Project 3

- Project 3 is on-line
- Topic: rasterization
- Due Friday, October 24
- To be presented during lab session as usual
- Like in project 2, no team submissions allowed
Today

Color

- Chromaticity diagram
- Color reproduction on standard monitors
- Perceptually uniform color spaces

Shading

- Introduction
- Local shading models
Addendum: Honeybees

(Source: Encyclopedia Britannica)

The Austrian naturalist Karl von Frisch has demonstrated that honeybees, although blind to red light, distinguish at least four different color regions, namely:

- yellow (including orange and yellow green)
- blue green
- blue (including purple and violet)
- ultraviolet
CIE color spaces

- Based on trichromatic theory
  - Claims any color can be represented as a weighted sum of three primary colors
- Propose red, green, blue as primaries

- Goal
  - Given arbitrary color, determine the weights for the three primaries (tristimulus value) to reproduce that color sensation
  - Weights are “coordinates” of that color
CIE RGB matching curves

- Spectral primary colors were chosen
  - Blue (435.8nm), green (546.1nm), red (700nm)
- Matching curves for monochromatic target

- Negative values!
Arbitrary spectrum

• Arbitrary spectrum as sum of “monochromatic” spectra

\[
\sum_{i} L_i(\lambda) \rightarrow \text{Wavelength}
\]

“Monochromatic” spectra, width \(\hbar\)

\[
\begin{align*}
L_0(\lambda) + & \quad \tilde{\hbar} \\
L_1(\lambda) + & \quad \tilde{\hbar} \\
L_2(\lambda) + & \quad \tilde{\hbar} \\
L_3(\lambda) & \quad \text{Arbitrary spectrum}
\end{align*}
\]
Arbitrary spectrum

Assume linearity (superposition principle)

- Matching value of sum of spectra is equal to sum of matching values of each spectrum

- Red primary

\[ R = \sum_i \bar{r}(\lambda) h L_i(\lambda) \]

Input \( L(\lambda) \)
Matching curve for red primary \( \bar{r}(\lambda) \)

- In the limit \( h \to 0 \)

\[ R = \int \bar{r}(\lambda)L(\lambda) d\lambda \]
CIE RGB values

- Given spectrum, CIE RGB values are defined as

\[
R = \int \bar{r}(\lambda) L(\lambda) d\lambda \\
G = \int \bar{g}(\lambda) L(\lambda) d\lambda \\
B = \int \bar{b}(\lambda) L(\lambda) d\lambda
\]

- Matching curves for primaries \( \bar{r}(\lambda), \bar{g}(\lambda), \bar{b}(\lambda) \)

- Problem: CIE RGB values can be negative
CIE XYZ color space

- Linear transformation of RGB values
  - Y corresponds to experimentally determined brightness
  - No negative values in matching curves
  - White is \( XYZ = (1/3, 1/3, 1/3) \)
- Matching curves do not correspond to physical primaries

\[
X = \int \bar{x}(\lambda) L(\lambda) d\lambda \\
Y = \int \bar{y}(\lambda) L(\lambda) d\lambda \\
Z = \int \bar{z}(\lambda) L(\lambda) d\lambda
\]
Chromaticity diagram

- 2D visualization of CIE XYZ color space
  - Fix Y coordinate (brightness)
  - Project XYZ coordinates onto X+Y+Z=1 plane
  - Drop Z coordinate

Colors shown do not correspond to colors represented by (x,y) coordinates!
Chromaticity diagram

- Visualizes x,y plane (chromaticities)
- Pure spectral colors on boundary
- Weighted sum of any two colors lies on line connecting colors
- Weighted sum of any number of colors lies in convex hull of colors (gamut)

Colors shown do not correspond to colors represented by (x,y) coordinates!
Gamut

- Any device based on three primaries can only produce colors within the triangle spanned by the primaries.
- Points outside gamut correspond to negative weights of primaries.
Today

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- Chromaticity diagram
- **Color reproduction on standard monitors**
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Shading

- Introduction
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RGB monitors

• Given rgb values, what color will your monitor produce?
  - I.e., what are the CIE XYZ or CIE RGB coordinates of the displayed color?
  - How are OpenGL RGB values related to CIE XYZ, CIE RGB?

• Often you don’t know
  - OpenGL RGB ≠ CIE XYZ, CIE RGB
RGB monitors

Ideally

- We know XYZ values for RGB primaries
  \[(X_r, Y_r, Z_r)(X_g, Y_g, Z_g)(X_b, Y_b, Z_b)\]

- Monitor is linear

• rgb signal corresponds to weighted sum

\[
\begin{bmatrix}
X_s \\
Y_s \\
Z_s
\end{bmatrix} = r \begin{bmatrix}
X_r \\
Y_r \\
Z_r
\end{bmatrix} + g \begin{bmatrix}
X_g \\
Y_g \\
Z_g
\end{bmatrix} + b \begin{bmatrix}
X_b \\
Y_b \\
Z_b
\end{bmatrix}
\]

\[
\begin{bmatrix}
X_s \\
Y_s \\
Z_s
\end{bmatrix} = \begin{bmatrix}
X_r & X_g & X_b \\
Y_r & Y_g & Y_b \\
Z_r & Z_g & Z_b
\end{bmatrix} \begin{bmatrix}
r \\
g \\
b
\end{bmatrix}
\]
RGB monitors

- Given desired XYZ values, find rgb values by inverting matrix

\[
\begin{bmatrix}
X_s \\
Y_s \\
Z_s
\end{bmatrix}
\begin{bmatrix}
X_r & X_g & X_b \\
Y_r & Y_g & Y_b \\
Z_r & Z_g & Z_b
\end{bmatrix}^{-1}
= \begin{bmatrix} r \\
g \\
b\end{bmatrix}
\]

- Similar to change of coordinate systems for 3D points
RGB monitors

In reality

- XYZ values for monitor primaries are usually not directly specified
  - Monitor brightness is adjustable

- Monitors are not linear

  Linear intensity \( I = \) 0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
  Linear encoding \( V_s = \) 0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

  - Need gamma correction \( I = V_s^\gamma \)
  - For typical CRT monitors \( \gamma \approx 2.2 \)
sRGB

- Standard color space, with standard conversion to CIE XYZ
- Designed to match RGB values of typical monitor under typical viewing conditions
  - If no calibration information available, it’s best to interpret RGB values as sRGB
- sRGB is supported by OpenGL 2.1
- For more details and transformation from CIE XYZ to sRGB:
  http://en.wikipedia.org/wiki/SRGB_color_space
Conclusions

• Color reproduction on consumer monitors less than perfect
  - Same RGB values on one monitor look different than on another
  - Given color in CIE XYZ coordinates, consumer systems do not reliably produce that color

• Need color calibration
  - Consumers do not seem to care
  - Standard for digital publishing, printing, photography
Further reading

• Wikipedia pages

• More details
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Perceptually uniform color spaces

Definition

Euclidean distance between color coordinates corresponds to perceived difference

- CIE RGB, XYZ are not perceptually uniform
  - Euclidean distance between RGB, XYZ coordinates does not correspond to perceived difference
MacAdam ellipses

- Experiment (1942) to identify regions in CIE xy color space that are perceived as the same color
- Found elliptical areas, MacAdam ellipses
- In perceptually uniform color space, each point on an ellipse should have the same distance to the center
  - Ellipses become circles
CIE L*, a*, b* (CIELAB)

- Most common perceptually uniform color space
  - L* encodes lightness
  - a* encodes position between magenta and green
  - b* encodes position between yellow and blue
- Uses asterisk (*) to distinguish from Hunter's Lab color space
- Conversion between CIE XYZ and CIELAB is non-linear
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Shading

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Shading

- Compute interaction of light with surfaces
- Requires simulation of physics
- “Global illumination”
  - Multiple bounces of light
  - Computationally expensive, minutes per image
  - Used in movies, architectural design, etc.
Global illumination

- CSE168!

(non-teapot images by Henrik Wann Jensen)
Interactive applications

- No physics based simulation
- Simplified models
- Reproduce perceptually most important effects
- Local illumination
  - Only one bounce of light between light source and viewer
Rendering pipeline

Scene data

Modeling and viewing transformation

Shading

Projection

Scan conversion, visibility

Image

- Position object in 3D
- Determine colors of vertices
  - Per vertex shading
- Map triangles to 2D
- Draw triangles
  - Per pixel shading
Today

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Shading

• Introduction
• Local shading models
Local illumination

• What gives a material its color?
• How is light reflected by a
  - Mirror
  - White sheet of paper
  - Blue sheet of paper
  - Glossy metal
Local illumination

- Model reflection of light at surfaces
  - Assumption: no subsurface scattering
- Bidirectional reflectance distribution function (BRDF)
  - Given light direction, viewing direction, how much light is reflected towards the viewer
  - For any pair of light/viewing directions!
Local illumination

Simplified model

- Sum of 3 components
- Covers a large class of real surfaces

\[
\text{diffuse} + \text{specular} + \text{ambient} = \]

[Image of the simplified model diagram]
Local illumination

Simplified model

- Sum of 3 components
- Covers a large class of real surfaces

diffuse + specular + ambient =

Diffuse reflection

- Ideal diffuse material reflects light equally in all directions
- View-independent
- Matte, not shiny materials
  - Paper
  - Unfinished wood
  - Unpolished stone
Diffuse reflection

- Beam of parallel rays shining on a surface
  - Area covered by beam varies with the angle between the beam and the normal
  - The larger the area, the less incident light per area
  - Incident light per unit area is proportional to the cosine of the angle between the normal and the light rays
- Object darkens as normal turns away from light
- Lambert’s cosine law (Johann Heinrich Lambert, 1760)
- Diffuse surfaces are also called Lambertian surfaces
Diffuse reflection

• Given
  - Unit surface normal \( n \)
  - Unit light direction \( L \)
  - Material diffuse reflectance (material color) \( k_d \)
  - Light color (intensity) \( c_l \)

• Diffuse color

\[
c_d = c_l k_d (n \cdot L)
\]

Proportional to cosine between normal and light
Diffuse reflection

Notes

- Parameters $k_d, c_l$ are r,g,b vectors
- Need to compute r,g,b values of diffuse color $c_d$ separately
- Parameters in this model have no precise physical meaning
  - $c_l$: strength, color of light source
  - $k_d$: fraction of reflected light, material color
Diffuse reflection

- Provides visual cues
  - Surface curvature
  - Depth variation

Lambertian (diffuse) sphere under different lighting directions
OpenGL

- **Lights** (*glLight*)
  - Values for light \((0, 0, 0) \leq c_l \leq (1, 1, 1)\)
    - Definition: \((0,0,0)\) is black, \((1,1,1)\) is white

- **OpenGL**
  - Values for diffuse reflection
  - Fraction of reflected light \((0, 0, 0) \leq k_d \leq (1, 1, 1)\)

- **Consult OpenGL Programming Guide (Red Book)**
  - Available on-line, for URLs see course web site
Local illumination

Simplified model

- Sum of 3 components
- Covers a large class of real surfaces

\[ \text{diffuse} + \text{specular} + \text{ambient} = \]
Specular reflection

- Shiny surfaces
  - Polished metal
  - Glossy car finish
  - Plastics

- Specular highlight
  - Blurred reflection of the light source
  - Position of highlight depends on viewing direction
Specular reflection

- Ideal specular reflection is mirror reflection
  - Perfectly smooth surface
  - Incoming light ray is bounced in single direction
  - Angle of incidence equals angle of reflection
Law of reflection

- Angle of incidence equals angle of reflection
Specular reflection

- Many materials are not perfect mirrors
  - Glossy materials

Glossy teapot
Glossy materials

- Assume surface composed of small mirrors with random orientation (micro-facets)
- Smooth surfaces
  - Micro-facet normals close to surface normal
  - Sharp highlights
- Rough surfaces
  - Micro-facet normals vary strongly
  - Blurry highlight

Polished
Smooth
Rough
Very rough
Glossy surfaces

- Expect most light to be reflected in mirror direction
- Because of micro-facets, some light is reflected slightly off ideal reflection direction

Reflection
- Brightest when view vector is aligned with reflection
- Decreases as angle between view vector and reflection direction increases
Phong model (Bui Tuong Phong, 1973)

- Specular reflectance coefficient $k_s$
- Phong exponent $p$
  - Higher $p$, smaller (sharper) highlight

$$c = k_s c_l (\mathbf{R} \cdot \mathbf{e})^p$$
Phong model
Blinn model (Jim Blinn, 1977)

• Define unit halfway vector

\[ h = \frac{L + e}{\|L + e\|} \]

• Halfway vector represents normal of micro-facet that would lead to mirror reflection to the eye
Blinn model

- The larger the angle between micro-facet orientation and normal, the less likely
- Use cosine of angle between them
- Shininess parameter $s$
- Very similar to Phong

$$c = k_s c_l (h \cdot n)^s$$
Local illumination

Simplified model

• Sum of 3 components
• Covers a large class of real surfaces

diffuse + specular + ambient =

ambient
Ambient light

- In real world, light is bounced all around scene
- Could use global illumination techniques to simulate
- Simple approximation
  - Add constant ambient light at each point $k_a c_a$
  - Ambient light $c_a$
  - Ambient reflection coefficient $k_a$
- Areas with no direct illumination are not completely dark
Complete model

- Blinn model with several light sources $i$

$$c = \sum_i c_i \left( k_d (L_i \cdot n) + k_s (h_i \cdot n)^s \right) + k_a c_a$$

diffuse + specular + ambient =

![Diagram of light interactions](image)
\[ c = \sum_i c_{li} (k_d (\mathbf{L}_i \cdot \mathbf{n}) + k_s (\mathbf{h}_i \cdot \mathbf{n})^s) + k_a c_a \]

- All colors, reflection coefficients have separate values for R,G,B
- Usually, ambient = diffuse coefficient
- For metals, specular = diffuse coefficient
  - Highlight is color of material
- For plastics, specular coefficient = (x,x,x)
  - Highlight is color of light
BRDFs

- Diffuse, Phong, Blinn models are instances of bidirectional reflectance distribution functions (BRDFs)
- For each pair of light directions $L$, viewing direction $e$, return fraction of reflected light
- Shading with general BRDF $f$
  $$c = \sum_i c_{li} f(L_i, e)$$
- Many forms of BRDFs in graphics, often named after inventors
  - Cook-Torrance
  - Ward
  - ...
Next time

- More shading