Today

Color and Light

What is Light?
- Radiation in a particular frequency range

Spectral Colors
- Light at a single frequency
- Bright and distinct in appearance

Reproduction only, not a real spectral color!
Other Colors

- Most colors seen are a mix light of several frequencies

Perception -vs- Measurement

- You do not “see” the spectrum of light
  - Eyes make limited measurements
  - Eyes physically adapt to circumstance
  - You brain adapts in various ways also
  - Weird psychological stuff happens

Image from David Forsyth
Everything is Relative

Adapt
It’s all in your mind...

Mach Bands

Everything’s Still Relative

Eyes as Sensors

- The human eye contains cells that sense light
  - Rods
    - No color (sort of)
    - Spread over the retina
    - More sensitive
  - Cones
    - Three types of cones
    - Each sensitive to different frequency distribution
    - Concentrated in fovea (center of the retina)
    - Less sensitive
Cones

- Each type of cone responds to different range of frequencies/wavelengths
  - Long, medium, short
  - Ratio: L10/M40/S1
- Also called by color
  - Red, green, blue
- Misleading: “Red” does not mean your red cones are firing...

Note: Rod response peaks between S&M

Cones

- Response of a cone is given by a convolution integral:
  \[ r(L, S) = \int L(\lambda) \cdot S(\lambda) d\lambda \]

Cones

- You can see that “red” and “green” respond to more more than just red and green...
Cones

- Response of a cone is given by a convolution integral:
  \[ r(L, S) = \int L(\lambda) \cdot S(\lambda) d\lambda \]

Images from David Forsyth

- Different light inputs \((L)\) may produce the same response \((r)\) in all three cones
  - Metamers: different “colors” that look the same
  - Can be quite useful...
  - Odd interactions between illumination and surfaces can be odd...

Trichromaticity

- Eye records color by 3 measurements
- We can “fool” it with combination of 3 signals
- Consequence: monitors, printers, etc...
- PS: The cone responses are linear

Additive Color

- Show color on left
- Mix “primaries” on right until they match
- The primaries need not be RGB
Color Matching Functions

- For primaries at 645.2, 526.3, and 444.4 nm
- Note negative region...

Additive Mixing

- Given three colors we agree on
- Make generic color with $M = \alpha A + \beta B + \gamma C$
- Negative not realizable
- Color now described by $\alpha, \beta, \gamma$
- If we match on $A, B, C$
- Example: computer monitor [RGB], paint

Subtractive Mixing

- Given three colors we agree on
- Make generic color with $M = W - (\alpha A + \beta B + \gamma C)$
- Max limited by $W$
- Color now described by $\alpha, \beta, \gamma$
- If we match on $A, B, C$
- Example: ink [CMYK]

CIE XYZ

- Imaginary set of color bases
- Match across spectrum with positive values
- $X, Y, Z$
- Normalized:
  $x = X / (X+Y+Z)$
  $y = Y / (X+Y+Z)$

Why 4th ink for black?
CIE Color Horseshoe Thinggy

Gamuts

Constraints on additive/subtractive mixing limit the range of color a given device can realize.

Devices may differ.

Matching between devices can be difficult.

Dynamic Range

- Max/min values also limited on devices
  - “blackest black”
  - “brightest white”

Tone Mapping

“Day for night”

(not the best example, done in Photoshop)
Color Spaces

- RGB color cube
- HSV color cone

MacAdam Ellipses (10x)
Colors in ellipses indistinguishable from center.

CIE
Scaled to be closer to circles.

\[ \left[ \begin{array}{c} u' \\ v' \end{array} \right] = \frac{1}{X + 15Y + 3Z} \left[ \begin{array}{c} 4X \\ 9Y \end{array} \right] \]
Color Spaces

- RGB color cube
- HSV color cone
- CIE \((x,y)\)
- CIE \((u,v)\)
- CMYK
- Many others...

Color Phenomena

- Light sources seldom shine directly in eye
- Light follows some transport path, i.e.:
  - Source
  - Air
  - Object surface
  - Air
  - Eye
- Color effected by interactions

Reflection

- Light strikes object
- Some frequencies reflect
- Some adsorbed
- Reflected spectrum is light times surface
- Recall metamers...

Transmission

- Light strikes object
- Some frequencies pass
- Some adsorbed (or reflected)
Scattering

- Interactions with small particles in medium
- Long wavelengths ignore
- Short ones scatter

Interference

- Wave behavior of light
  - Cancelation
  - Reinforcement
- Wavelength dependent

Iridescence

- Interaction of light with
  - Small structures
  - Thin transparent surfaces
Iridescence

Fluorescence / Phosphorescence

- Photon come in, knocks up electron
- Electron drops and emits photon at other frequency
- May be some latency
- Radio active decay can also emit visible photons

Black Body Radiation

- Hot objects radiate energy
- Frequency is temperature dependent
- Moderately hot objects get into visible range
- Spectral distribution is given by
  \[ E(\lambda) \propto \left( \frac{1}{\lambda^5} \right) \left( \frac{1}{\exp(hc/k\lambda T) - 1} \right) \]
- Leads to notion of “color temperature”
Black Body Radiation

\[
\sigma(\nu, T) = \frac{2 \pi^2 h^3}{c^5 (\lambda^3)} \left( \frac{1}{e^{\frac{h \nu}{kT}} - 1} \right)
\]

\[
\sigma(\lambda, T) = \frac{2 \pi^2 h c^3}{k^2 T^5} \left( \frac{1}{e^{\frac{h c}{kT}} - 1} \right)
\]

Wavelength (nm)