Color

CPSC 314
Basics Of Color

Elements of color:

- Illumination
- Reflectance
- Perception
Basics of Color

**Physics**

- Illumination
  - *Electromagnetic spectra*
- Reflection
  - *Material properties*
  - *Surface geometry and microgeometery (i.e., polished versus matte versus brushed)*

**Perception**

- Physiology and neurophysiology
- Perceptual psychology
Electromagnetic Spectrum

THE ELECTROMAGNETIC SPECTRUM

Wavelength (In meters): $10^3$, $10^2$, $10^1$, 1, $10^{-1}$, $10^{-2}$, $10^{-3}$, $10^{-4}$, $10^{-5}$, $10^{-6}$, $10^{-7}$, $10^{-8}$, $10^{-9}$, $10^{-10}$, $10^{-11}$, $10^{-12}$

Size of a wavelength:
- Soccer Field
- House
- Baseball
- This Period
- Cell
- Bacteria
- Virus
- Protein
- Water Molecule

Common name of wave:
- Radio Waves
- Infrared
- Visible
- Ultraviolet
- "Hard" X-rays
- Gamma Rays

Sources:
- FM Radio
- Microwave Oven
- Radar
- The ALS
- X-Ray Machines
- Radioactive Elements

Frequency (waves per second): $10^6$, $10^7$, $10^8$, $10^9$, $10^{10}$, $10^{11}$, $10^{12}$, $10^{13}$, $10^{14}$, $10^{15}$, $10^{16}$, $10^{17}$, $10^{18}$, $10^{19}$, $10^{20}$

Energy of one photon (electron volts): $10^{-9}$, $10^{-8}$, $10^{-7}$, $10^{-6}$, $10^{-5}$, $10^{-4}$, $10^{-3}$, $10^{-2}$, $10^{-1}$, 1, $10^1$, $10^2$, $10^3$, $10^4$, $10^5$, $10^6$
Common light sources differ in the kind of spectrum they emit:

- **Continuous spectrum**
  - *Energy is emitted at all wavelengths*
    - Blackbody radiation
    - Tungsten light bulbs
    - Certain fluorescent lights
    - Sunlight
    - Electrical arcs

- **Line spectrum**
  - *Energy is emitted at certain discrete frequencies*
**Blackbody Radiation**

**Black body**
- Dark material, so that reflection can be neglected
- Spectrum of emitted light changes with temperature
  - *This is the origin of the term “color temperature”*
    - E.g. when setting a white point for your monitor
      - Cold: mostly infrared
      - Hot: redish
      - Very hot: bluish
- Demo:
  
  http://www.mhhe.com/physsci/astronomy/applets/Blackbody/frame.html
White Light

- Sun or light bulbs emit all frequencies within the visible range to produce what we perceive as the "white light"
- But the exact tone depends on the emitted spectrum
Sunlight Spectrum
Continuous Spectrum

Example:
- Sunlight
- Various “daylight” lamps
Line Spectrum

**Examples:**
- Ionized gases
- Lasers
- Some fluorescent lamps

-hydrogen
-helium
-oxygen
-nitrogen
-neon
-argon
-krypton
White Light and Color

- When white light is incident upon an object, some frequencies are reflected and some are absorbed by the object
  - But generally, the wavelength of reflected photons remains the same
  - Exceptions: fluorescense, phosphorescense…
- Combination of frequencies present in the reflected light that determines what we perceive as the color of the object
Physiology of Vision

The retina

- Rods
  - B/w, edges
- Cones
  - Color!
Physiology of Vision

**Center of retina is densely packed region called the fovea.**

- Cones much denser here than the *periphery*

1.35 mm from retina center

8 mm from retina center

© Wolfgang Heidrich
Hue

Hue (or simply, "color") is dominant wavelength/frequency

- Integration of energy for all visible wavelengths is proportional to intensity of color
Saturation or Purity of Light

**How washed out or how pure the color of the light appears**

- Contribution of dominant light vs. other frequencies producing white light
- Saturation: how far is color from grey
  - *Pink is less saturated than red, sky blue is less saturated than royal blue*
Intensity vs. Brightness

**Intensity**: *physical term*
- Measured radiant energy emitted per unit of time, per unit solid angle, and per unit projected area of the source (related to the luminance of the source)

**Lightness/brightness**: *perceived intensity of light*
- Nonlinear
## Perceptual vs. Colorimetric Terms

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Color/Lightness Constancy

Color perception also depends on surrounding

- Colors in close proximity
- Illumination under which the scene is viewed
Adaptation, Surrounding Color

**Color perception is also affected by**

- Adaptation (move from sunlight to dark room)
- Surrounding color/intensity:
  - *Simultaneous contrast effect*

![Image showing the simultaneous contrast effect](image-url)
Color/Lightness Constancy

Do they match?

Image courtesy of John MCann

© Wolfgang Heidrich
Color/Lightness Constancy

Do they match?
Color/Lightness Constancy
Color/Lightness Constancy
Color/Lightness Constancy
Color/Lightness Constancy
Color Constancy

- Automatic “white balance” from change in illumination
- Vast amount of processing behind the scenes!
- Colorimetry vs. perception

From Color Appearance Models, fig 8-1
Tristimulus Theory of Color Vision

- Although light sources can have extremely complex spectra, it was empirically determined that colors could be described by only 3 *primaries*.

- Colors that look the same but have different spectra are called *metamers*.

- Metamer demo:
  
Color Matching Experiments

Performed in the 1930s

Idea: perceptually based measurement

- shine given wavelength ($\lambda$) on a screen
- User must control three pure lights producing three other wavelengths (say R=700 nm, G=546 nm, and B=438 nm)
- Adjust intensity of RGB until colors are identical
Color Matching Experiment

**Results**

- It was found that any color $S(\lambda)$ could be matched with three suitable primaries $A(\lambda)$, $B(\lambda)$, and $C(\lambda)$.
- *Used monochromatic light at 438, 546, and 700 nanometers*
- Also found the space is linear, i.e. if

  $$R(\lambda) \equiv S(\lambda)$$

  then

  $$R(\lambda) + M(\lambda) \equiv S(\lambda) + M(\lambda)$$

  and

  $$k \cdot R(\lambda) \equiv k \cdot S(\lambda)$$
Negative Lobes

**Actually:**

- Exact target match possible sometimes requires “negative light”
- Some red has to be added to target color to permit exact match using “knobs” on RGB intensity output
- Equivalent mathematically to removing red from RGB output
Notation

Don’t confuse:

- Primaries: the spectra of the three different light sources: \( R, G, B \)
  - For the matching experiments, these were **monochromatic** (i.e. single wavelength) light!
  - Primaries for displays usually have a wider spectrum
- Coefficients \( R, G, B \)
  - Specify how much of \( R, G, B \) is in a given color
- Color matching functions: \( r(\lambda), g(\lambda), b(\lambda) \)
  - Specify how much of \( R, G, B \) is needed to produce a color that is a metamer for pure monochromatic light of wavelength \( \lambda \)
Negative Lobes

So:

• Can’t generate all other wavelengths with any set of three positive monochromatic lights!

Solution:

• Convert to new synthetic “primaries” to make the color matching easy

\[
\begin{pmatrix}
X \\
Y \\
Z
\end{pmatrix} = \begin{pmatrix}
2.36460 & -0.51515 & 0.00520 \\
-0.89653 & 1.42640 & -0.01441 \\
-0.46807 & 0.08875 & 1.00921
\end{pmatrix} \begin{pmatrix}
R \\
G \\
B
\end{pmatrix}
\]

Note:

• R, G, B are the same monochromatic primaries as before
• The corresponding matching functions x(\lambda), y(\lambda), z(\lambda) are now positive everywhere
• But the primaries contain “negative” light contributions, and are therefore not physically realizable
Matching Functions - CIE Color Space

- CIE defined three “imaginary” lights X, Y, and Z, any wavelength $\lambda$ can be matched perceptually by positive combinations.
Matching Functions - Measured vs. CIE Color Spaces

**Measured basis**
- Monochromatic lights
- Physical observations
- Negative lobes

**Transformed basis**
- "imaginary" lights
- All positive, unit area matching functions
- Y is luminance, no hue
- X,Z no luminance
Notation

**Don’t confuse:**

- Synthetic primaries $X$, $Y$, $Z$
  - *Contain negative frequencies*
  - *Do not correspond to visible colors*
- Color matching functions $x(\lambda)$, $y(\lambda)$, $z(\lambda)$
  - *Are non-negative everywhere*
- Coefficients $X$, $Y$, $Z$
- Normalized **chromaticity values**

\[
x = \frac{X}{X + Y + Z}, \quad y = \frac{Y}{X + Y + Z}, \quad z = \frac{Z}{X + Y + Z}
\]
CIE Gamut and $\lambda$ Chromaticity Diagram

3D gamut

Chromaticity diagram

- Hue only, no intensity
Facts about the CIE “Horseshoe” Diagram

• All visible colors lie inside the horseshoe
  – *Result from color matching experiments*

• Spectral (monochromatic) colors lie around the border
  – *The straight line between blue and red contains the purple tones*

• Colors combine linearly (i.e. along lines), since the xy-plane is a plane from a linear space
Facts about the CIE  
“Horseshoe” Diagram (cont.)

A point C can be chosen as a white point corresponding to an illuminant

- Usually this point is of the curve swept out by the black body radiation spectra for different temperatures
- Relative to C, two colors are called complementary if they are located along a line segment through C, but on opposite sides (i.e. C is an affine combination of the two colors)
- The dominant wavelength of the color is found by extending the line from C through the color to the edge of the diagram
- Some colors (i.e. purples) do not have a dominant wavelength, but their complementary color does.
CIE Diagram

- Blackbody curve
- Illumination:
  - Candle 2000K
  - Light bulb 3000K (A)
  - Sunset/sunrise 3200K
  - Day light 6500K (D)
  - Overcast day 7000K
  - Lightning >20,000K
Color Interpolation, Dominant & Opponent Wavelength

Complementary wavelength
RGB Color Space (Color Cube)

Define colors with \((r, g, b)\) amounts of red, green, and blue

- Used by OpenGL
- Hardware-centric
- Describes the colors that can be generated with specific RGB light sources

RGB color cube sits within CIE color space

- Subset of perceivable colors
- Scaled, rotated, sheared cube
Device Color Gamuts

*Use CIE chromaticity diagram to compare the gamuts of various devices*

- X, Y, and Z are hypothetical light sources, not used in practice as device primaries
Gamut Mapping

Where does this color go?
Additive vs. Subtractive Colors

**Additive: light**
- Monitors, LCDs
- RGB model

**Subtractive: pigment**
- Printers
- CMY(K) model

\[
\begin{bmatrix}
C \\
M \\
Y
\end{bmatrix} = \begin{bmatrix}
1 \\
1 \\
1
\end{bmatrix} - \begin{bmatrix}
R \\
G \\
B
\end{bmatrix}
\]
HSV Color Space

More intuitive color space for people

- H = Hue
- S = Saturation
- V = Value
  - Or brightness B
  - Or intensity I

![HSV Color Space Diagram](image.png)
Monitors

Monitors have nonlinear response to input

- Characterize by \( \gamma \)
  - \( \text{displayedIntensity} = a^\gamma \text{(maxIntensity)} \)

Gamma correction

- \( \text{displayedIntensity} = \left(a^{1/\gamma}\right)^\gamma \text{(maxIntensity)} \)
  - \( = a \text{(maxIntensity)} \)

Gamma for CRTs:

- Around 2.4