# Color Vision

Light enters the eye

Absorbed by cones

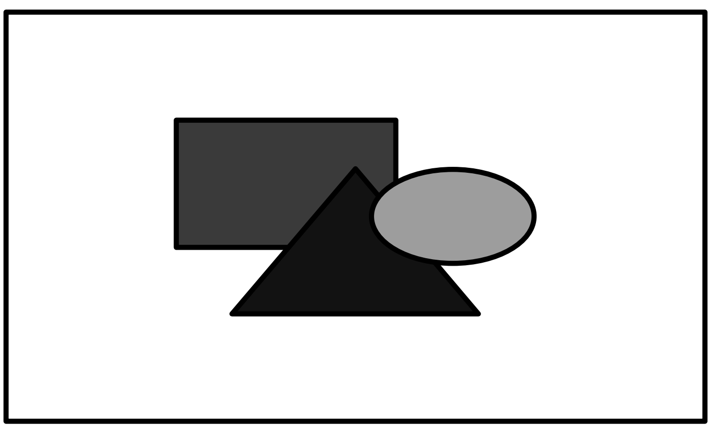
Transmitted to brain

Interpreted to perceive color

Foundations of Vision
Brian Wandell

# Spectral Distributions

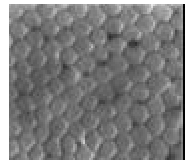
## Various Light Sources



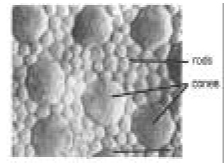
# Cones and Rods

Cones: color vision
- Photopic vision
- Daylight levels
- Concentrated in fovea (center)

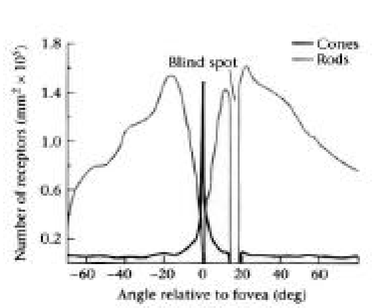
Rods: grayscale
- Low light levels
- Scotopic vision
- Peripheral vision



Fovial cones



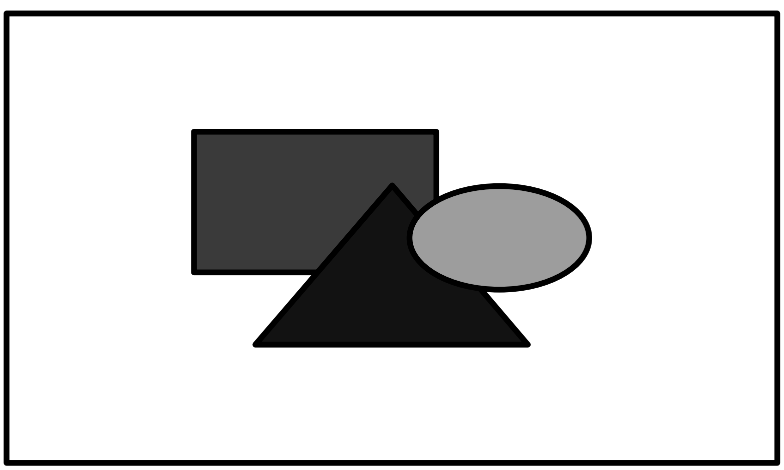

Cones and rods




Distribution of rods and cones

From Foundations of Vision, fig 3.1 & 3.4,


# Retinal Response Curves



# Demo

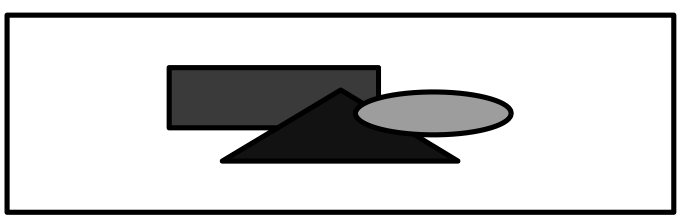
Java applets from Brown

- Trichromacy
- Metamerism
- Reflectance

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

# Metamerism

Different spectra appear the same

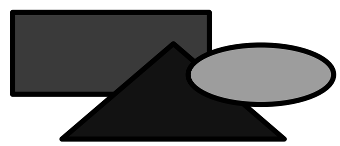


Fundamental principle of
Color Reproduction

# Colorimetry

Measurement of color

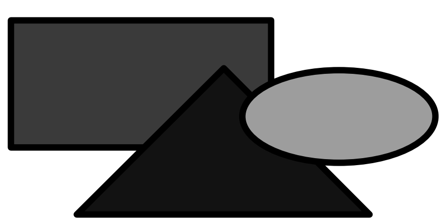
- Color matching experiments
- Grassman's Laws
- CIE Standards



Color Science
Wyszecki & Stiles

# Color Matching Experiments

Match any color by adding any* three primaries

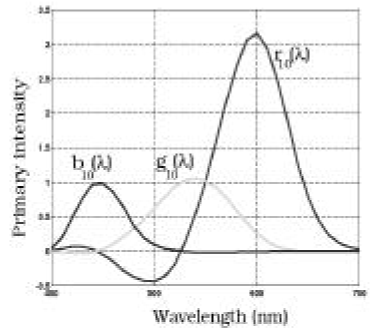


*Linearly independent

# 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:

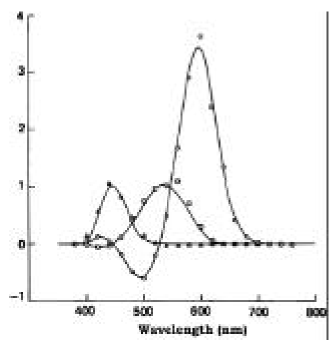
$$[R\ G\ B] \begin{bmatrix} X_R & Y_R & Z_R \\ X_G & Y_G & Z_G \\ X_B & Y_B & Z_B \end{bmatrix} = XYZ_{RGB}$$

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)

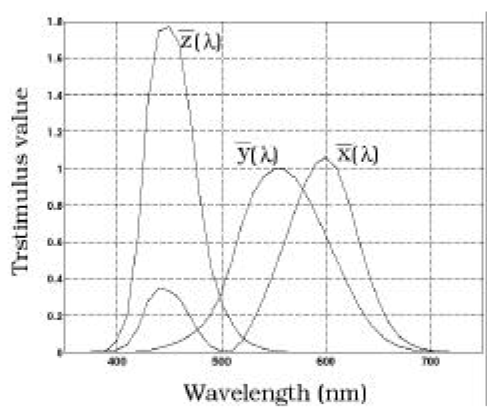
# CIE Color Matching

CMF's all positive

Unit area for each

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

Easily encoded in instruments



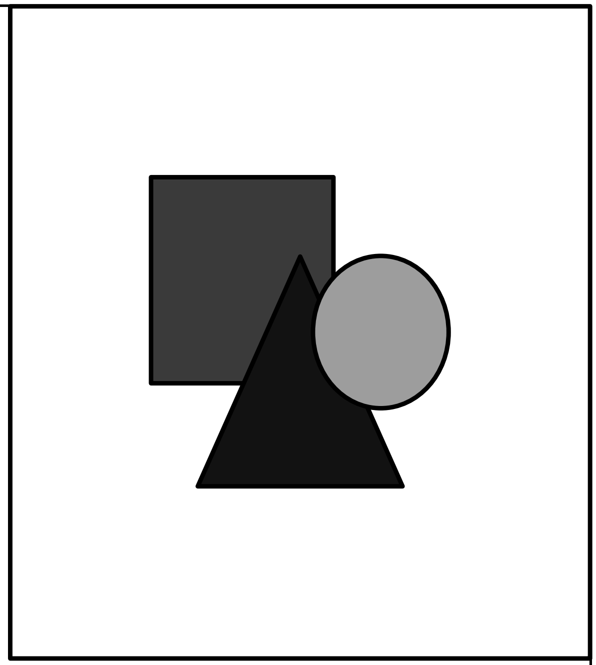

From Foundations of Vision, fig 4.14

## Chromaticity Coordinates

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

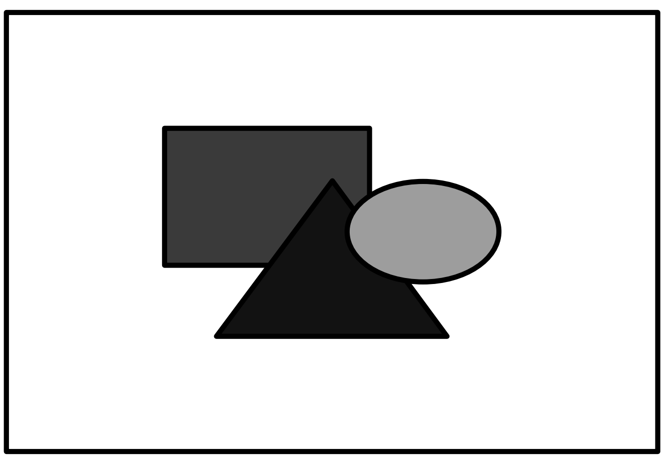
$x = X/(X+Y+Z)$
$y = Y/(X+Y+Z)$
$z = 1-(x+y)$

Colorfulness separate from Brightness



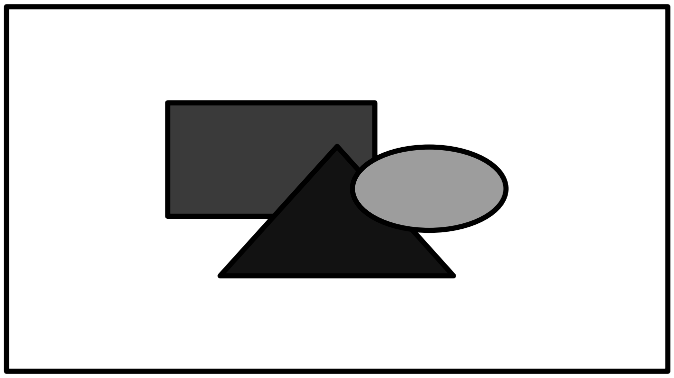
Courtesy of Photo Research

## Color Appearance

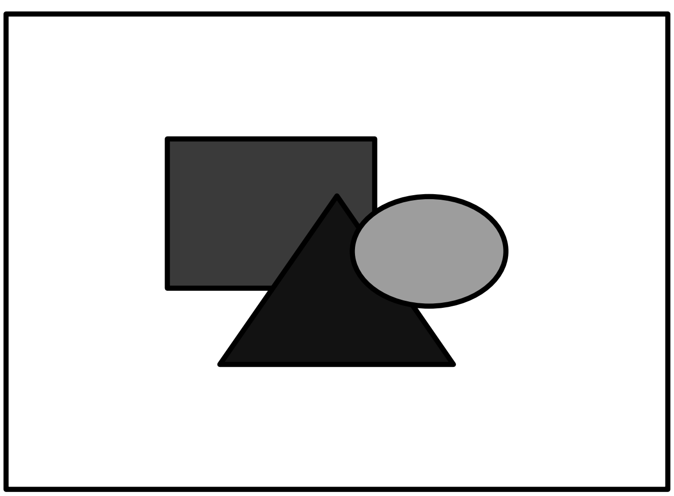


Interaction of Color
Josef Albers

## Matching Patches?

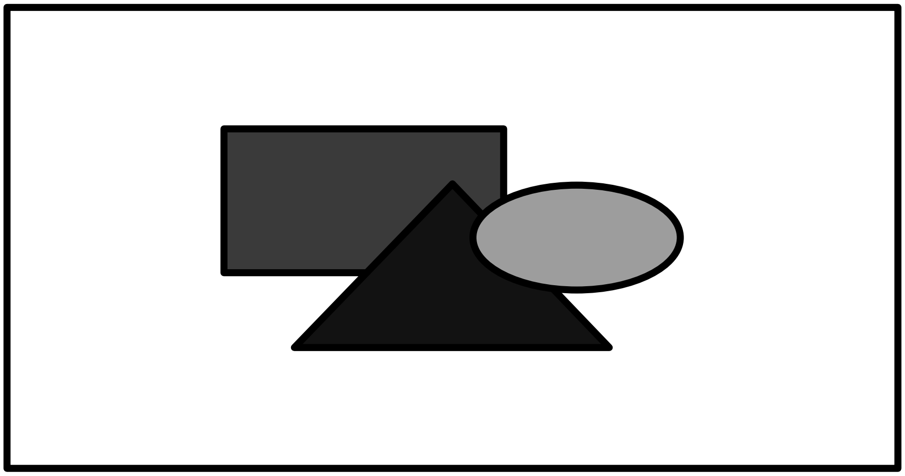


## Depends on Background



## Perceptual Organization of Color

Not “RGB” as in Colorimetry



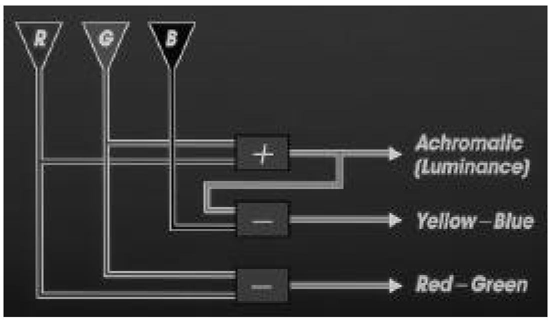
## Opponent Color

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

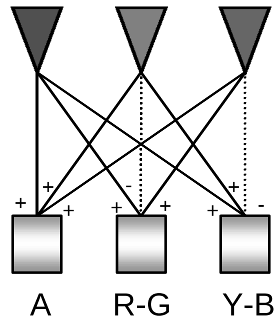
Definition
- Lightness, R-G and B-Y axis

Color Vision
Leo Hurvich

# Opponent Color Encoding

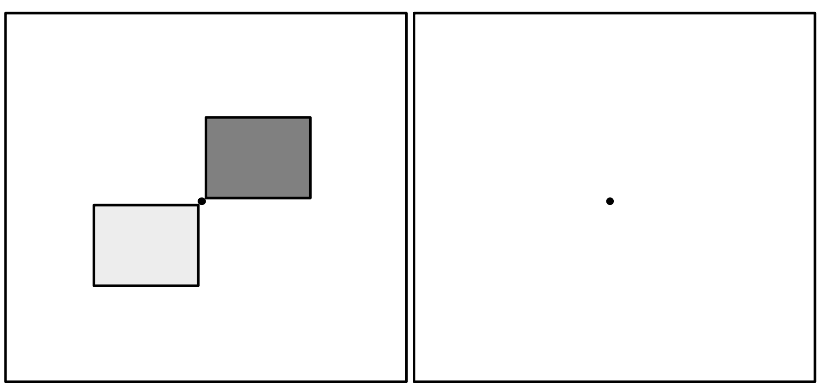



Traditional model




Fairchild, Figure 1-13

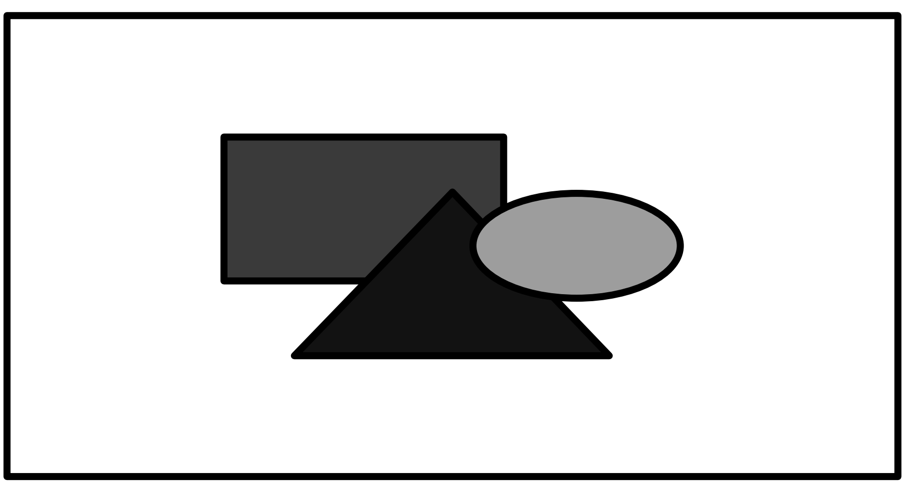
# Afterimages



## 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

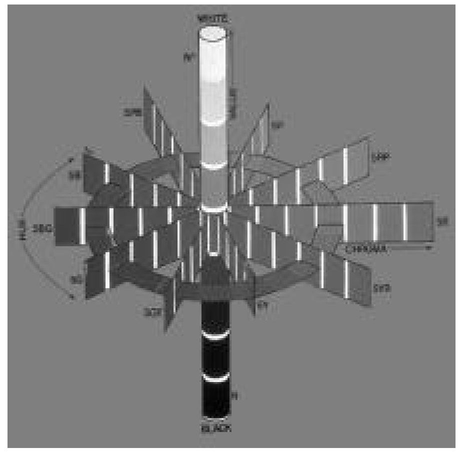


# Munsell Color Space

Chroma, Hue, Value

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

Now CIE XYZ defined



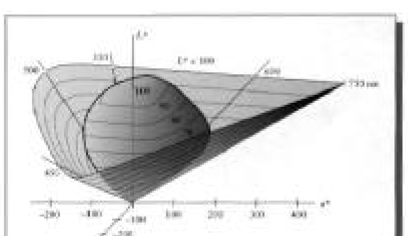

# CIELAB and CIELUV

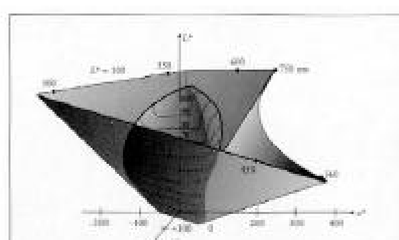
## Color Difference Spaces

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

Lightness (L*) plus two color axis

Function of XYZ of color plus XYZ of white


CIELAB


CIELUV

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

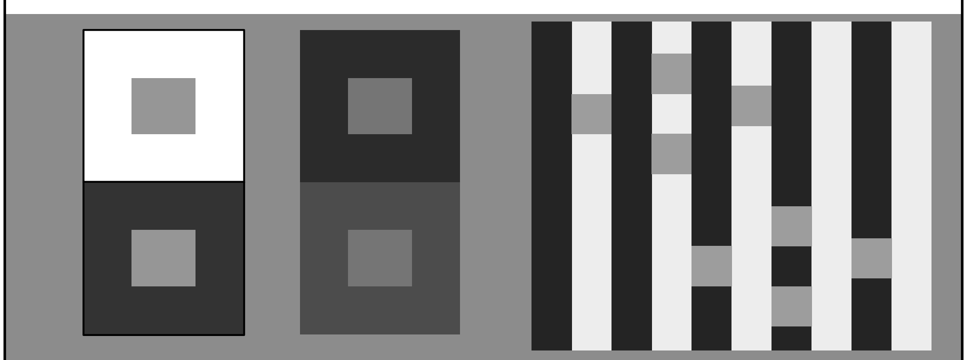
Adaptation

- Light/dark adaptation
- Chromatic adaptation

Geometric effects

- Spatial frequency
- Outlines, etc.

# Simultaneous Contrast

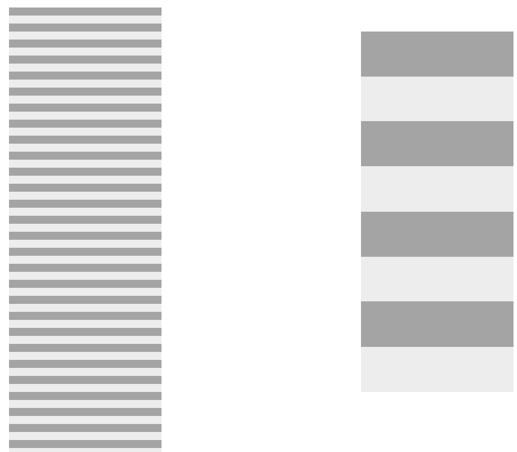


"After image" of surround adds to the color

Reality is more complex
Identical patch and surround

# Effect of Spatial Frequency

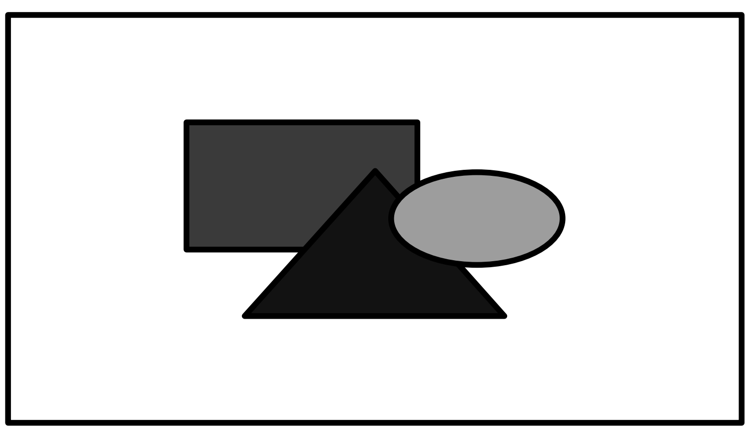
## “Spreading” Effect



Redrawn from Foundations of Vision, fig 6

# Impact of Outlines

## The Bezold Effect

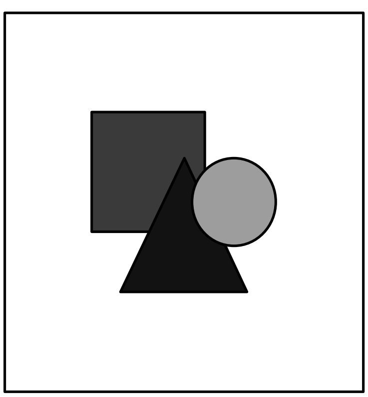


# Chromatic Adaption

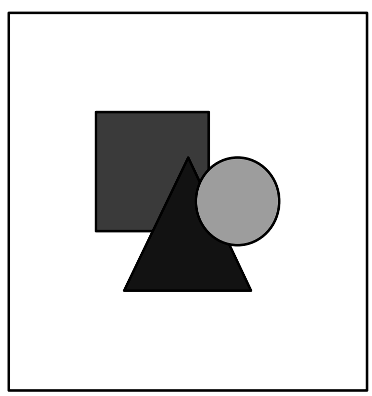
- Change in illumination
- Automatic “white balance”
- Scale cone sensitivities
  - von Kries
  - CIELAB formulation
- Pictures illustrate effect of no adaptation

Color Appearance Models
Mark Fairchild


# Hunt’s Illustration

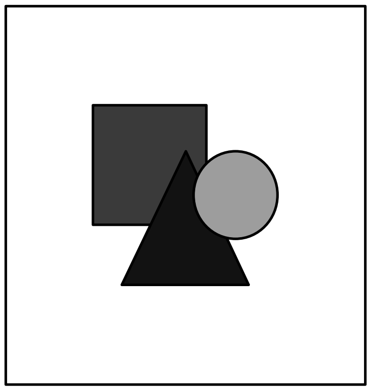


Original

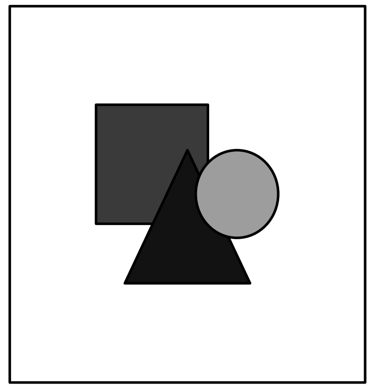


Add cyan filter

# 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