Color Vision

Light enters the eye

Absorbed by cones

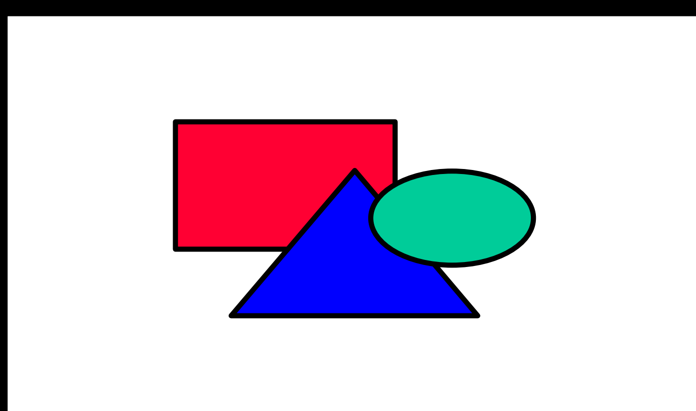
Transmitted to brain

Interpreted to perceive color

Foundations of Vision
Brian Wandell

Spectral Distributions

Various Light Sources



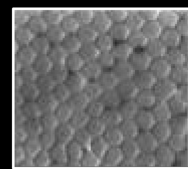
Cones and Rods

Cones: color vision

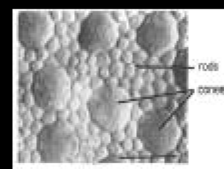
- Photopic vision
- Daylight levels
- Concentrated in fovea (center)

Rods: grayscale

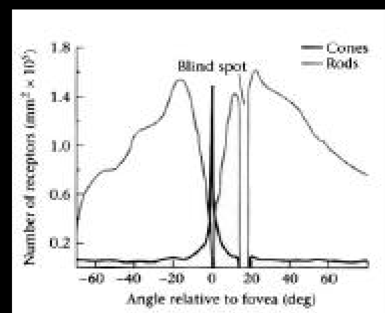
- Low light levels
- Scotopic vision
- Peripheral vision



Fovial cones



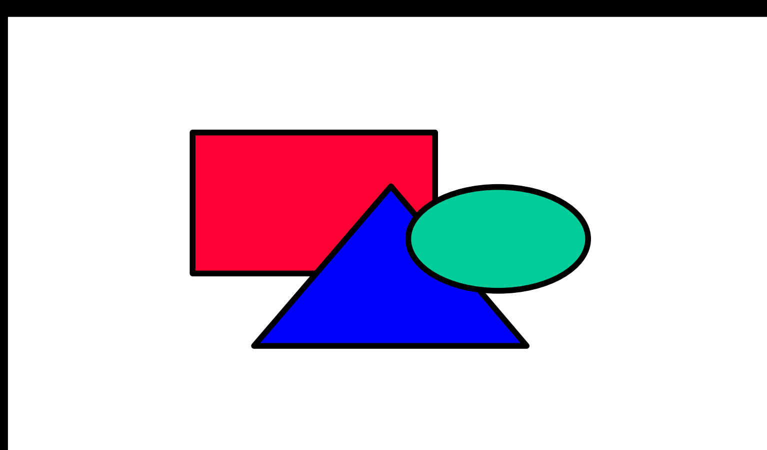
Cones and rods



Distribution of rods and cones

From Foundations of Vision, fig 3.1 & 3.4,
© Brian Wandell, Stanford University

Retinal Response Curves



Demo

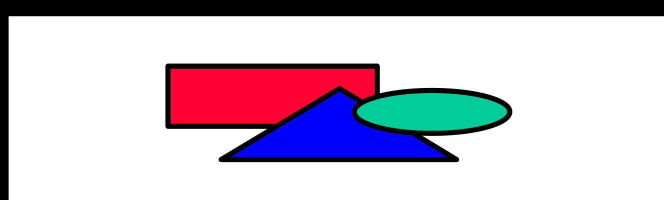
Java applets from Brown

- Trichromacy
- Metamerism
- Reflectance

http://www.cs.brown.edu/research/graphics/research/illus/spectrum/

Metamerism

Different spectra appear the same

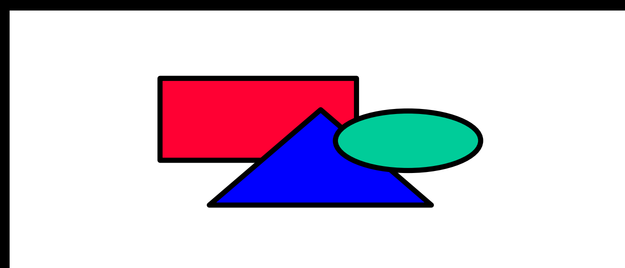


Fundamental principle of
Color Reproduction

Colorimetry

Measurement of color

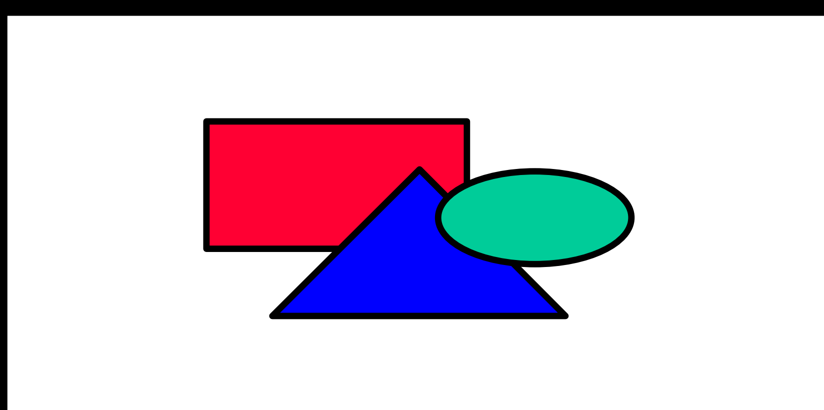
- Color matching experiments
- Grassman's Laws
- CIE Standards



Color Science
Wyszecki & Stiles

Color Matching Experiments

Match any color by adding any* three primaries



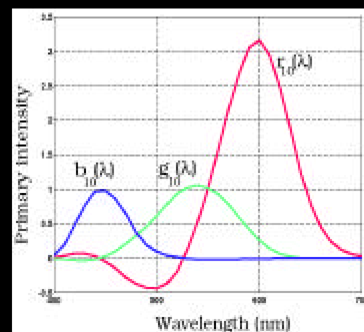
Color Matching Functions

For any three primaries

- Match monochromatic colors
- Plot values vs. wavelength

To match any spectrum

- Multiply by CMF
- Integrate



R=645 nm, G=526 nm, B=444 nm
Styles and Burch

CMF for all real lights have negative lobes

Grassman's Laws

Superposition

- S is stimulus, R is response
- If $S_{a+b} = S_a + S_b$
- Then $R_{a+b} = R_a + R_b$

Linear system

- 3x3 matrix
- Applies to primaries, CMFs and tristimulus values

RGB to XYZ

Let X_R, Y_R, Z_R be the CIEXYZ value for R, etc.

Then:

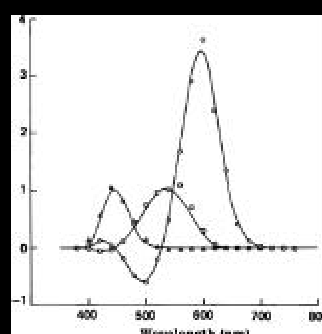
$$[R\ G\ B] \begin{bmatrix} X_R & Y_R & Z_R \\ X_G & Y_G & Z_G \\ X_B & Y_B & Z_B \end{bmatrix} = XYZ_{RGB}$$

Any system of RGB primaries can be transformed to another with a 3x3 matrix

Convert CMF's

All CMF's are linear transformations of the cone response curves

Figures shows cone response transformed to match Stiles and Burch CMF



From Foundations of Vision, fig 4.20
© Brian Wandell, Stanford University

Any CMF can be transformed to another with the same 3x3 matrix used to transform the primaries

CIE Standard

Commission Internationale de l'Eclairage

Standard primaries

- Imaginary lights
- Linear transformation of real lights
- All positive

Standard observer

- Color matching functions $(\bar{x}(\lambda),\bar{y}(\lambda),\bar{z}(\lambda))$
- CIE tristimulus values (X,Y,Z)

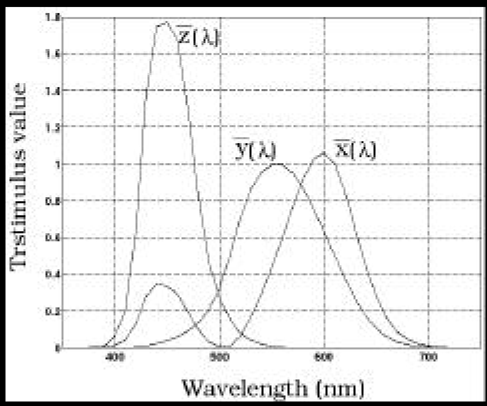
CIE Color Matching

CMF's all positive

Unit area for each

$\bar{y}(\lambda)$ is luminance

Easily encoded in instruments



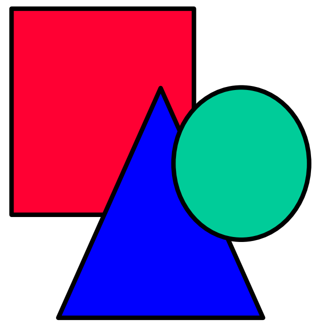
From Foundations of Vision, fig 4.14

Chromaticity Coordinates

Project X,Y,Z on the (X+Y+Z)=1 plane

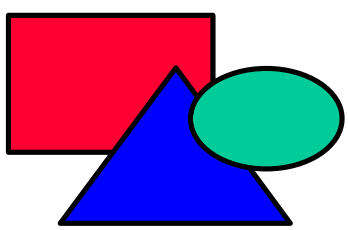
$$x = X / (X+Y+Z)$$
$$y = Y / (X+Y+Z)$$
$$z = 1-(x+y)$$

Colorfulness separate from Brightness



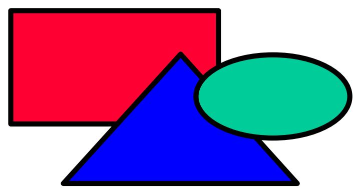
Courtesy of Photo Research

Color Appearance

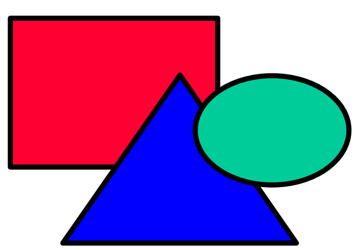


Interaction of Color
Josef Albers

Matching Patches?

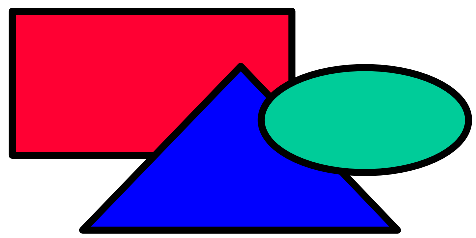


Depends on Background



Perceptual Organization of Color

Not “RGB” as in Colorimetry



Opponent Color

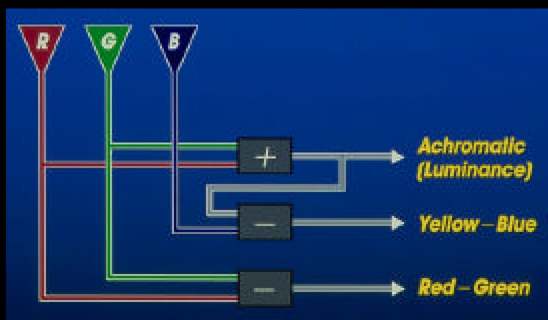
History

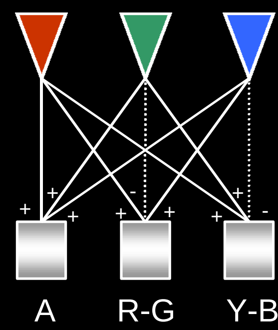
- Originally proposed in 1878 by Herring
- Hue-cancellation experiments by Jameson & Hurvich (1955)
- Now accepted as “first level processing”

Definition

- Lightness, R-G and B-Y axis

Opponent Color Encoding

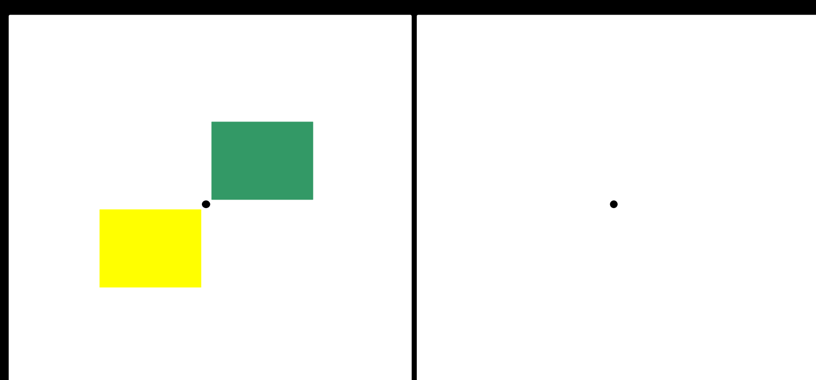




Traditional model

Fairchild, Figure 1-13

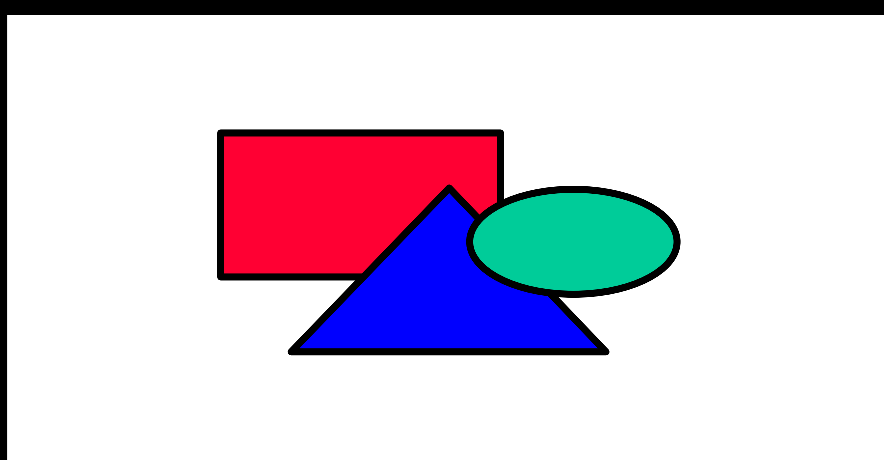
Afterimages



Color Vision Deficiencies

- Missing or weak photoreceptor
- Best described in opponent terms
  - Red-green anomolies
  - Blue-yellow anomolies
  - Very few achromats (no cones)
- Red-green anomolies most common

Perceptual Color Spaces

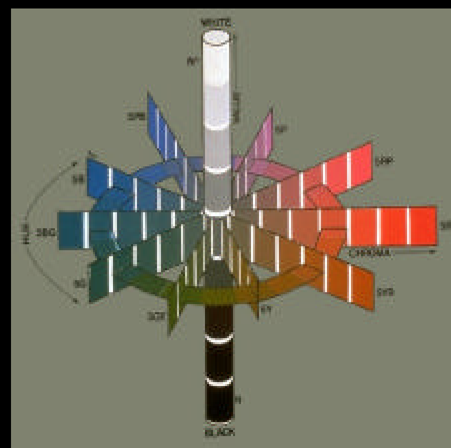


Munsell Color Space

Chroma, Hue, Value

- 4R 5 (bright red)
- Perceptually uniform
- Book of painted chips

Now CIE XYZ defined



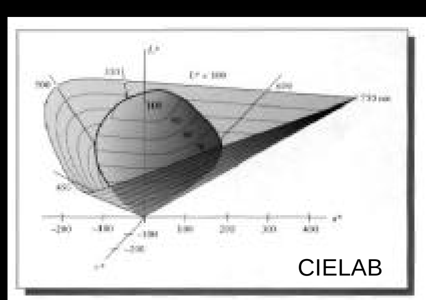
CIELAB and CIELUV

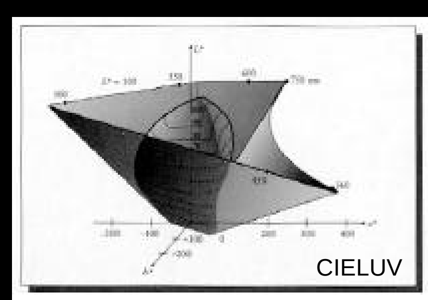
Color Difference Spaces

1 unit = “just noticeable difference” (1 jnd)

Lightness (L*) plus two color axis

Function of XYZ of color plus XYZ of white





From Principles of Digital Image Synthesis by Andrew Glassner. SF: Morgan Kaufmann Publishers, Fig. 2.4 & 2.5, Page 63 & 64

Color Appearance Phenomena

Simultaneous contrast

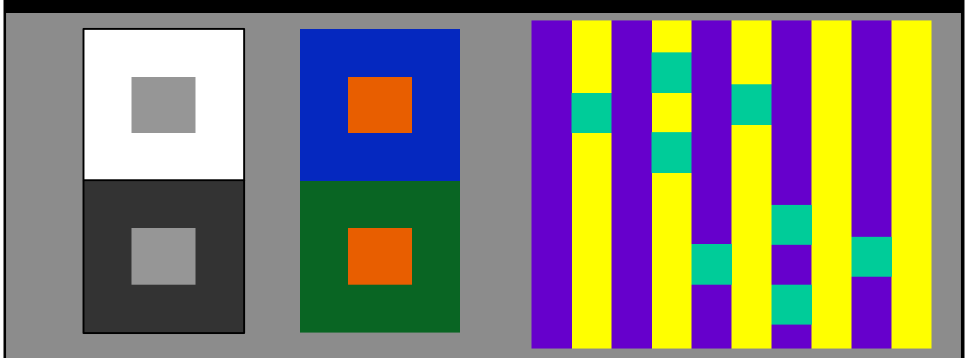
Adaptation

- Light/dark adaptation
- Chromatic adaptation

Geometric effects

- Spatial frequency
- Outlines, etc.

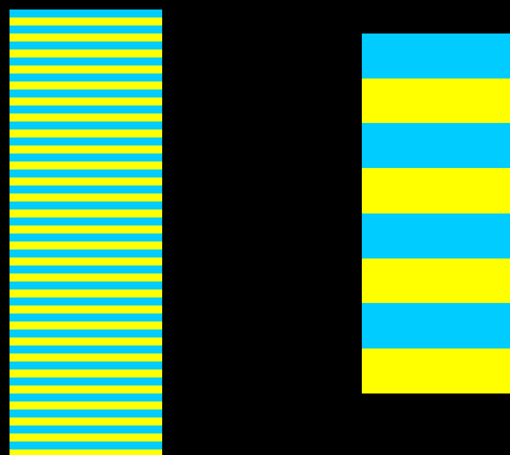
Simultaneous Contrast



"After image" of surround adds to the color

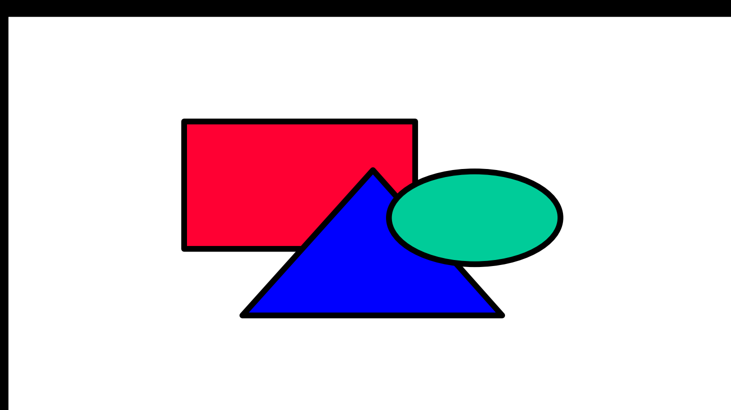
Reality is more complex
Identical patch and surround

Effect of Spatial Frequency
“Spreading” Effect



Redrawn from Foundations of Vision, fig 6

Impact of Outlines
The Bezold Effect



Chromatic Adaption

Change in illumination

Automatic “white balance”

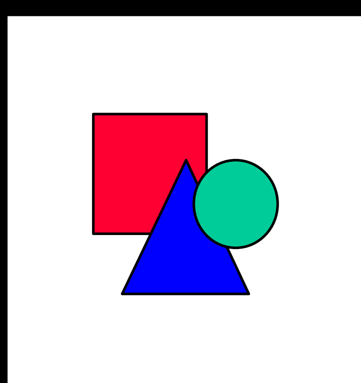
Scale cone sensitivities

- von Kries
- CIELAB formulation

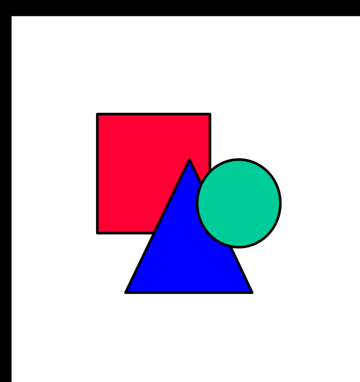
Pictures illustrate effect of no adaptation

Color Appearance Models
Mark Fairchild

Hunt’s Illustration

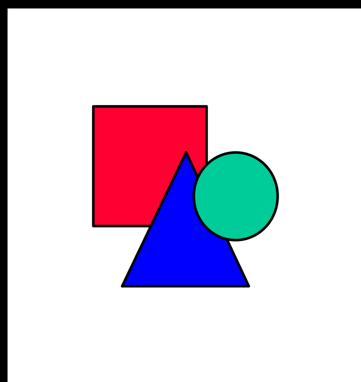


Original

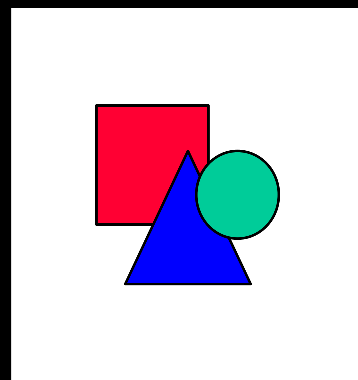


Add cyan filter

Object Colors in Context



Original



Filter only on pillow

Color Appearance Models

Models used to predict appearance

Beyond "tristimulus values"

CIELAB and its varients

- RLAB (Fairchild)
- CIECAM97

Other models

- Hunt
- Nayatoni et al.

Color Appearance Models
Mark Fairchild