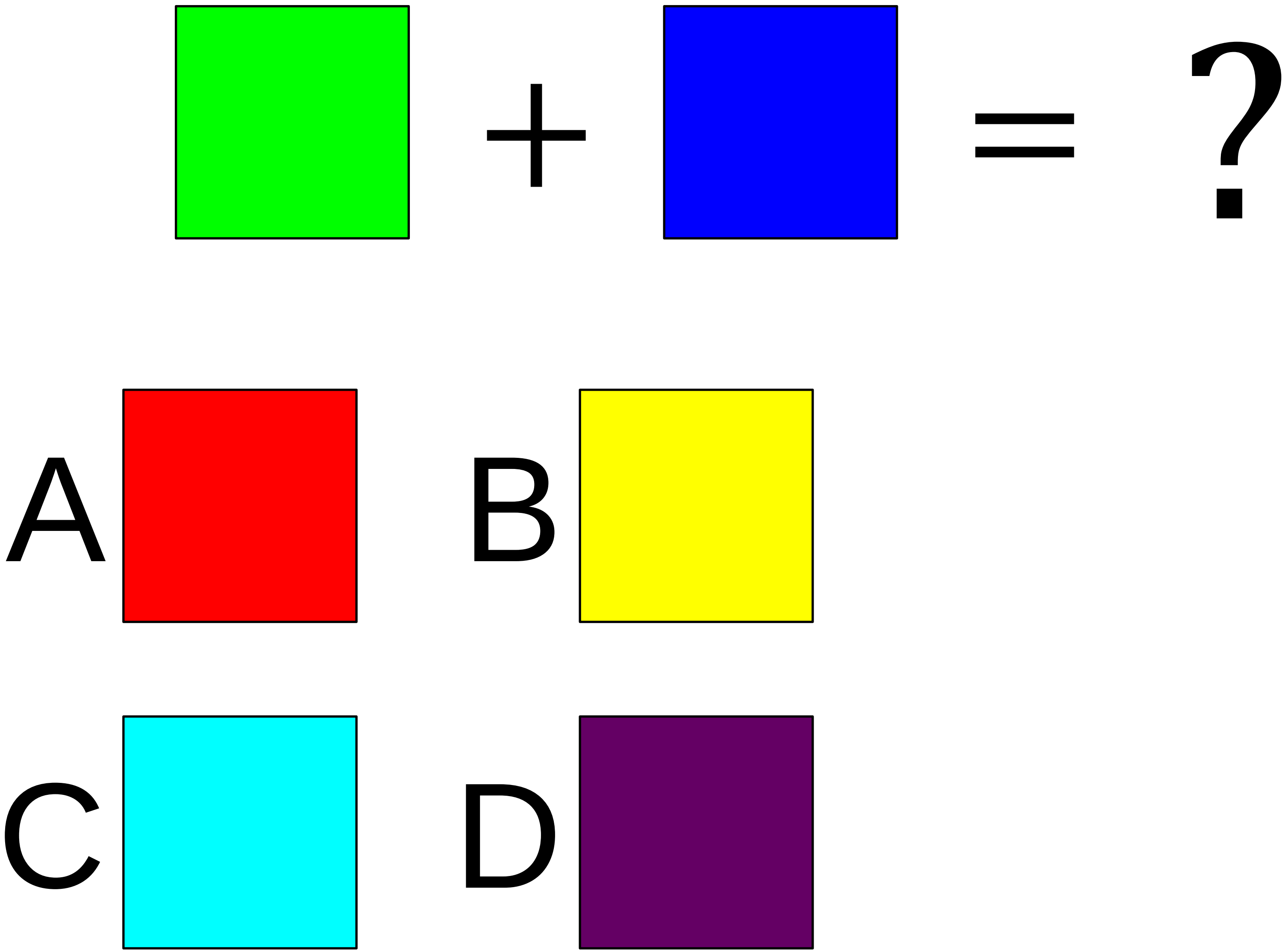
Let’s take some simple tests…

 +  = ?

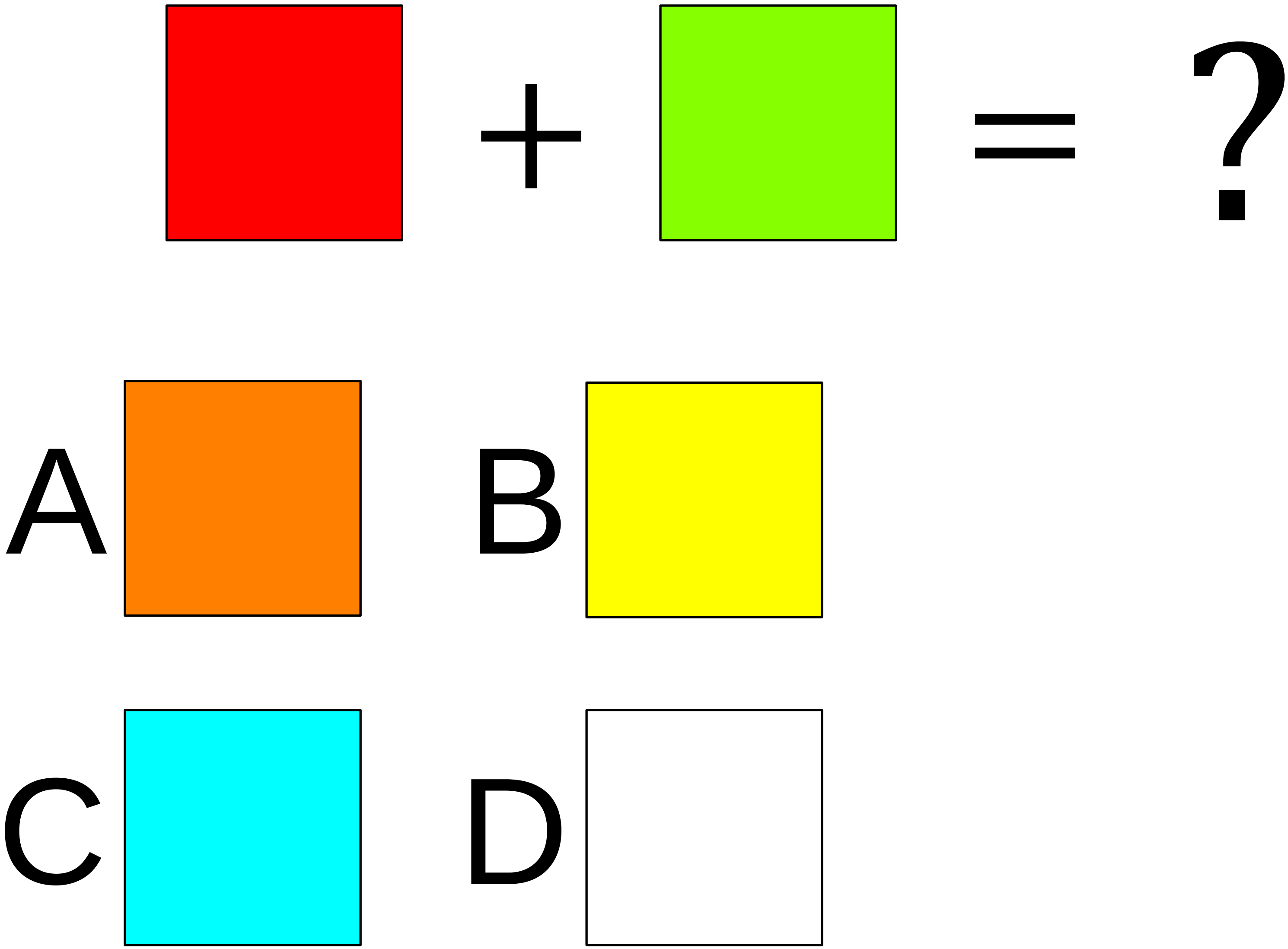
A  B 

C  D 

How about this...

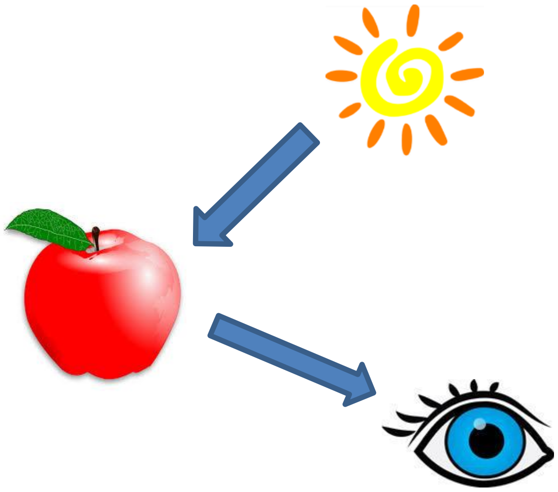


And this…



Color

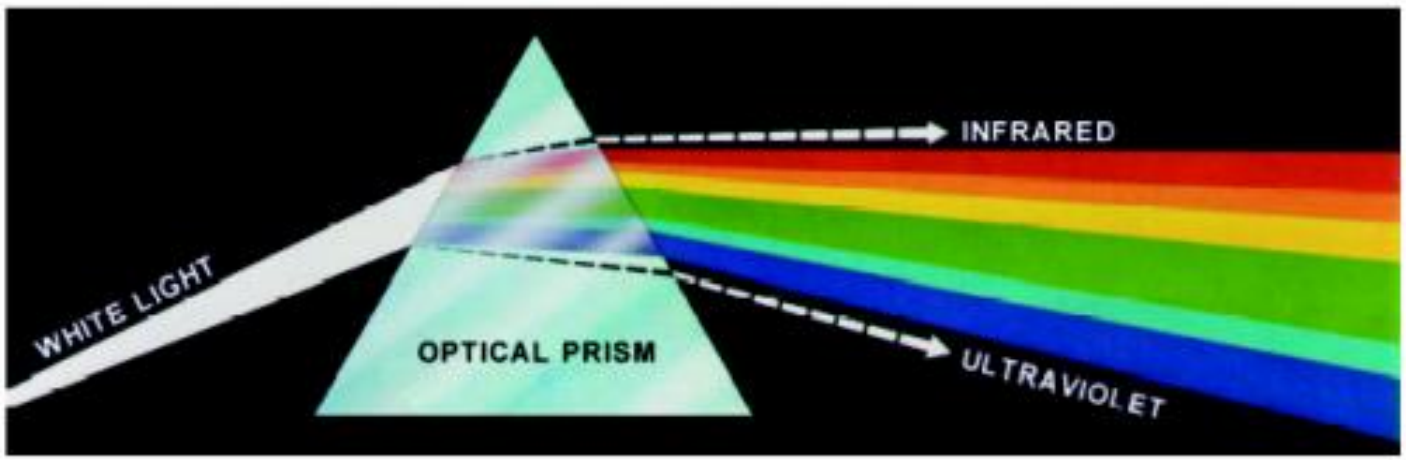
- What is **color**?
  - The result of interaction between physical light in the environment and our visual system
  - A psychological property of our visual experiences when we look at objects and lights, not a physical property of those objects or lights



Source: Vision Science: Photons to Phenomenology (Palmer 1999)

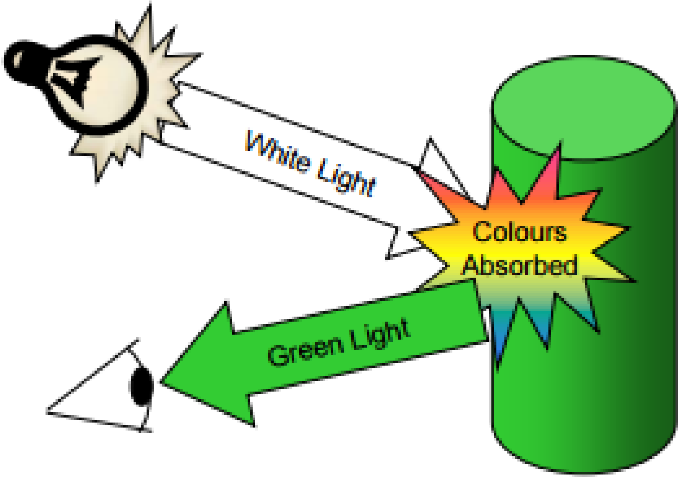
Color

- In 1666, Isaac Newton discovered that when a beam of sunlight passes through a glass prism, the emerging beam is split into a spectrum of colors



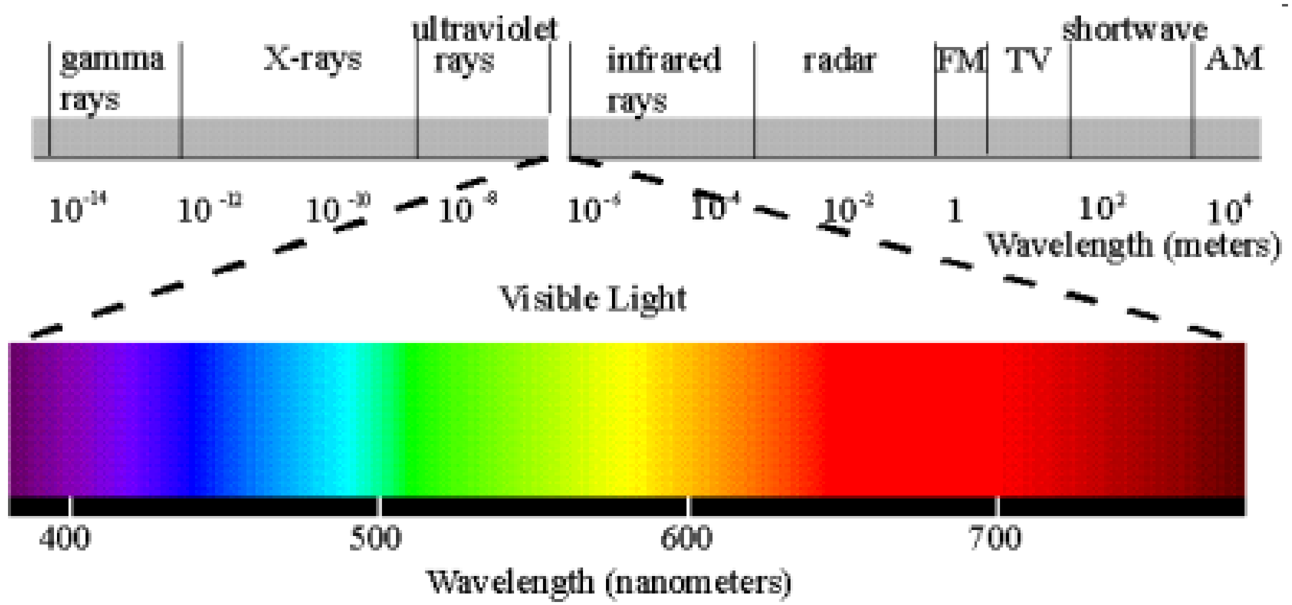
Color

- The colors that humans and most animals perceive in an object are determined by the nature of the light reflected from the object
  - E.g. Green objects reflect light with wavelengths primarily in the range 500-570 nm while absorbing most of the energy at other wavelengths



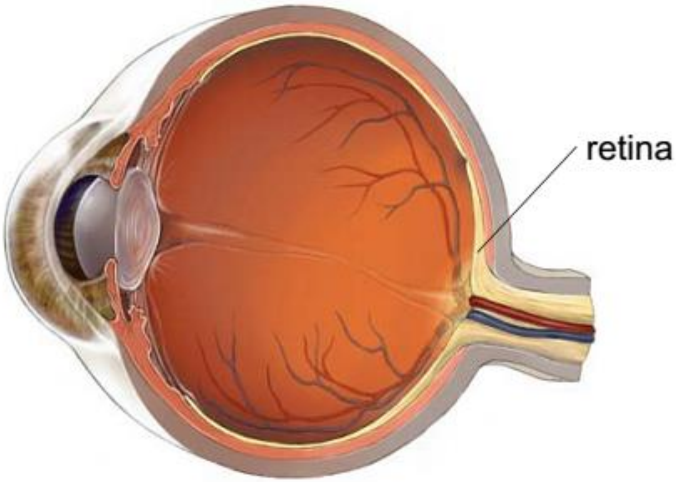
Color

- Chromatic light spans the electromagnetic spectrum from approximately 400 to 700 nm



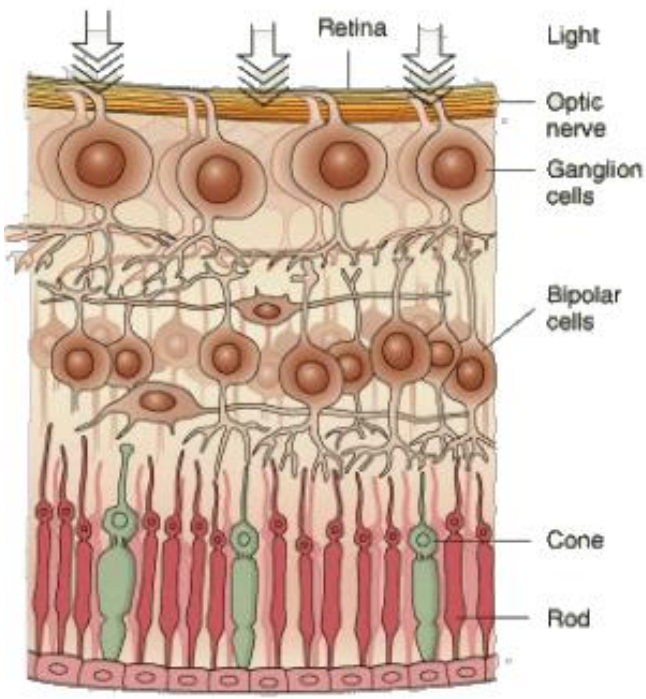
Human Color Perception

- Human eye has retina that senses light
- Human retina has 2 kinds of light receptors (or *photoreceptor* cells)



Rods:
- Sensitive to amount of light
- operate more at night
- gray-scale vision

Cones:
- Sensitive to lights of different wavelengths
- operate in high light
- color vision



Human Color Perception

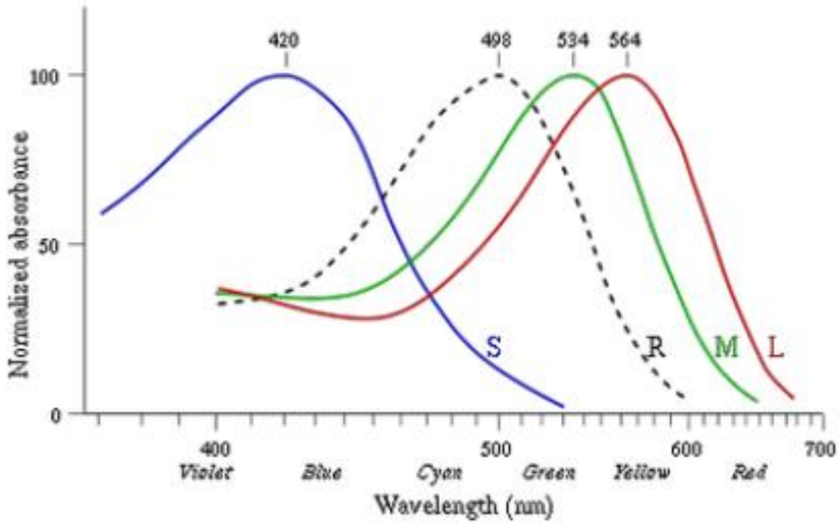
- 3 kinds of cones:

  Short (S): most sensitive to blue

  Medium (M): most sensitive to green

  Long (L): most sensitive to red

  (~ 66% of all cones, the most)



- Cone sends signals to brain
- Brain interprets mixture of signals as colours
- That's why colours are coded with 3 primary values
- Different coding schemes give different colour spaces

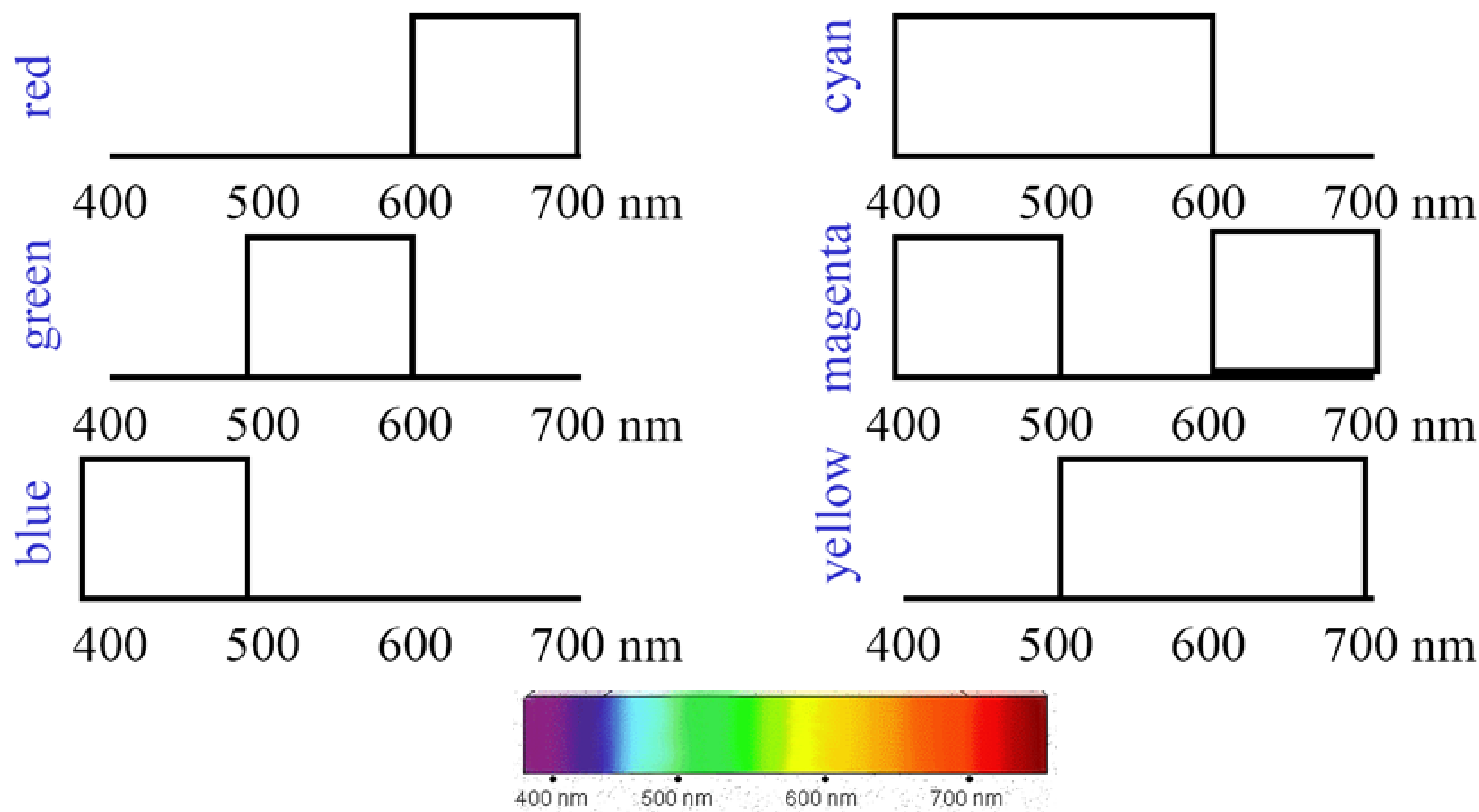
Fun fact:

- Mantis shrimp has 12-16 cones

Source: National Geographic (https://www.nationalgeographic.com/science/article/natures-most-amazing-eyes-just-got-a-bit-weirder)

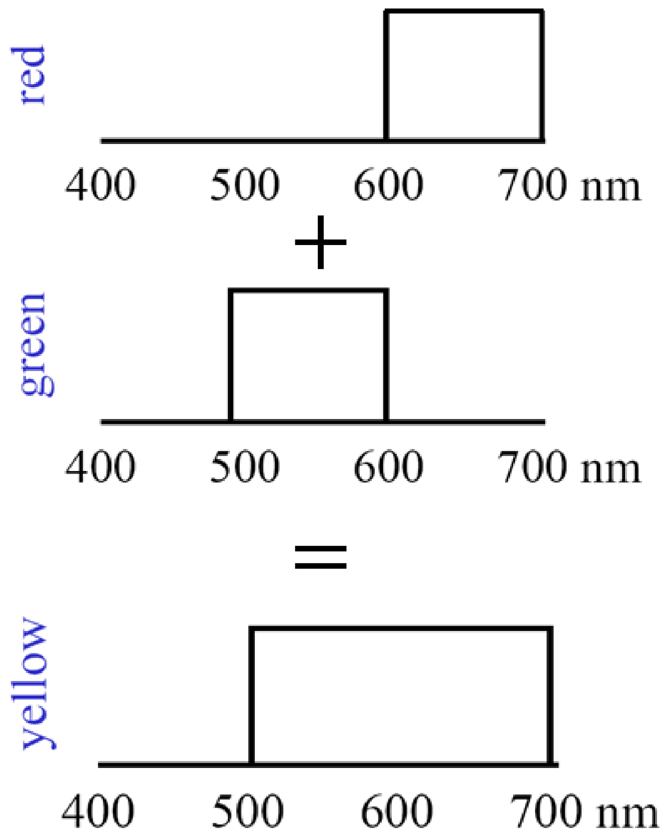
Color Mixing

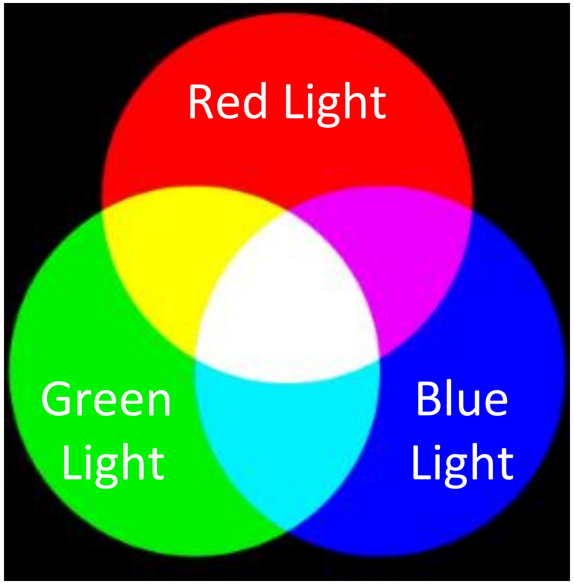
- Spectra for color names:



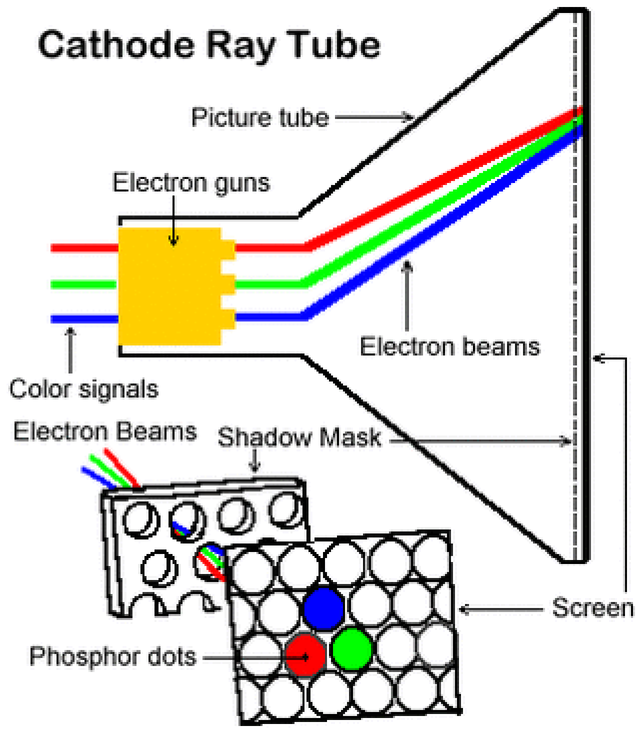
Additive Color Mixing

- Colors are combined by adding to the color spectra
- The light colors are added on to the black so it becomes white when all colors are added
- Different from mixing paint





E.g. of additive color systems

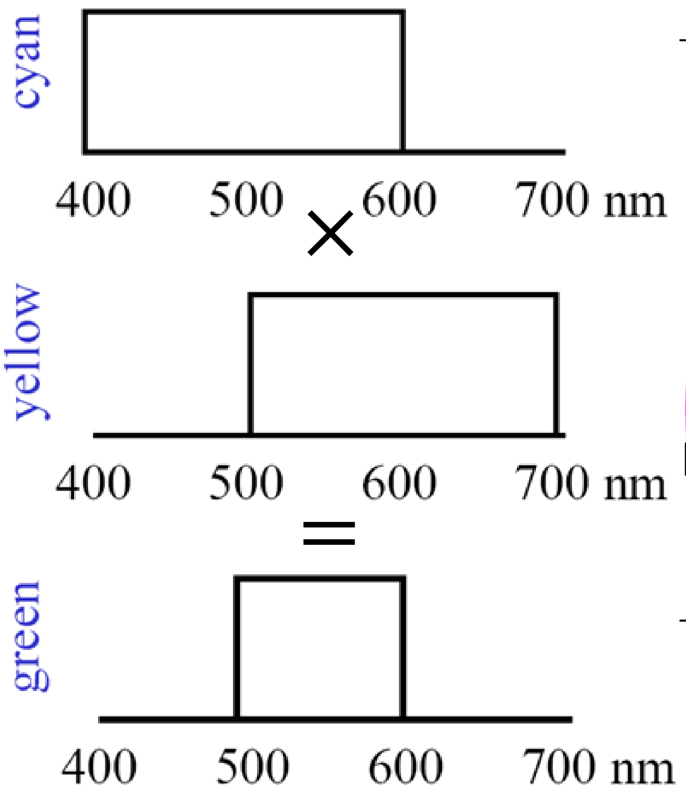


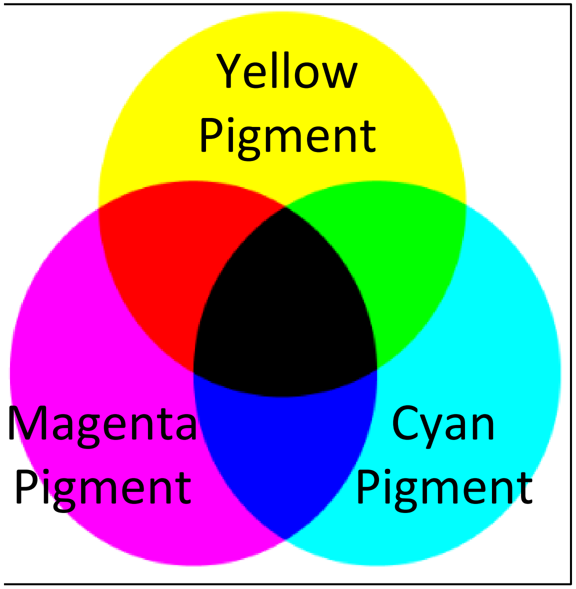
CRT Phosphors

Multiple projectors

Subtractive Color Mixing

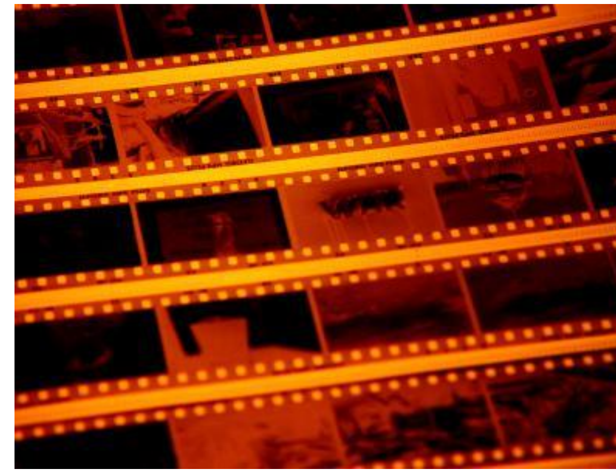
- Colors are combined by multiplying to the color spectra
- The pigments remove color from white so it becomes black when all colors are removed
- This is mixing paint
  - And also film photography





E.g. of subtractive color systems

- Printing on paper
- Photographic film



Problems with Processing Colour Images

- When processing colour images, the following problems (amongst others) have to be dealt with:
  - **The images are vectorial** → 3 numbers are associated with each pixel.
  - The colours recorded by a camera are heavily **dependent on the lighting conditions**.

Lighting conditions

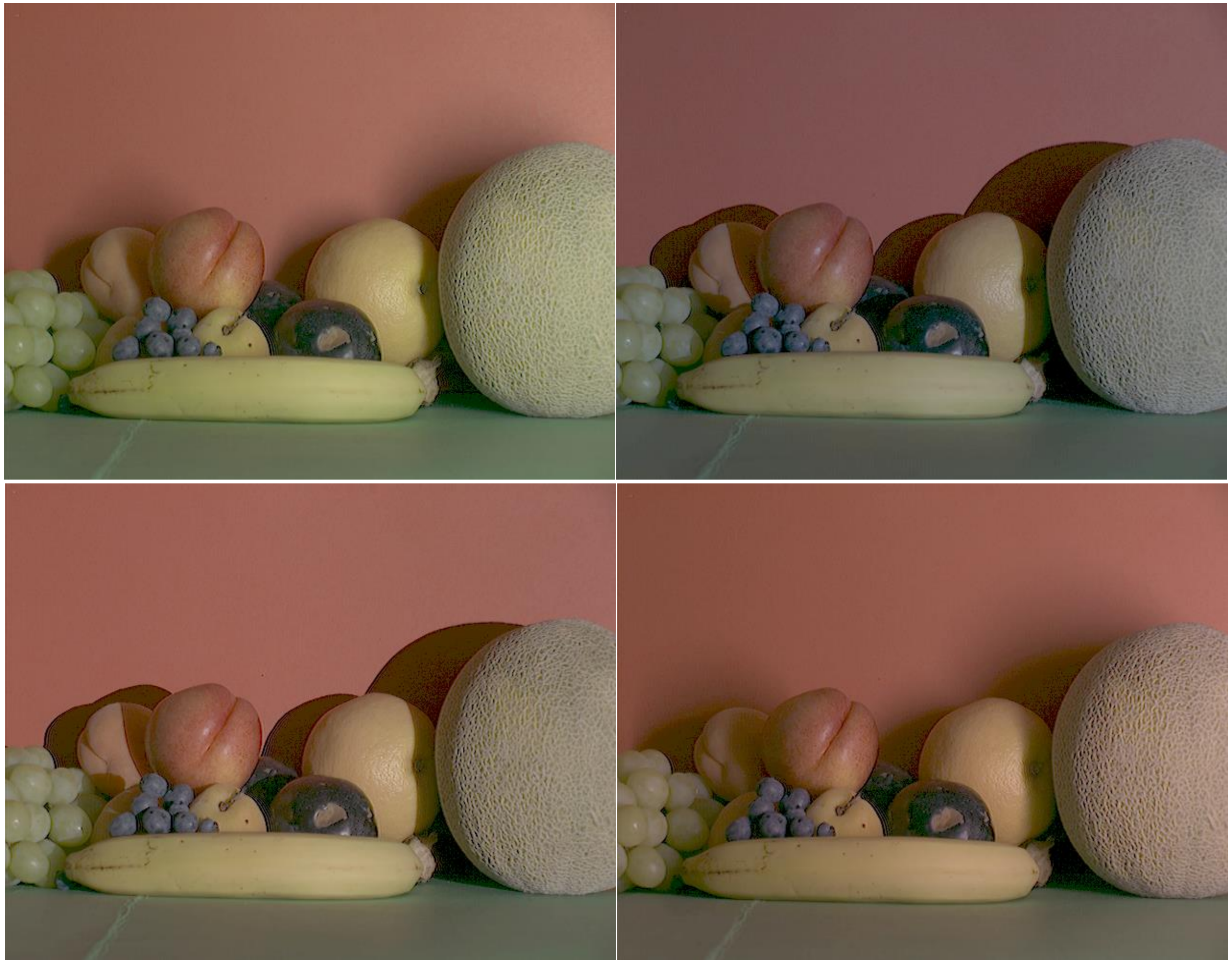
- The lighting conditions of the scene have a large effect on the colours recorded.

Image taken lit by a flash.

Image taken lit by a tungsten lamp.

Lighting conditions

- The following four images of the same scene were acquired under different lighting conditions:



Dealing with Lighting Changes

- **Knowing just the RGB values is not enough** to know everything about the image.
  - The R, G and B primaries used by different devices are usually different.
- For **scientific work**, the camera and lighting should be calibrated.
- For **multimedia applications**, this is more difficult to organise:
  - Algorithms exist for estimating the illumination colour.

Color spaces/models

Color space/model

- **Color space/model**
  - to facilitate the specification of colors in some standard
  - specification of a coordinate system and a subspace within the system where each color is represented by a single point
- Most color models are oriented either toward specific hardware or application

Standard color spaces

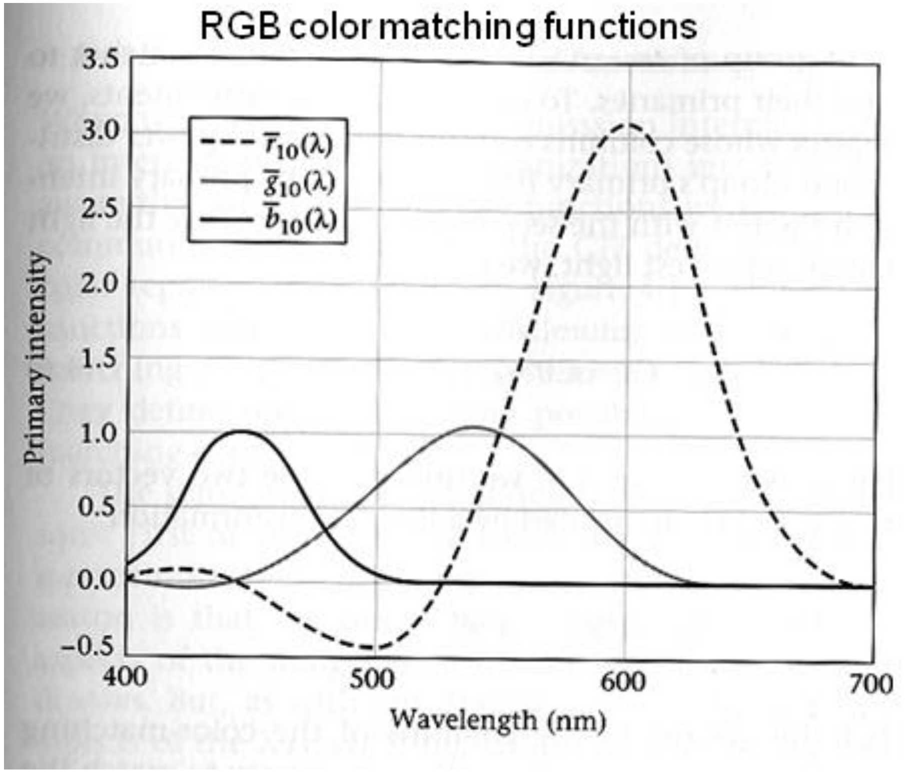
- Use a common set of primitives/color matching functions

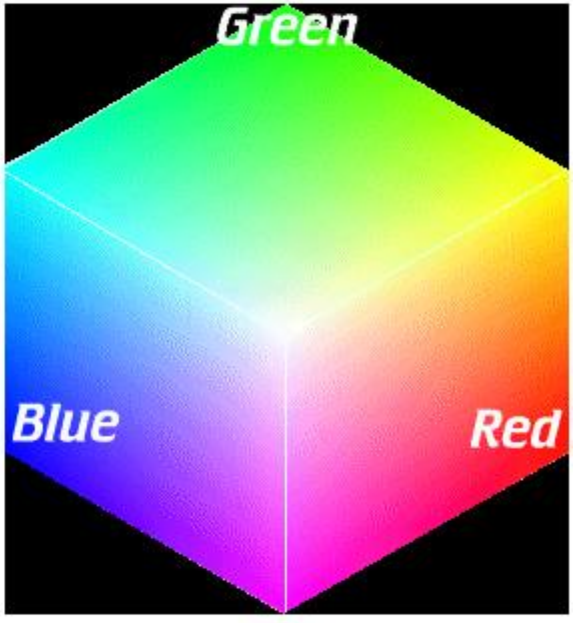
- **Linear** color spaces
  - RGB, CMY, NTSC, YCbCr
  - CIE XYZ, CIE Lab

  (Commission internationale de l'éclairage / International Commission on Illumination)
- **Non-linear** color space
  - HSV (or HSB/HSI)

RGB Color Space

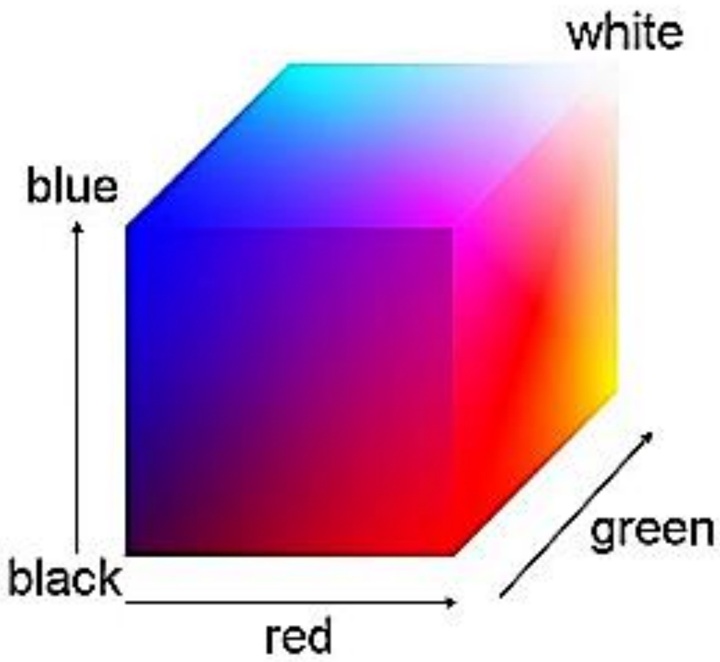
- Single wavelength primaries
- Good for devices (e.g. phosphors for monitor), but not for perception
- Suitable for displays (additive color model)

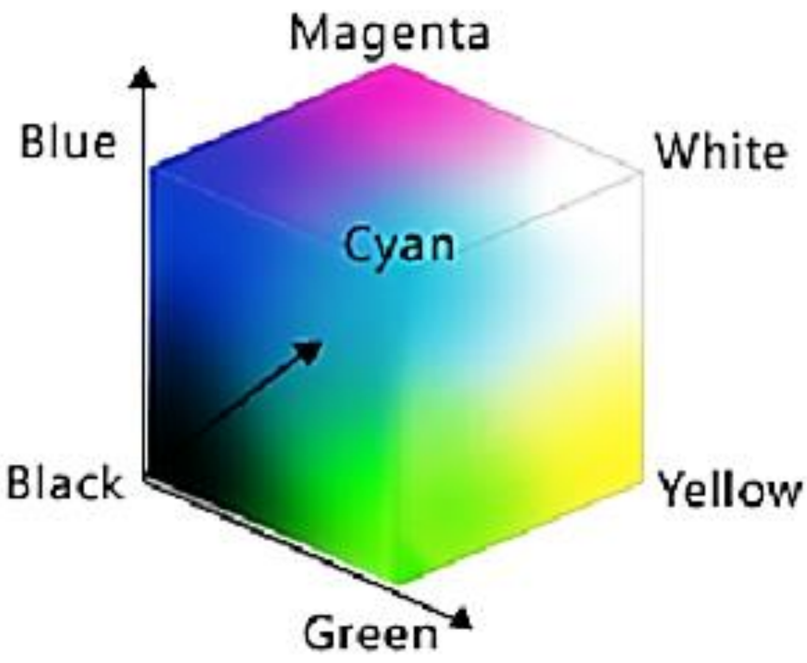




RGB Color Space

- Color is coded with a triplet: (red, green, blue)
- The three values are known as the **primary colors**



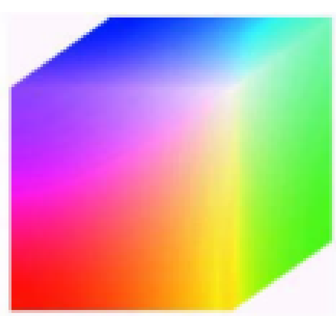


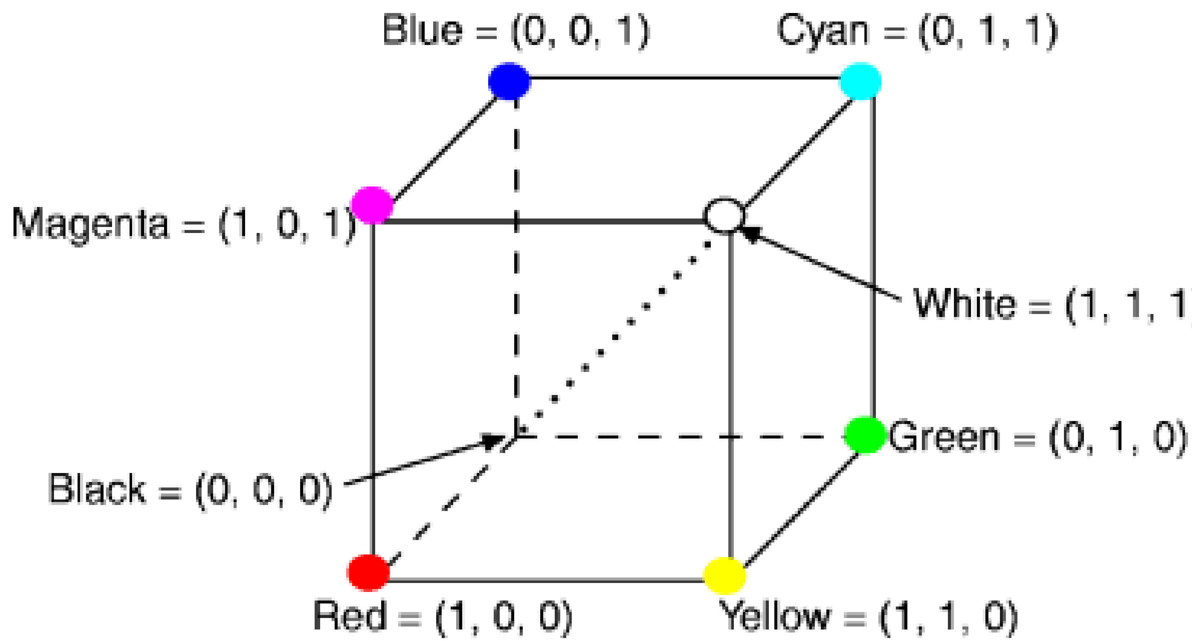
3 “Primary” Colours

- **Common misconception of the word “primary”:**
  - Widely misinterpreted to mean that the three primaries, when mixed in various proportions, can produce ***all*** visible colors
- We can only **approximate** all the spectrum colors by mixing the primaries

RGB Model

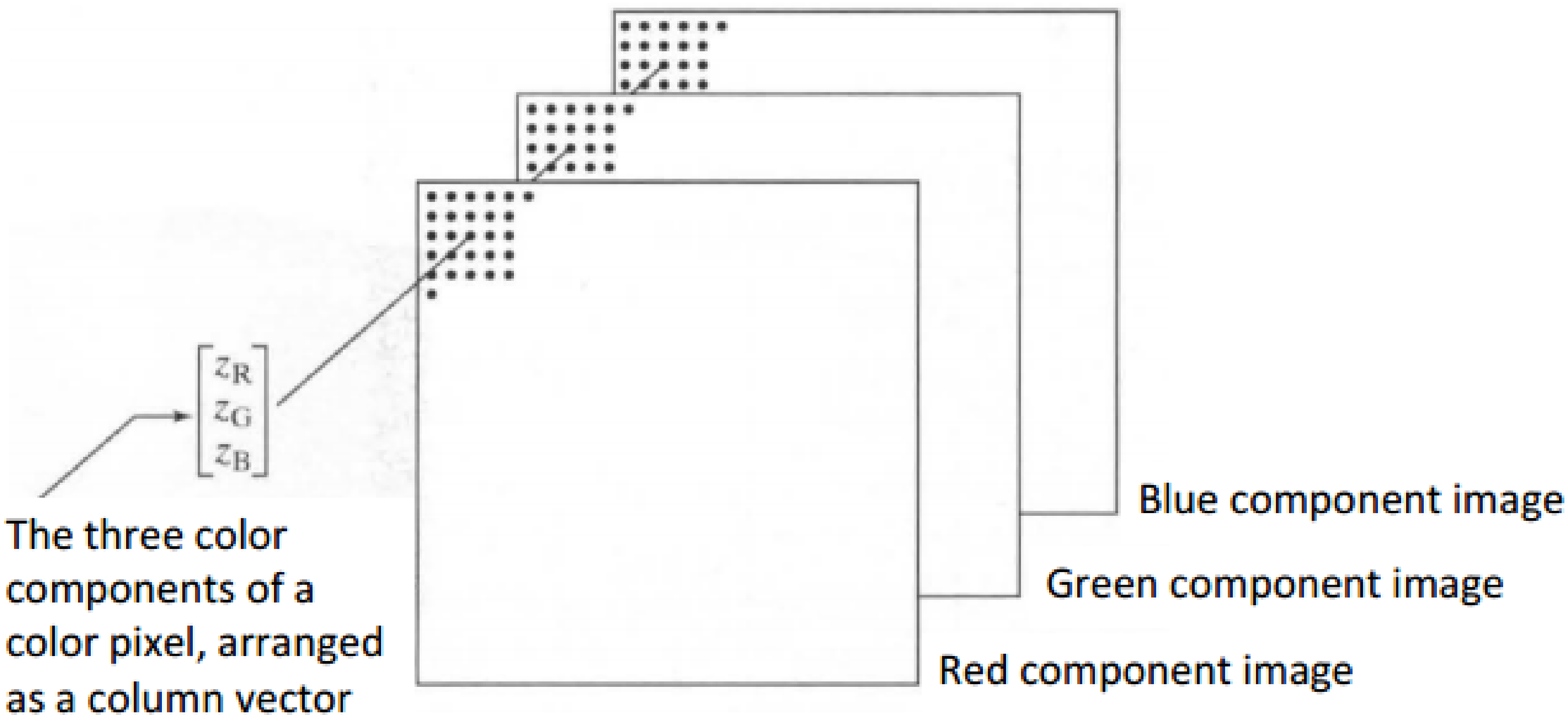
- This model is based on a Cartesian coordinate system
- Color subspace is in a cube: RGB primary values are at three corners; black is at the origin while white is at the corner farthest from the origin





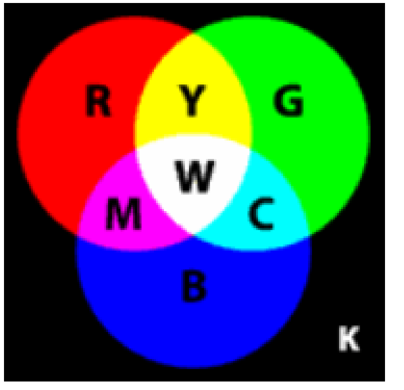
RGB Model

- Can be viewed as a “stack” of 3 grayscale images



CMY (CMYK) Model

- The primary colors (R, G, B) can be added to produce the **secondary** colors
  – Red + Blue = Magenta
  – Green + Blue = Cyan
  – Red + Green = Yellow



- It takes **c**yan, **m**agenta and **y**ellow as "primary colors"
- Easily converted from RGB model by

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

where all color values have been normalized to the range [0, 1]

CMY (CMYK) Model

- In theory: Equal amounts of <u>**c**</u>yan, <u>**m**</u>agenta and <u>**y**</u>ellow (pigment primaries) should produce "black"
  - But such a method usually generates quite a muddy black (not a true black)
- To produce "true black", a 4th color, "black" is added, giving rise to a CMYK color model (K stands for "blank in<u>**K**</u>"
  - Suitable for printing (subtractive color model)

Test-It-Yourself (TIY)

1. Convert the following color (0.4, 0.7, 1.0) from CMY to RGB
   A. (-0.4, -0.7, -1.0)
   B. (0.4, 0.7, 1.0)
   C. (-0.6, -0.3, 0.0)
   D. (0.6, 0.3, 0.0)

Test-It-Yourself (TIY)

2. Make a good guess what colours are represented by these RGB values.

   $C_1 = (1.0, 0.5, 0.0)$

   A. Red?

   B. Orange?

   C. Yellow?

   D. Green?

Test-It-Yourself (TIY)

2. Make a good guess what colours are represented by these RGB values.

   $C_2 = (0.5, 0.0, 0.5)$

   A. Red?

   B. Pink?

   C. Magenta?

   D. Blue?

Test-It-Yourself (TIY)

2. Make a good guess what colours are represented by these RGB values.

   $C_3 = (0.6, 0.6, 0.6)$

   A. White?

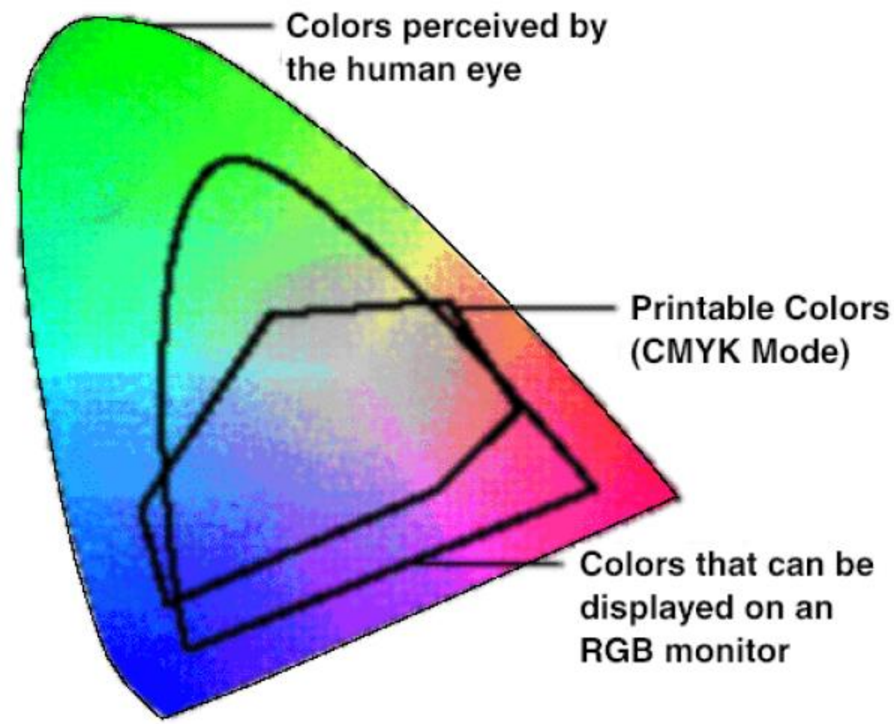
   B. Cyan?

   C. Grey?

   D. Black?

Color Gamut

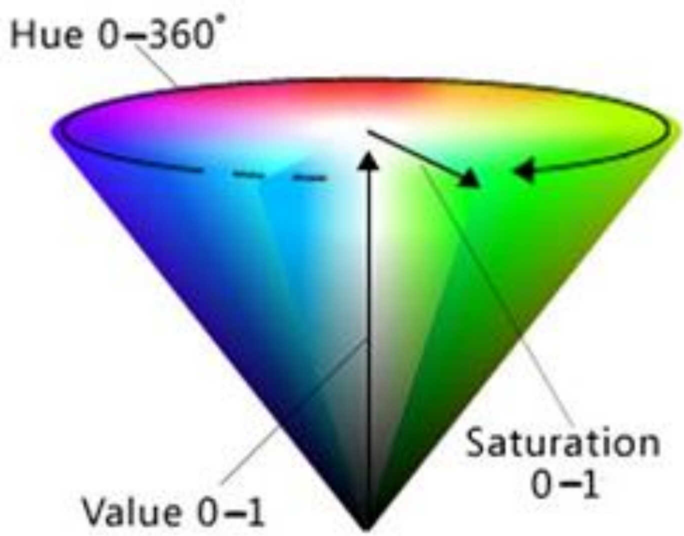
- **Gamut**: Color range of a model
  - RGB model has larger gamut than CMY
- Some colors on screen (RGB) may not be printable (CMY)
  - Replaced by closest color in the CMY gamut

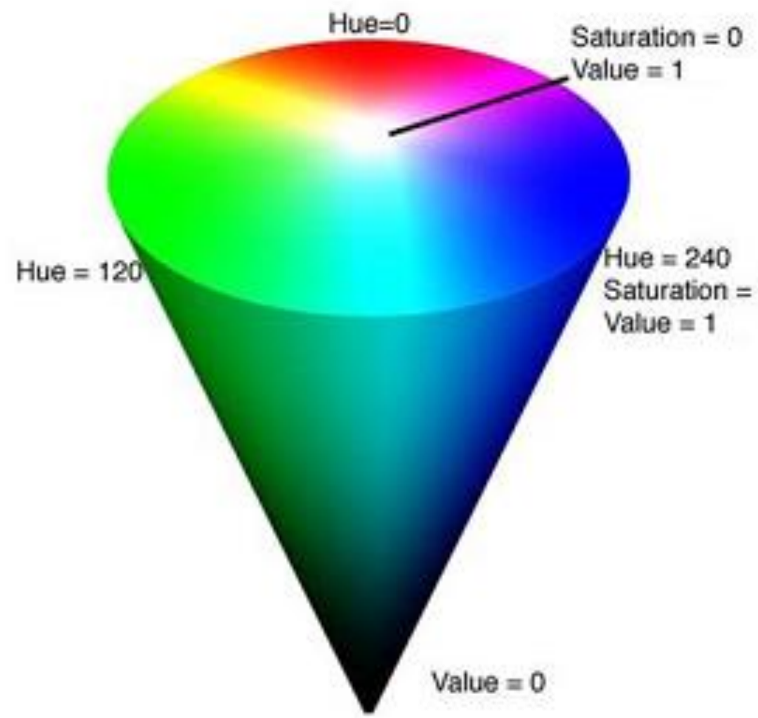


Chromaticity Diagram

HSV (or HSI) Color Space

- Color coded as **hue**, **saturation** and **value**
  - Also called HSB (B for brightness) or HSI (I for intensity) sometimes



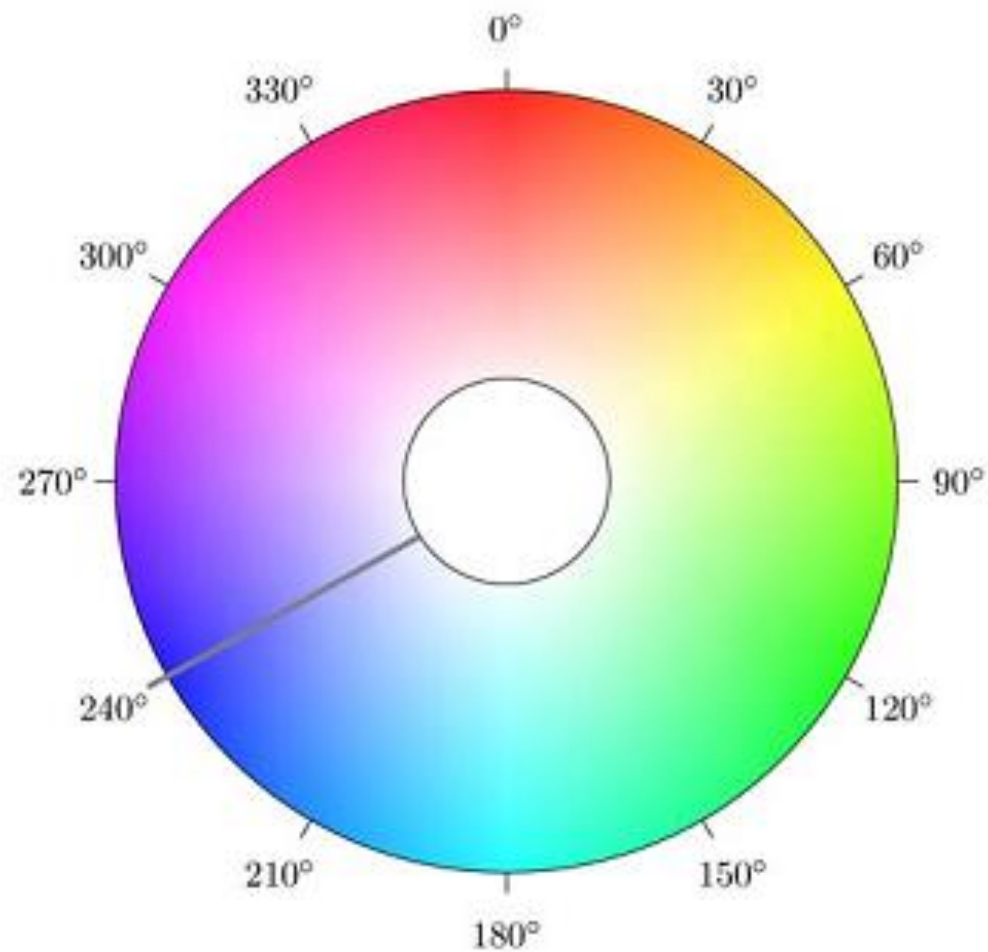


HSV (or HSI) Color Space

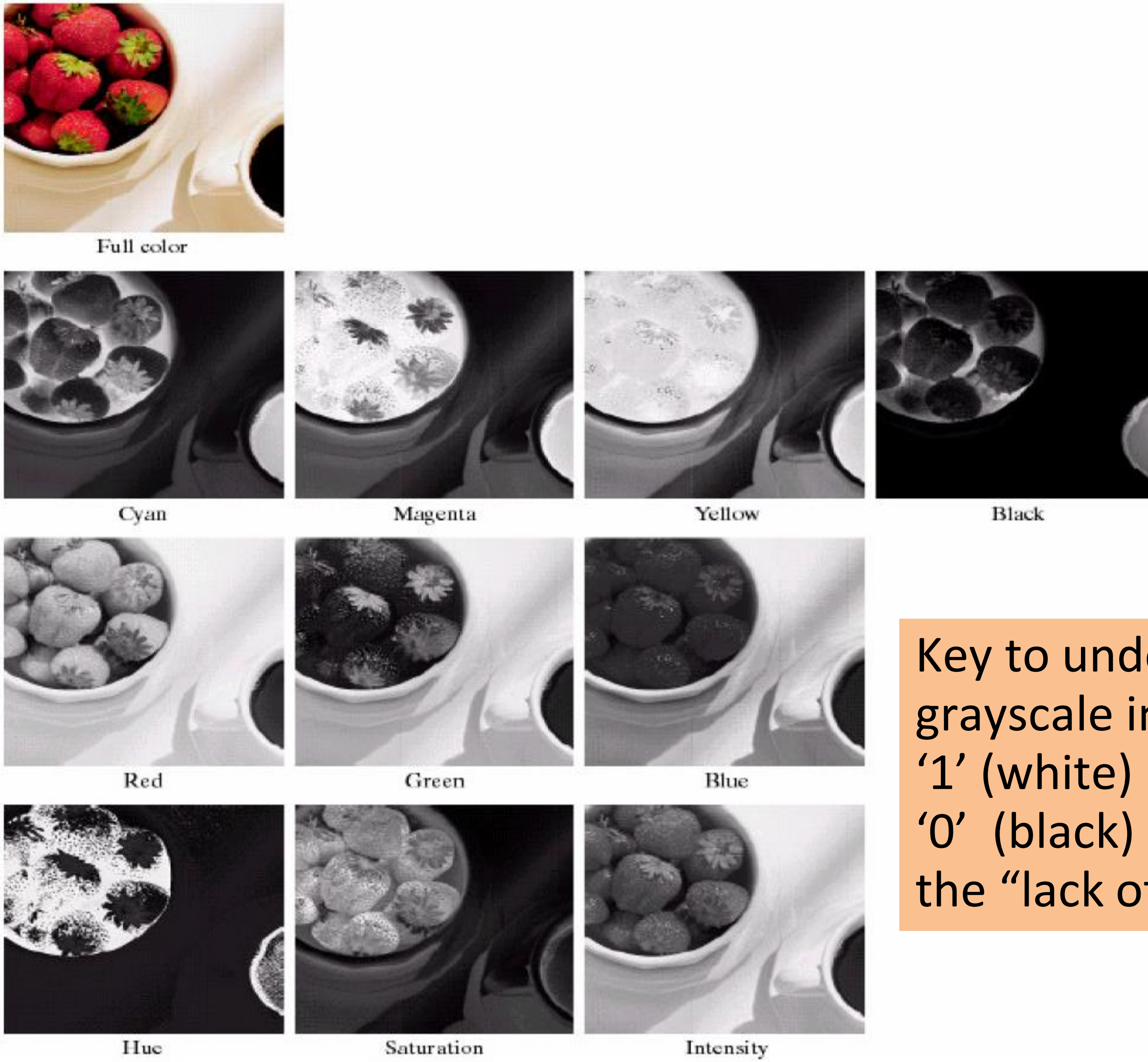
- Closer to human perception – More intuitive than RGB
  - **Hue**: Dominant color as perceived by the observer
  - **Saturation** (purity): Relative amount of white light mixed with the hue
  - **Value or Brightness**: Amount of light, or intensity of the hue
- Hue and Saturation together are called **Chromaticity** which are properties related to the perceived color or *"chroma"*

HSV (or HSI) Model

- Hue
  - colour type
  - 0° (red) to 360°
- Saturation
  - Colourfulness
  - 0 to 1 (full colour)
- Value
  - Brightness
  - 0 (black) to 1 (white)



Comparison between color spaces



Key to understand these grayscale images:
'1' (white) is "full of it"
'0' (black) is "empty" or the "lack of it"

YCbCr Model

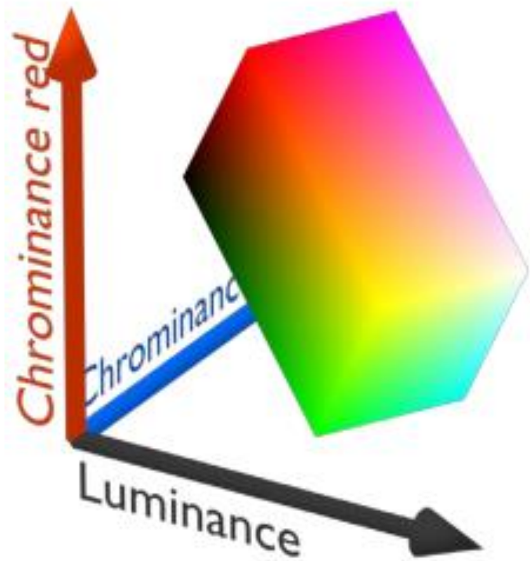
- **YCbCr** color space is extensively used in digital video
  - **Y**: Luminance

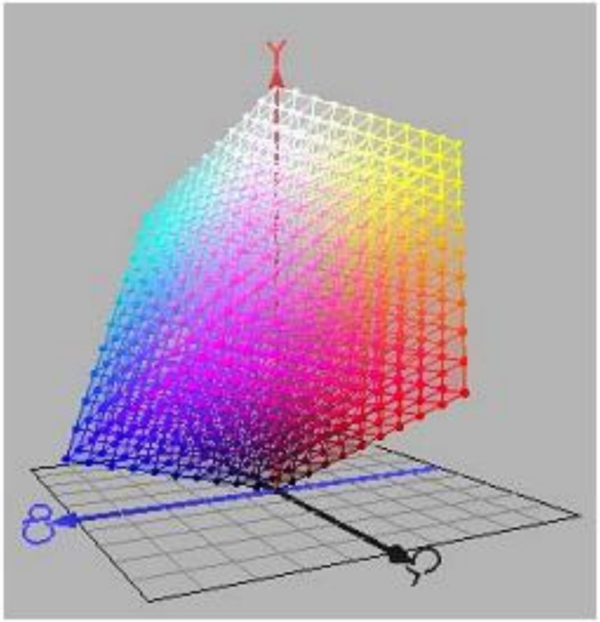
  Color information is stored as two color-difference components, Cb and Cr
  - **Cb**: Difference between blue and reference component
  - **Cr**: Difference between red and reference component

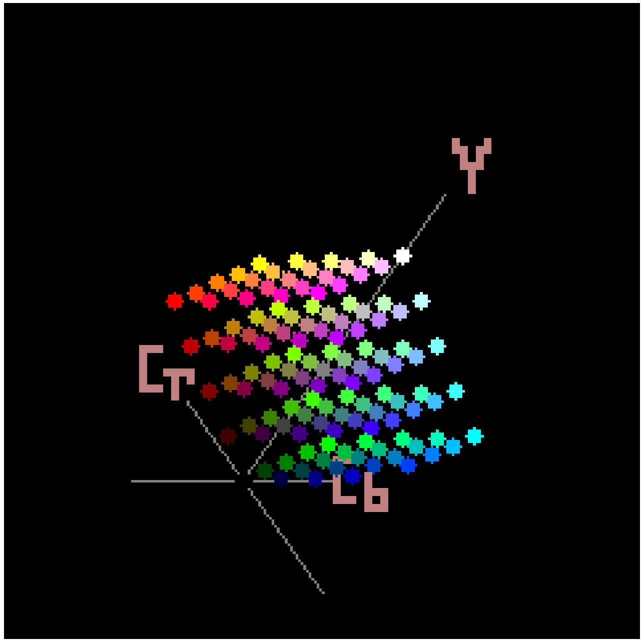
– Conversion from RGB to YCbCr

$$\begin{bmatrix} Y \\ Cb \\ Cr \end{bmatrix} = \begin{bmatrix} 16 \\ 128 \\ 128 \end{bmatrix} + \begin{bmatrix} 65.481 & 128.553 & 24.966 \\ -37.797 & -74.203 & 112.000 \\ 112.000 & -93.786 & -18.214 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

YCbCr Model

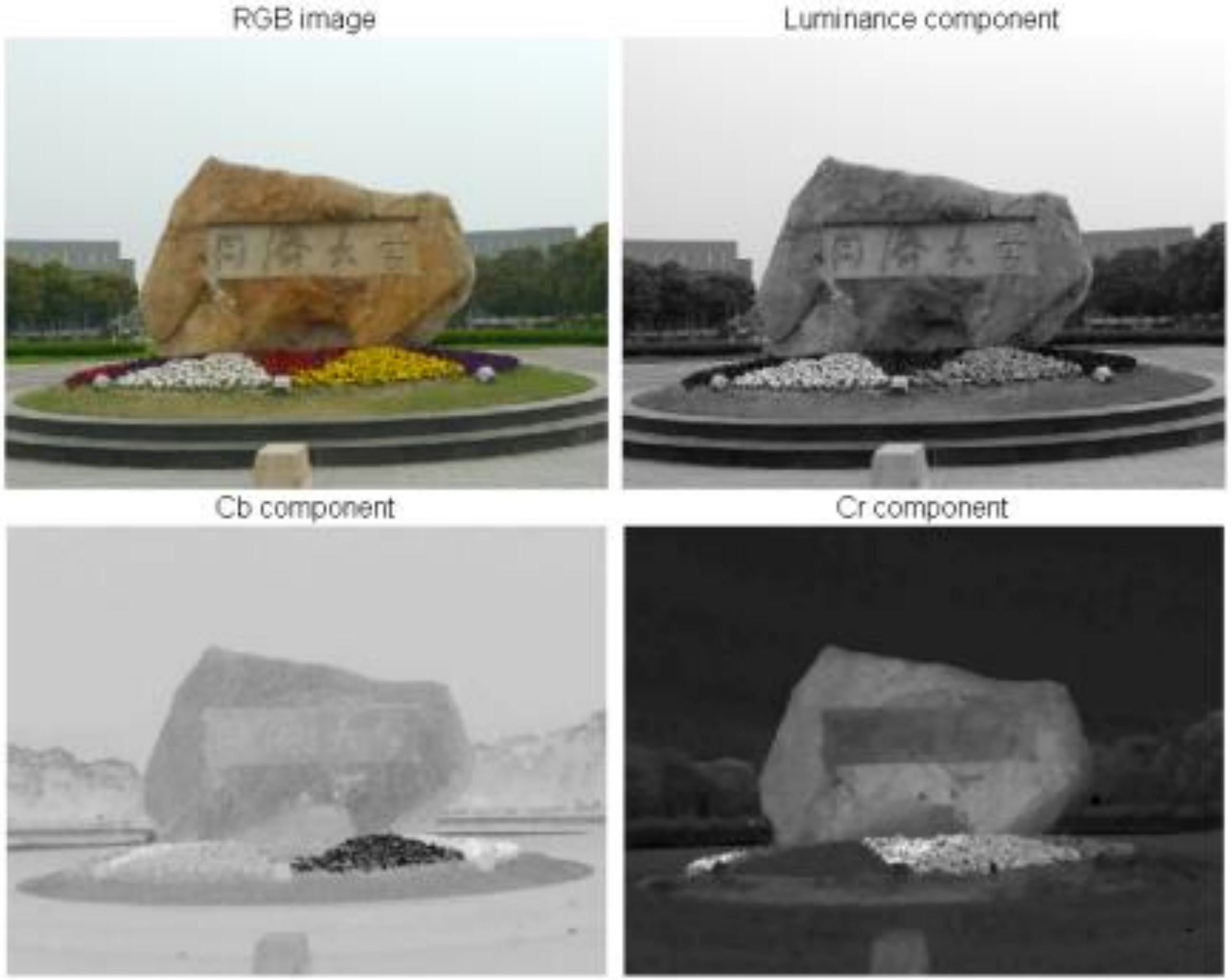






Source: Wikipedia

YCbCr Model



Distances in color space

and knowing what “perceptually meaningful” means

Color Difference

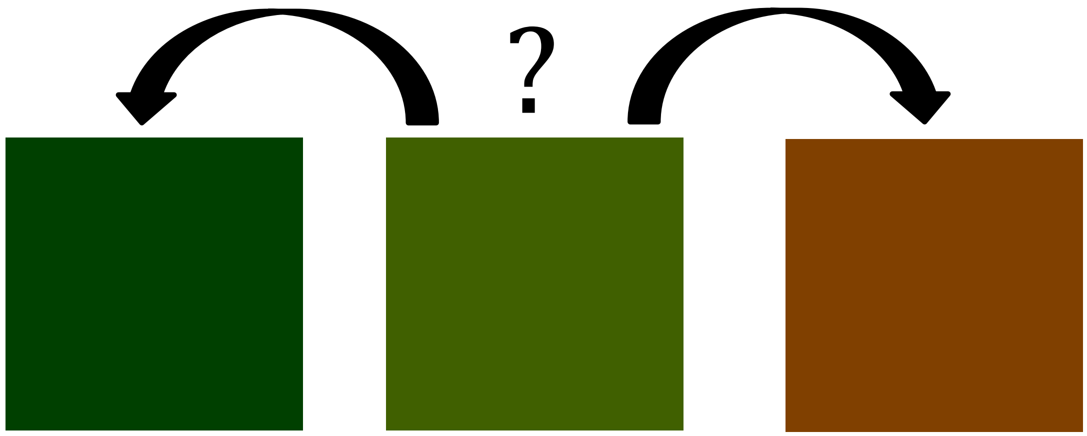
- Consider two colors C_1 and C_2
- How to measure difference between C_1 and C_2 ?
- Simplest difference measure: Euclidean distance

$$d(C_1, C_2) = \sqrt{(R_1 - R_2)^2 + (G_1 - G_2)^2 + (B_1 - B_2)^2}$$

Straight line distance in color space (in this e.g. RGB)

Let’s do a test…

- Which color looks more similar to the middle color, left or right?

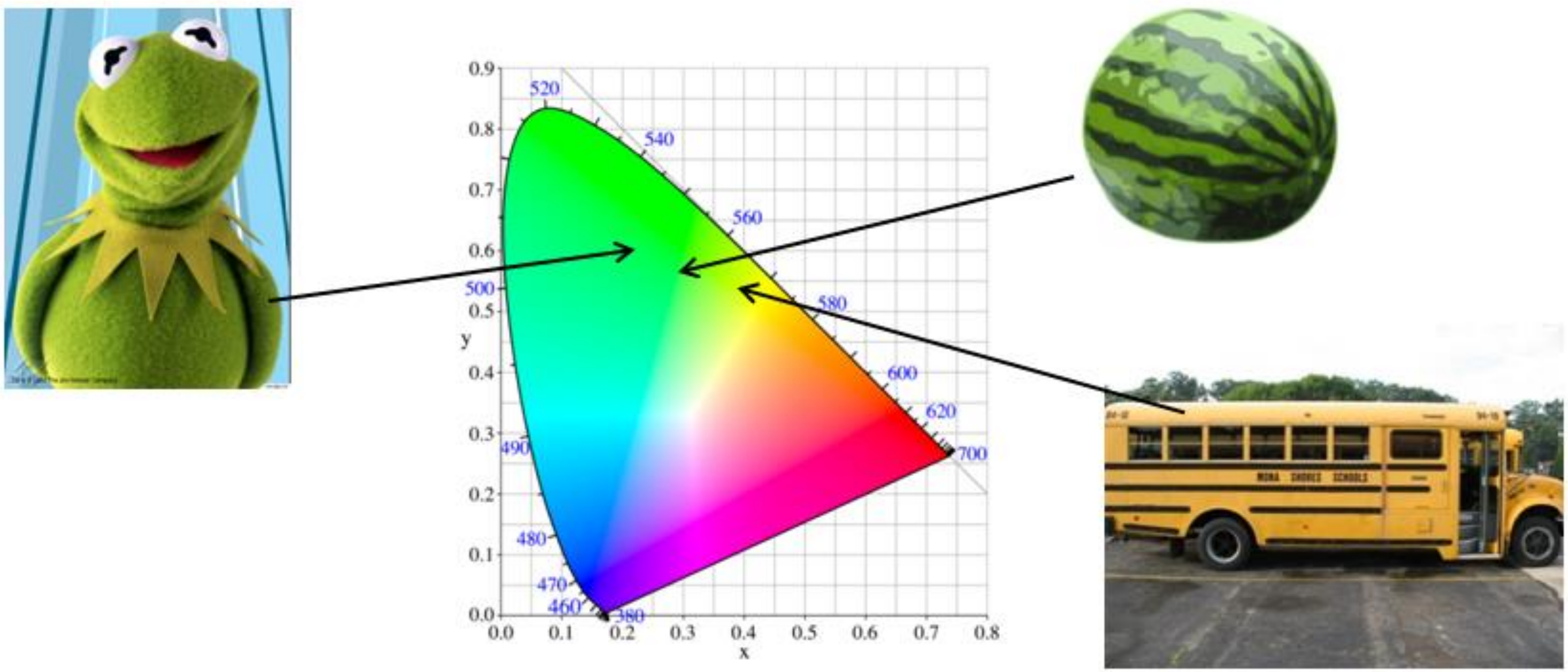


(0, 64, 0) (64, 96, 0) (128, 64, 0)

(1) (2)

Distances in color space

- Are distance between points in a color space **perceptually meaningful?**



Color Difference

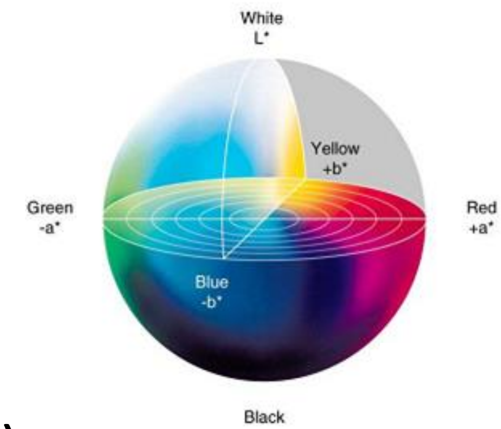
- Not necessary
- RGB space is not perceptually uniform
  - magnitude of differences in coordinates are poor indicator of color "distance"
  - Equal color distance ≠ Equal perceptual difference
  - Inappropriate if need to match human perception
- HSV, YCbrCr also not perceptually uniform
- Perceptually (more) uniform color spaces:
  - **CIE LAB, CIE LUV**

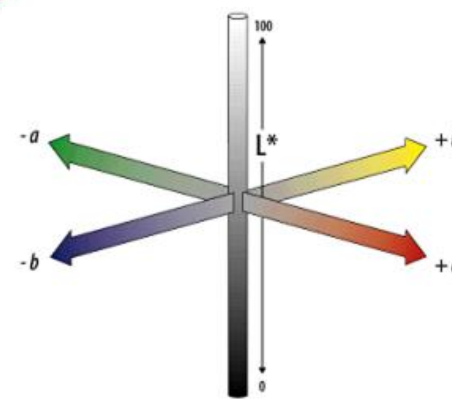
Uniform color spaces

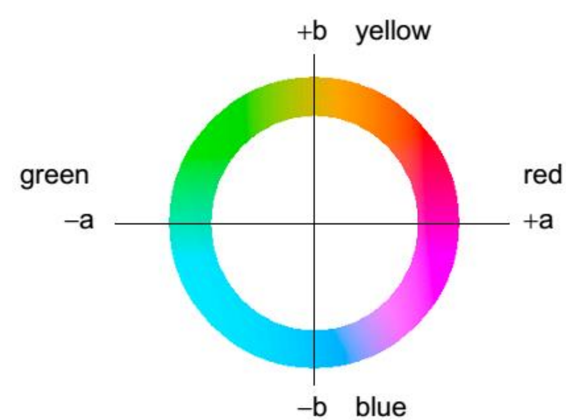
- Attempt to correct this limitation by re-mapping color space so that just noticeable differences are contained in more circular spots and they are **separated more uniformly**
  $\Longrightarrow$**distances more perceptually meaningful**

CIE LAB and CIE LUV

- **CIE 1976 L*a*b** color space
  - L* : matches human perception of lightness
    - From 0 (black) to 100 (white)
  - a*, b* : hue
- **CIE 1976 L*u*v** color space
  - Similar to CIE LAB color space
  - **L*** : range from 0 to 100
  - **u*, v*** : typically range from -100 to +100



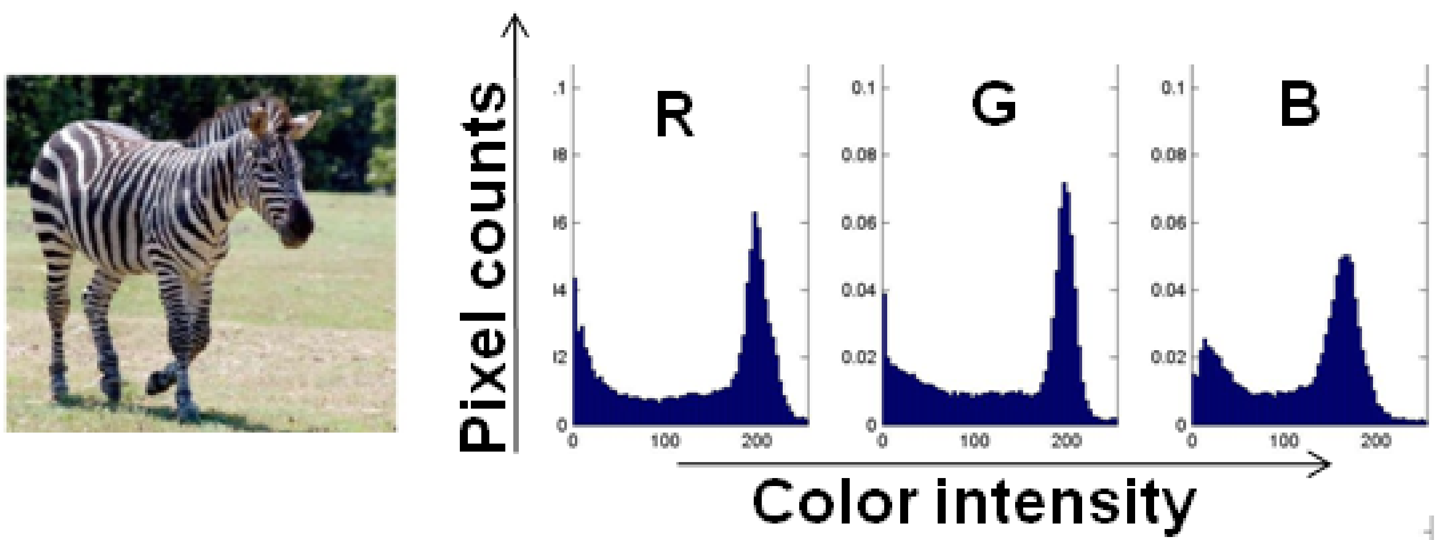




Applications:
Using color information

Color as a low-level cue for CBIR

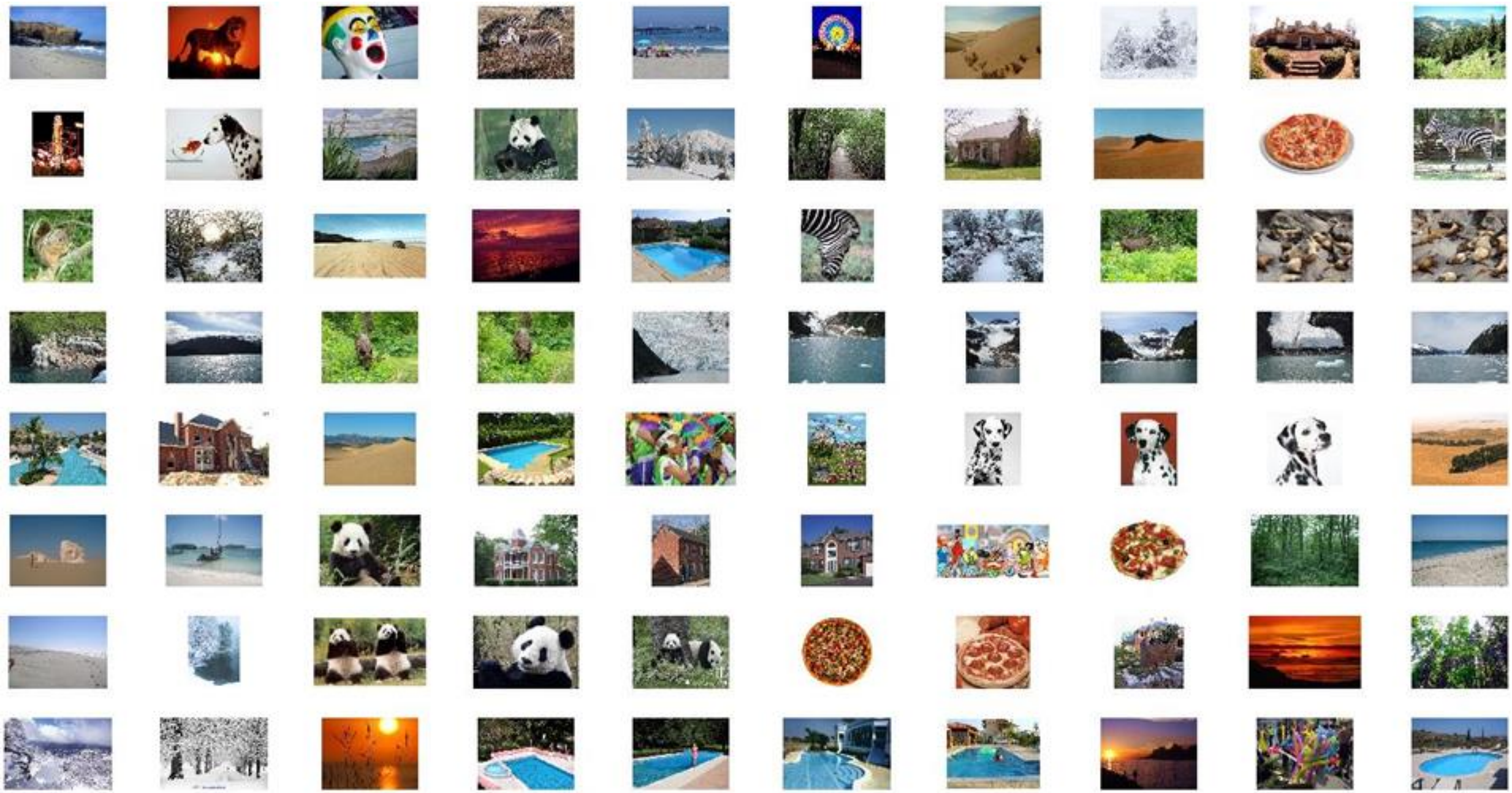
- **CBIR**: Content-Based Image Retrieval
- **Color histograms**
  - Use <u>distribution of colors</u> to describe image
  - No spatial info – <u>invariant to translation, rotation, scale</u>



Color-based image retrieval

- Given **collection (database) of images**
  - Extract and store one color histogram per image
- Given **new query image**
  - Extract its color histogram (similar way as before)
  - For each database image, compute distance between query histogram and database histogram
  - Sort distances (**smallest score = most similar image**)
  - Rank database items relative to query based on this sorted order

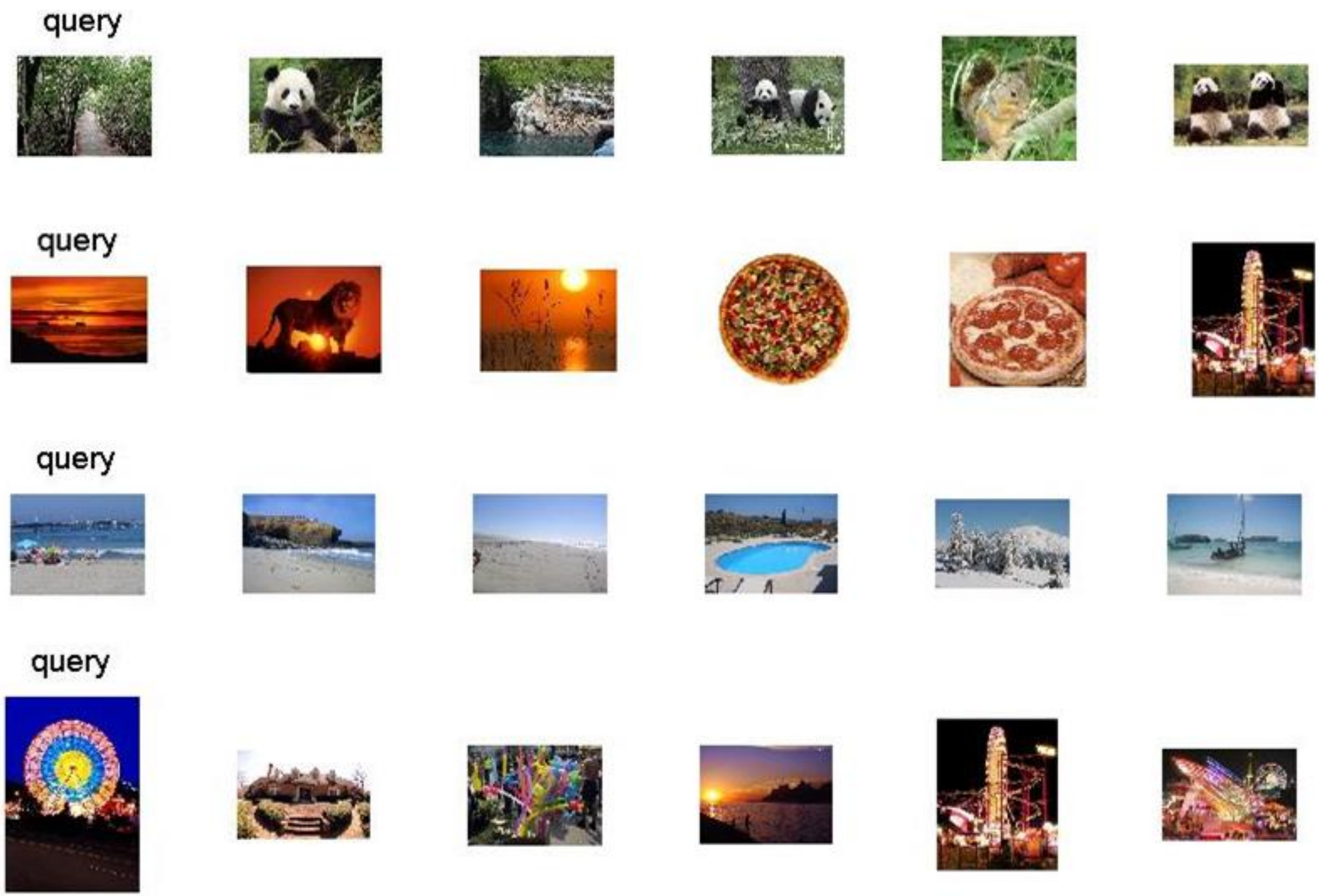
Color-based image retrieval



Example Database

Source: Kristen Grauman

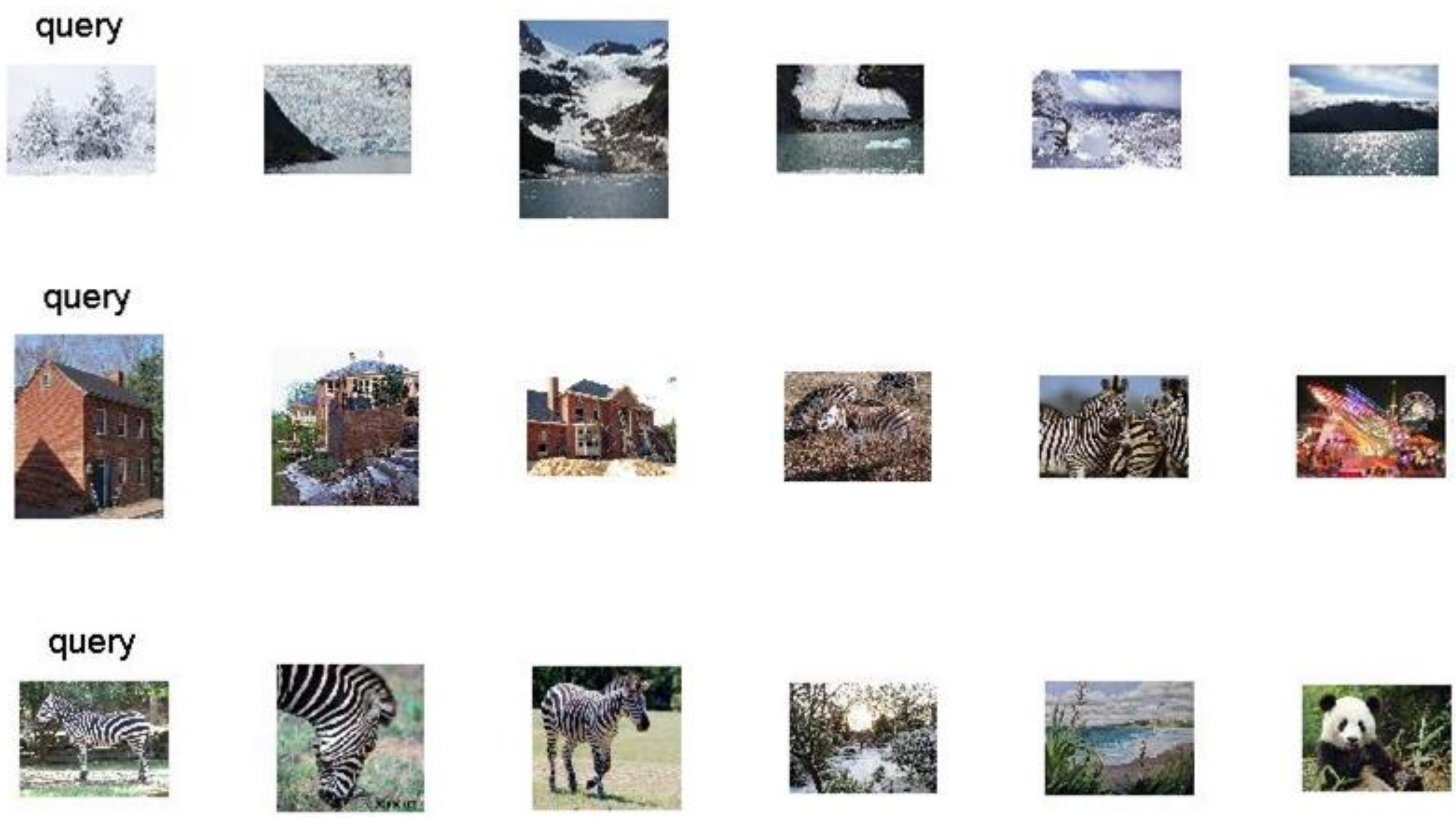
Color-based image retrieval



Example Retrievals

Source: Kristen Grauman

Color-based image retrieval

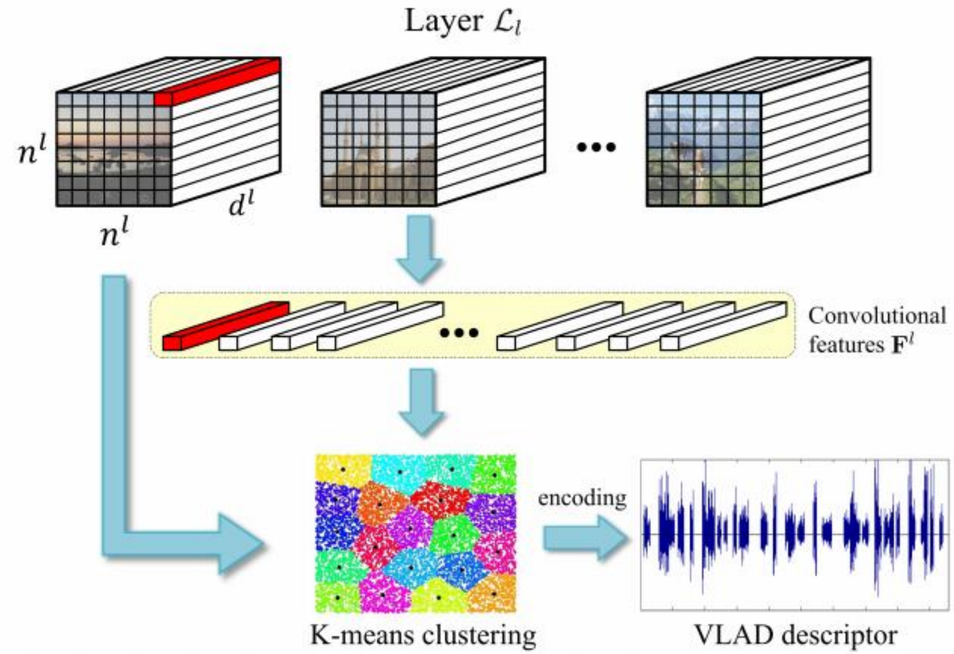


Example Retrievals

- What can you observe from the results?

Source: Kristen Grauman

Exploiting Local Features from Deep Networks for Image Retrieval

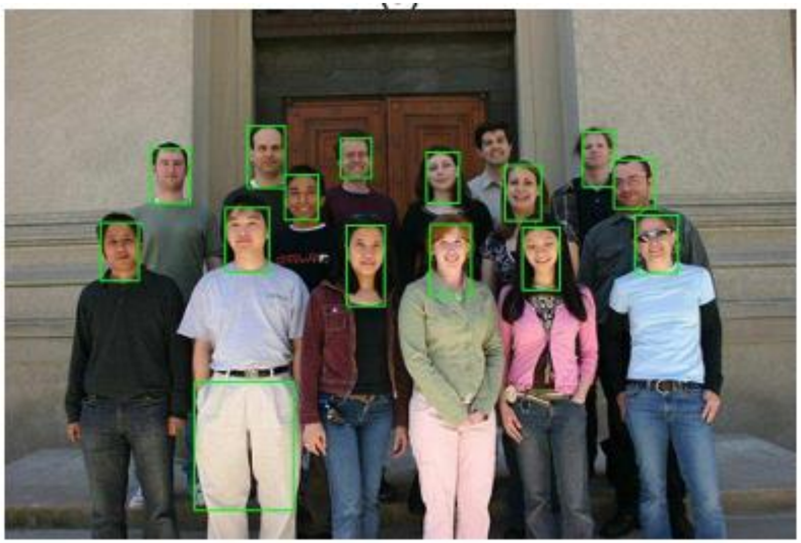


Yue-Hei Ng, J., Yang, F., & Davis, L. S. (2015). Exploiting local features from deep networks for image retrieval. In *Proceedings of the IEEE conference on computer vision and pattern recognition workshops* (pp. 53-61)

Color-based Skin Detection

Jones, M. J., & Rehg, J. M. (2002). Statistical color models with application to skin detection. *International Journal of Computer Vision*, *46*(1), 81-96.

Color-based Skin Model for Face Detection



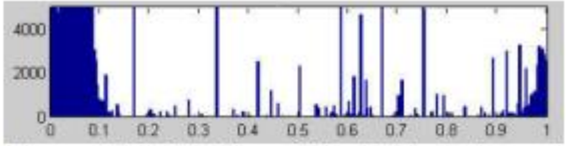


Figure 4. Distribution of the H (Hue) channel

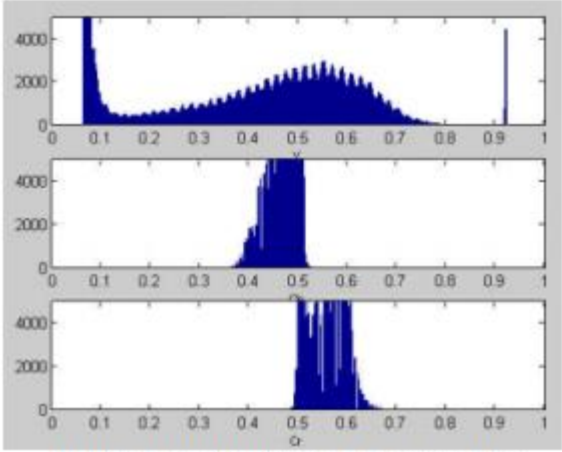
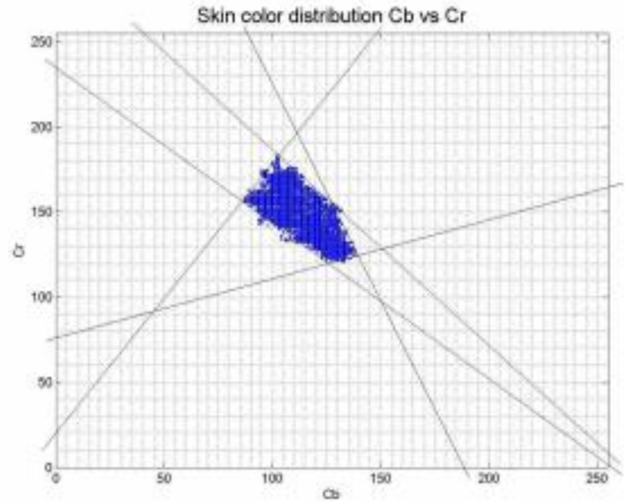


Figure 5. Distribution of Y, Cb and Cr

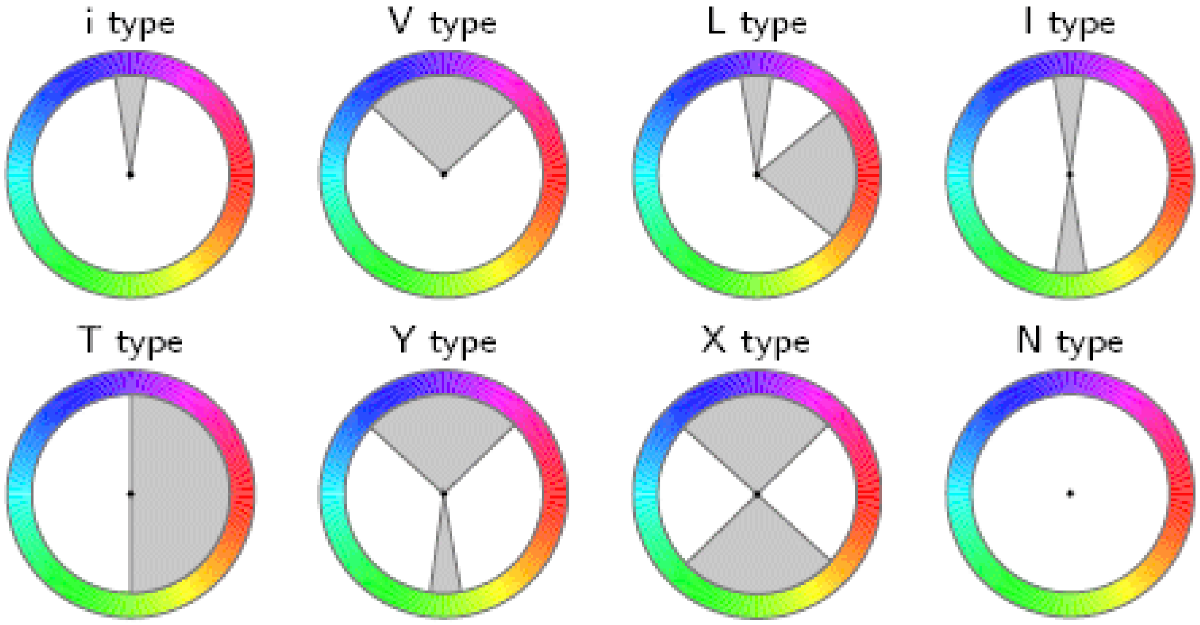


RGB-H-CbCr Fusion Color Space

(Nusirwan, Kit & See, 2006)

Color harmonization

- **Harmonic colors** are sets of colors that are aesthetically pleasing in terms of human visual perception
- **Color harmonization** is an artistic technique to adjust the colors of a given image in order to enhance their visual harmony.



M. Tokumaru, N. Muranaka, and S. Imanishi. Color design support system considering color harmony. Proc. of IEEE Fuzzy Systems, 1:378–383, 2002.

Color harmonization

- Image color harmonization

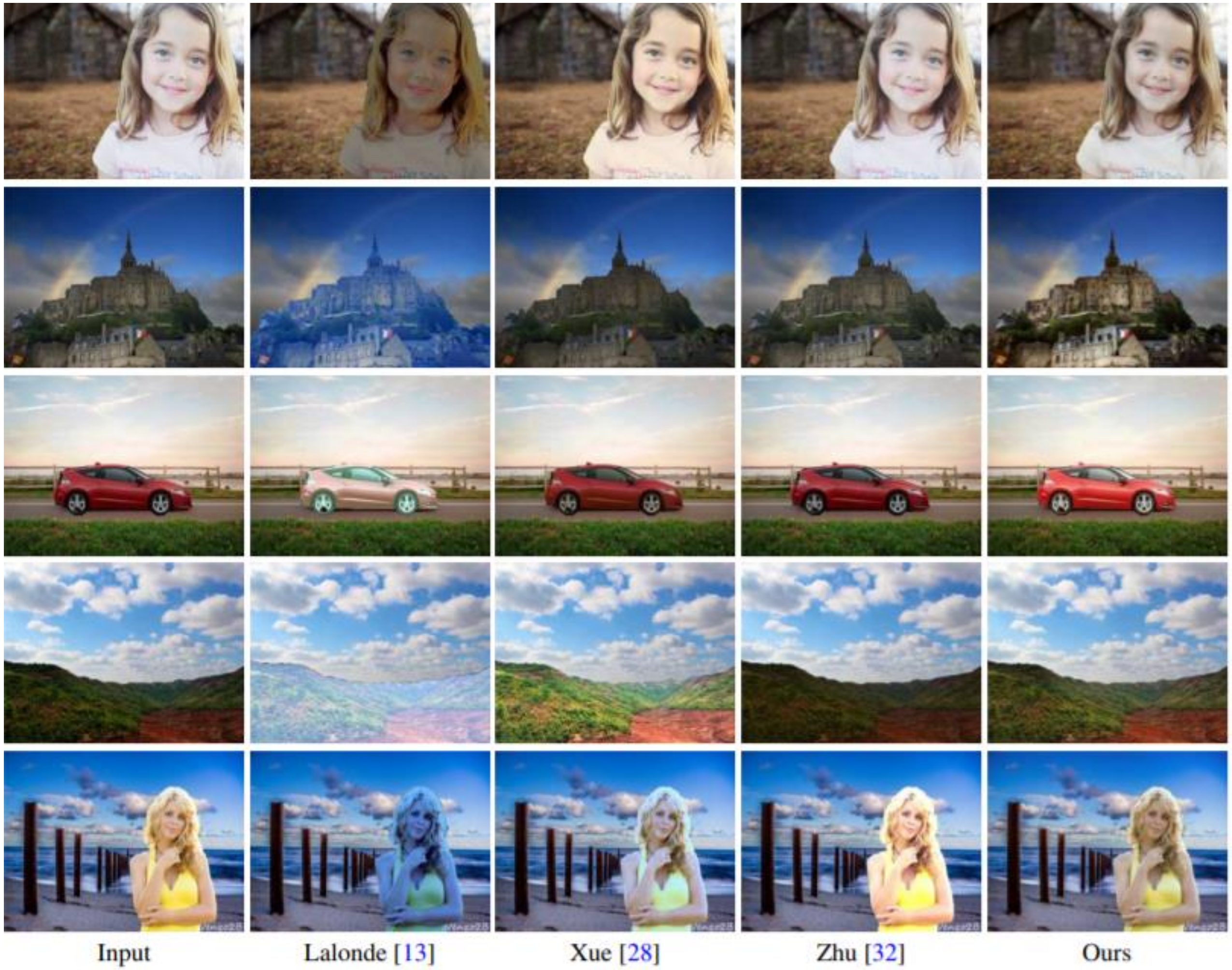
original image

harmonized image

Cohen-Or, D., Sorkine, O., Gal, R., Leyvand, T., & Xu, Y. Q. (2006, July). **Color harmonization**. In *ACM Transactions on Graphics (TOG)* (Vol. 25, No. 3, pp. 624-630). ACM.

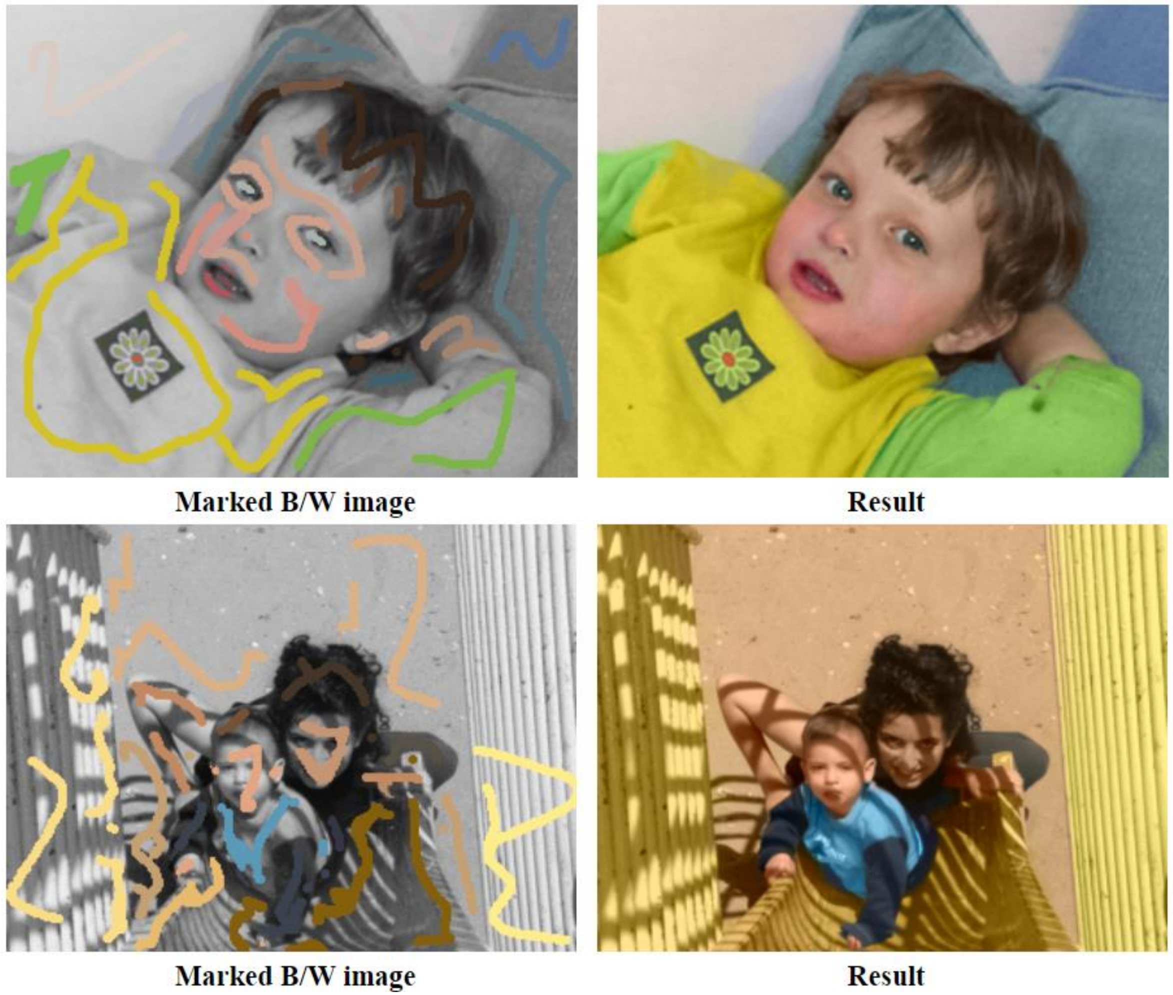
Color Harmonization

- Deep Image Harmonization



Tsai, Y. H., Shen, X., Lin, Z., Sunkavalli, K., Lu, X., & Yang, M. H. (2017). Deep image harmonization. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition* (pp. 3789-3797).

Colorization



Levin, A., Lischinski, D., & Weiss, Y. (2004, August). **Colorization using optimization**. In *ACM transactions on graphics (TOG)* (Vol. 23, No. 3, pp. 689-694). ACM.

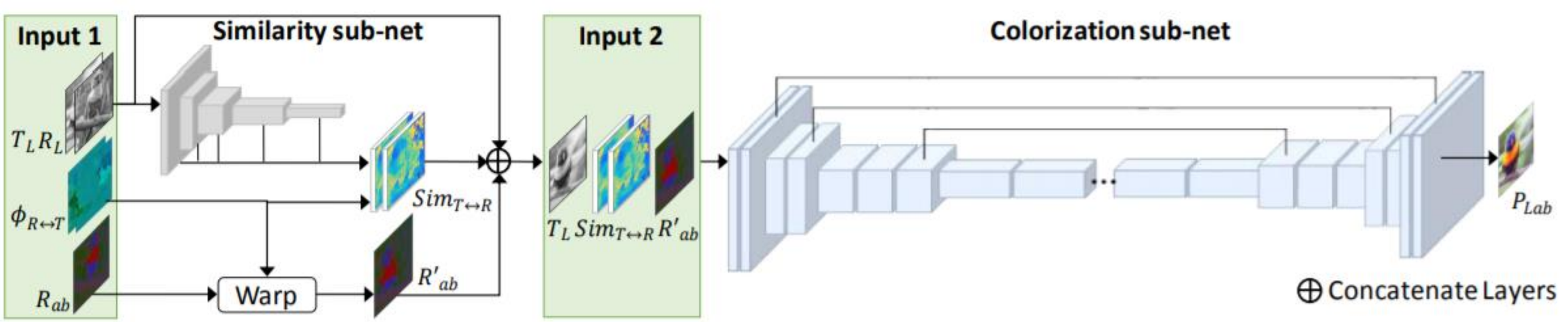
Colorization

Deep Exemplar-based Colorization*

Mingming He*[1], Dongdong Chen*[2] †Jing Liao[3], Pedro V. Sander[1], and Lu Yuan[3]
[1]Hong Kong UST, [2]University of Science and Technology of China, [3]Microsoft Research

Target Reference 1 Result 1 Reference 2 Result 2 Reference 3 Result 3

Figure 1: *Colorization results of black-and-white photographs. Our method provides the capability of generating multiple plausible colorizations by giving different references. Input images (from left to right, top to bottom): Leroy Skalstad/pixabay, Peter van der Sluijs/wikimedia, Bollywood Hungama/wikimedia, Lorri Lang/pixabay, Aamir Mohd Khan/pixabay, Official White House Photographer/wikimedia, Anonymous/wikimedia and K. Krallis/wikimedia.*



He, M., Chen, D., Liao, J., Sander, P. V., & Yuan, L. (2018). **Deep exemplar-based colorization**. ACM Transactions on Graphics (TOG), 37(4), 47.

Summary

- Fundamentals of color
- Human color perception
- Color spaces/models
  - RGB, CMY, CIE XYZ, HSV, NTSC, YCbCr
  - Perceptually meaningful color spaces: CIE LAB, CIE LUV
- Applications using color information
  - Content-based image retrieval
  - Color-based skin detection
  - Color harmonization
  - Image colorization

Recommended Reading

- [Gonzalez & Woods] Chapter 6
- [Forsyth & Ponce] Chapter 3