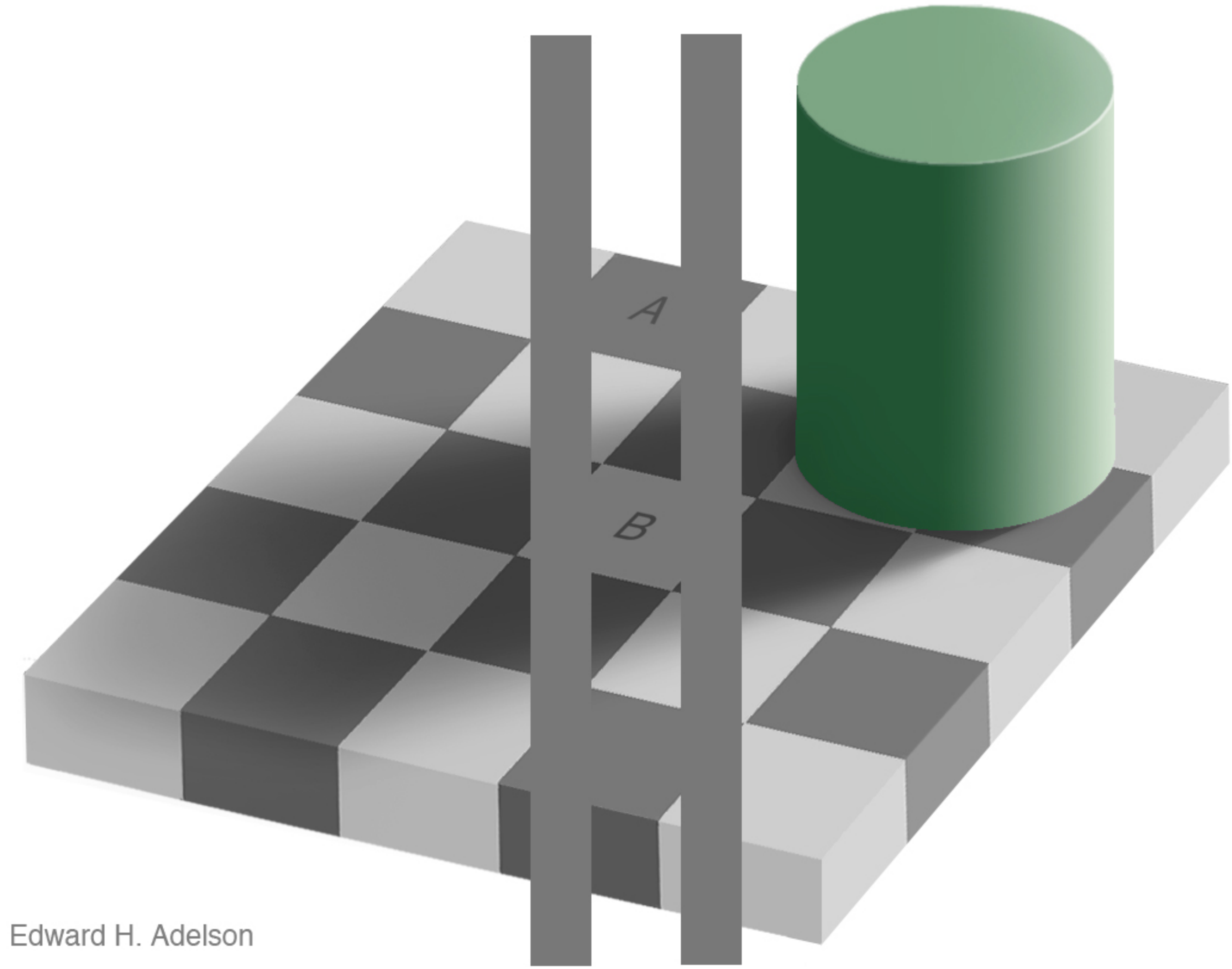
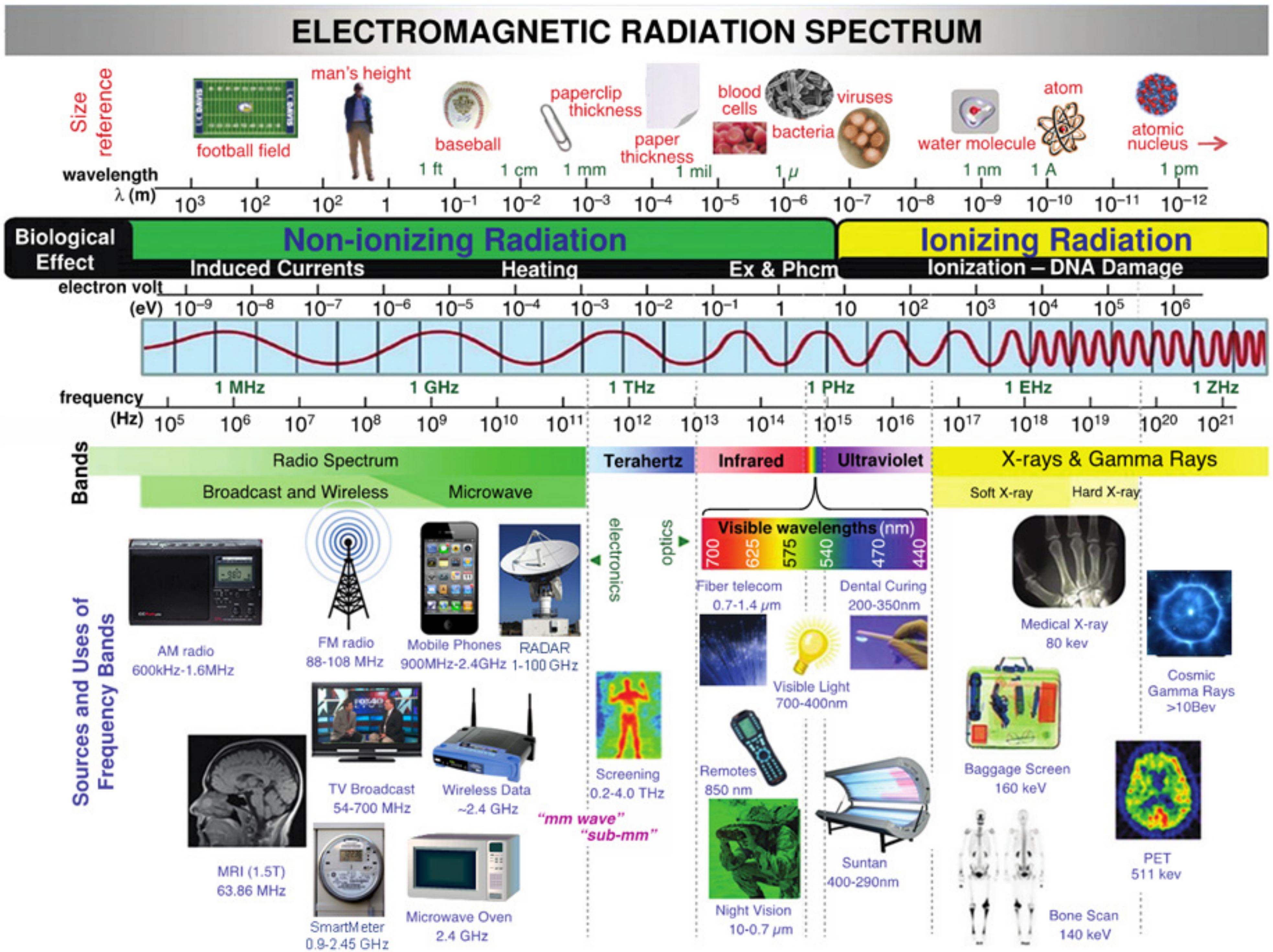
Color

Introduction to Computer Graphics
CSE 533/333

Color Perception



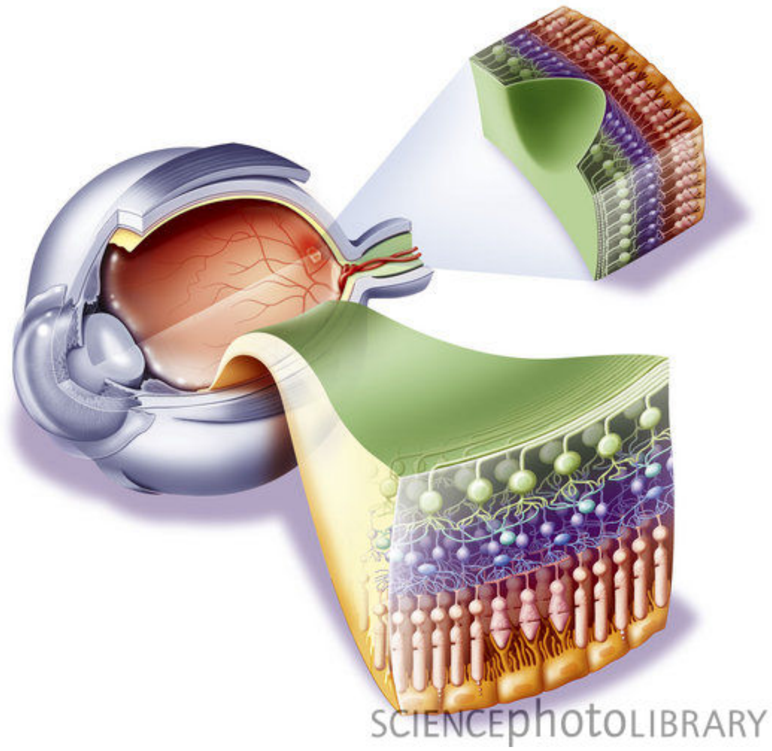
What Light Is



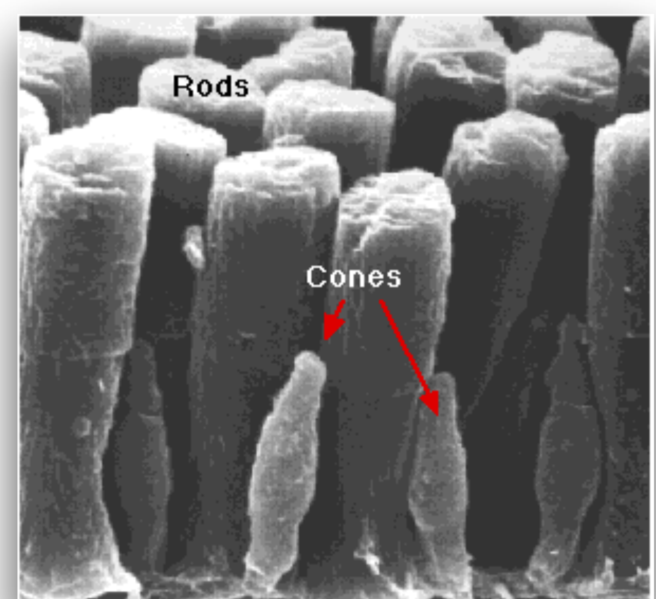
Measuring Light

- Colorimetry is the science of color measurement
- Colors are sensations that arise from light energy of different wavelengths
  - For humans: 380 nm - 760 nm
- Color is a phenomenon of human perception and not a universal property of light
- The photodetectors in human retina consists of *rods* and *cones*

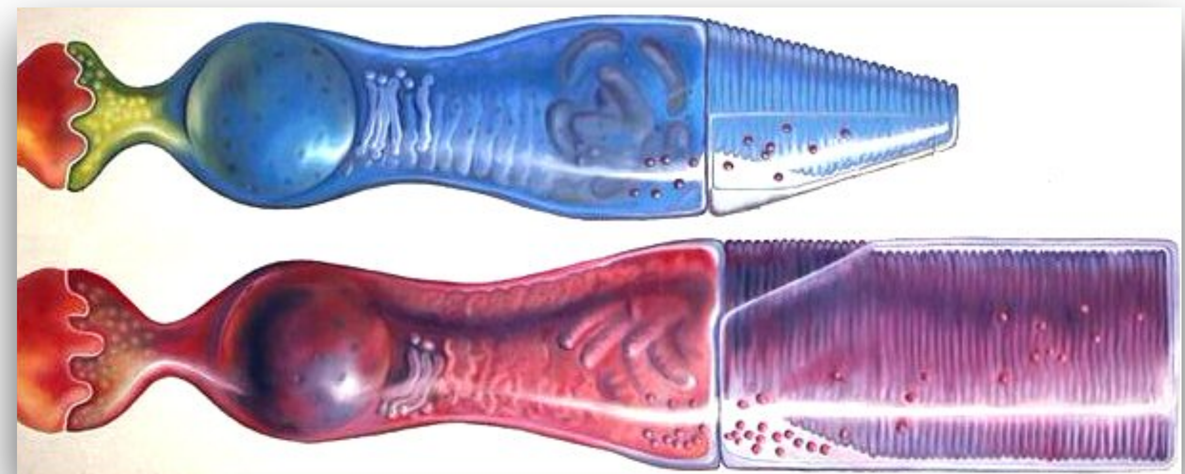
Measuring Light



Source: http://iaincarstairs.wordpress.com/2011/07/26/the-willing-pupil/



Source: http://www.willamette.edu/~gorr/classes/GeneralGraphics/Color/tristimulus.htm



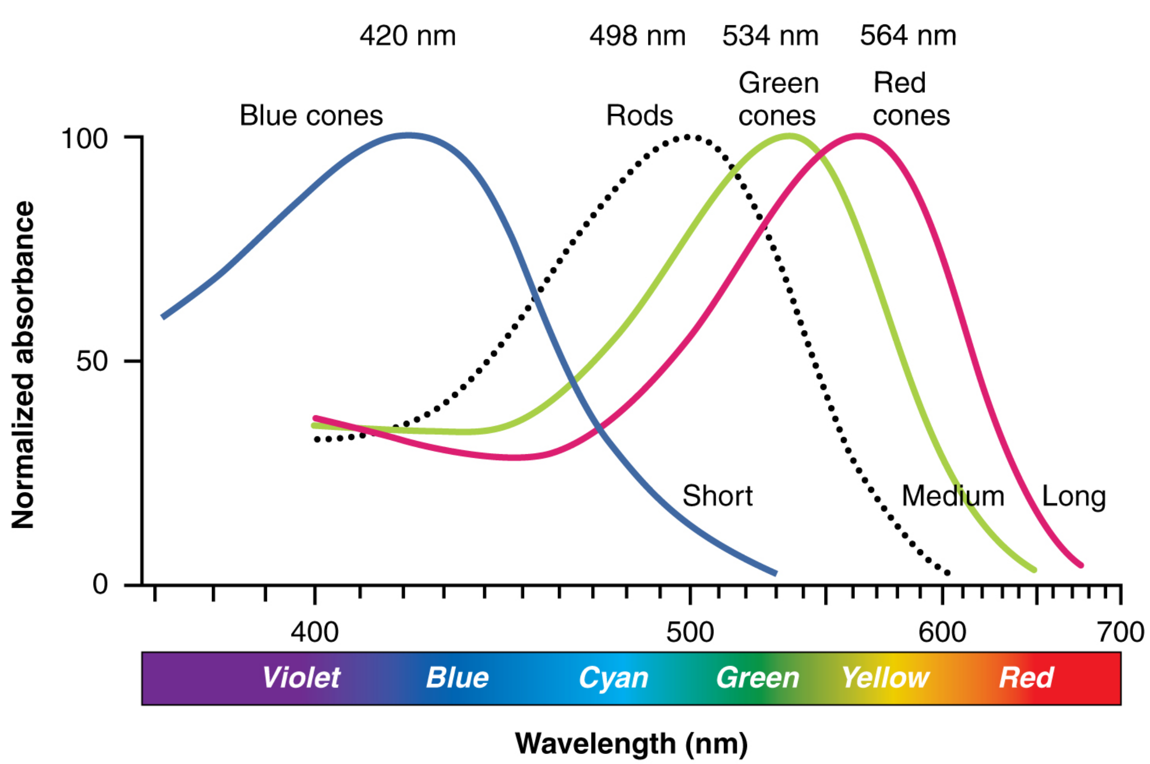
Rods are highly sensitive and responsible for low-light vision

Cones are responsible for colour vision. Three types of photoreceptors in retina:

- photopsin I: sensitive to red (L, erythrolabe)
- Photopsin II: sensitive to green (M, chlorolabe)
- Photopsin III: sensitive to bluish-violet (S, cyanolabe)

Cone Responses

- Each cone is sensitive to a range of wavelengths, spanning most of the visible range
- *Response of a cone*: magnitude of the electrical signal it outputs as a function of incident wavelength



$$L = \int_\lambda \Phi(\lambda) L(\lambda) \mathrm{d}\lambda$$

$$M = \int_\lambda \Phi(\lambda) M(\lambda) \mathrm{d}\lambda$$

$$S = \int_\lambda \Phi(\lambda) S(\lambda) \mathrm{d}\lambda$$

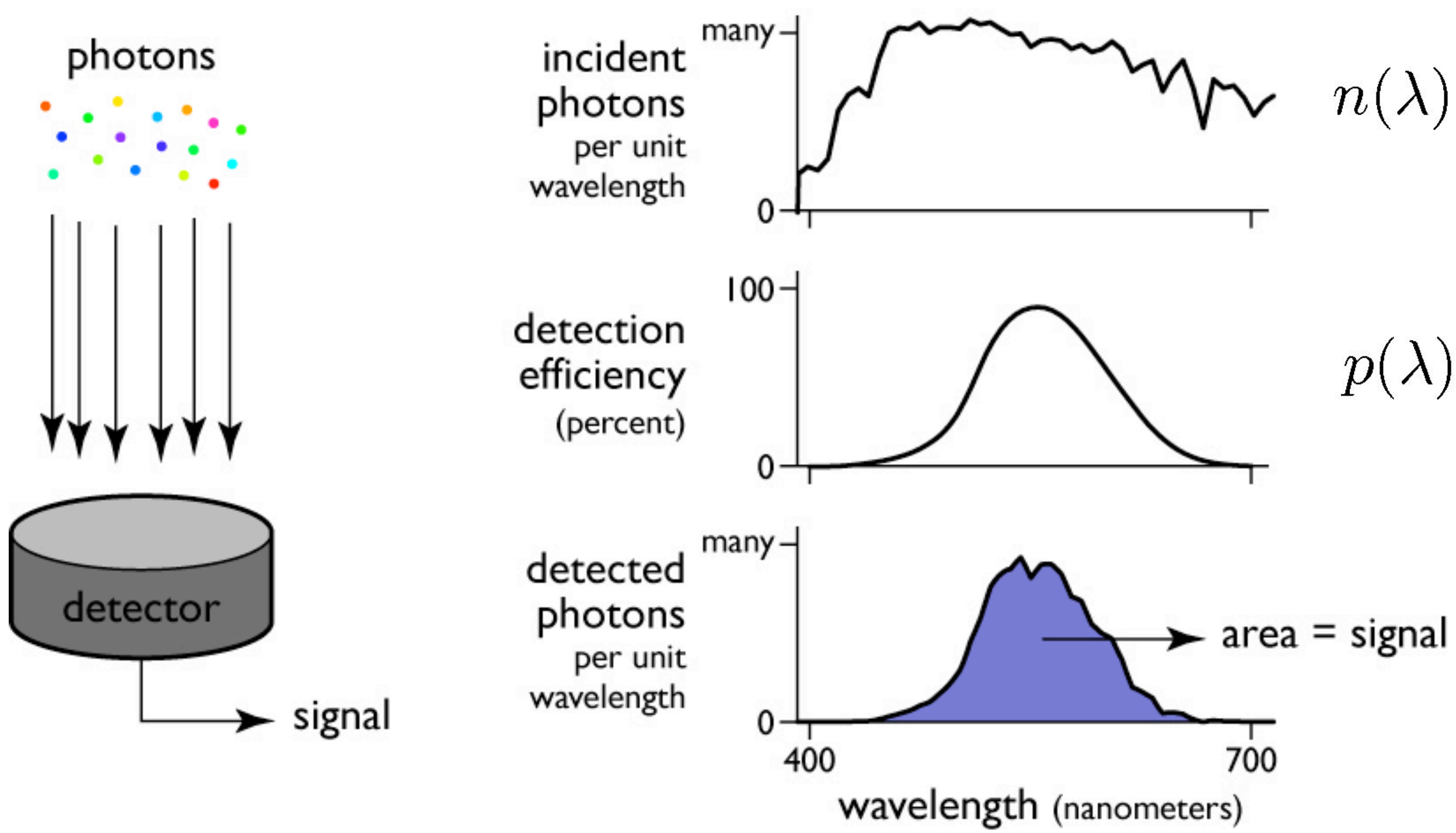
Tristimulus values

$\Phi(\lambda)$: Incident light intensity

$L(\lambda), M(\lambda), S(\lambda)$: Response functions

A Simple Light Detector

- Produces a scalar value when exposed to photons



$$X = \int n(\lambda)p(\lambda)\,d\lambda$$

Source: Steve Marschner

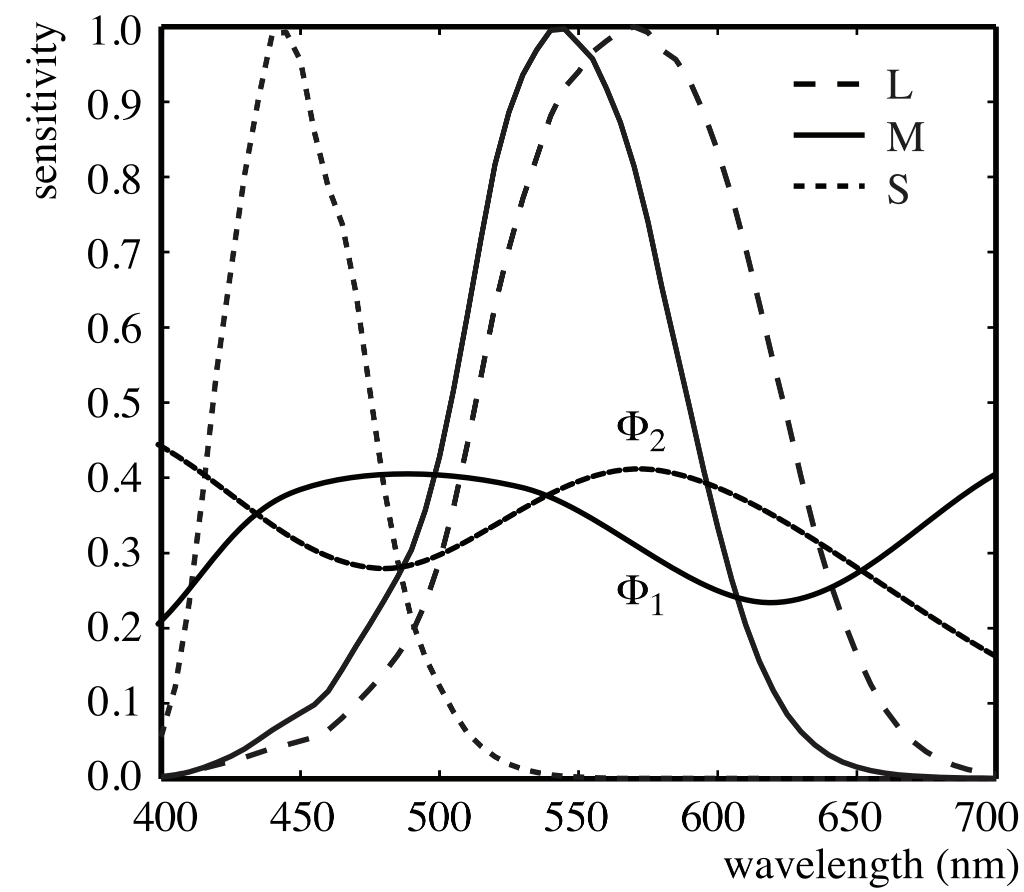
Colorimetric Concepts

- **Luminance**: overall magnitude of the visual response to a spectrum (independent of its colour) ≈ brightness
- **Chromaticity**: what is left after luminance is factored out ≈ color without overall brightness
- **Dominant wavelength**: Single spectral color ≈ hue
- **Purity**: ratio of pure color to white in a matching mixture ≈ saturation

Source: Steve Marschner

Color Matching

- Photoreceptors act as linear integrators
- Possible to find two different spectral compositions - $\Phi_1(\lambda)$ and $\Phi_2(\lambda)$ yielding same response (L, M, S)
- This feature of human vision is called *metamerism*
- Allows for color reproduction on different media
- leading to producing same tristimulus values



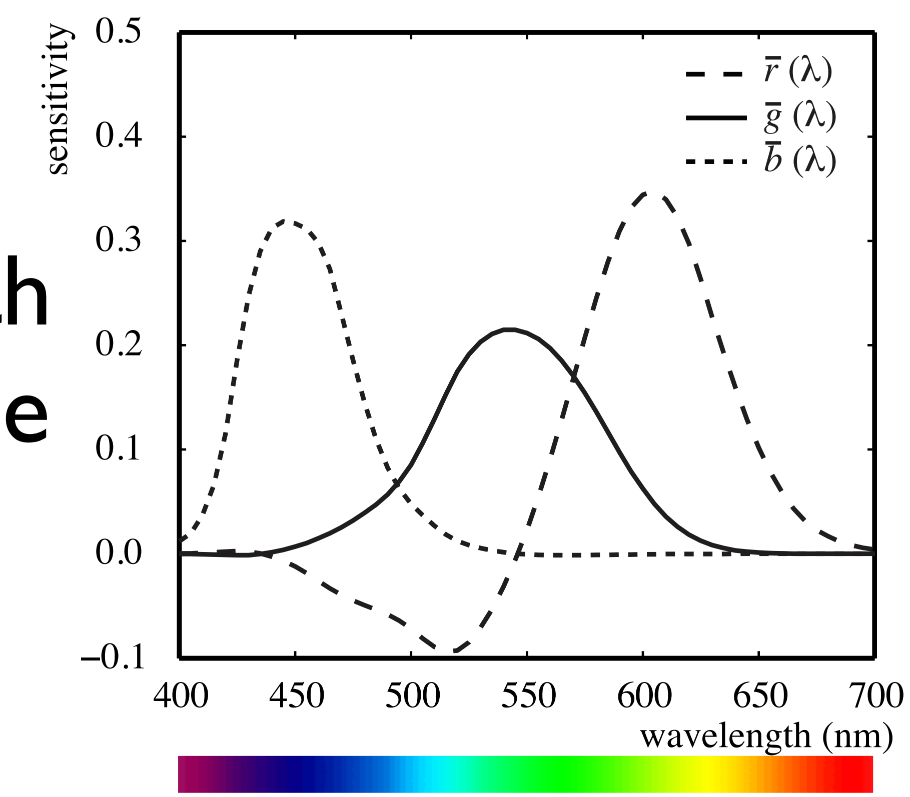
Grassmann's Laws

For humans, any color stimulus can be matched completely with an additive mixture of three appropriately modulated color sources:

1. **Symmetry law**: If color stimulus A matches color stimulus B, then B matches A.
2. **Transitive law**: If A matches B and B matches C, then A matches C.
3. **Proportionality law**: If A matches B, then αA matches αB, where α is a positive scale factor.
4. **Additivity law**: If A matches B, C matches D, and A+C matches B+D, then it follows that A+D matches B+C.

Standard Observers

- *Spectral tristimulus values*: tristimulus values resulting from using monochromatic light sources to match colors
- CIE† defined three primaries: 435.8 (B), 546.1 (G), and 700 nm (R)
- A color can be produced by a mixture of primaries
  - Negative value means that wavelength is too saturated to be matched by the particular primaries (out of gamut!)



†CIE: Commission Internationale d'Eclairage

Standard Observers

- Possible to transform one set of tristimulus values into another set of tristimulus vales
- CIE defined the X Y Z primaries
  - All positive over the visible range
- Cannot be physically realised (imaginary)
  - Primaries have negative regions in their spectra
- Known as **CIE 1931 standard observer**

Color Space

- We could define an orthogonal coordinate system with X, Y, and Z axes of primaries
- *Color gamut*: spatial extent of the volume in which colors lie

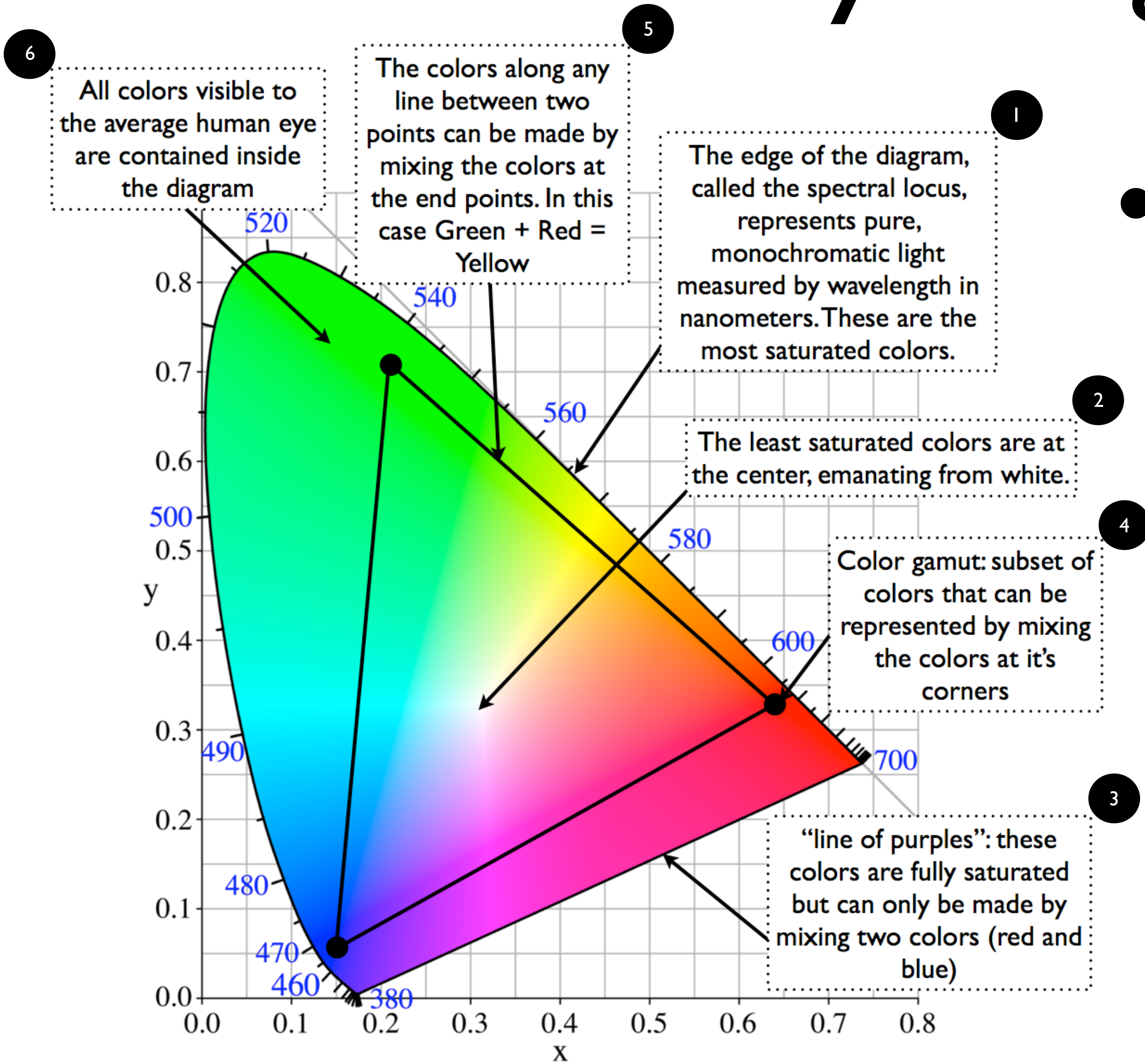
Y carries the luminance information

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

$$y = \frac{Y}{X+Y+Z} \quad \longleftrightarrow \quad X = \frac{x}{y}Y,$$

$$z = \frac{Z}{X+Y+Z} \qquad Z = \frac{1-x-y}{y}Y$$

Chromaticity Diagram

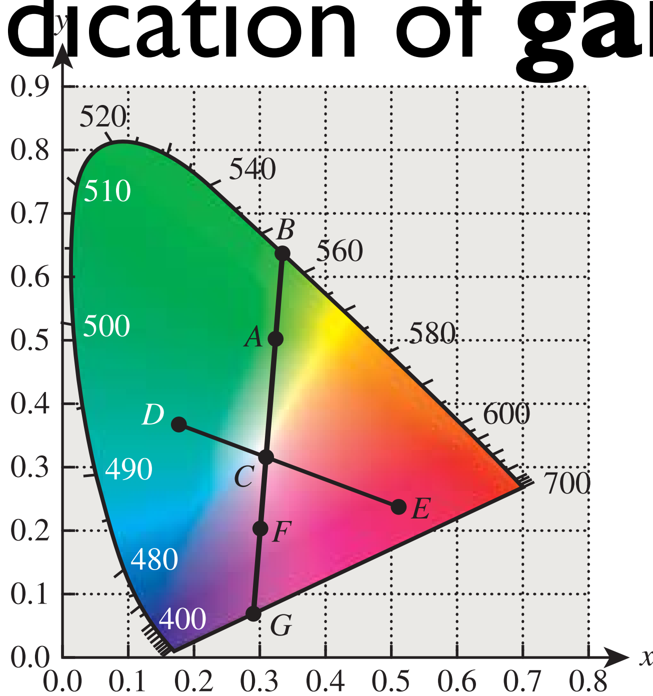


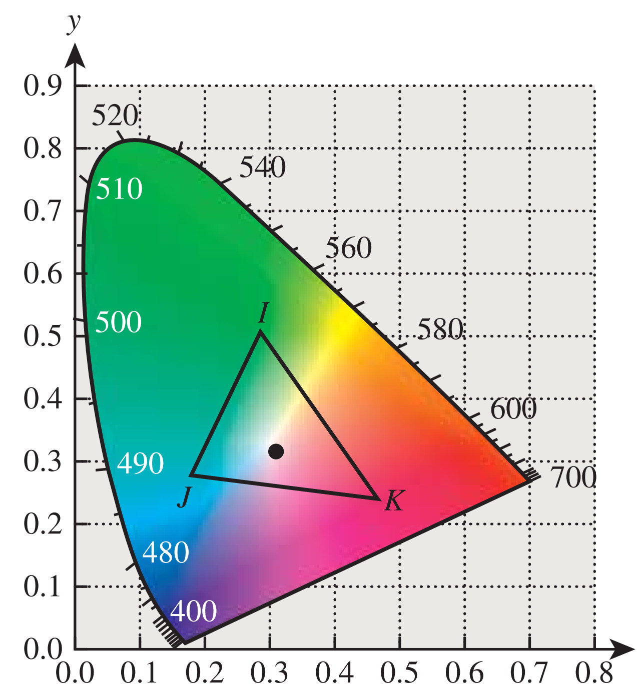
- Plot of x,y chromaticities

Source: http://dot-color.com/2012/08/14/color-space-confusion/

Applications of Chromaticity diagram

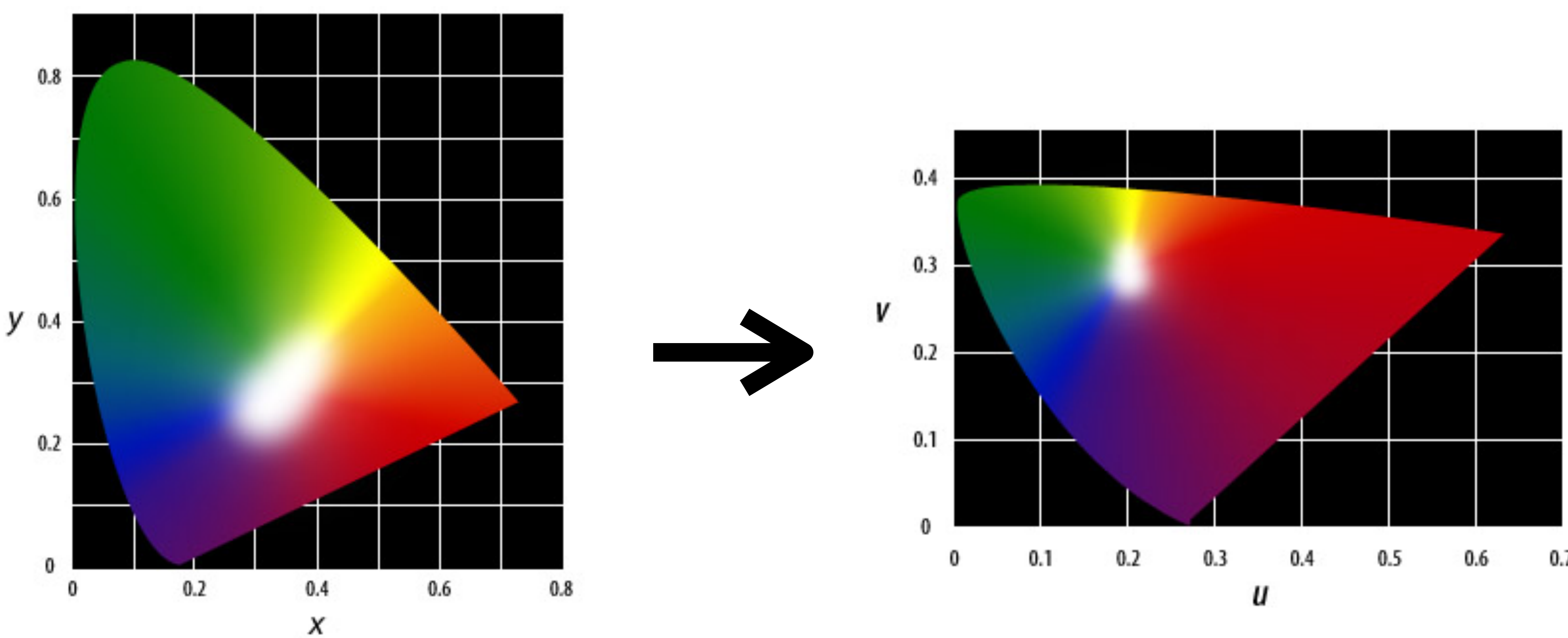
1. Define **complementary colors**
2. make precise notion of **excitation purity**
3. Indication of **gamuts**





CIE u’v’ Chromaticity Diagram

A perceptually better chromaticity diagram



Color Matrix Transform

- For a display with three primaries:
  red (1, 0, 0), green (0, 1, 0), and blue (0, 0, 1)
- We can compute chromaticity coordinates (x_R, y_R), (x_G, y_G), and (x_B, y_B)
- The *white point* of a display is defined as the spectrum emitted when the color vector (1, 1, 1) is sent to the display $\longmapsto$ corresponding chromaticity coordinate is (x_W, y_W)

Color Matrix Transform

- Chromaticity coordinates can be extended to triples with $z = 1 - x - y$
- Given the maximum luminance, of the white point, its tristimulus (X_W, Y_W, Z_W) can be computed
- Luminance ratio scalars S_R, S_G, and S_B are solutions to:

$$X_W = x_R S_R + x_G S_G + x_B S_B$$
$$Y_W = y_R S_R + y_G S_G + y_B S_B$$
$$W_W = z_R S_R + z_G S_G + z_B S_B$$

Color Matrix Transform

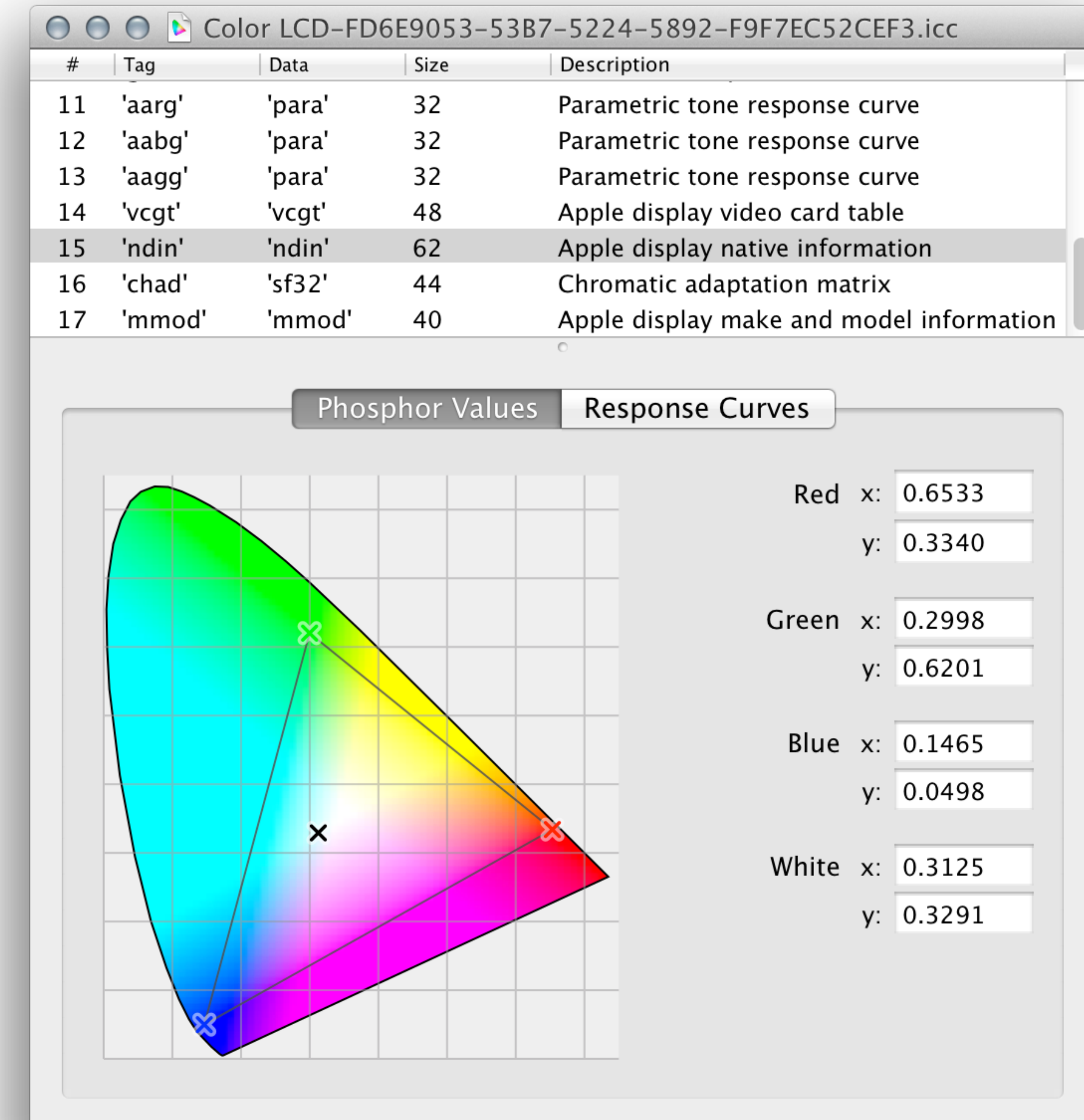
- Conversion between RGB and XYZ is given by:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} x_R S_R & x_G S_G & x_B S_B \\ y_R S_R & y_G S_G & y_B S_B \\ z_R S_R & z_G S_G & z_B S_B \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

- The luminance of any color can be computed by evaluating the middle row:

$$Y = y_R S_R R + y_G S_G G + y_B S_B B$$

Color Matrix Transform



Demo

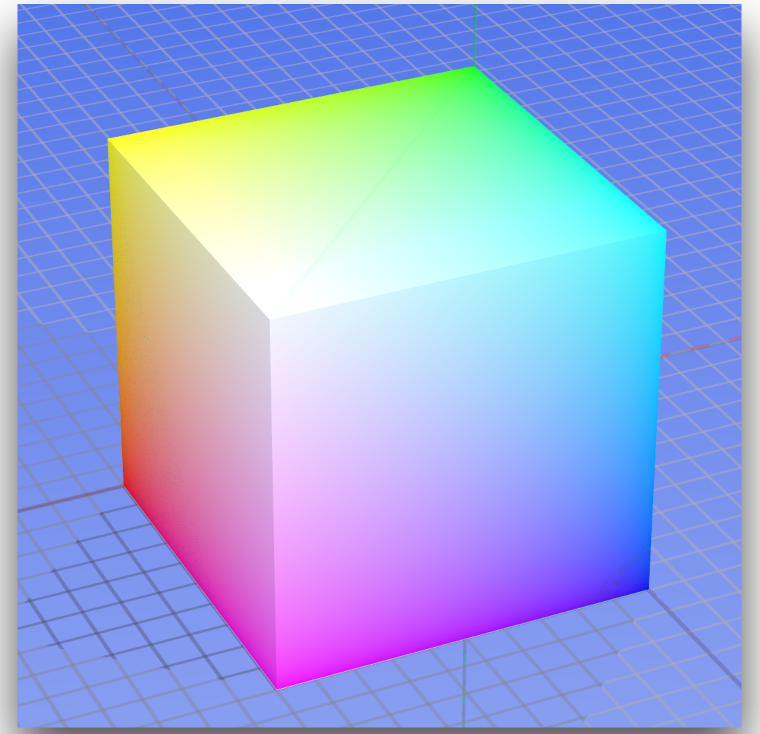
Other Color Spaces

- Color is the way the Human Visual System (HVS) measures a part of the electromagnetic spectrum
- Classification of color spaces:
  - HVS based colour spaces
  - Application specific
  - CIE color spaces

RGB Color Space

HVS Based

- Based on LMS (cones) in human eye; roughly sensitive to red, green, and blue colours
- *Cons:*
  - High correlation between components
  - Perceptual non-uniformity (distances in RGB space)

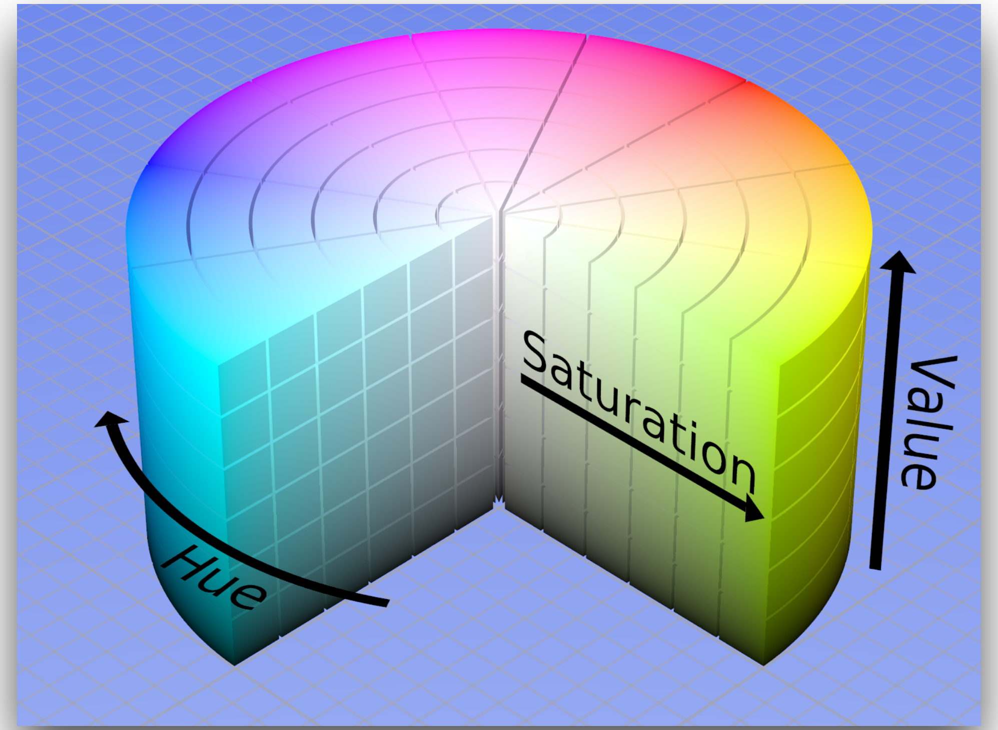


"RGB color solid cube" by SharkD

HSV Color Space

HVS Based

- a phenomenal color space
- Mind's representation of colours
  - Hue (H),
  - Saturation (S), and
  - Value (V)
- *Cons*:
  - Hue discontinuity at 2π
  - Bad correlation b/w computed and perceived lightness



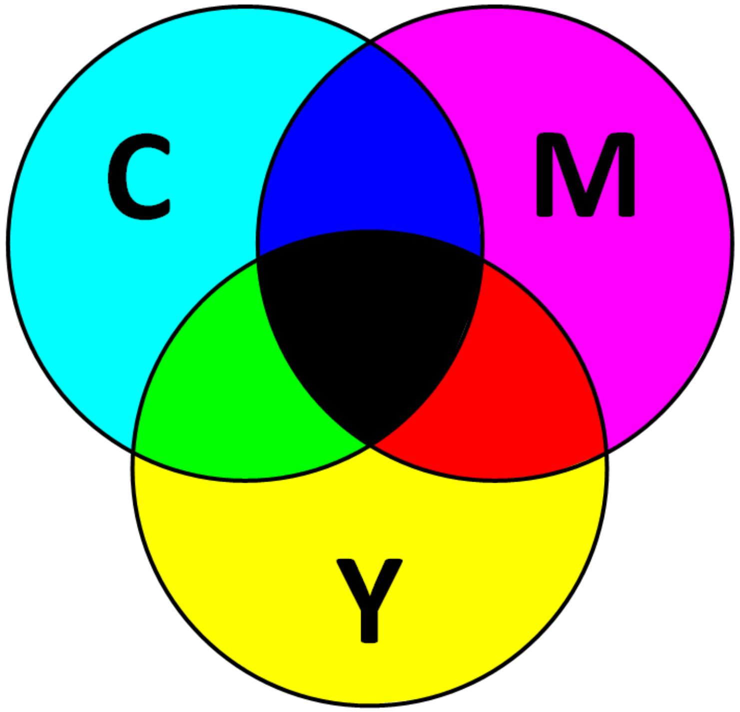
"HSV color solid cylinder" by SharkD

CMYK Color Space

Application Specific - Printing

- Subtractive color space
- Mainly used in printing
- CMY: Cyan - Magenta - Yellow, K: Black

Source: http://w3.unisa.edu.au

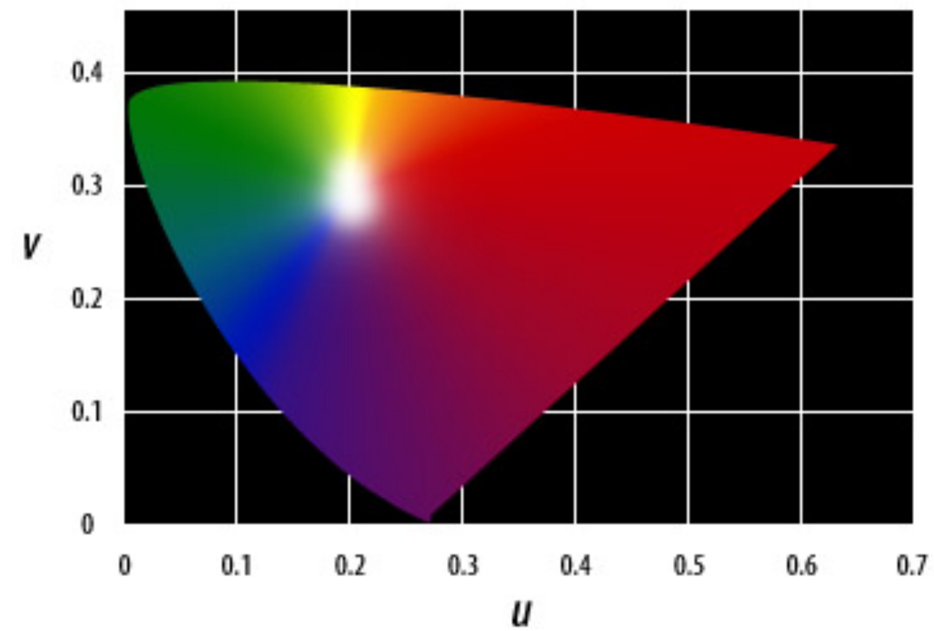


CIE XYZ, Luv, Lab

CIE

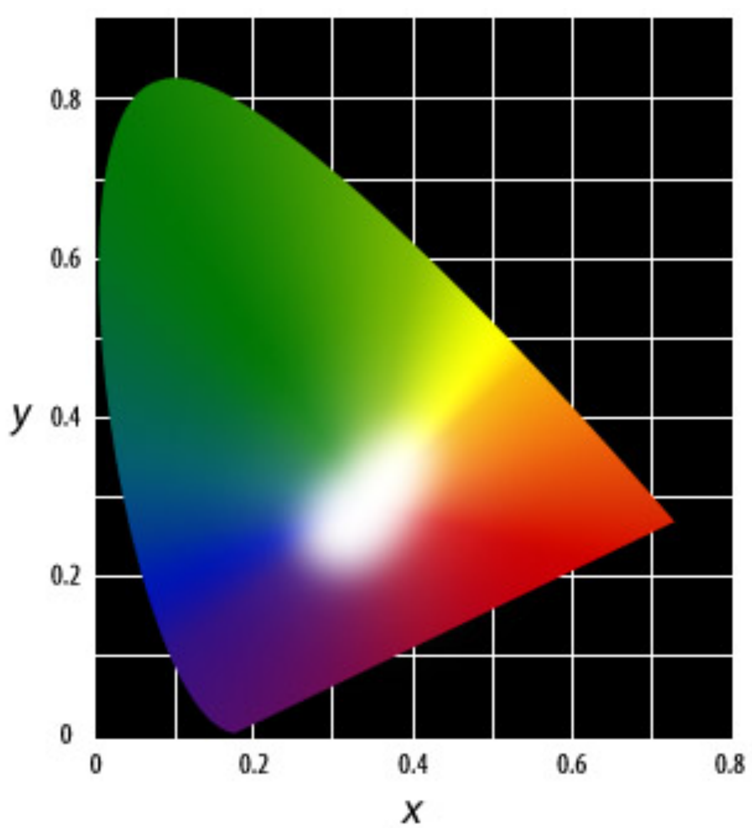
- Strongly correlated with human visual perception
- Two main constraints:
  - chromatic adaptation
  - non-linear visual response
- CIE Lab normalises values by division with white point
- CIE Luv normalizes values by subtraction of white point

CIE XYZ, Luv, Lab

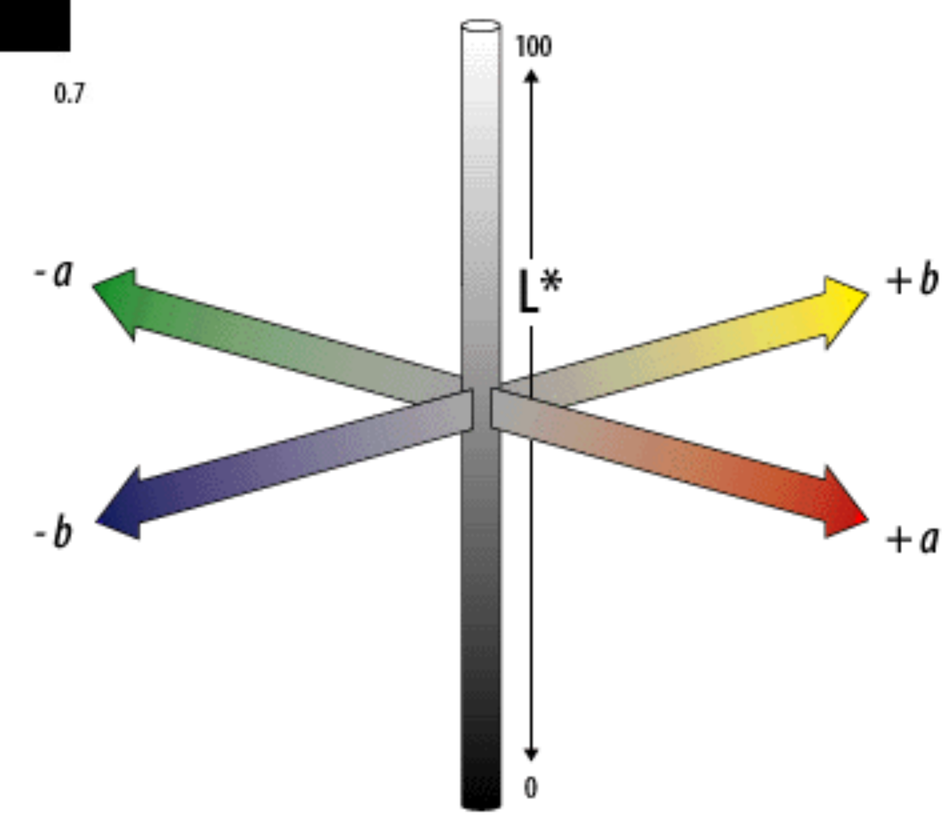


CIE Luv

CIE XYZ



CIE Lab



Reading

- FCG: 21
- Notes: Colour spaces - perceptual, historical and applicational background, Marko T., Juri F. T.
- Web: Color Models, Adobe Systems http://dba.med.sc.edu/price/irf/Adobe_tg/models/main.html

ICG: Interactive Computer Graphics, E. Angel, and D. Shreiner, 6th ed.
FCG: Fundamentals of Computer Graphics, P. Shirley, M. Ashikhmin, and S. Marschner, 3rd ed.
CG: Computer Graphics, principles and Practice, J. F. Hughes, et al.