Human Vision and Color

For students of HI 5323

"Image Processing"

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http://biomachina.org/courses/processing/12.html
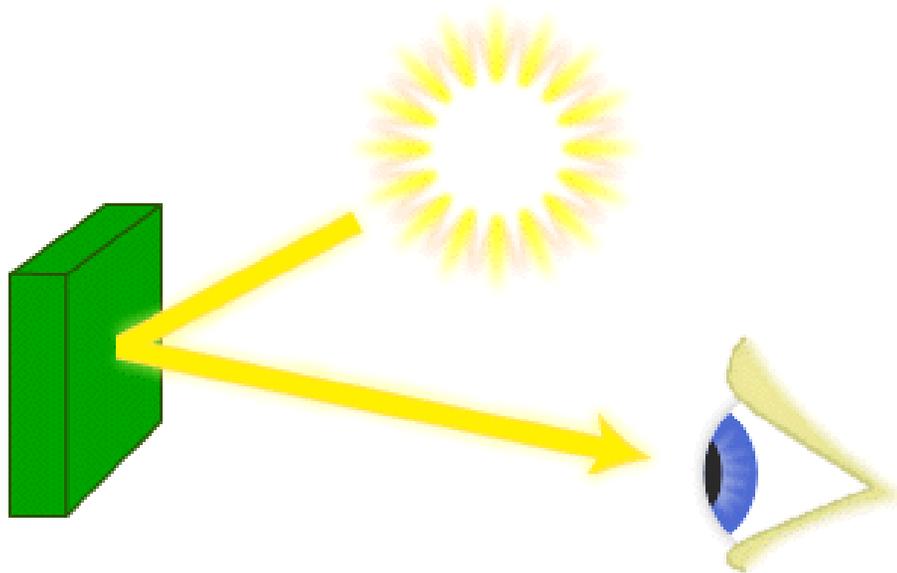
Human Vision

Human Vision

Some properties of human vision that affect image perception:

- Linear and non-linear parts

- Non-linear (approx. logarithmic) encoding of input

- Adaptation

- Relative-contrast encoding

- Varying sensitivity to spatial frequencies

- Generally treats brightness and color separately

Discrimination Experiments

Many vision experiments involve comparisons

"Two alternative, forced choice" (2-AFC) experiments:

- Is there a difference? (yes/no)
- Which is brighter, farther apart, etc. (top/bottom, left/right, etc.)

Random guessing without bias: 50% correct

Pick some percentage above which the observer must get it right: often 75% (half the time they "see it", half the time they guess)

Vary experimental parameter to determine the threshold T above which the observer reaches this desired level of confidence

This is called the just noticeable difference (JND)

Sensitivity: $1/T$

Weber's Law

Many visual properties obey Weber's Law

For intensity discrimination:

$$\frac{\Delta I}{I} = c$$

for some constant c

In other words, *the JND ΔI for intensity is proportional to the intensity itself*

Also applies to distance judgments, spatial frequency discrimination, and many others

Example: 1 mile vs. 2 miles; 51 miles vs. 52 miles!

Weber's Law and Logarithmic Encoding

$$\log(I + \Delta I) - \log I = \log\left(\frac{I + \Delta I}{I}\right)$$

$$= \log(1 + c)$$

$$= \text{constant}$$

Differences of logarithmic encoding produces Weber's Law

The human intensity sensitivity function isn't exactly logarithmic, but it's close enough to be a useful model

Adaptation

Our eyes have an incredible ability to adapt to lighting conditions

Total JND steps for the eye is about 1000

Total JND steps for fixed adaptation is about 200

Contrast Encoding

The response of the eye to light isn't absolute – it's relative to the surrounding intensities

This causes the *Mach effect* at strong intensity transitions:

Even our color perception seems to be, to a degree, based on relative differences

Intensity: measurable light

Brightness: the perceived illumination

Spatial Frequencies

Stimulus: sinusoidal grating of some frequency f and amplitude A

Vary A in a 2-AFC and find the JND for each frequency f

Plot the sensitivity as a function of frequency f: the contrast sensitivity function (CSF)

Implications:

– The eye is less sensitive to extremely gradual changes

– The eye is fairly sensitive to more rapid changes

– The eye is decreasingly sensitive to yet higher spatial frequencies
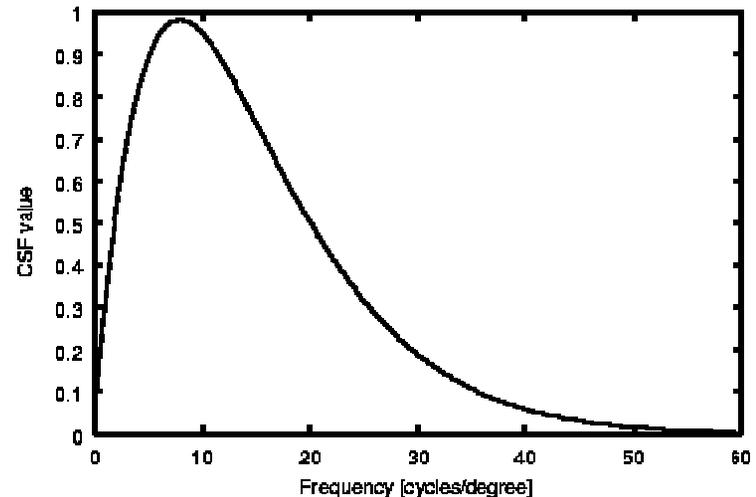
Brightness vs. Color

- The human visual system seems to treat brightness and color separately

- Physically separate pathways in the visual cortex (brain)
  - Some crossover, but weak

- Perception of shape and form seems to be based on brightness, not color

- Much more sensitive to changes in brightness than to changes in color

Time-Dependent Limitations

Incomplete capture of time-dependent images or scenes:

- Change blindness:

  http://www.usd.edu/psyc301/ChangeBlindness.htm

- Motion induced blindness:

  http://www.michaelbach.de/ot/mot_mib

- More visual illusions:

  http://www.michaelbach.de/ot

Displays

When building visual displays you have to consider properties of human vision:

- Exponential encoding for perceptual linearization

- Be careful of Mach effects

- Consider adaptation

- Make it bright!

- Consider the human CSF

- Be careful with color

Color

What is Color?

- Color is the spectrum of light being perceived by the human visual system

- Visible light is electromagnetic energy in the 400 to 700 nm wavelength range of the spectrum

- Why discuss color?

  - Many ways to talk about color: tint, shade, hue, brightness, luminance, color, chromaticity, …

  - Useful to understand how the eye perceives color

Electromagnetic Radiation - Spectrum

Gamma	X rays	Ultra-violet		Infrared	Radar	FM	TV	Short-wave	AM	AC electricity

10^{-12} $\qquad$ 10^{-8} $\qquad$ 10^{-4} $\qquad$ 1 $\qquad$ 10^{4} $\qquad$ 10^{8}

Wavelength in meters (m)

Visible light

400 nm $\qquad$ 500 nm $\qquad$ 600 nm $\qquad$ 700 nm

Wavelength in nanometers (nm)

WAVELENGTH

AMPLITUDE

CREST

TROUGH
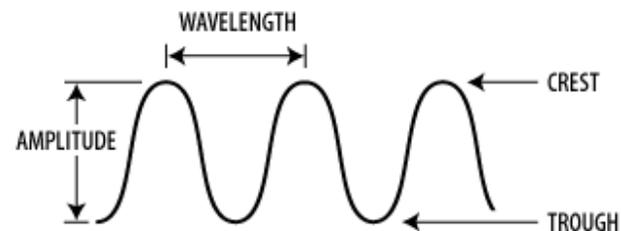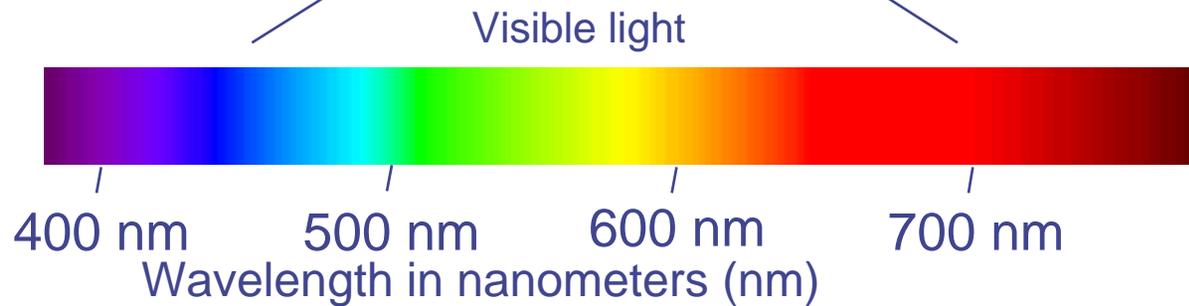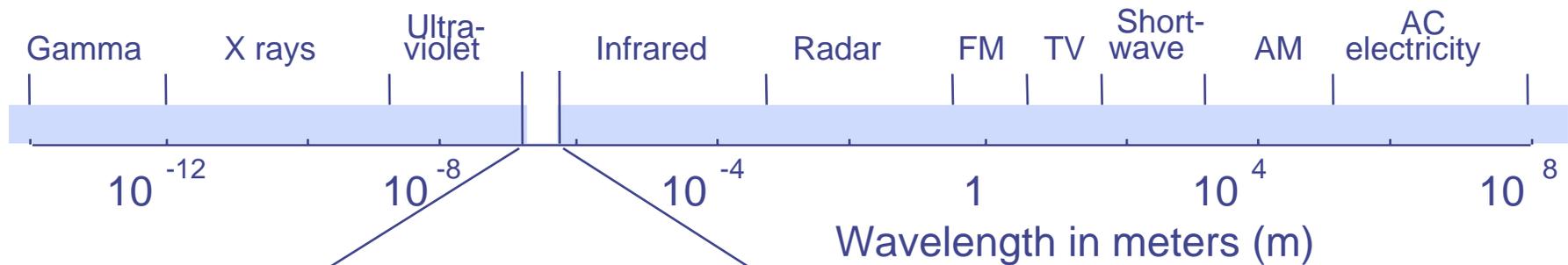
The Interaction of Light and Matter

- Some or all of the light may be absorbed depending on the pigmentation of the object.
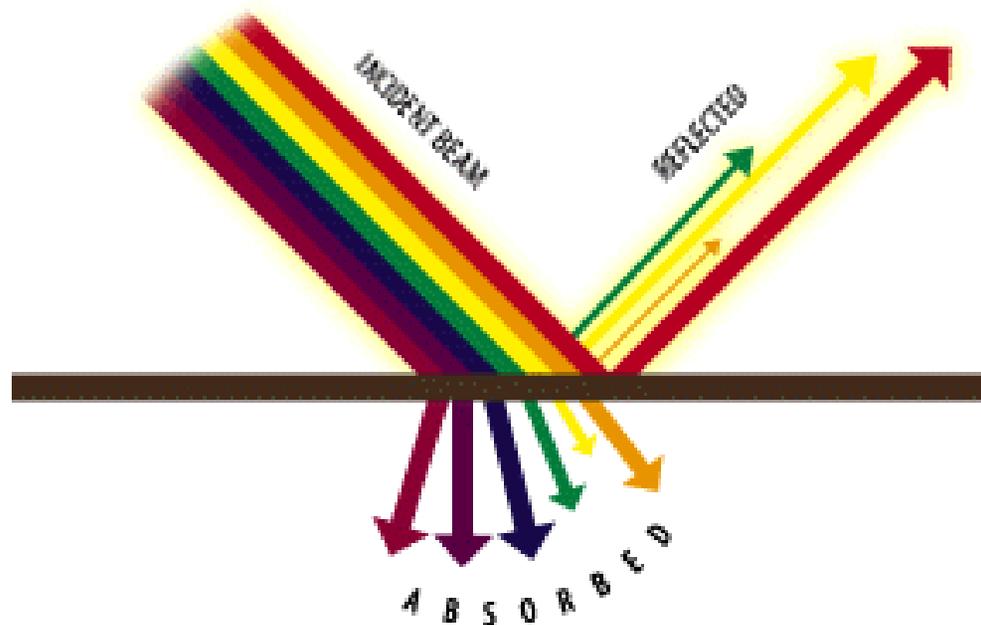
Spectral Power Distribution

- The **Spectral Power Distribution** (SPD) of a light is a function P(λ) which defines the power in the light at each wavelength
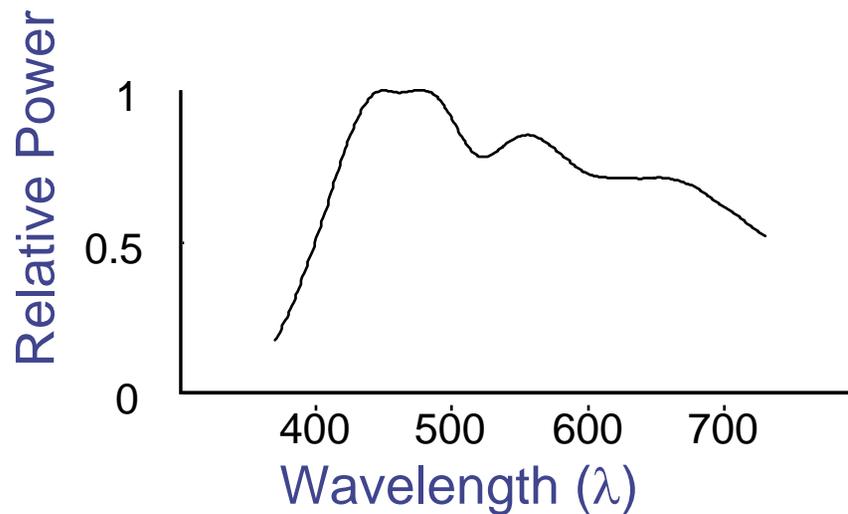
Examples
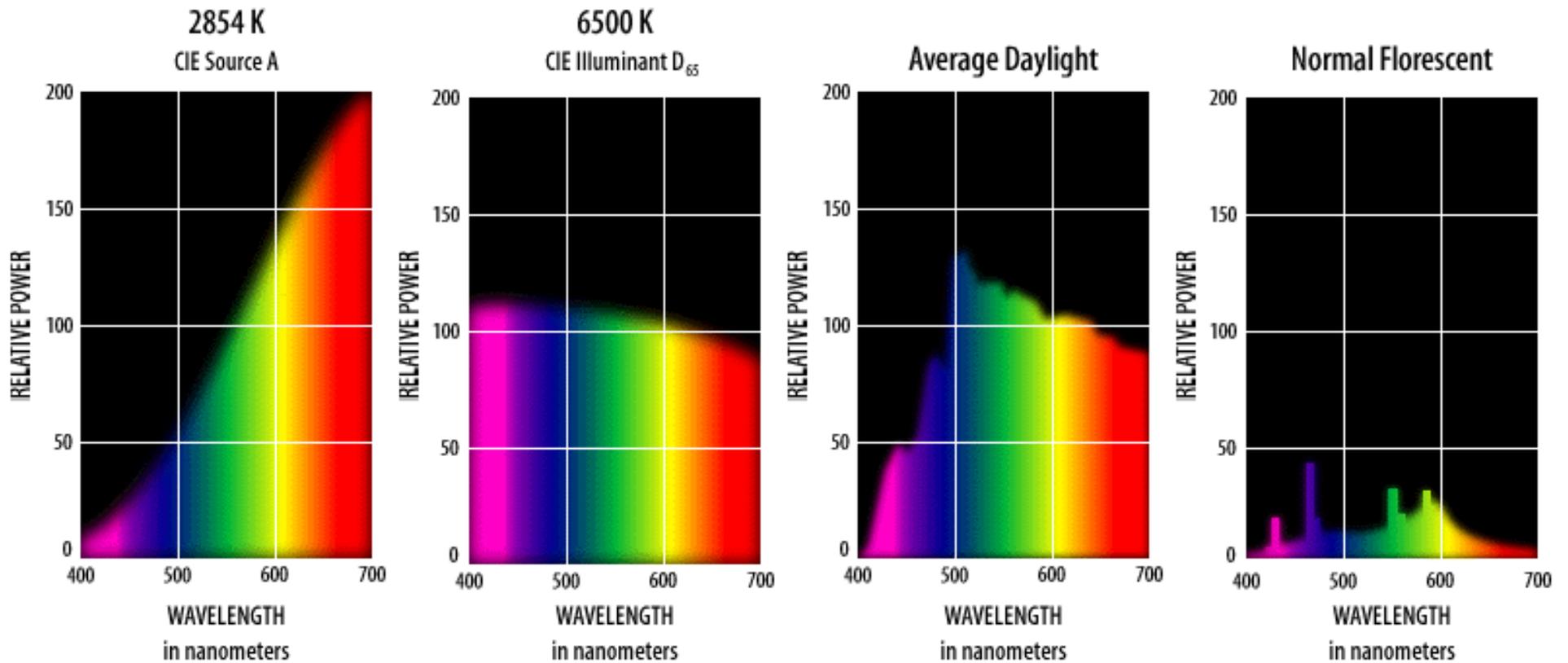
Color Receptors and the Eye

The Physiology of Human Vision
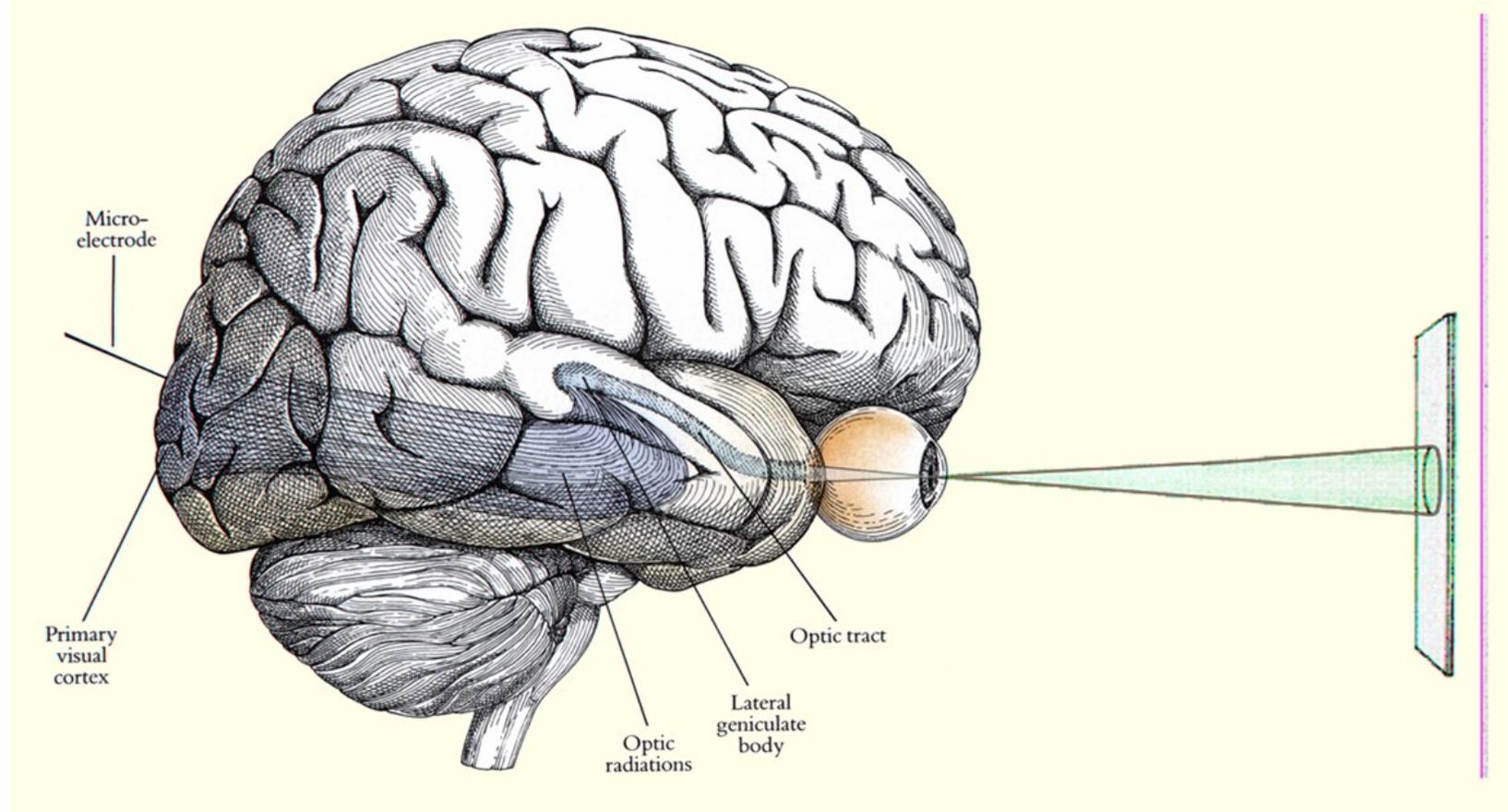
The Human Eye

The Human Retina

rods   cones

bipolar

horizontal

ganglion

amacrine
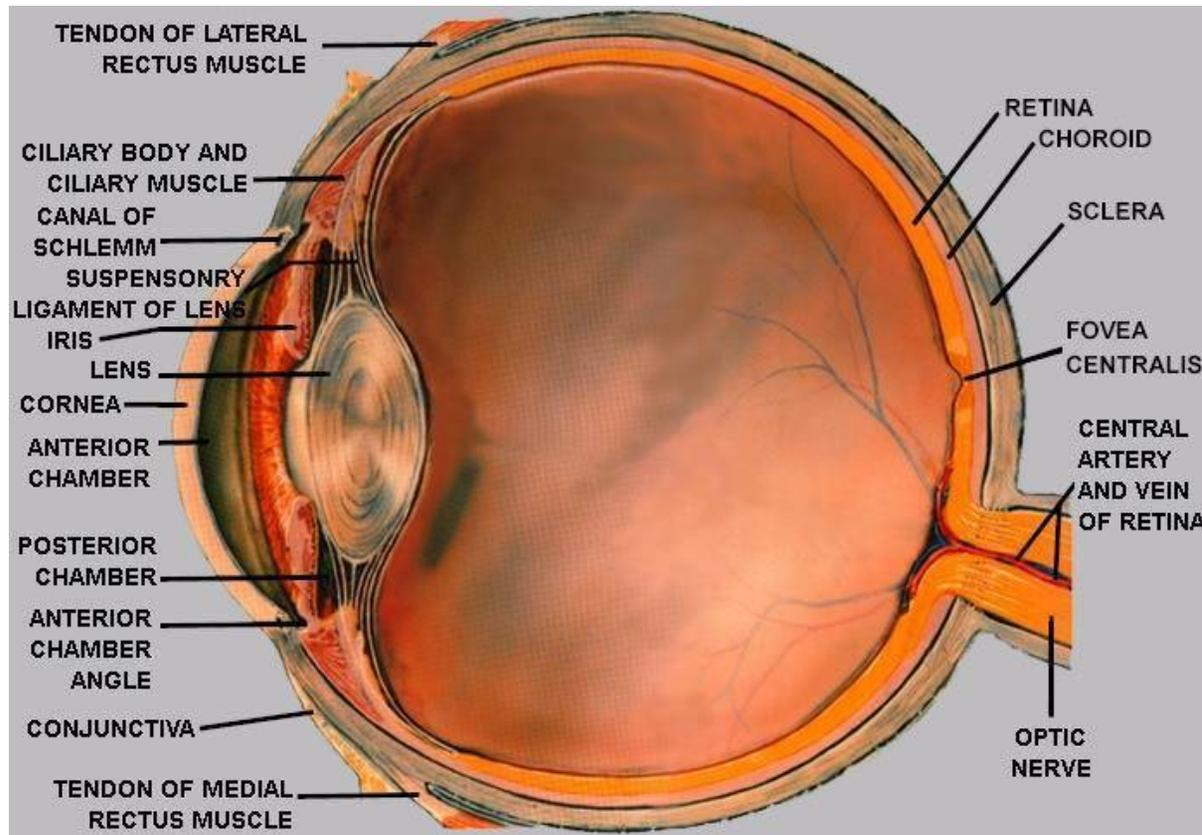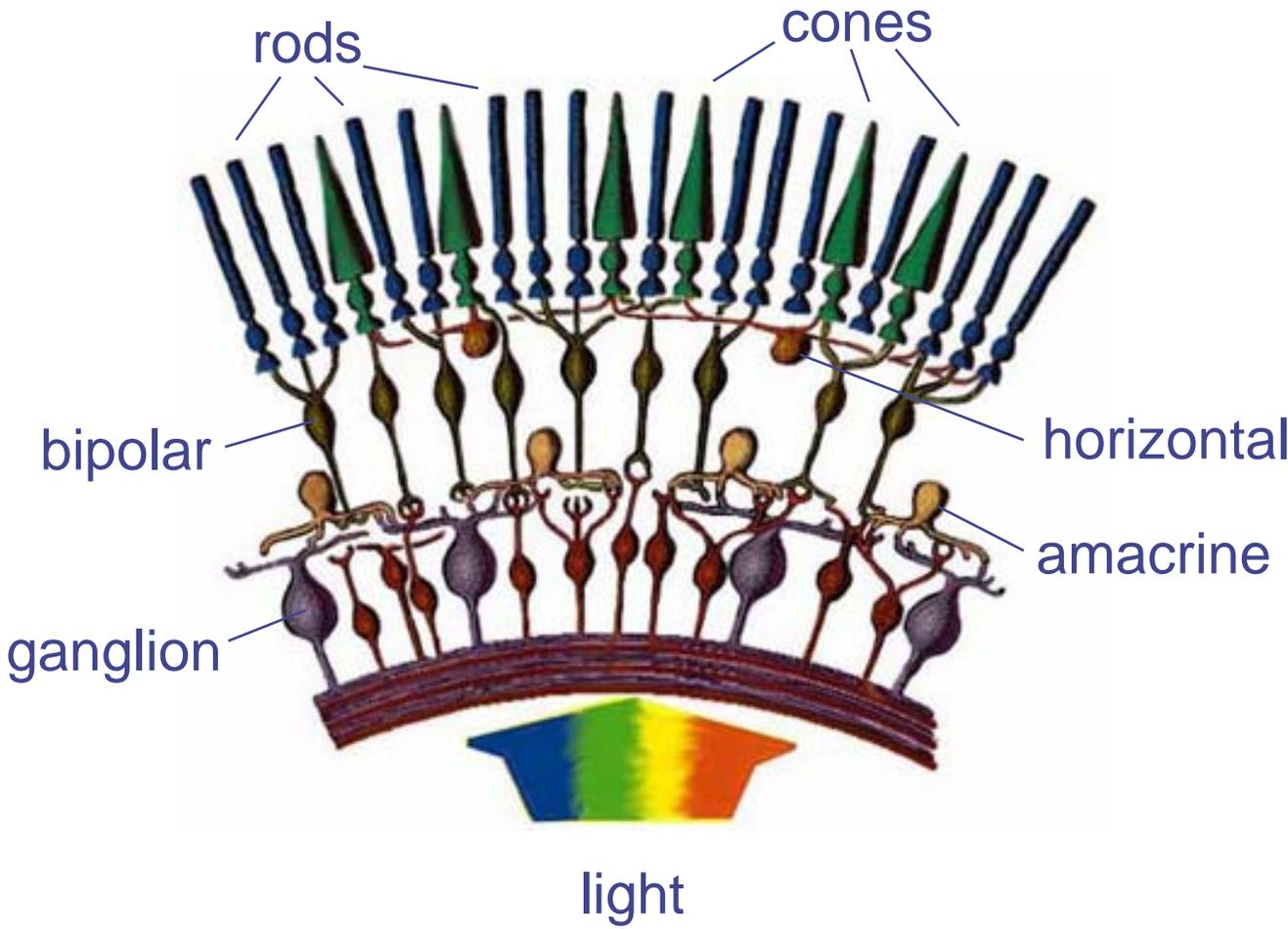
light

The Human Retina
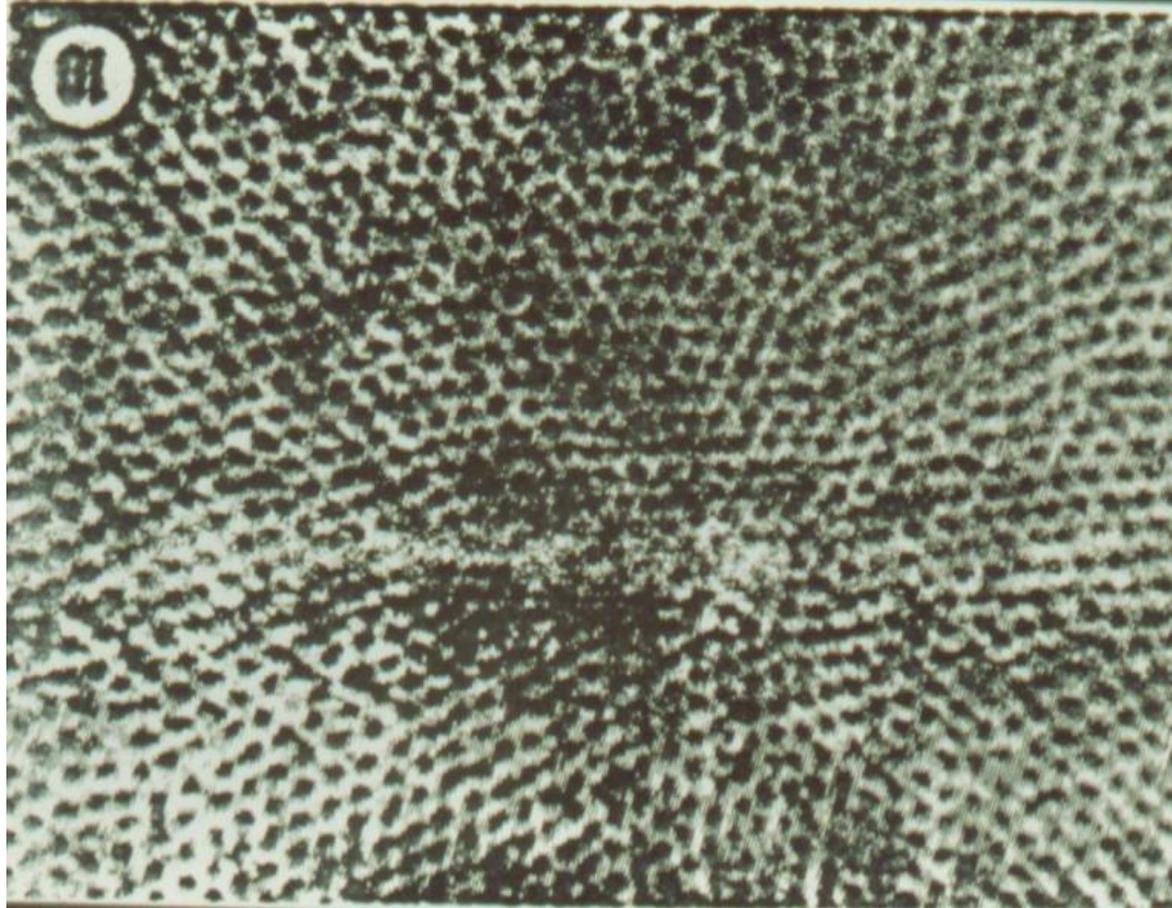
Retinal Photoreceptors
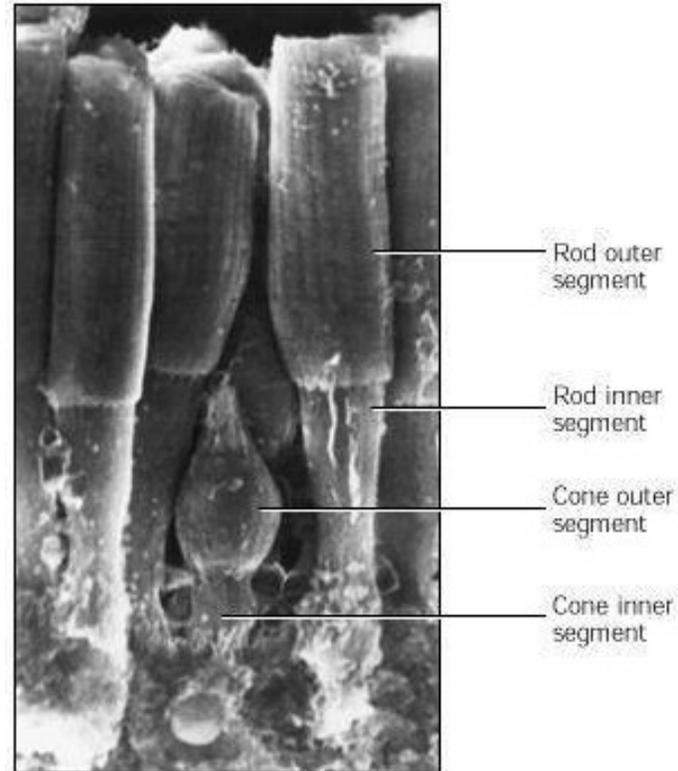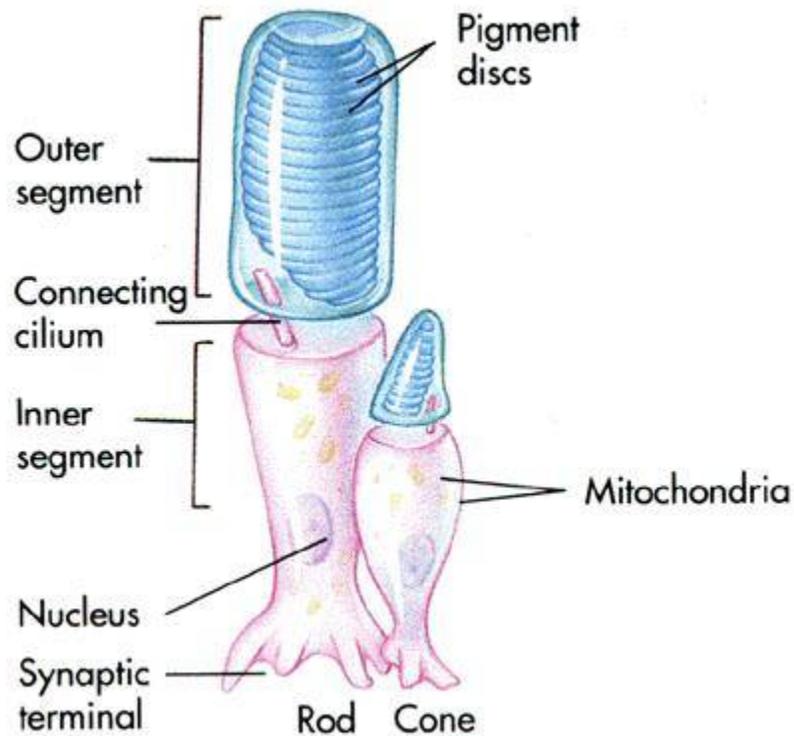
- Outer segments contain the photopigment rhodopsin
- Light absorption induces conformational changes in rhodopsin
- Second messenger cascade (reduced cGMP concentration)
- Closing of cation channels leads to hyperpolarization of photoreceptor
- Receptor currents evoked by decreased neurotransmitter at synaptic terminals

Cones

- High illumination levels (Photopic vision)

- Less sensitive than rods.

- 5 million cones in each eye.

- Density decreases with distance from fovea.

1.35 mm from rentina center

4 μm
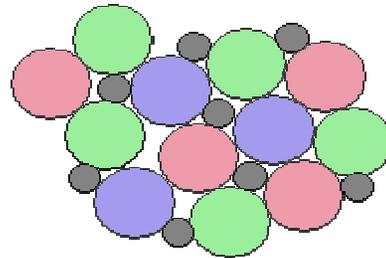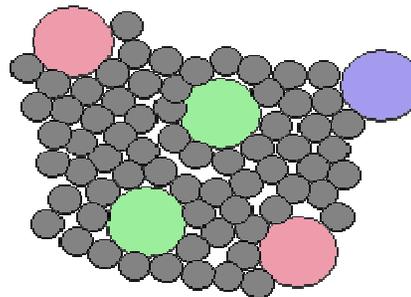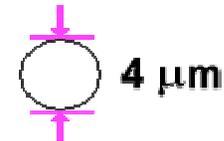
8 mm from rentina center

3 Types of Cones

- **L**-cones, most sensitive to red light (610 nm)

- **M**-cones, most sensitive to green light (560 nm)

- **S**-cones, most sensitive to blue light (430 nm)

S-cone   M-cone   L-cone   rod
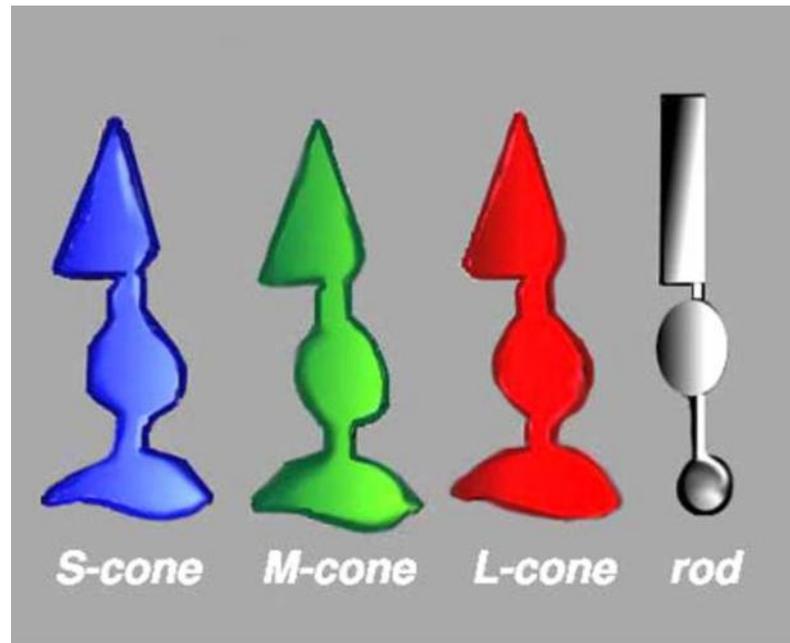
Color Receptors

- Cones have three kinds of color-sensitive pigments, each responding to a different range of wavelengths

- These are roughly "red", "green" and "blue" in their peak response but each responds to a wide range of wavelengths

- The combination of the responses of these different receptors gives us our color perception

- This is called the tri-stimulus model of color vision

Cones Spectral Sensitivity
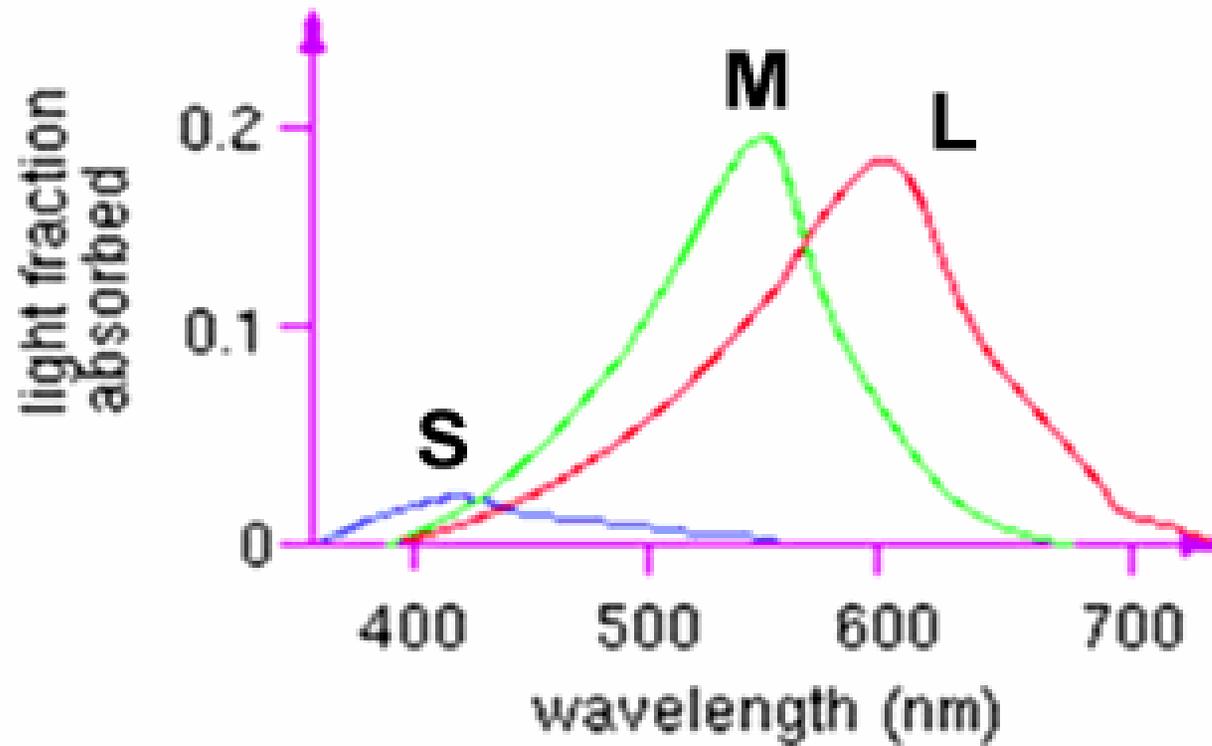
Metamers

- Two lights that appear the same visually. They might have different SPDs (spectral power distributions)
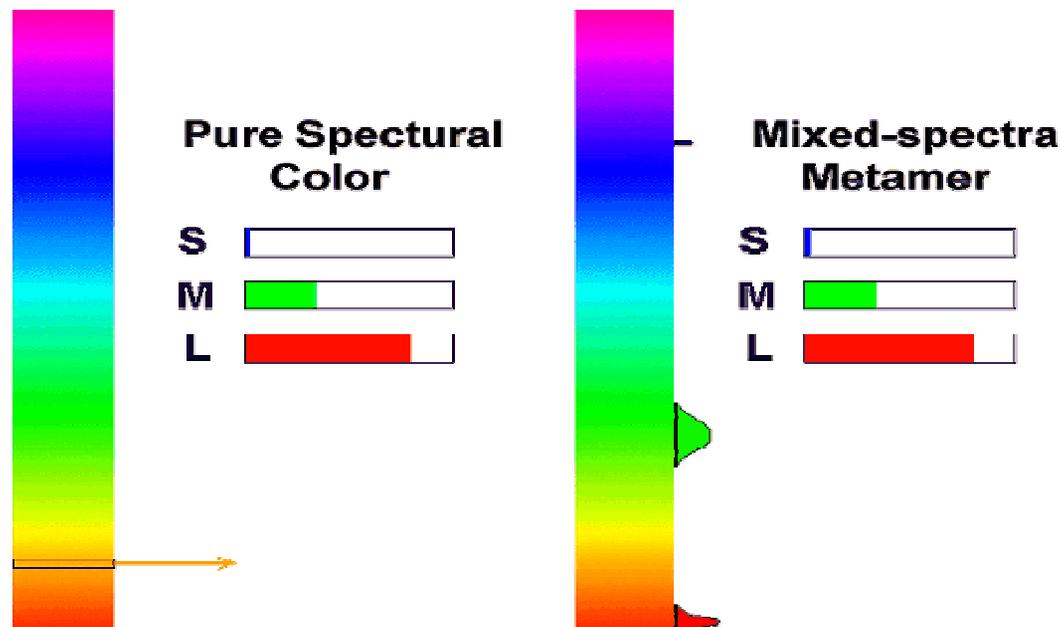
Color Spaces

History

- Thomas Young (1773-1829)

  "A few different retinal receptors operating with different wavelength sensitivities will allow humans to perceive the number of colors that they do. "

- James Clerk Maxwell (1872)

  "We are capable of feeling three different color sensations. Light of different kinds excites three sensations in different proportions, and it is by the different combinations of these three primary sensations that all the varieties of visible color are produced. "

- Trichromatic: "Tri"=three "chroma"=color

3D Color Spaces

- Three types of cones suggests color is a 3D quantity. How to define 3D color space?

Cubic Color Spaces
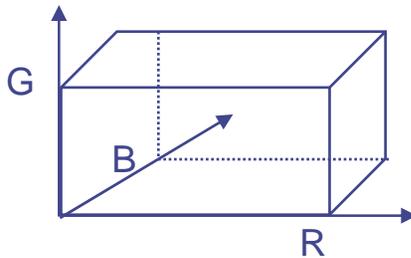
Polar Color Spaces
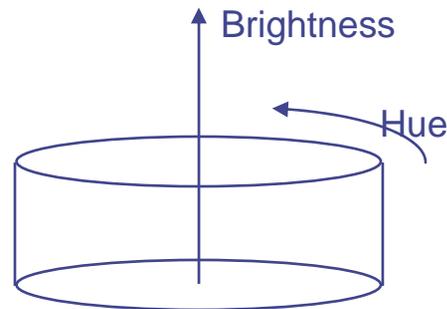
Opponent Color Spaces
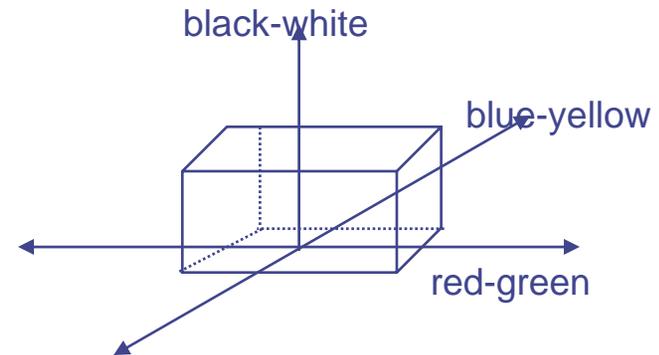
The RGB Color Model

- The simplest color model is to attempt to model these three stimulus values: red, green, blue

- 24-bit color: one byte each for red, green, and blue

- Each is called a channel

RGB Image

Blue channel:

111	14	126	36	12	36
36	111	36	12	17	111
				2	36
				4	36
				7	111
				12	36

Green channel:

200	36	12	36	14	36
200	111	14	126	17	111
				4	36
				7	111
				2	126
				4	36

Red channel:

10	128	126	200	12	111
17	36	36	14	36	72
12	17	126	17	111	200
14	200	36	12	126	17
126	200	111	14	36	72
36	12	17	72	106	155

Combined RGB:

10 200 111	128 36 14	126 12 126	200 36 36	12 14 12	111 36 36
17 200 36	36 111 111	36 14 36	14 126 12	36 17 17	72 111 111
12 36 17	17 36 111	126 111 200	17 36 36	111 14 12	200 36 36
14 17 14	200 126 36	36 72 12	12 126 36	126 17 14	17 111 36
126 200 17	200 36 111	111 12 14	14 36 126	36 12 17	72 126 111
36 72 12	12 12 126	17 17 200	72 111 36	106 14 12	155 36 36

Luminance and Chromaticity

RGB isn't the most intuitive model of color

Artists usually think of dark/light and color as two different things:

- Luminance
- Chromaticity

Luminance

- Luminance
- Intensity
- Brightness
- Lightness
- Luma
- Value

- All refer to the light/dark properties of the stimulus

- Some models use linear, non-linear, or perceptually linear encoding

Chromaticity

Requires two parameters

Example:

- Hue   →   The dominant wavelength
- Saturation   →   How pure/deep that color is relative to gray

Note: Some models use different chromaticity parameters

CIE *XYZ*

- CIE:
  - In French: Commission Internationale de l'Eclairage
  - In English: International Commission on Illumination

- Not the same as RGB and not tied to hardware

- Describes the entire visible gamut
  - Two chromaticity (similar to hue or color) values: X and Z
  - One luminous efficiency (similar to intensity) value: Y

- Provides a standard for sharing color information between disciplines
  - Computer graphics and fabric design

The CIE Chromaticity Diagram

CIE uses three primaries, X, Y, and Z, to replace red, green, and blue

XYZ primaries computed from RGB (Rec. 709) through a linear transform:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.412453 & 0.357580 & 0.180423 \\ 0.212671 & 0.715160 & 0.072169 \\ 0.019334 & 0.119193 & 0.950227 \end{bmatrix} \begin{bmatrix} R_{709} \\ G_{709} \\ B_{709} \end{bmatrix}$$

Normalized CIE primaries:

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

The CIE Chromaticity Diagram

Consider the plane

$$x + y + z = 1$$

Every point on this plane can be characterized by unique x and y ($z = 1 - x - y$)

Plotting on this plane the color of each wavelength gives the CIE chromaticity diagram

The CIE Chromaticity Diagram
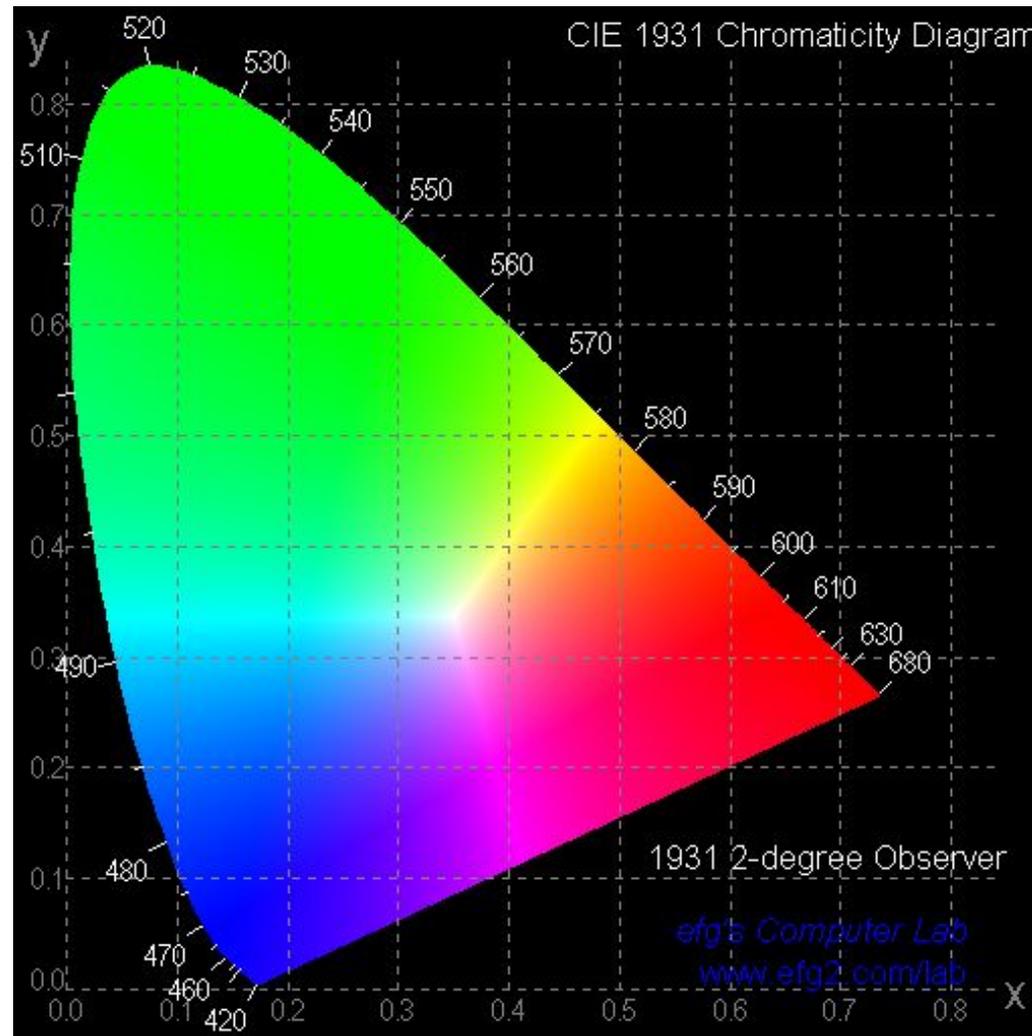
Color Gamuts

- The color space spanned by a set of primary (base) colors is called a color gamut

- Example: the space of all colors that can be displayed by a device with three color phosphors is the gamut of that device

- No three-primary color (with positive weights) spans the full space of perceivable colors!

- The CIE chromaticity diagram spans the gamut of human color vision

  - Recall that cones in the eye integrate over a wide range of wavelengths

The RGB Model

When light is mixed, wavelengths combine (add)

The Red-Green-Blue (*RGB*) model is used most often for
additive models

Adding a color and its complement create white

Primary	Complement
Red	*Cyan*
Green	*Magenta*
Blue	*Yellow*

RGB Space

- Can't produce all visible colors

- Contained within CIE *XYZ*

- Additive to produce other colors

- Perfect for imaging since hardware uses three color phosphors

Various RGB Color Spaces

Legend:
- Visible Gamut
- Wide Gamut, 700/525/450
- CIE RGB
- CCIR 601-1,NTSC(1953)
- Adobe RGB(1998)
- Apple RGB,Trinitron
- CCIR 709,sRGB,HDTV
- CIE_XYZitu,EBU-ITU,Pal-Secam
- ColorMatch RGB,P22-EBU
- SMPTE-C
- D50
- D55
- D65
- D75
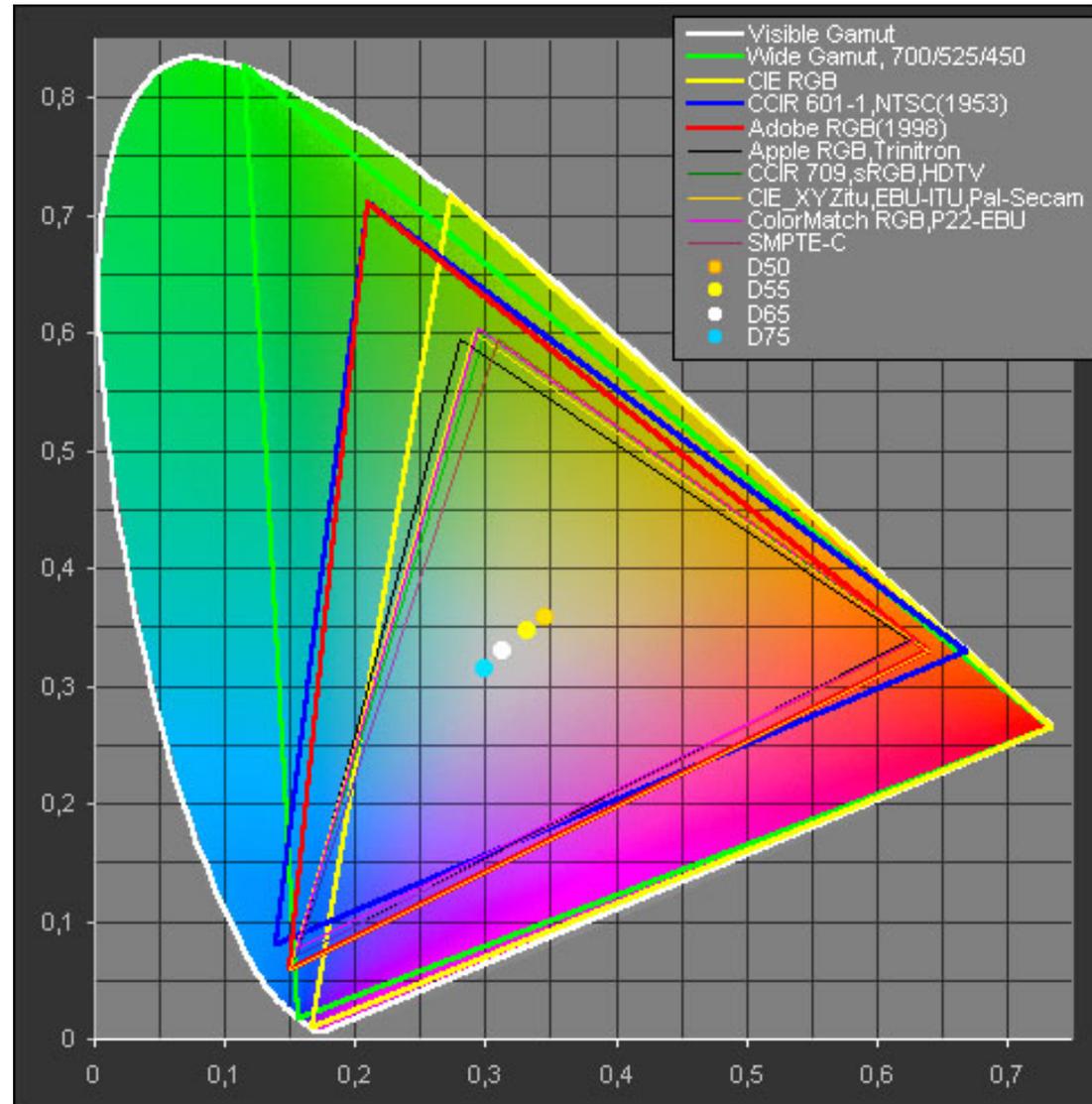
RGB Color Space

Subset of 3-D Cartesian space

Additive Colors: *RGB*

Green

Yellow

Cyan

White

Red

Magenta

Blue
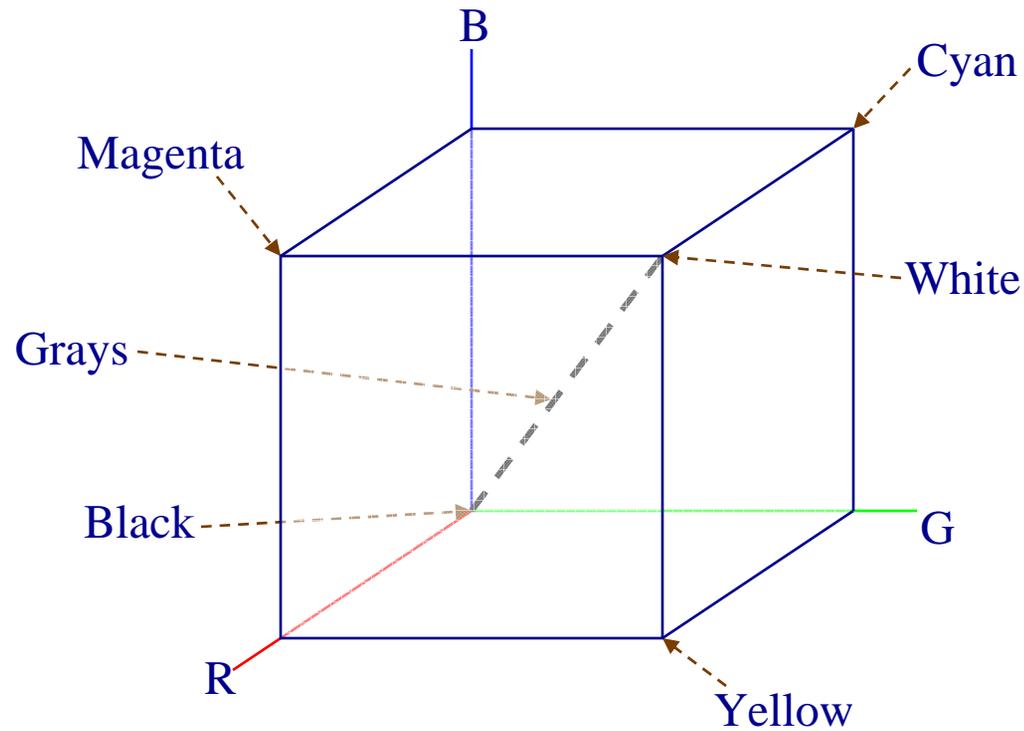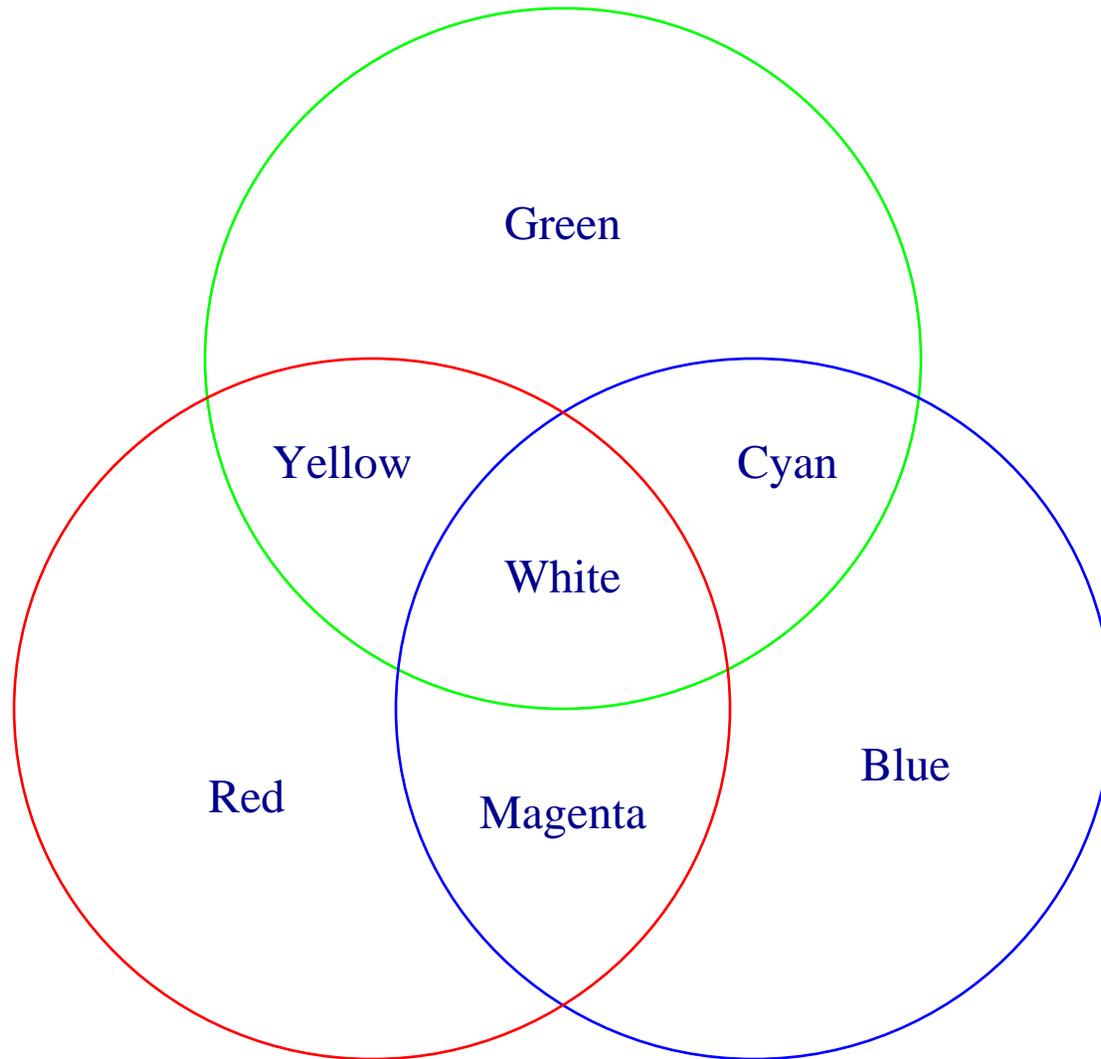
Subtractive Colors
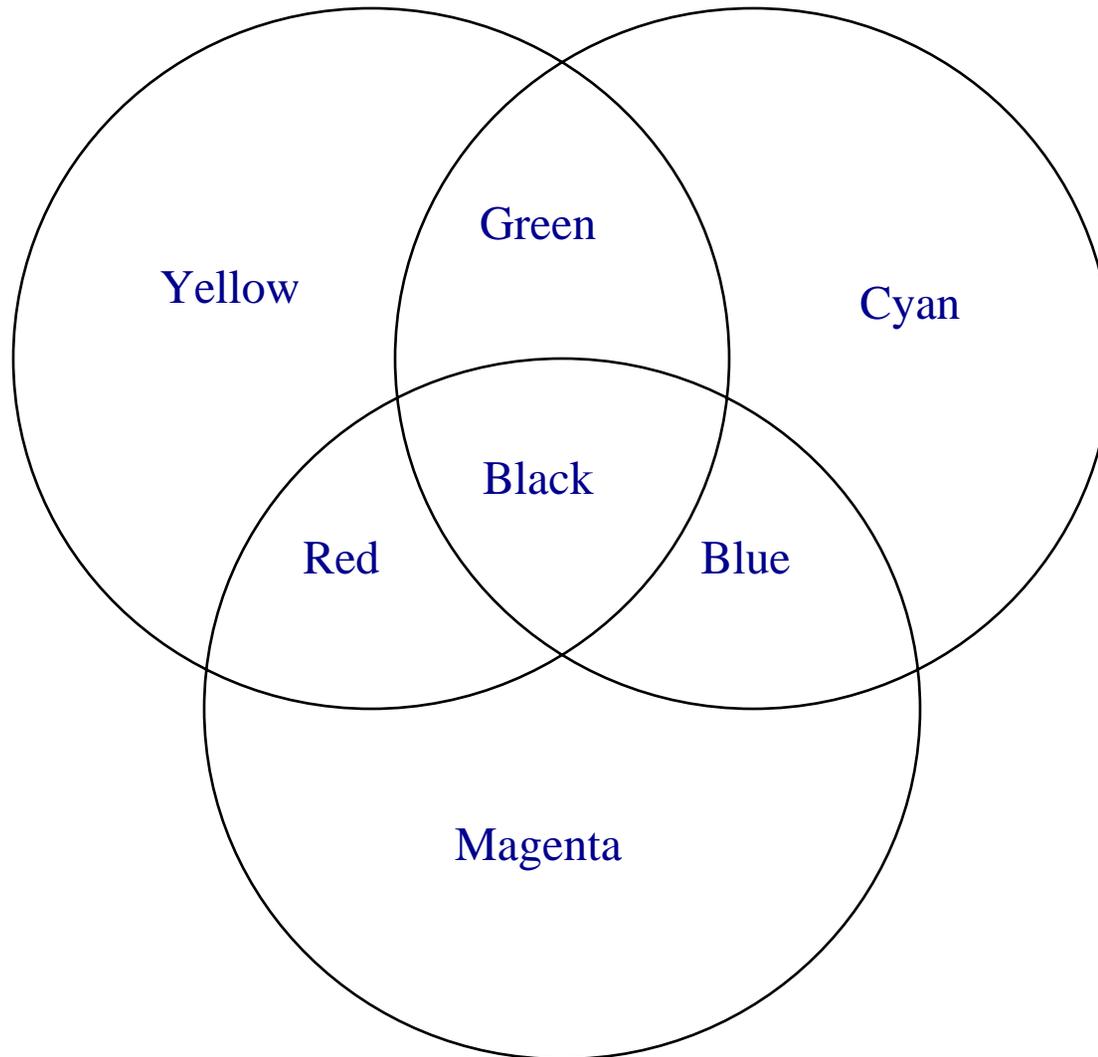
The CMY Model

- Paint/ink/dye subtracts color from white light and reflects the rest

- Mixing paint pigments subtracts multiple colors

- The Cyan-Magenta-Yellow (*CMY*) model is the most common *subtractive model*
  - Same as RGB except white is at the origin and black is at the extent of the diagonal

- Very important for hardcopy devices

CMY vs. RGB

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

Yellow Magenta

White → minus Blue minus Green = Red
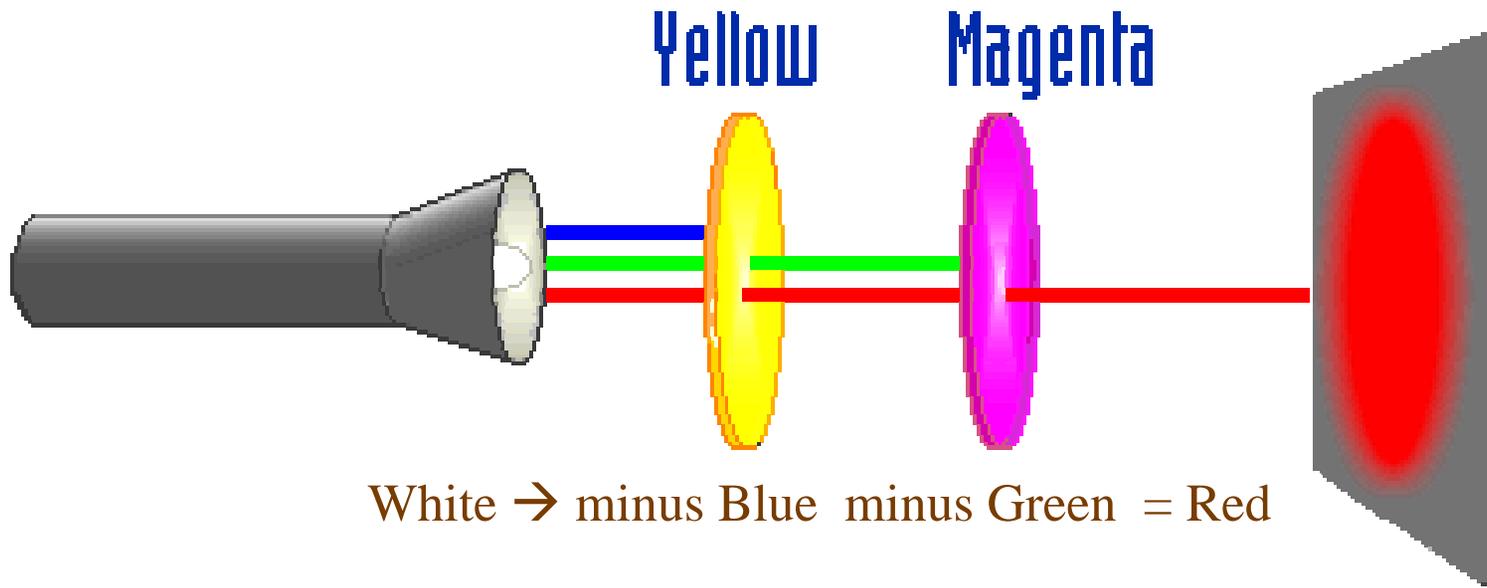
CMY Color Model

CMY = Cyan, Magenta, Yellow

Cyan – removes Red

transmit

B G R

Magenta – removes Green

B G R

Yellow – removes Blue

B G R

Black – removes all

1,1,0
Yellow

1,1,1
White

0,1,0
Green

0,1,1
Cyan

1,0,0
Red

1,0,1
Magenta

0,0,0
Black

0,0,1
Blue
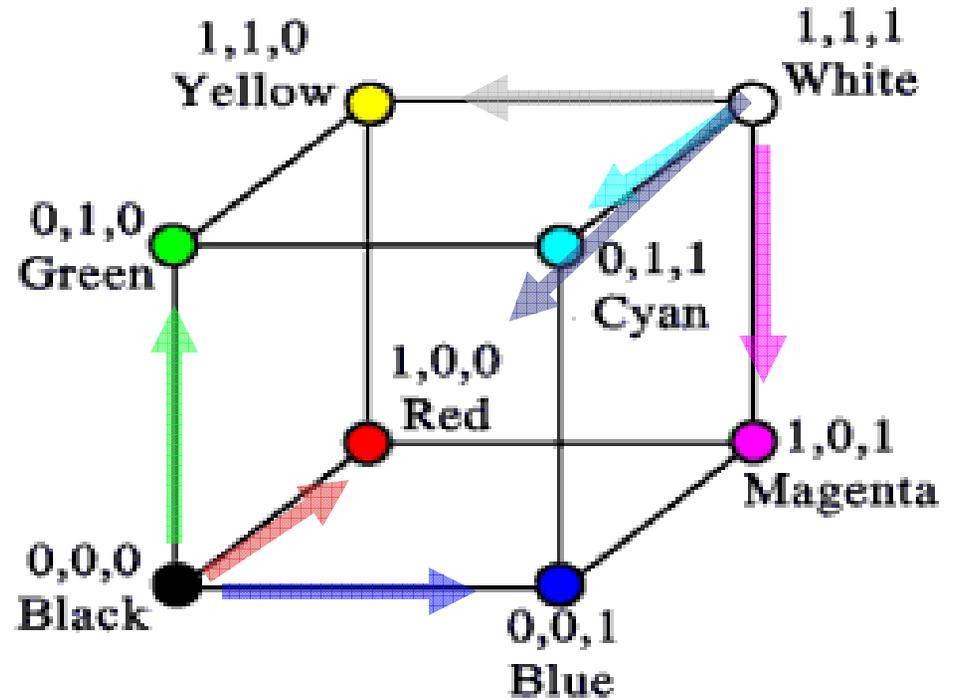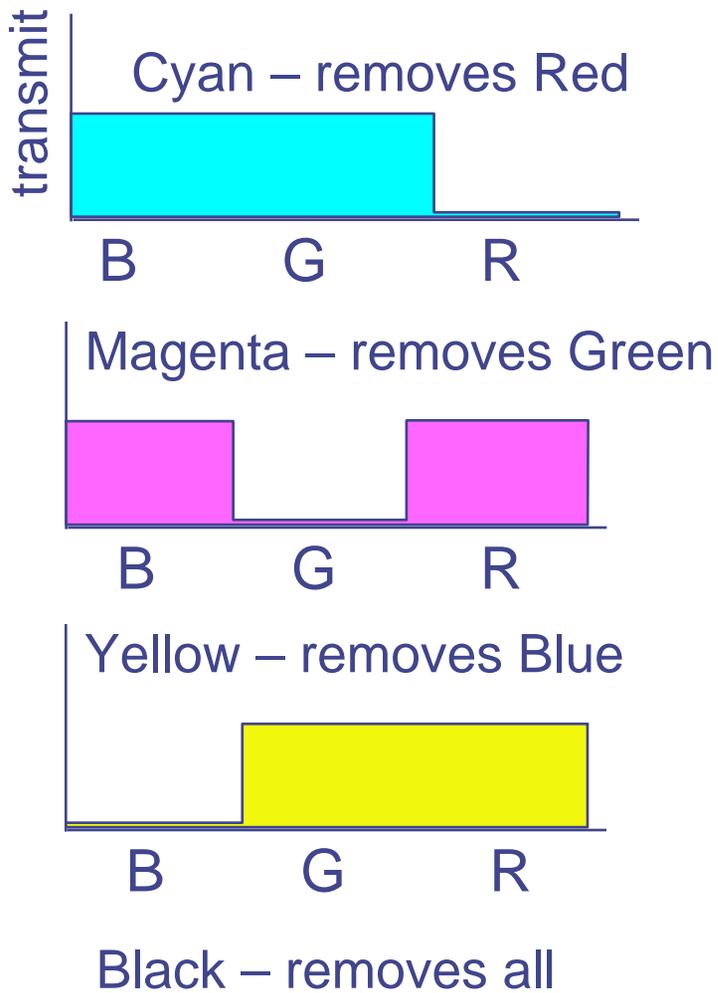
Combining Colors

Additive (RGB)

ADDITIVE COLOR MIXING
RED
GREEN
BLUE
The Mixture of Colored Light

Subtractive (CMY)
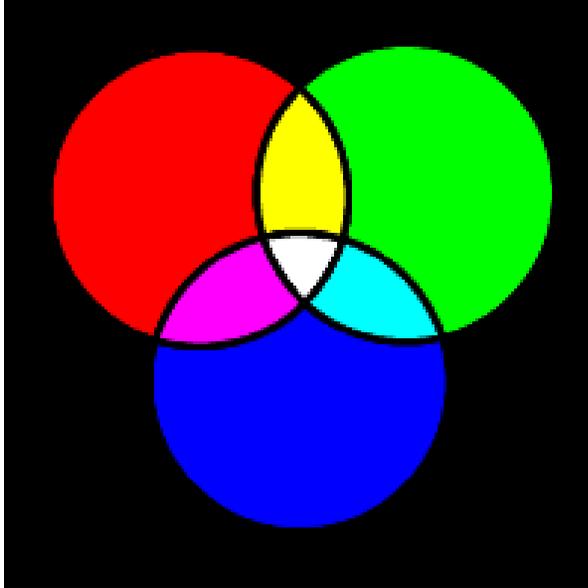
Subtractive Color Mixing
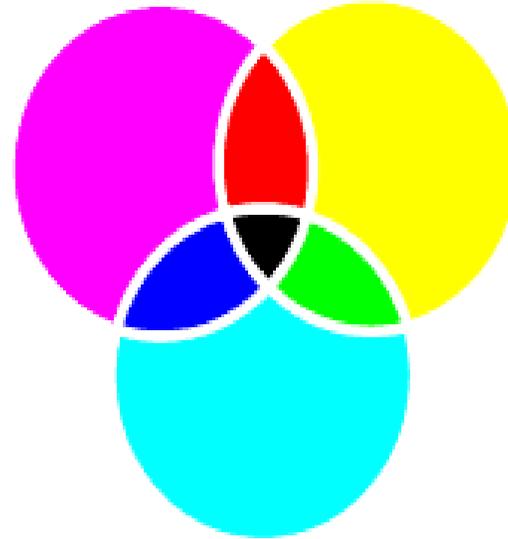
Example: Red = Magenta + Yellow
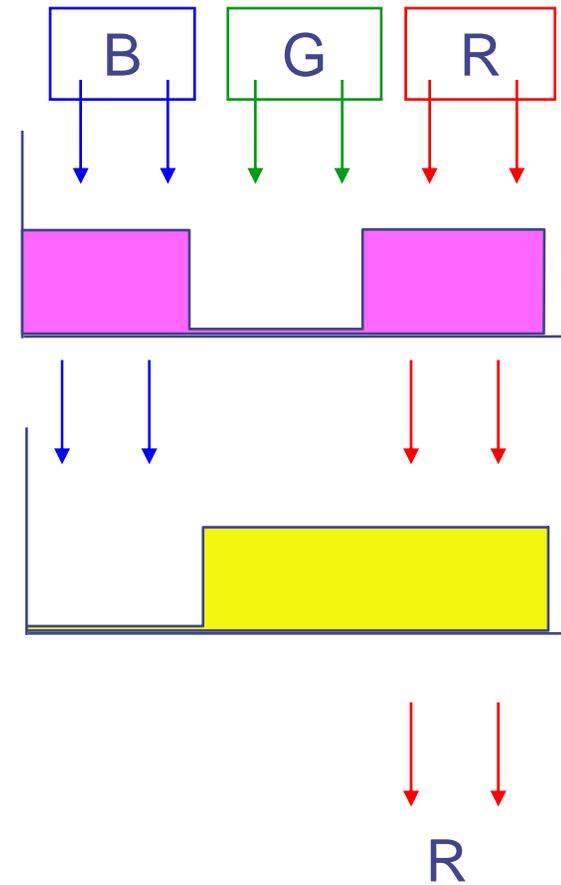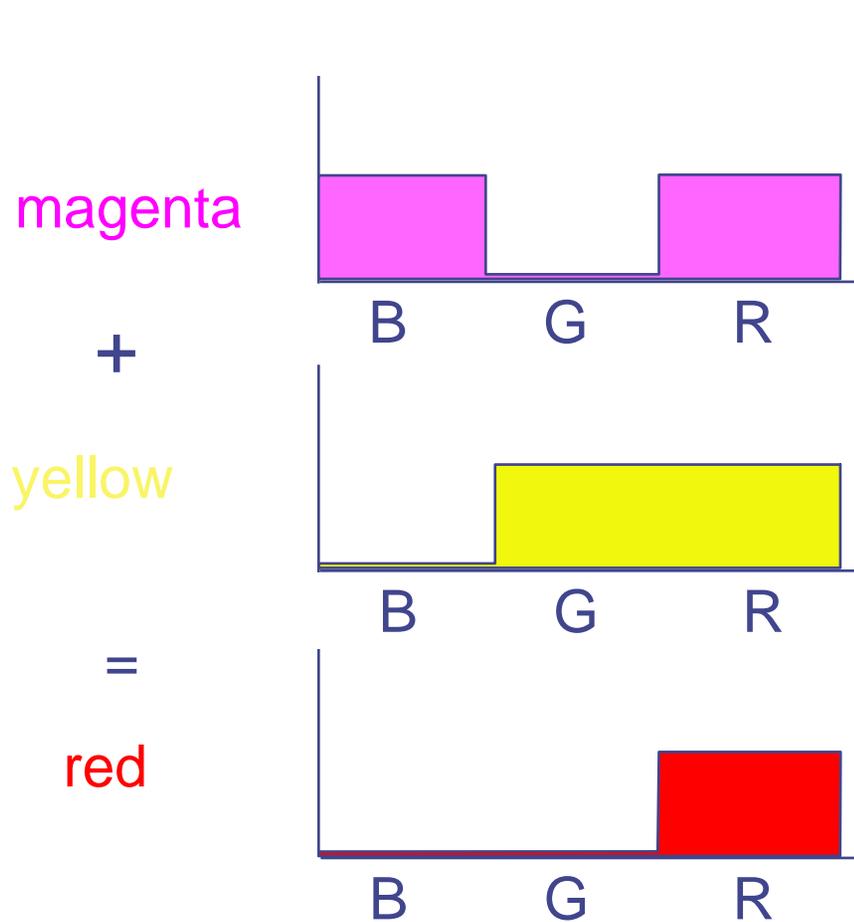
The CMYK Model

- Black created by:
  - Adding a subtractive color and its complement
  - Adding all three subtractive colors

- Problem: paints/inks/dyes are imperfect, so it's hard to make pure black (especially a problem in print where black is used so often)

- C+M+Y = dark brown not black

- Solution: add black (*K*) as a fourth primary → *CMYK* color model

CMY + Black

$$C + M + Y = K \;\; \text{(black)}$$

- Using separate ink for black is more economical

- Black instead of C+M+Y is crisper with more contrast

100	50	70
C	M	Y

=

50
K

+

50	0	20
C	M	Y
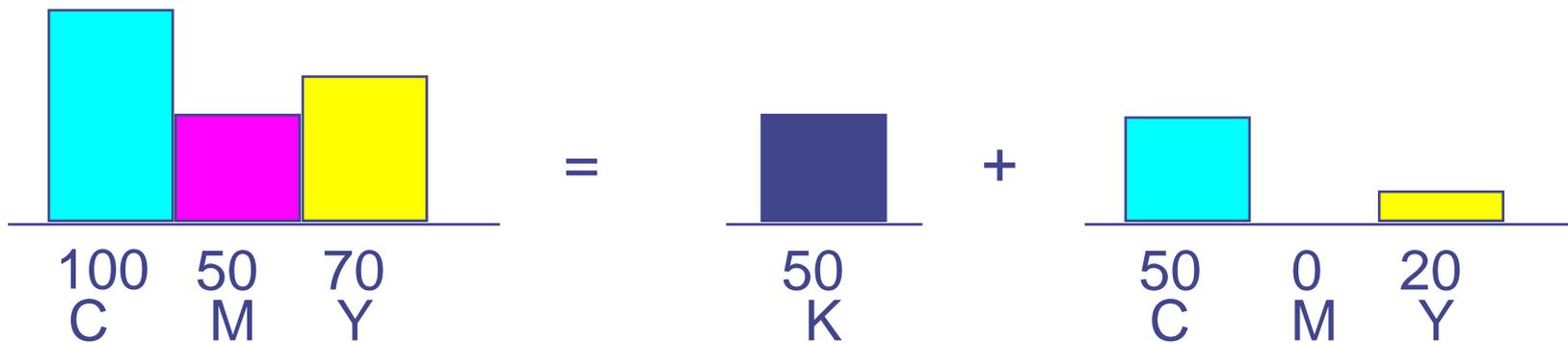
Example

Example
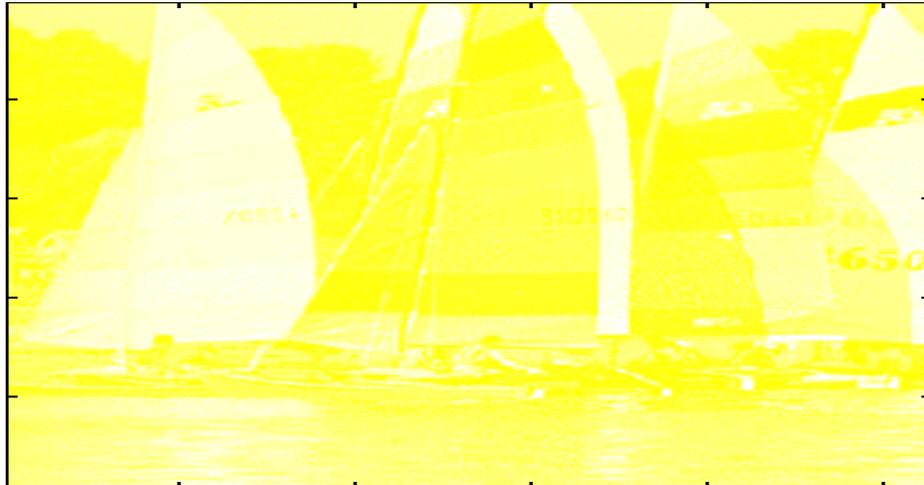
Example

Example

Example

Various CMY & RGB Gamuts

RGB scanner   CMYK offset
RGB monitor   CMYK inkJet

Visible spectrum

Simplified:

RGB

CMY

© http://www.phototests.com/Photoshop/help.html
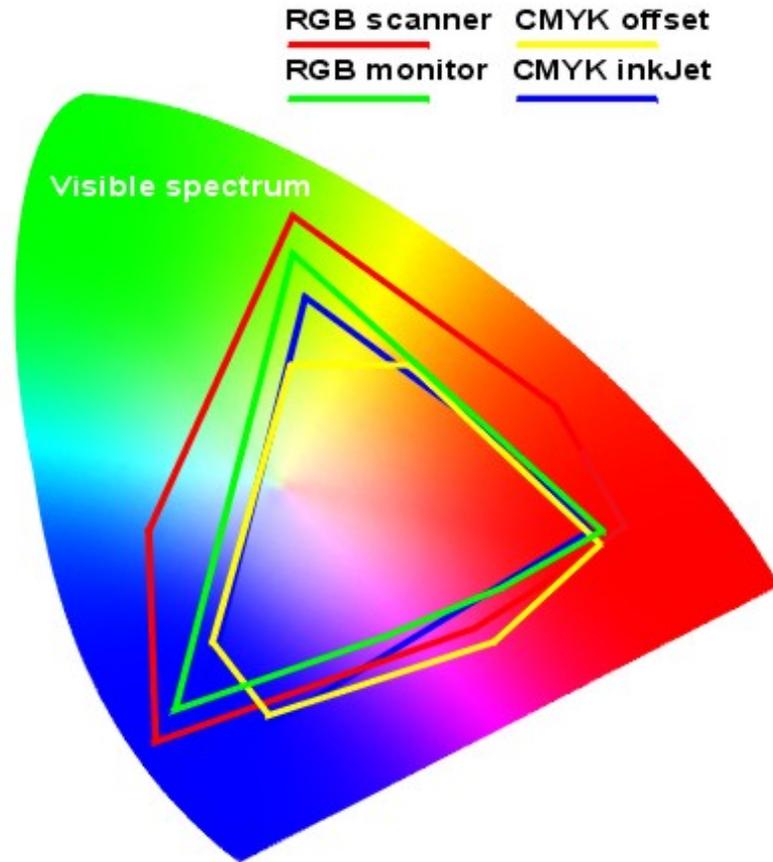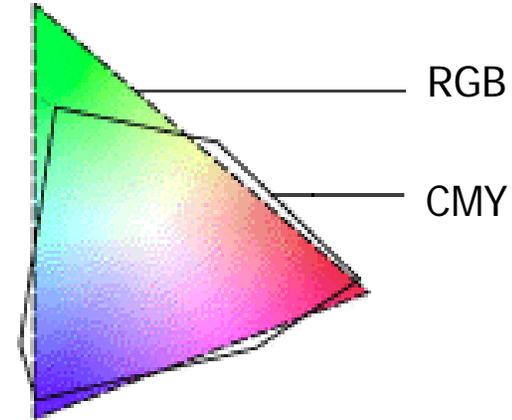
© http://www.mlab.nl/GtoDSA/05_Techniques/02_Colour/Colour_Gamut.htm

Printing Color Transfer

Although the color gamuts for different devices overlap, they don't match exactly, so colors available on video monitor may not be printable on a press.

VISIBLE LIGHT
(billions of colors)

COLOR FILM
(10-15,000)

OFFSET PRINTING
coated paper
newsprint

COLOR MONITOR
(16 million colors)
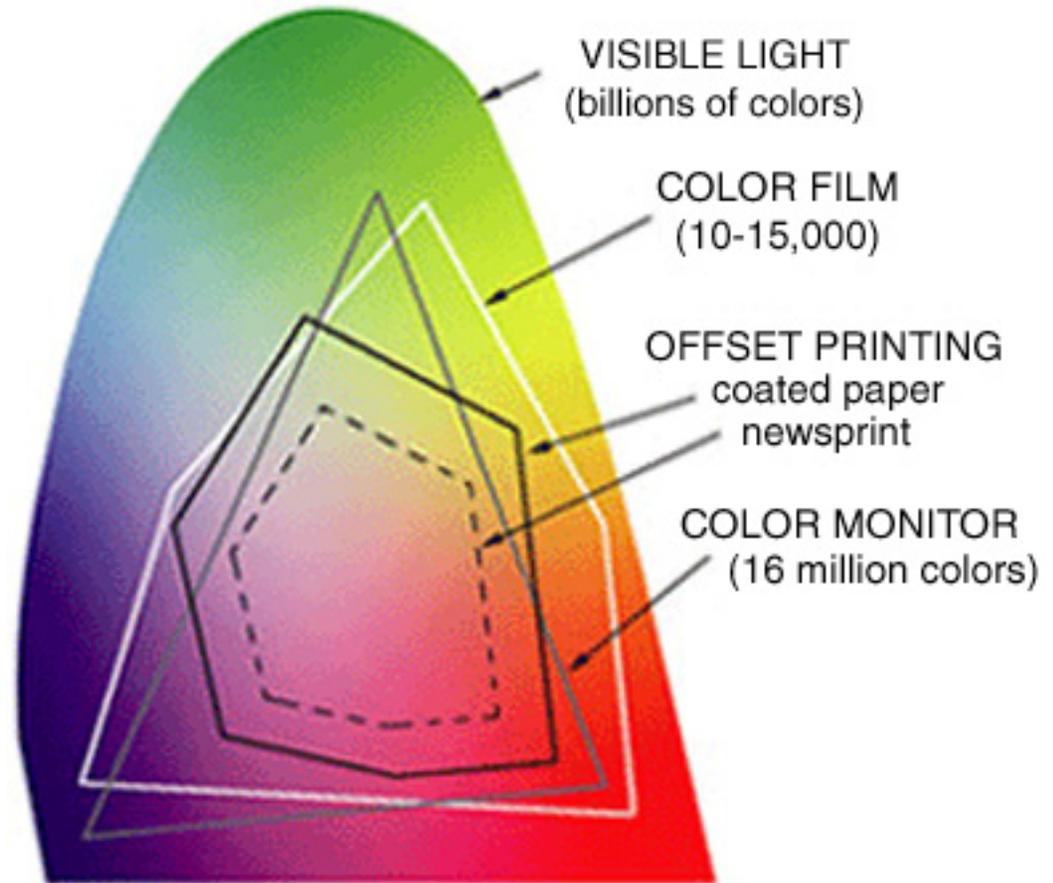
Printing Color Transfer

When colors are translated from the RGB gamut of the computer monitor to CMYK gamut of process printing inks, the CMYK range does a better job of reproducing some colors than it does with others.
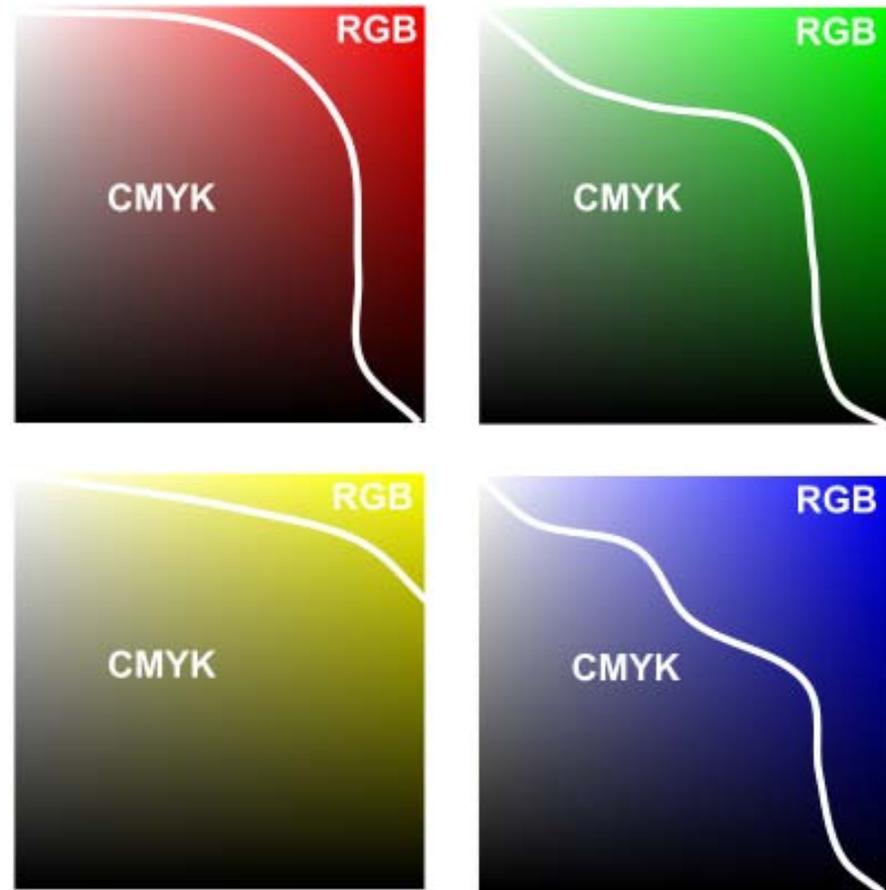
YIQ Color Model

- **YIQ** is the color model used for color TV in America (NTSC= National Television Systems Committee)

- **Y** is luminance, **I** & **Q** are color (I=red/green,Q=blue/yellow)
    - Note: **Y** is the same as CIE's **Y**
    - Result: backwards compatibility with B/W TV!

- Convert from RGB to YIQ:

$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.30 & 0.59 & 0.11 \\ 0.60 & -0.28 & -0.32 \\ 0.21 & -0.52 & 0.31 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

- The YIQ model exploits properties of our visual system, which allows to assign different bandwidth for each of the primaries.

YIQ Bandwith

Why separates luminance or brightness from color?

- We perceive brightness ranges better than color so we can give it more bandwidth:

  Y: 4.5 MHz

  I: 1.5 MHz

  Q: 0.6 MHz

YUV Color Model

- **YUV** is the color model used for color TV in Europe (PAL), and in video. Also called YCbCr.

- **Y** is luminance as in YIQ.

- U and V are blue and red (Cb and Cr).

- The YUV uses the same benefits as YIQ, (5.5 MHz for Y, 1.3 for U and V).

- Converting from RGB to YUV:
  - $Y = 0.299R + 0.587G + 0.114B$
  - $U = 0.492(B - Y)$
  - $V = 0.877(R - Y)$

YUV - Example
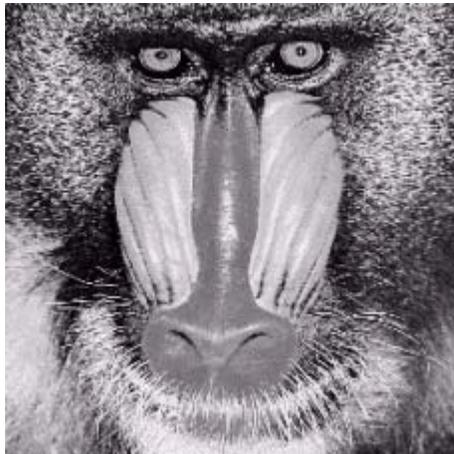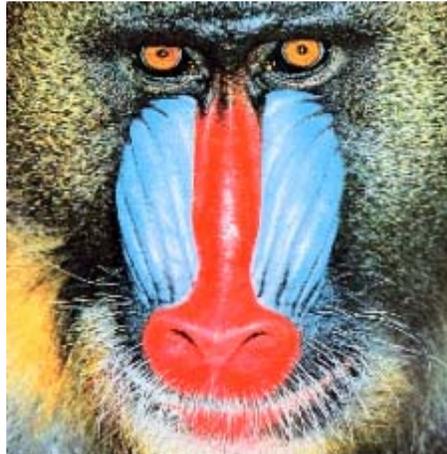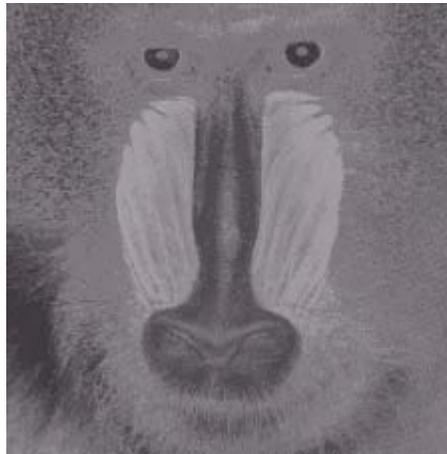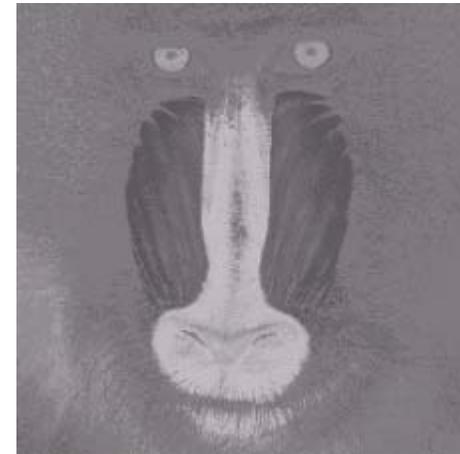
Y　　　　　　　　　　U　　　　　　　　　　V

Tints and Shades

Tint: adding more white to a color

Shade: adding more black to a color

Tints and shades are not inverses! Why? Hint: Saturation…

HSV Color Space

HSV = Hue Saturation Value
a.k.a. HSB = Hue Saturation Brightness
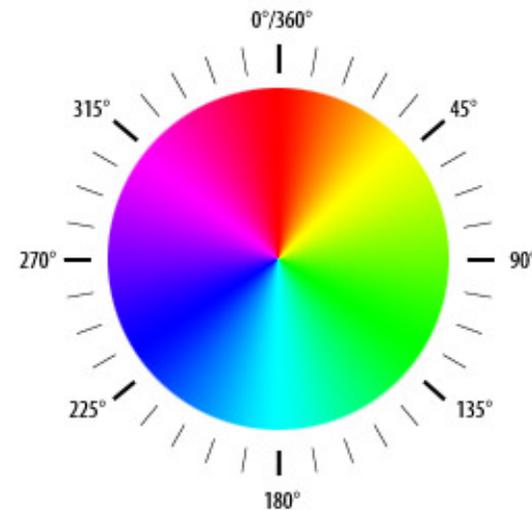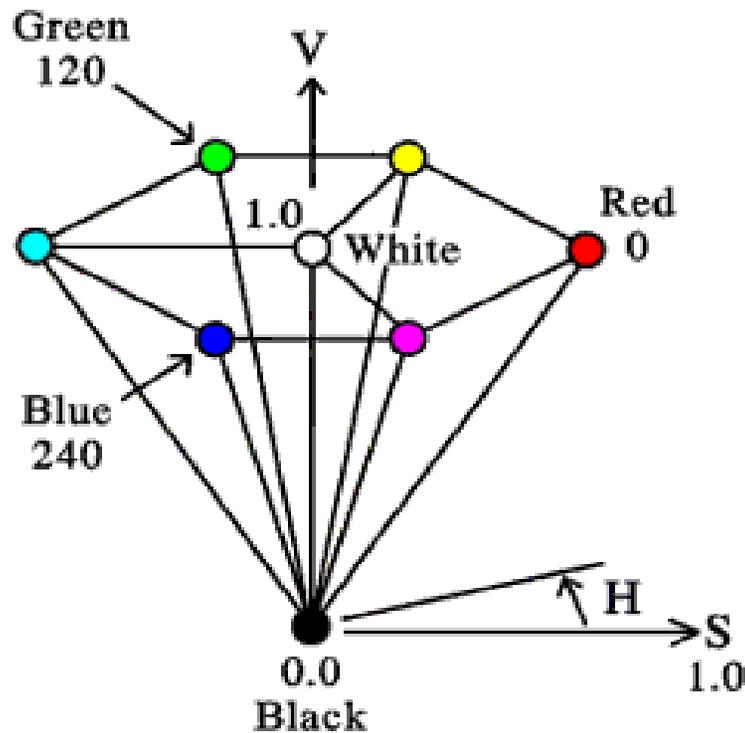
Saturation Scale

Brightness Scale

HSV

Saturation

Value

Hue
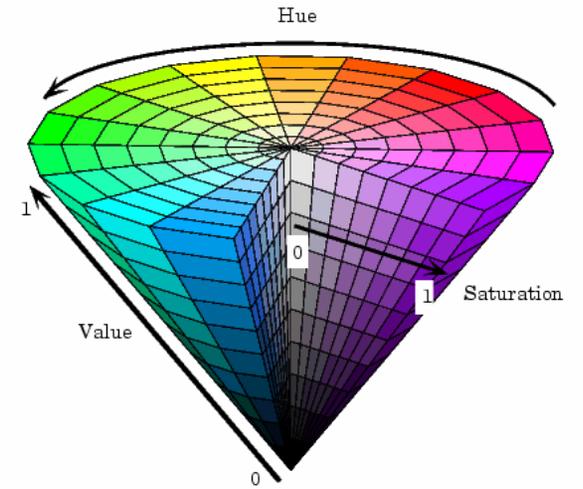
Colors

Standard | Custom

Colors:

Hue:	47
Sat:	162
Lum:	154

Red:	206
Green:	218
Blue:	90

OK | Cancel | Preview

New

Current

HSV

- Much more intuitive for specifying colors!

- Hue: the color

- Saturation: the depth of the color

- Value: the brightness of the color

- Results from a non-linear distortion of the RGB cube

- Singularities at pure black and pure white

HSV

Value (*v*)

Hue (*h*)

Saturation (*s*)

$$0 \leq s \leq 1$$
$$0 \leq v \leq 1$$
$$0 \leq h \leq 360$$

B

Cyan

Magenta

Grays

Black

White

G

R

Yellow

Non-linear distortion

White

Green

Yellow

Cyan

Red

Blue

Magenta

Grays

Black
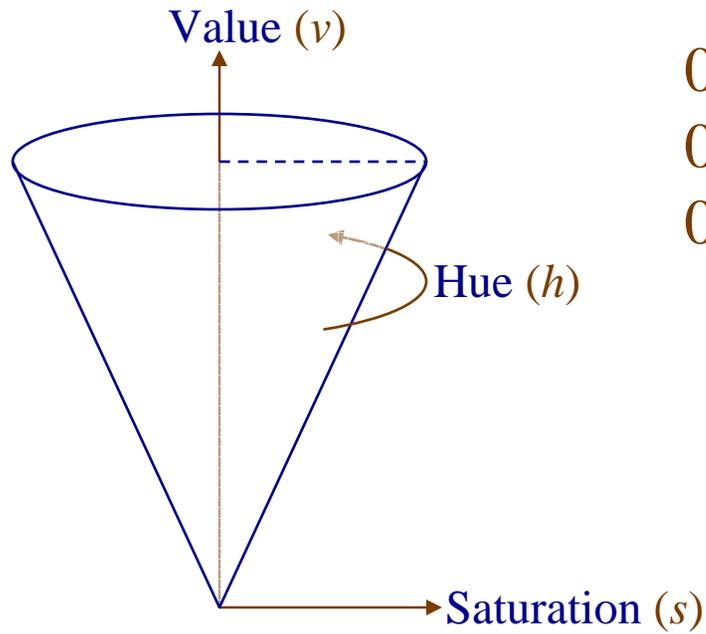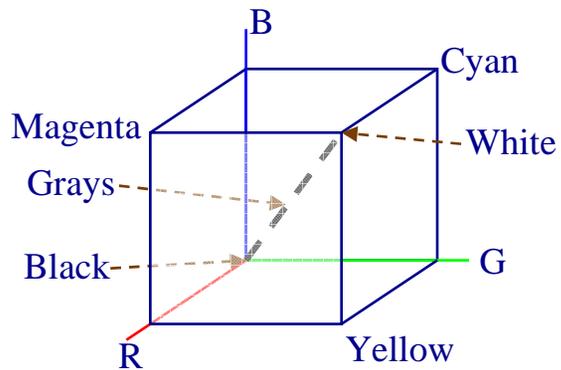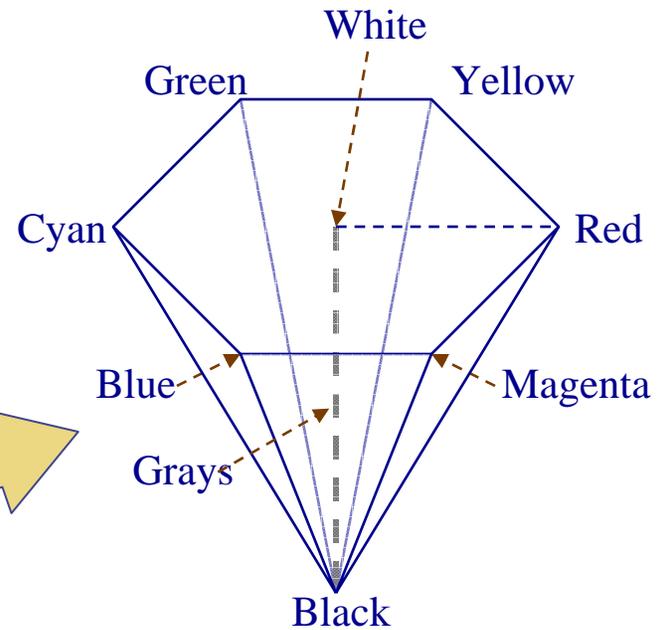
HLS Color Space

HLS = Hue Lightness Saturation
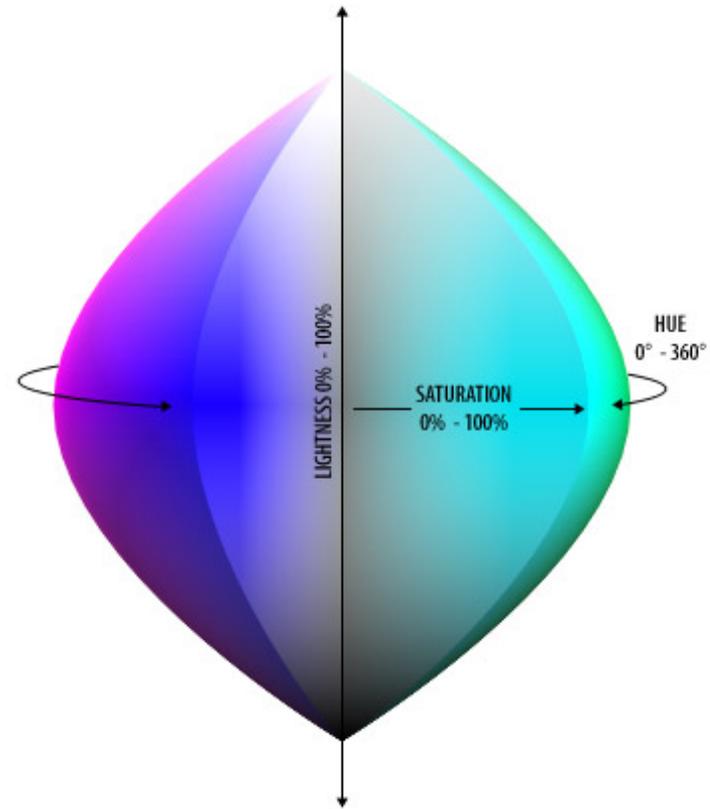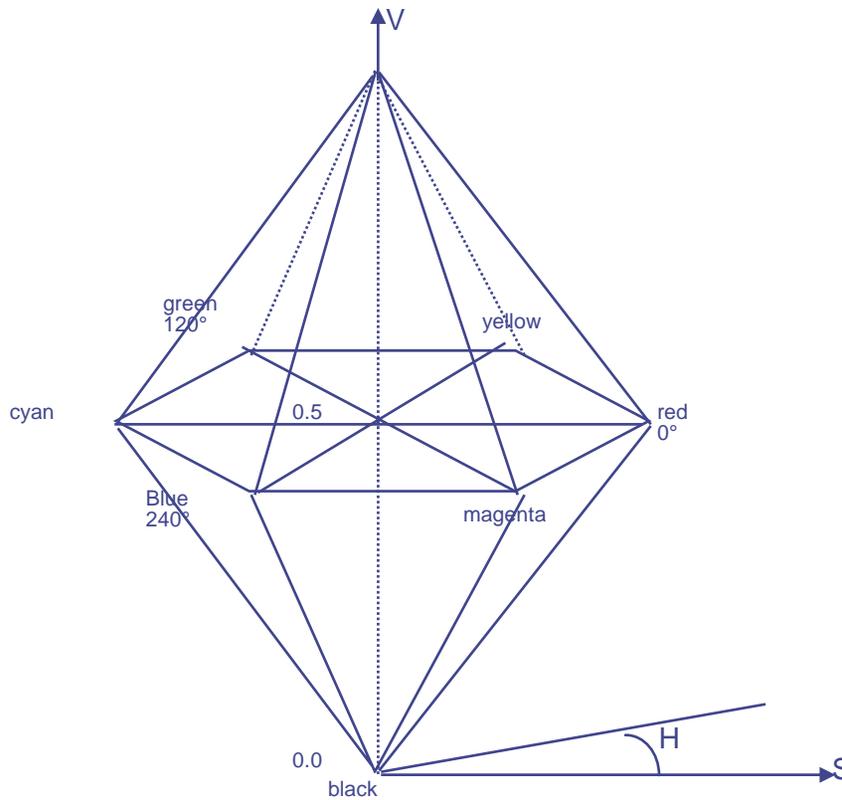
The Artist Point of View

- **Hue** - The color we see (red, green, purple)

- **Saturation** - How far is the color from gray (pink is less saturated than red, sky blue is less saturated than royal blue)

- **Brightness/Lightness (Luminance)** - How bright is the color
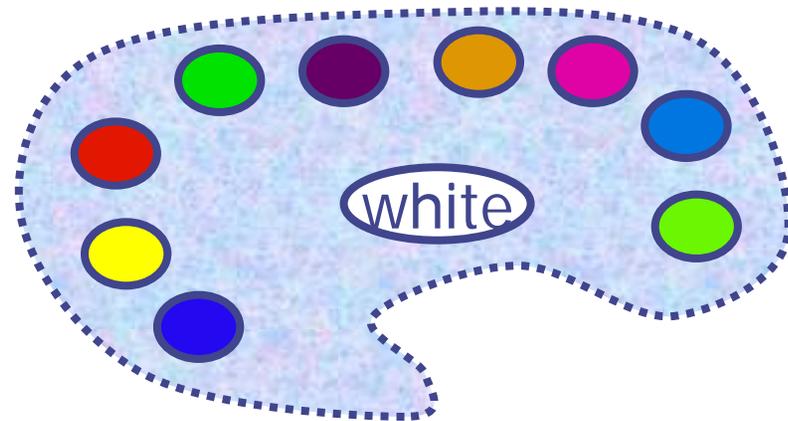
white

Munsell Color System

Equal perceptual steps in Hue Saturation Value.

Hue: R, YR, Y, GY, G, BG, B, PB, P, RP

               (each subdivided into 10)

Value: 0 ... 10   (dark ... pure white)

Chroma: 0 ... 20   (neutral ... saturated)

Example:
5YR 8/4
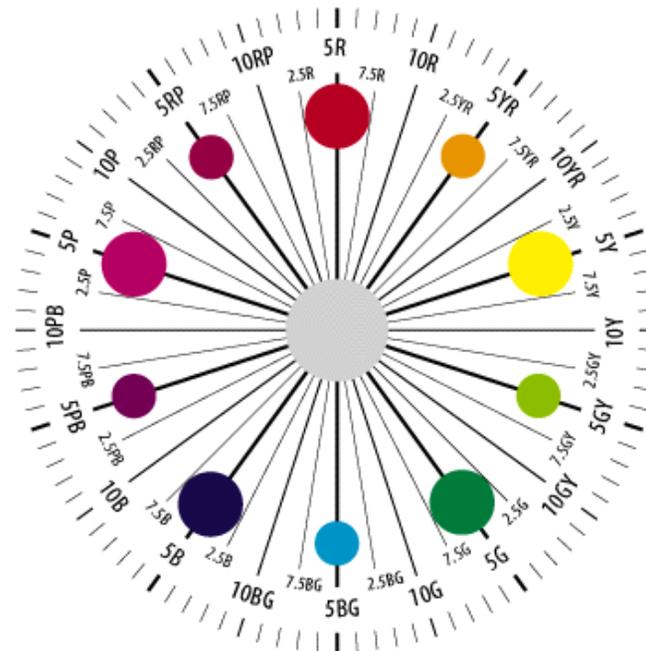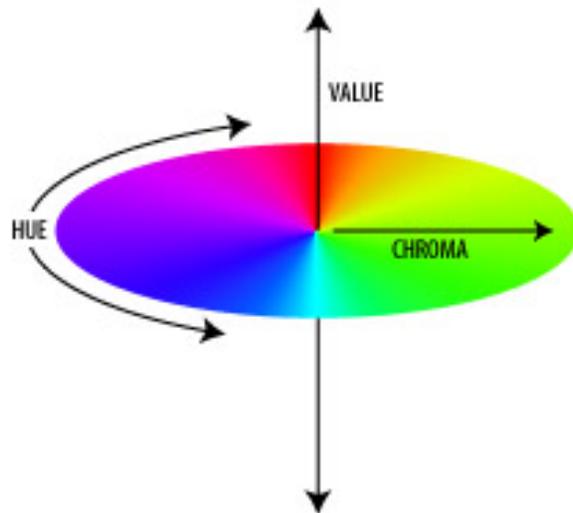
Munsell Book of Colors
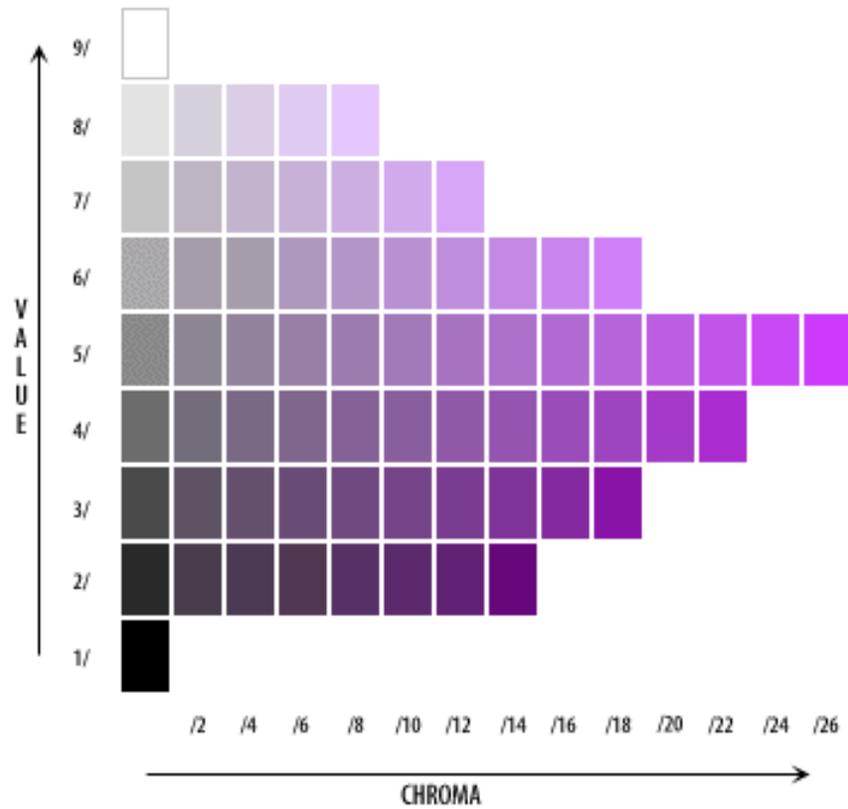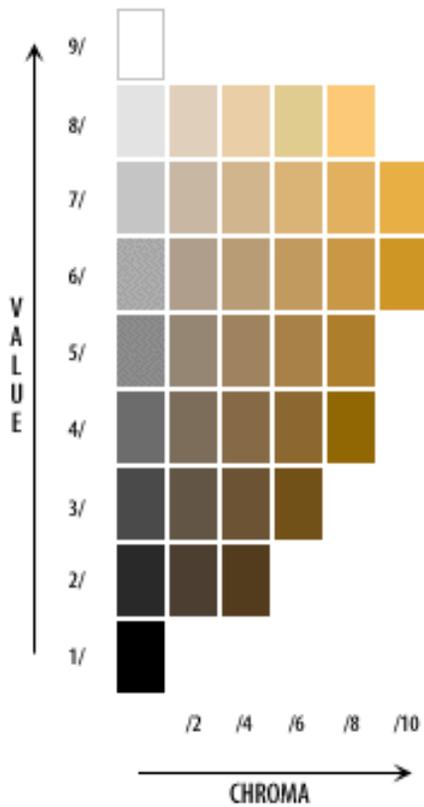
Munsell Book of Colors

Color-Encoding

Pseudo Color

Color can make information visualization more interesting, but be careful using color to convey information

Specific color meanings: useful, but keep them limited

Color scales are harder to interpret than intensity scales

(Heat scale is one of the few that partially works)
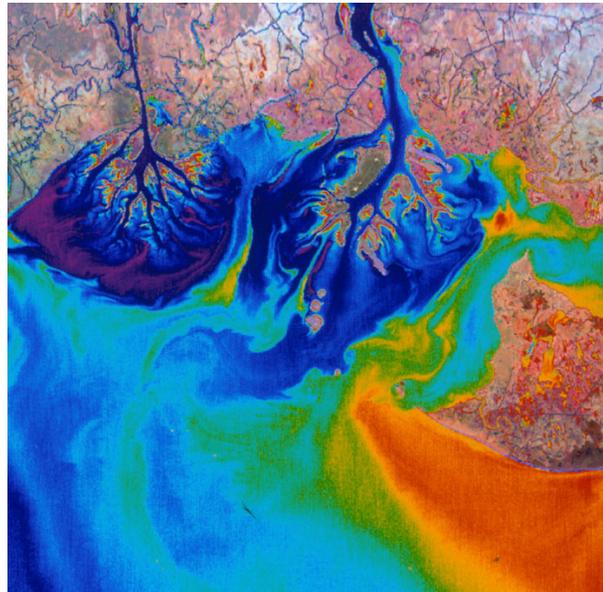
Atchafalya Bay Thermal Pseudocolor Image

http://asapdata.arc.nasa.gov

Color Image Processing

Pick a color space that makes sense for your application

To manipulate intensity without changing chromaticity (or to manipulate chromaticity without affecting intensity), use an intensity-chromaticity based model

For perceptual linearity (interpolation, etc.) use CIE *Luv* or CIE *Lab* (or similar) color space

For user interaction, try *HSV* or something similar

Point: *Don't just think that RGB is the only way to manipulate color*

Color-Reduction

Many color-encoding schemes use some finite number of colors from a larger palette

Example: 8-bit color uses a 256-element look-up table (LUT) to map pixel values (indices) to 24-bit color values

Problem: how to convert 24-bit image to 8-bit pseudo-color

Answer: *Color Quantization*

Color Quantization

Common color resolution for high quality images is 256 levels for each Red, Green, Blue channels, or $256^3 = 16777216$ colors.

How can an image be displayed with fewer colors than it contains?

Select a subset of colors (the colormap or pallet) and map the rest of the colors to them.

With e.g. 8 bits per pixel and color look up table we can display at most 256 distinct colors at a time.

To do that we need to choose an appropriate set of representative colors and map the image into these colors

Color Quantization

2 colors

4 colors

16 colors

256 colors

Quantization Phases

Sample the original image for color statistics

Select color map based on those statistics

Map the colors to their representative in the color map

Redraw the image, quantizing each pixel

Vector Quantization

Mapping…
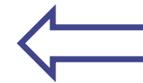
Naive Color Quantization (I)

Retaining the 16 most popular RGB colors.

The reds are not that popular (but needed)

Naive Color Quantization (II)

24 bit to 8 bit:

Retaining 3-3-2 most significant bits of the R,G and B components.

3-3-2
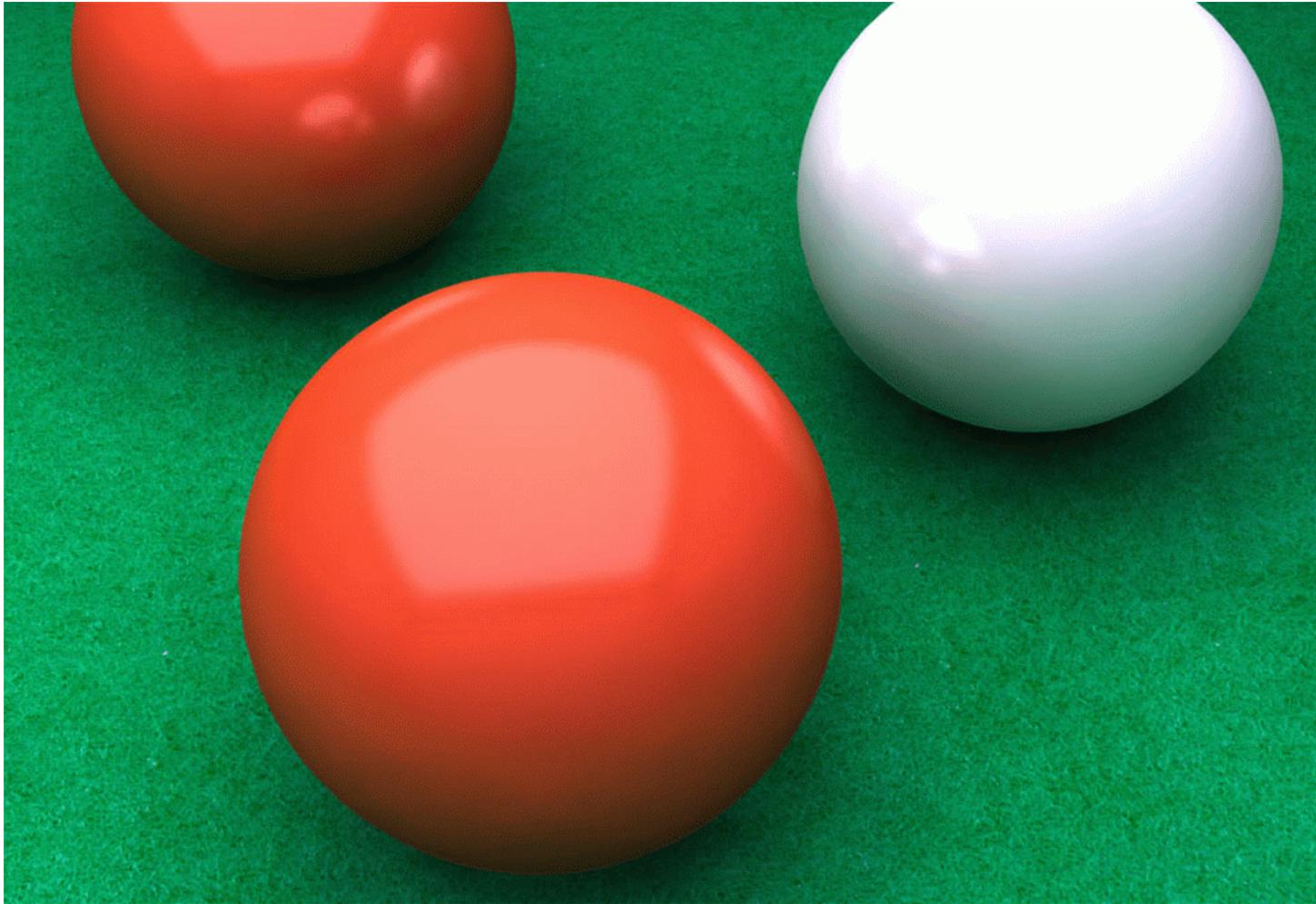
3-3-2
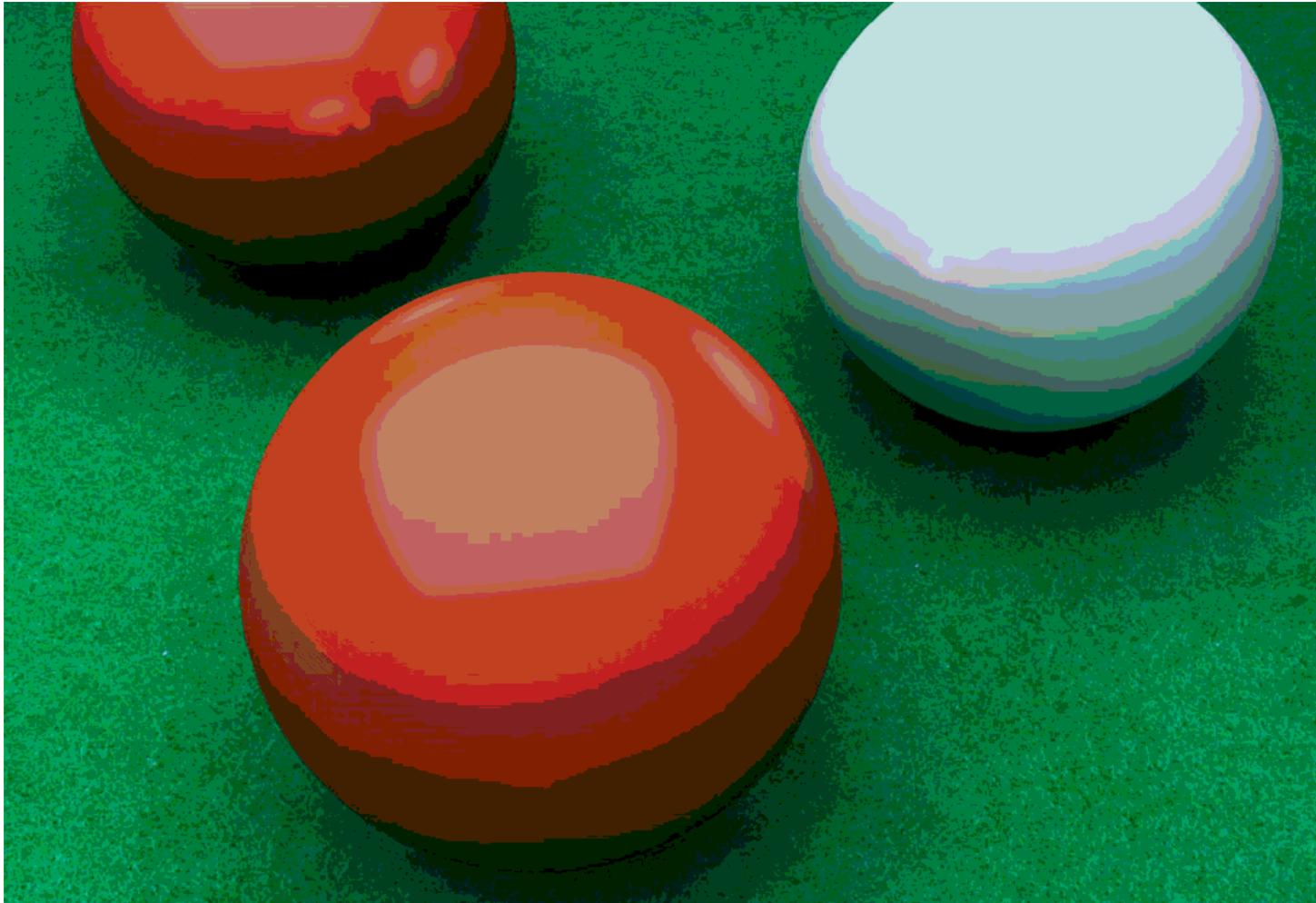
3-3-2

3-3-2

Median Cut
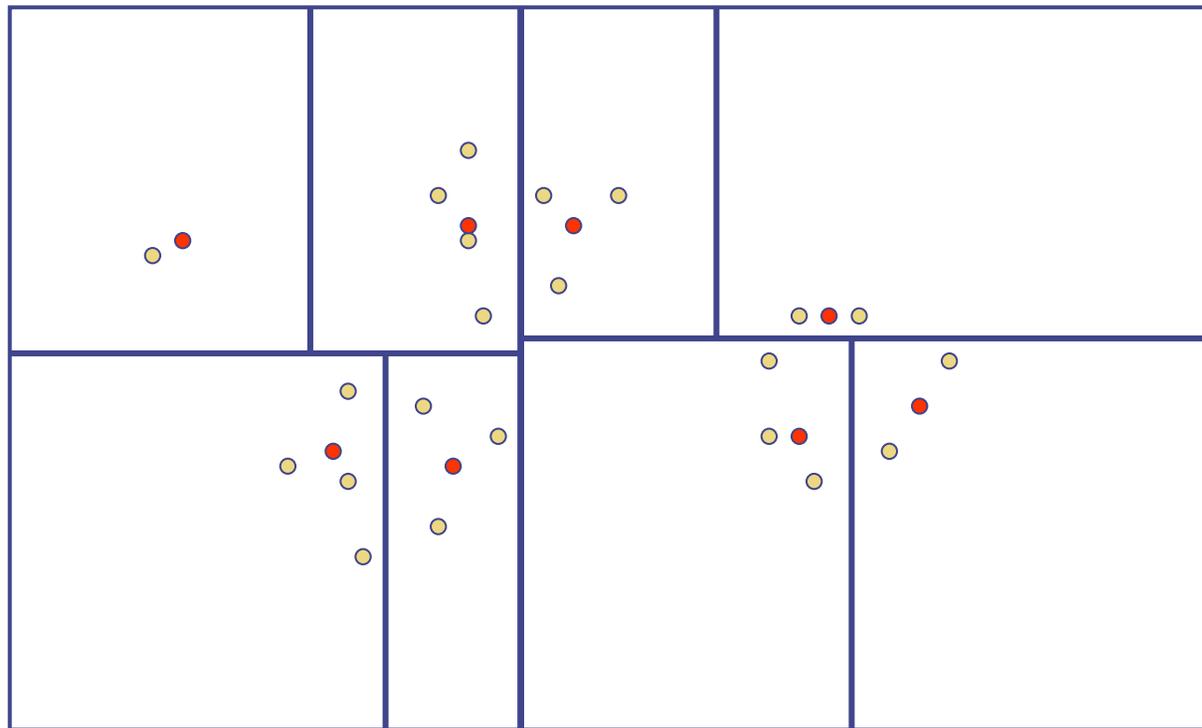
Original Image

Threshholding

Median Cut (4 Gray levels)

Median Cut (8 Gray levels)
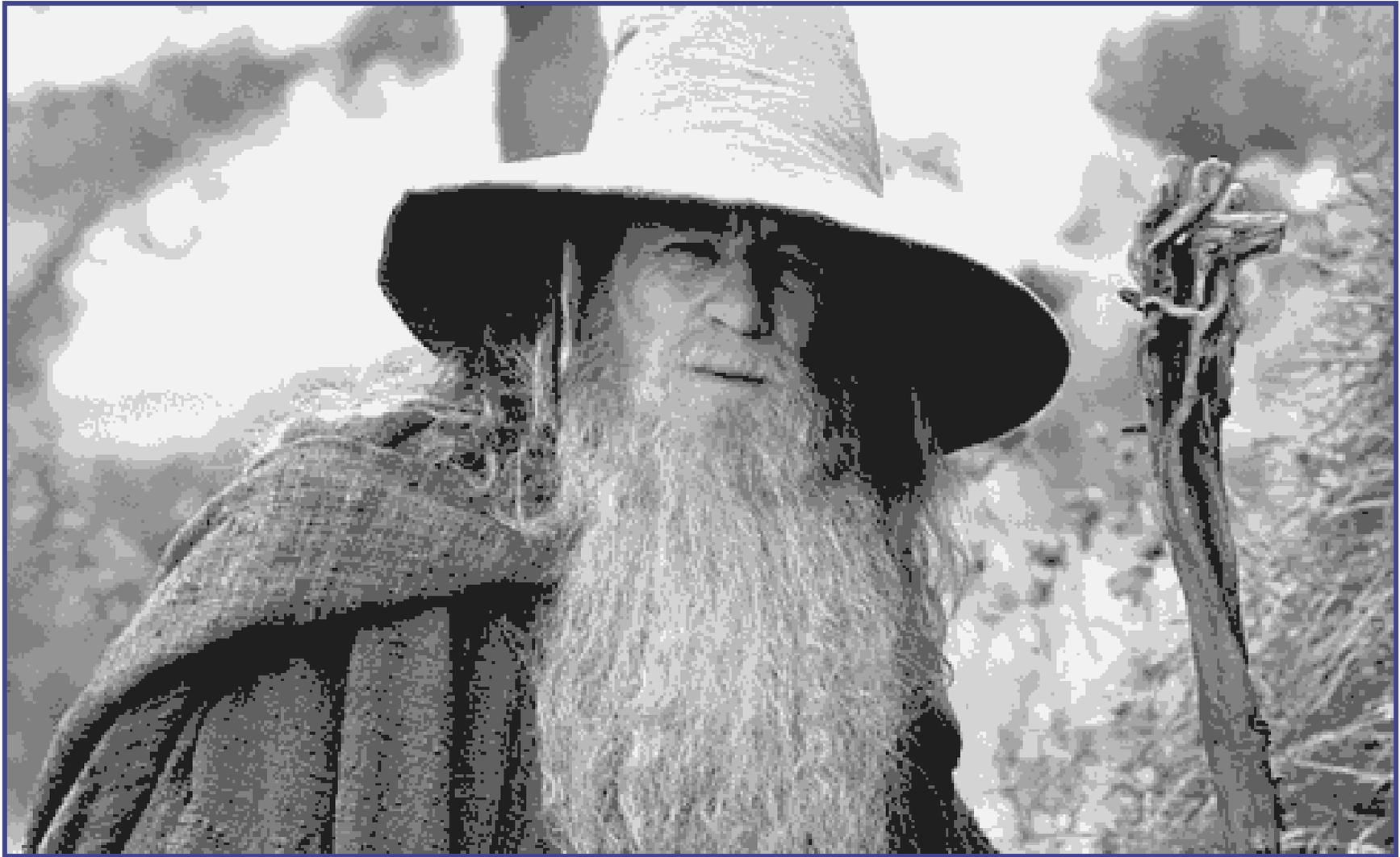
A Better Solution: *k*-Means
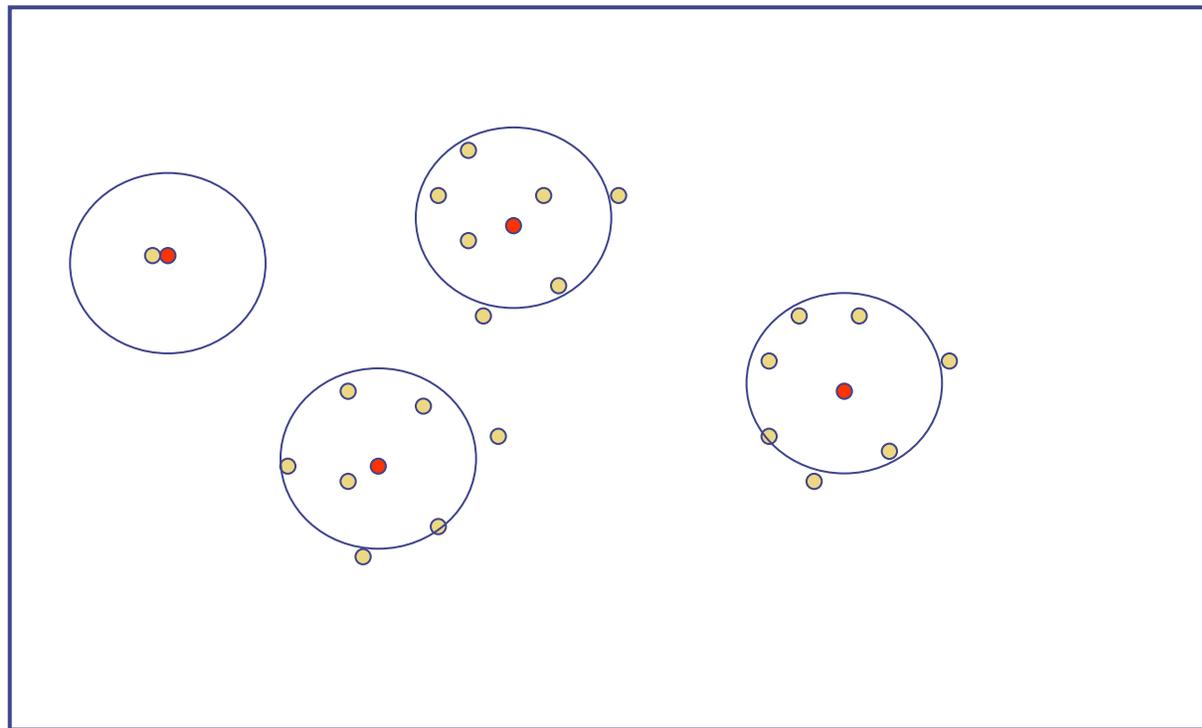
24 bit

8 bit

4 bit

Resources

Textbook:

Kenneth R. Castleman, Digital Image Processing, Chapter 15, 21, 22