Announcements

- Sunday, October 25 at 11:59pm:
  - Homework Project 1 due
  - Submission on Canvas
  - Follow instructions at end of project write-up
- Next Wednesday at 1pm:
  - Discussion Project 2
- Sunday, November 8th at 11:59pm:
  - Homework Project 2 due
- Extra extra credit option for project 2:
  - Degree completion plan
  - Submission independent of homework project
LERP Function

- LERP = Linear intERPolation
- Can be used with scalars or vectors, and even points
- Useful for smooth transitions

```javascript
// Linear Interpolation
// Also known as "lerp" or "mix"
function lerp(start, end, t) {
    return start * (1 - t) + end * t;
}

// Examples:
lerp(0, 100, 0.5); // 50
lerp(20, 80, 0); // 20
lerp(30, 5, 1); // 5
lerp(-1, 1, 0.5); // 0
lerp(0.5, 1, 0.5); // 0.75
```
Shading
Normal Shading

- Coloring based on surface normal
  - X coordinate maps to Red
  - Y coordinate maps to Green
  - Z coordinate maps to Blue

- Need to map normal range of -1 to +1 to color range of 0.0 to 1.0
Realistic 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.
- Appearance = Material Definition + Light Sources
Global Illumination
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
Local Illumination

- Gives material its color
- Light can be reflected by
  - Mirror
  - White wall
  - Glossy metal
  - etc.
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
Local Illumination

Simplified model

- Sum of 3 components
- Covers a large class of real surfaces
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 (normalized!) surface normal \( \mathbf{n} \)
  - Unit (normalized!) light direction \( \mathbf{L} \)
  - Material diffuse reflectance (material color) \( k_d \)
  - Light color (intensity) \( c_l \)

- **Diffuse color** \( c_d \) is:
  \[
  c_d = c_l k_d (\mathbf{n} \cdot \mathbf{L})
  \]
  Proportional to cosine between normal and light
Diffuse Reflection

Notes
- Parameters \(k_d, c_l\) are r,g,b vectors (colors)
- Need to compute r,g,b values of diffuse color \(c_d\) separately
- Parameters in this model have no precise physical meaning
  - \(c_l\): intensity and 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
Local Illumination

Simplified model

- Sum of 3 components
- Covers a large class of real surfaces
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 highlight
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
Projection of vector on another vector

Projection of \( \vec{a} \) on \( \vec{b} \) is XY

The projection of \( \vec{a} \) onto \( \vec{b} \) will be given by:

\[
proj_{\vec{b}} \vec{a} = |a| \cos \theta \frac{\vec{b}}{|\vec{b}|}
\]

In summary, the \( proj_{\vec{a}} \vec{b} \) has length

\[
|a| \cos \theta,
\]

and direction \( \frac{\vec{b}}{|\vec{b}|} \).

It is called the scalar component of \( \vec{a} \) in the direction of \( \vec{b} \).
Law of Reflection

- Angle of incidence equals angle of reflection

Using these equations:

\[ \text{proj}_b a = |a| \cos \theta \frac{b}{|b|} \]

\[ \cos \theta = \left( \frac{a \cdot b}{|a||b|} \right) \]

We can derive the reflection vector \( \mathbf{R} \):

\[ \mathbf{R} + \mathbf{L} = 2 \cos \theta \mathbf{n} = 2(\mathbf{L} \cdot \mathbf{n}) \mathbf{n} \]

\[ \mathbf{R} = 2(\mathbf{L} \cdot \mathbf{n}) \mathbf{n} - \mathbf{L} \]
Specular Reflection

- Many materials are not perfect mirrors
  - Glossy materials
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 Shading Model

- Developed by Bui Tuong Phong in 1973
- Specular reflectance coefficient (color) $k_s$
- Phong exponent $p$
  - Greater $p$ means smaller (sharper) highlight

$$c = k_s c_l (\mathbf{R} \cdot \mathbf{e})^p$$
Phong Shading Model
Local Illumination

Simplified model
- Sum of 3 components
- Covers a large class of real surfaces
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 color: $c_a$
  - Ambient reflection coefficient: $k_a$
- Areas with no direct illumination are not completely dark
Complete Phong Shading Model

- Phong model supports multiple light sources
- All light colors \( c \) and material coefficients \( k \) are 3-component vectors for red, green, blue

\[
c = \sum_i c_i (k_d (L_i \cdot n) + k_s (R \cdot e)^p + k_a)
\]

Image by Brad Smith
Types of Shading

- Per-triangle
- Per-vertex
- Per-pixel
Per-Triangle Shading

- A.k.a. *flat shading*
- Evaluate shading once per triangle, based on normal vector

**Advantage**
- Fast

**Disadvantage**
- Faceted appearance
Per-Vertex Shading

- Known as *Gouraud shading* (Henri Gouraud, 1971)
- Interpolates vertex colors across triangles

**Advantages**
- Fast (no less work in fragment shader)
- Smoother surface appearance than with flat shading

**Disadvantage**
- Problems with small highlights
Per-Pixel Shading

- A.k.a. *Phong Interpolation* (not to be confused with *Phong Illumination Model*)
  - Rasterizer interpolates *normals* (instead of colors) across triangles
  - Illumination model is evaluated at each pixel
  - Simulates shading with normals of a curved surface

- Advantage
  - Highest rendering quality

- Disadvantage
  - Slow

Source: Penny Rheingans, UMBC
Gouraud vs. Per-Pixel Shading

- Gouraud shading has problems with highlights when polygons are large
- More triangles improve the result, but reduce frame rate
- Video: [https://www.youtube.com/watch?v=Fl5i-UnlQps&feature=youtu.be](https://www.youtube.com/watch?v=Fl5i-UnlQps&feature=youtu.be)

![Per-Vertex (Gouraud) vs. Per-Pixel](image)
Summary

- Per-pixel shading looks best and is only slightly more computationally expensive.
- On slower GPUs Gouraud shading may make sense (e.g., in OpenGL ES on older mobile devices).
- In CSE 167 we always use per-pixel shading.