

## Nano-Imaging and Human Color Vision

Hirohisa Yaguchi

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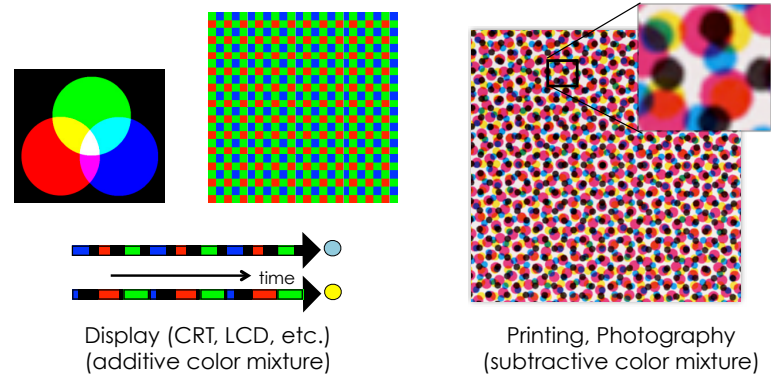
- Principle of color reproduction
- Metamerism
- Human color vision model
- CIE colorimetry
- Advanced colorimetry

## Additive and Subtractive Color Mixture

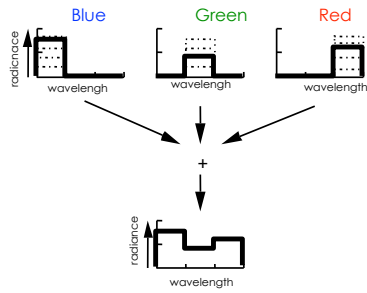


(Billmeyer and Saltzman's principles of color technology, Roy S. Berns)

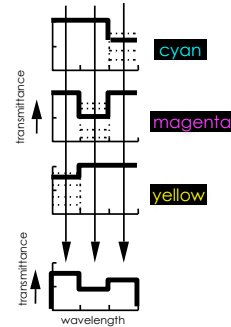
## Color Reproduction



# Spectral Color Reproduction of Additive and Subtractive Color Mixture

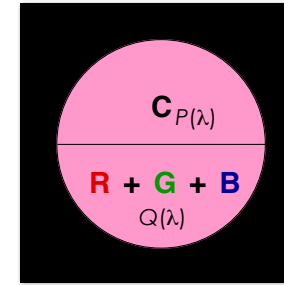


Additive color mixture



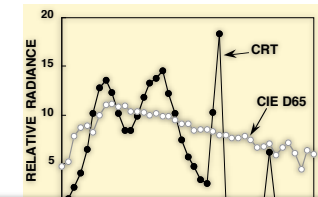
Subtractive color mixture

# Color Matching and Metamerism



Trichromatic theory  
Any color can be color matched by a mixture of three color stimuli.

$$P(\lambda) \neq Q(\lambda)$$



$$L = \int_{\lambda} P(\lambda)l(\lambda)d\lambda = \int_{\lambda} Q(\lambda)l(\lambda)d\lambda$$

$$M = \int_{\lambda} P(\lambda)m(\lambda)d\lambda = \int_{\lambda} Q(\lambda)m(\lambda)d\lambda$$

$$S = \int_{\lambda} P(\lambda)s(\lambda)d\lambda = \int_{\lambda} Q(\lambda)s(\lambda)d\lambda$$

# Metamerism

Color = Light • Object • Eye

$$L = \int E(\lambda)\rho(\lambda)l(\lambda)d\lambda$$

$$M = \int E(\lambda)\rho(\lambda)m(\lambda)d\lambda$$

$$S = \int E(\lambda)\rho(\lambda)s(\lambda)d\lambda$$

$$\int E(\lambda)\rho(\lambda)l(\lambda)d\lambda = \int E(\lambda)\rho'(\lambda)l(\lambda)d\lambda$$

$$\int E(\lambda)\rho(\lambda)m(\lambda)d\lambda = \int E(\lambda)\rho'(\lambda)m(\lambda)d\lambda$$

$$\int E(\lambda)\rho(\lambda)s(\lambda)d\lambda = \int E(\lambda)\rho'(\lambda)s(\lambda)d\lambda$$

$$\rho(\lambda) \neq \rho'(\lambda)$$

illuminant metamerism

metamar

observer metamerism

$$\int E'(\lambda)\rho(\lambda)l(\lambda)d\lambda \neq \int E'(\lambda)\rho'(\lambda)l(\lambda)d\lambda$$

$$\int E'(\lambda)\rho(\lambda)m(\lambda)d\lambda \neq \int E'(\lambda)\rho'(\lambda)m(\lambda)d\lambda$$

$$\int E'(\lambda)\rho(\lambda)s(\lambda)d\lambda \neq \int E'(\lambda)\rho'(\lambda)s(\lambda)d\lambda$$

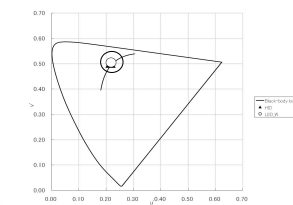
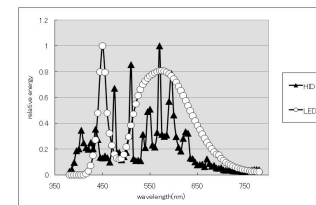
$$\int E(\lambda)\rho(\lambda)l'(\lambda)d\lambda \neq \int E(\lambda)\rho'(\lambda)l'(\lambda)d\lambda$$

$$\int E(\lambda)\rho(\lambda)m'(\lambda)d\lambda \neq \int E(\lambda)\rho'(\lambda)m'(\lambda)d\lambda$$

$$\int E(\lambda)\rho(\lambda)s'(\lambda)d\lambda \neq \int E(\lambda)\rho'(\lambda)s'(\lambda)d\lambda$$

# Metamerism of automotive headlamps (HID)

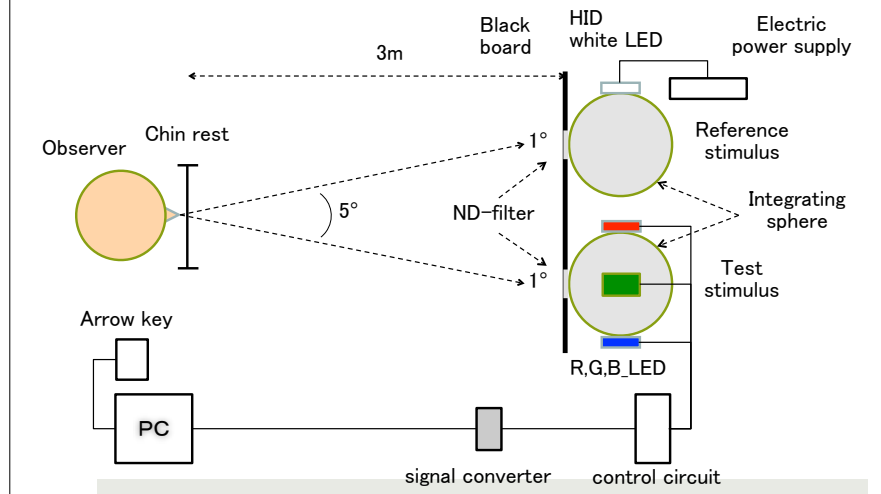
- These spectral power distributions are different with each other.
- These chromaticity coordinates are the same.



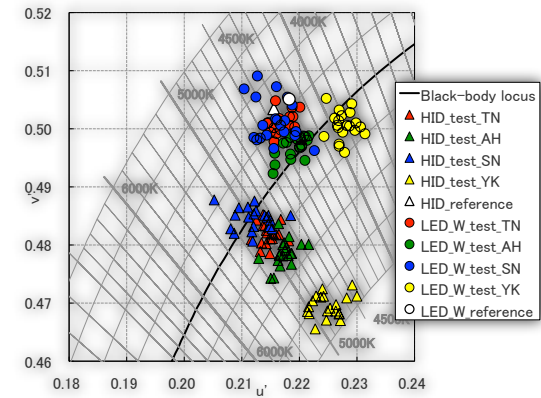
Different colour



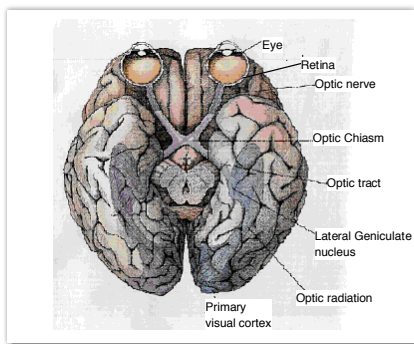
## Color matching experiment



## Results of color matching

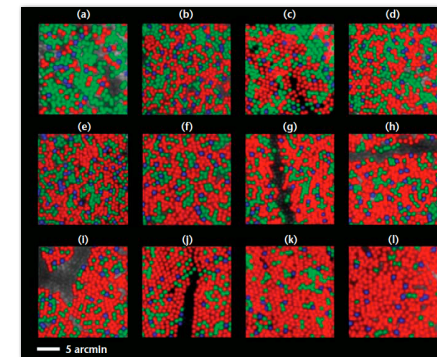


## Human Visual Information Processing



- Eye balls: Optical system
- Retina: High intelligent input device
  - Photoreceptors (Rods and Cones)
  - Luminance and chromatic channels (Horizontal cells)
  - Contrast (Ganglion cells)
- LGN: Parallel information processing
  - Magno path (where?): place, motion, depth
  - Parvo path (what?): shape, color, texture, detail
- Primary visual cortex
- Parietal stream and Inferotemporal stream

## Cone Mosaic



Joseph Carroll, Daniel C. Gray, Austin Roorda and David R. Williams,  
Optics & Photonics News, vol. 16, 36-41 (2005)

## Retinal images by the adaptive optics (A. Roorda and D. Williams, Nature, 1999)

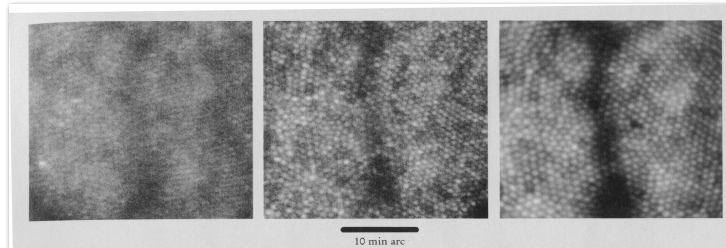
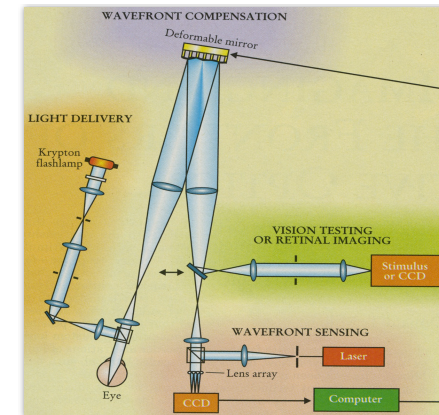


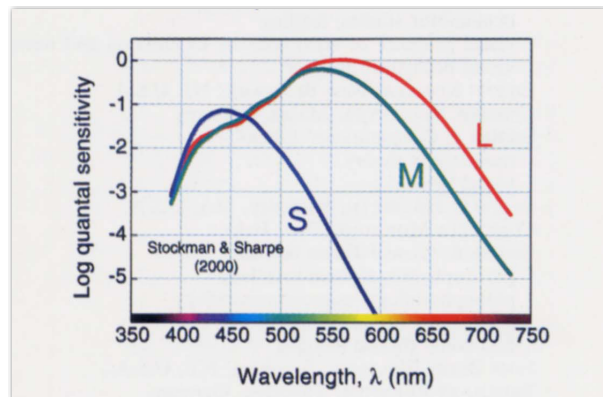
FIGURE 3. RETINAL IMAGES, before and after adaptive compensation. All three images are of the same  $0.5^\circ$  patch of retina, obtained with 550 nm light through a 6 mm pupil. The dark vertical band across each image is an out-of-focus shadow of a blood vessel. The leftmost image shows a single snapshot taken when only defocus and astigmatism had been corrected. The middle image shows additional aberrations having been corrected with adaptive optics. It also shows noticeably higher contrast and resolution, with individual photoreceptors more clearly defined. To reduce the effect of noise present in the images, the rightmost image demonstrates the benefit of registering and then averaging 61 images of a single retinal patch. (Images courtesy of Austin Roorda and David Williams, University of Rochester.)

(from D. T. Miller, PHYSICS TODAY, Jan 2000, p.35)

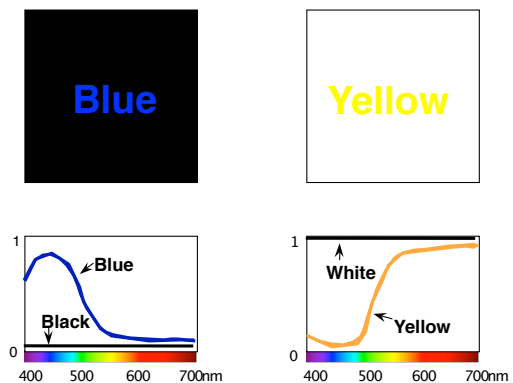
## Adaptive Optics Retina Camera



## Spectral Sensitivities of Cone

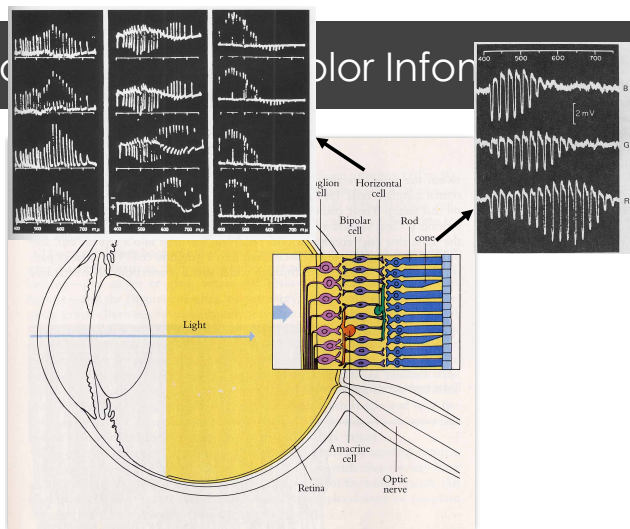


## Why blue on black and yellow on white look

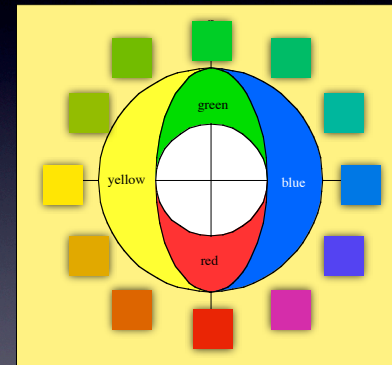


# Structure of

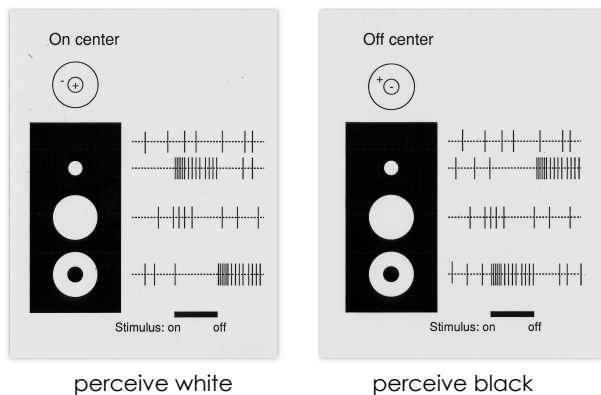
# Color Inform



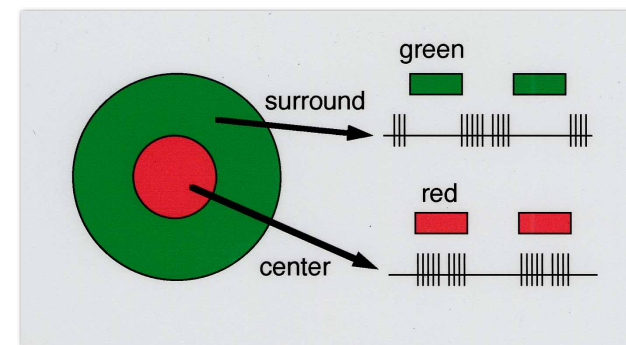
# Hering's opponent color theory



# Receptive Fields of Retinal Ganglion Cells

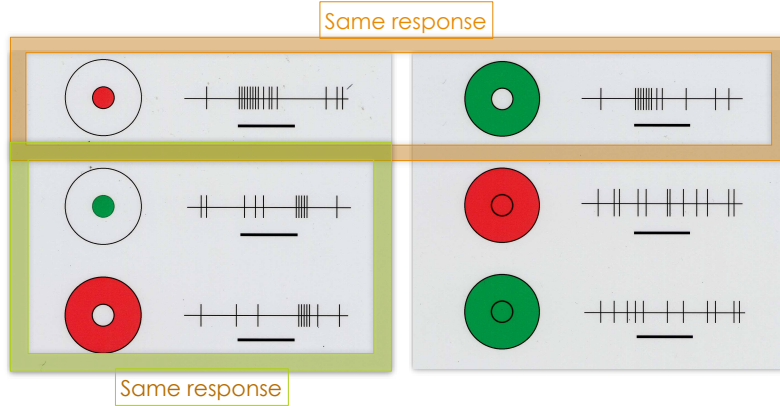


# A Color Opponent Cell of the Retinal

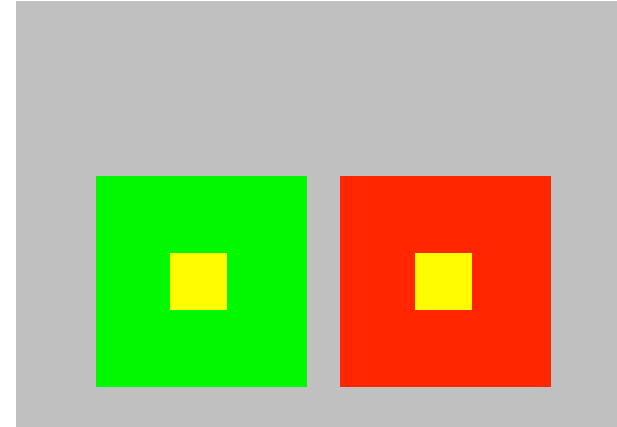


Red sensitive and green inhibited

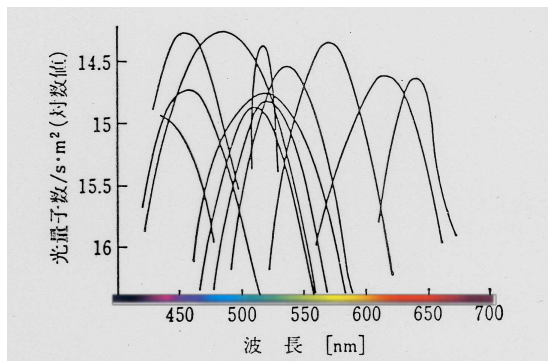
## Double Opponent Color Cell



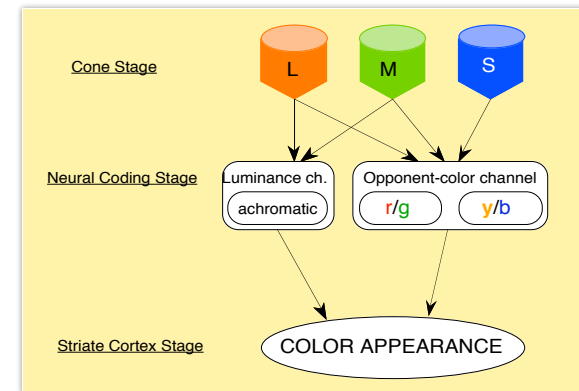
## Color contrast



## Spectral Selectivity of the V4 Cells in the



## Color Vision Model

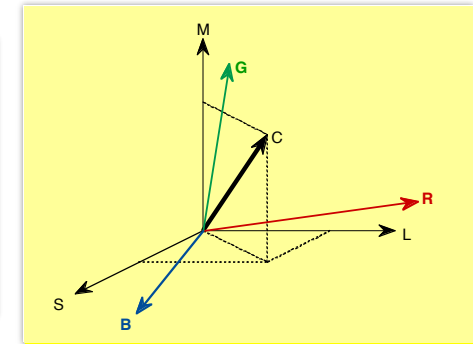
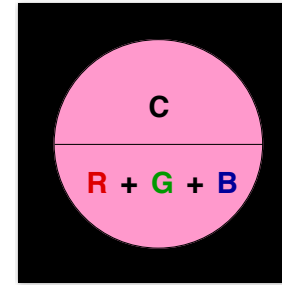


## Basic Colorimetry

Gunter Wyszecki (1973)

- Colorimetry is a tool used to making a prediction on whether two lights of different spectral power distributions will **match in color** for certain given conditions of observation. The prediction is made by determining the tristimulus values of the two visual stimuli. If the tristimulus values of a stimulus are identical to those of the other stimulus, a color match will be observed by an average observer with normal color vision.

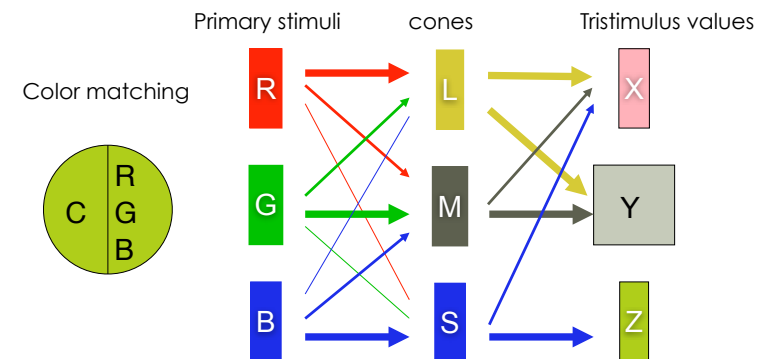
## Color Matching Experiment



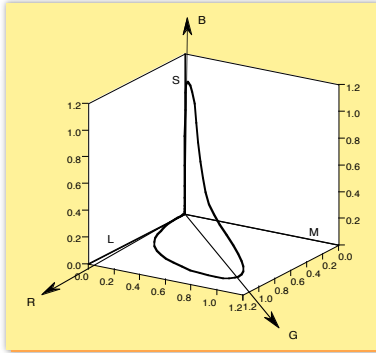
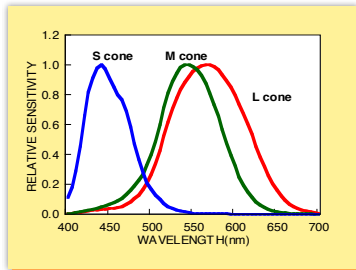
## Basic Colorimetric System

- LMS (Physiological system)**
  - How many photons are absorbed in L, M, and S cone system?
- RGB (Physical system)**
  - How much red, green and blue light are needed to make a color match?
- XYZ (Mathematical system)**
  - To make a color match using three imaginary stimuli

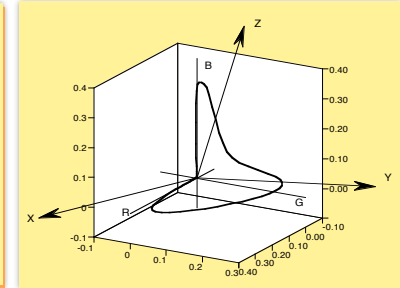
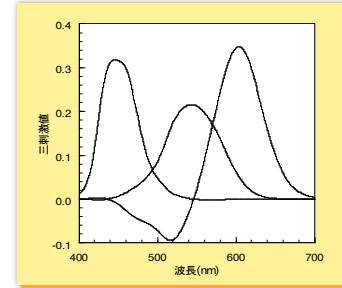
## Color Matching and Tristimulus Values



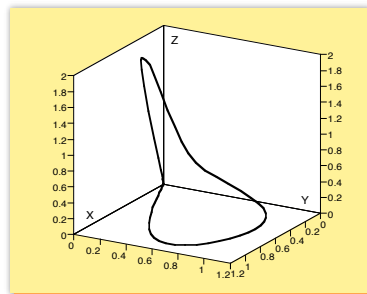
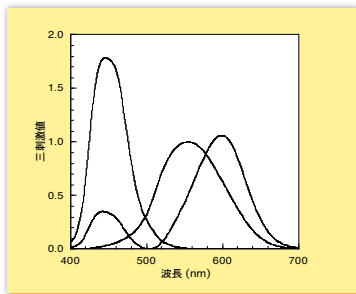
## LMS: Physiological Colorimetry



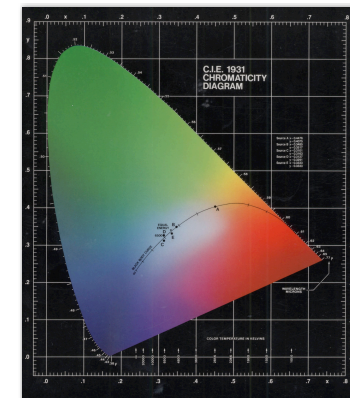
## RGB: Physical Colorimetry



## XYZ: Mathematical Colorimetry



## CIE 1931 (x, y) Chromaticity Diagram





## Advanced Colorimetry

Gunter Wyszecki (1973)

- Colorimetry in its broader sense includes methods of assessing the **appearance of color** stimuli presented to the observer in complicated surroundings as they may in occur in everyday life. This is considered the ultimate goal of colorimetry, but because of its enormous complexity, this goal is far from being reached.

## CIELAB (CIE 1976 L\*a\*b\*)

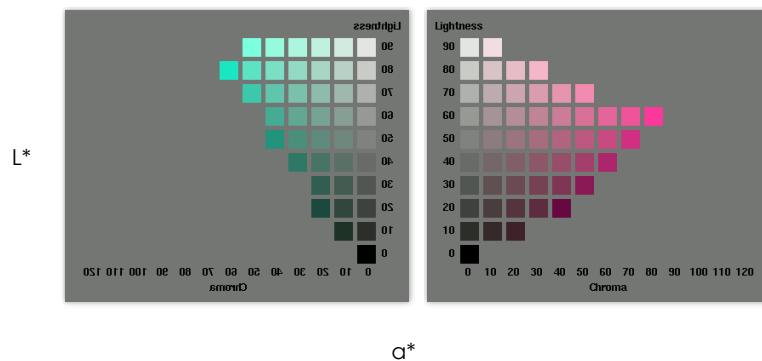
$$L^* = 116 \left( \frac{Y}{Y_n} \right)^{\frac{1}{3}} - 16$$

$$a^* = 500 \left\{ \left( \frac{X}{X_n} \right)^{\frac{1}{3}} - \left( \frac{Y}{Y_n} \right)^{\frac{1}{3}} \right\}$$

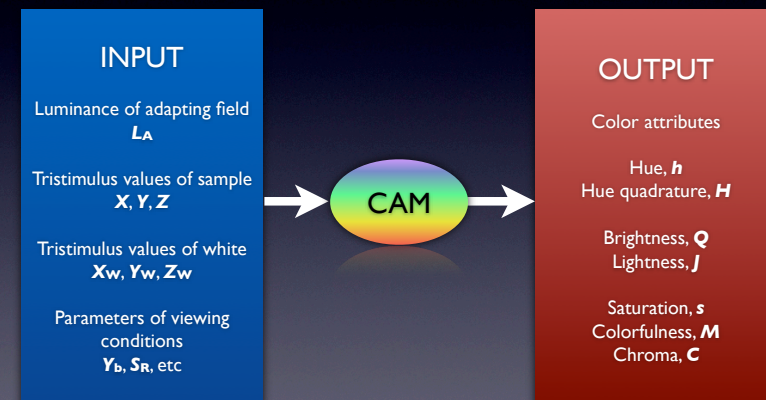
$$b^* = 200 \left\{ \left( \frac{Y}{Y_n} \right)^{\frac{1}{3}} - \left( \frac{Z}{Z_n} \right)^{\frac{1}{3}} \right\}$$

- Color adaptation
  - White is always white
- Non-linearity
  - Physical unit to psychological unit
- Color opponency
  - Luminance and chromaticness

## CIELAB Color Space



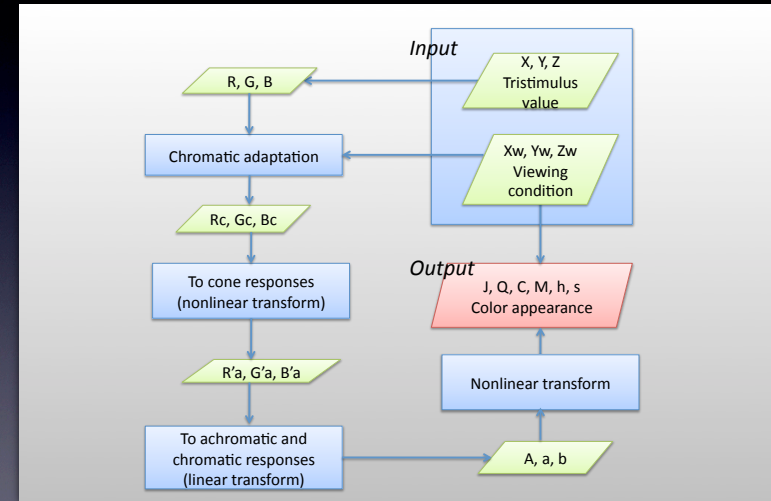
## Color appearance model (CAM)



# Color attributes

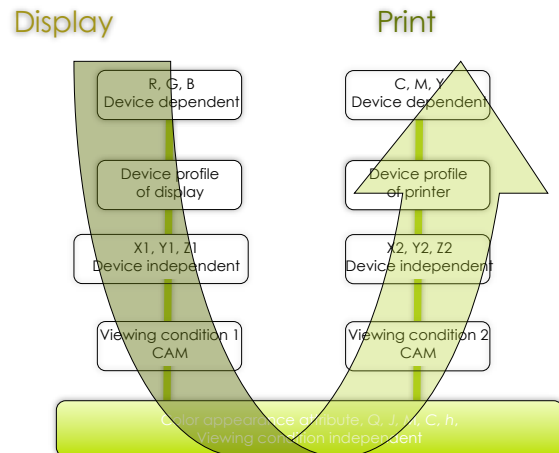
- Absolute attributes
  - Brightness:  $Q$
  - Colorfulness:  $M$
  - Hue:  $h$
- Relative attributes
  - Lightness:  $J = Q/Q_{white}$
  - Chroma:  $C = M/Q_{white}$
  - Saturation:  $s = M/Q = C/J$

# Outline of the CIECAM02

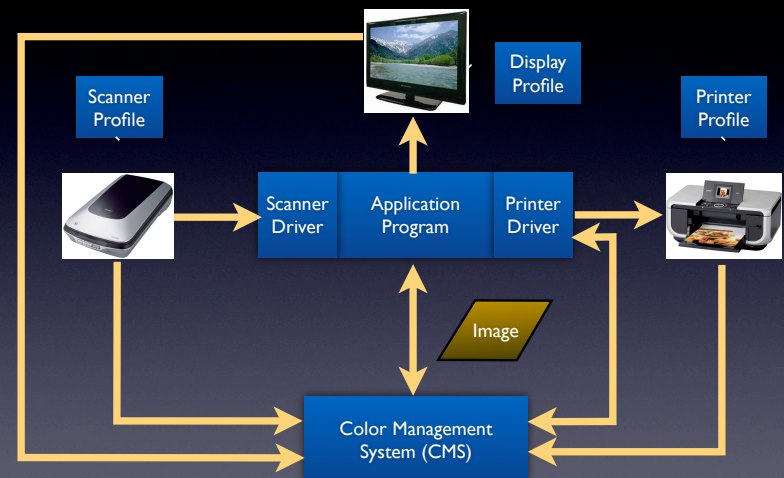


# Application of CIECAM02

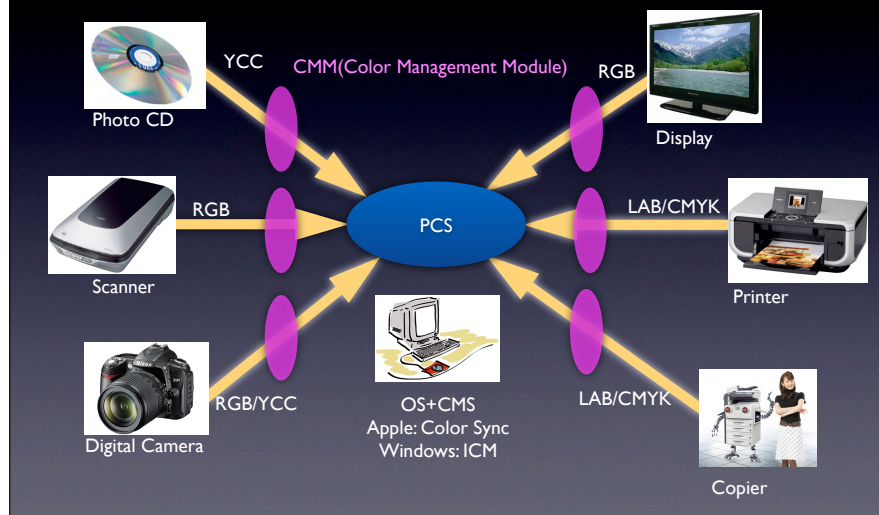
Color reproduction between different imaging media



# Color Management System



# Concept of CMS



# Color vision, colorimetry and color appearance model

