CS-184: Computer Graphics

Lecture #7: Color

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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

Image from David Forsyth
Other Colors

- Most colors seen are a mix of light of several frequencies

![Graph showing the spectrum of different light sources](Image from David Forsyth)

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
Everything is Relative

[Diagrams showing different geometric shapes]
Adapt

![Flag Image]

Adapt
It’s all in your mind...

| XXXXXXX | GREEN | GREEN |
| XXXXXXX | BLUE | BLUE |
| XXXXXXX | YELLOW | YELLOW |
| XXXXXXX | PURPLE | PURPLE |
| XXXXXXX | ORANGE | ORANGE |
| XXXXXXX | RED | RED |
| XXXXXXX | WHITE | WHITE |
| XXXXXXX | PURPLE | PURPLE |
| XXXXXXX | ORANGE | ORANGE |
| XXXXXXX | BLUE | BLUE |
| XXXXXXX | RED | RED |
| XXXXXXX | GREEN | GREEN |
| XXXXXXX | WHITE | WHITE |
| XXXXXXX | YELLOW | YELLOW |
| XXXXXXX | PURPLE | PURPLE |
| XXXXXXX | RED | RED |
| XXXXXXX | GREEN | GREEN |
| XXXXXXX | BLUE | BLUE |

Mach Bands
Eyes as Sensors

- The human eye contains cells that sense light
  - Rods
    - No color
    - 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

- Also called by color
  - Red, green, blue
  - Misleading:
    - “Red” does not mean your red cones are firing...

\[ r(L, S) = \int L(\lambda) \cdot S(\lambda) d\lambda \]
Cones

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

Images from David Forsyth
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]

Why 4th ink for black?

CIE XYZ

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

Color Spaces

- RGB color cube
- HSV color cone
Color Spaces

- RGB color cube
- HSV color cone
- CIE

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

Color Spaces

- RGB color cube
- HSV color cone
- CIE \((x,y)\)
- CIE \((u,v)\)

Scaled to be closer to circles.

\[
\begin{bmatrix}
  u' \\
  v'
\end{bmatrix} = \frac{1}{X + 15Y + 3Z} \begin{bmatrix}
  4X \\
  9Y
\end{bmatrix}
\]
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

Fig. 1.22 Iridescence: when a light wave is partially reflected and partially transmitted at the surface of a thin layer of transparent material (e.g. a bubble), the two parts of the original wave may interfere with each other when the transmitted wave is reflected from a lower layer and re-emerges at the surface. In this case the blue waves are in phase and their colour is reinforced (a) but the red waves are out of phase and their colour is cancelled (b).
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
Fluorescence / Phosphorescence

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

![Graph showing Black Body Radiation with different temperatures and wavelengths.]

Suggested Reading

- Fundamentals of Computer Graphics by Pete Shirley
  - Chapters 16, 17, & 18