29 - COLOR

Textbook: 19

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ELECTROMAGNETIC SPECTRUM

700 nm  400 nm

10^15 10^13 10^{11} 10^9 10^7 10^5 10^3 10^{1} 10^{-1} 10^{-3}

10^4 10^6 10^8 10^{10} 10^{12} 10^{14} 10^{16} 10^{18} 10^{20}

frequency (Hz)

wavelength (nm)

AM radio  microwave  ultraviolet  gamma rays
FM radio, TV  infrared  x-rays
THE ELECTROMAGNETIC SPECTRUM

WAVELENGTH SIZE

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

COMMON NAME

RADIO WAVES - INFRARED - ULTRAVIOLET - "HARD" X RAYS
MICROWAVES - "SOFT" X RAYS - GAMMA RAYS

ACCELERATOR-BASED LIGHT SOURCES

COMMON SOURCES


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

Soccer Field - House - Baseball - This Period - Cell - Bacteria - Virus - Protein - Water Molecule
Visible energy - small portion of the electro-magnetic spectrum
Pure *monochromatic* colors are found at wavelengths between 380nm (violet) and 780nm (red)
• Eye can perceive other colors as combination of several pure colors
• Most colors may be obtained as combination of small number of primaries
• Output devices use this approach
WHITE LIGHT

- sun or light bulbs emit all frequencies within visible range to produce what we perceive as "white light"
SUNLIGHT SPECTRUM

• spectral distribution: power vs. wavelength

![Emission Graph](image1)

![Electromagnetic Spectrum](image2)
CONTINUOUS SPECTRUM

- sunlight
- various “daylight” lamps
LINE SPECTRUM

- ionized gases
- lasers
- some fluorescent lamps
PHYSIOLOGY OF VISION

• the retina
  • rods
    • b/w, edges
  • cones
    • 3 types
      • color sensors
• uneven distribution
  • dense fovea
RODS AND CONES

A

B

Rod outer segment

Rod inner segment

Cone outer segment

Cone inner segment

Outer segment

Inner segment

Cell body

Rod

Cone
FOVEAL VISION

• hold out your thumb at arm’s length
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

4 µm

8 mm from retina center
```
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
TRICHROMACY

• three types of cones
  • L or R, most sensitive to red light (610 nm)
  • M or G, most sensitive to green light (560 nm)
  • S or B, most sensitive to blue light (430 nm)

• color blindness results from missing cone type(s)
METAMERS

• a given perceptual sensation of color derives from the stimulus of all three cone types

• identical perceptions of color can thus be caused by very different spectra

• demo

http://www.cs.brown.edu/exploratories/freeSoftware/catalogs/color_theory.html
MANUFACTURING DISPLAYS

• This means we can only have R,G,B lights and mix them to get any color!
• Can we?
• Humans won’t know the difference
MANUFACTURING DISPLAYS

• This means we can only have R,G,B lights and mix them to get any color!
• Can we?
• Humans won’t know the difference

• An experiment: show a pure color and ask a person to mix R,G,B to match it perfectly
NEGATIVE LOBES

• sometimes they couldn’t match the color perfectly!
  • sometimes RGB produced “too much red”
  • but physically impossible to remove red from CRT phosphors

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

• solution: convert to new synthetic coordinate system to make the job easy
CIE COLOR SPACE

• CIE defined 3 “imaginary” lights X, Y, Z
  • any wavelength $\lambda$ can be matched perceptually by positive combinations
  • basis functions!

Note that:

$X \sim R$
$Y \sim G$
$Z \sim B$
COLOR SPACES
RGB COLOR SPACE (COLOR CUBE)

- define colors with \((r, g, b)\) amounts of red, green, and blue
  - used by OpenGL
  - hardware-centric

- RGB color cube sits within CIE color space
  - subset of perceivable colors
  - scale, rotate, shear cube
XYZ AND RGB COLOUR SPACES

• colour transformation matrix:
  (for monochromatic R=700nm, G=546nm, B=436nm)

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

• each monitor has its own RGB-to-XYZ transformation matrix

• suppose we have a colour \( R_A G_A B_A \) on monitor A and wish to view the same colour on monitor B:

\[
\begin{align*}
2 & \quad \begin{bmatrix}
R_B \\
G_B \\
B_B
\end{bmatrix} = \begin{bmatrix}
M_B^{-1}
\end{bmatrix}
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} \\
1 & \quad \begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} = \begin{bmatrix}
M_A
\end{bmatrix}
\begin{bmatrix}
R_A \\
G_A \\
B_A
\end{bmatrix}
\end{align*}
\]

\[
C_B = M_B^{-1} M_A C_A
\]
CIE CHROMATICITY DIAGRAM

- produce a 2D colour space by projecting onto the plane given by $X+Y+Z = 1$

$$x = \frac{X}{X+Y+Z}, \quad y = \frac{Y}{X+Y+Z}$$
RGB VS XYZ REVISITED

- another view of why the R curve goes negative
CIE CHROMATICITY DIAGRAM

- C: white point
- complementary colours
- dominant wavelength
- non-spectral colors
COLOR INTERPOLATION, DOMINANT & OPPONENT WAVELENGTH

Complementary wavelength

White point

Dominant wavelength

Complementary wavelength

520
540
560
580
620
700
490
480
470
430
380
CIE “HORSESHOE” DIAGRAM FACTS

- all visible colors lie inside the horseshoe
  - result from color matching experiments
- spectral (monochromatic) colors lie around the border
  - straight line between blue and red contains purple tones
- colors combine linearly (i.e. along lines), since the xy-plane is a plane from a linear space
DEVICE COLOR GAMUTS

- gamut is polygon, device primaries at corners
  - defines reproducible color range
  - X, Y, and Z are hypothetical light sources, no device can produce entire gamut
GAMUT MAPPING

• how to handle colors outside gamut?
  • one way: construct ray to white point, find closest displayable point within gamut
THE CMY COLOR MODEL

• Used in color printing
  • light is absorbed by dyes
• Cyan, Magenta and Yellow primaries are complements of Red, Blue and Green
• Primaries (dyes) subtracted from white paper
  • Red = White-Cyan = White-Green-Blue  \((0,1,1)\)
  • Green = White-Magenta = White-Red-Blue \((1,0,1)\)
  • Blue = White-Yellow = White-Red-Green \((1,1,0)\)
  • \((r,g,b) = (1-c,1-m,1-y)\)
HSV COLOR SPACE

more intuitive color space for people

• H = Hue
  • dominant wavelength, “color”

• S = Saturation
  • how far from grey/white

• V = Value
  • how far from black
  • also: brightness B, intensity I, lightness L
HSI/HSV AND RGB

• HSV/HSI conversion from RGB is non-linear
  • H=hue same in both
  • V=value is max, I=intensity is average

\[
H = \cos^{-1} \left[ \frac{1}{2} \left[ \frac{(R - G) + (R - B)}{\sqrt{(R - G)^2 + (R - B)(G - B)}} \right] \right] \quad \text{if } (B > G), \quad H = 360 - H
\]

HSI:
\[
S = 1 - \frac{\min(R,G,B)}{I} \quad I = \frac{R + G + B}{3}
\]

HSV:
\[
S = 1 - \frac{\min(R,G,B)}{V} \quad V = \max(R,G,B)
\]
YIQ COLOR SPACE

color model used for color TV
• Y is luminance (same as CIE)
• I & Q are color (not same I as HSI!)
• using Y backwards compatible for B/W TVs
• conversion from RGB is linear
  • expressible with matrix multiply

\[
\begin{bmatrix}
Y \\
I \\
Q
\end{bmatrix}
= \begin{bmatrix}
0.30 & 0.59 & 0.11 \\
0.60 & -0.28 & -0.32 \\
0.21 & -0.52 & 0.31
\end{bmatrix}
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix}
\]

• green is much lighter than red, and red lighter than blue
LUV COLOR SPACE

• Our precision in distinguishing close colors is different for different areas in CIE XYZ
  • “Tolerance”
LUV COLOR SPACE

- Our precision in distinguishing close colors is different for different areas in CIE XYZ
- “Tolerance”
COLOUR BLINDNESS, TETRACHROMATS

• simulating color vision deficiencies

Normal vision  Deuteranope  Protanope  Tritanope
COLOR/LIGHTNESS CONSTANCY

- color perception depends on surrounding
  - colors in close proximity
  - illumination under which the scene is viewed
STROOP EFFECT

- blue
- green
- purple
- red
- orange

- interplay between cognition and perception
- used as a test (of what?)
STROOP EFFECT

• зеленый
• оранжевый
• синий
• красный
• фиолетовый

• interplay between cognition and perception
• used as a test (of what?)