Color and Color Models

Werner Purgathofer
Color

- problem specification
- light and perception
- colorimetry
- device color systems
- color ordering systems
- color symbolism
Color - Why Do We Care?

- Visual Computing is all about the generation and the manipulation of color images
- Proper understanding & handling of color is necessary at every step
Color - A Visual Sensation

Object → Light stimulus → Eye → Nerve signal → Brain

electromagnetic rays → color sensation

realm of direct observables → realm of psychology

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What is Light?

- "light" = narrow frequency band of electromagnetic spectrum
- red border: 380 THz ≈ 780 nm
- violet border: 780 THz ≈ 380 nm
Light - An Electromagnetic Wave

- Light is electromagnetic energy.
- Monochrome light can be described either by frequency $f$ or wavelength $\lambda$.
- $c = \lambda \cdot f$ (c = speed of light)
- Shorter wavelength equals higher frequency.
- Red $\approx 700$ nm
- Violet $\approx 400$ nm
normally, a ray of light contains many different waves with individual frequencies

the associated distribution of wavelength intensities per wavelength is referred to as the *spectrum* of a given ray or light source
- dominant wavelength | frequency (hue, color)
- brightness (area under the curve)
- purity \( \frac{E_D - E_W}{E_D} \)  
  \( E_D \) ... dominant energy density  
  \( E_W \) ... white light energy density

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The Human Eye

- retina contains
  - rods: b/w
  - cones: color
The Human Eye

- 3 types of cones
- Different wavelength sensitivities:
  - Red
  - Green
  - Blue
Color Blindness

- red/green blindness
- red & green cones too similar

![Graph showing fraction of absorbed light vs. wavelength]

- fraction of absorbed light varies with wavelength,
- peaks at around 440 nm and 550 nm,
- red and green cones absorb light similarly at these peaks.
Color Blindness

- red/green blindness
  - red & green cones too similar

- blue blindness
  - no blue cones

![Color Blindness Graph]

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Color Blindness

- red/green blindness
  - red & green cones too similar

- blue blindness
  - no blue cones

- monochromatism
  - all cones missing
What do you see?
Color Blindness Tests

5 = normal
nothing = red/green blind

2 = red/green weak
nothing = normal
Color Blindness Tests

What do you see?
Color Blindness Tests

8 = normal
3 = red/green weak
nothing = red/green blind

8 = red/green blind
12 = blue/yellow blind
182 = normal
normal vision
Color Blindness Example

red/green weakness
red/green blindness
Color Spaces

- **Color Metric Spaces** (CIE XYZ, L*a*b*)
  - used to measure absolute values and differences
    – has roots in colorimetry

- **Device Color Spaces** (RGB, CMY, CMYK)
  - used in conjunction with devices

- **Color Ordering Spaces** (HSV, HLS)
  - used to find colors according to some criterion

- the distinction between them is somewhat obscured by the prevalence of multi-purpose RGB in computer graphics
What is our Goal?

- to be able to **quantify** color in a meaningful, expressive, consistent and reproducible way

- problem: color is a *perceived quantity*, not a direct, physical observable
Color - A Visual Sensation

Object → light stimulus → eye → nerve signal → brain

Electromagnetic rays → color sensation

Realm of direct observables

Realm of psychology
Colorimetry is the branch of color science concerned with numerically specifying the color of a physically defined visual stimulus in such manner that

- stimuli with the same specification look alike (under the same viewing conditions)
- stimuli that look alike have the same specification
- numbers used are continuous functions of the physical parameters
Colorimetry Properties

- Colorimetry only considers the **visual discriminability** of physical beams of radiation.
- For the purposes of Colorimetry, a "color" is an equivalence class of mutually *indiscriminable beams*.
- Colors in this sense cannot be said to be "red", "green" or any other "color name".
- Discriminability is decided before the brain.
  - Colorimetry is not psychology.
observers had to match *(monochromatic)* test lights by combining 3 fixed primaries

- test box: compare test light with combined light
Color Matching Experiments

- observers had to match *(monochromatic)* test lights by combining 3 fixed primaries

\[ R = 700.0 \text{ nm} \]
\[ G = 546.1 \text{ nm} \]
\[ B = 435.8 \text{ nm} \]

- goal: find the *unique* RGB coordinates for each stimulus
Tristimulus Values

- the values $R_Q$, $G_Q$ and $B_Q$ of a stimulus $Q$ that fulfill

$$Q = R_Q \cdot R + G_Q \cdot G + B_Q \cdot B$$

are called the tristimulus values of $Q$

- in case of a monochromatic stimulus $Q_\lambda$, the values $R_\lambda$, $G_\lambda$ and $B_\lambda$ are called spectral tristimulus values
(1) test field = 700 nm-red with radiance $P_{\text{ref}}$
- observer adjusts luminance of R ($G=0$, $B=0$)

(2) test light wavelength is decreased in constant steps
   (radiance $P_{\text{ref}}$ stays the same)
- observer adjusts R, G, B

(3) repeat for entire visible range
observers want to „subtract“ red light from the match side...!?
Color Matching Experiment Problem

- for some colors observers want to reduce red light to negative values...!
- but there is no negative light...!
if a match using only positive RGB values proved impossible, observers could simulate a *subtraction* of red from the match side by adding it to the test side.
CIE RGB Color Matching Functions

\[ r(\lambda) \]
\[ g(\lambda) \]
\[ b(\lambda) \]

350 nm 400 nm 450 nm 500 nm 550 nm 600 nm 650 nm 700 nm

350 400 450 500 550 600 650 700 nm

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- problem solution: *XYZ color system*
- tristimulus system derived from RGB
- based on 3 *imaginary* primaries
- all 3 primaries are *imaginary* colors
- only positive XYZ values can occur!
- 1931 by **CIE**
  (Commission Internationale de l’Eclairage)
negative component disappears

$\bar{y}(\lambda)$ is the achromatic luminance sensitivity

RGB system

XYZ system

amounts of RGB primaries needed to display spectral colors

amounts of CIE primaries needed to display spectral colors
CIE Color Model Formulas

- **XYZ color model** \( C(\lambda) = X \cdot X + Y \cdot Y + Z \cdot Z \) (X, Y, Z are primaries)

- **Normalized chromaticity values** \( x, y \)

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

\( z = 1 - x - y \)

- **Complete description of a color**: \( x, y, Y \)
CIE Chromaticity Diagram

- identifying complementary colors
- determining dominant wavelength & purity
- comparing color gamuts

spectral color positions are along the boundary curve
representing complementary colors in the chromaticity diagram
determining dominant wavelength and purity with the chromaticity diagram

\[ C_1 \rightarrow C_s \]

\[ C_2 \rightarrow C_p \rightarrow \text{complement } C_{sp} \]
Properties of CIE Diagram (4)

Gamut of a typical RGB monitor

Only the colors inside the triangle can be produced
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RGB Color Model

- primary colors red, green, blue
- additive color model (for monitors)

\[ C(\lambda) = R \cdot \mathbf{R} + G \cdot \mathbf{G} + B \cdot \mathbf{B} \]
3 views of the RGB color cube
Gamuts of RGB Monitors

- Monitor gamuts can be very different
- No monitor can display all colors
CMY Color Model

- primary colors: cyan, magenta, yellow
- **subtractive** color model (for hardcopy devices)
  - $C = G + B$, using $C$ “subtracts” $R$

\[
\begin{bmatrix}
C \\
M \\
Y
\end{bmatrix}
= \begin{bmatrix}
1 \\
1 \\
1
\end{bmatrix} - \begin{bmatrix}
R \\
G \\
B
\end{bmatrix}
\]
3 views of the CMY color cube
printer gamuts can be very different
no printer can display all colors
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Color Ordering Systems (COS)

- **primary aim:** enable the user to intuitively choose colour values according to certain criteria
- choice can yield single or multiple colour values
- **examples:** HSV, HLS, Munsell, NCS, RAL Design, Coloroid
- used in bottom-up parts of a design process
- sometimes physical samples are provided
HSV Color Model

- more *intuitive* color specification
- derived from the RGB color model:
  - when the RGB color cube is viewed along the diagonal from white to black, the color cube outline is a hexagon
HSV Color Model Hexcone

- color components:
  - hue (H) \(\in [0^\circ, 360^\circ]\)
  - saturation (S) \(\in [0, 1]\)
  - value (V) \(\in [0, 1]\)

**HSV hexcone**
HSV Color Model Hexcone

- **color components:**
  - hue (H) \( \in [0°, 360°] \)
  - saturation (S) \( \in [0, 1] \)
  - value (V) \( \in [0, 1] \)

**HSV hexcone**
HSV Color Definition

- color definition
  - select hue, S=1, V=1
  - add black pigments, i.e., decrease V
  - add white pigments, i.e., decrease S

Cross section of the HSV hexcone showing regions for shades, tints, and tones
HLS Color Model

- **color components:**
  - hue (H) $\in [0^\circ, 360^\circ]$
  - lightness (L) $\in [0, 1]$
  - saturation (S) $\in [0, 1]$

*HLS double cone*
HLS Color Model

- color components:
  - hue (H) ∈ [0°, 360°]
  - lightness (L) ∈ [0, 1]
  - saturation (S) ∈ [0, 1]

*HLS double cone*
Color Model Summary

- **Colorimetry:**
  - **CIE XYZ:** contains all visible colors

- **Device Color Systems:**
  - **RGB:** *additive* device color space (monitors)
  - **CMY(K):** *subtractive* device color space (printers)

- **Color Ordering Systems:**
  - **HSV, HLS:** for user interfaces
Color Symbolism: Some Aspects

- 6 to 11 basic colors
- categories, hierarchies
- dependent on context / application
- large variation in use
  - what is red?
  - what is blue?
  - what is white?!
Islam: green

Buddhism: yellow, orange, red & purple

Hinduism: orange, blue & blue-violet

Christ: liturgical colors without theological connex
Political Symbol Colors

- parties
- revolutions / movements
- flags

![Flags of various countries](image)
Color Labeling

- at home
  - water pipes
  - electrical wires
  - waste separation

- traffic
  - traffic signs
  - traffic lights
  - parking concepts
  - public transport

- ...

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Color Labeling

- technology
  - resistors
  - thermochrome colors

- nature
  - courtship [Balz]
  - warning colors
  - protective mimicry [Tarnfarben]
  - ...

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Color Effect: BLUE

- distance
- faithfulness \([\text{Treue}]\)
- loyalty
- desire
- phantasy
- male
- devine
- peace
- cold
- ...

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Color Effect: RED

- blood
- energy
- love
- female
- rich, noble
- labor movement
- warm
- corrections
- ...

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Color Effect: GREEN

- profit
- young love
- hope
- prematurity, unripe
- poison
- nature
- neutral
- environment protection
- ...

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Color Effect: YELLOW

- sun
- optimism
- enlightenment
- jealousy \([\text{Neid}]\)
- stinginess \([\text{Geiz}]\)
- warning color
- warm
- ...

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- end, death
- sadness
- negative emotions
- bad luck
- elegance
- emptiness
- cold
- ...