CS148: Introduction to Computer Graphics and Imaging

Light and Color

Painting by Cheryl Yaney

Topics

Physics of light
  ■ Electromagnetic spectrum
  ■ Fundamental operations: add, filter, measure

Perception of color
  ■ Trichromatic theory
  ■ Luminance
  ■ Color spaces

Art
  ■ Color terms
  ■ Color wheels and intuitive color spaces
Physics of Light

Light

Glass prism

White light

Newton's experiment for splitting white light into a spectrum

Image from Clive Maxfield
Electromagnetic Spectrum

Visible Light

Microwaves Radio waves X-rays Gamma-rays

Infrared Ultraviolet

The visible portion of the electromagnetic spectrum

Image from Clive Maxfield

Spectral Power Distribution of Lights

Outdoor daylight

Incandescent bulb

Mercury lamp

SP65 triphosphor fluorescent

CS148 Lecture 10  Pat Hanrahan, Fall 2010
Adding Light Energy

Yellow
Green
Red
Cyan
Blue
Magenta

Reflecting Light

Shining white light on different colored paints
Light Operations

Add spectra $L(\lambda) = S_1(\lambda) + S_2(\lambda)$

- $R = R_1 + R_2$
- $G = G_1 + G_2$
- $B = B_1 + B_2$

Multiply spectra $L(\lambda) = T(\lambda)S(\lambda)$

- $R = R_1 R_2$
- $G = G_1 G_2$
- $B = B_1 B_2$

Measuring Light

Photon detector $R = \int R(\lambda)L(\lambda)\, d\lambda$
Trichromatic Theory

RGB Color

Result: colors can be matched with three colors
Color Matching Experiment

Adjust brightness of three primaries
Lasers: R = 700 nm, G = 546 nm, B = 435 nm until it “matches” another color C

\[ C = R + G + B \]

Result: all colors can be matched with three colors
Therefore: humans have trichromatic color vision

Color Matching is Linear

Grassman’s Laws

1. Scaling the color and the primaries by the same factor preserves the match

\[ 2C = 2R + 2G + 2B \]

2. To match a color formed by adding two colors, add the primaries that match each color

\[ C_1 + C_2 = (R_1 + R_2) + (G_1 + G_2) + (B_1 + B_2) \]
Human Retina: Three Types of Cones

Fig. 13. Tangential section through the human fovea. Larger cones (arrows) are blue cones.

From http://webvision.med.utah.edu/imageswv/fovmoswv.jpeg

Response of Three Cones

Typical humans are trichromats
(three color cone/pigment types – blue, blue-green, and yellow-green)
Cone Response

Three cones

L (long) \[ L = \int L(\lambda)E(\lambda) \, d\lambda \]

M (medium) \[ M = \int M(\lambda)E(\lambda) \, d\lambda \]

S (short) \[ S = \int S(\lambda)E(\lambda) \, d\lambda \]

Metamerism: Different spectra, same color response

Color Blindness: Ishihara Test

Normal

Color Blindness: Ishihara Test


Types of Color Blindness

Dichromacy: missing pigment (10% M, 1% F)
- Protanopia – missing L
- Deuteranopia – missing M (red-green)
- Tritanopia – missing S

www.vischeck.com
**Rod**

Humans also have rod cells (black, white, shades of gray)

**Luminance**

Compare color to a gray source

\[ Y = \int V(\lambda)E(\lambda) \, d\lambda \]

Luminance (B&W TV)

\[ Y = 0.30R + 0.59G + 0.11B \]
Spectral Matching Functions

Match each pure (monochromatic) color in the visible spectrum (rainbow) and record the color coordinates as a function of wavelength.

Gotcha! Sometime you have to add R to the color and then match it to a combination of B and G. This situation means that R is negative.
CIE XYZ Space

From RGB to XYZ
- Y is luminance
- Force X, Y and Z to be positive

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} =
\begin{bmatrix}
2.77 & 1.75 & 1.13 \\
1.00 & 4.59 & 0.06 \\
0.00 & 0.57 & 5.59
\end{bmatrix}
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix}
\]

Colors of the rainbow are on the outer horseshoe curve

All perceivable colors are inside the curve

CIE XYZ Chromaticity Coordinates

\[
x = \frac{X}{X + Y + Z}
\]

\[
y = \frac{Y}{X + Y + Z}
\]

\[
z = \frac{Z}{X + Y + Z}
\]
Perceptual Models of Color

Early Visual Processing

\[ A = R + G + B \]
\[ (Y - B) = R + G - B \]
\[ (R - G) = R - G \]
Perceptual Organization

![Diagram of Perceptual Organization]

Intuitive Color Space

![Diagram of Intuitive Color Space]

MetaDesign Color Picker
### HSV

\[ M = \max (R, G, B) \]
\[ m = \min (R, G, B) \]
\[ r = \frac{M - R}{M - m} \]
\[ g = \frac{M - G}{M - m} \]
\[ b = \frac{M - B}{M - m} \]

\[ V = M \]
\[ S = \frac{M - m}{M} \]

\[ H = \frac{(6 + b - g)}{6} \]

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### Things to Remember

**Physics of color**
- Addition, transmission/reflection, measurement

**Perception of color**
- Three colors will match another color
- Trichromatic because we have 3 cones
- Explains metamerism, color blindness
- Color matching is linear
- Perceptual organization in terms of BW, YB, RG
- Hue-Saturation-Value