Outline

• 3D Clipping
• Light
• Physical Properties of Light and Color
• Eye Mechanism for Color
• Systems to Define Light and Color
Simple Mesh Format (SMF)


- Triangle data

- Vertex indices begin at 1

```plaintext
#$SMF 1.0
#$vertices 5
#$faces 6
v 2.0 0.0 2.0
v 2.0 0.0 -2.0
v -2.0 0.0 -2.0
v -2.0 0.0 2.0
v 0.0 5.0 0.0

f 1 3 2
f 1 4 3
f 3 5 2
f 2 5 1
f 1 5 4
f 4 5 3
```
3D Clipping

- Cohen-Sutherland and Cyrus-Beck can be trivially extended to 3D
- We will cover:
  - Cohen-Sutherland for 3D, (parallel projection)
  - Cohen-Sutherland for 3D, (perspective projection)
Recall: Cohen-Sutherland

- Line is completely visible iff both code values of endpoints are 0, i.e. $C_0 \lor C_1 = 0$
- If line segments are completely outside the window, then $C_0 \land C_1 \neq 0$
Cohen-Sutherland for 3D, Parallel Projection

- Use 6 bits
- Trivially accept if all end-codes are 0
- Trivially reject if bit-by-bit AND of end-codes is not 0
- Up to 6 intersections may have to be computed

<table>
<thead>
<tr>
<th>bit</th>
<th>Condition</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>point ABOVE the view volume</td>
<td>( y &gt; 1 )</td>
</tr>
<tr>
<td>2</td>
<td>point BELOW the view volume</td>
<td>( y &lt; -1 )</td>
</tr>
<tr>
<td>3</td>
<td>point RIGHT OF the view volume</td>
<td>( x &gt; 1 )</td>
</tr>
<tr>
<td>4</td>
<td>point LEFT OF the view volume</td>
<td>( x &lt; -1 )</td>
</tr>
<tr>
<td>5</td>
<td>point BEHIND the view volume</td>
<td>( z &lt; -1 )</td>
</tr>
<tr>
<td>6</td>
<td>point IN FRONT the view volume</td>
<td>( z &gt; 0 )</td>
</tr>
</tbody>
</table>
Cohen-Sutherland for 3D computing intersection points.

- Use parametric representation of the line to compute intersections
- So for $y=1$ replace $y$ with 1 and solve for $t$
- If $1 \geq t \geq 0$ use it to find $x$ and $z$
- Test if $x$ and $z$ are in valid range
- Repeat for planes $y=-1$, $x=1$, $x=-1$, $z=-1$, $z=0$

\[
\begin{align*}
x &= x_0 + t(x_1 - x_0) \\
y &= y_0 + t(y_1 - y_0) \\
z &= z_0 + t(z_1 - z_0)
\end{align*}
\]

\[
t = \frac{(1 - y_0)}{(y_1 - y_0)}
\]
Cohen-Sutherland for 3D, Perspective Projection

- Use 6 bits identical to parallel view volume clipping
- Conditions on the codes are different
- Trivially accept/reject lines using same roles
- Intersection points computed differently

<table>
<thead>
<tr>
<th>bit</th>
<th>Description</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>point ABOVE the view volume</td>
<td>( y &gt; -z )</td>
</tr>
<tr>
<td>2</td>
<td>point BELOW the view volume</td>
<td>( y &lt; z )</td>
</tr>
<tr>
<td>3</td>
<td>point RIGHT OF the view volume</td>
<td>( x &gt; -z )</td>
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<td>( x &lt; z )</td>
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<td>5</td>
<td>point BEHIND the view volume</td>
<td>( z &lt; -1 )</td>
</tr>
<tr>
<td>6</td>
<td>point IN FRONT the view volume</td>
<td>( z &gt; z_{\text{min}} )</td>
</tr>
</tbody>
</table>
Cohen-Sutherland for 3D computing intersection points.

- Intersections with planes $z=-1$, $z=z_{\text{min}}$ is the same.
- Calculating intersections with a sloping plane ...
- For plane $y=z$ these two equations are equal
- Repeat for planes $y=-z$, $x=z$, $x=-z$

\[
\begin{align*}
x &= x_0 + t(x_1 - x_0) \\
y &= y_0 + t(y_1 - y_0) \\
z &= z_0 + t(z_1 - z_0)
\end{align*}
\]

\[
t = \frac{(z_0 - y_0)}{(y_1 - y_0) - (z_1 - z_0)}
\]
“3D Clipping” for HWs 4 & 5

• Only do trivial reject test
• For HW4 just do X and Y tests
• ‘AND’ all vertex bit codes for a polygon
• If result ≠ 0, then reject polygon
  – i.e. remove from projection pipeline
More Efficient Alternative?

- Use Cohen-Sutherland to do trivial reject
- Project remaining polygons onto view plane
- Clip polygons in 2D
- Remember that user-defined window is redefined for canonical view volumes!
end clipping
Achromatic Light

- Light without color
- Basically Black-and-White
- Defined in terms of “energy” (physics)
  - Intensity and luminance
  - or Brightness (perceived intensity)

http://www.thornlighting.com/
Quantizing Intensities

• Q: Given a limited number of colors/shades, which ones should we use?
• Suppose we want 256 “shades”
• Idea #1 (bad)
  – 128 levels from 0.0 – 0.9
  – 128 levels from 0.9 – 1.0
  – Problems
    • Discontinuities at 0.9
    • Uneven distribution of samples
Quantizing Intensities

• Suppose we want 256 “shades”
• Idea #2 (also bad)
  – Distribute them evenly
  – Problem
    • This is not how the human eye works!
    • The eye is sensitive to *relative* intensity variations, not absolutes
      – The intensity change between 0.10 and 0.11 looks like the change between 0.50 and 0.55
Optical Illusion

Checker-shadow illusion:
The squares marked A and B are the same shade of gray.

Edward H. Adelson
Optical Illusion Revealed

Checker-shadow illusion:
The squares marked A and B are the same shade of gray.

Edward H. Adelson
Quantizing Intensities

• Idea #3
• Start with intensity $I_0$, go to $I_{255}=1$ by making $I_1 = r*I_0$, $I_2 = r*I_1$, etc.
• $I_0, I_1 = r*I_0, I_2 = r^2*I_0, \ldots I_{255} = r^{255}*I_0 = 1$
• $r = (1/I_0)^{1/255} = I_0^{-1/255}$
• $r^j = I_0^{-j/255}$
• $I_j = r^j I_0 = I_0^{(1 - j/255)} = I_0^{(255-j)/255}$
• $r = (1/I_0)^{1/n} \quad I_j = r^j I_0 = I_0^{(n-j)/n}$
Selecting Intensities

- **Dynamic range** of a device
  - Max intensity/Min intensity
  - Min display intensity ~ $1/500^{\text{th}}$ to $1/200^{\text{th}}$ of max

- **Gamma correction**: adjusting intensities to compensate for the device
  - $I = v^\gamma$, $\gamma$: 2 $\Rightarrow$ 2.5 Implement w/ look-up table

- **How many intensities are enough?**
  - Can’t see changes below 1%
  - $1.01 = (1/I_0)^{1/n}$
  - $n = \log_{1.01}(1/I_0)$, $I_0 = 1/200$, $n = 532$
Chromatic Light!

• Let there be colored light!
• Major terms
  – Hue
    • Distinguish colors such as red, green, purple, etc.
  – Saturation
    • How far is the color from a gray of equal intensity (i.e. red=high saturation; pastels are low)
  – Lightness
    • Perceived intensity of the reflecting object
    • **Brightness** is used when the object is an emitter
Physics of Light and Color

• Light: a physical phenomenon:
  – Electromagnetic radiation in the [400 nm-700nm] wavelength range

• Color: psychological phenomenon:
  – Interaction of the light of different wavelength with our visual system.

http://prometheus.cecs.csulb.edu/~jewett/colors/
Spectral Energy Distributions

Violet: 388-440nm
Blue: 440-490nm
Green: 490-565nm
Yellow: 565-590nm
Orange: 590-630nm
Red: 630-780nm

Laser
Pure day light

White
Less White (Gray)
Colorimetry (Physics)

• Define color in terms of the light spectrum and wavelengths
  – Dominant Wavelength: what we see
  – Excitation Purity: saturation
  – Luminance: intensity of light

• Ex:
  – Pure color, 100% saturated, no white light
  – White/gray lights are 0% saturated
Specifying Colors

• Can we specify colors using spectral distributions?
  – We can, but we do not want to.
  – More than one set of distributions corresponds to the same color. *Reason?*
  – Too much information
Seeing in Color

• The eye contains rods and cones
  – Rods work at low light levels and do not see color
  – Cones come in three types (*experimentally and genetically proven*), each responds in a different way to frequency distributions

http://www.thornlighting.com/
Tristimulus Theory

- The human retina has 3 color sensors – the cones
- Cones are tuned to red, green and blue light wavelengths – Note: R&G are both “yellowish”
- Experimental data
Luminous-Efficiency Function

- The eye’s response to light of constant luminance as the dominant wavelength is varied
- Peak sensitivity is at ~550nm (yellow-green light)
- This is just the sum of the earlier curves
Eye Sensitivity

• Can distinguish 100,000s of colors, side by side
• When color only differs in hue, wavelength between noticeably different colors is between 2nm and 10nm (most within 4nm)
• Hence, 128 fully saturated hues can be distinguished
• Less sensitive to changes in hue when light is less saturated
• More sensitive at spectrum extremes to changes in saturation a
  – about 23 distinguishable saturation grades/steps
• Static luminance dynamic range: 10,000:1
Device Sensitivity

• Static eye luminance dynamic range
  – 10,000:1
• With iris adjustment
  – 1,000,000:1
• CRT luminance range, 200:1
• LCD luminance range, 5,000:1(?), 500:1
• How to recreate on a monitor/scanner what the eye perceives?
• The focus of high dynamic range (HDR) imaging research
HDR Image
Terms

• Perceptual Term
  – Hue
  – Saturation
  – Lightness
    • self reflecting objects
  – Brightness
    • self luminous objects

• Colorimetry
  – Dominant Wavelength
  – Excitation purity
  – Luminance
  – Luminance
Color Models RGB

• Idea: specify color in terms of weighted sums of R-G-B

• Almost: may need some <0 values to match wavelengths

• Hence, some colors cannot be represented as sums of the primaries
RGB is an Additive Color Model

- Primary colors:
  - red, green, blue
- Secondary colors:
  - yellow = red + green,
  - cyan = green + blue,
  - magenta = blue + red.
- All colors:
  - white = red + green + blue (#FFFFFF)
  - black = no light (#000000).

http://prometheus.cecs.csulb.edu/~jewett/colors/
RGB Color Cube

- RGB used in Monitors and other light emitting devices
- TV uses YIQ encoding which is somewhat similar to RGB

http://prometheus.cecs.csulb.edu/~jewett/colors/
Color Models CMY

- Describes hardcopy color output
- We see colors of reflected light
- Cyan ink absorbs red light and reflects green and blue
- To make blue, use cyan ink (to absorb red), and magenta ink (to absorb green)

http://prometheus.cecs.csulb.edu/~jewett/colors/
CMY(K) is a Subtractive Color Model

• Primary colors:
  – cyan, magenta, yellow

• Secondary colors:
  – blue = cyan \& magenta
  – red = magenta \& yellow
  – green = yellow \& cyan

• All colors:
  – black = cyan \& magenta \& yellow (in theory).
  – Black (K) ink is used in addition to C,M,Y to produce solid black.
  – white = no color of ink (on white paper, of course).

http://prometheus.cecs.csulb.edu/~jewett/colors/
Color Models XYZ

- Standard defined by International Commission on Illumination (CIE) since 1931
- Defined to avoid negative weights
- These are not real colors

\[
X = k \int P(\lambda)\bar{x}_\lambda d\lambda \quad Y = k \int P(\lambda)\bar{y}_\lambda d\lambda \quad Z = k \int P(\lambda)\bar{z}_\lambda d\lambda
\]
Color Models XYZ

- Cone of visible colors in CIE space
- $X+Y+Z=1$ plane is shown
- Constant luminance
- Only depends on dominant wavelength and saturation
CIE Chromaticity Diagram

- Plot colors on the $x + y + z = 1$ plane (normalize by brightness)

  $x = \frac{X}{X + Y + Z}$
  $y = \frac{Y}{X + Y + Z}$
  $z = \frac{Z}{X + Y + Z}$

- Gives us 2D Chromaticity Diagram

http://www.cs.rit.edu/~ncs/color/a_chroma.html
Working with Chromaticity Diagram

• C is “white” and close to $x=y=z=1/3$
• E and F can be mixed to produce any color along the line EF
• Dominant wavelength of a color $B$ is where the line from C through $B$ meets the spectrum (D).
• BC/DC gives saturation

http://www.cs.rit.edu/~ncs/color/a_chroma.html
Working with Chromaticity Diagram

• A & B are “complementary” colors. They can be combined to produce white light
• Colors inside ijk are linear combinations of i, j & k

http://www.cs.rit.edu/~ncs/color/a_chroma.html
Gamut

- **Gamut**: all colors produced by adding colors - a polygon
- Green contour – RGB Monitor
- White – scanner
- Black – printer
- Problem: How to capture the color of an original image with a scanner, display it on the monitor and print out on the printer?
- A triangle can’t cover the space → Can’t produce all colors by adding 3 different colors together

http://www.cs.rit.edu/~ncs/color/a_chroma.html
Color Models YIQ

• National Television System Committee (NTSC)
  \[
  \begin{bmatrix}
  Y \\
  I \\
  Q
  \end{bmatrix} =
  \begin{bmatrix}
  0.299 & 0.587 & 0.114 \\
  0.596 & -0.275 & -0.321 \\
  0.212 & -0.528 & 0.311
  \end{bmatrix}
  \begin{bmatrix}
  R \\
  G \\
  B
  \end{bmatrix}
  \]

• Y is same as XYZ model and represents brightness. Uses 4MHz of bandwidth.

• I contains orange-cyan hue information (skin tones). Uses about 1.5 Mhz

• Q contains green-magenta hue information. Uses about 1.5 Mhz

• B/W TVs use only Y signal.
Tint-Shade-Tone

- Relationships of tints, shades and tones.
  - Tints - mixture of color with white.
  - Shades – mixture of color with black.
- Both ignore one dimension.
- Tones respect all three.

Foley/VanDam, 1990/1994
HSB: hue, saturation, and brightness

- Also called HSV (hue saturation value).
- Hue is the actual color. Measured in degrees around the cone (red = 0 or 360, yellow = 60, green = 120, etc.).
- Saturation is the purity of the color, measured in percent from the center of the cone (0) to the surface (100). At 0% saturation, hue is meaningless.
- Brightness is measured in percent from black (0) to white (100). At 0% brightness, both hue and saturation are meaningless.

http://www.mathworks.nl/
HLS hue, lightness, saturation

- Developed by Tektronix
- Hue define like in HSB. Complimentary colors 180 apart
- Gray scale along vertical axis L from 0 black to 1 white
- Pure hues lie in the L=0.5 plane
- Saturation again is similar to HSB model