PERCEIVING COLOR

Visual Perception
Functions of Color Vision

- Object identification
  - Evolution: Identify fruits in trees
- Perceptual organization
- Add beauty to life
Theories of Color

- Trichromatic Theory
- Opponent Theory
- Adaptation Theory
- Higher Visual Mechanisms
- Category Based Perception
The Color Stimuli
Color is due to..

- Selective emission/reflection of different wavelengths by surfaces in the world
- Different response to different wavelengths of the eye
Illumination – $I(\lambda)$
Reflectance – $R(\lambda)$
Color Stimuli – $C(\lambda)$

$I(\lambda) \times R(\lambda) = C(\lambda)$
Different Types of Stimuli

- **Monochromatic**
  - Laser

- **Achromatic**
  - Sunlight (close to)

- **Polychromatic**
  - Most common
Properties of Stimulus

- Brightness/Intensity
  - Total energy of the color spectrum
  - Estimated by the area under the curve
Properties of Stimulus

- Luminance
  - Perceived brightness
  - Depends also on the response of the eye
  - Multiplication of color spectrum with the luminous efficacy function
Properties of Stimulus

- **Hue**
  - Predominant wavelength
  - Weighted Mean
Properties of Stimulus

- Saturation
  - Amount of Achromatic light
  - Variance from the weighted mean

All these three parameters are interrelated. Cannot be changed independently.
Lightness

- Relative amount of light reflected
- A black ball does remains black both outside and inside
  - Relative amount of light reflected remains same
  - Absolute amount of light reflected changes
  - Lightness remains same, brightness changes
Color Mixtures

- **Additive**
  - Union of the wavelengths present in each spectrum
  - Addition of two spectrums $C_1(\lambda)$ and $C_2(\lambda)$

![Graph showing the power spectrum of color mixtures with additive mixing.]
Color Mixtures

- **Subtractive**
  - Intersection of the wavelengths in each

- **Difference**: Absorption of the remaining ones

![Color Mixtures Diagram](image_url)
Newton’s Additive Color Wheel

- **Boundary is saturated color**
  - Unsaturated colors in the interior
- **Combination of two colors generate a color on the line joining them**
- **Displays create color likewise**
Newton’s Additive Color Wheel

- Three colors to create a reasonable subset
  - Devices
  - Even Eye
- Same color can be created by a different set of primaries
A set of primaries is a linear transformation of another set of primaries

- Since they define different 2D coordinates
Newton’s Additive Color Wheel

- Increasing the number of primaries
- More colors can be represented
- Do you see a problem?
Helmholtz/Maxwell’s Color Matching Experiment

- All colors can be produced by different amounts of three wavelengths
- Cannot match certain wavelengths
- Register as negative amount

Present each visible wavelength
Add the wavelength here

Match by adjusting amounts of three wavelengths (420nm, 560nm, 640nm)
Color Matching Functions

Three wavelengths used for matching can be thought of as the response of sensors with peak sensitivity at the matching wavelengths.
CIE Standard Color Matching Functions

- Negative weights do not make sense
- The sensitivities of the cones cannot be mapped directly to properties like brightness, hue and saturation
- Need to organize colors based on these perceptual properties
- Need some color matching functions that would be able to span the entire range
  - With only positive weights
- Imaginary color matching functions
  - Can be found by linear transformations
  - Does not correspond to real colors
CIE Functions for Standard Observer

![Graph showing CIE functions for standard observer](image-url)
Color Perceived

- The response generated by a stimulus in the cones gives the perceived color.
Metamerism

- Because of this selective response
  - Two dissimilar stimuli can generate equal strength of $x$, $y$ and $z$
  - Phenomenon is called metamerism
  - The two stimuli are called the metamers
  - So, we experience all the metamers similarly
Tristimulus Values

Integration over wavelength

\[ X = \int_{\lambda=400}^{\lambda=700} C(\lambda)x(\lambda) = \sum_{\lambda=400}^{\lambda=700} C(\lambda)x(\lambda) \]

\[ Y = \int_{\lambda=400}^{\lambda=700} C(\lambda)y(\lambda) = \sum_{\lambda=400}^{\lambda=700} C(\lambda)y(\lambda) \]

\[ Z = \int_{\lambda=400}^{\lambda=700} C(\lambda)z(\lambda) = \sum_{\lambda=400}^{\lambda=700} C(\lambda)z(\lambda) \]
Tristimulus Values

- Metameric colors have same value
- Real colors span a sub-set of the XYZ space
  - Since imaginary primaries
Tristimulus Values

- XYZ forms a three dimensional space to define color
- Two colors added by just adding the XYZ coordinates
Perceptual Parameters

- No physical feel as to how colors are arranged
- How are saturated hues arranged?
- How are unsaturated hues arranged?
- Perceptually not easy to deal with
- Experiment with color palette
Chromaticity Chart

- Relative proportions of X, Y, and Z are more important
- For example, equal proportions of each signifies an achromatic color
- Chromaticity Diagram: 2D projection of 3D colors on X+Y+Z = d plane

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

- Energy of the spectrum (Intensity) estimated by $X+Y+Z$
- Points on a vector originating at zero coincide at the same point
  - $(X,Y,Z)$ and $(2X,2Y,2Z)$ generate same $(x,y)$
- Colors on this vector have same intensity but different chrominance
- NOTE: Luminance is perceived brightness, given by $Y$, and different from energy of the spectrum
- Problem with current color nomenclature
Chromaticity Coordinates

- Shows all the visible colors
- Achromatic Colors are at (0.33, 0.33)
  - Why?
  - Called white point
- The saturated colors at the boundary
  - Spectral Colors
Chromaticity Chart

- Exception is purples
  - Non-spectral region in the boundary
- All colors on straight line from white point to a boundary has the same spectral hue
  - Dominant wavelength
What happens here?
- Complimentary wavelength
- When mixed generate achromatic color

Purity (Saturation)
- How far shifted towards the spectral color
- Ratio of $a/b$
- Purity = 1 implies spectral color with maximum saturation
How to combine colors?

- Board Work
  - Using just *XYZ*
  - Using hue, saturation and brightness
- What happens when add two colors of same hue and saturation?
What is the RGB color?

\[
\begin{align*}
X &= X_r X_g X_b \\
Y &= Y_r Y_g Y_b \\
Z &= Z_r Z_g Z_b
\end{align*}
\]
What is gamma function?

\[
\begin{align*}
X & = X_r X_g X_b \\
Y & = Y_r Y_g Y_b \\
Z & = Z_r Z_g Z_b
\end{align*}
\]
Color reproducibility

- Only a subset of the 3D CIE XYZ space called 3D color gamut
- Projection of the 3D color gamut on the same plane with normal (1,1,1)
  - Triangle
  - 2D color gamut
    - Cannot describe brightness range reproducibility
Specification Protocols

- Brightness or Luminance
- 2D gamut
  - Large if using more saturated primaries
Current standards and devices
Gamut Transformation

- Assume linear gamma

\[
[X \ Y \ Z \ 1]^T = M \ [R \ G \ B \ 1]^T
\]

- Two devices

  \[
  [X \ Y \ Z \ 1]^T = M_1 \ [R_1 \ G_1 \ B_1 \ 1]^T
  \]

  \[
  [X \ Y \ Z \ 1]^T = M_2 \ [R_2 \ G_2 \ B_2 \ 1]^T
  \]

- \[
  [R_2 \ G_2 \ B_2 \ 1]^T = M_2^{-1}[X \ Y \ Z \ 1]
  \]

  \[
  = M_2^{-1}M_1[R_1 \ G_1 \ B_1 \ 1]^T
  \]
Gamut Transformation

- How to get the matrix from the standard spec?
- Given \((Y,x,y)\) or \((I,x,y)\) for the three vectors, you can compute \((X,Y,Z)\)
  - \((x \cdot Y/y, Y, (1-x-y) \cdot Y/y)\)
  - \((x \cdot I, y \cdot I, (1-x-y) \cdot I)\)
- **Does not change the color**, finds the new coordinates when using the new basis
Problem
Problem: Out of Gamut colors
Gamut Matching

- Find a common color gamut defined by $R_c$, $G_c$, $B_c$
- Find the common function $M_c$
  - $[X \ Y \ Z \ 1]^T = M_c \ [R_c \ G_c \ B_c \ 1]^T$
- For any device $i$
  - $[R_i \ G_i \ B_i \ 1]^T = M_i^{-1}M_c \ [R_c \ G_c \ B_c \ 1]^T$
Two gamut
Find their intersection

Need not be a parallelopipeded
Find the common gamut

\[ G_1 \cap G_2 \]

Aditi Majumder, UCI
Find the mapping function
Human Visual Response (Later)
CIE Functions for Standard Observer

![Graph showing CIE functions for standard observer](image)
Human Visual Response

- Trichromatic Theory
  - Proposed by Thomas Young
  - Eye has three kinds of receptors
  - Produce psychologically similar sensations of red, green and blue
You have seen different sets of primaries

- Helmholtz color matching functions
- CIE Standard Observer functions
- Human visual cone functions
- Should all be the same but are not
  - Due to historical legacy
- Each can be transformed to other by a 3x3 linear transformation function
In the Eye

- All colors can be produced by mixing various proportions of three wavelengths
  - 420nm, 560nm and 640nm
  - Young Helmholtz theory of color vision
- Three types of receptors excited
  - Pattern of excitation depends on the color or the wavelength of the light
Physiological Explanation

- Three different types of cone
  - Different pigment with different absorption spectra
- Pigments have different amino acids in their opsin
  - Causes the different absorption spectra
- S, M, L
  - S and M are 44% similar, peaks 112nm apart
  - M and L are 96% similar, peaks 27nm apart
Response of Cones
Color Deficiency

- Monochromat
- Dichromat
- Color weakness
- Cerebral achromatopsia
Reasons

- **Monochromat**
  - No cones

- **Dichromat**
  - No L, No M, and No S

- **Color weakness**
  - S, M and L of reduced sensitivity

- **Cerebral achromatopsia**
  - Cones are fine but problem in visual cortex
Dichromatism

Why more males?

- Resides in X chromosome
- Both X’s need to have the defect in women
- Can be passed on by women with one deficient X to the male offspring
Trichromatic Theory Cannot Explain

- Complementary afterimages
  - Red green complements
  - Blue yellow complements
Trichromatic Theory Cannot Explain

- Complementary afterimages
  - Red green complements
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Trichromatic Theory Cannot Explain
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Trichromatic Theory Cannot Explain

- Simultaneous color contrast
- Visualizing colors
Another experiment
Another experiment
Opponent Theory

- Herring proposed three types of cell
- Long struggle between trichromatic and opponent theory
- In 1965, such cells were found in LGN (not in eye as proposed by Herring)
Opponent Theory

- How does signal from the S, M and L cells get processed by the opponent cells?
Why Opponent Theory?
Why long gaze?

- Theory of Adaptation
Light Adaptation

- Dark Adaptation
- Light Adaptation
  - Not symmetric (5 minutes, not 30 minutes)
  - Covers a very large dynamic range
    - 10 orders of magnitude
    - How?
Light Adaptation

![Graph showing light adaptation curves with relative response on the y-axis and log relative energy on the x-axis.](image)
Chromatic Adaptation (Cones)
Example of chromatic adaptation
Example of chromatic adaptation
Example of chromatic adaptation
Adaptation

- Prolonged exposure to red
  - R+G- cells fire less strongly
  - G+R- cells fire more strongly
- Red looks less saturated
- Green looks more saturated
- Other colors have a greenish tint
Aftereffects

- Prolonged exposure to green
  - G+R- cells are fatigued
- When trying to view white
  - R+G- cells fire more strongly
  - Hence, red afterimage
- Similarly for blue yellow
- Still cannot explain simultaneous color contrast
Lightness and Color Constancy

- Lightness remains relatively same even under varying illumination
- Color remains relatively same under vastly different illuminations
Lightness Constancy

- An achromatic surface appears to have same lightness irrespective of different illumination conditions
  - Indoor illumination: 100 photons
    - Black: 10 photons
    - White: 90 photons
  - Outdoor Illumination: 10,000 photons
    - Black: 1000 photons
    - White: 9000 photons
- Black in outdoor is almost 900 times more than white in indoor
  - Still it is perceived as black
Simultaneous Color Contrast

- Double opponent cells in visual cortex
- Same as lateral inhibition
Eye and Devices

- Difference between the eye and the devices
  - Eye has unique properties
  - Devices cannot reproduce that

- Gamut
  - Any color within the gamut can be reproduced by the device
Eye and Devices

- Gamut Mapping
- Gamut Matching
- More primaries can give wider gamut
- Why not?
  - Underconstrained system
  - No unique solution