Reading for Today

- RB Chap Color
- FCG Sections 3.2-3.3
- FCG Chap 20 Color
- FCG Chap 21 Visual Perception
Reading for Next Time
Project 1 Grading News

- don’t forget to show up 10 min before your slot
  - see news item on top of course page for signup slot reminders
- signup snafu: 10-11 Wed overlaps with class
  - reschedule if possible
Midterm News

- midterm Friday Feb 9
  - closed book
  - no calculators
  - allowed to have one page of notes
    - handwritten, one side of 8.5x11” sheet
  - this room (DMP 301), 10-10:50

- material covered
  - transformations, viewing/projection
Review: N2D Transformation

\[
\begin{bmatrix}
x_D \\
y_D \\
z_D \\
1
\end{bmatrix}
= \begin{bmatrix}
1 & 0 & 0 & \frac{\text{width}}{2} - \frac{1}{2} \\
0 & 1 & 0 & \frac{\text{height}}{2} - \frac{1}{2} \\
0 & 0 & 1 & \frac{\text{depth}}{2} \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\frac{\text{width}}{2} & 0 & 0 & 0 \\
0 & \frac{\text{height}}{2} & 0 & 0 \\
0 & 0 & \frac{\text{depth}}{2} & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & -1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
x_N \\
y_N \\
z_N \\
1
\end{bmatrix}
= \begin{bmatrix}
\frac{\text{width}(x_N + 1) - 1}{2} \\
\frac{\text{height}(-y_N + 1) - 1}{2} \\
\frac{\text{depth}(z_N + 1)}{2} \\
\frac{2}{1}
\end{bmatrix}
\]
Review: Perspective Derivation

- shear
- scale
- projection-normalization

\[
\begin{bmatrix}
\frac{2n}{r-l} & 0 & \frac{r+l}{r-l} & 0 \\
0 & \frac{2n}{t-b} & \frac{t-b}{t-b} & 0 \\
0 & 0 & \frac{-(f+n)}{f-n} & -2fn \\
0 & 0 & f-n & 0 \\
\end{bmatrix}
\]

VCS

NDCS

(1,1,1)

(-1,-1,-1)
Review: OpenGL Example

```c
// CCS
glMatrixMode( GL_PROJECTION );
glLoadIdentity();
gluPerspective( 45, 1.0, 0.1, 200.0 );

// VCS
glMatrixMode( GL_MODELVIEW );
glLoadIdentity();
glTranslatef( 0.0, 0.0, -5.0 );

// WCS
glPushMatrix();
glTranslatef( 4, 4, 0 );

// OCS1
glutSolidTeapot(1);
glPopMatrix();
glTranslatef( 2, 2, 0 );

// OCS2
glutSolidTeapot(1);
```

- Transformations that are applied first are specified last.
Review: Projection Taxonomy

- **planar projections**
  - perspective: projectors converge
  - orthographic, axonometric: projectors parallel and perpendicular to projection plane
  - oblique: projectors parallel, but not perpendicular to projection plane

- **orthographic**
  - cabinet
  - cavalier
  - top, front, side
  - axonometric: isometric, dimetric, trimetric

- **parallel**
  - perspective: projectors converge

- **oblique**

See the image for additional visual representations. 

http://ceprofs.tamu.edu/tkramer/ENGR%20111/5.1/20
Vision/Color
RGB Color

- triple \((r, g, b)\) represents colors with amount of red, green, and blue
  - hardware-centric
  - used by OpenGL
Alpha

• fourth component for transparency
  • (r,g,b,\(\alpha\))

• fraction we can see through
  • \(c = \alpha c_f + (1-\alpha)c_b\)

• more on compositing later
Additive vs. Subtractive Colors

- additive: light
  - monitors, LCDs
  - RGB model
- subtractive: pigment
  - printers
  - CMY model
  - dyes absorb light

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

- component-wise multiplication of colors
  - \((a_0, a_1, a_2) \times (b_0, b_1, b_2) = (a_0 \times b_0, a_1 \times b_1, a_2 \times b_2)\)

- why does this work?
  - must dive into light, human vision, color spaces
Electromagnetic Spectrum

- **Frequency (Hz)**
- **Wavelength (nm)**

- $10^4$ to $10^6$: AM radio, FM radio, TV
- $10^8$: Ultraviolet
- $10^{11}$ to $10^{13}$: Microwave
- $10^{14}$: Infrared
- $10^{16}$ to $10^{18}$: Gamma rays
- $10^{20}$: X-rays

- 700 nm to 400 nm
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

![Sunlight Spectrum Diagram]
White Light and Color

• when white light is incident upon an object, some frequencies are reflected and some are absorbed by the object
• combination of frequencies present in the reflected light that determines what we perceive as the color of the object
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
Physiology of Vision

• the retina
  • rods
    • b/w, edges
  • cones
    • 3 types
    • color sensors
• uneven distribution
  • dense fovea
Foveal Vision

- hold out your thumb at arm’s length
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
Color Spaces

- three types of cones suggests color is a 3D quantity. How to define 3D color space?

- idea: perceptually based measurement
  - shine given wavelength ($\lambda$) on a screen
  - user must control three pure lights producing three other wavelengths (say R=700nm, G=546nm, and B=436nm)
  - adjust intensity of RGB until colors are identical
    - this works because of metamers!
Negative Lobes

• exact target match with phosphors not possible
  • possible: point red light to shine on target
  • impossible: 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 three “imaginary” lights X, Y, and Z, any wavelength $\lambda$ can be matched perceptually by positive combinations

Note that:
- $X \sim R$
- $Y \sim G$
- $Z \sim B$
Measured vs. CIE Color Spaces

- measured basis
  - monochromatic lights
  - physical observations
  - negative lobes

- transformed basis
  - “imaginary” lights
  - all positive, unit area
  - $Y$ is luminance, no hue
  - $X,Z$ no luminance
CIE and Chromaticity Diagram

• X, Y, Z form 3D shape
• project X, Y, Z on X+Y+Z=1 plane for 2D color space
  • separate color from brightness
  • chromaticity diagram
• \( x = \frac{X}{X+Y+Z} \)
• \( y = \frac{Y}{X+Y+Z} \)
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
Display Gamuts

Projector Gamuts

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
HSV Color Space

• more intuitive color space for people
  • H = Hue
  • S = Saturation
  • V = Value
    • or brightness B
    • or intensity I
    • or lightness L
HSV and RGB

• HSV/HSI conversion from RGB
  • not expressible in matrix

\[
I = \frac{R + G + B}{3} \quad S = 1 - \frac{\min(R + G + B)}{I} \\
H = \cos^{-1}\left[ \frac{1}{2} \left[ \frac{(R - G) + (R - B)}{\sqrt{(R - G)^2 + (R - B)(G - B)}} \right] \right]
\]
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

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

- green is much lighter than red, and red lighter than blue
Luminance vs. Intensity

- **luminance**
  - \( Y \) of YIQ
  - \( 0.299R + 0.587G + 0.114B \)

- **intensity/brightness**
  - I/V/B of HSI/HSV/HSB
  - \( 0.333R + 0.333G + 0.333B \)

Opponent Color

• definition
  • achromatic axis
  • R-G and Y-B axis
  • separate lightness from chroma channels

• first level encoding
  • linear combination of LMS
  • before optic nerve
  • basis for perception
  • defines “color blindness”
vischeck.com

• simulates color vision deficiencies

Normal vision  Deuteranope  Protanope  Tritanope
Adaptation, Surrounding Color

- color perception is also affected by
  - adaptation (move from sunlight to dark room)
  - surrounding color/intensity:
    - simultaneous contrast effect
Color/Lightness Constancy

Do they match?

Image courtesy of John McCann
Color/Lightness Constancy

Image courtesy of John McCann
Color Constancy

- automatic “white balance” from change in illumination
- vast amount of processing behind the scenes!
- colorimetry vs. perception
Stroop Effect

- red
- blue
- orange
- purple
- green
Stroop Effect

- **blue**
- **green**
- **purple**
- **red**
- **orange**

- interplay between cognition and perception