(I'm Fun) Digital Image Fundamentals

Week 5: Color Science

Thuong Nguyen Canh

Institute for Datability Science, Osaka University

November 2019

This material is based on the Digital Image Processing, Stanford University, Prof. Bernd Girod.
Color Science presentation from Prof. W. Freeman at MIT.
Kristen Grauman's Slides for Computer Vision

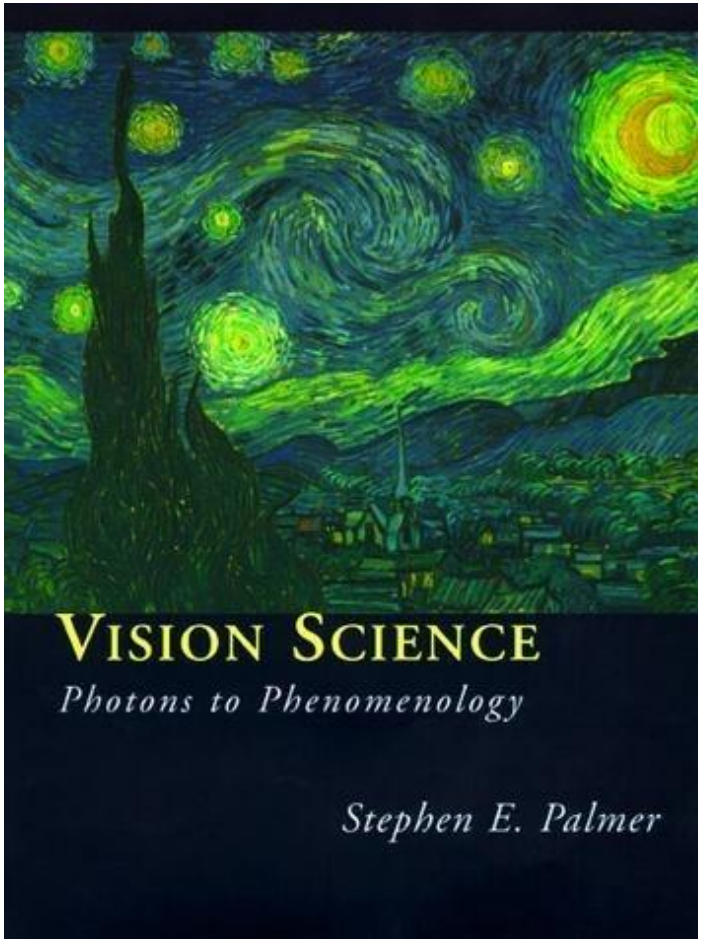
Contents

Introduction to Color Science

- 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.



What is Color?

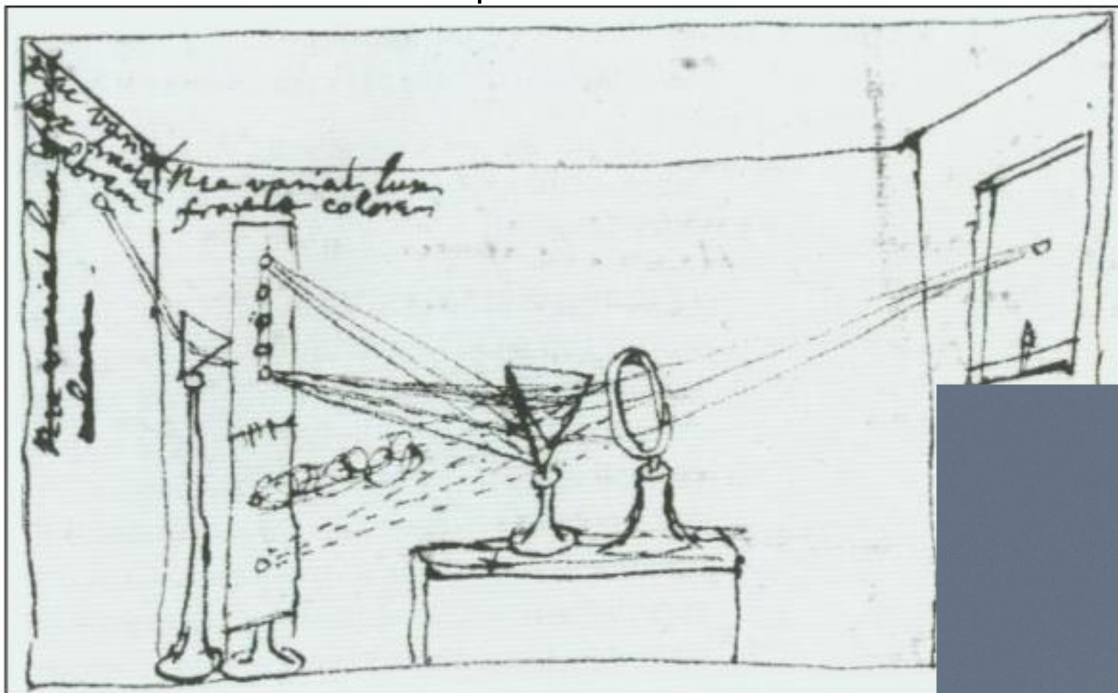
- Color is a property of light
- Color of light arriving at camera
  - Light source (multiple light sources, different property)
  - Light coming to the object/surface (diffraction, observe, reflection),
  - Light going with different path to hit the camera/eye

White paper under candle's light

White paper under sunlight

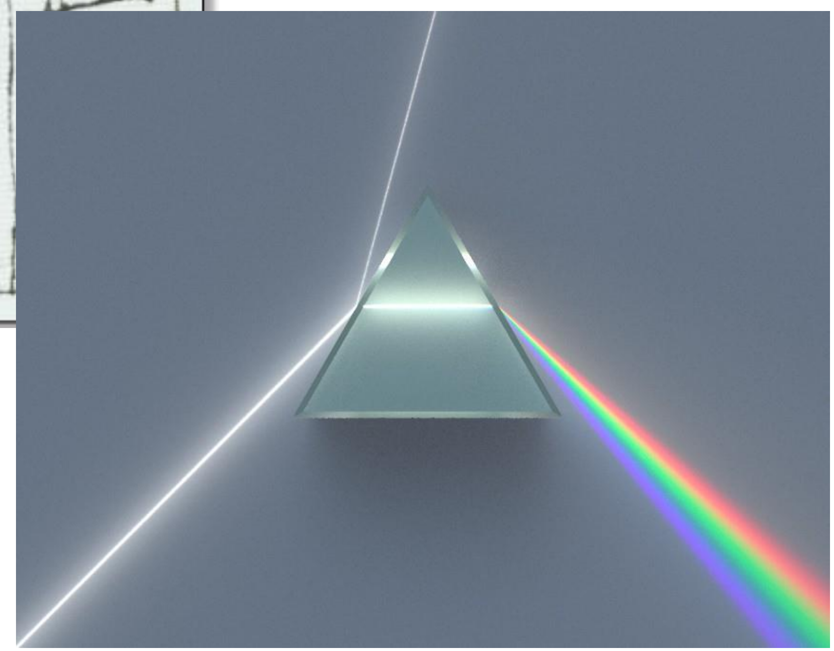
Color is a part of Physic

Prism Experiment - 1666

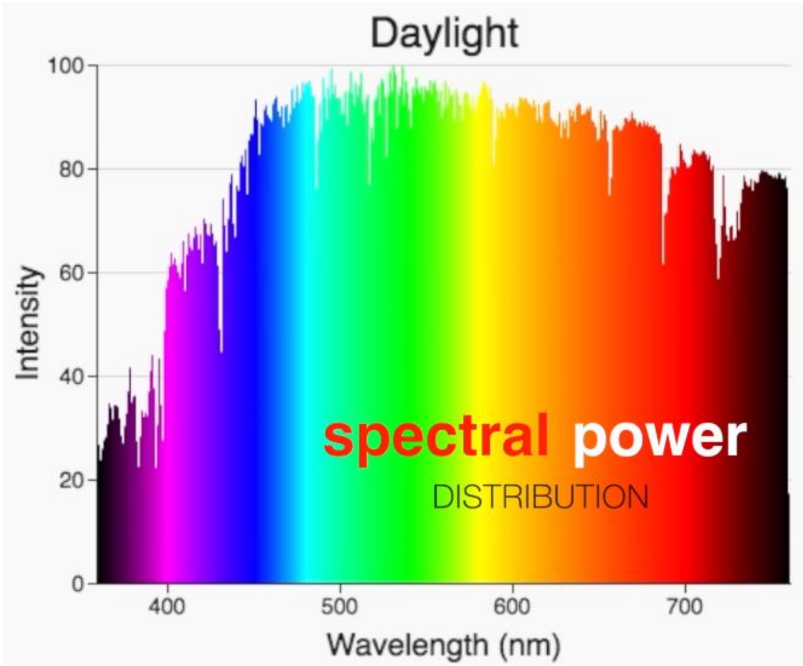


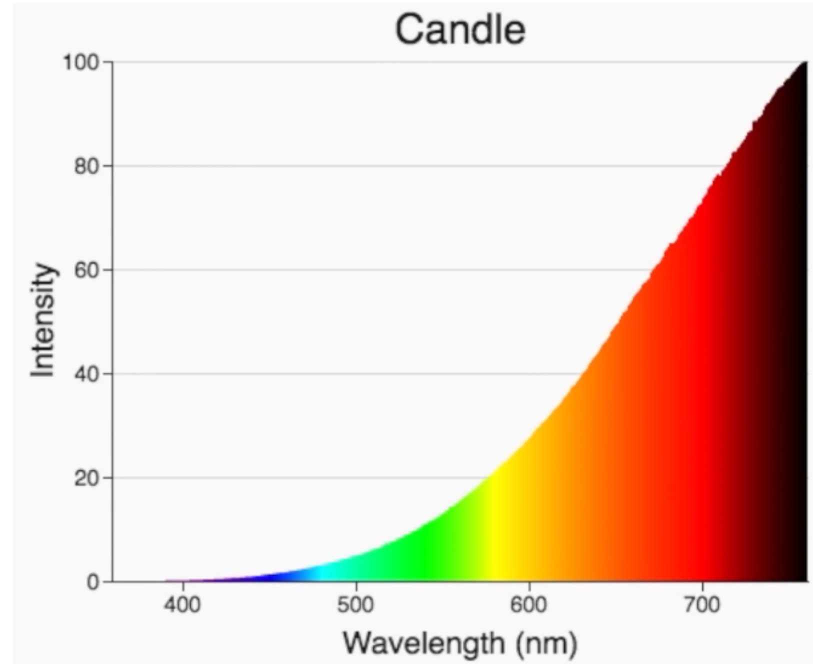
All light is a mixture of color

White light: composed of about equal energy in all wavelengths of the visible spectrum

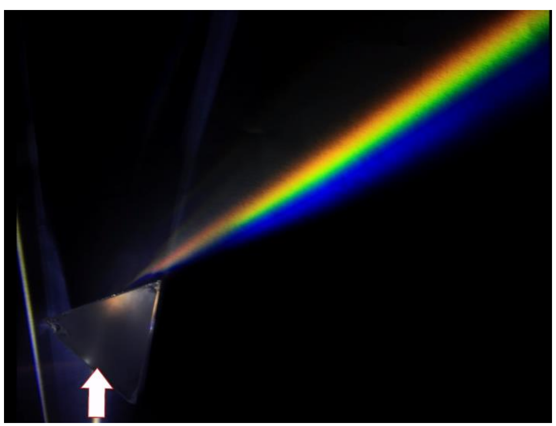


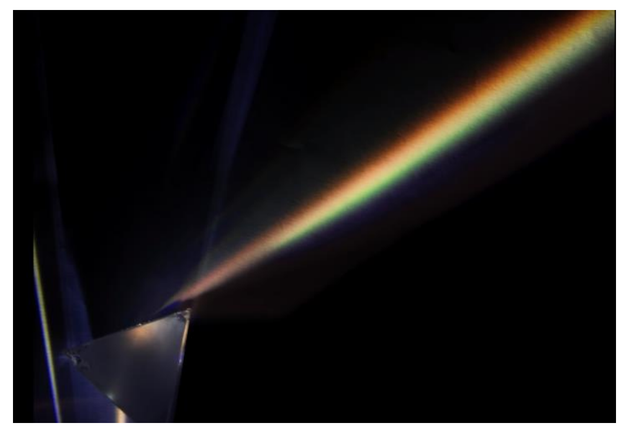
Spectrum of light



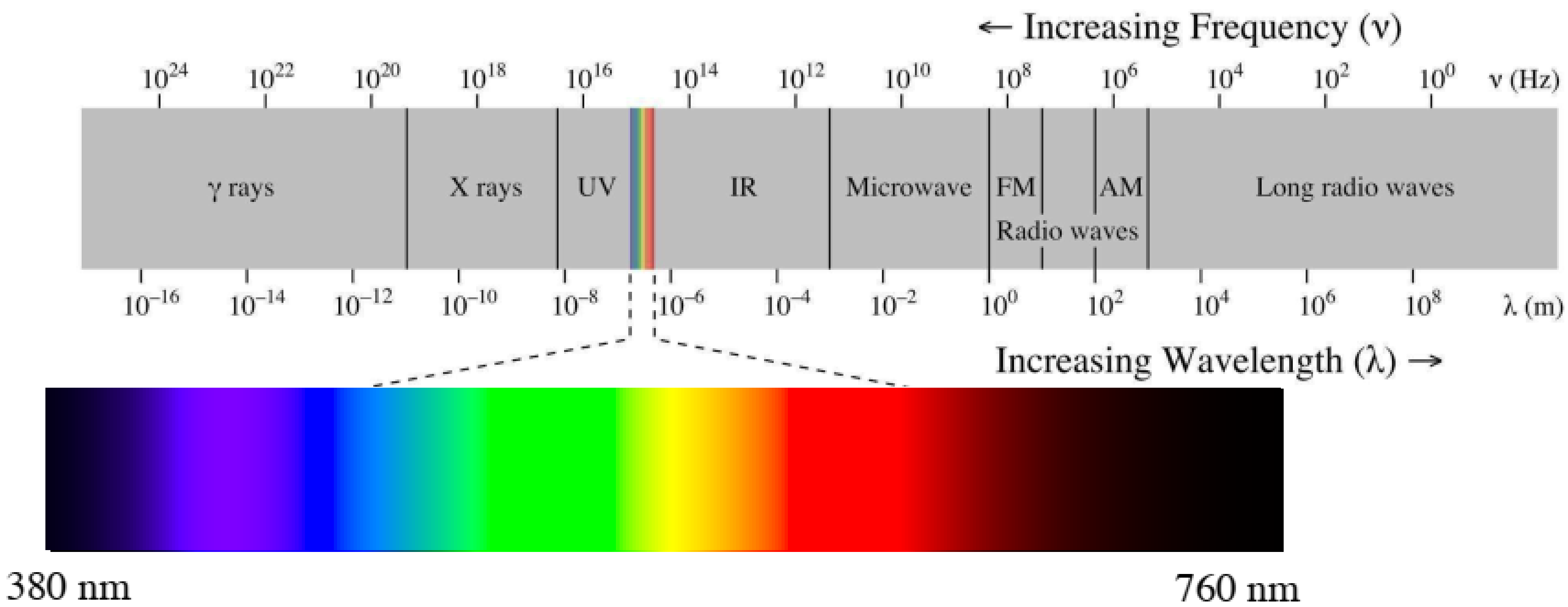


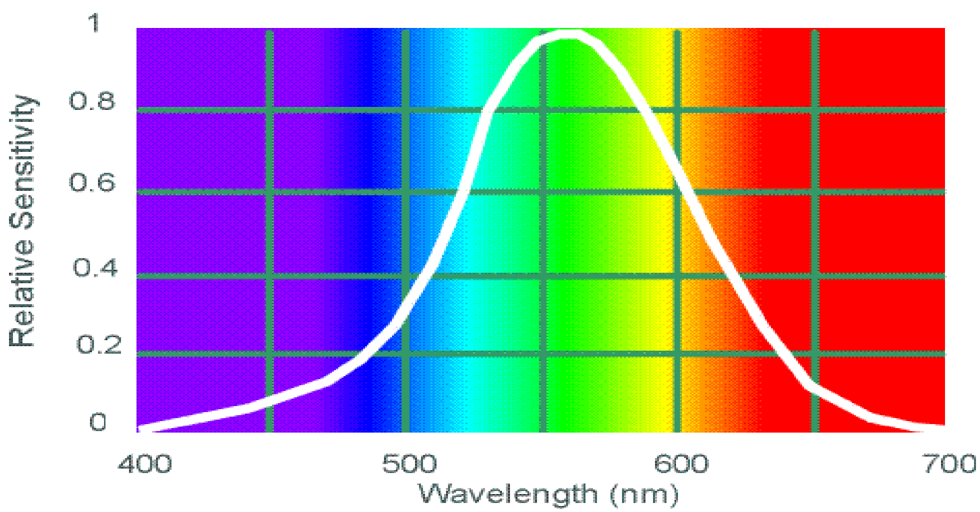
Via PRISM





Color Visible Range

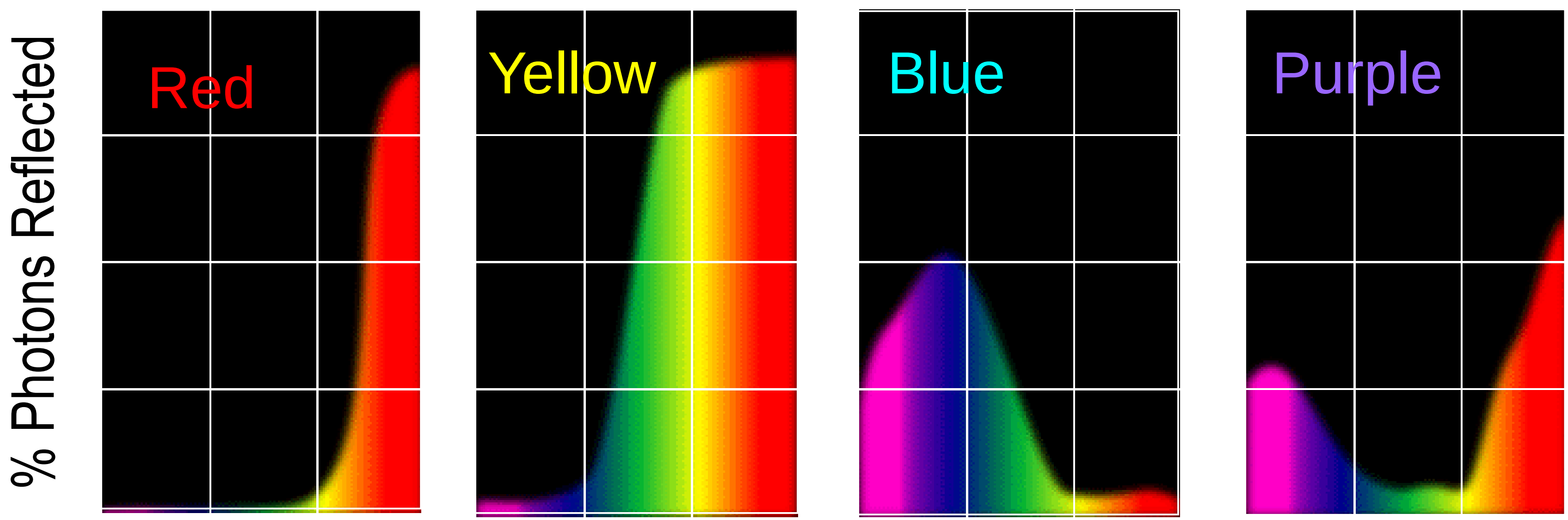




Human Luminance
Sensitivity Function

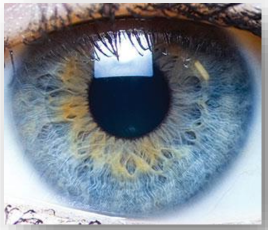
Surface reflectance spectra

Some examples of the reflectance spectra of surfaces



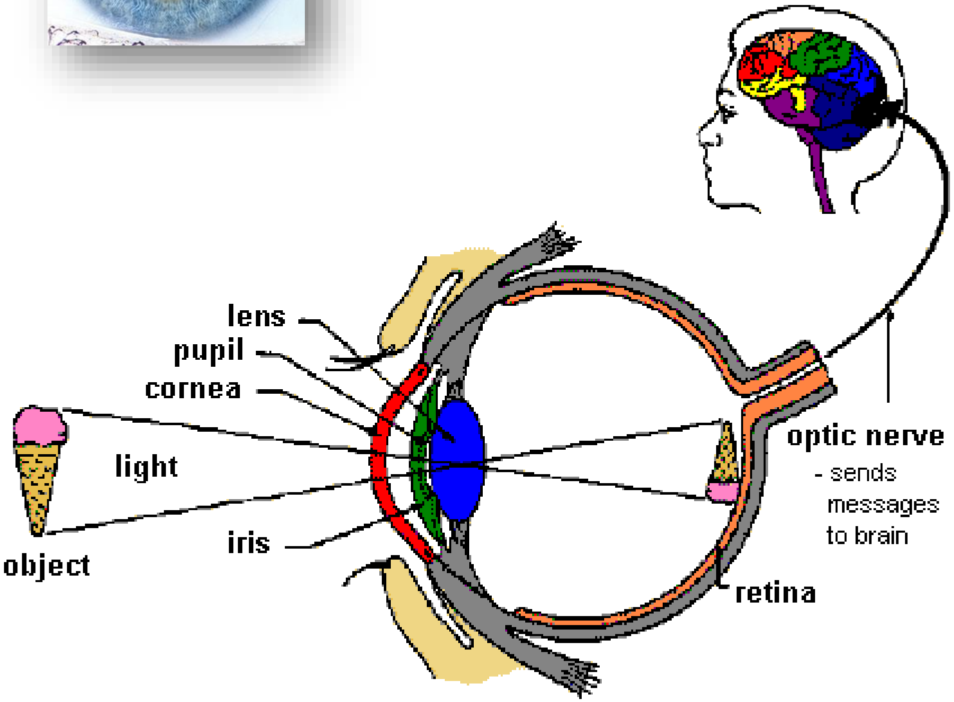
Color is a part of Human Perception

- Color perceived depends on
  - Physics of light
  - Visual system receptors
  - Brain processing, environment



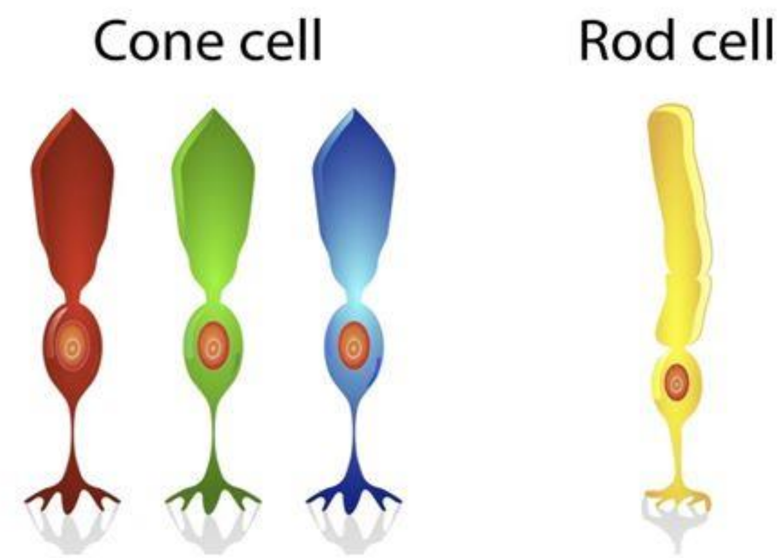
The human eye is a camera!

- **Iris** - colored annulus with radial muscles
- **Pupil** - the hole (aperture) whose size is controlled by the iris
- **Lens** - changes shape by using muscles (t o focus on objects at different distances)
- **Retina** - photoreceptor cells



Human's Eye

- Types of light-sensitive receptors
  - Cones
    - cone-shaped
    - less sensitive
    - operate in high light
    - color vision
  - Rods
    - rod-shaped
    - highly sensitive
    - operate at night
    - gray-scale vision



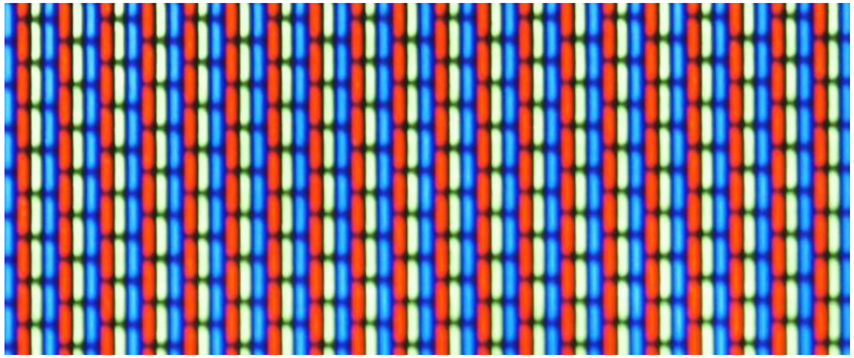
Human brain blend 3 (primary) color to represent all other

Cone type	Peak wavelength	Colour	Colour axis
S (Short)	420nm	Blue	Tritan
M (Medium)	534nm	Green	Deutan
L (Long)	564nm	Red	Protan

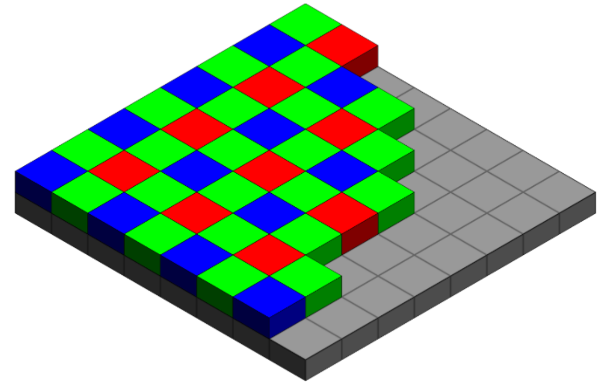
RGB Color Space

- Multimedia/TV industry/Camera borrow the same concept

RGB
Color Space

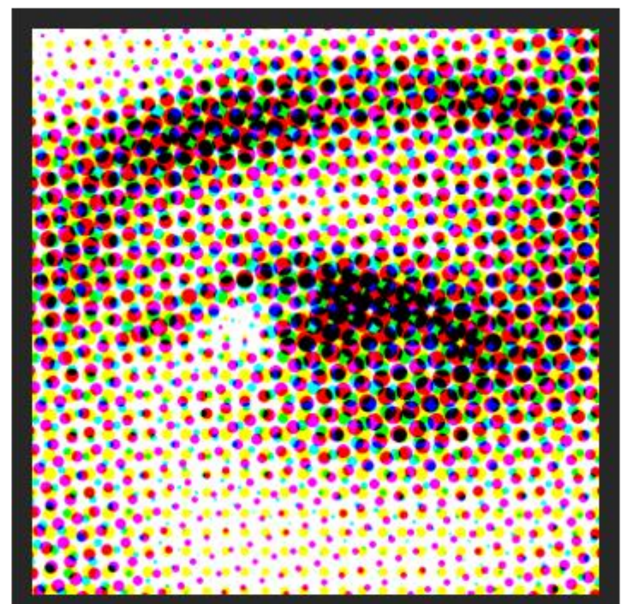


Zoom in TV/Monitor



Camera pixels captures

CMYK Color Space
(details come later)



Why Color Matter?

- For label, measure, represent, or imitate reality, to enliven or decorate

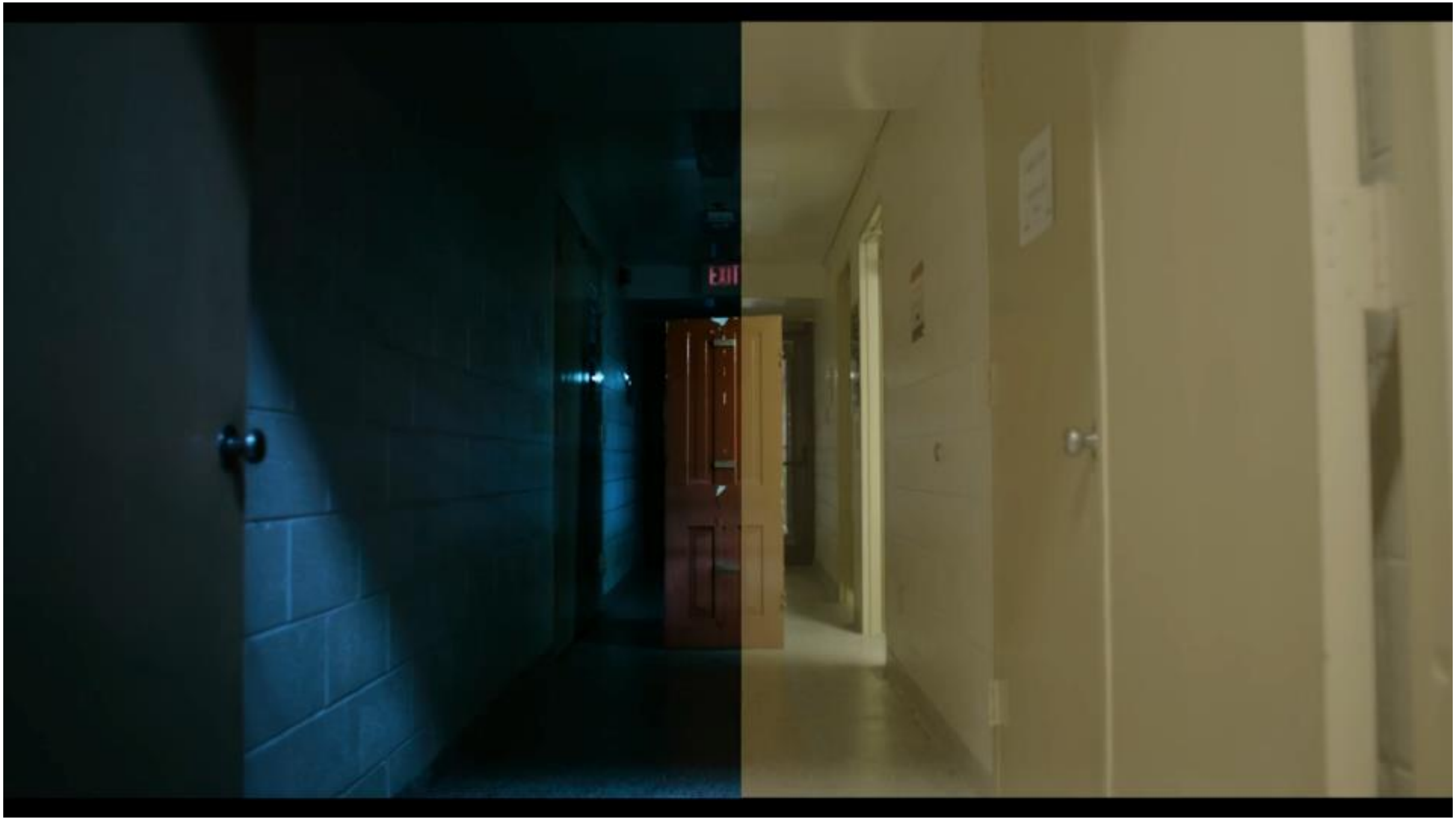
Why Color Matter?

- For Label, Measure, Represent,

Movie
Image enhancement
Marketing
Advertisements
Products
Psychology
Visualization

Why Color?

Horror Setting | Normal Setting



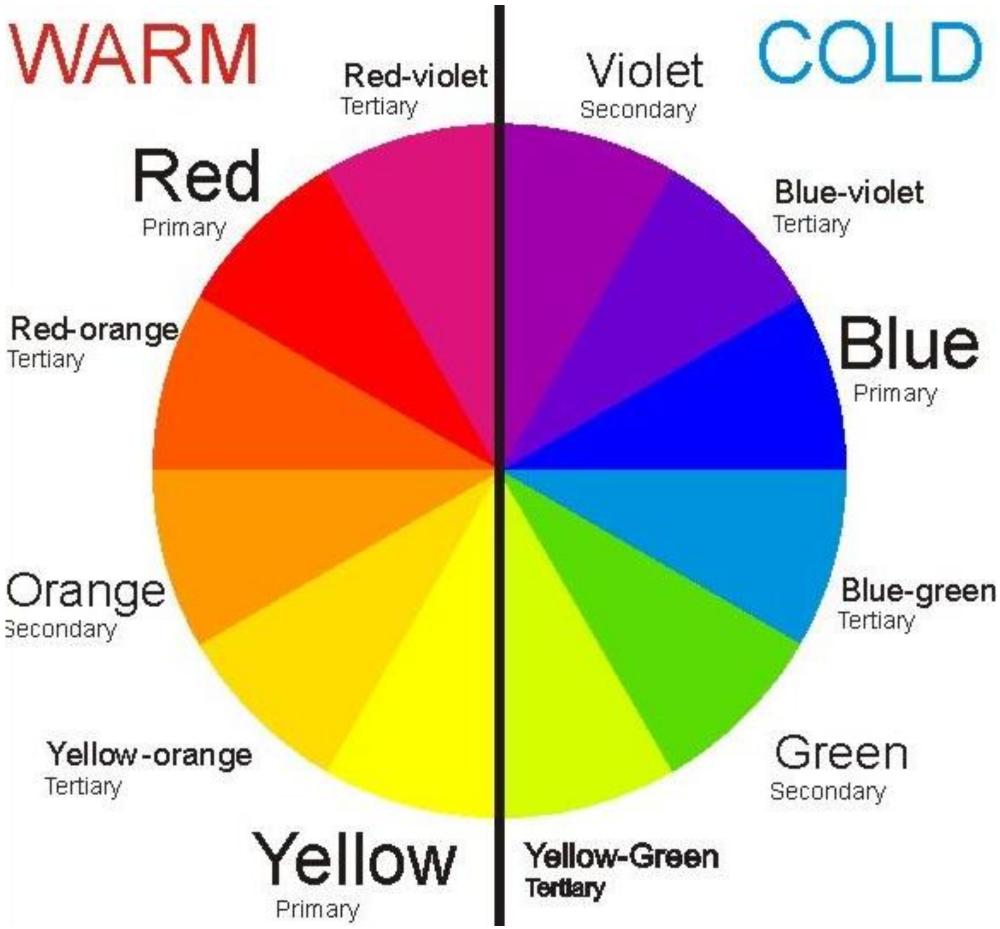
Color tells/supports story/emotion.

Most people has favorite colors

Why Color?

Advance, stimulate, toward the viewers

Exciting for eye, lead to tired



Create calm, quiet, and moody effect

Color Grading/Filter

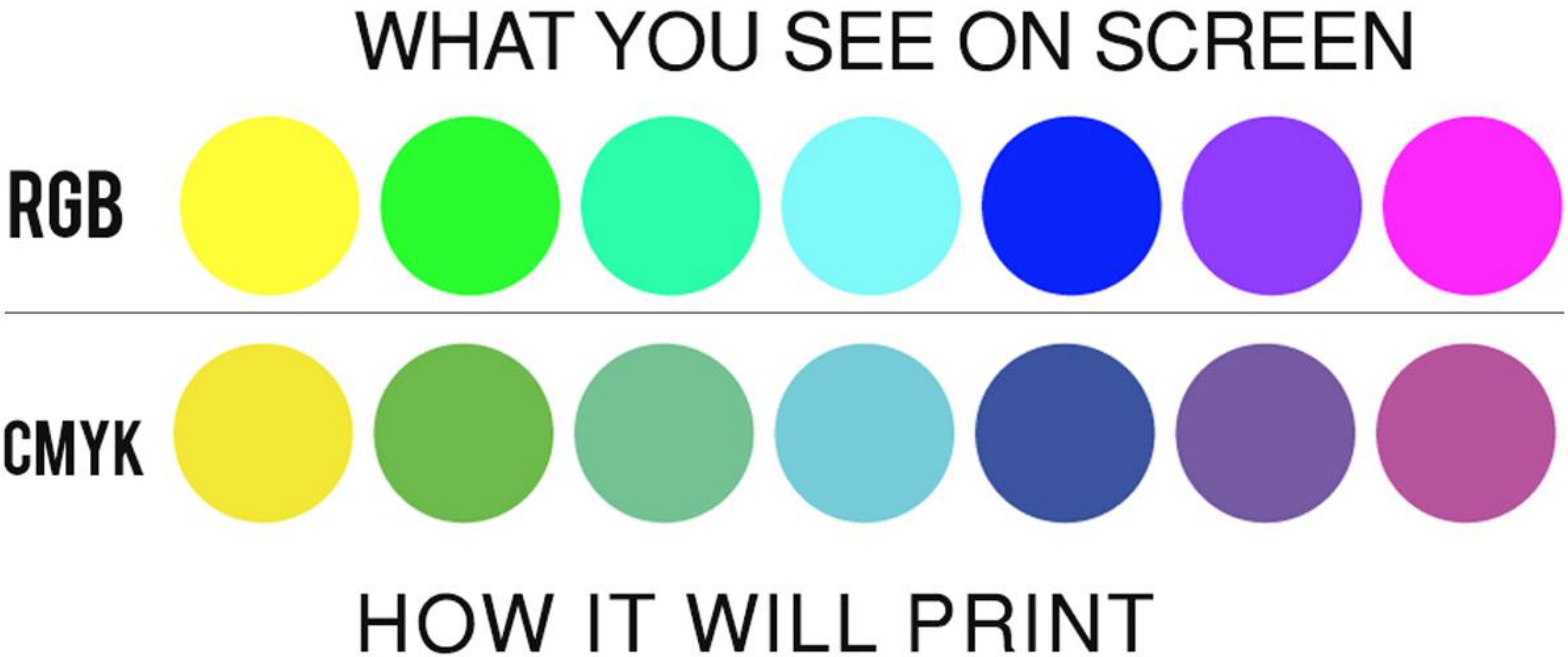
HDR is better than 4K

We are reaching the physical limitation of resolution

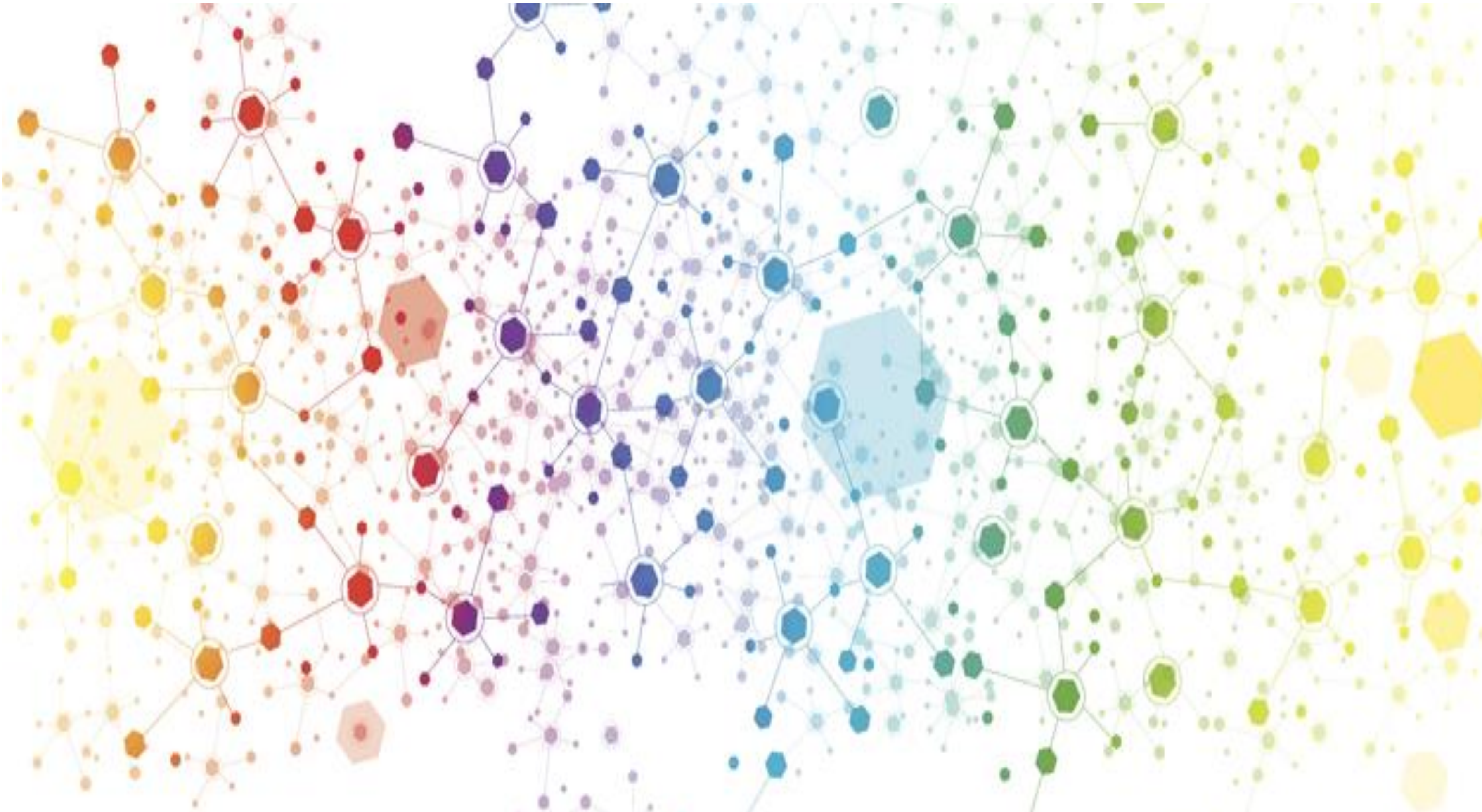
HDR is better than SDR, easier to observe

Reproduction

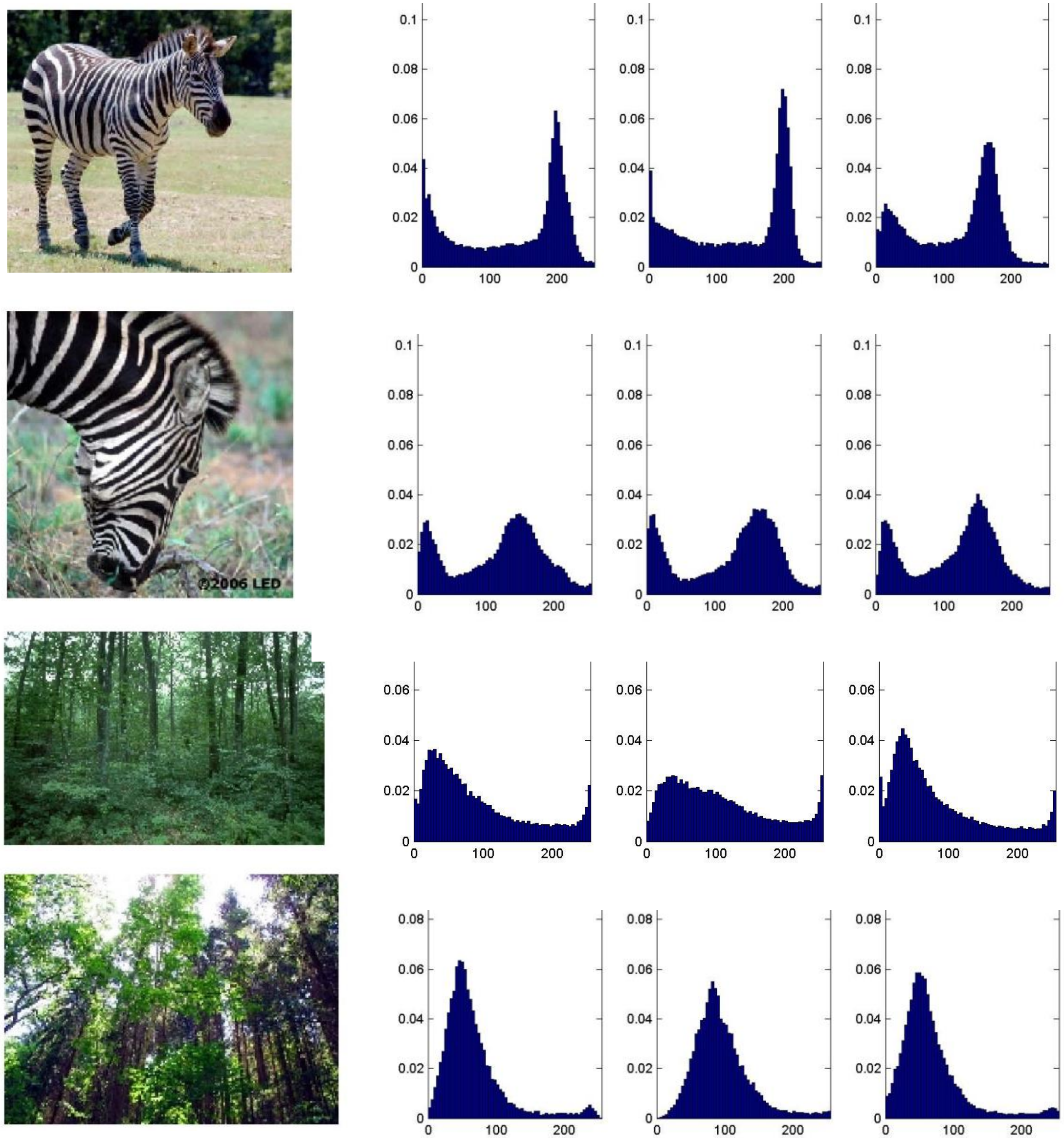
Same color across multiple displays, reproduce existing product



Visualization



Color-based Computer Vision

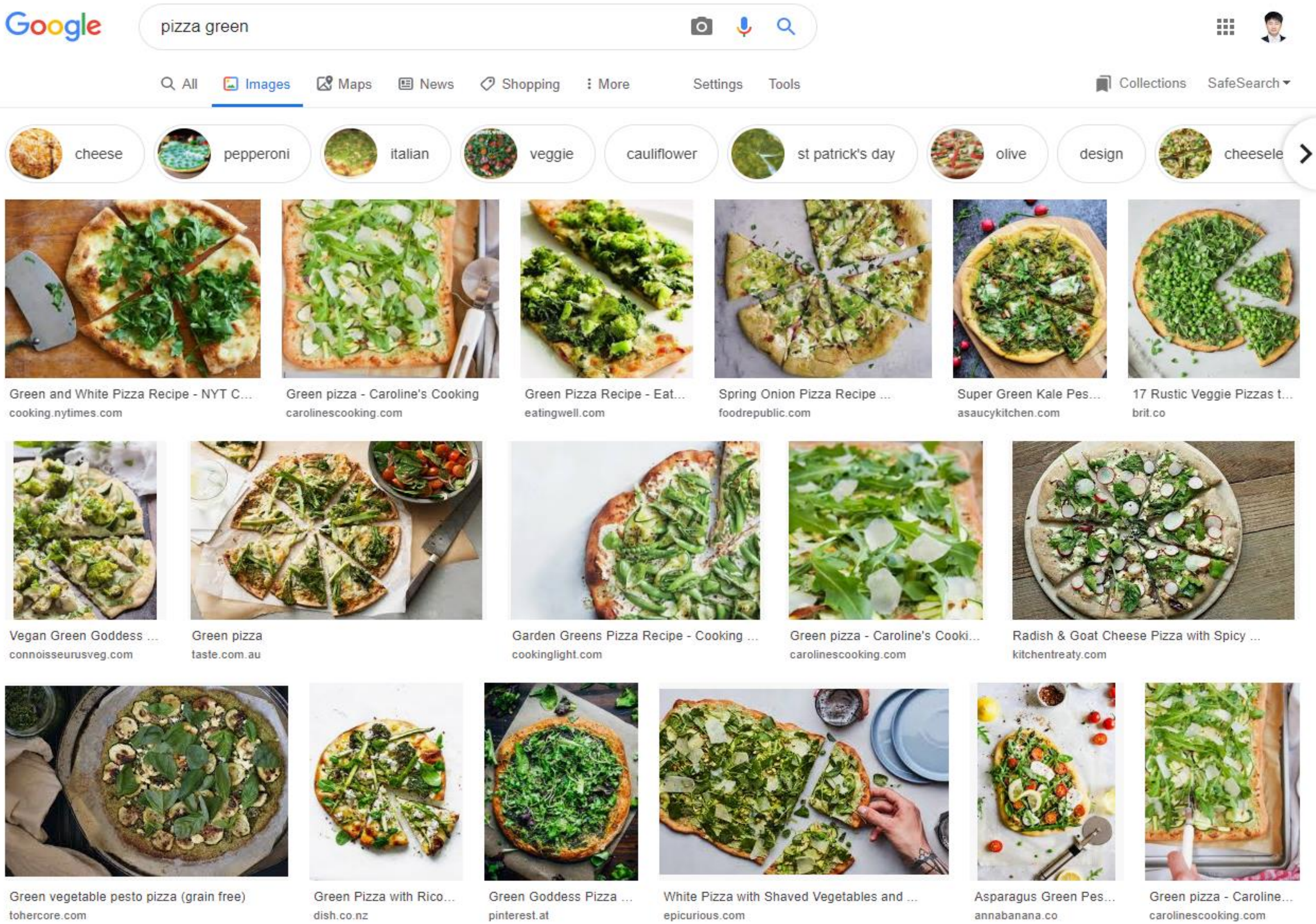


Color as a low-level feature

- Color histograms: Use distribution of colors to describe image
- No spatial info – invariant to translation, rotation, scale

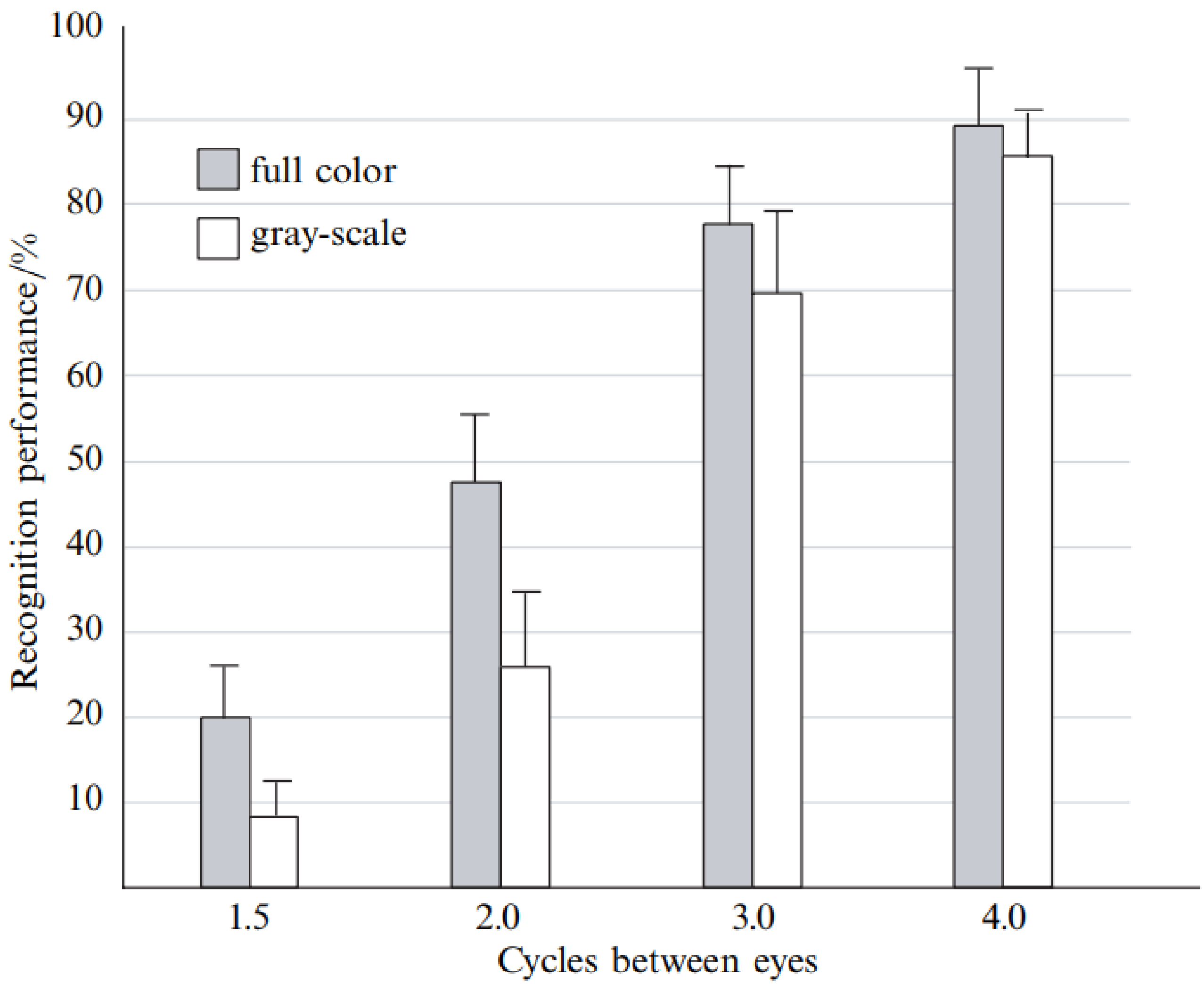
Color-based Computer Vision

- Color based image retrieval



Color-based Computer Vision

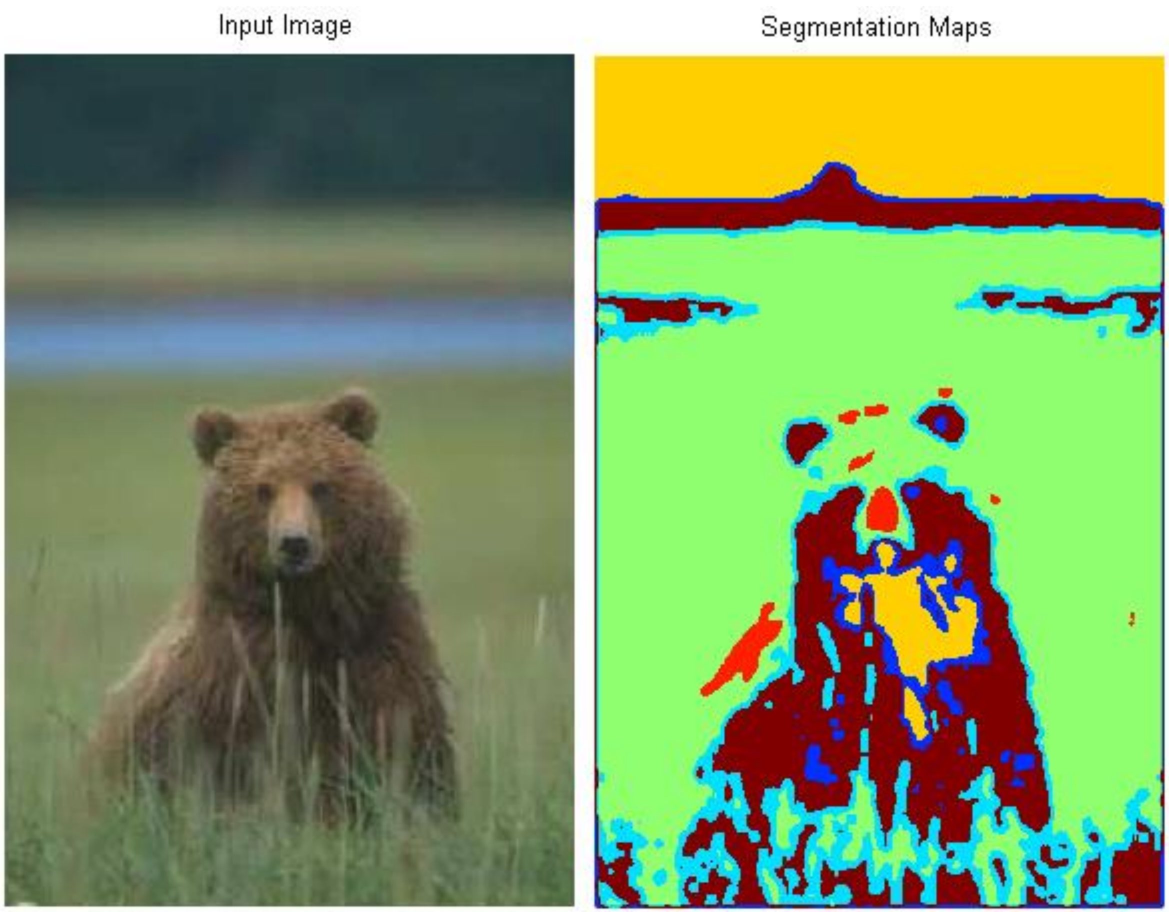
- Color-based Skin detection



A. W. Yip, P. Sinha, Contribution of color to face recognition, Perception 2002.

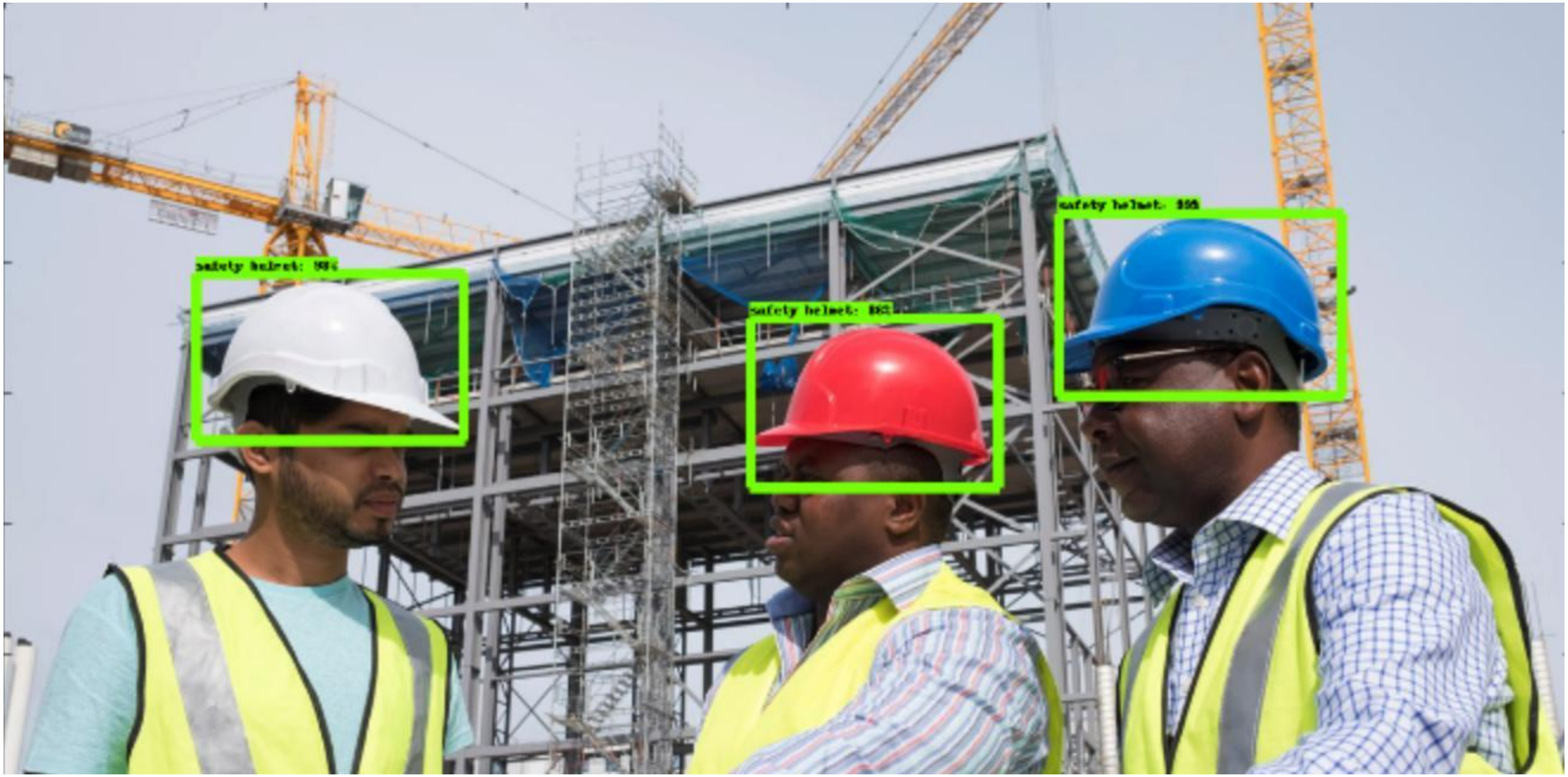
Color-based Computer Vision

- Color based segmentation

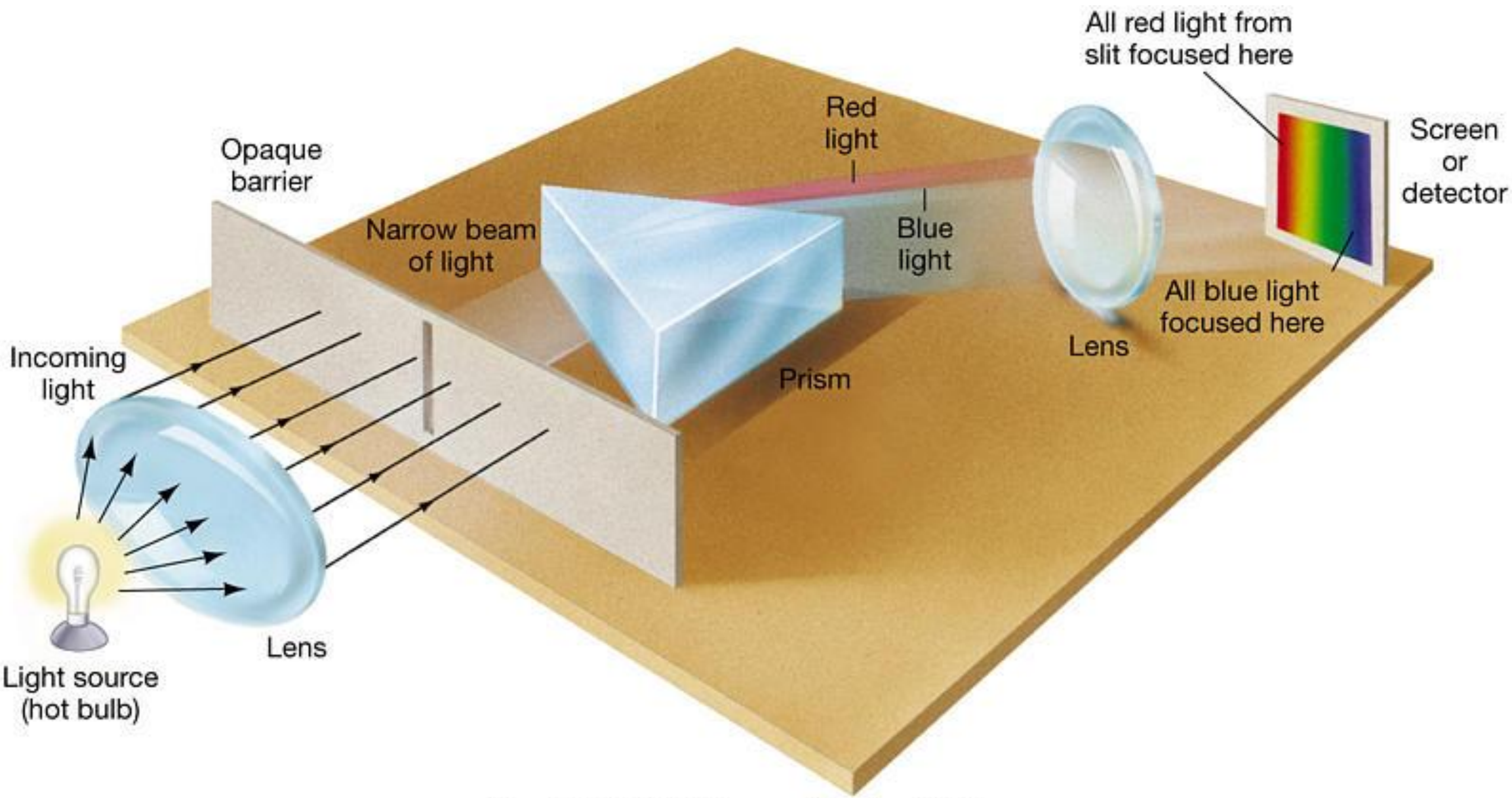


Color-based Computer Vision

Counting objects in different color

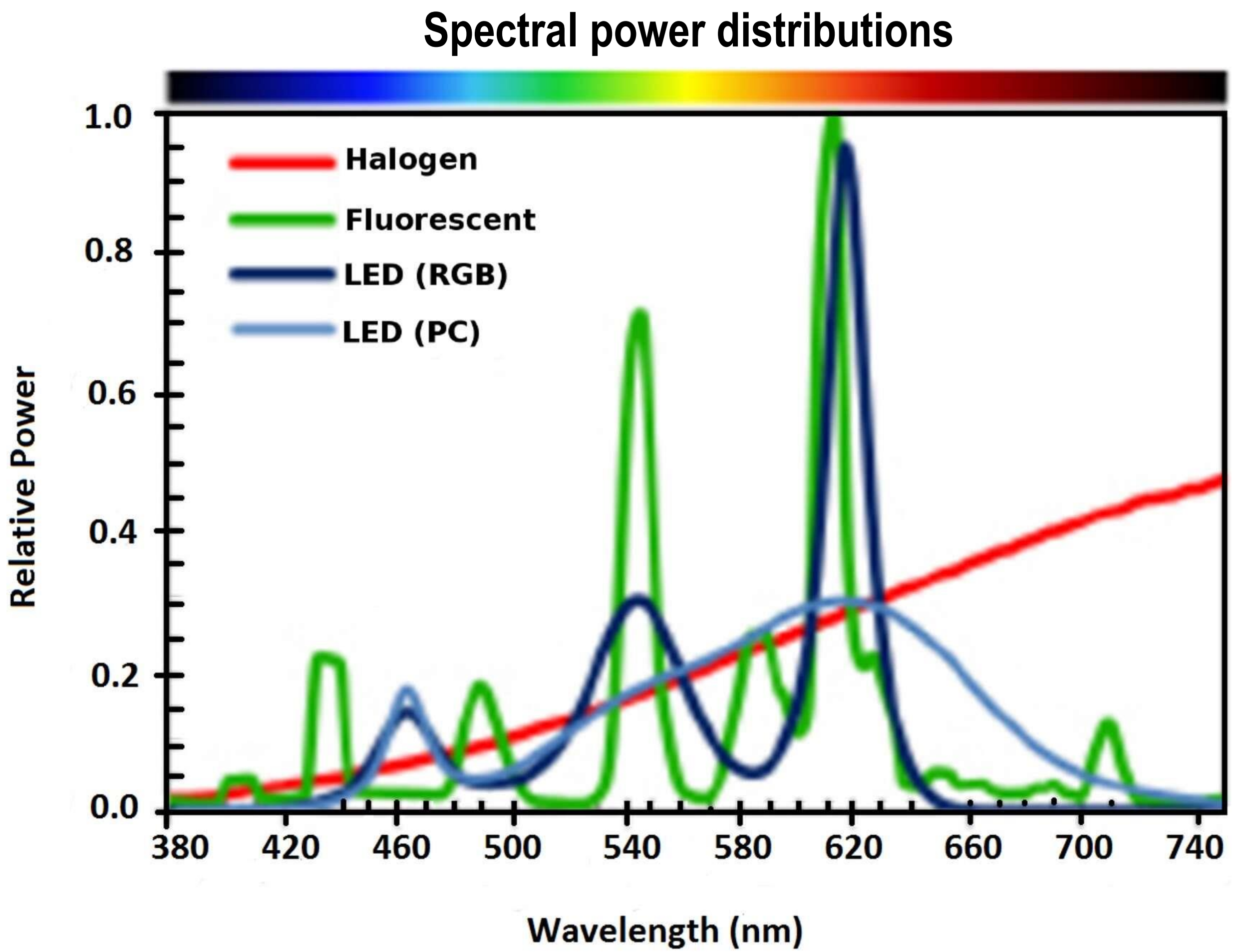


Measuring Spectra (Spectroscopy)



The Physic of Light

- Any source of light can be completely described physically by its spectrum: the amount of energy emitted (per time unit) at each wavelength 400 - 700 nm.

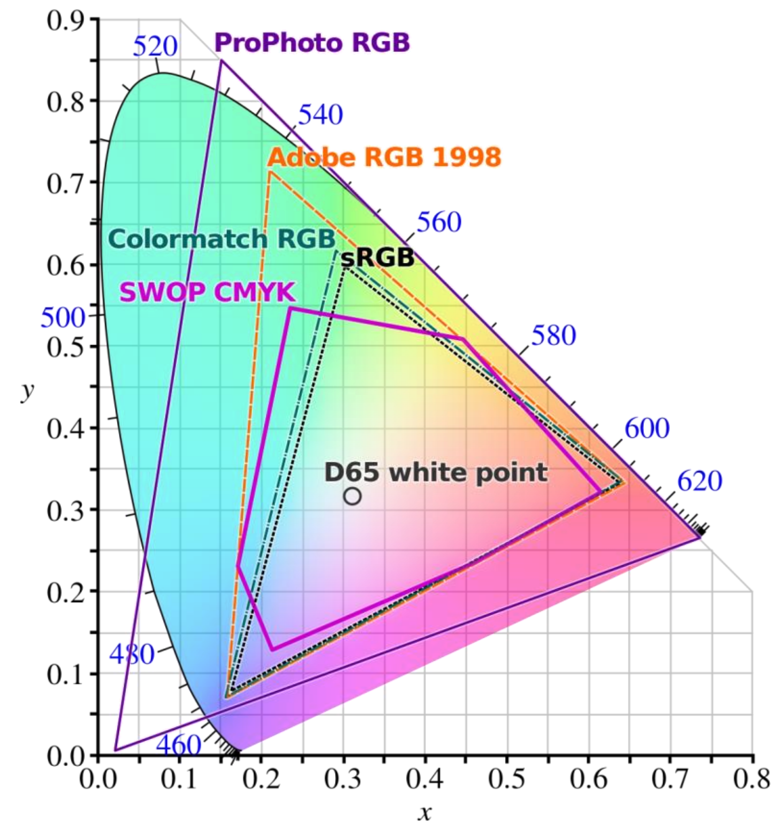


https://www.edn.com/electronics-blogs/led-diva/4460550/How-is-a-light-source-s-spectrum-measured-

Color Space

- Color space is a abstract mathematical model to describe the range of color
  - Use a common set of primaries/color matching functions
  - Create a sub-space of the color-space

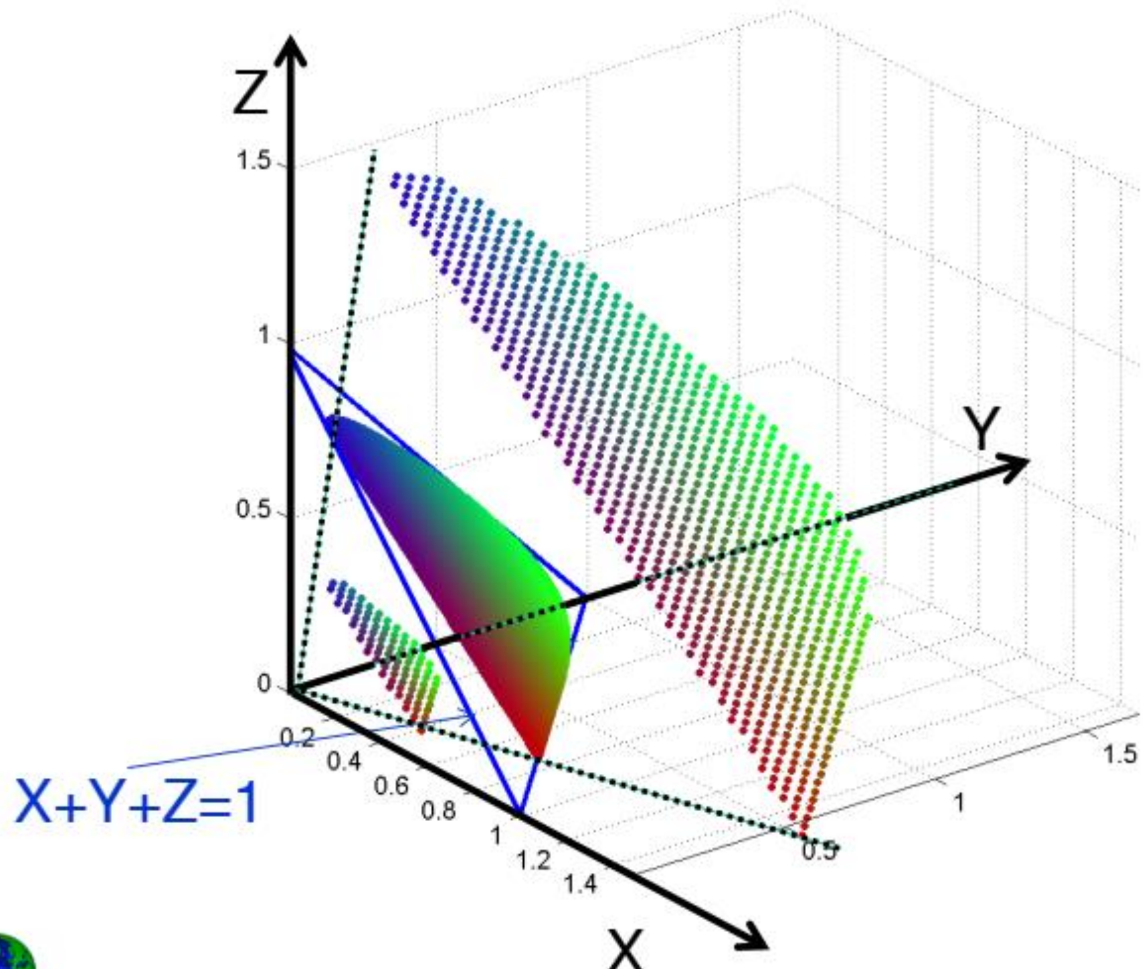
In order to count/represent color digitally



- Linear color space examples
  - RGB
  - CIE XYZ
- Non-linear color space
  - HSV (Hue-Saturation-Value)

Color Space

Every point in the cube represent one color

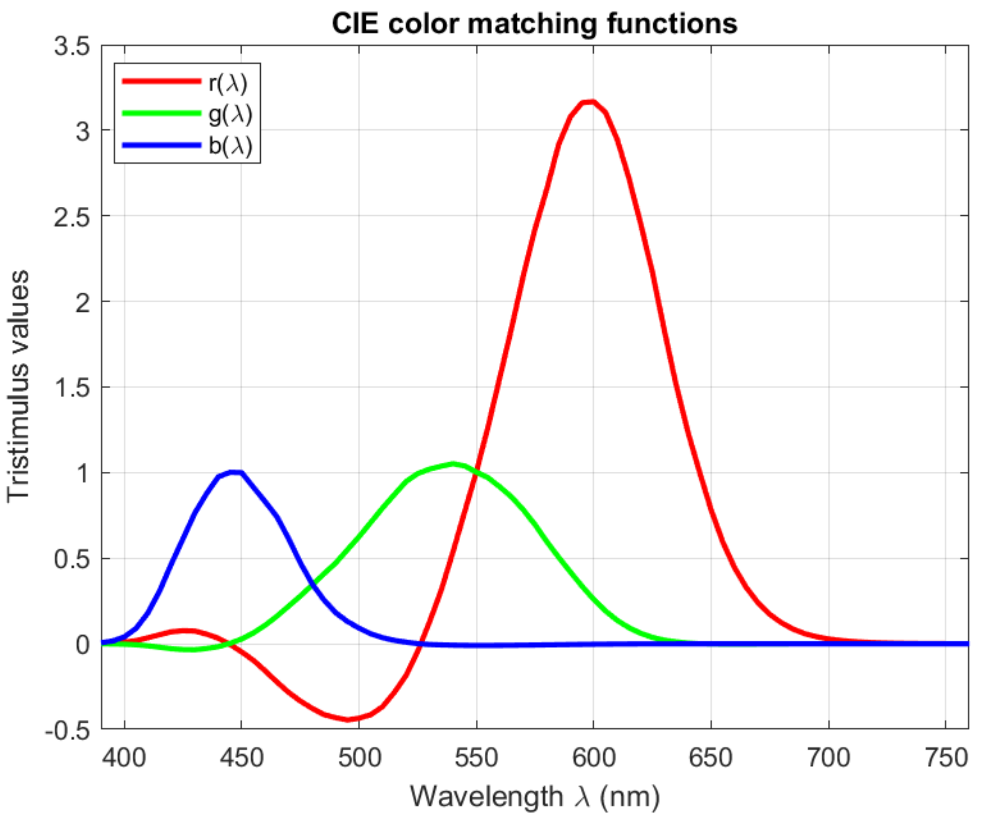


$$x = \frac{X}{X+Y+Z}$$

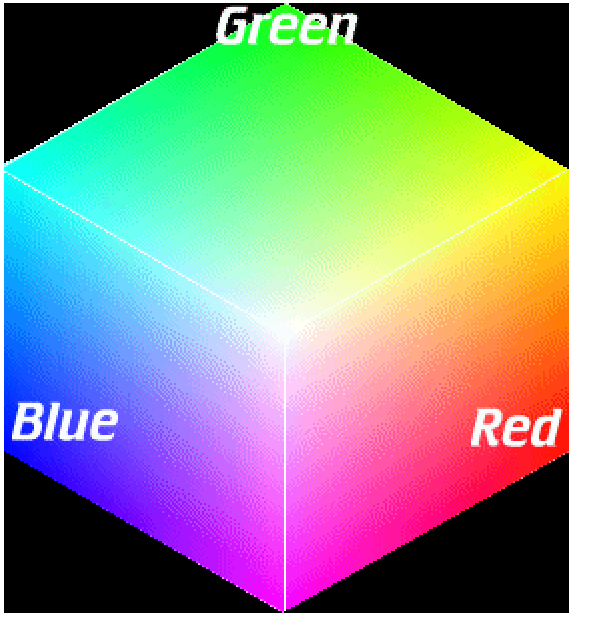
$$y = \frac{Y}{X+Y+Z}$$

RGB Color Space

- Single wavelength primaries (0 – 255 intensity)
  - Black: 0, 0, 0
  - White: 255, 255, 255



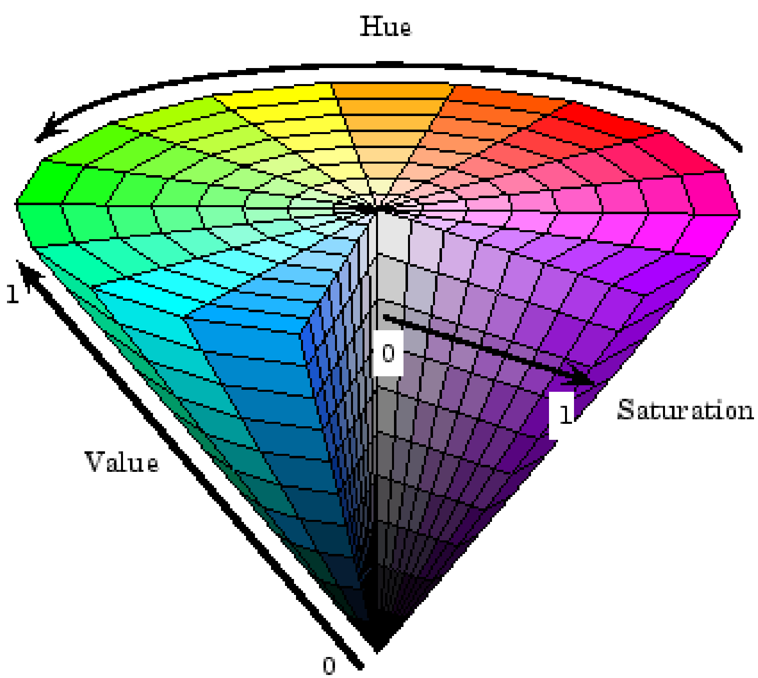
RGB Triple

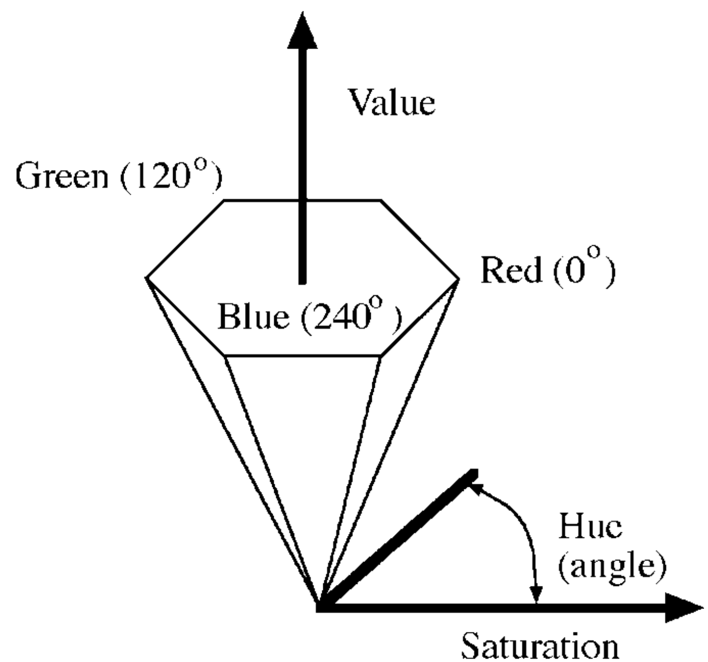


HSV Color Space

- Hue, Saturation, Value
  - Hue: color portion (0 – 360)
  - Saturation: amount of gray in a particular color 0 (gray) – 100% (primary color)
  - Value: Brightness: 0 (black) – 100 (white)

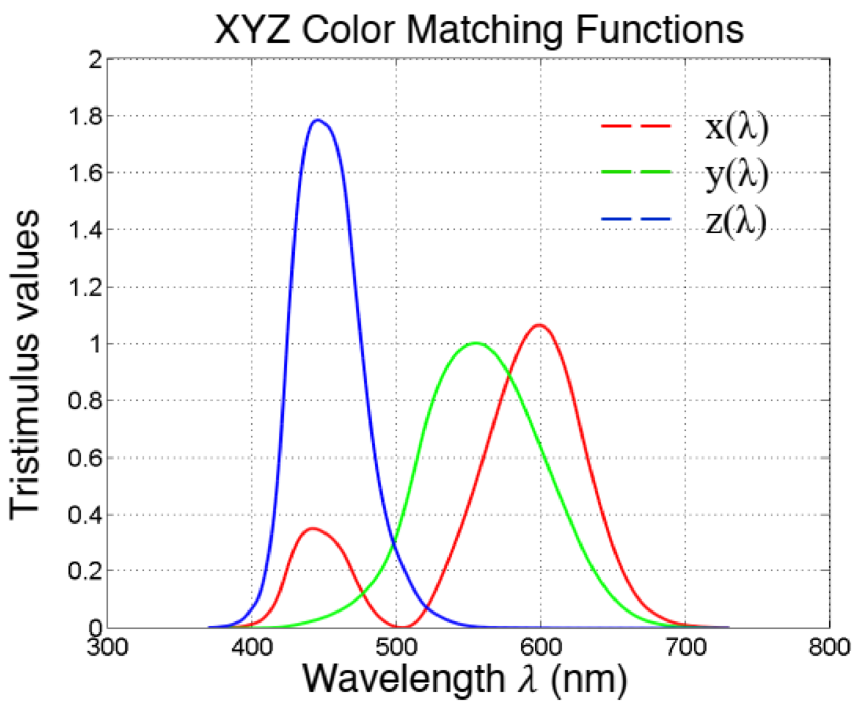
Easier to find the desired color





CIE 1931 XYZ Color System

Match all visible color as linear combinations with positive coefficient only

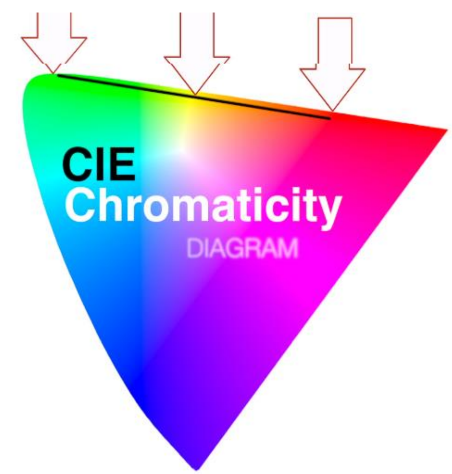


Properties:

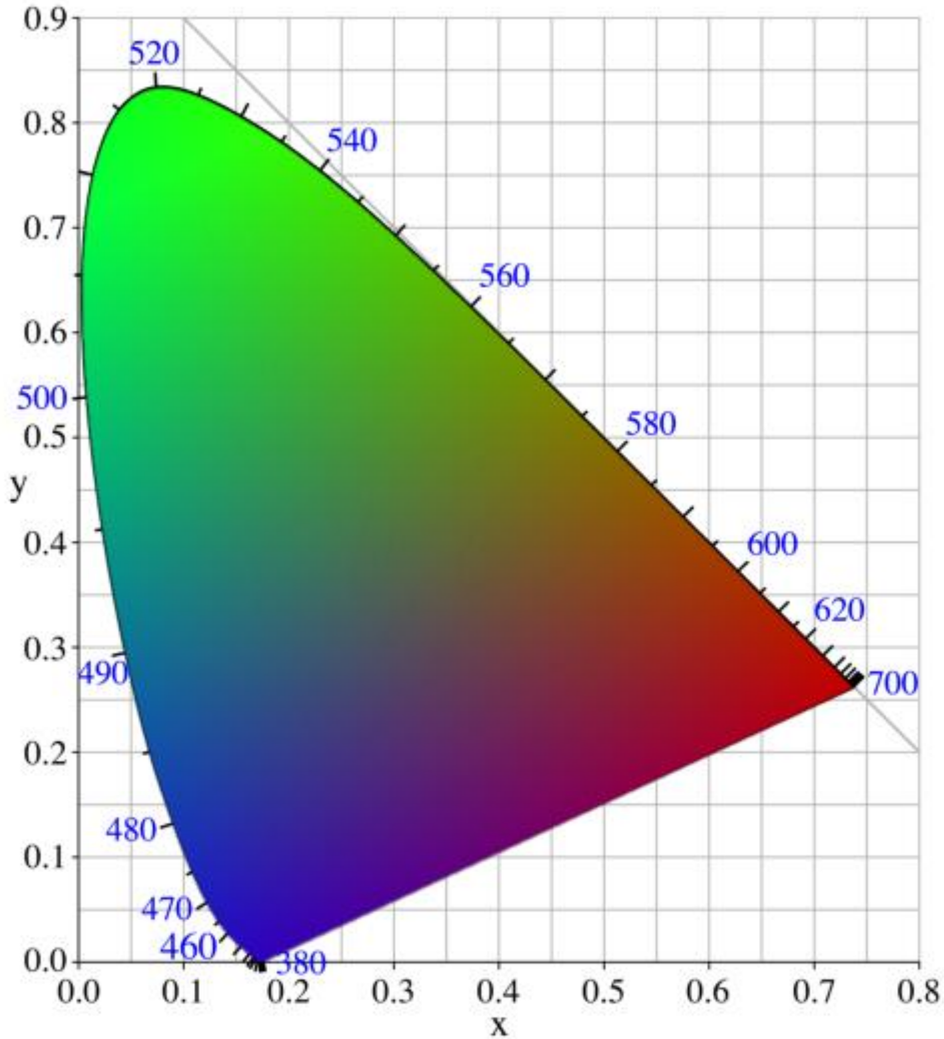
- All positive spectral matching functions

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} .490 & .310 & .200 \\ .177 & .813 & .011 \\ .000 & .010 & .990 \end{pmatrix} \begin{pmatrix} R_\lambda \\ G_\lambda \\ B_\lambda \end{pmatrix}$$

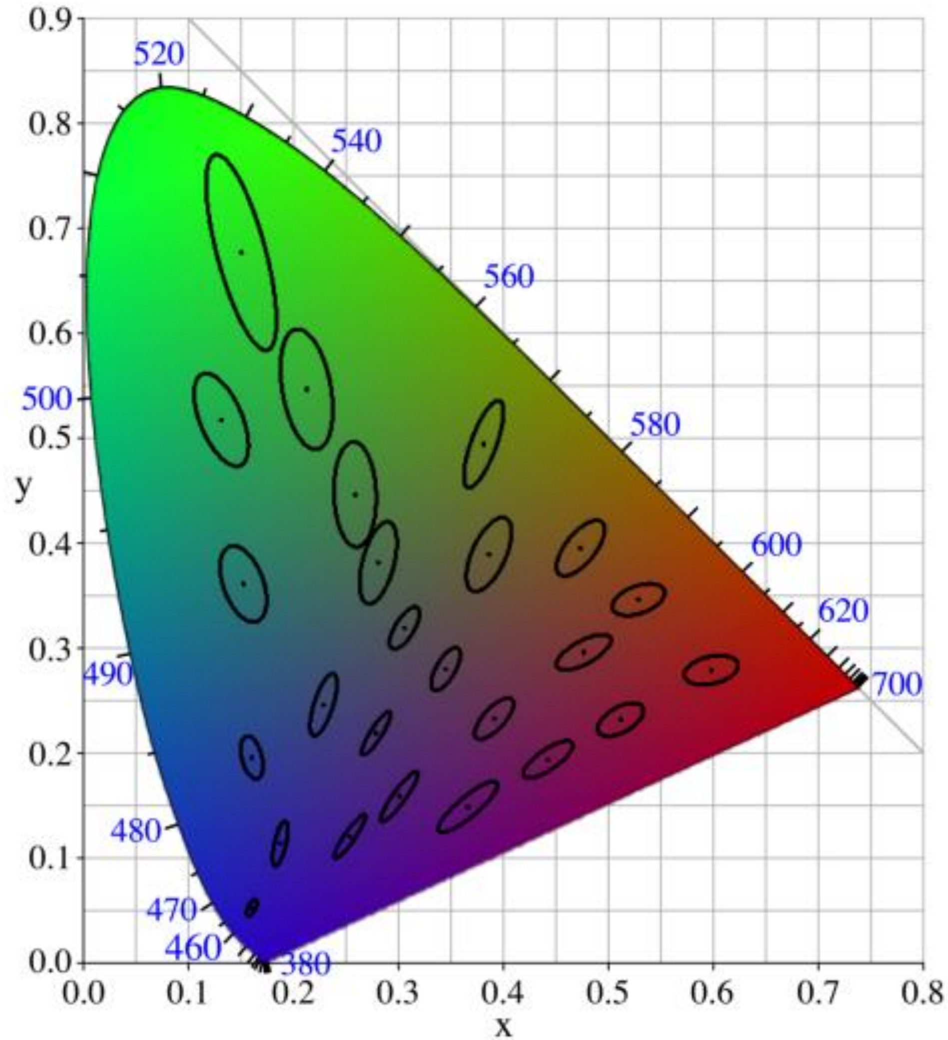
- Y corresponds to luminance
- Equal energy white: X=Y=Z
- Virtual primaries



CIE Chromaticity Diagram



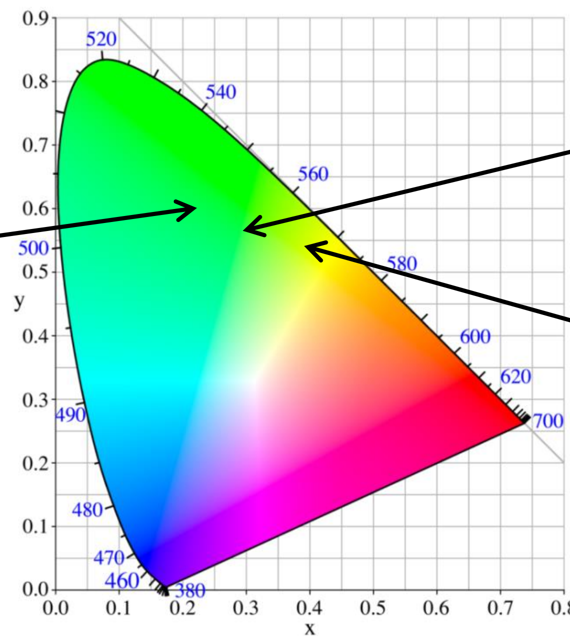
Perceptual non-uniformity of xy chromaticity



Not necessarily: CIE XYZ is not a uniform color space, so magnitude of differences in coordinates are poor indicator of color "distance".

Distances in Color Space

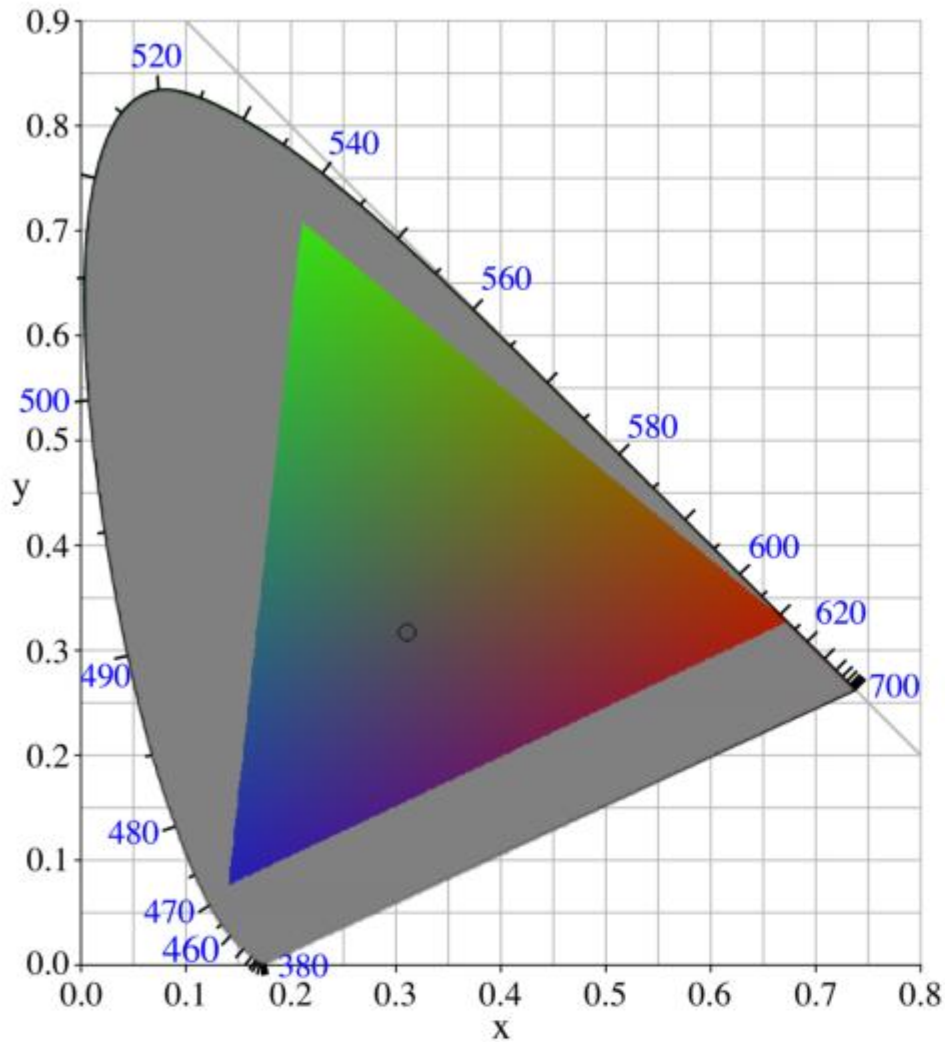
- Are distances between points in a color space perceptually meaningful?



Color Gamut

- **Color gamut** is a certain complete subset of colors within a color space
  - Different device has difference color gamut

Color Gamut



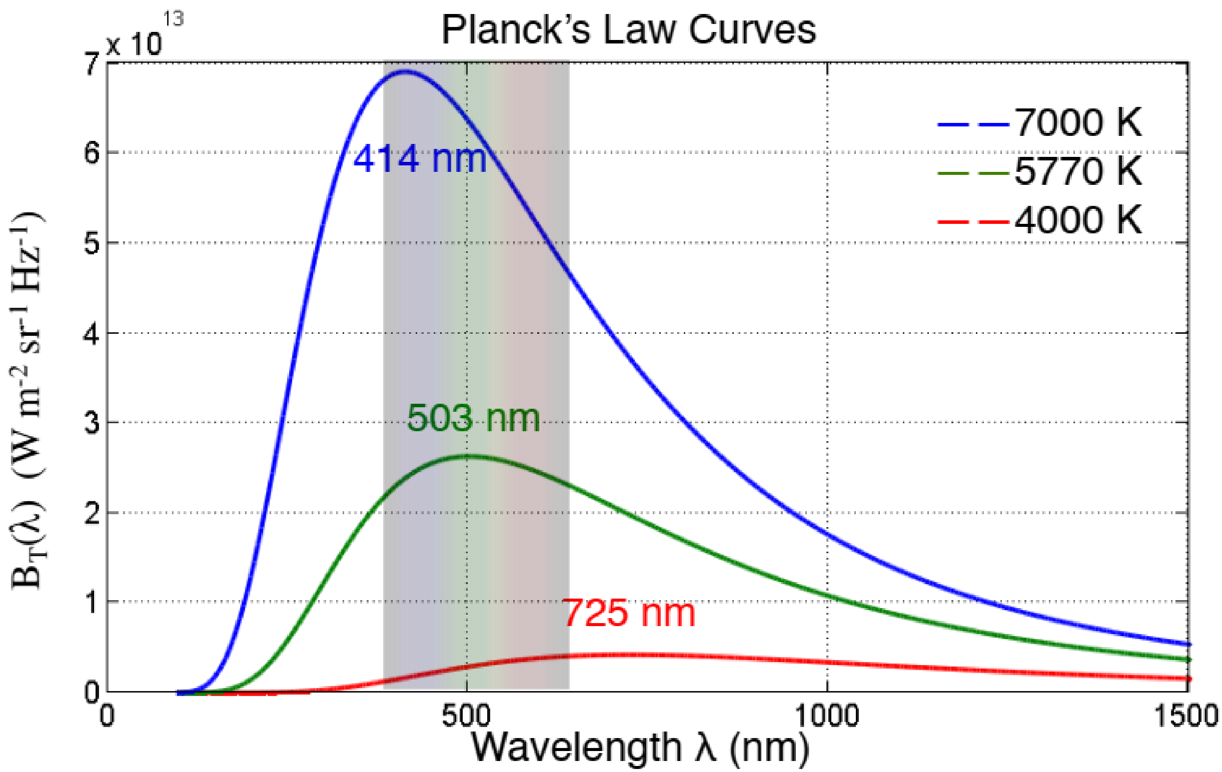
NTSC phosphors

R: x=0.67, y=0.33
G: x=0.21, y=0.71
B: x=0.14, y=0.08

Reference white:
x=0.31, y=0.32
Illuminant C

Blackbody radiation

Color temperature of a light source is the temperature of an ideal black-body radiator that radiates light of a color comparable to that of the light source.



Planck's Law, 1900

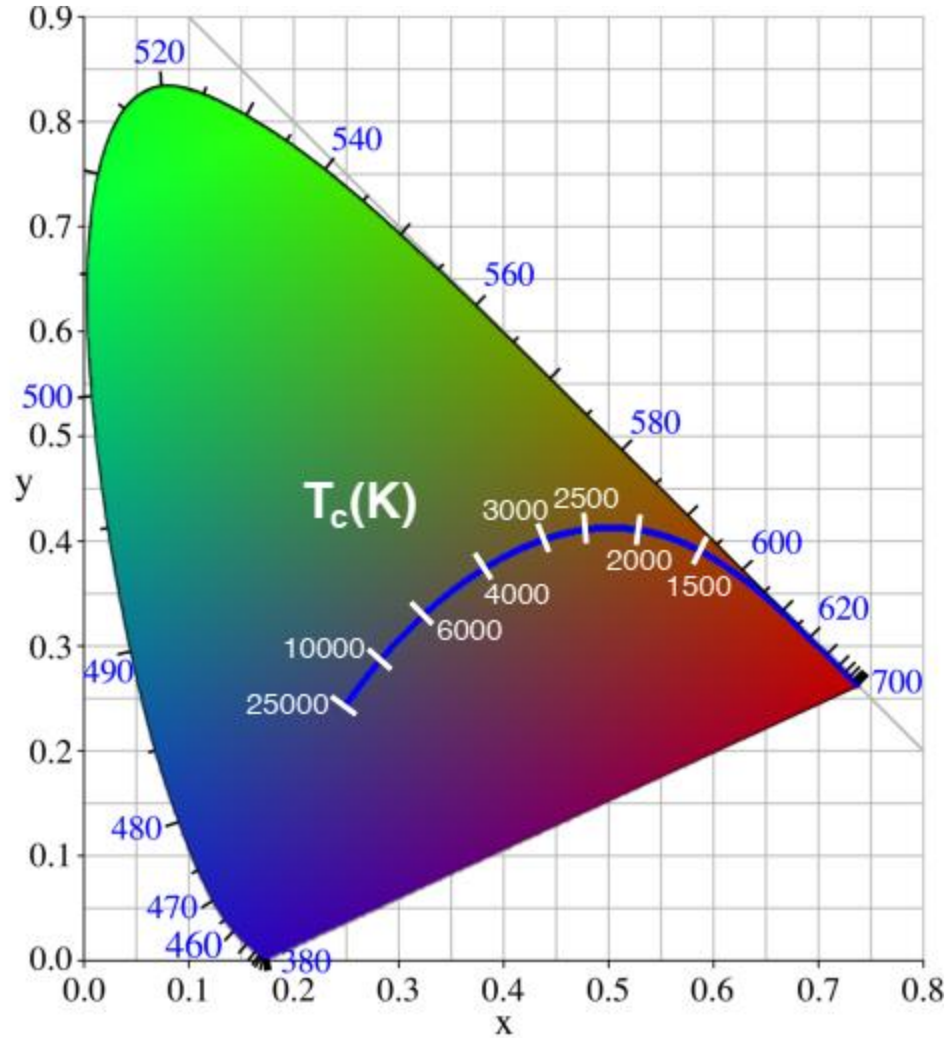
$$B_T(\lambda) = \frac{2hc^2 / \lambda^5}{e^{hc/\lambda kT} - 1}$$

Wien's Law

$$\lambda_{peak}[nm] = \frac{2{,}900{,}000}{T[K]}$$

White at different color temperatures

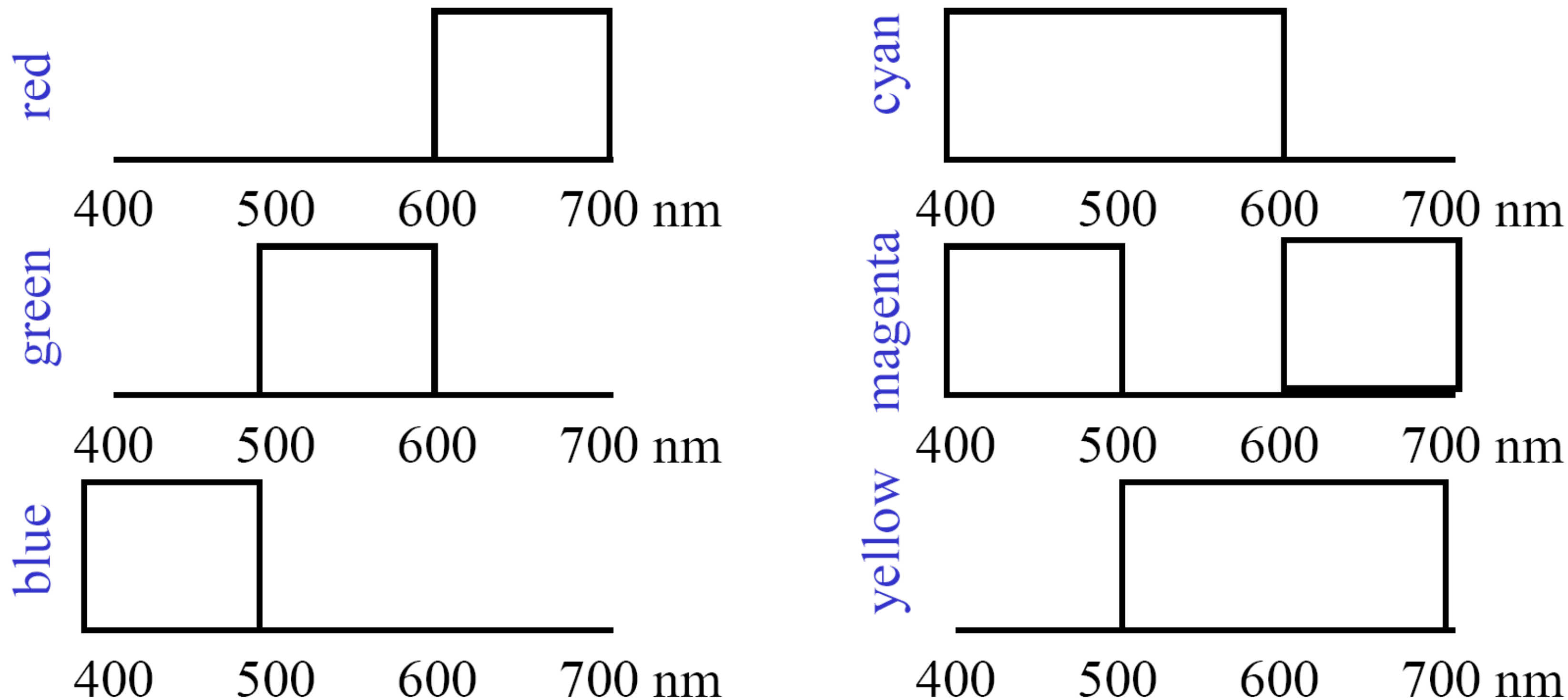
The CIE 1931 x,y chromaticity space, also showing the chromaticities of black-body light sources of various temperatures (Planckian locus), and lines of constant correlated color temperature.

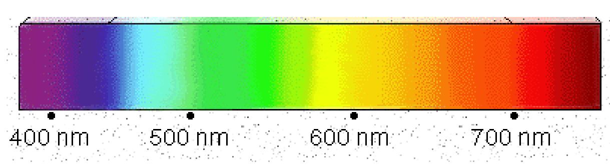


https://en.wikipedia.org/wiki/Color_temperature

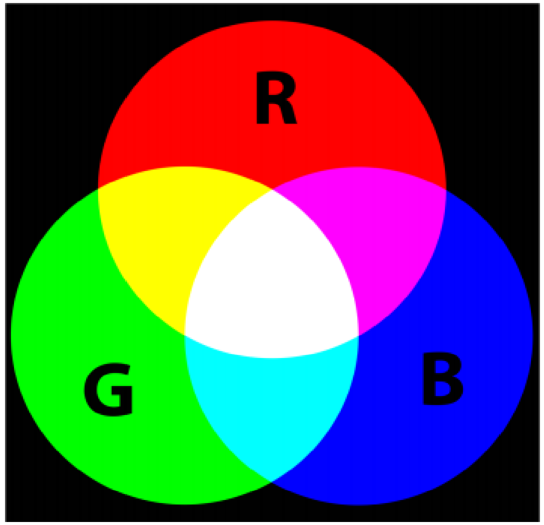
Color mixing

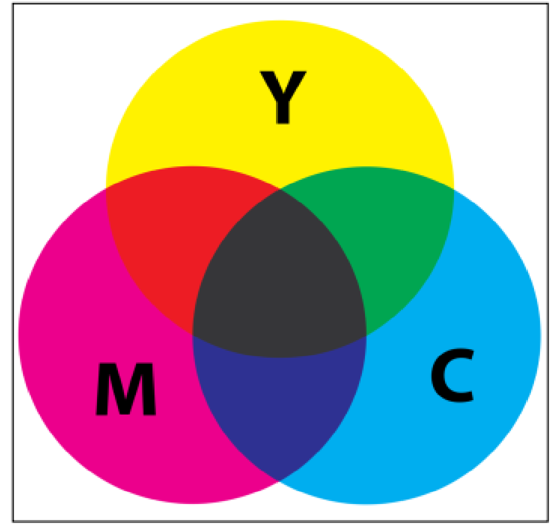
Cartoon spectra for color names:





Additive vs. Subtractive Color Mixing





- Colors combine by adding color spectra
- Light *adds* to black.

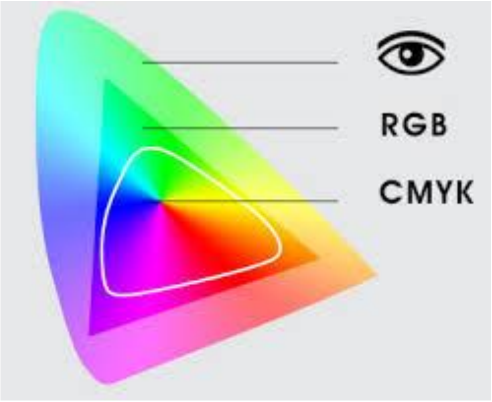
  - *Monitor/display*
  - *Projector*

- Colors combine by multiplying color spectra.
- Pigments remove color from incident light (white)

  - *Printing on paper*
  - *Crayons*
  - *Photographic film*

Why Subtractive Model?

- CMYK has smaller color space than RGB
- Printer use CMYK Ink instead of RGB



CMYK are lighter color (Cyan, magenta, yellow) than red, green and blue

- Able to cover most lighter color range
- Monitor: combining color is good at dark screen, emit color light is ok
- Print: Ink absorb and reflect color (not reflect), print on white paper

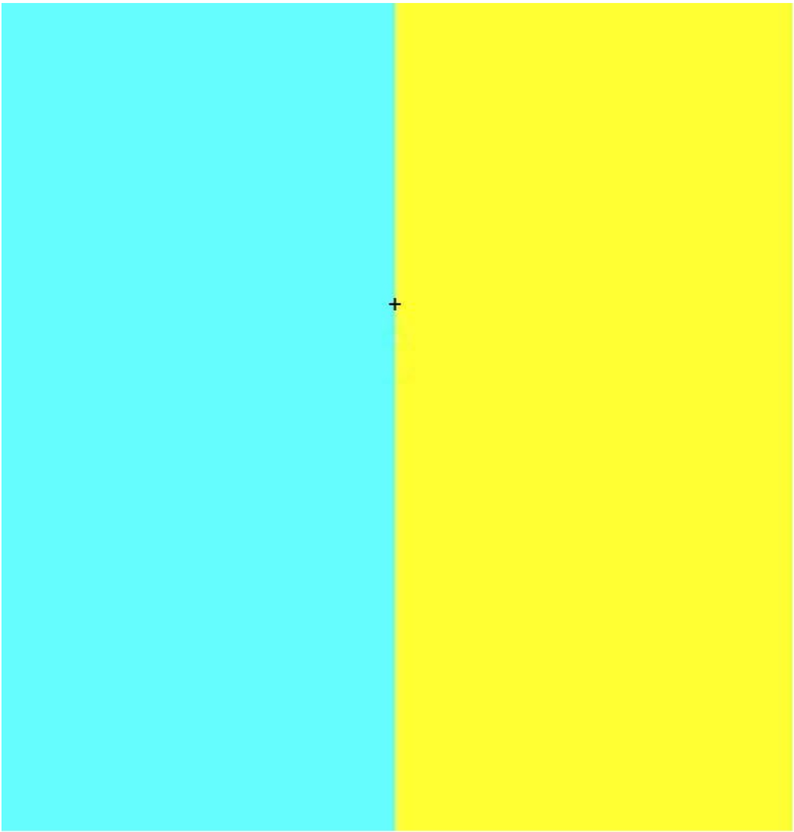
Color Contrast

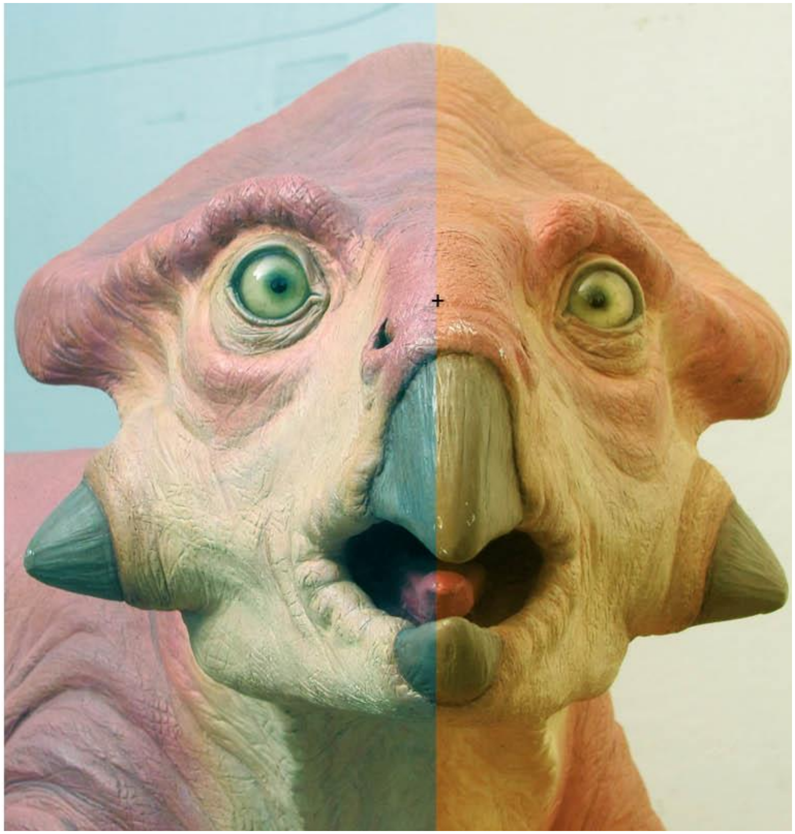
- How brain process incoming visual signal
  - Human need to survive
  - → quickly adapt/identify the dangers
  - → require rapidly refocus the attention

- Human eye automatically
  - Refocusing the image by adaptive to the contrast, brightness or movement

Chromatic adaptation

- Chromatic adaptation: HVS adjust to the change in illumination to preserve the appetence of object colors



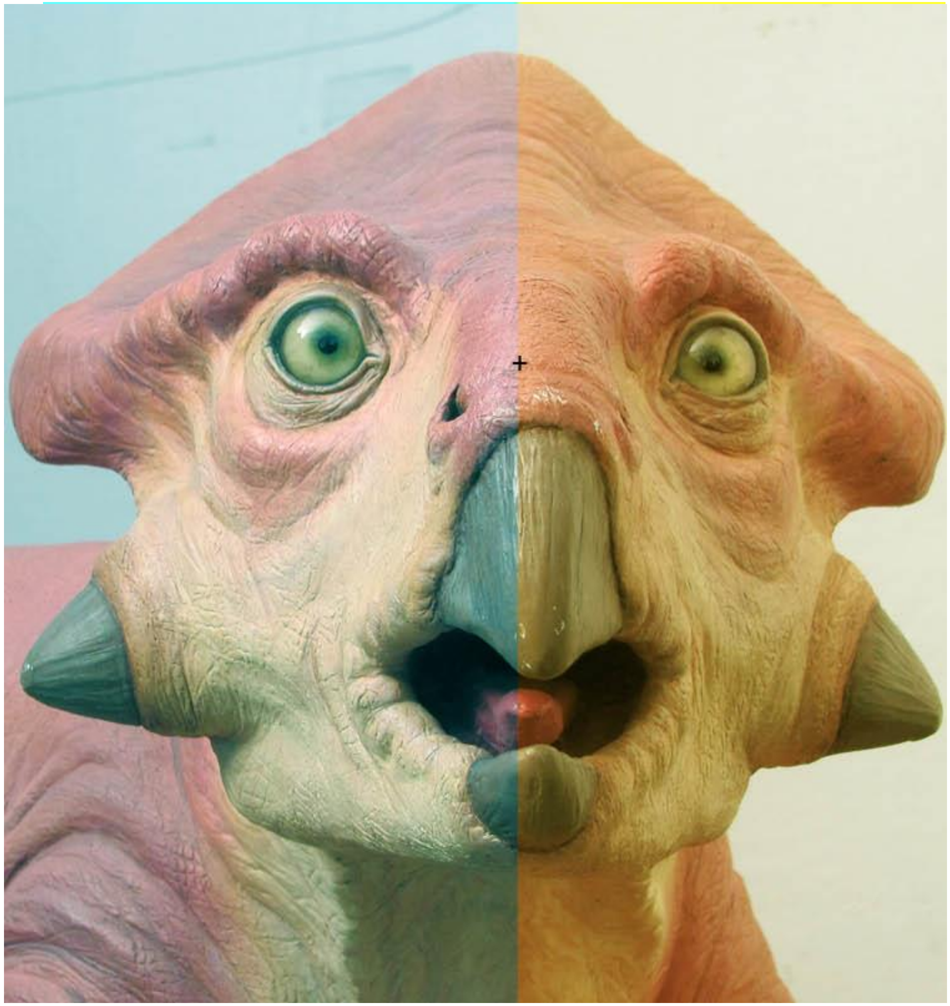


What do you see from the dinosaur Bix on the right?
Do you see the color split at the middle with cyan (left) and yellowish (right) ?

Chromatic adaptation

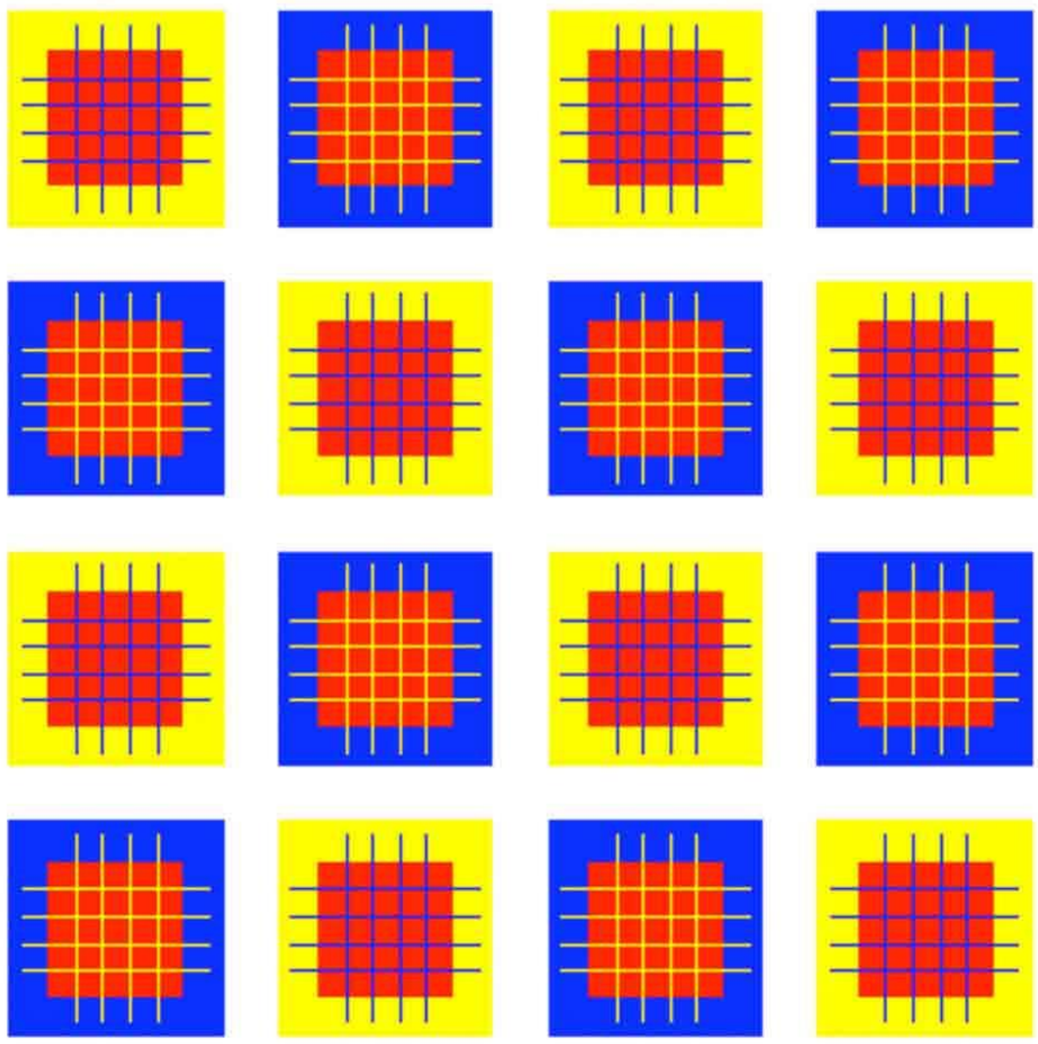
- Chromatic adaptation

Stare at “+” for 30 seconds



Chromatic adaptation

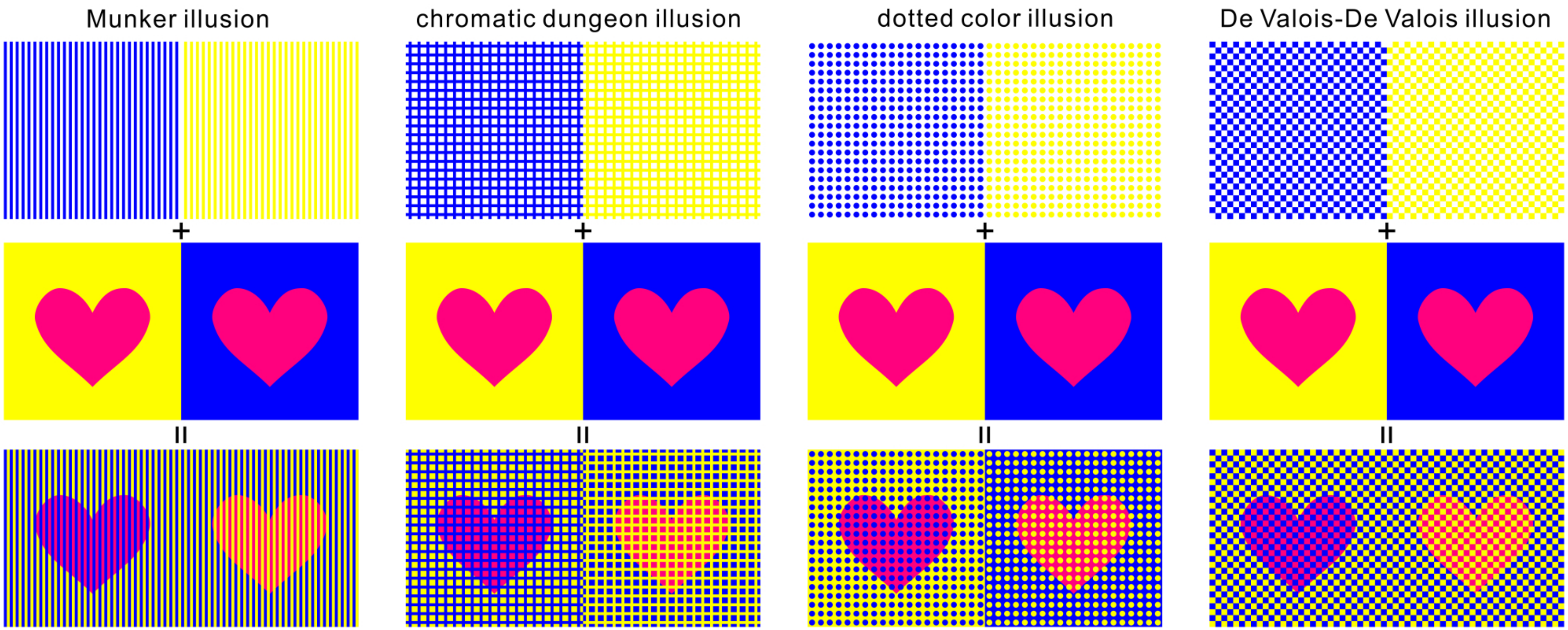
Are the squares inside the blue and yellow squares all the same color?



Bezold effect

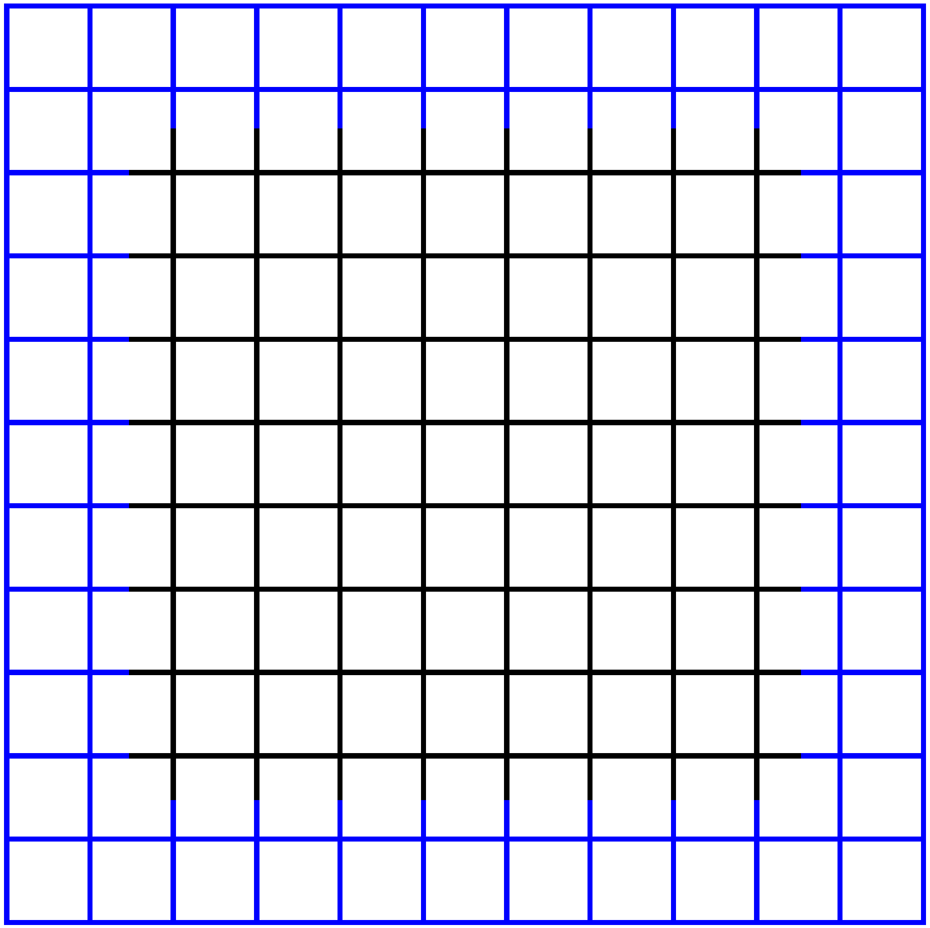
Color is perceived differently depending on its relation to adjacent colors

Chromatic adaptation



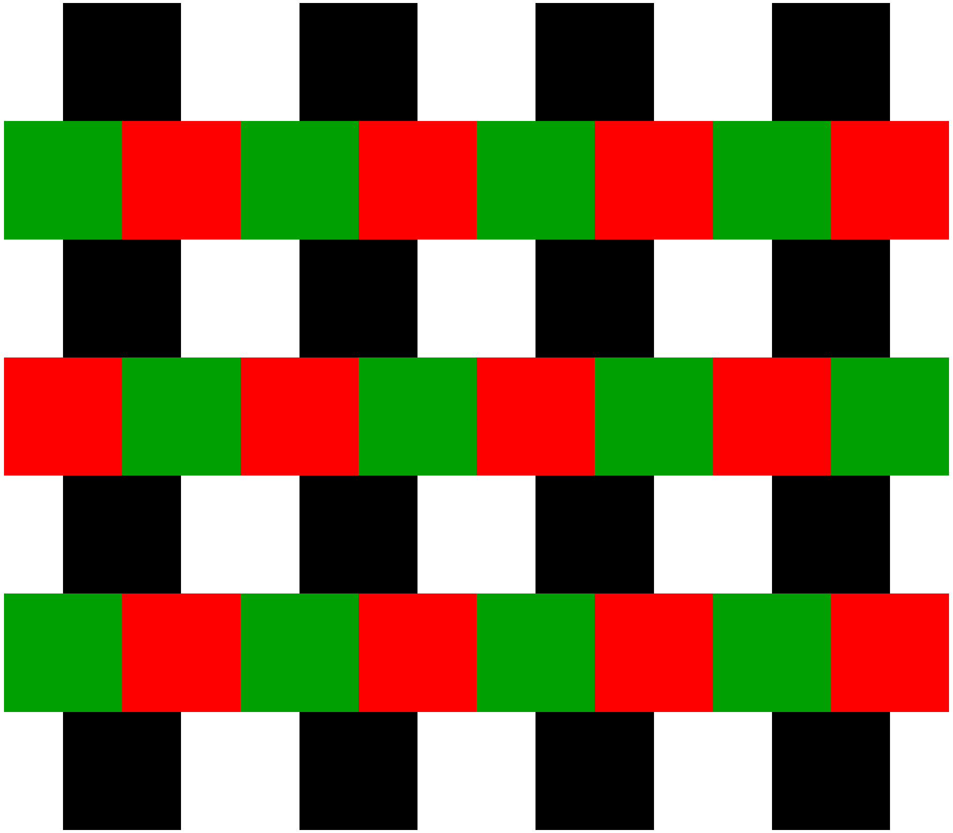
Chromatic adaptation

A stain

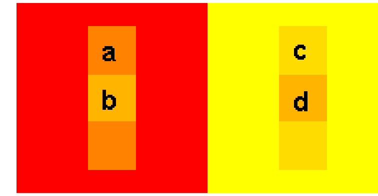


Chromatic adaptation

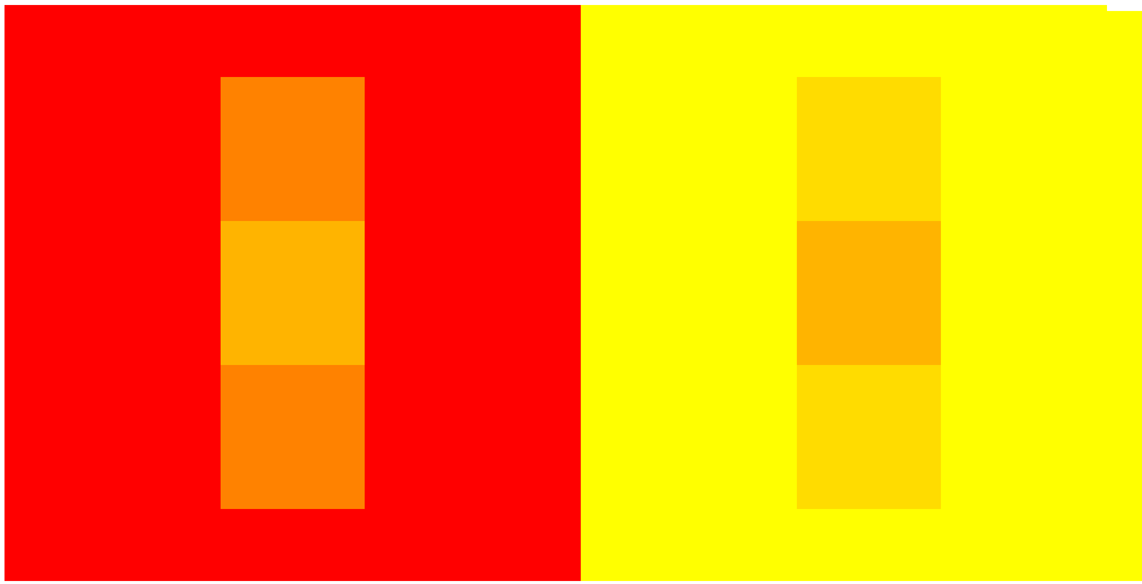
The Shonan-shinjuku line



Chromatic adaptation



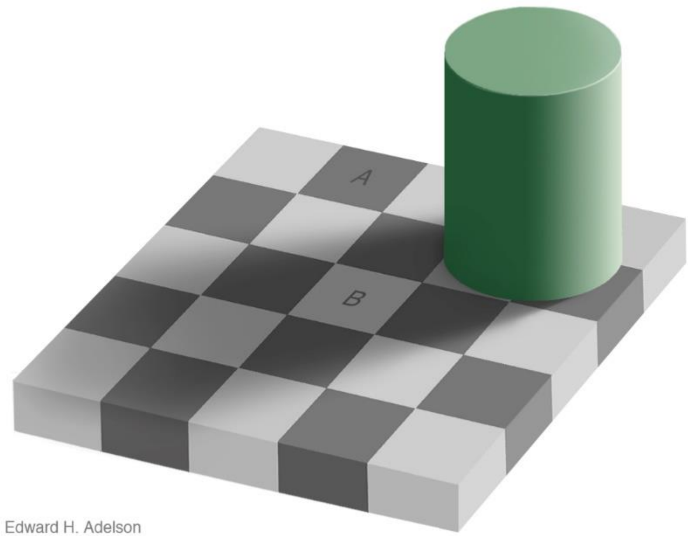
"Enhanced color contrast"

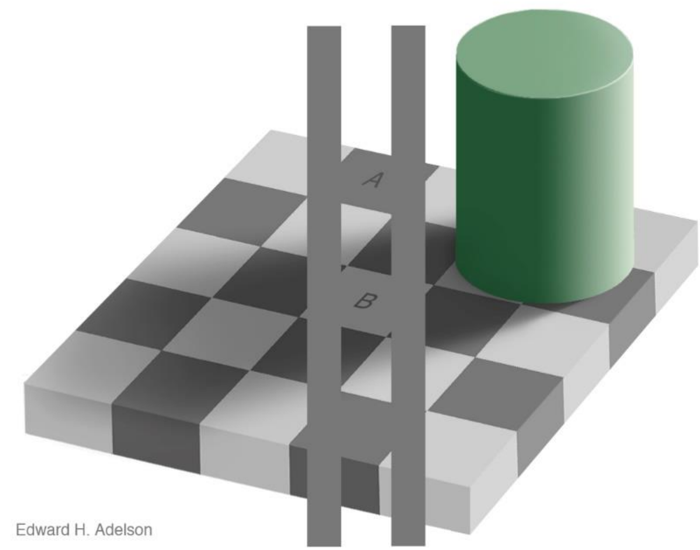


It appears that a = d or b = c in color, but actually b = d.

Chromatic adaptation

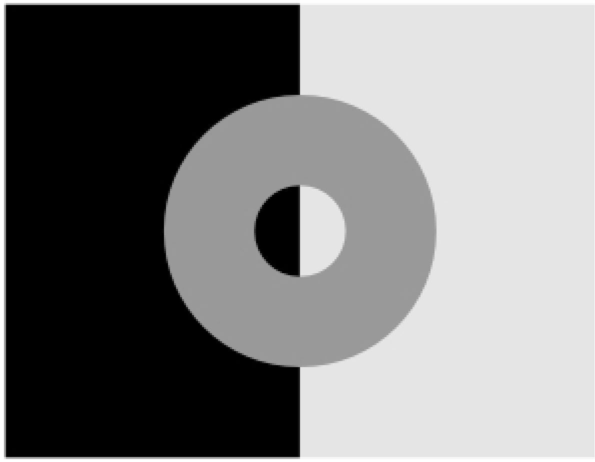
- Brightness perception

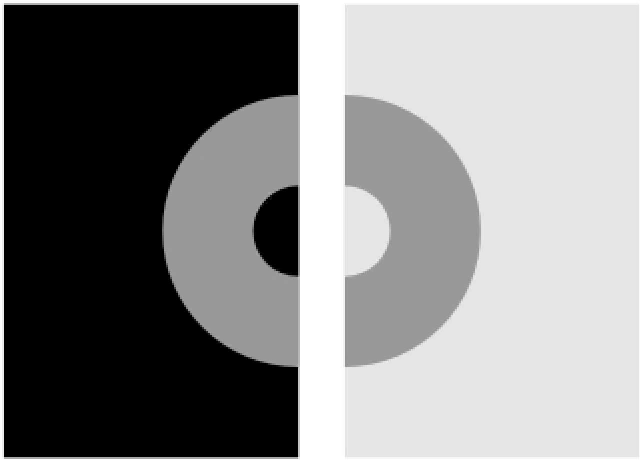


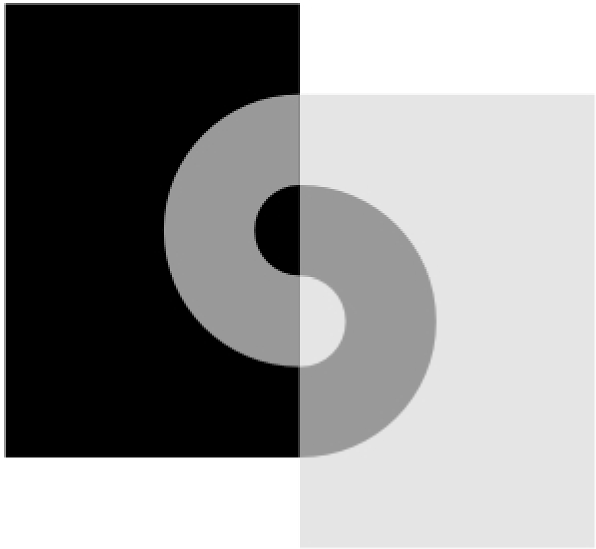


Chromatic adaptation

- Brightness perception







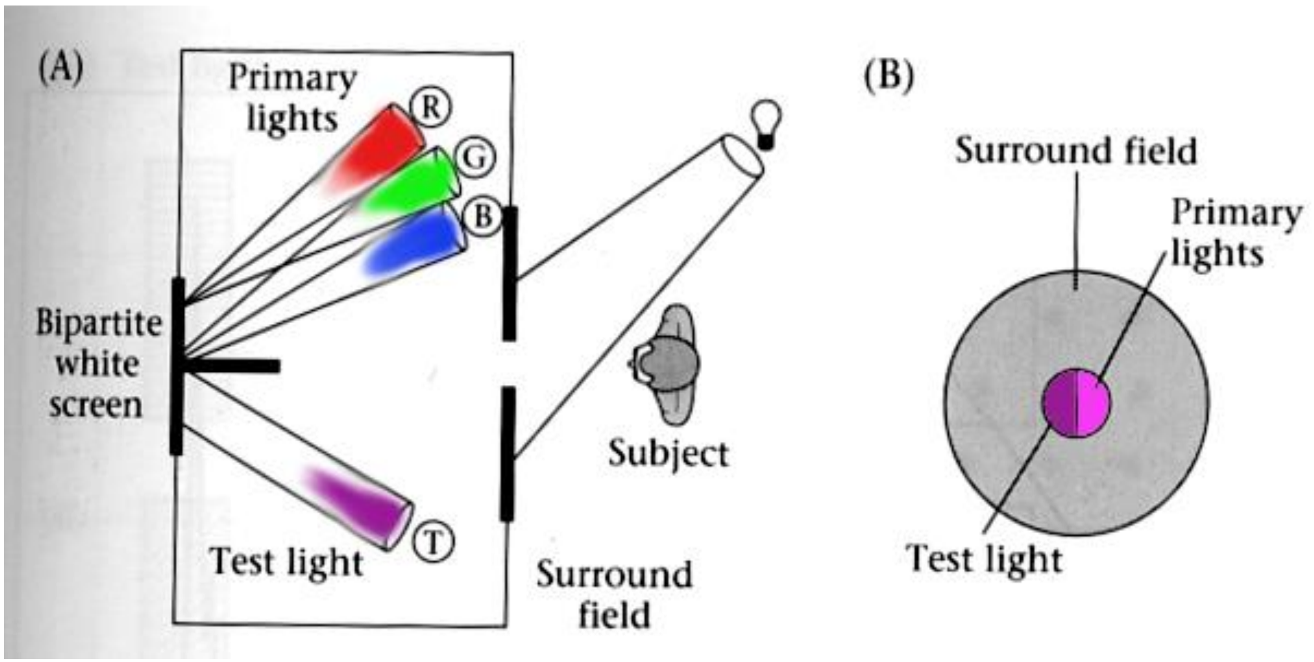
Do people perceive the same color?

- Important to reproduce color reliably
  - Commercial products, digital imaging/art
- Only a few color names recognized widely
  - English ~11: black, blue, brown, grey, green, orange, pink, purple, red, white, and yellow
- We need to specify numerically.
- Question: What spectral radiances produce the same response from people un der simple viewing conditions?

Color Matching

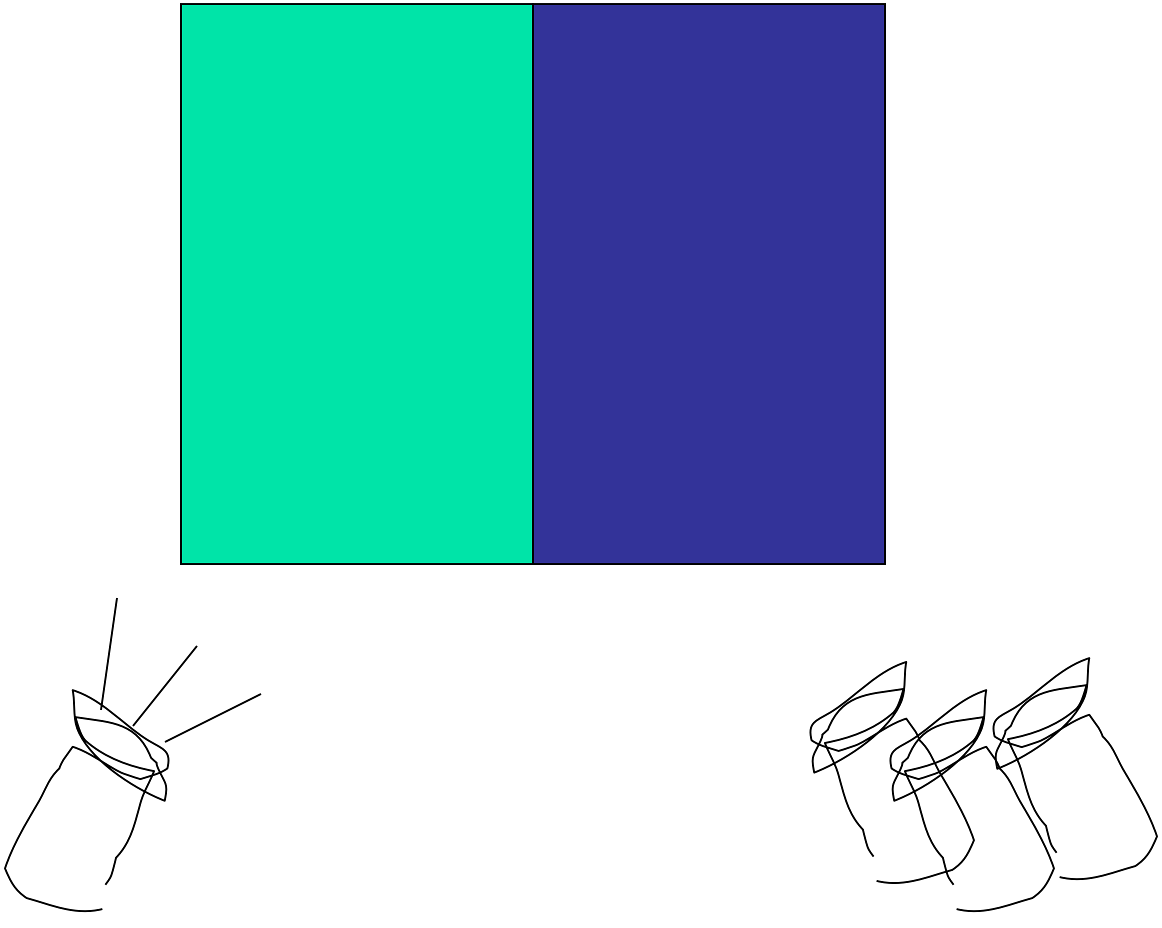
Color Matching

- **Goal**: find spectral radiances produce same response in human observers.
- **Assumption**: simple viewing conditions, test light alone affects perception
  - Ignoring additional factors of adaptation, complex surrounding scenes, etc.



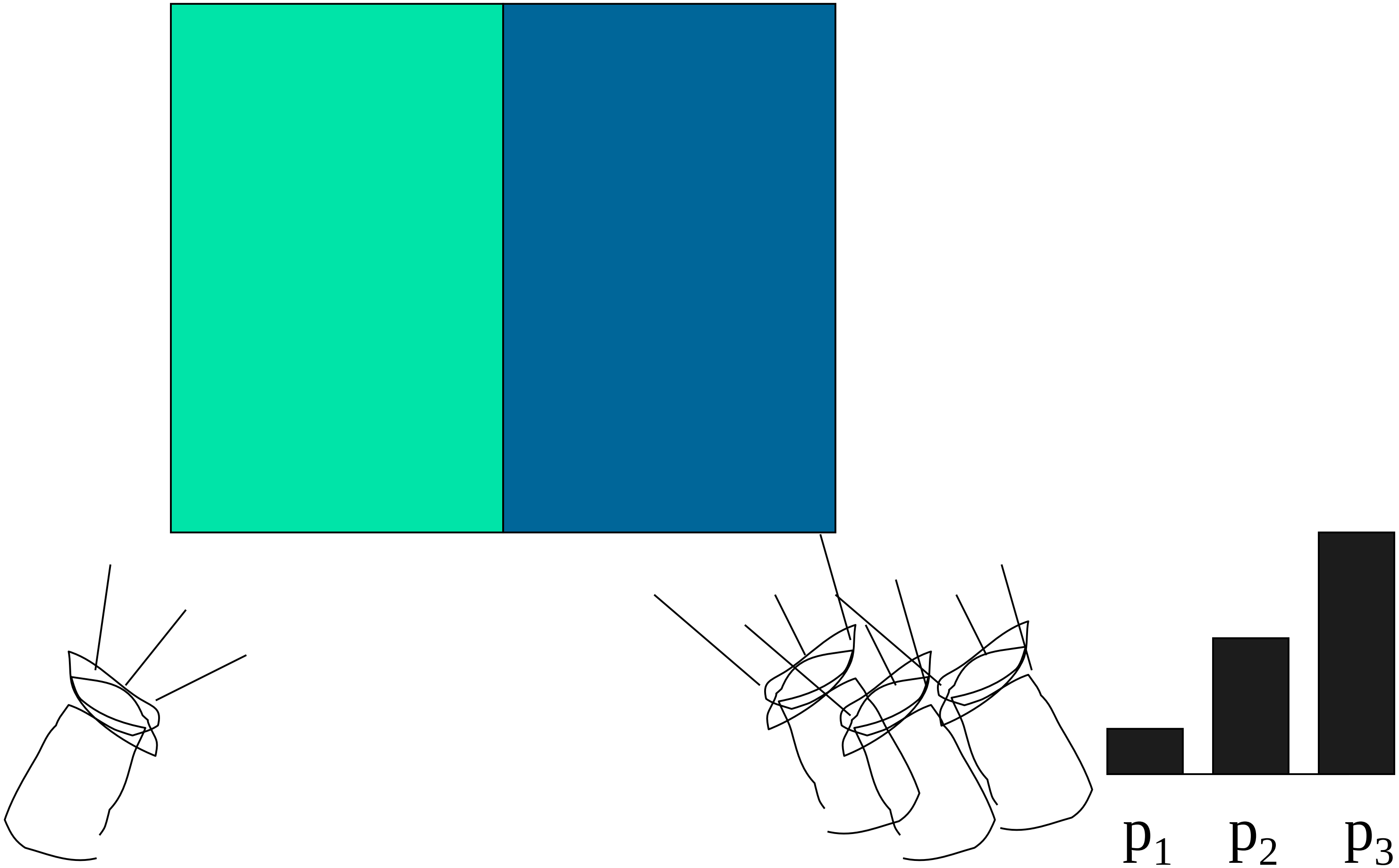
Observer adjusts weight (intensity) for primary lights (fixed SPD's) to match appearance of test light.

Color Matching Experiment

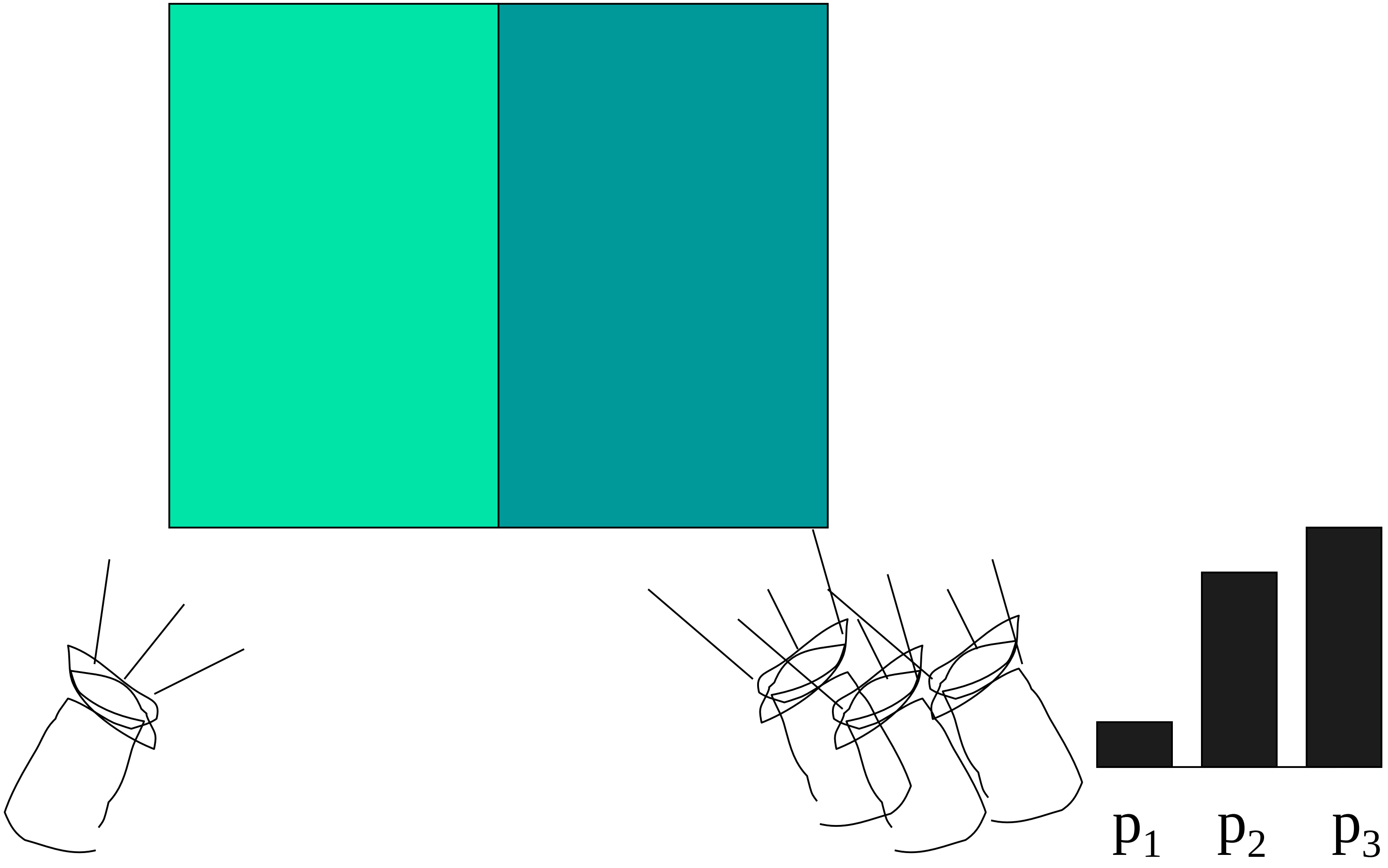


Slide credit: W. Freeman

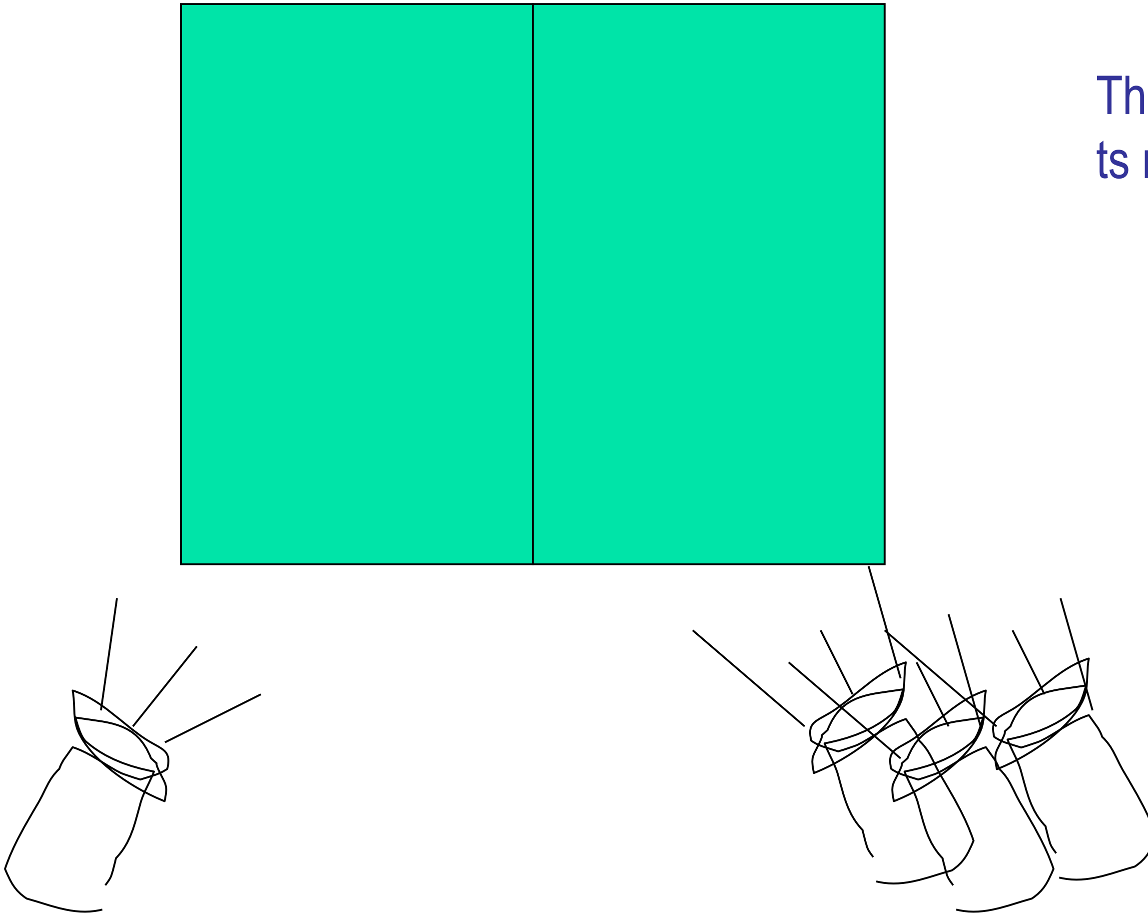
Color Matching Experiment



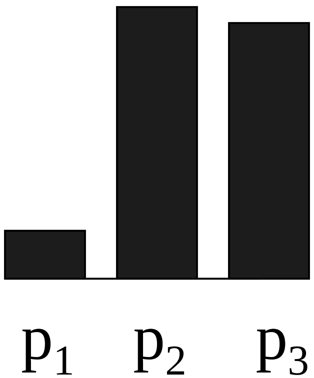
Color Matching Experiment



Color Matching Experiment

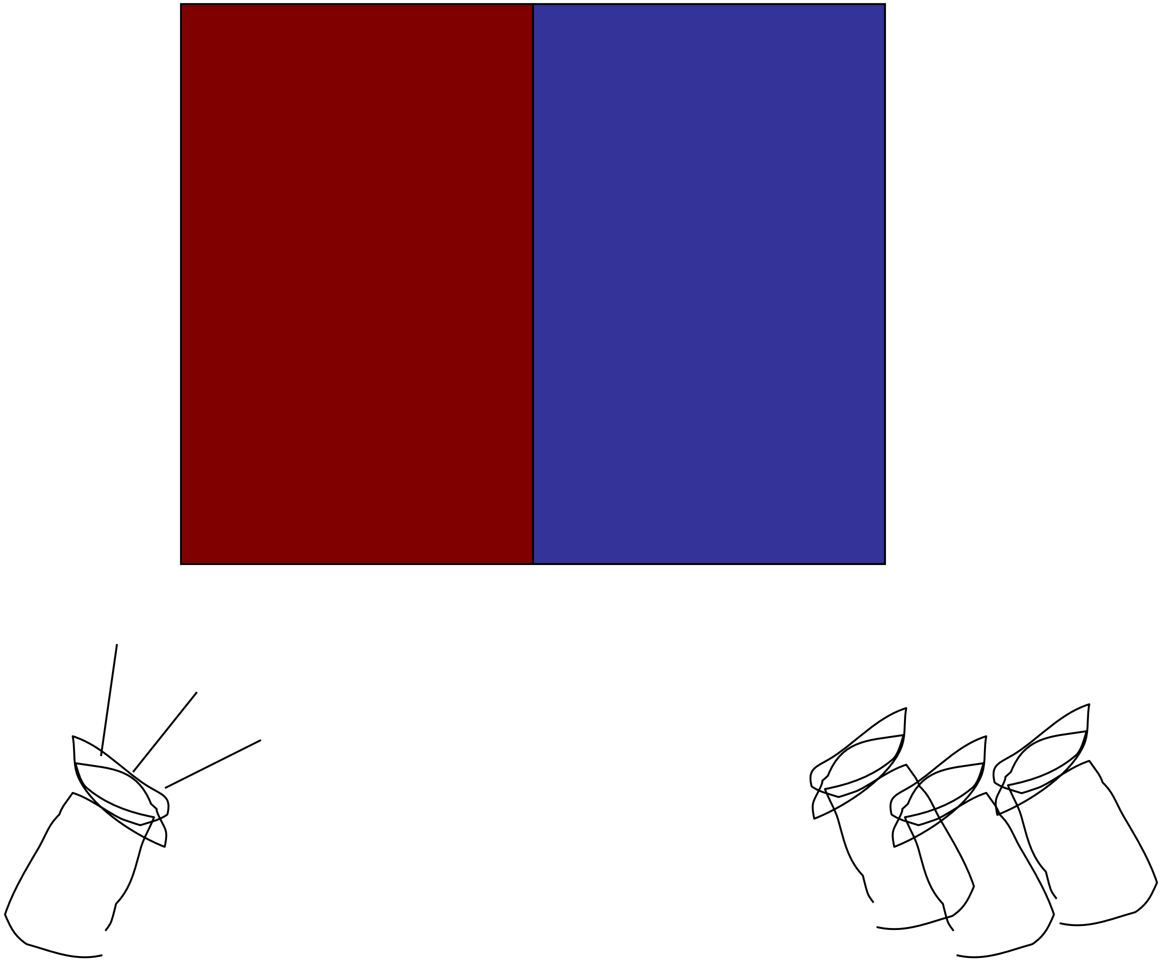


The primary color amounts needed for a match

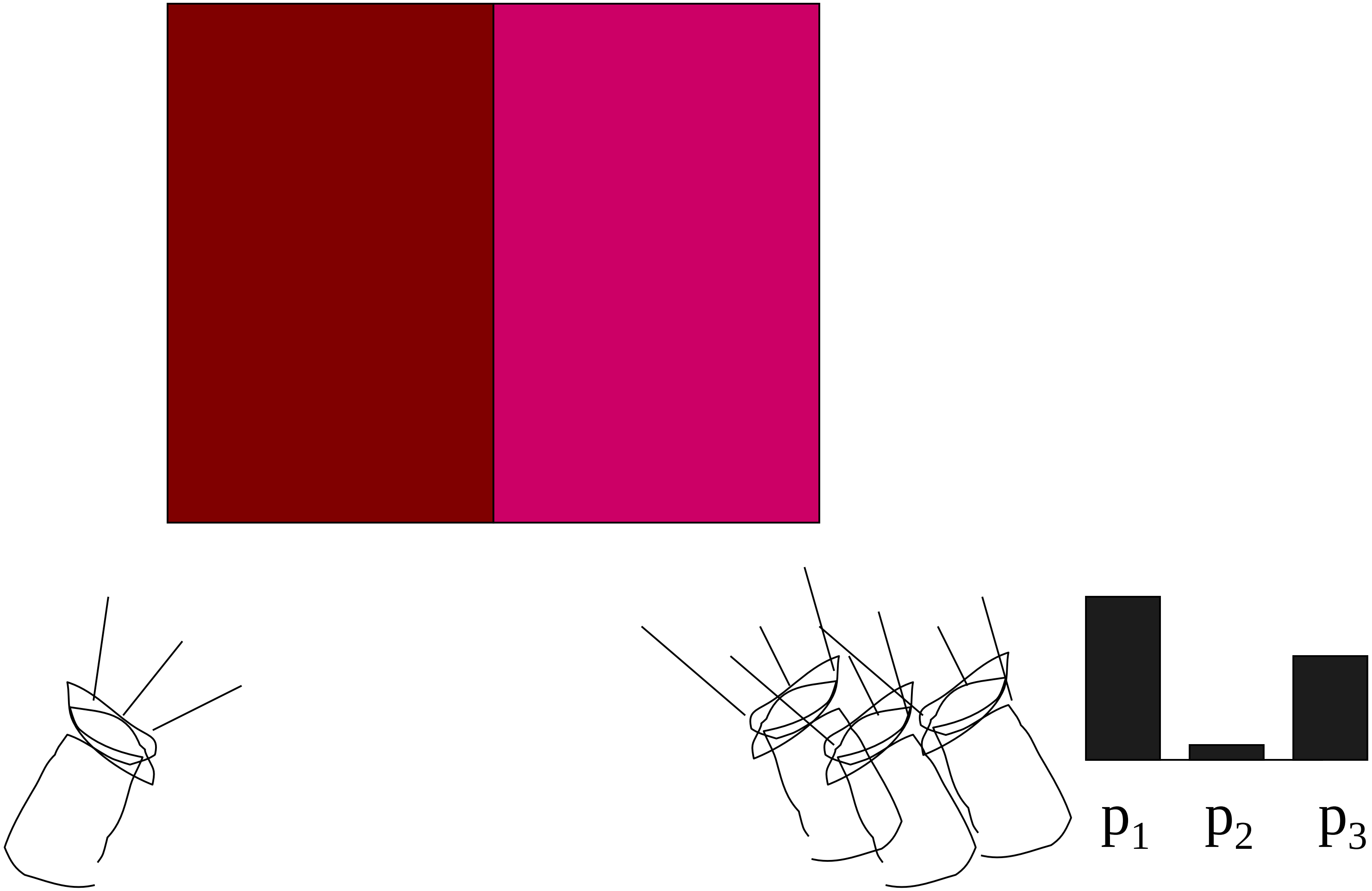


Slide credit: W. Freeman

Color Matching Experiment

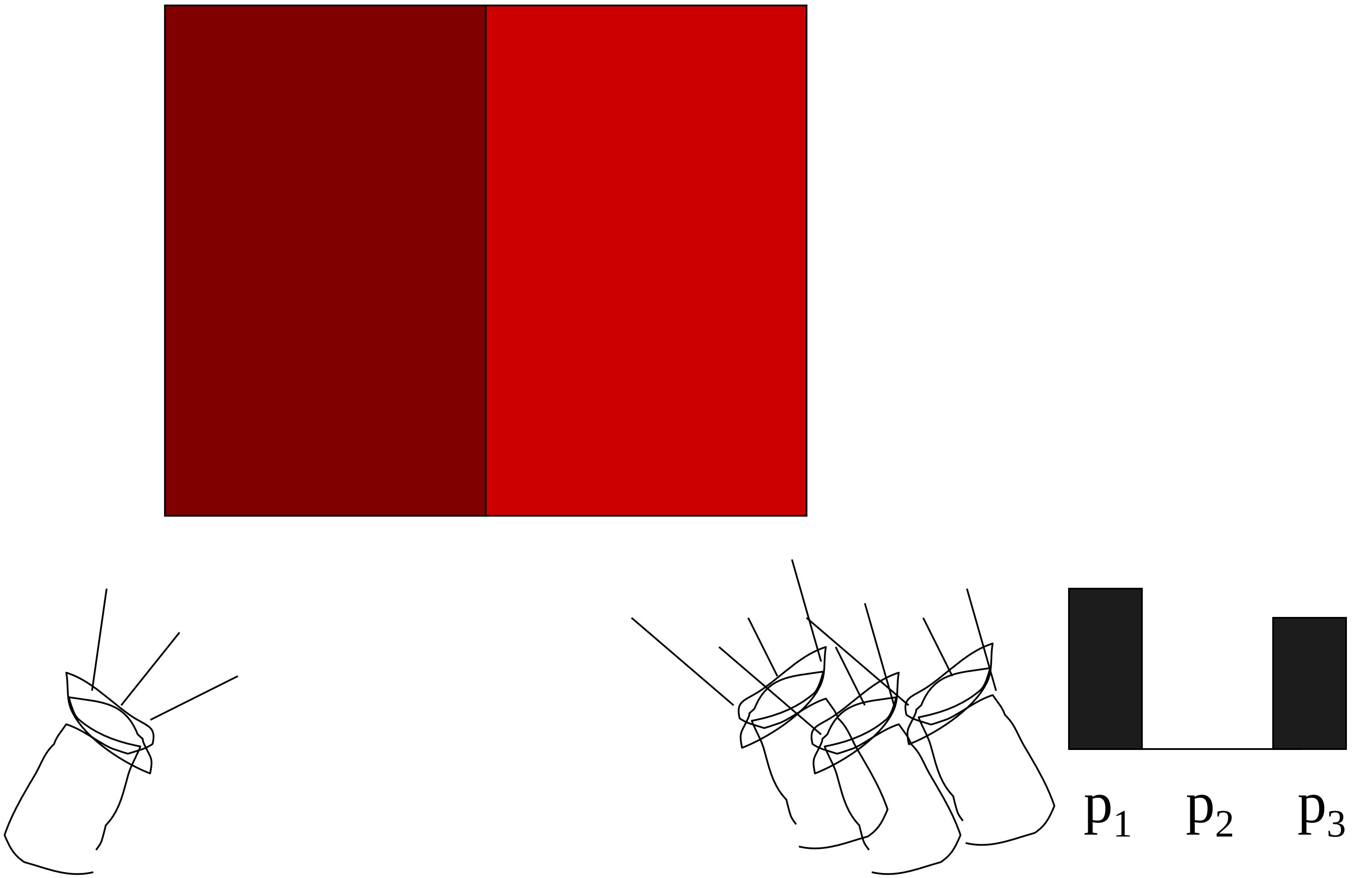


Color Matching Experiment



Slide credit: W. Freeman

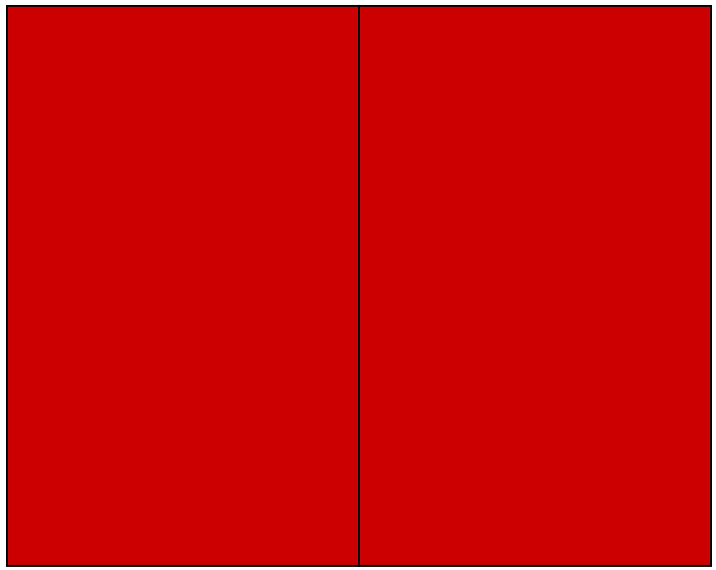
Color Matching Experiment



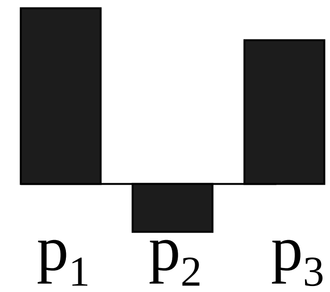
Slide credit: W. Freeman

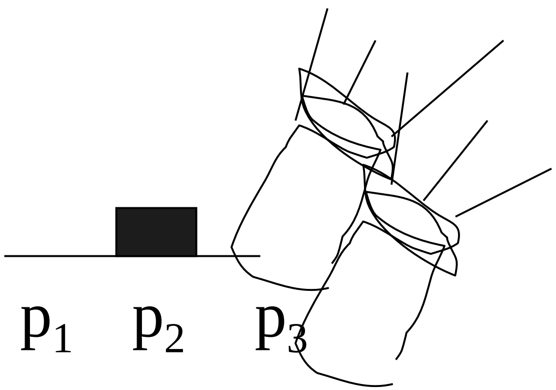
Color Matching Experiment

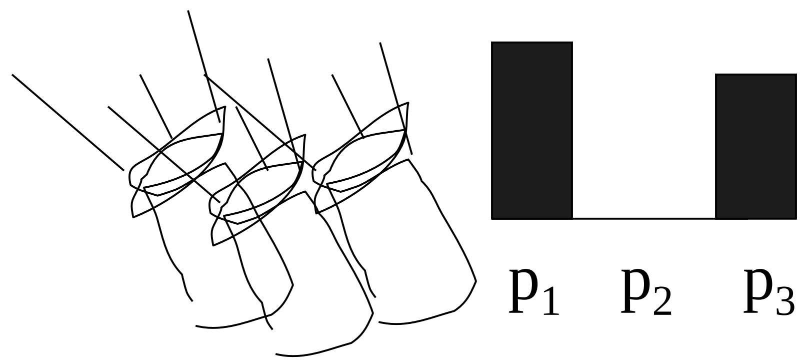
We say a “negative” amount of p_2 was needed to make the match, because we added it to the test color’s side.



The primary color amounts needed for a match:

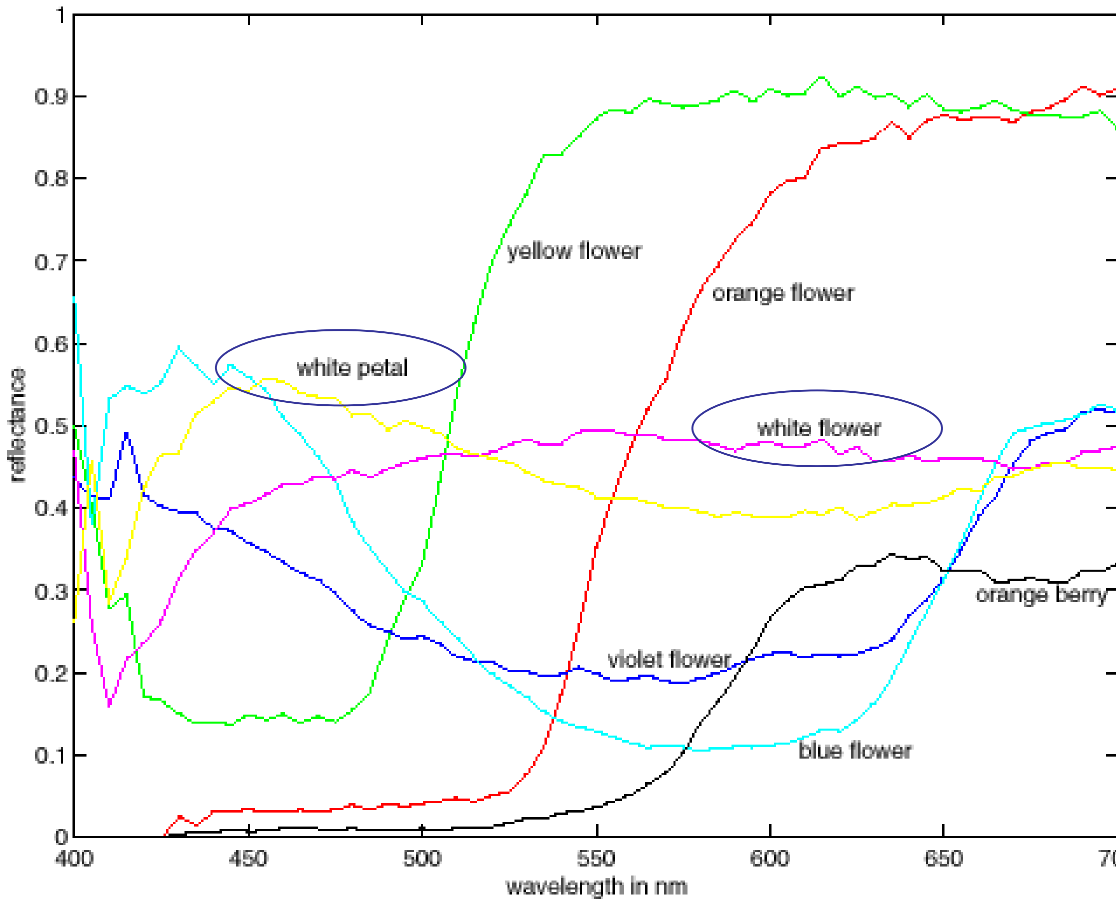






Color Matching

- Main questions: Primary lights? Number of primary lights?
  - If observer says a mixture is a match → receptor excitations of both stimuli must be equal.
  - A perceptual match still may be physically different
    - Match light: must be combination of primaries , Test light: any light
  - pairs of lights that match perceptually but not physically



Forsyth & Ponce, measurements by E. Koivisto

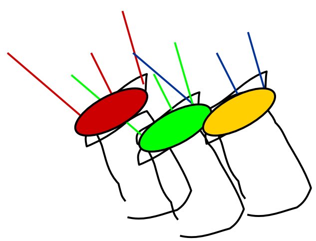
Grassman's Laws

- If two test lights can be matched with the same weights, they match each other
  - Suppose
    - A = u1 P1 + u2 P2 + u3 P3
    - B = u1 P1 + u2 P2 + u3 P3.
  - Then
    - A = B.
- If we scale the test light, then the matches get scaled by the same amount:
  - Suppose
    - A = u1 P1 + u2 P2 + u3 P3.
  - Then
    - kA = (ku1) P1 + (ku2) P2 + (ku3) P3.
- If we mix two test lights, then mixing the matches will match the result :
  - Suppose
    - A = u1 P1 + u2 P2 + u3 P3
    - B = v1 P1 + v2 P2 + v3 P3.
  - Then A+B = (u1+v1) P1 + (u2+v2) P2 + (u3+v3) P3.

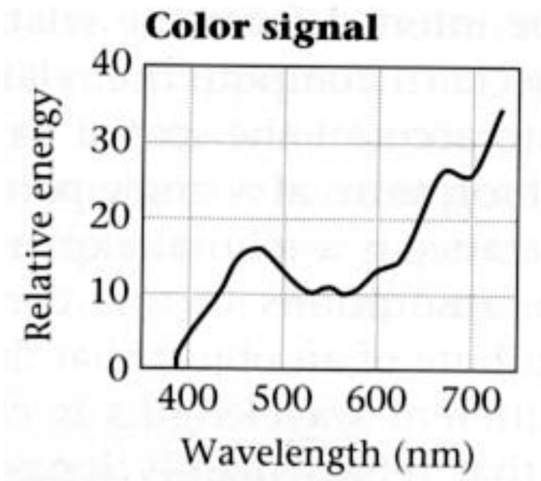
Here "=" means "matches".

Compute Weight

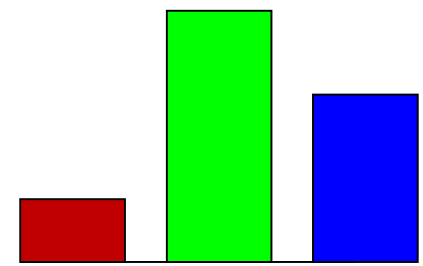
- **Given**: a choice of three primaries and a target color signal
- **Find**: weights of the primaries needed to match the color signal



p_1 p_2 p_3



?

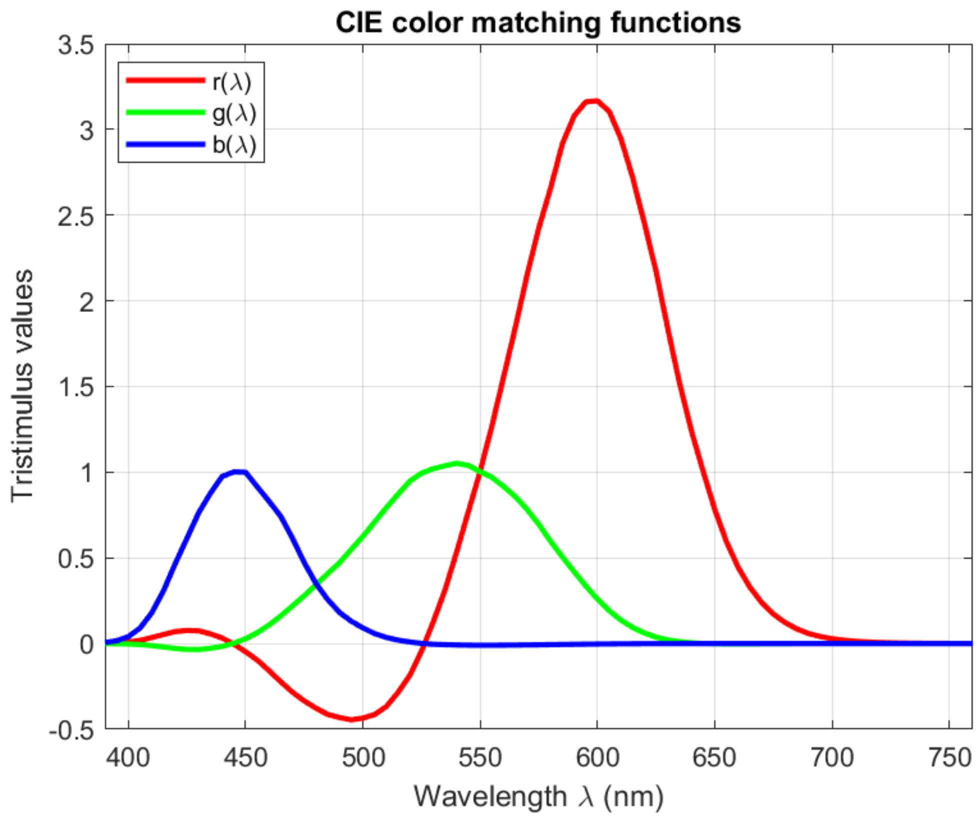


p_1 p_2 p_3

- **Estimate** their color matching functions: observer matches series of monochromatic lights, one at each wavelength.
- **Compute** weights for new test light, multiply with matching functions.

$$\mathbf{C} = \begin{pmatrix} c_1(\lambda_1) \\ c_2(\lambda_1) \\ c_3(\lambda_1) \end{pmatrix}$$

Compute Color Matches



$p_1 = 645.2$ nm

$p_2 = 525.3$ nm

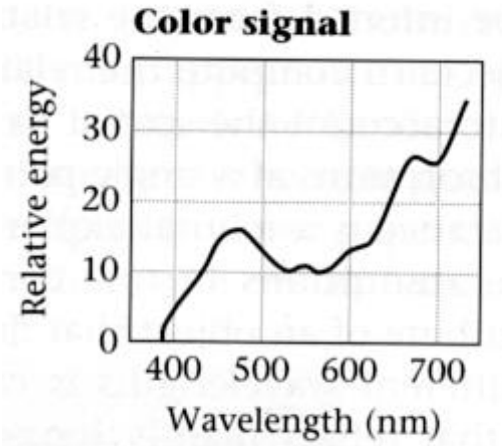
$p_3 = 444.4$ nm

Rows of matrix C

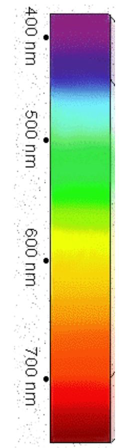
$$\mathbf{C} = \begin{pmatrix} c_1(\lambda_1) & \dots & c_1(\lambda_N) \\ c_2(\lambda_1) & \cdots & c_2(\lambda_N) \\ c_3(\lambda_1) & \cdots & c_3(\lambda_N) \end{pmatrix}$$

Compute Color Matches

- New spectral signal is linear combination of the monochromatic sources.



$$\mathbf{t} = \begin{pmatrix} t(\lambda_1) \\ \cdots \\ t(\lambda_N) \end{pmatrix}$$



- Color matching functions specify how to match a *unit* of each wavelength, so:

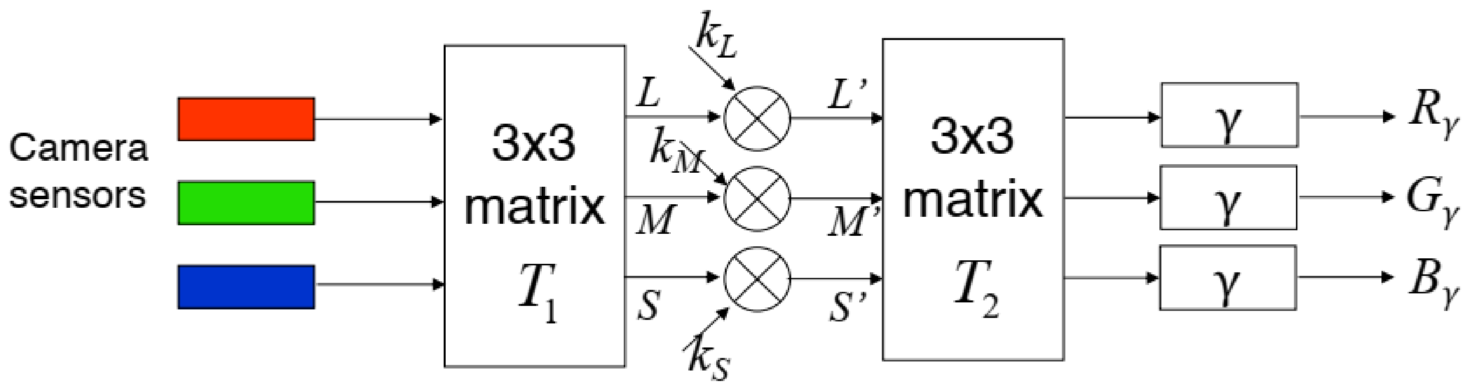
$$\begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{pmatrix} c_1(\lambda_1) & \cdots & c_1(\lambda_N) \\ c_2(\lambda_1) & \cdots & c_2(\lambda_N) \\ c_3(\lambda_1) & \cdots & c_3(\lambda_N) \end{pmatrix} \begin{bmatrix} t(\lambda_1) \\ t(\lambda_2) \\ \vdots \\ t(\lambda_N) \end{bmatrix} \qquad \mathbf{e} = \mathbf{C}\mathbf{t}$$

Why Compute Color Matches?

- Why this is useful?
  - Want to paint a carton of Kodak film with the Kodak yellow color.
  - Want to match skin color of a person in a photograph printed on an ink jet printer t o their true skin color.
  - Want the colors in the world, on a monitor, & in a print format to all look the same.

Color Balancing

- Effect of different illuminants can be cancelled only in the spectral domain (impractical)
- Color balancing in 3-d color space is practical approximation
- Color constancy in human visual system: gain control in cone space LMS *[von Kries,1902]*
- Von Kries hypothesis applied to image acquisition devices (cameras, scanners)



- How to determine k_L, k_M, k_S automatically?

Color Balancing

- Von Kries hypothesis

$$\begin{pmatrix} L' \\ M' \\ S' \end{pmatrix} = \begin{pmatrix} k_L & 0 & 0 \\ 0 & k_M & 0 \\ 0 & 0 & k_S \end{pmatrix} \begin{pmatrix} L \\ M \\ S \end{pmatrix}$$

- If illumination (or a patch of white in the scene) is known, calculate

$$k_L = \frac{L_{desired}}{L_{actual}}; \quad k_M = \frac{M_{desired}}{M_{actual}}; \quad k_S = \frac{S_{desired}}{S_{actual}}$$

Color Balancing with Unknown Illumination

- Gray-world

$$k_L \sum_{x,y} L[x,y] = k_M \sum_{x,y} M[x,y] = k_S \sum_{x,y} S[x,y]$$

- Scale-by-max

$$k_L \max_{x,y} L[x,y] = k_M \max_{x,y} M[x,y] = k_S \max_{x,y} S[x,y]$$

- Shades-of-gray
  [Finlayson, Trezzi, 2004]

$$k_L \left(\sum_{x,y} L^p[x,y] \right)^{\frac{1}{p}} = k_M \left(\sum_{x,y} M^p[x,y] \right)^{\frac{1}{p}} = k_S \left(\sum_{x,y} S^p[x,y] \right)^{\frac{1}{p}}$$

  - » Special cases: gray-world ($p = 1$), scale-by-max ($p = \infty$)
  - » Best performance for $p \approx 6$

- Refinements:
  smooth image, exclude saturated color/dark pixels,
  use spatial derivatives instead ("gray-edge," "max-edge")
  [van de Weijer, 2007])

Color Balancing Example

Original Gray-world Scale-by-max Gray-edge Max-edge Shades-of-gray