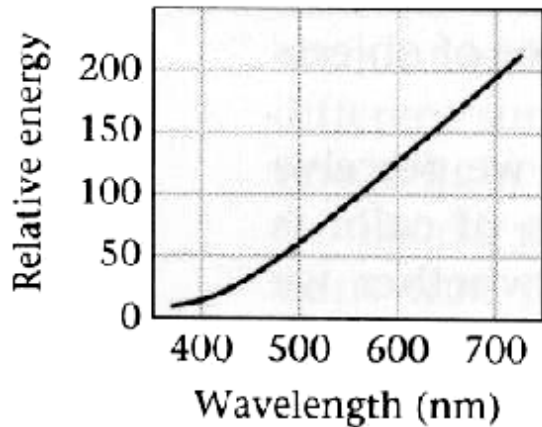


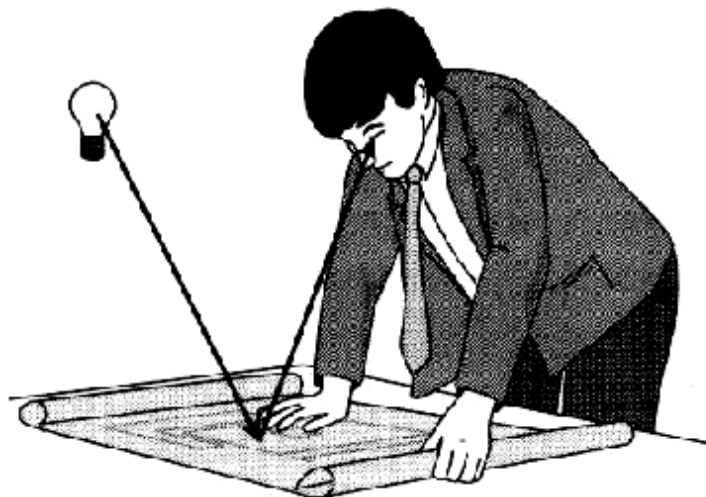
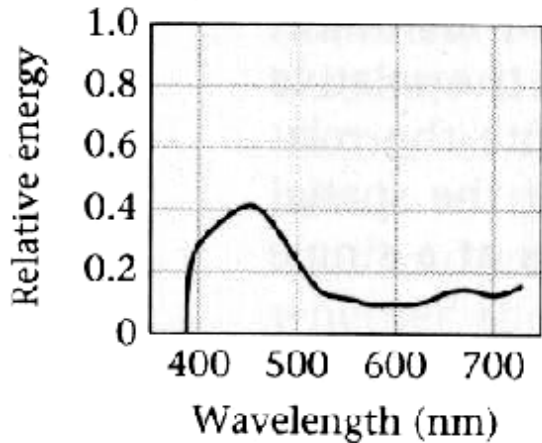
IFT3355: Infographie Couleur

© Victor Ostromoukhov, Pierre Poulin
Dép. I.R.O.
Université de Montréal

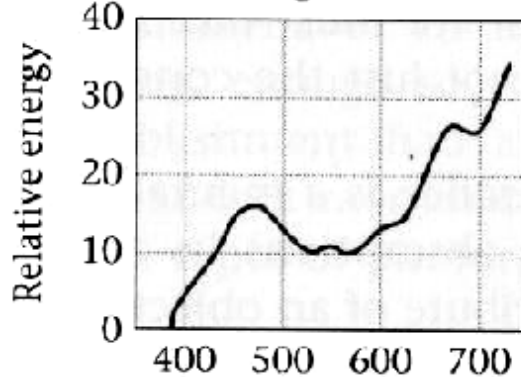
Illumination



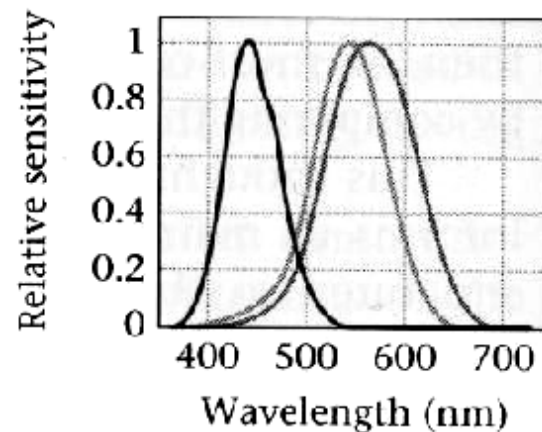
Reflectance



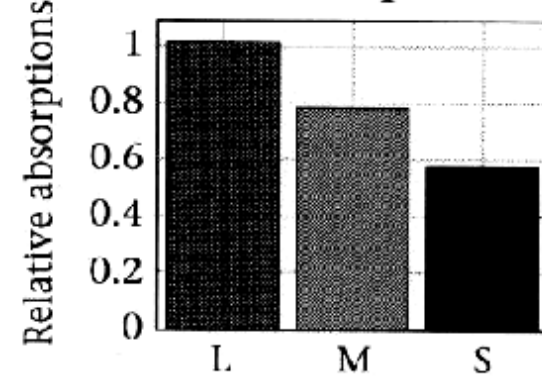
Color signal



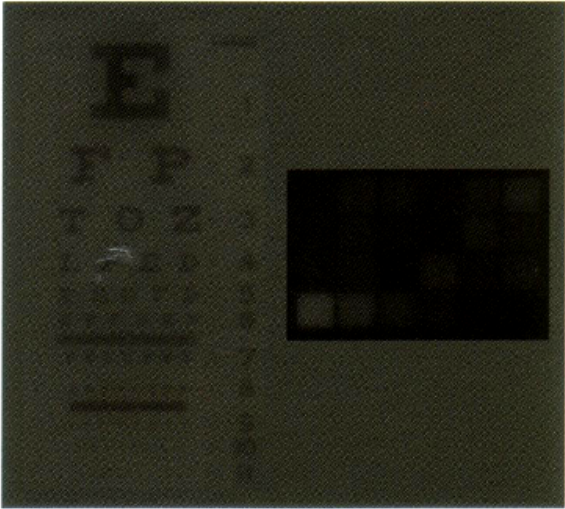
Cone sensitivities



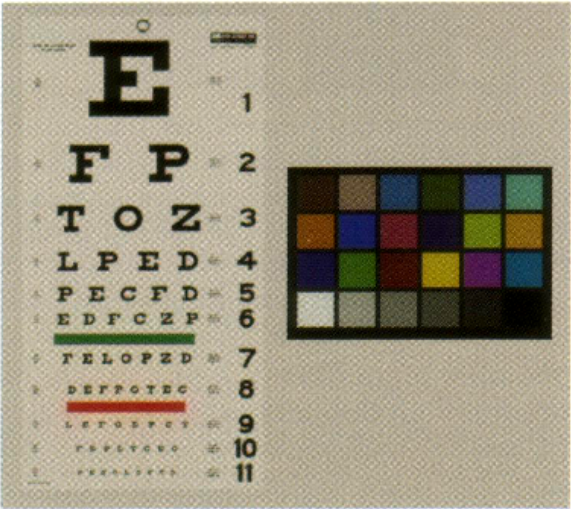
Cone absorptions



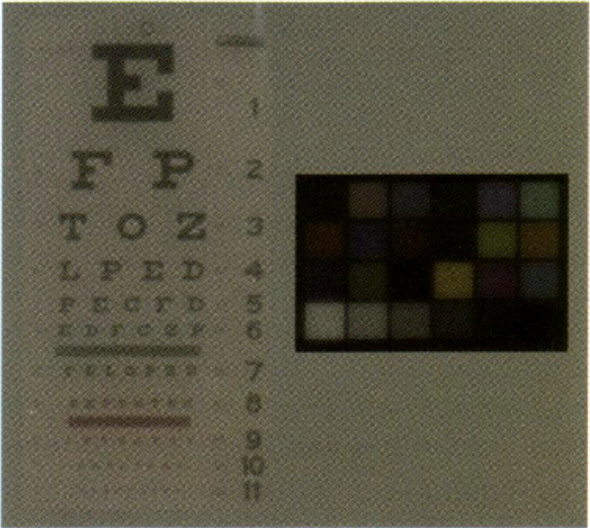
Color Appearance



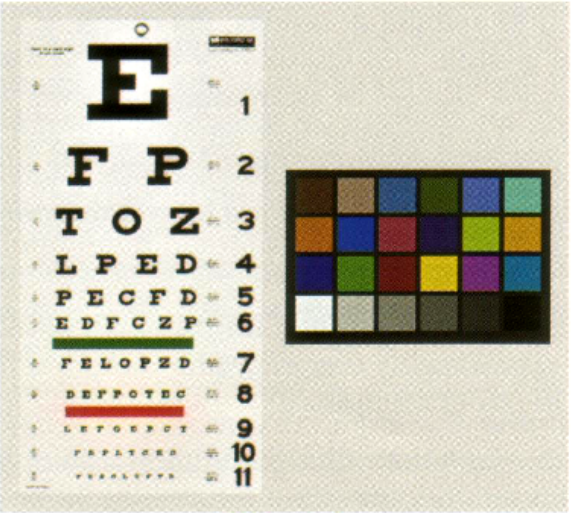
0.1 cd/m²



100 cd/m²



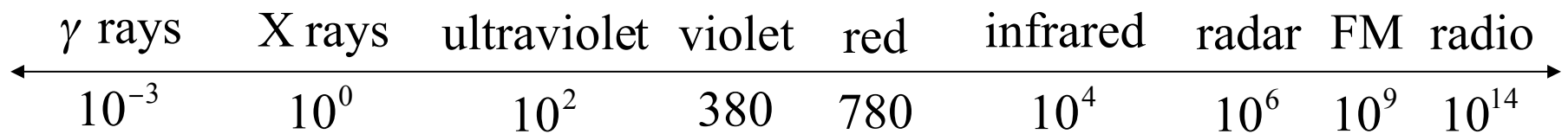
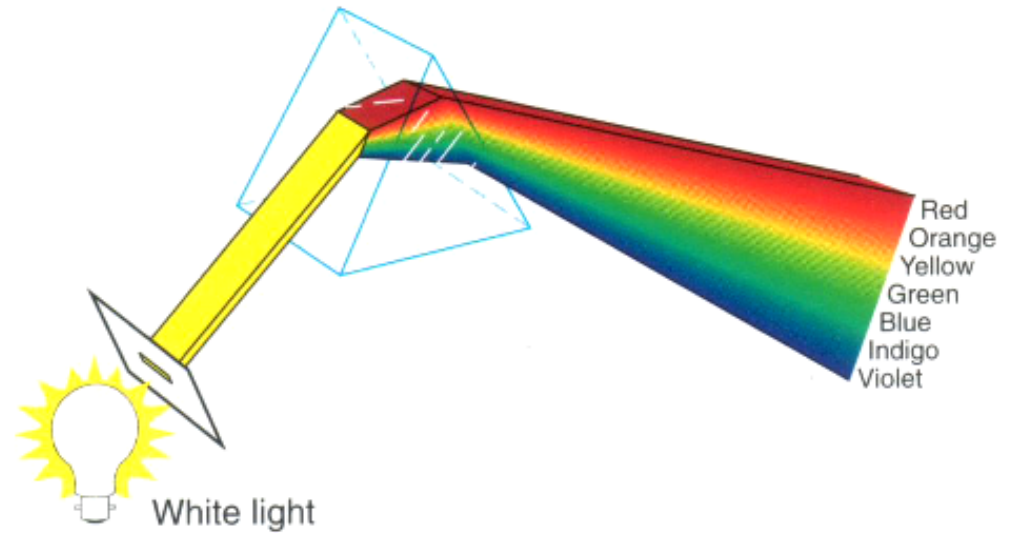
1 cd/m²



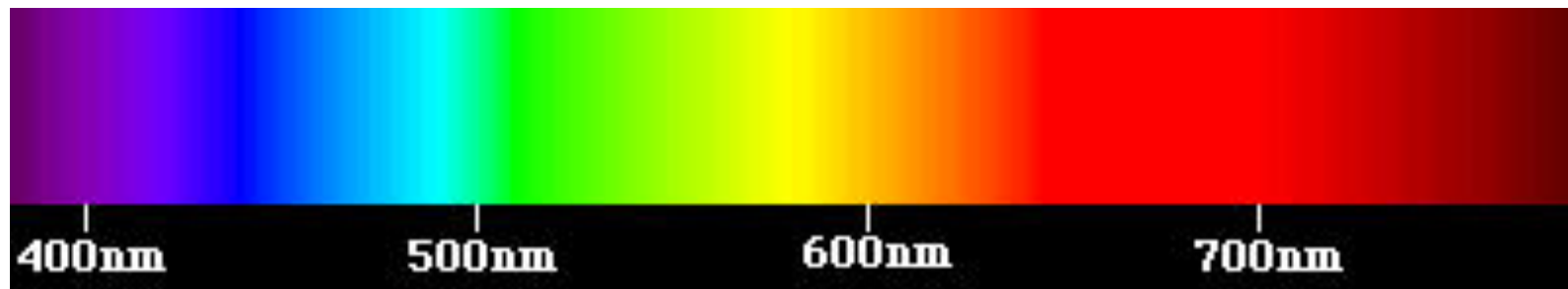
1000 cd/m²

Visual Range

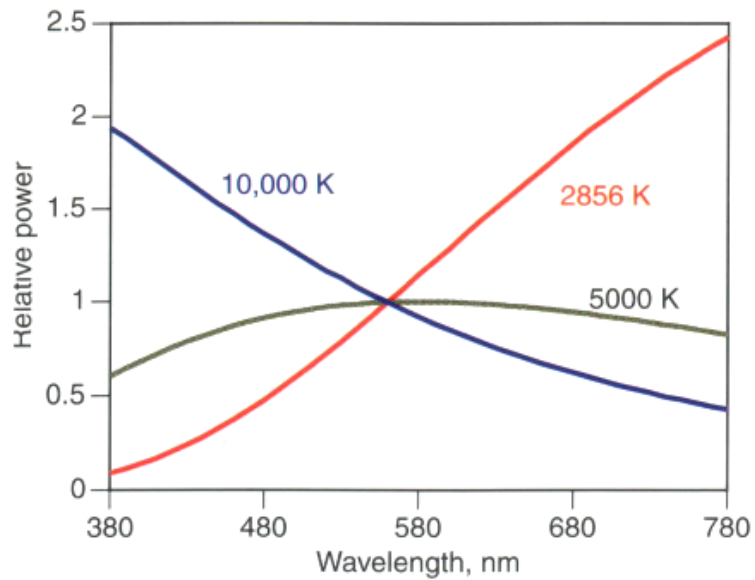
- Electromagnetic waves
- (in nanometres)



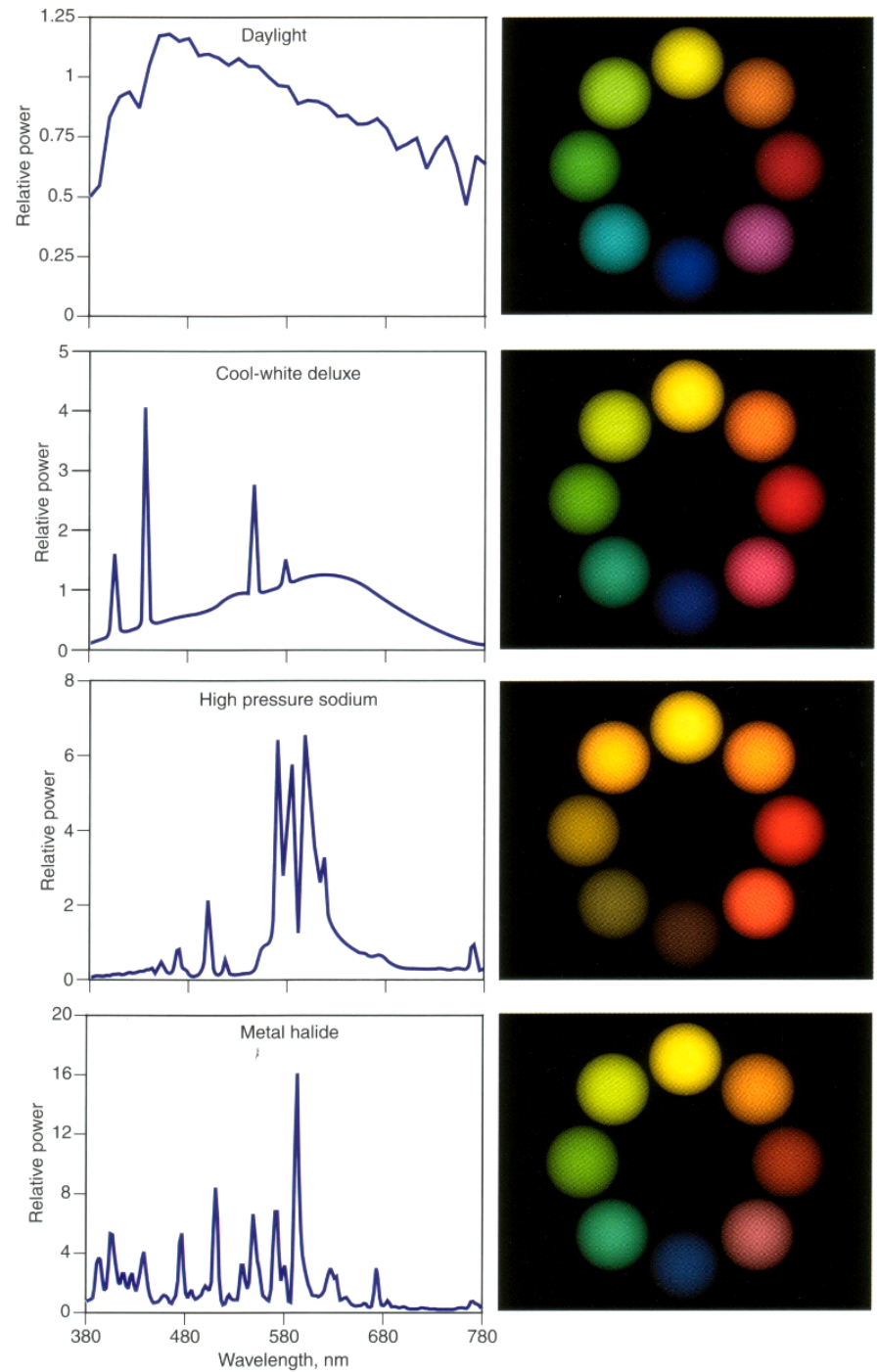
- Color corresponds to an electromagnetic wave between 380 and 780 *nm*



Color as a Spectral Distribution of Intensities

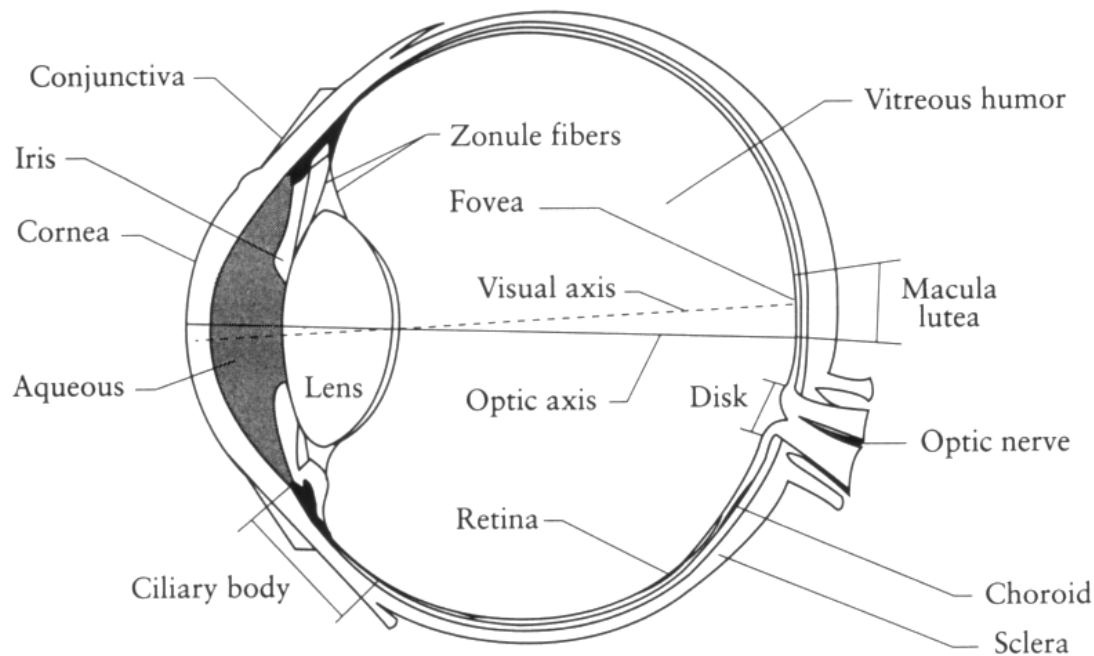


The relative spectral power distribution of blackbody (or Planckian) radiators with color temperatures of 2856 K, 5000 K, and 10,000 K.

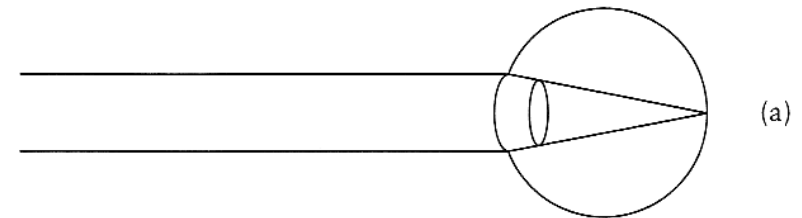
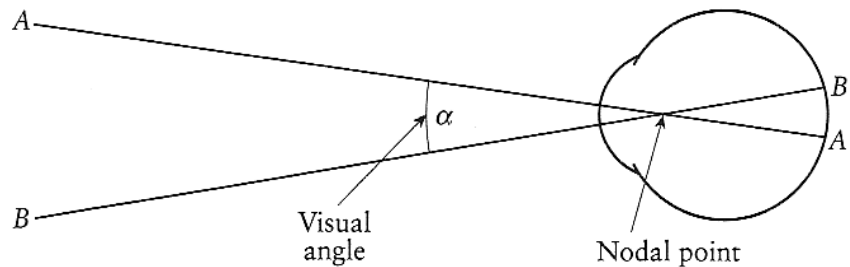


Structures of the Human Eye - Cornea

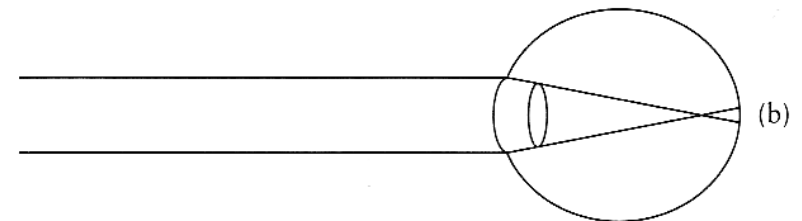
- Clear coating over the front of the eye
- Protects the eye and initial focusing
- 40 *D* (curvature + refraction)
- Strongest focusing element in the eye



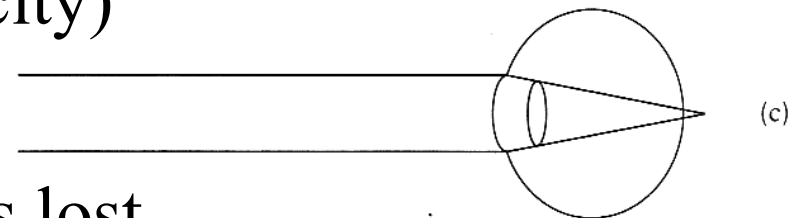
Structures of the Human Eye - Lens



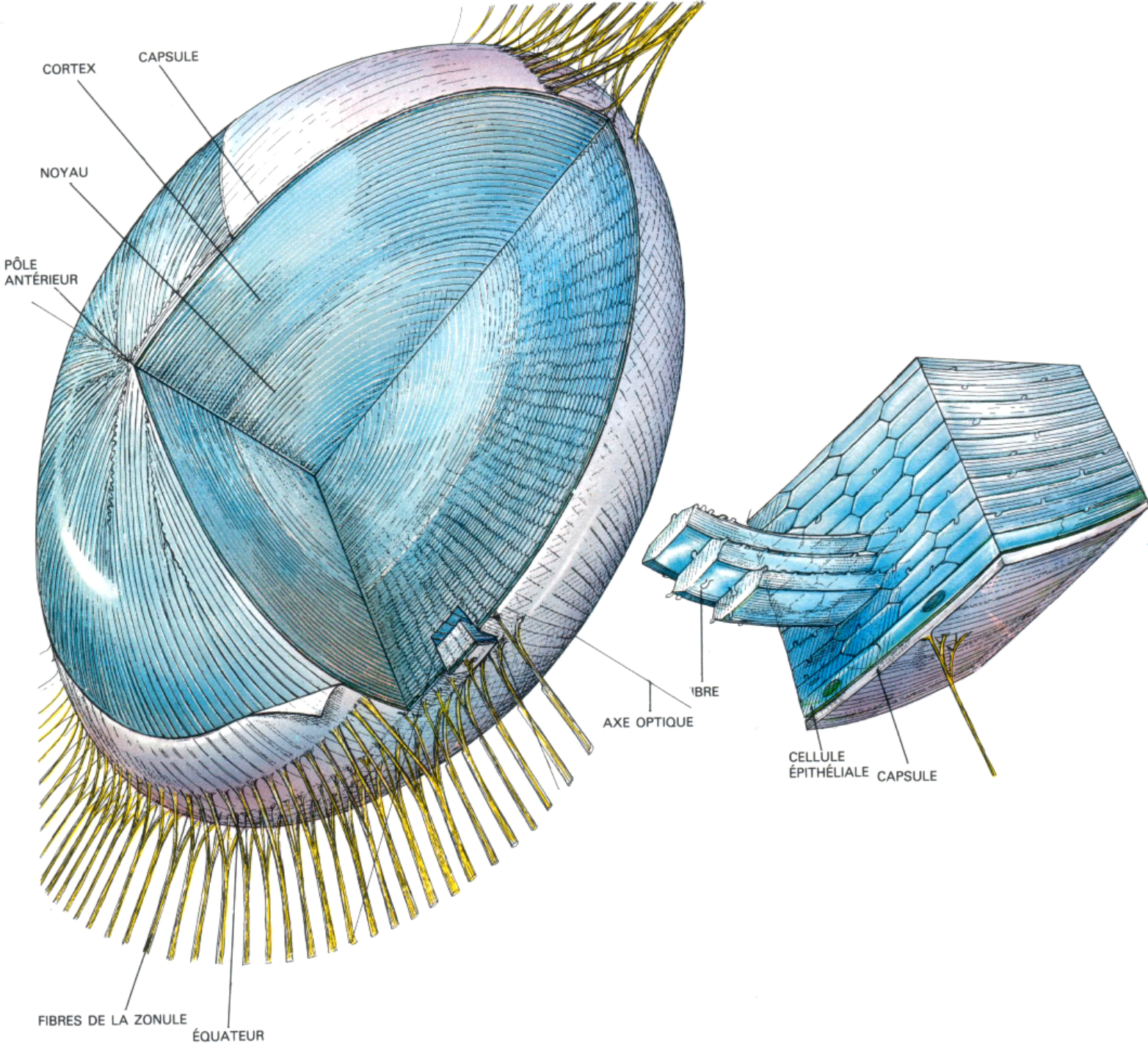
- Crystalline lens
- Ciliary muscles tense to compress (rounder) the lens
 - uncompressed : far focus
 - compressed : near focus



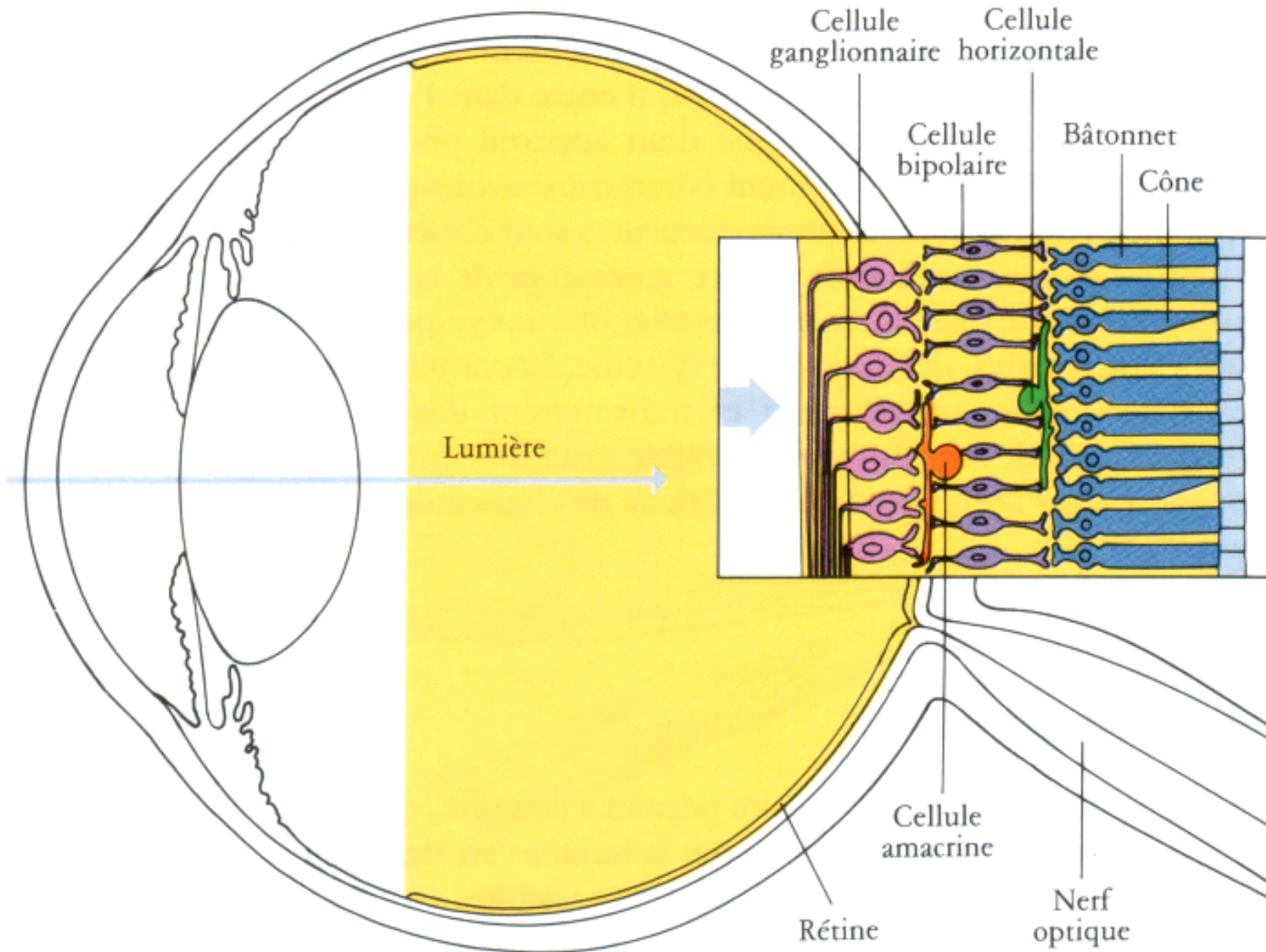
- Accommodation
 - ability of lens to stretch (elasticity)
 - 10-30 D in children
 - after 45 years, most elasticity is lost



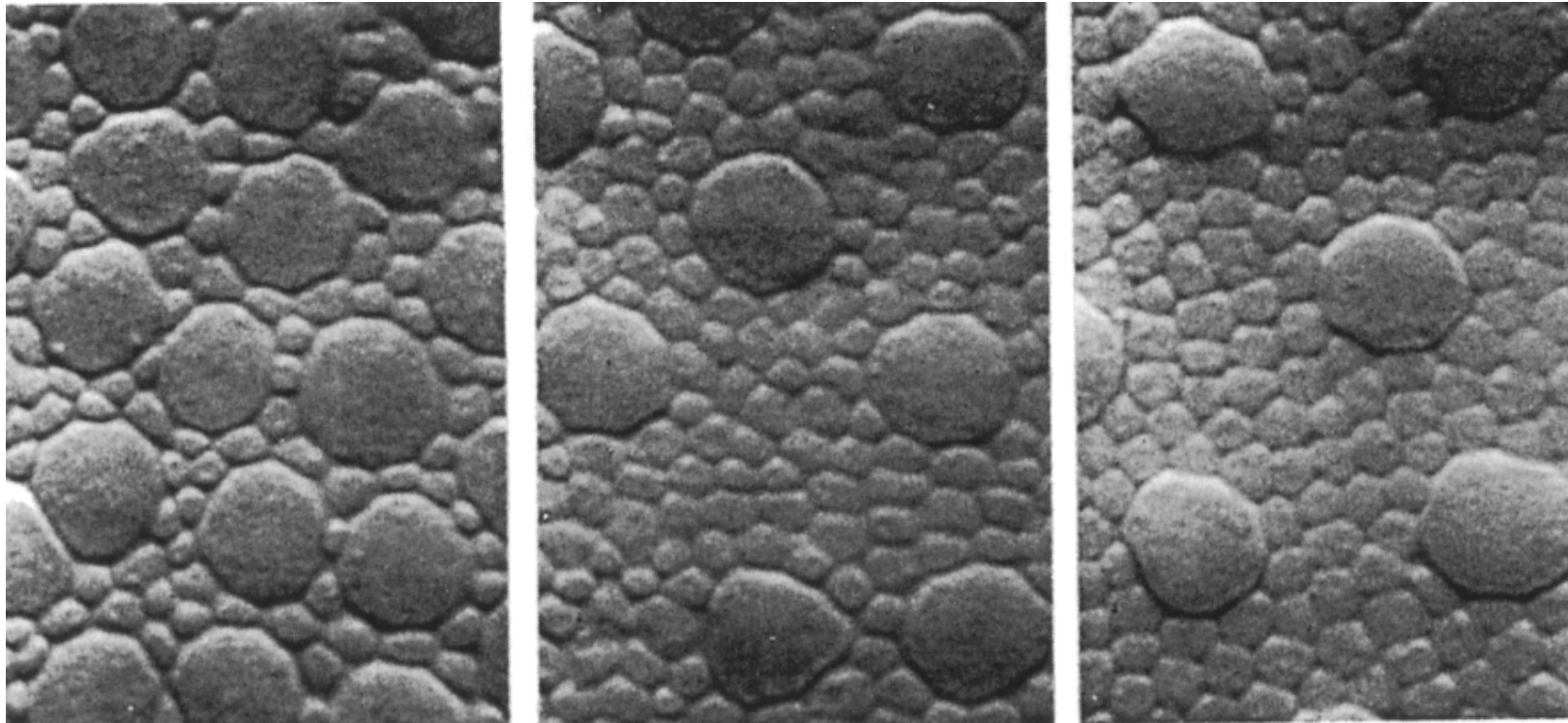
Crystalline



Structures of the Human Eye - Retina

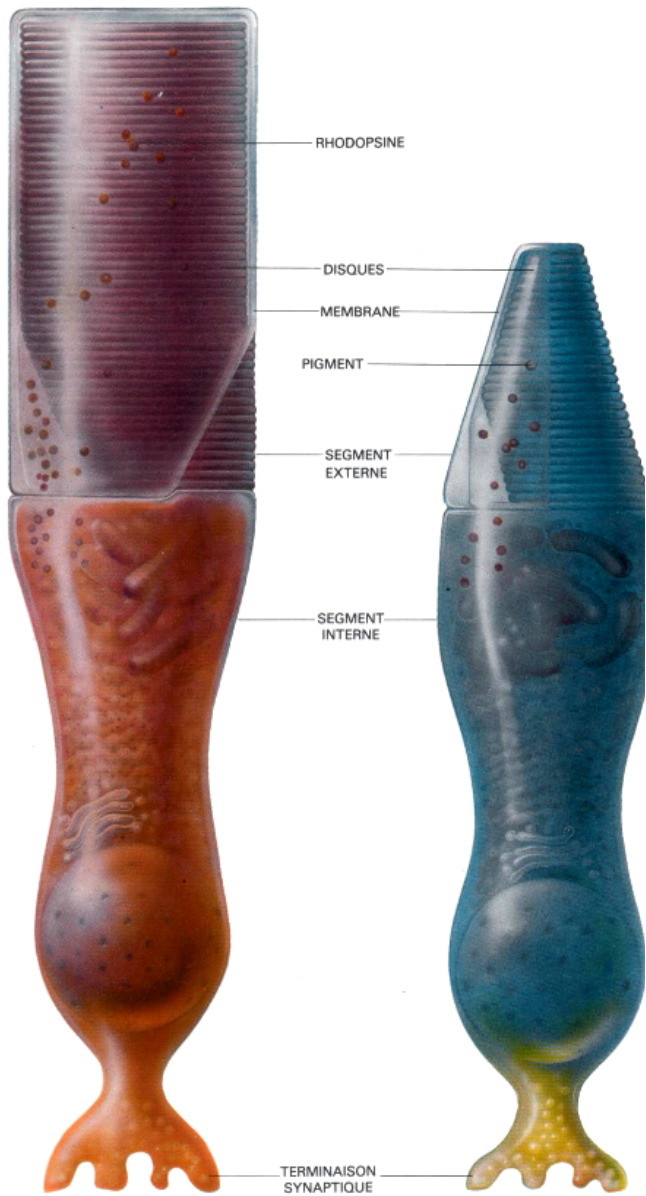


Structures of the Human Eye - Retina



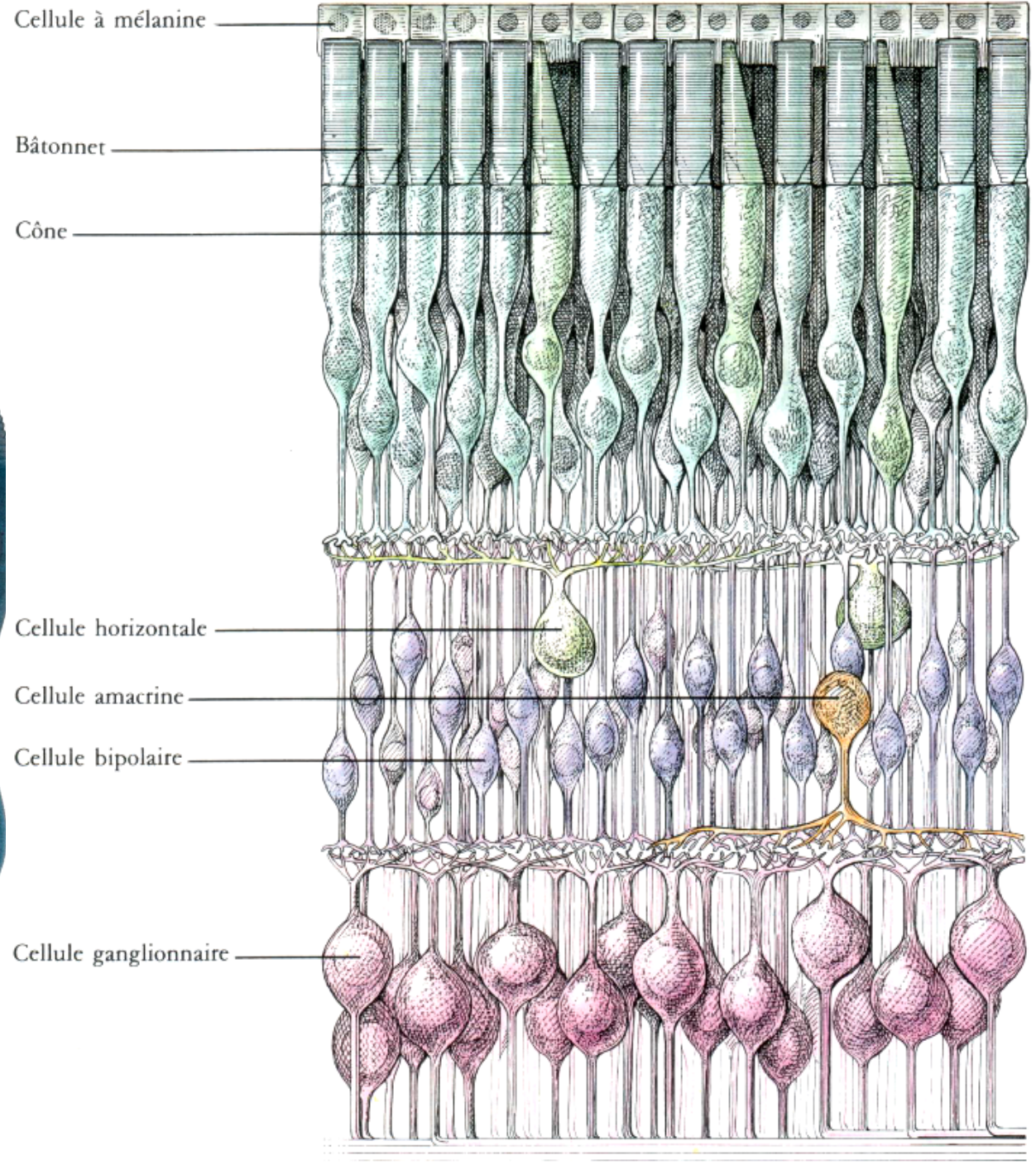
Rods / Cones

- Rods
 - 10x more sensitive than cones
 - night vision (scotopic)
 - beyond a certain intensity, rods are completely saturated
 - no synaptic chemicals released
 - typical daylight
- Cones
 - day vision (photopic)
 - when adapted, cones react like rods wrt saturation



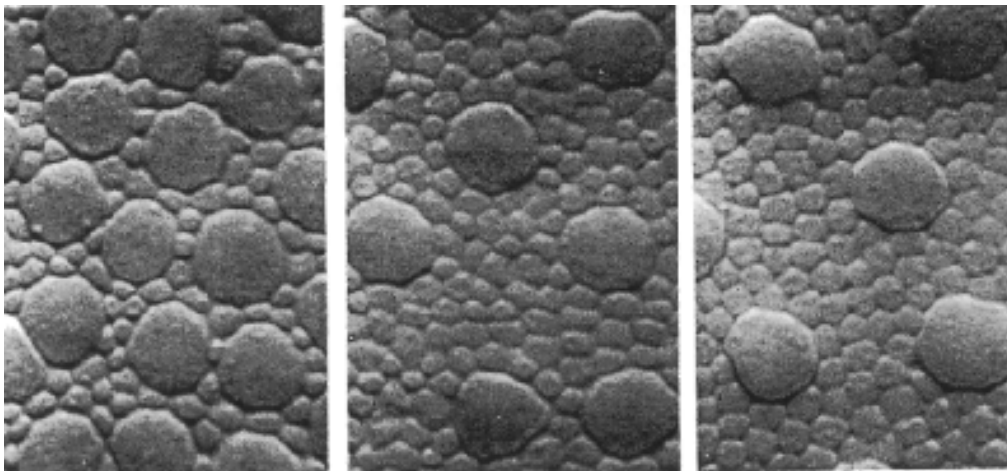
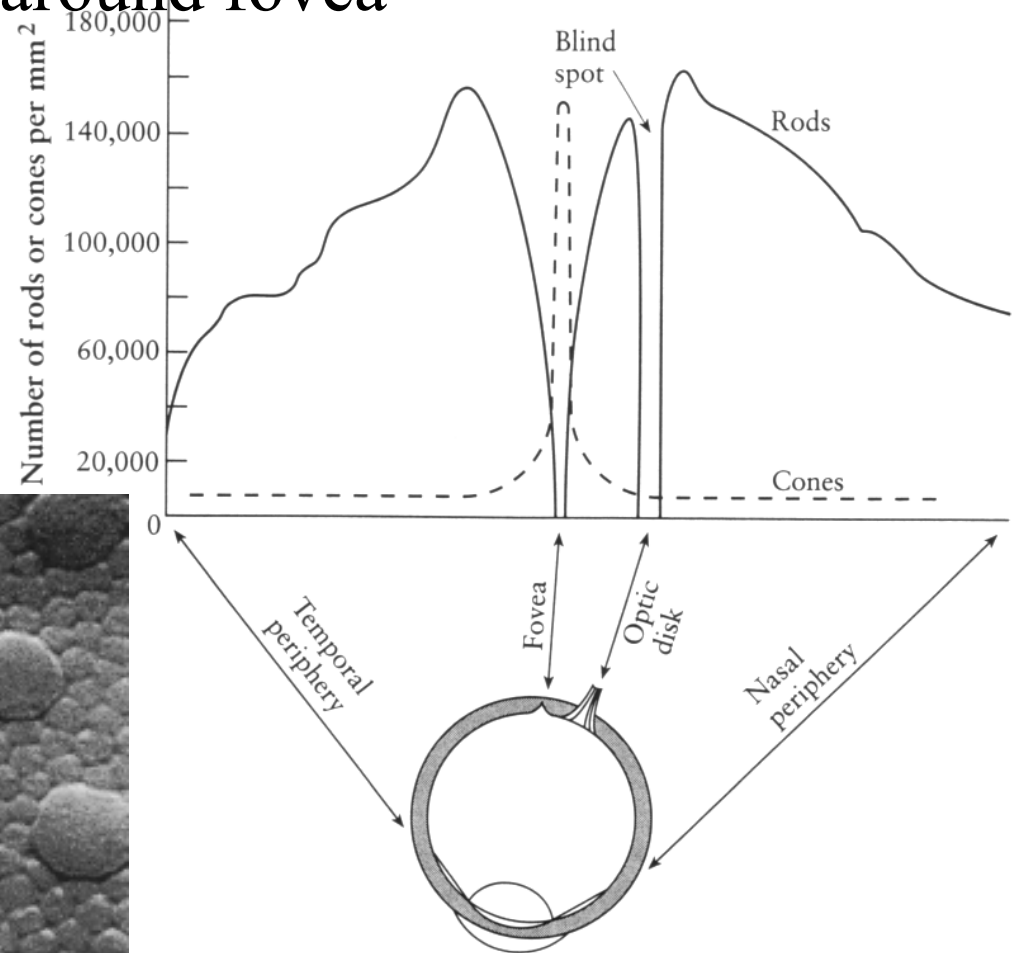
BÂTONNET

CÔNE



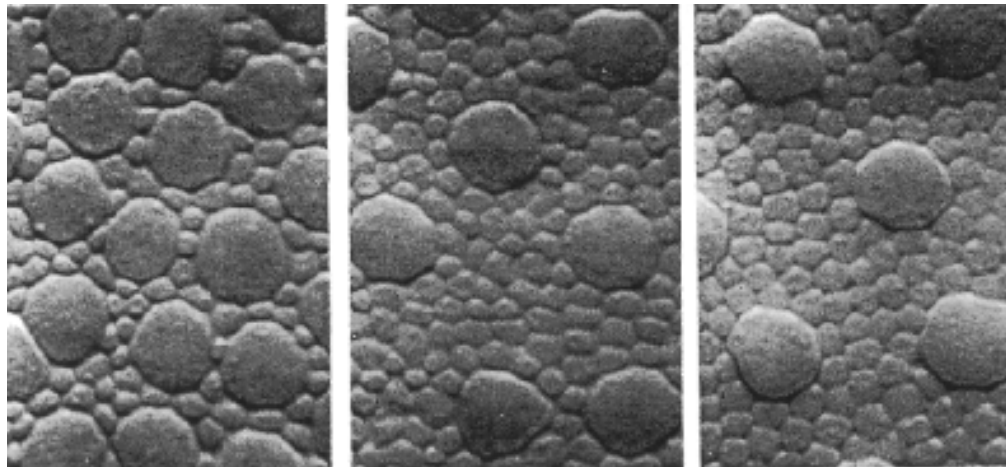
Structures of the Human Eye - Fovea

- Center of visual axis
- 1-2 degree of visual angle
- Roughly radially symmetric around fovea
- Contains only cones
- 147,000 cones/mm



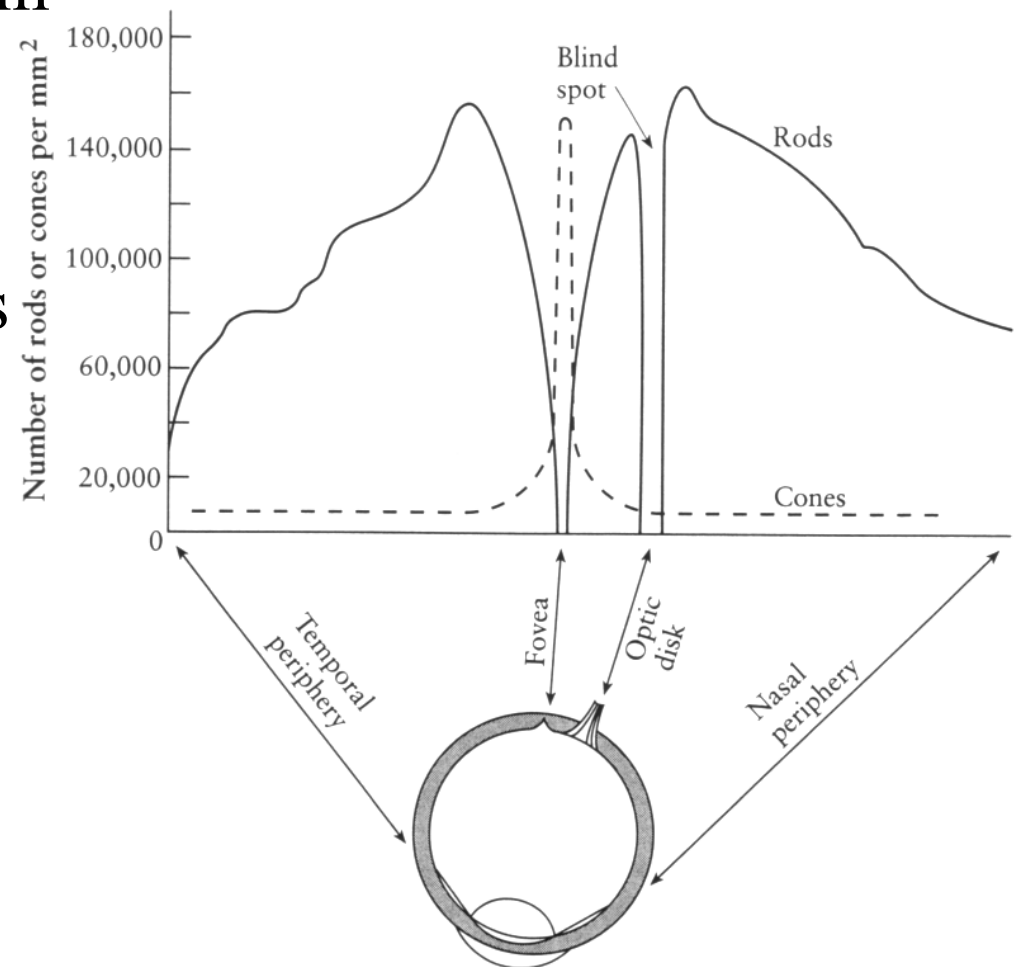
Structures of the Human Eye - Retina

- Rods increase when moving away from fovea
- At edge of fovea, more rods than cones
- Further away, rods form rings around cones
- Highest rod density at 20 degree from fovea point
- Photoreceptors diminish when moving away from fovea
- Visual acuity at fovea, less precision away
- 120 million rods / 6 million cones



Structures of the Human Eye - Optic Nerve

- 1 million fibers : eye does some processing before signal reaches the brain
- Blind spot
 - no photoreceptors
 - completion process

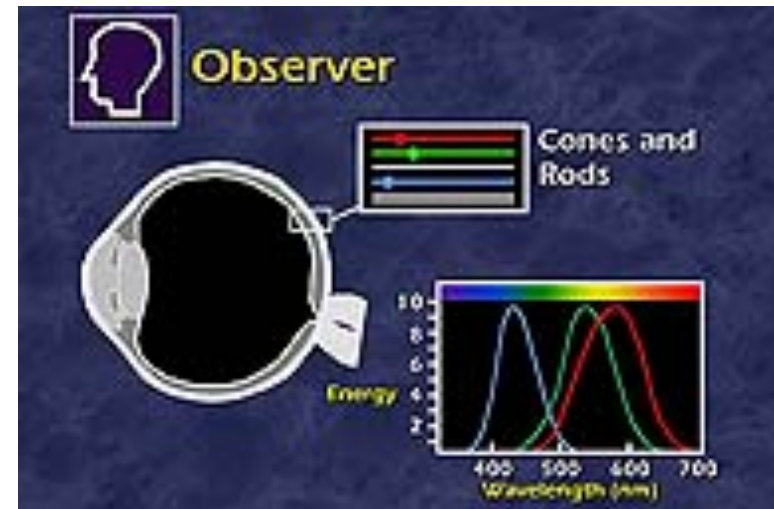
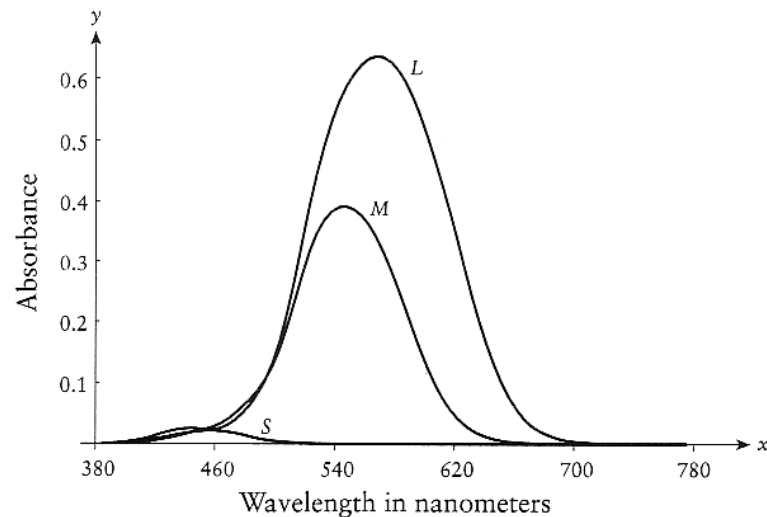


Structures of the Human Eye - Eye Shape

- Cornea + lens = 60-80 D
- With 24 mm , only 42 D is needed
 - compensating for the imperfect shape of the eye
- Corrective lenses
 - Myopic
 - near-sighted, focus in front of retina
 - Hyperopic
 - far-sighted, focus behind retina

Cones

- 3 types of cones in human eye
 - **S** 420 *nm*
 - **M** 530 *nm*
 - **L** 560 *nm*



- Bell-shaped curves
- No S cones in very center of fovea

Color Blindness

Original



Missing S cones



Missing L cones



Missing M cones



A simulation of what an observer missing either S, L, or M cones might see. Notice that the red apple and red pepper become very dark to an observer missing L cones. [After Burnham (1963). See Brettel (1997) for a more quantitative simulation.]

Color Blindness



Rainbow colors



Protanopia
No Red



Deuteranopia
Only 2 Cones



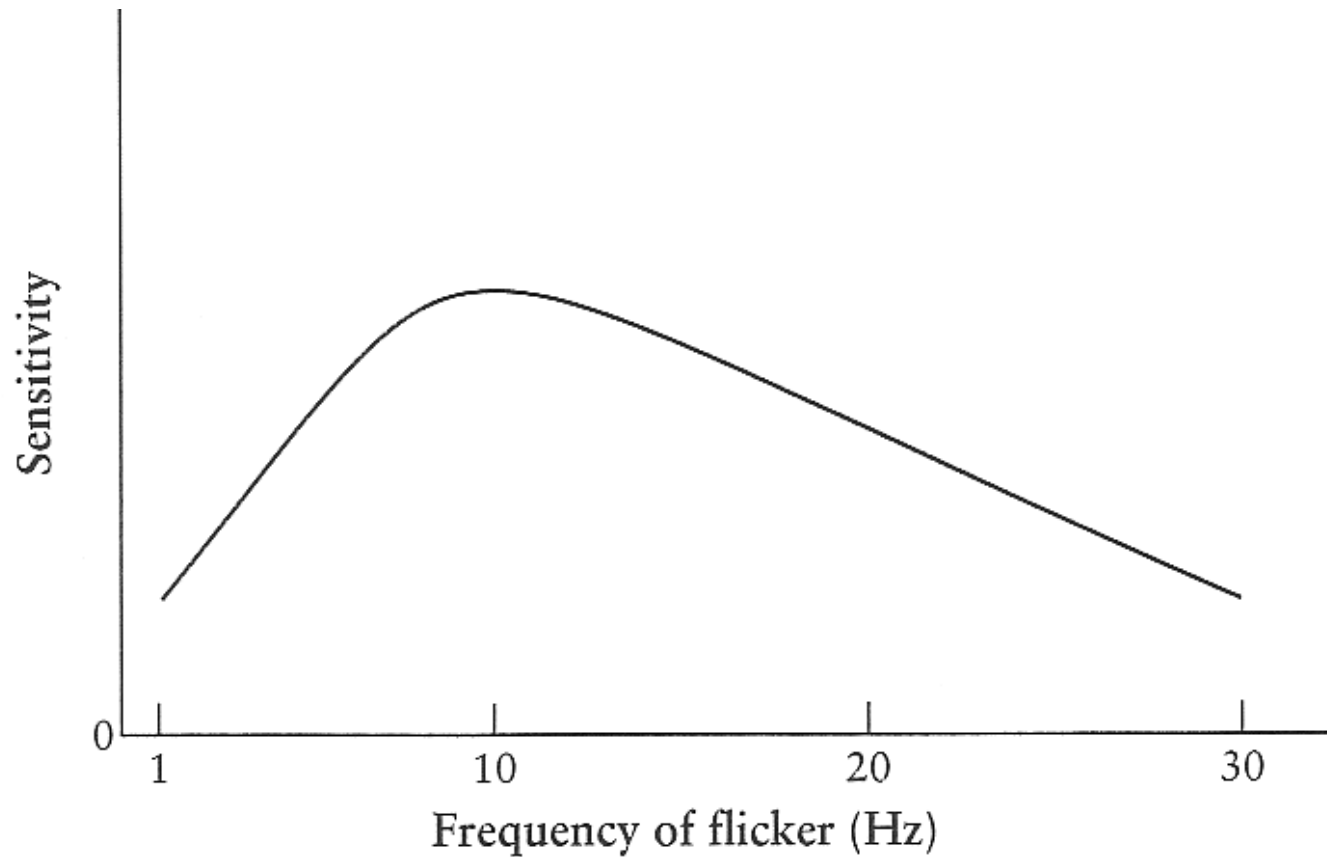
Tritanopia
No Blue
Only 2 Cones

Reaction to Light

- One photon is enough to produce a chemical reaction
- Info transmitted by the cone or rod is the stimulation, but not the associated wavelength
- Spatial vs. spectral density
 - “more types of cones” takes more space
 - “less types of cones” requires to reconstruct the spectrum
 - some birds have 5-7 types of cones

Temporal Smoothing

- Flicker disappears at 60 Hz in best conditions
- 300 Hz for a bee

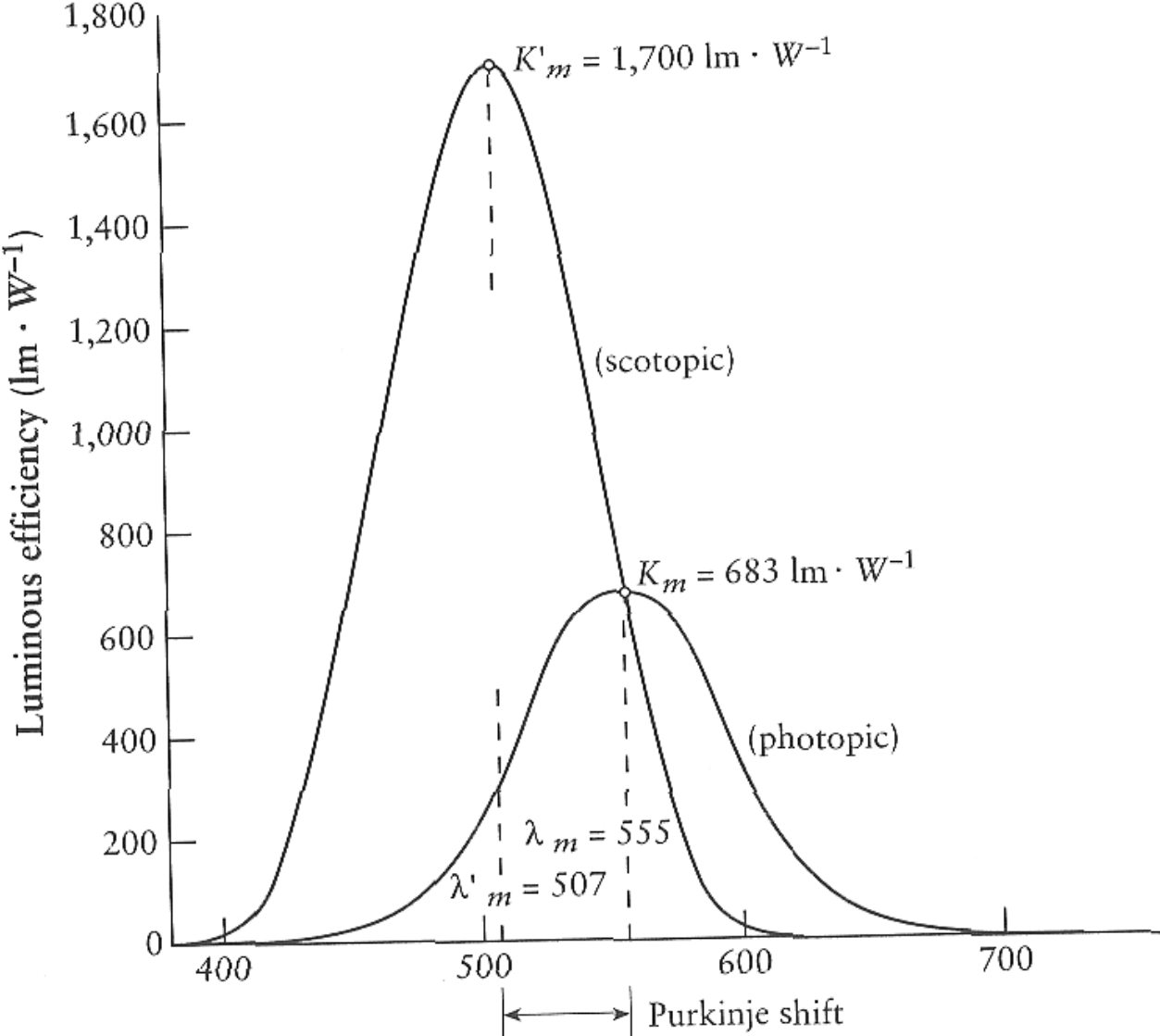


Adaptation

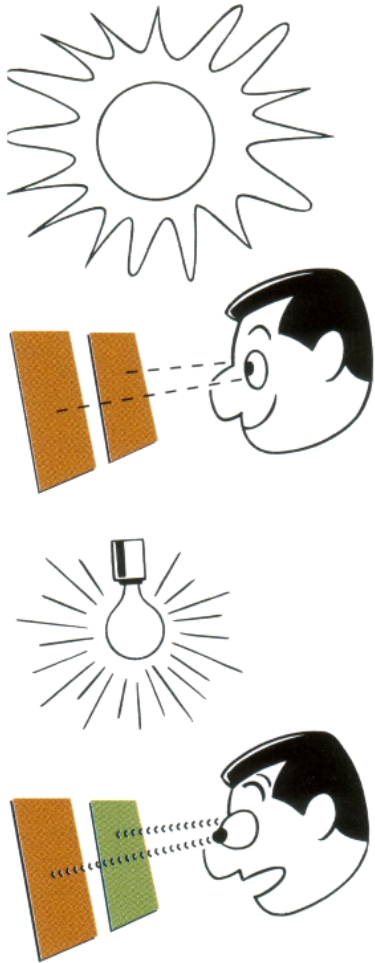
- Eye responds to enormous variations in levels of incoming light

moonless overcast night	0.00003	candelas / m^2
twilight	3	
clear day	3,000	
snow in sunlight	16,000	

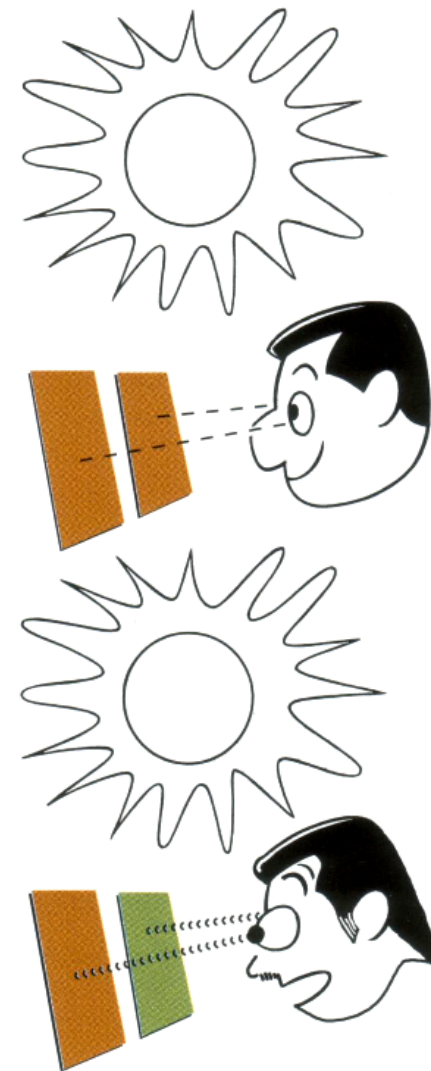
Luminous Efficiency Curves



Metamerism

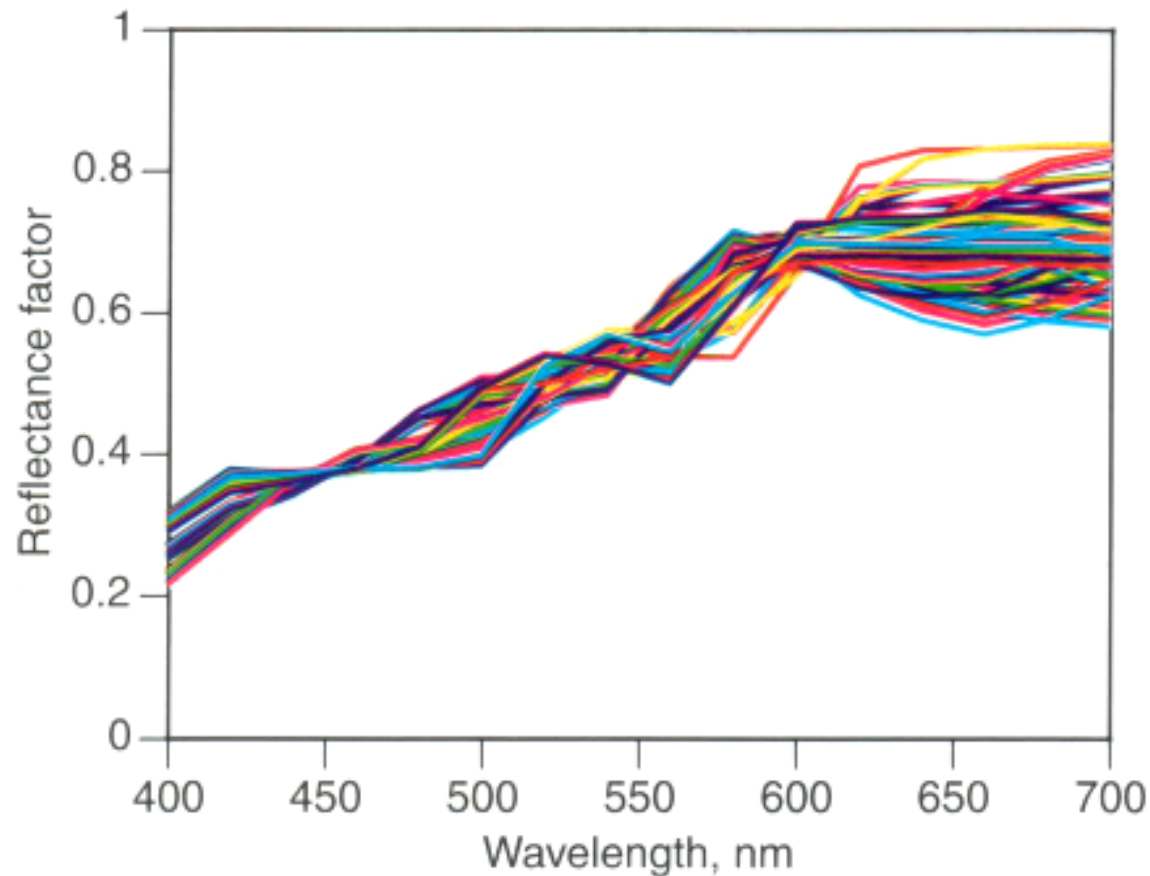


It is a common (and sometimes unpleasant) fact that pairs of colors with different spectral reflectance curves can match under one set of viewing and illuminating conditions, but fail to match under another. They are called *metameric pairs* or *metamers*. When the mismatch occurs due to a change in illumination, the phenomenon is called *illuminant metamerism*.



When the mismatch occurs due to a change in observer, the phenomenon is called *observer metamerism*.

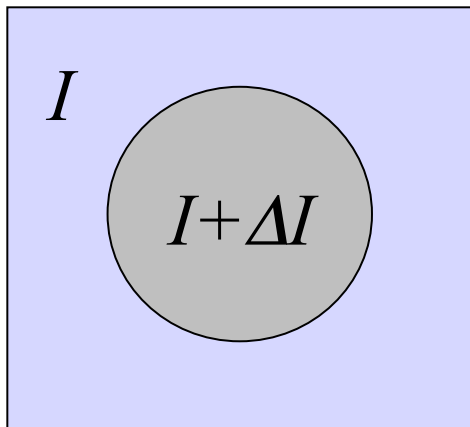
Metamerism



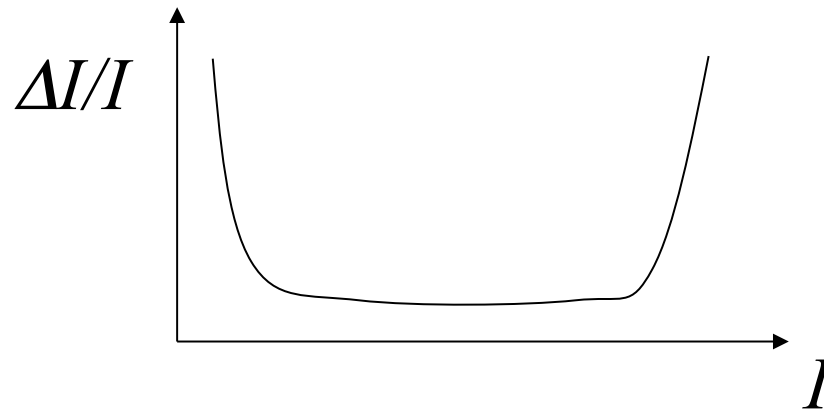
Ensemble of spectral reflectance curves corresponding to three chromatic-pigment recipes all matching a tan material when viewed by an average observer under daylight illumination. [Based on Berns (1988b).]

Visual Phenomena - Contrast Sensitivity

- Eye is sensitive to intensity ratios, not absolute values
- Adaptation plays an important role in contrast sensitivity



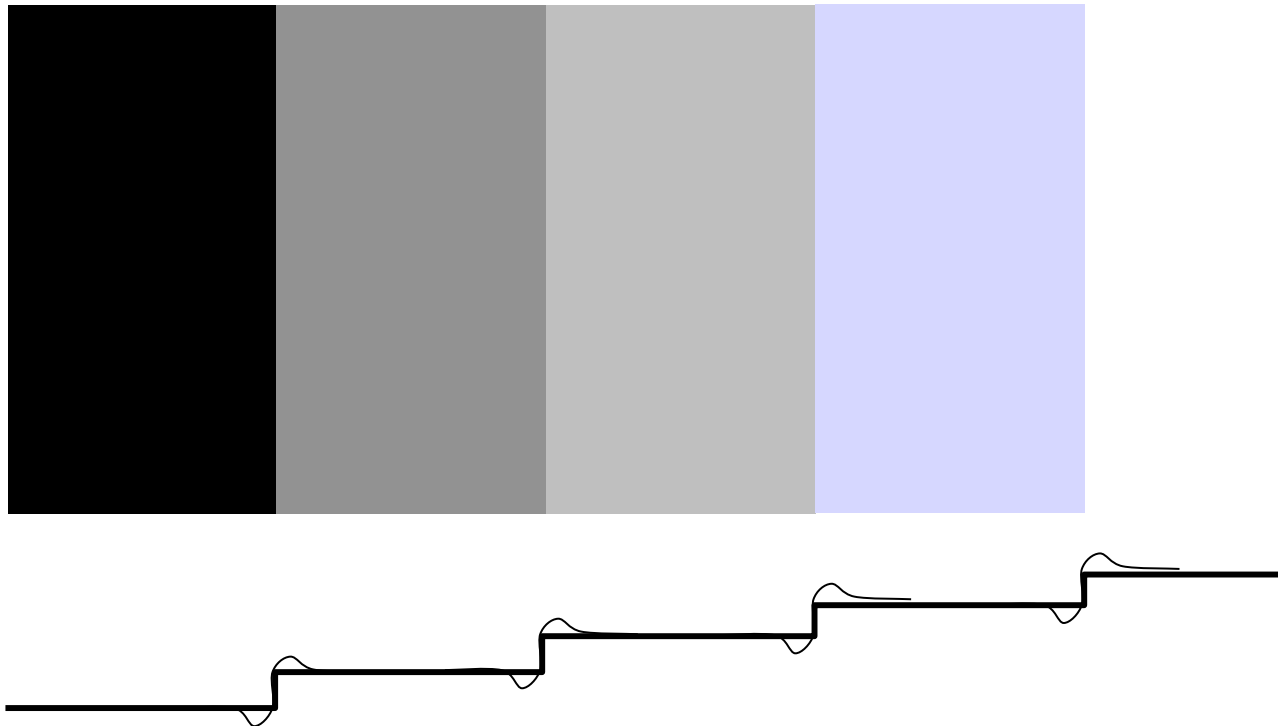
ΔI : just noticeable difference



ratio $\Delta I/I$ (Weber fraction) is nearly at 0.02 over a range of intensities

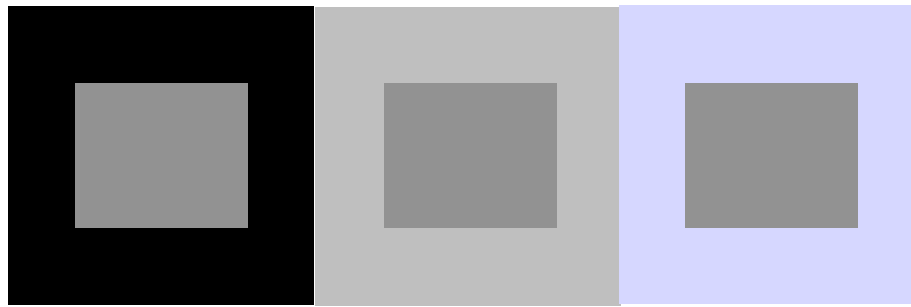
Visual Phenomena - Mach Bands

- Variously emphasizes edges or suggests edges where the signal changes smoothly
- Regions of high changes and high first derivatives



Visual Phenomena - Lightness Contrast

- Lightness of a region seems to depend on surrounding intensity

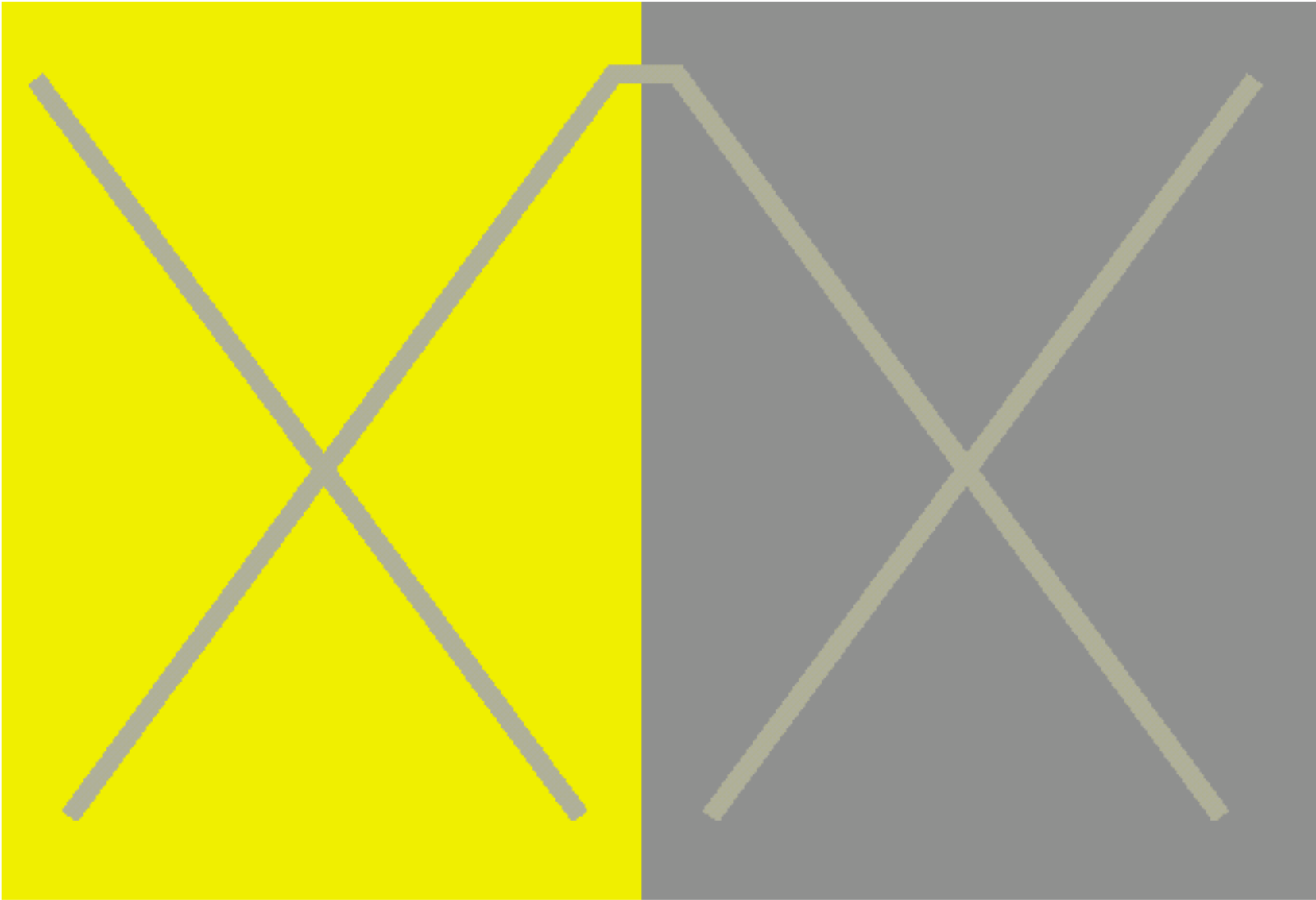


- Difficulty to pick a color that will appear the same throughout the picture, but the eye is used to that...
- Color constancy : change illumination but keep the same mental image of the scene

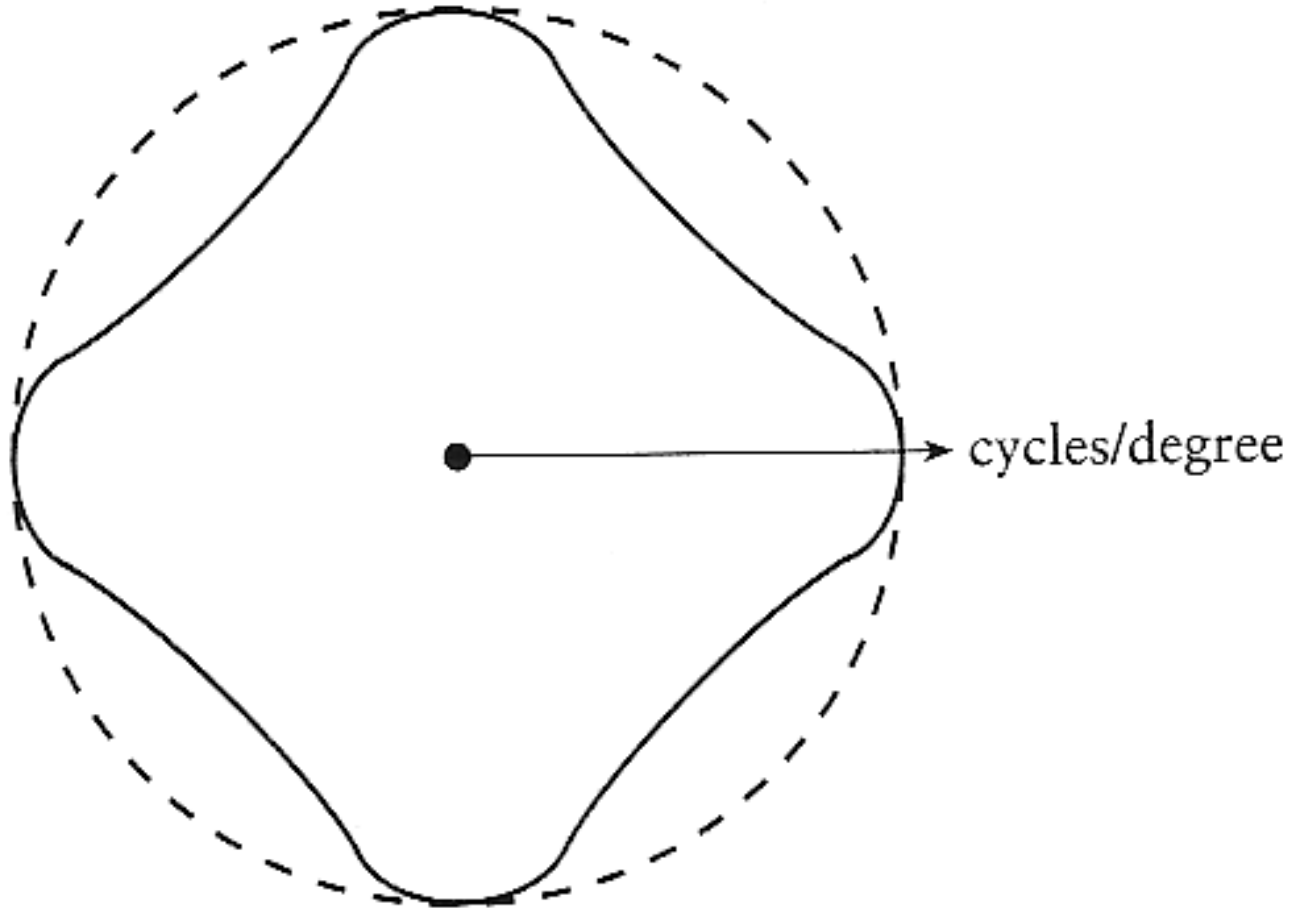
Color Appearance, Color Constancy



Color Appearance



Visual Phenomena - CSF (contrast spatial frequency?)

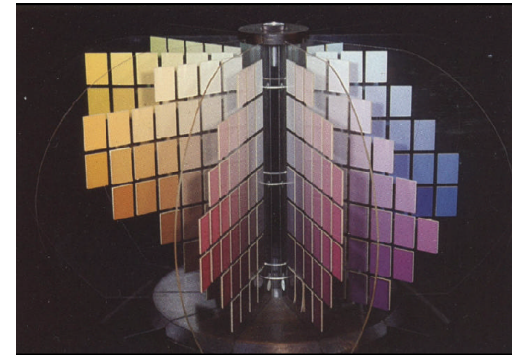





Factors Affecting the Visual System Response

- Adaptation of eye
- Psychological processing
- Frequency and distribution of background illumination
- Image size
- Frequency and intensity of recent stimuli
- Fatigue
- Age
- Nutrition
- etc.

Hopeless... but it isn't that bad!

Color Perception (Three Properties)



- *Hue* 
 - determined by the dominant wavelength
 - red, yellow, purple
- *Saturation* 
 - distance from grey from the same intensity
 - from neutral to vivid
- *Lightness* (luminance) 
 - quantity of light the color reflects/transmits
 - *brightness* for emission

Additive vs. Subtractive Models

Fig. 169 Color mixtures of reflected pigment—subtractive process.

Fig. 170 Color mixtures of refracted light—additive process.

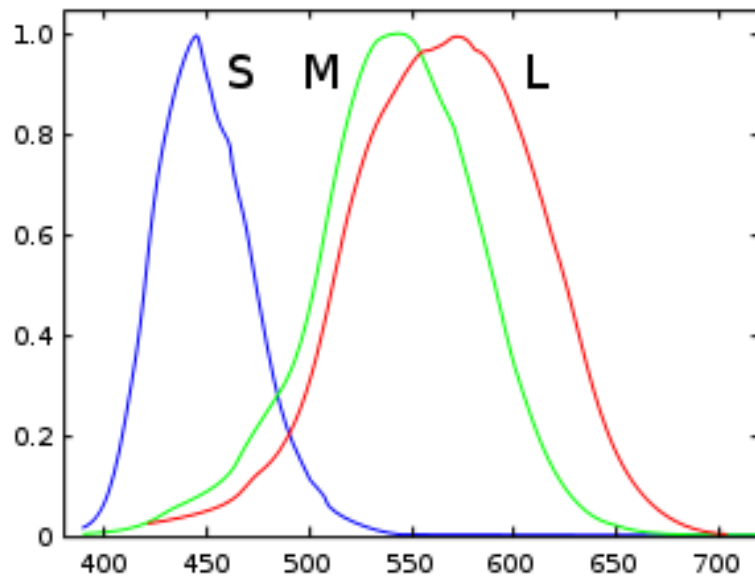
Additive
red, green, blue

Subtractive
cyan, magenta, yellow

WRONG

RIGHT

Cone Response Functions for S, M, L



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

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

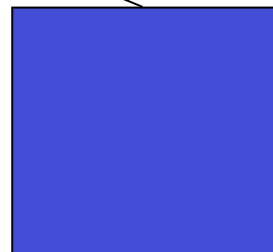
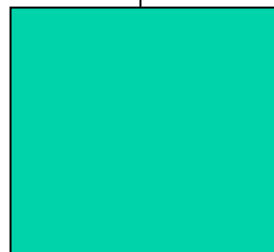
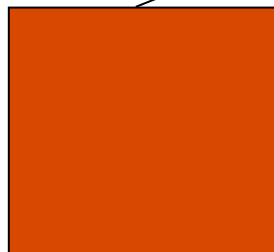
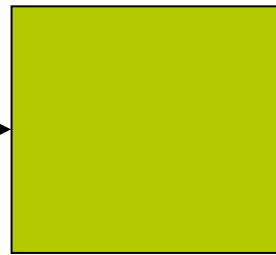
$$L = \int_{\lambda} \Phi(\lambda)L(\lambda)d\lambda$$

For a spectral $\Phi(\lambda)$ signal, the response of each type of cone corresponds to the integral of the product at each wavelength

Color in 3D Space

monochromatic
color to match

sum of the
monochromatic lights

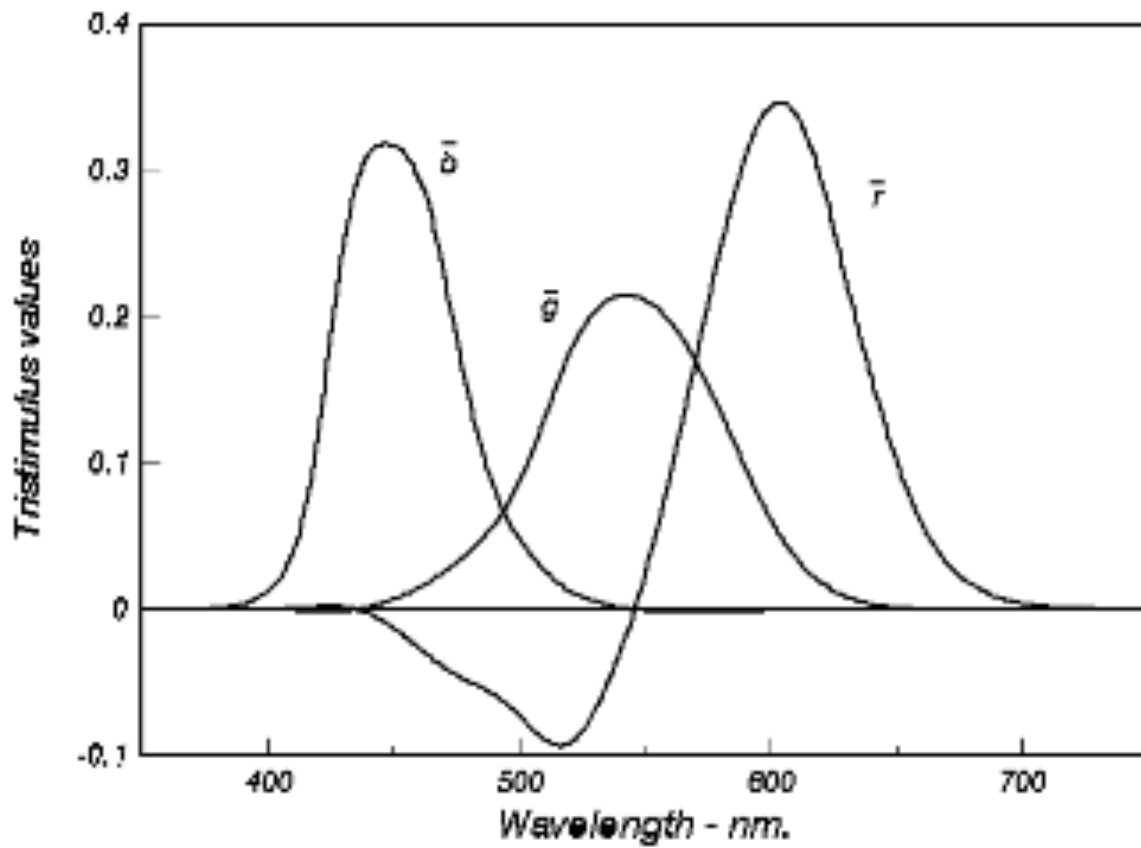


CIE 1961
R: 700 *nm*
G: 546.1 *nm*
B: 435.8 *nm*



three primary monochromatic lights

CIE RGB - Tristimulus Values



standard observer

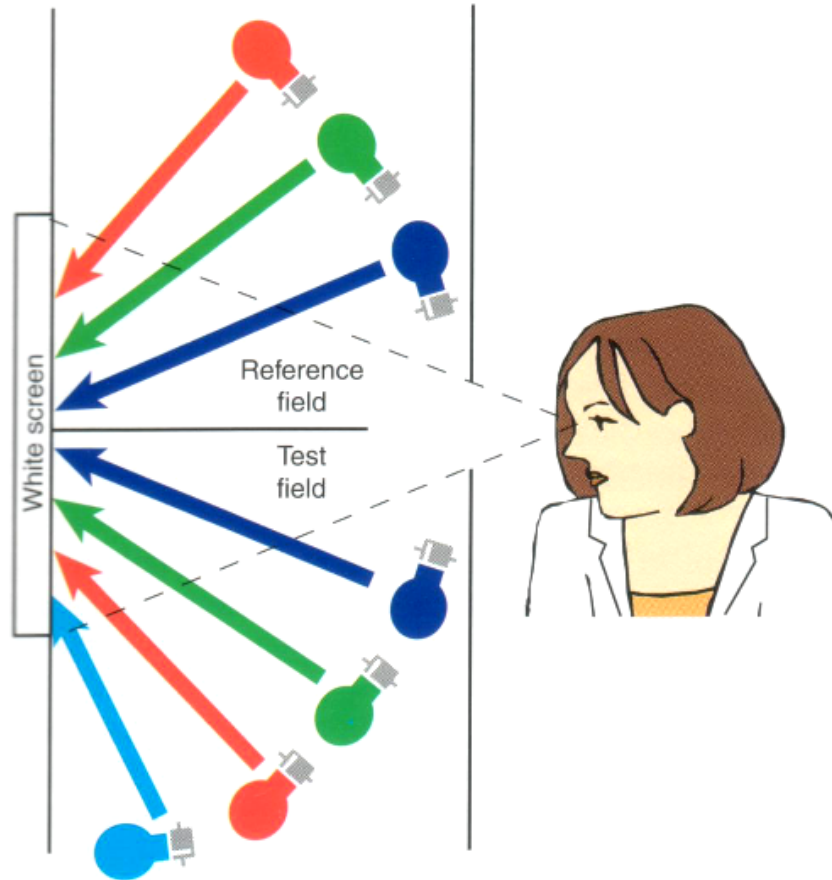
must add color
to color to match

$\Delta\lambda = 4 \text{ nm}$ (mostly)

Distinguishable colors : $\Delta\lambda = 2 \text{ nm}$ (peaks)

$\Delta\lambda = 10 \text{ nm}$ (extremities)

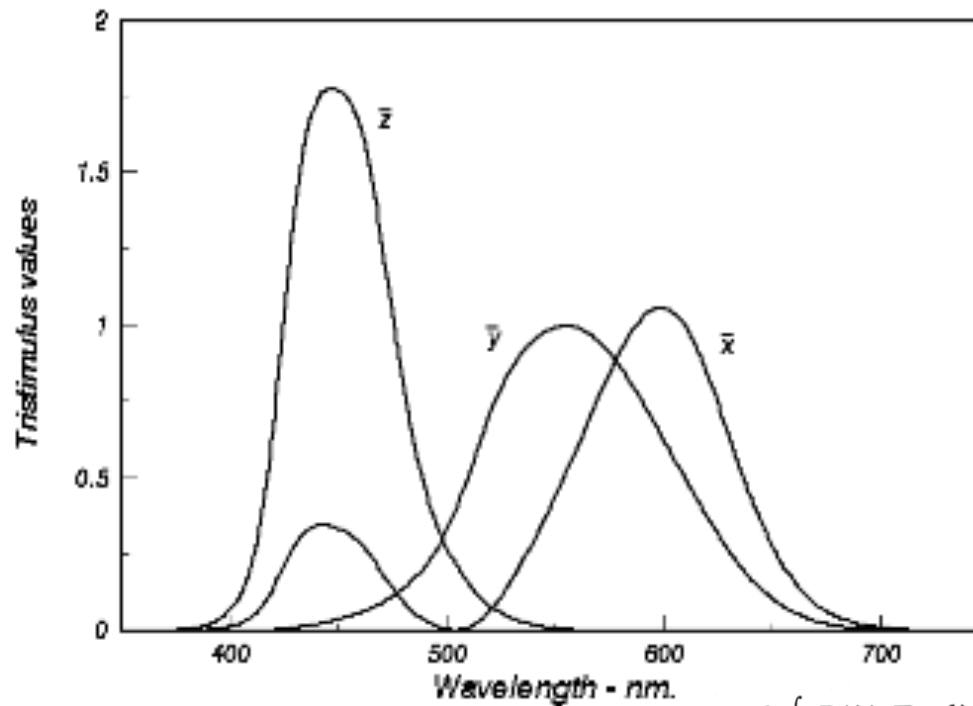
The Color Matching System



A flexible color-matching apparatus can be constructed in which red, green, and blue primaries are projected onto a screen. The intensity of each primary can be adjusted by the observer. In the bottom test field, a test light is also projected (shown as cyan) along with a second set of identical red, green, and blue primaries.

CIE XYZ

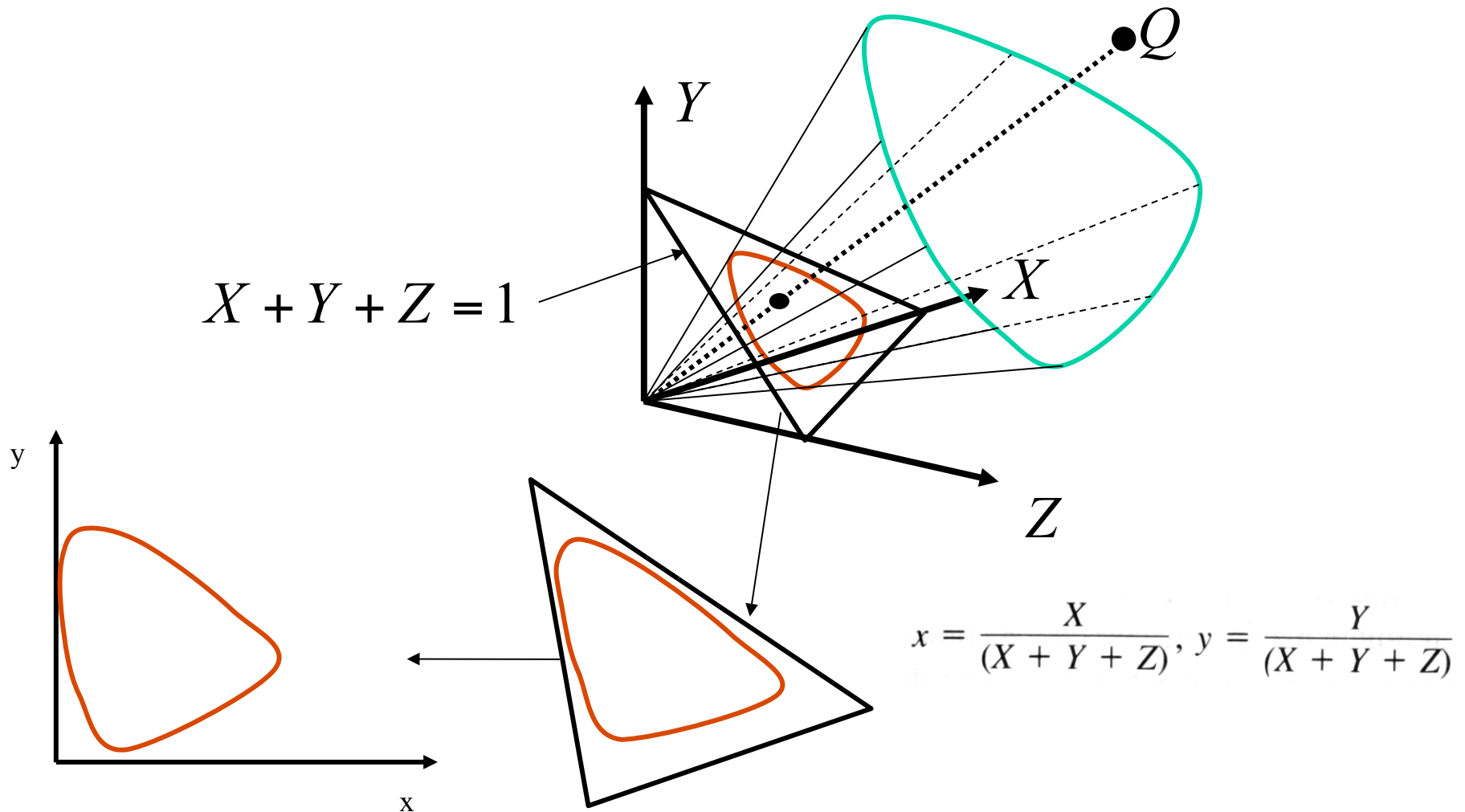
- Negative portion of CIE RGB is inconvenient
- Choose three different primaries : X , Y , Z
- Y is the same as the luminous efficiency curve



$$X = k \int P(\lambda) \bar{x}_\lambda d\lambda, \quad Y = k \int P(\lambda) \bar{y}_\lambda d\lambda, \quad Z = k \int P(\lambda) \bar{z}_\lambda d\lambda.$$

“Cone” of Colors to CIE Chromaticity Diagram

$$X = k \int P(\lambda) \bar{x}_\lambda d\lambda, \quad Y = k \int P(\lambda) \bar{y}_\lambda d\lambda, \quad Z = k \int P(\lambda) \bar{z}_\lambda d\lambda.$$

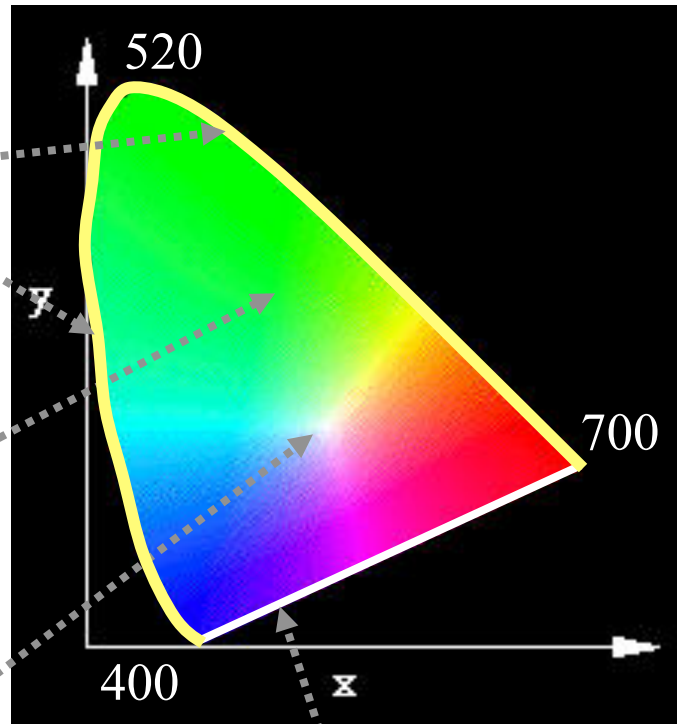


The Colors in the Chromaticity Diagram

Spectrally pure colors
(monochromatic)
on the contour

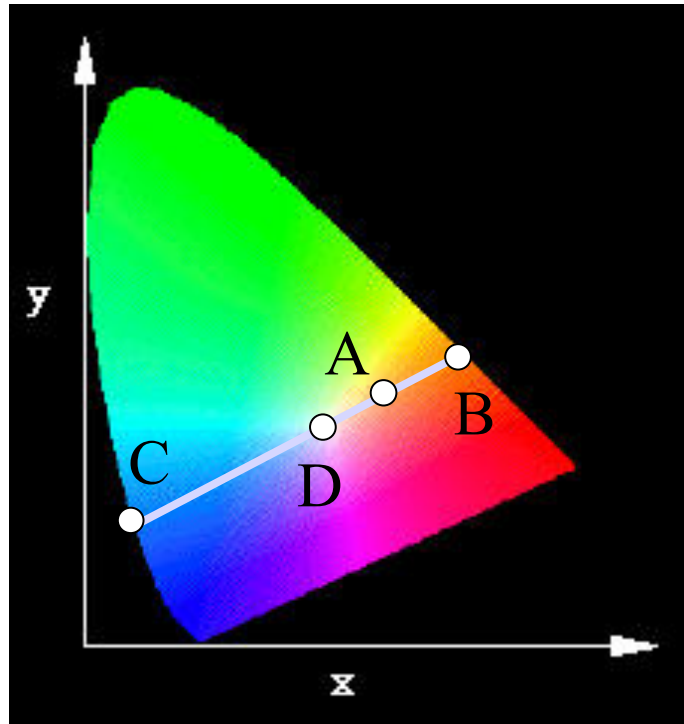
Visible spectrum

Neutral illuminant
white
(sun, D6500, etc.)



Non-spectral colors
(purples and magentas)
no dominant wavelength

Chromaticity Diagram



A: color

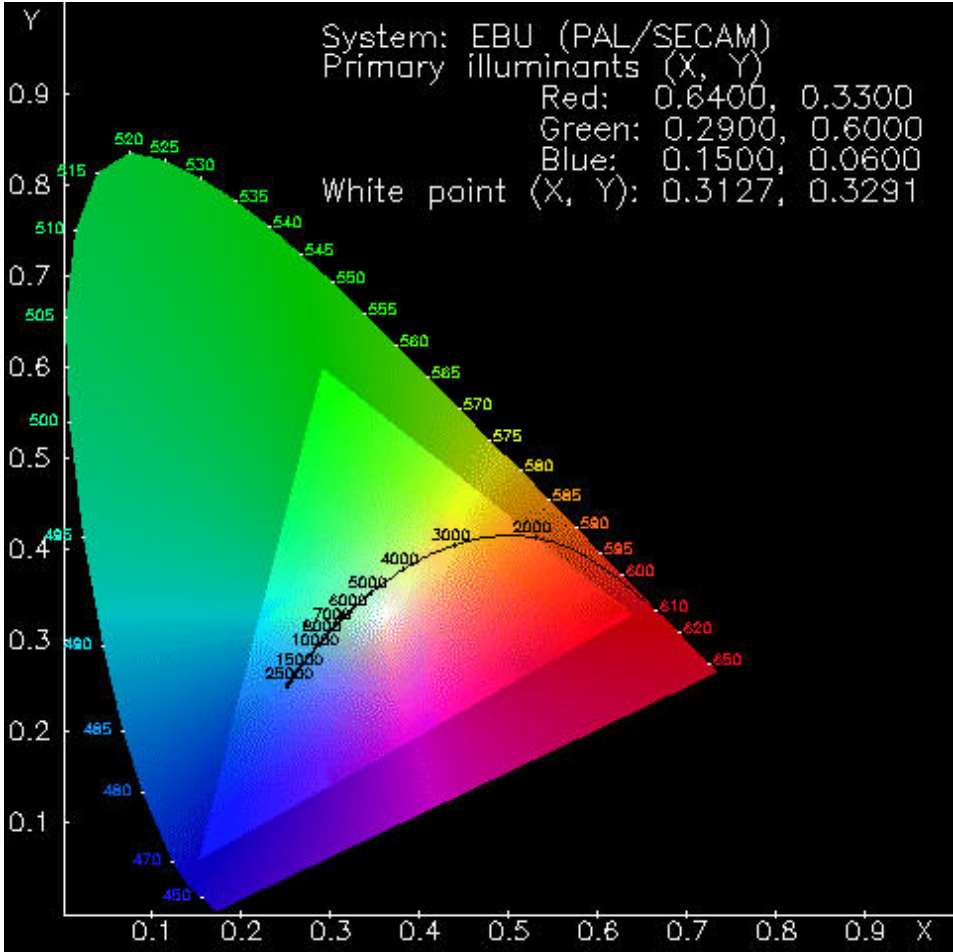
D: illuminant

B: dominant wavelength of A

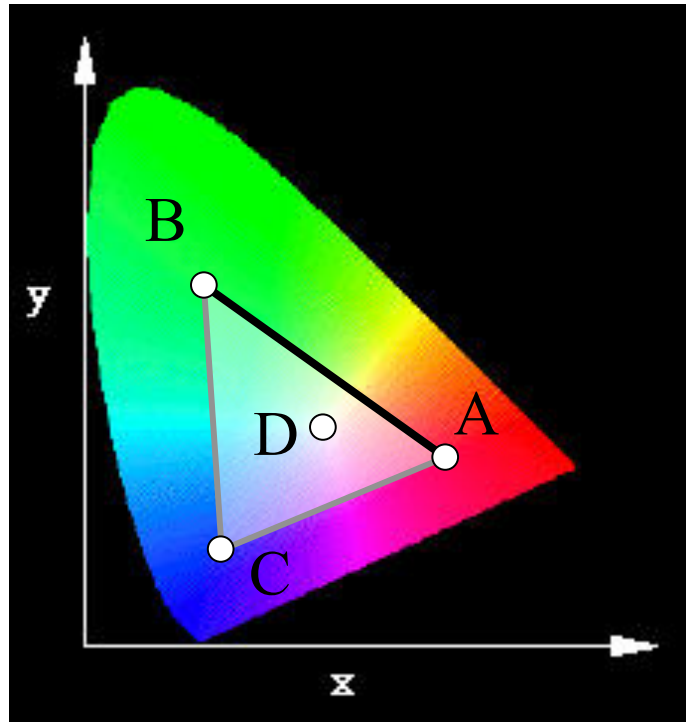
C: complementary color of A
(can be mixed with A to give white)

$\frac{AD}{BD}$: purity of A

Chromaticity Diagram - White



Color Gamut



AB: all colors defined by a mix of colors A and B

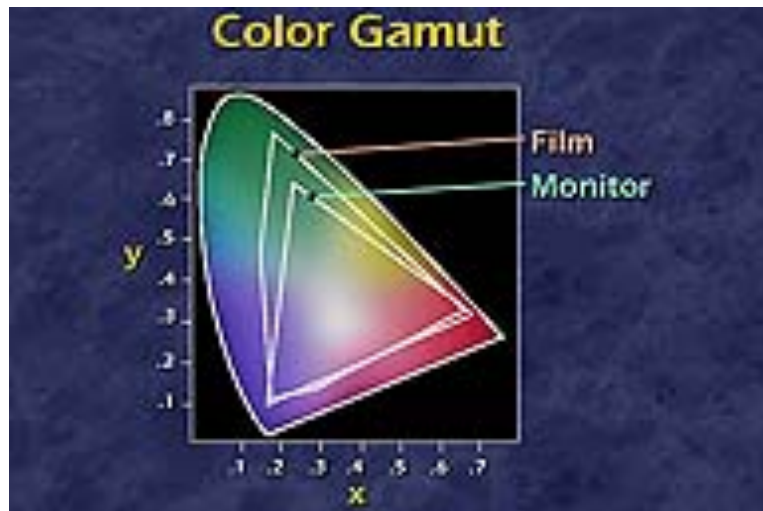
ABC: all colors defined by a linear combination of A, B, and C

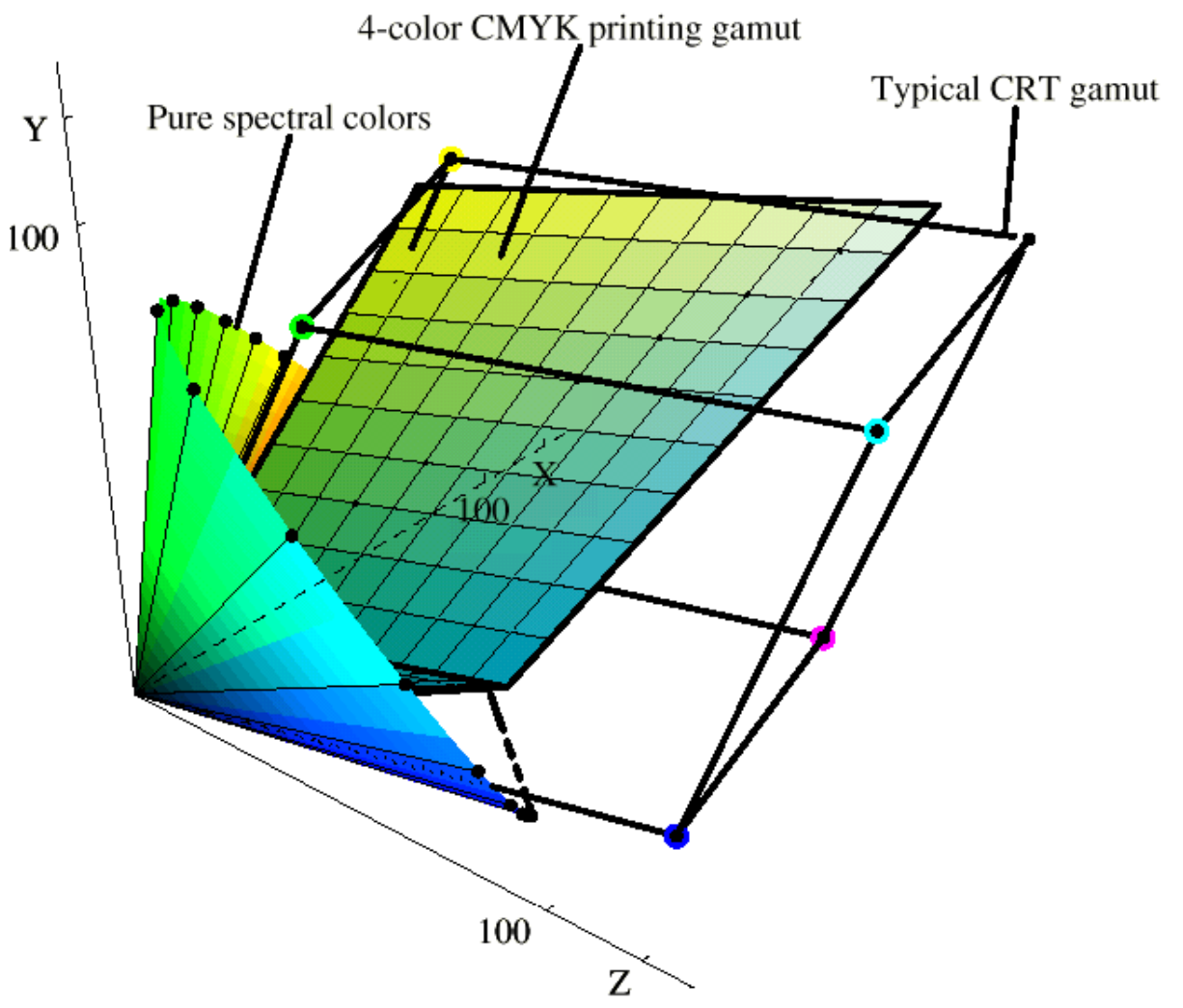
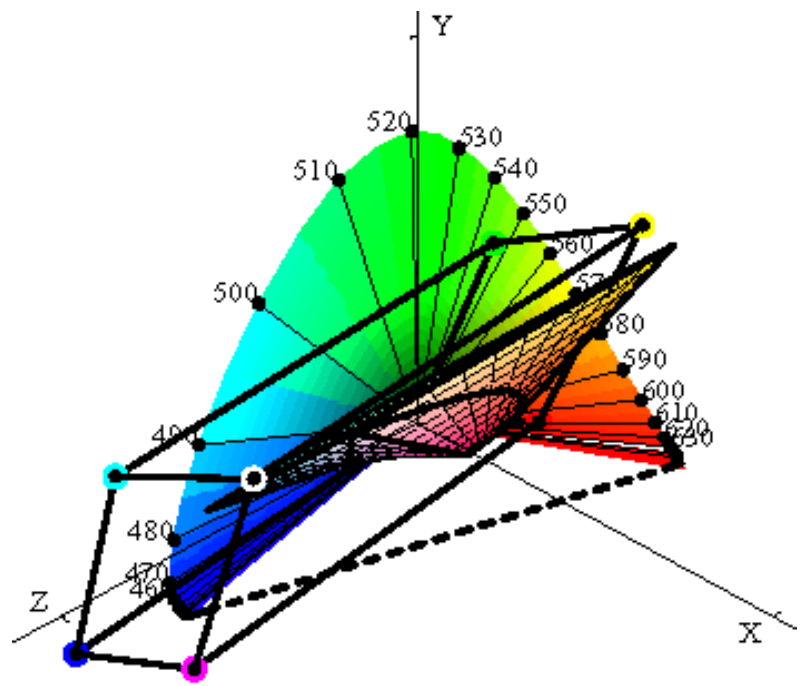
Three visible colors cannot produce all visible colors

Gamut is formed by a convex polygon with primaries at the vertices

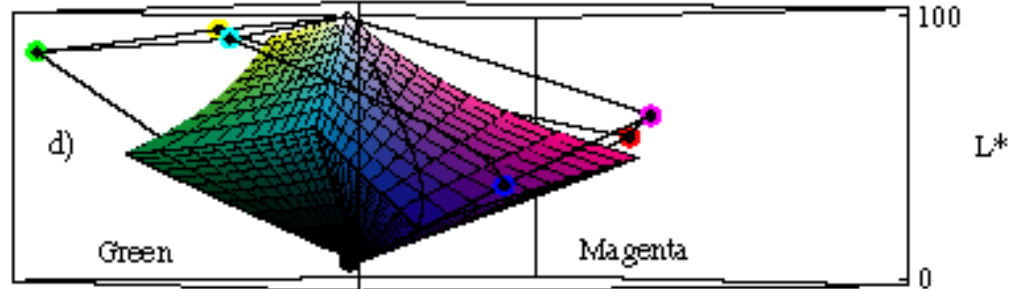
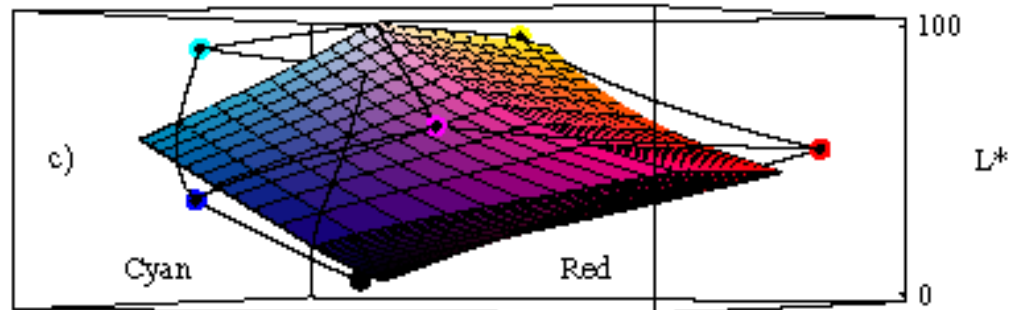
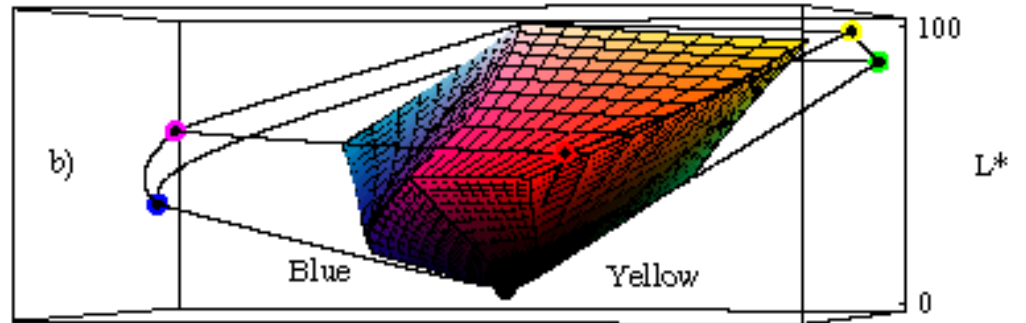
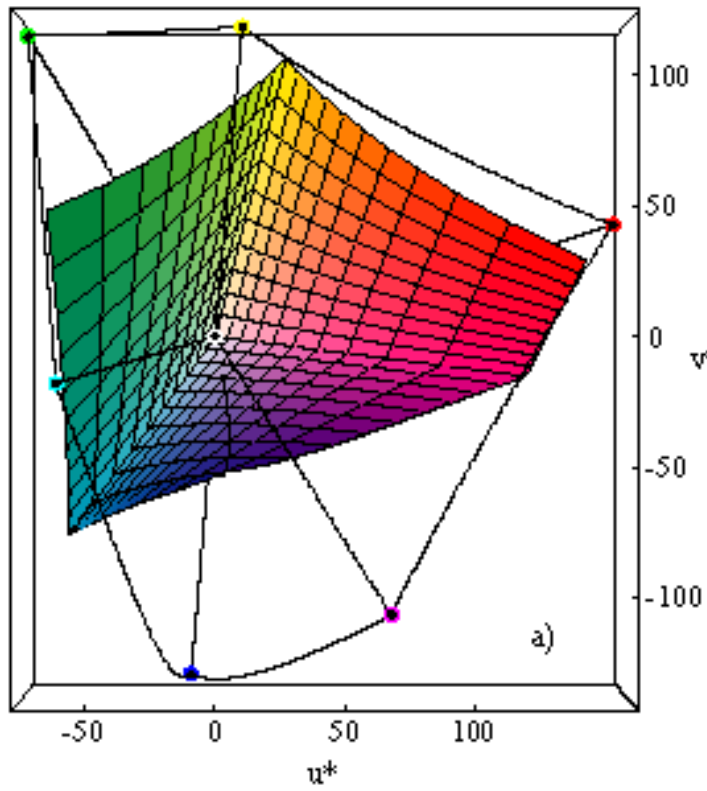
Color Gamut

- Each medium has its own color gamut
- Mapping from one gamut to another (for relative fidelity) is a difficult problem

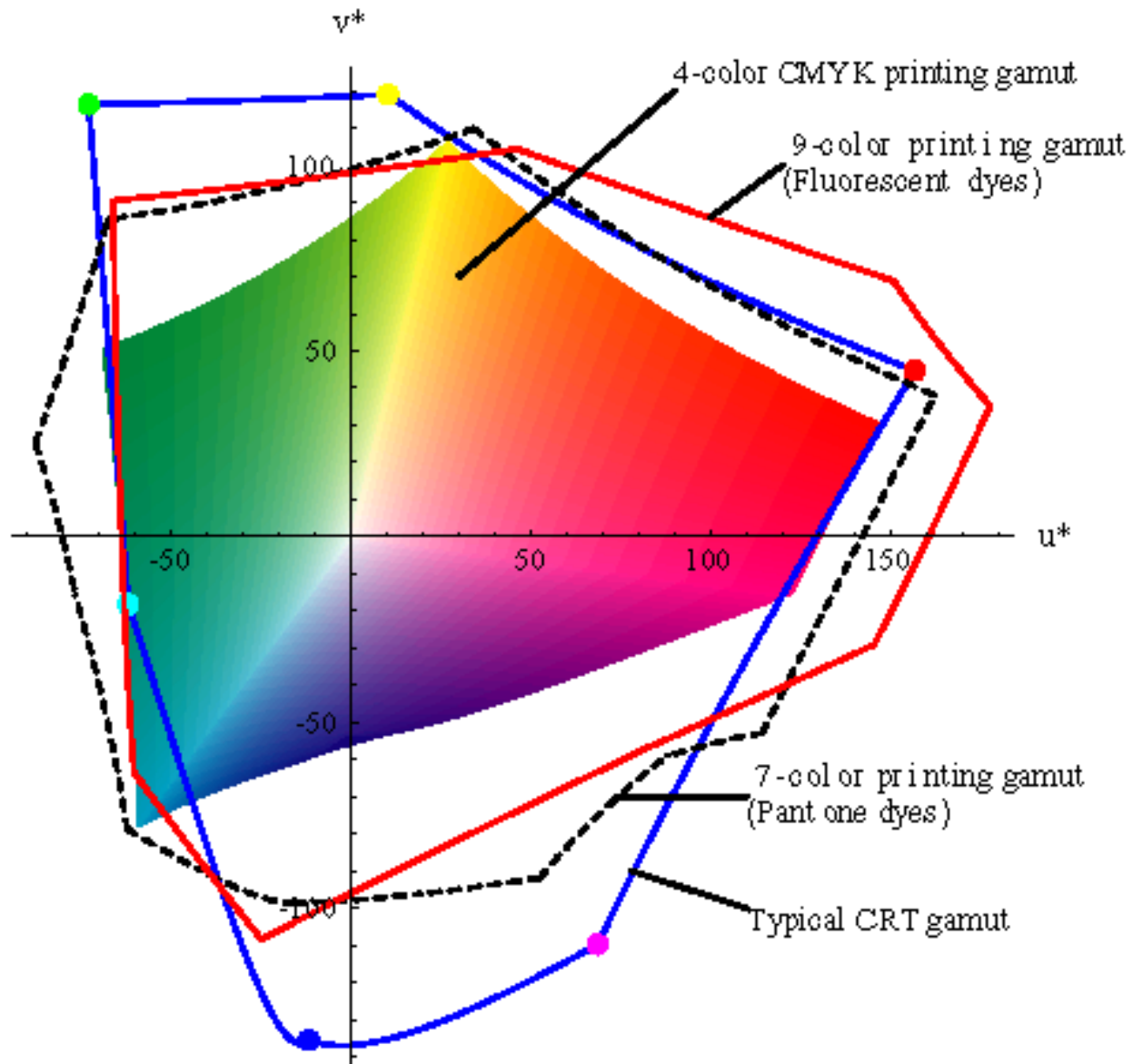




Gamut Mapping

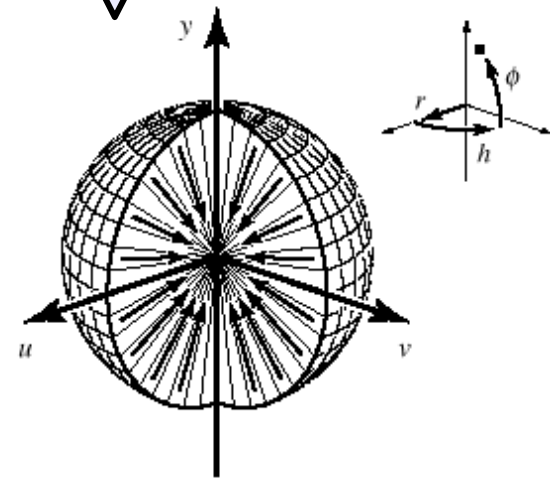
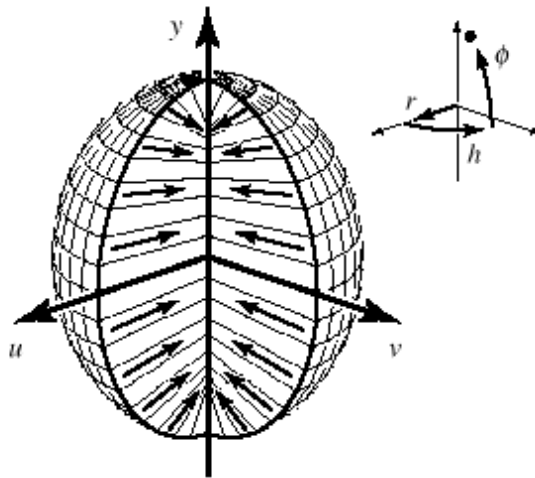
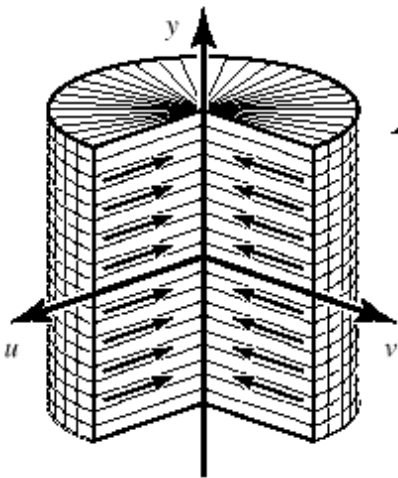
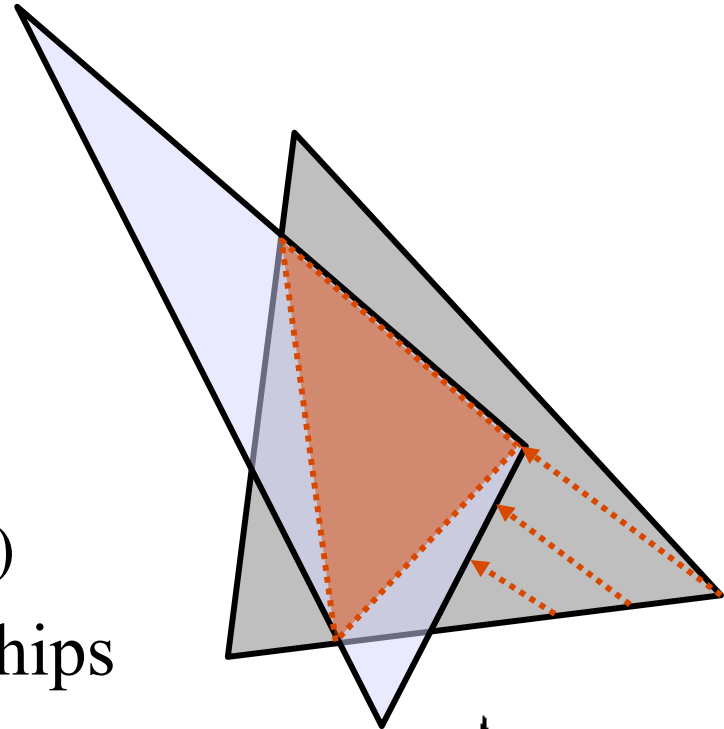


Gamut Mapping

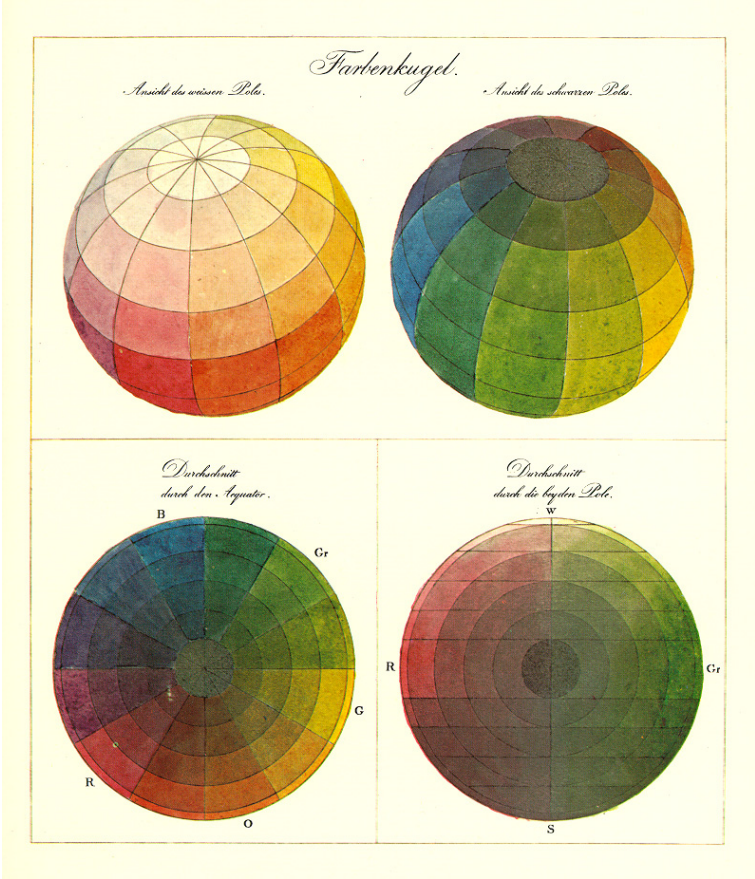
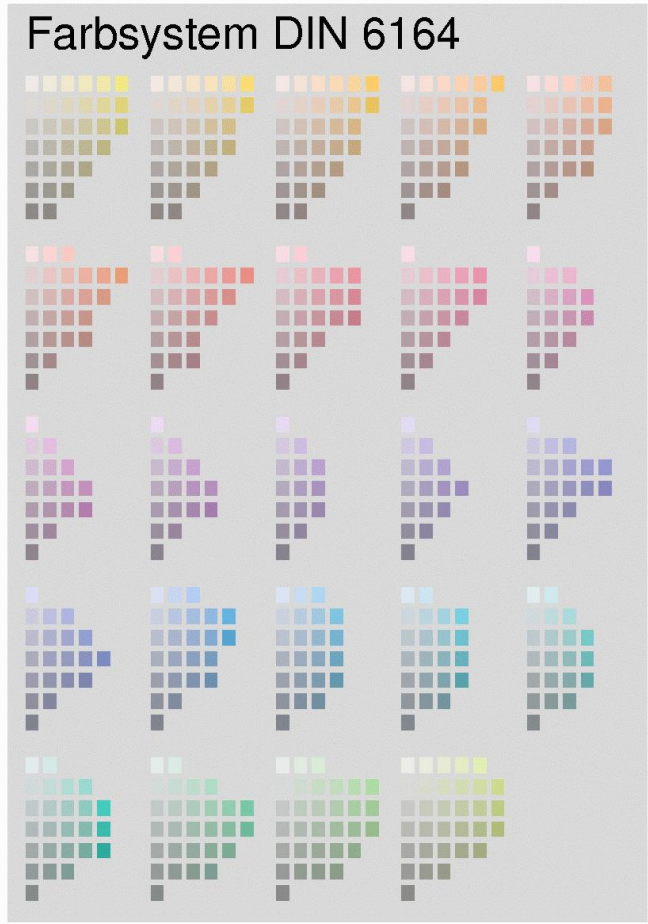


Gamut Mapping

- Given two arbitrary gamuts
 - projection
 - over-saturation
 - linear transformations
 - lost of contrasts
 - shift in the colors (e.g., skin)
- Must maintain color relationships

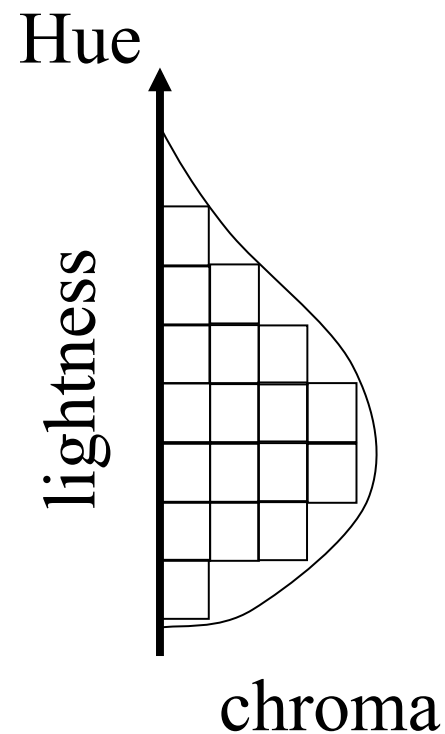
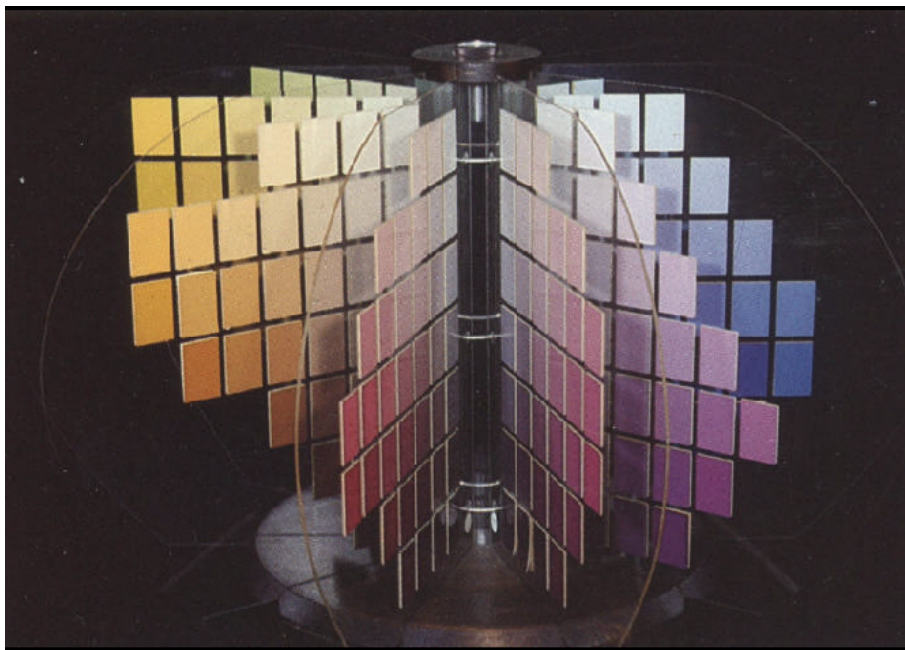


Many Ancestors to Experimental Color Spaces



Perceptually Uniform Space: Munsell book of colors

- 1500 color plates separated by strict perception experiments
- hue, chroma, value : 9R5/8

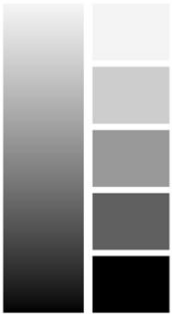


Munsell

Hue



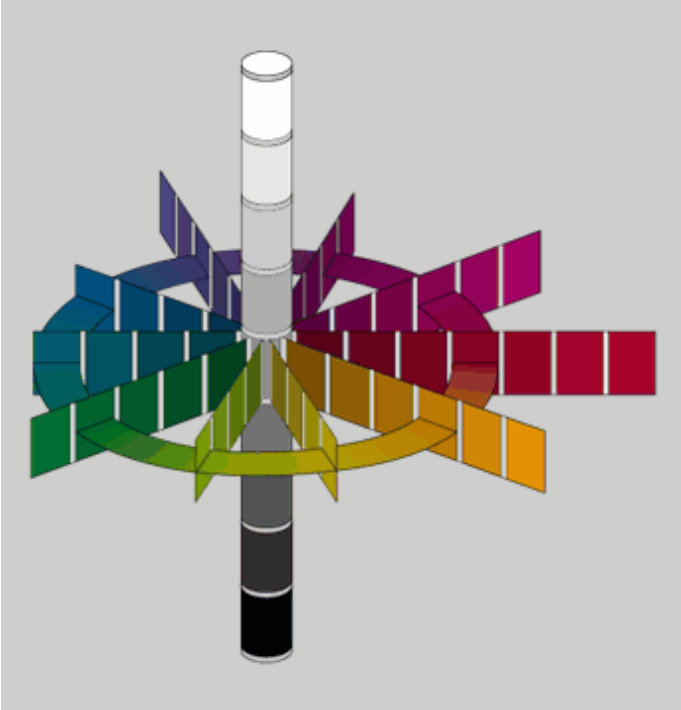
Value



Chroma



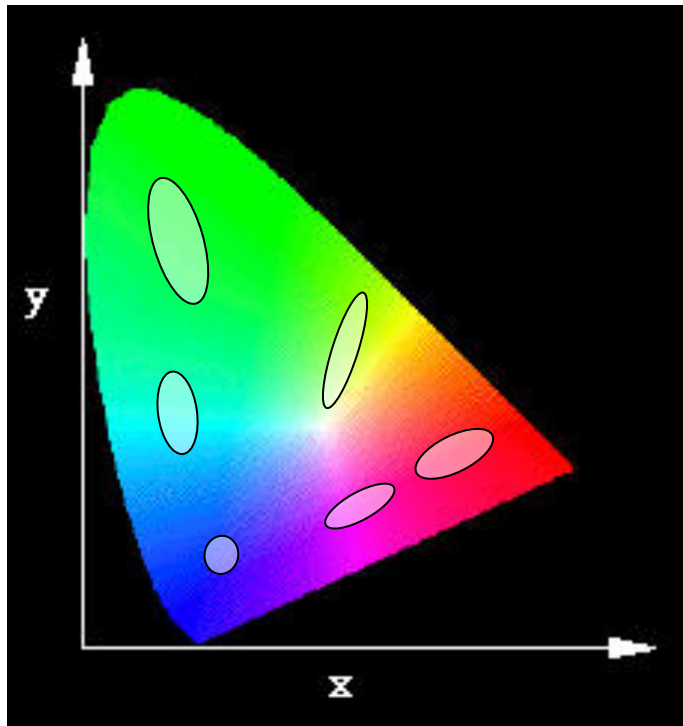
Munsell Color Space



munsell.com

CIE Luv

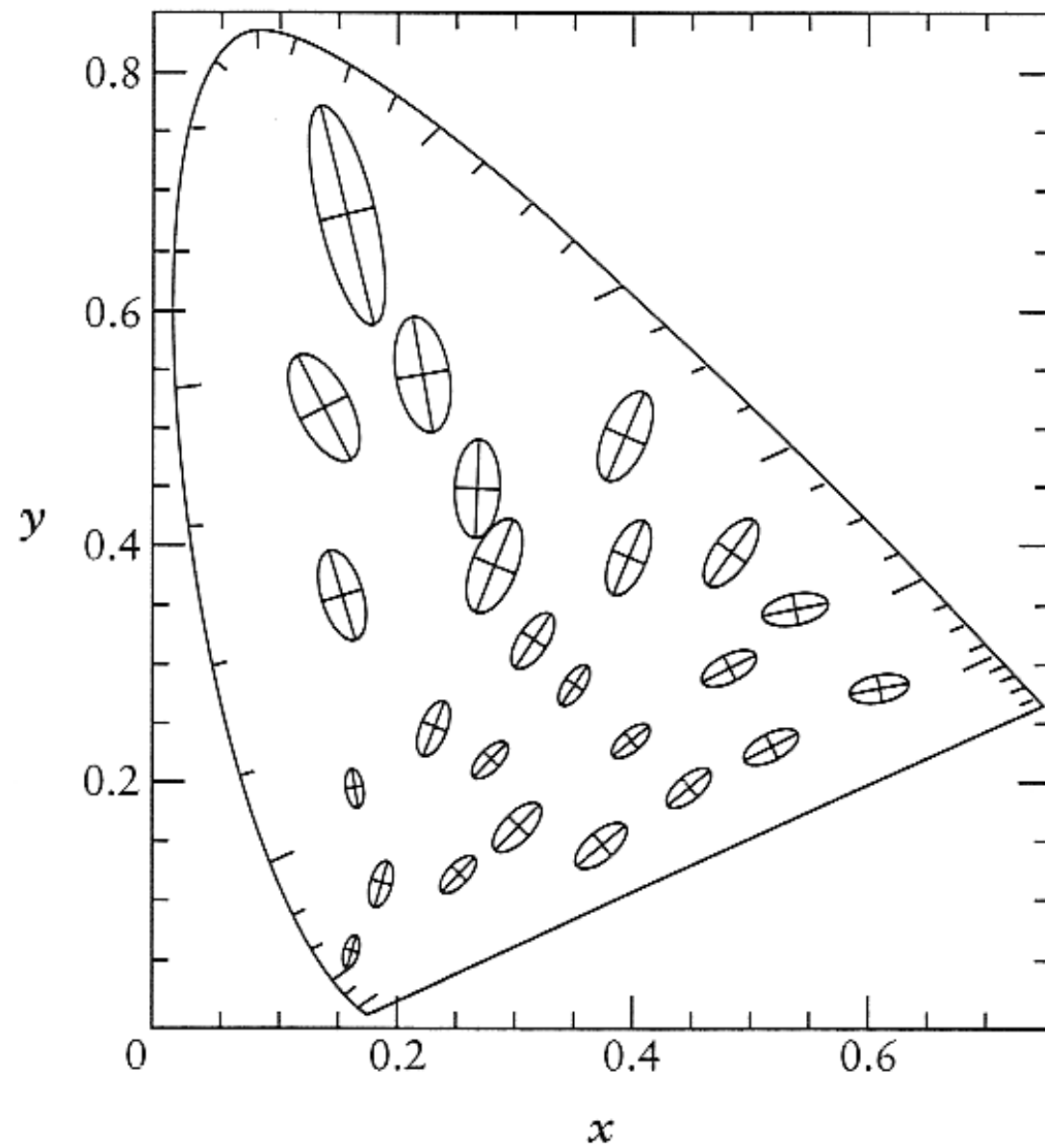
- In color space CIE XYZ , the perceived distance between colors (points) is not equal everywhere



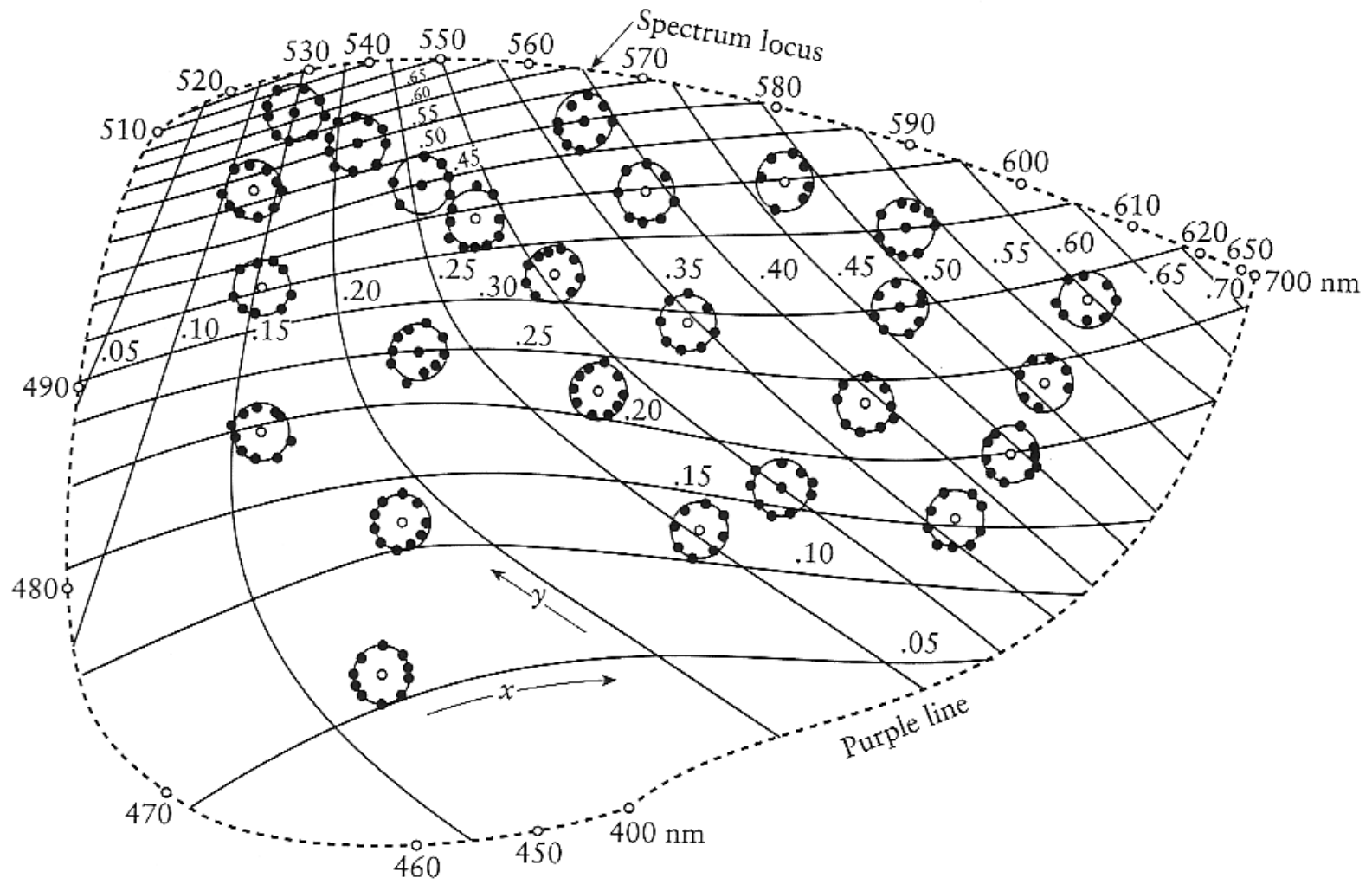
MacAdam ellipses

- Encode perceived differences
- 15:1 differences between radii
- here, exaggerated by factor of 10

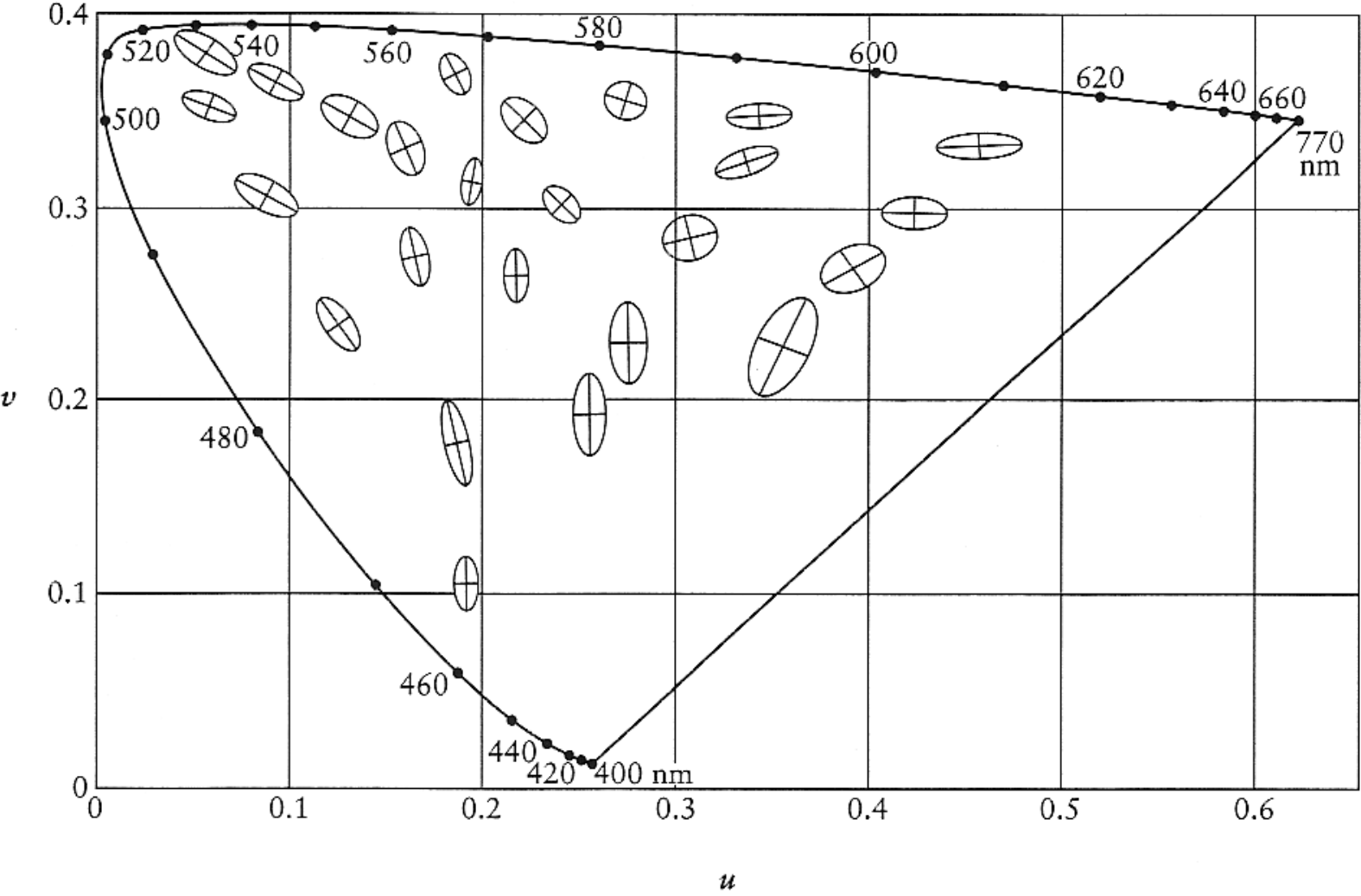
Measured Differences by MacAdam



Measured Differences by MacAdam



Measured Differences by MacAdam



CIE Luv

- CIE Luv is an attempt to better distribute the colors in a more perceptual fashion
- Transform CIE XYZ to be more perceptual homogeneous
- Radii closer to 4:1

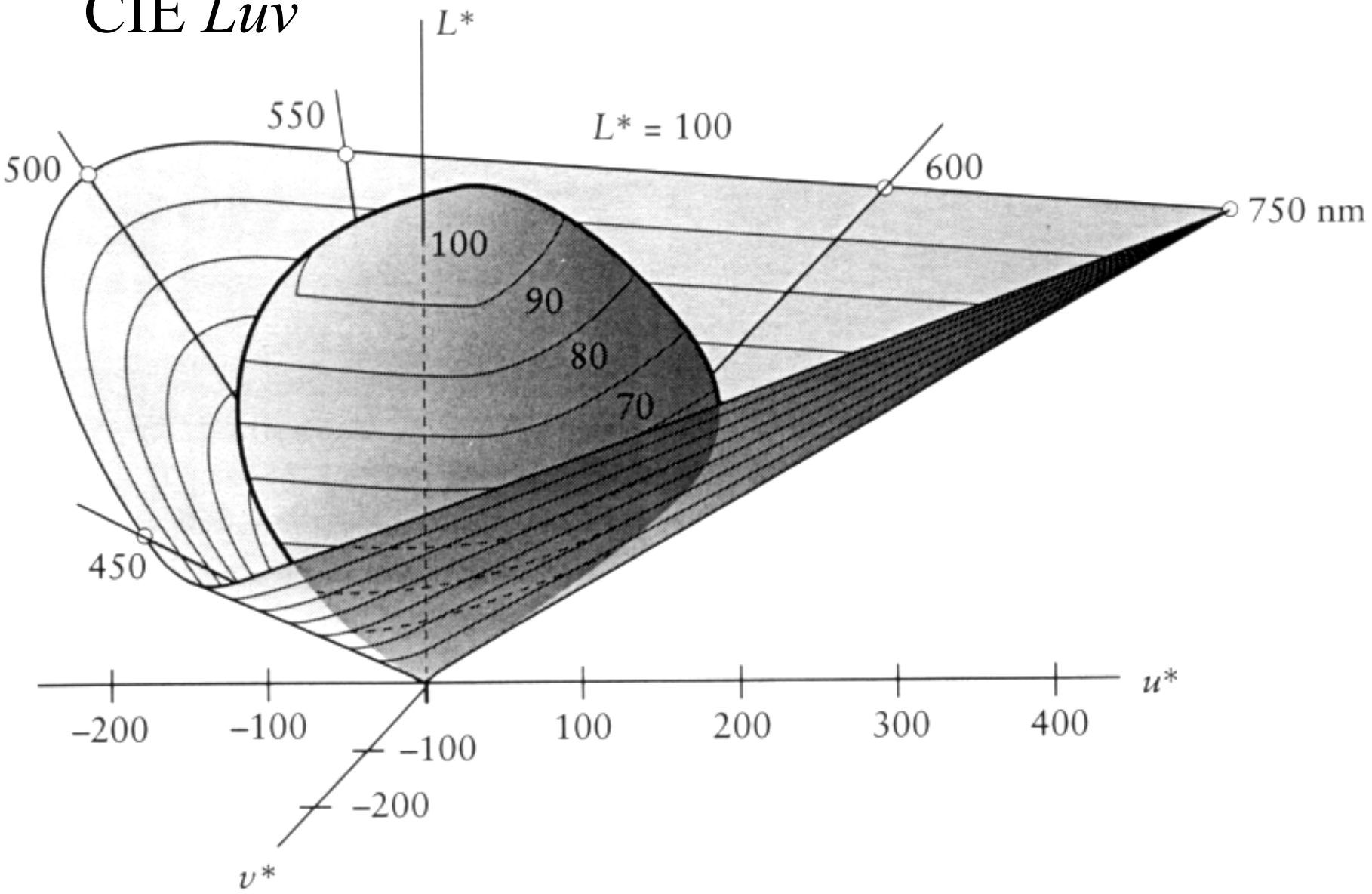
$$L^* = 116(Y / Y_n)^{1/3} - 16 \quad \text{for } (Y / Y_n > 0.01)$$

$$u^* = 13L^* (u' - u'_n)$$

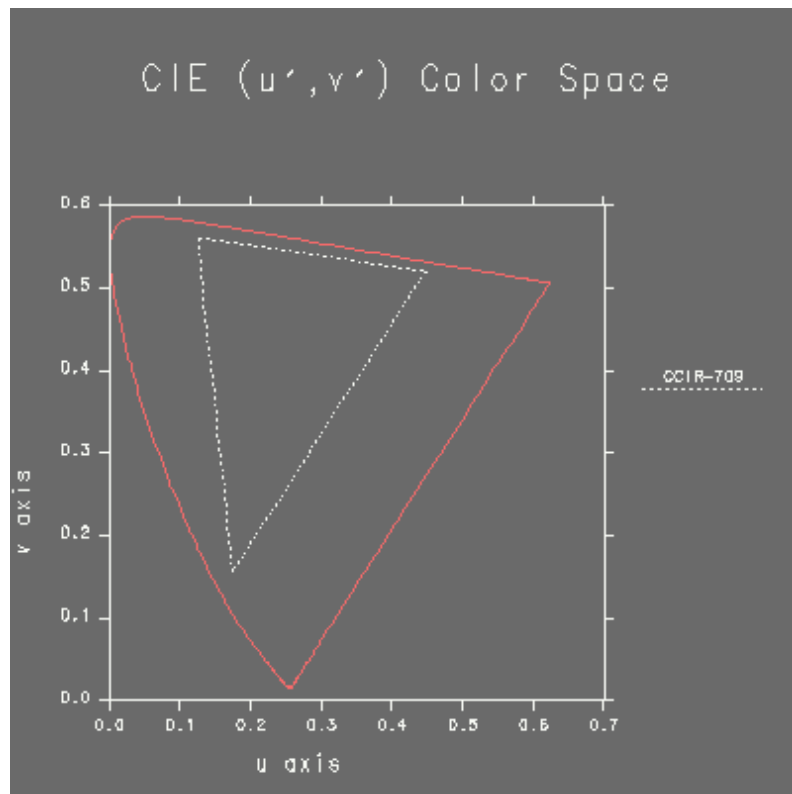
$$v^* = 13L^* (v' - v'_n)$$

$$u' = \frac{4X}{X+15Y+3Z} \qquad v' = \frac{9Y}{X+15Y+3Z}$$

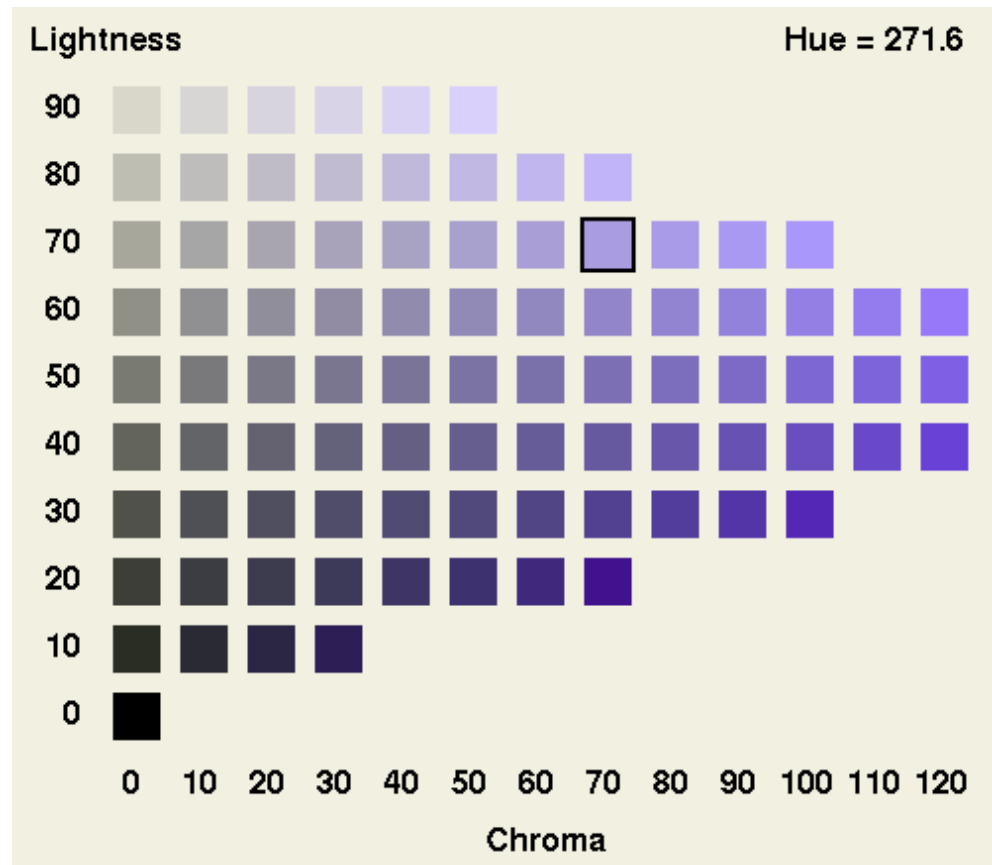
CIE Luv



CIE Luv



Larson



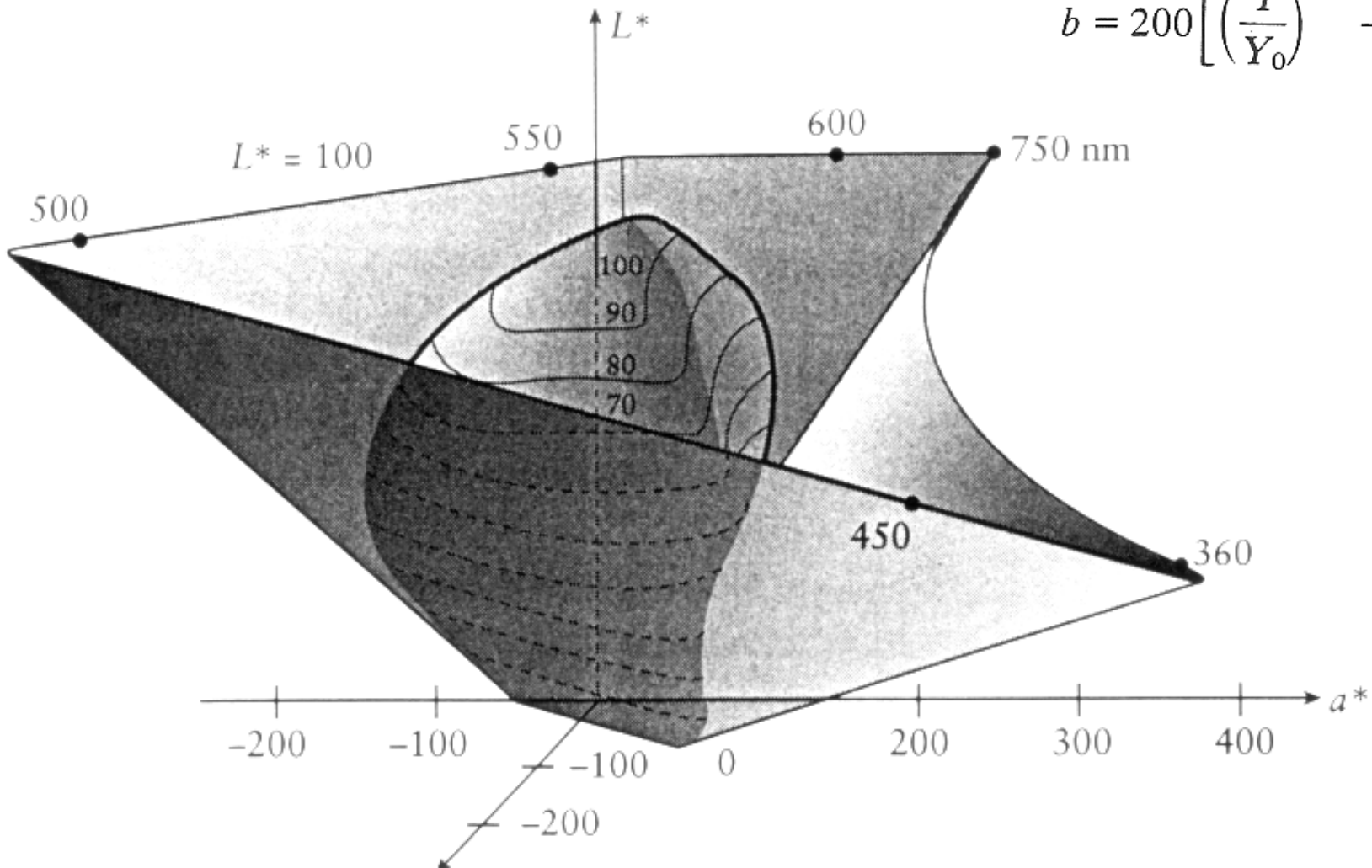
CIE Lab for textiles developed in parallel

CIE *Lab*

$$L = 25 \left(100 \frac{Y}{Y_0} \right)^{1/3} - 16$$

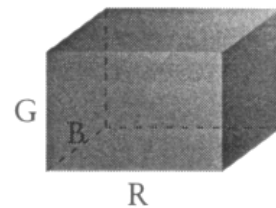
$$a = 500 \left[\left(\frac{X}{X_0} \right)^{1/3} - \left(\frac{Y}{Y_0} \right)^{1/3} \right]$$

$$b = 200 \left[\left(\frac{Y}{Y_0} \right)^{1/3} - \left(\frac{Z}{Z_0} \right)^{1/3} \right]$$

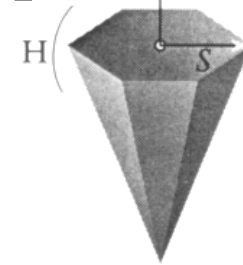


Color Spaces

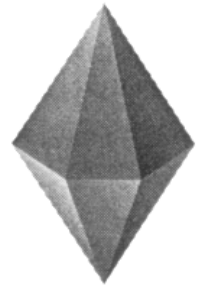
- We need a space to manipulate colors
- Chromaticity diagram does not provide an intuitive tool to manipulate colors
- Color spaces based on medium cannot reproduce all visible colors
- Hardware
 - *RGB, CMY, YIQ, HSV, HLS*
- Experiments
 - *Ostwald, Munsell, CNS*



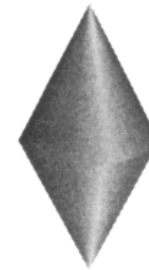
(a)



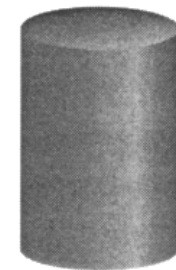
(b)



(c)



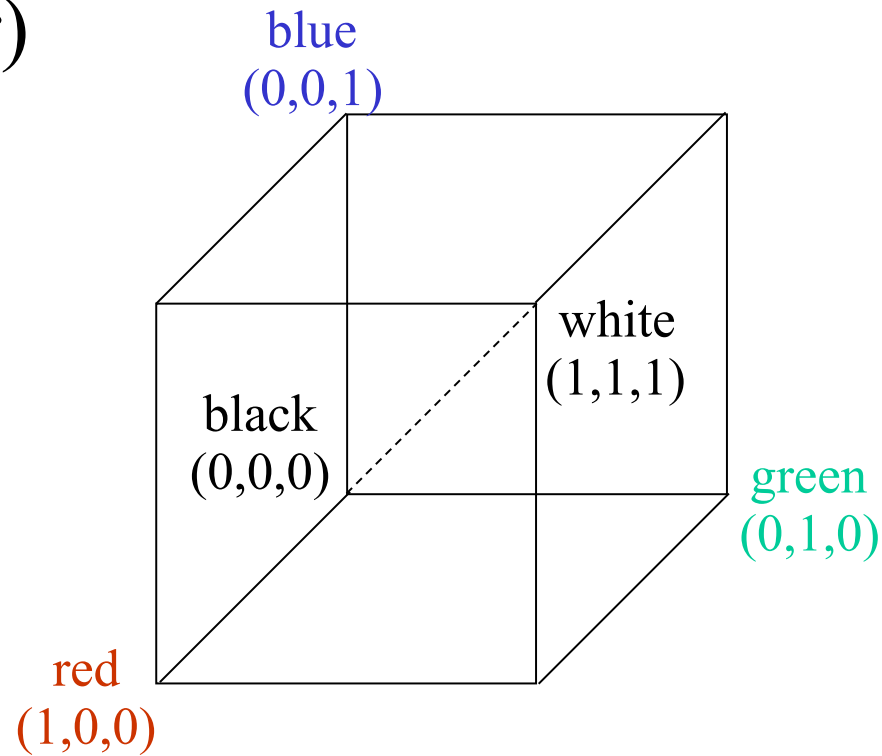
(d)



(e)

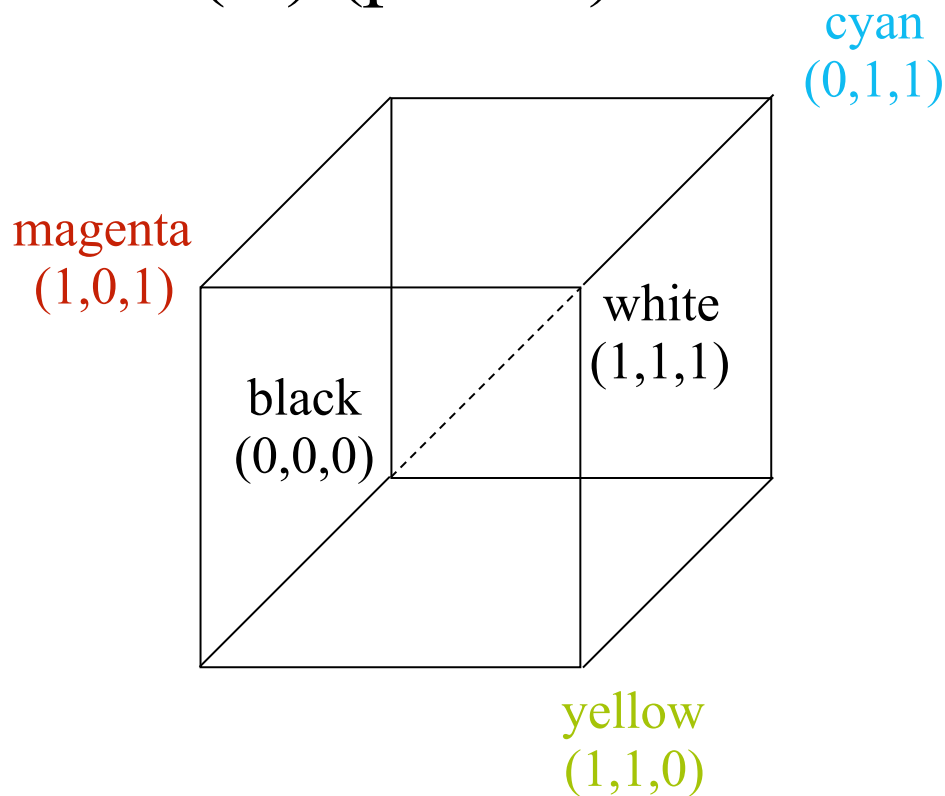
RGB (monitor)

- Additive

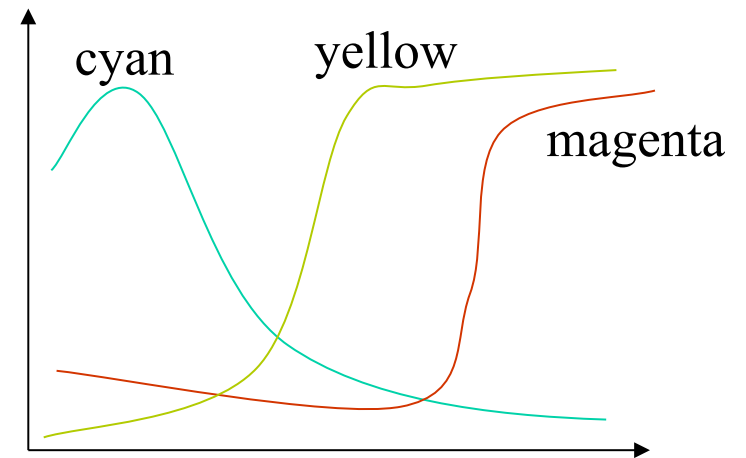


- Depends on the monitor phosphores
 - clipping produces color shifts and saturation
 - transformations

CMY(K) (printer)



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



- Subtractive
- $K = \min (C, M, Y)$: black ink in 4-color printing

YIQ (NTSC transmission)

- Y : Y from CIE XYZ (2/3 of the signal)
luminance used for black-and-white TVs
- I : *in phase* (1/4 of the signal)
skin colors
- Q : *quadrature* (1/12 of the signal)
green-purple

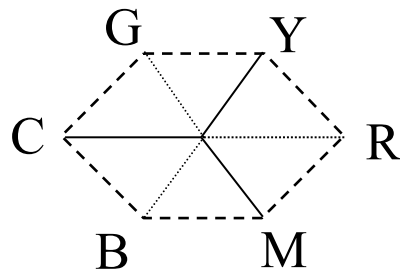
$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.275 & -0.321 \\ 0.212 & -0.523 & 0.311 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

convert
to grays



HSV - HLS

- Hue-Saturation-Value / Hue-Lightness-Saturation
- More intuitive, closer to artist perceptions
- Cylindrical coordinates



Horizontal cut : corners of RGB cube

$S = 0$: gray

$S = 1$: saturated color

