CSE 167: Introduction to Computer Graphics Lecture #6: Illumination

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Announcements

- Project 2 due this Friday at 2pm
  - Grading in CSE basement labs B260 and B270
  - This time using Autograder (no whiteboard)
  - Upload code to TritonEd by 2pm

Internship Opportunity

- Jurgen –

  I actually may need your help sooner then later. I'm actually looking to get one or two interns into this new company to help with the application. It's a web based SAAS app and I'm looking for a full stack developer that knows react and node. They use meteor (which is just a package of custom java scripts), but finding anyone with meteor experience is rare and not mission critical if they know how to trace the information.

  The company is called "SimpleForms" (www.simpleforms.com). If you know any students that may be interested please let me know.

  My email is danlipsky0@gmail.com

  …Dan

Overview

- Appearance = Material Definition + Light Sources
- Shading defines how surfaces interact with light

Shading

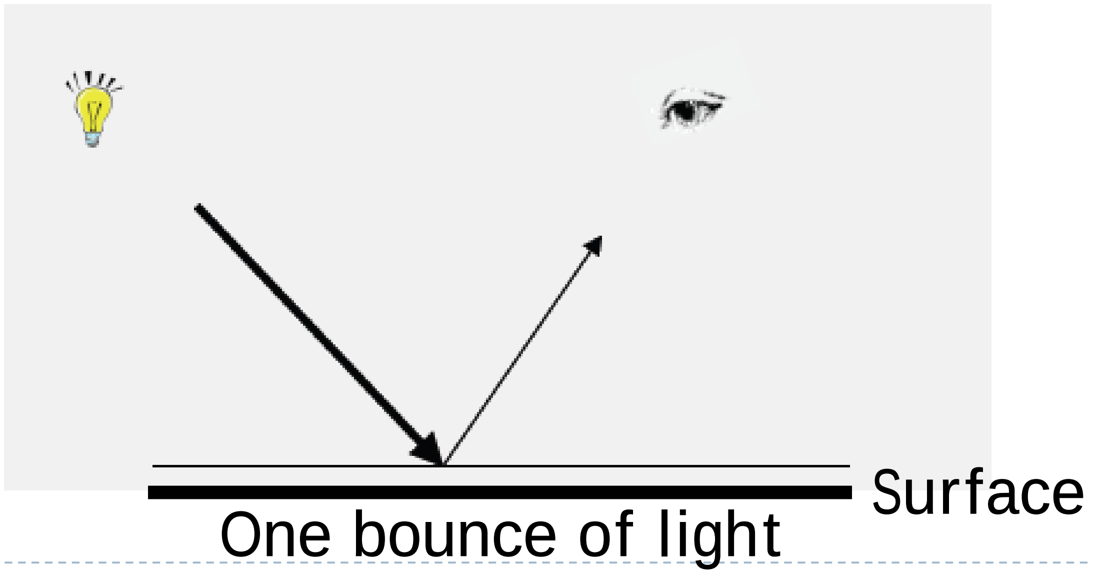
Shading

- 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.

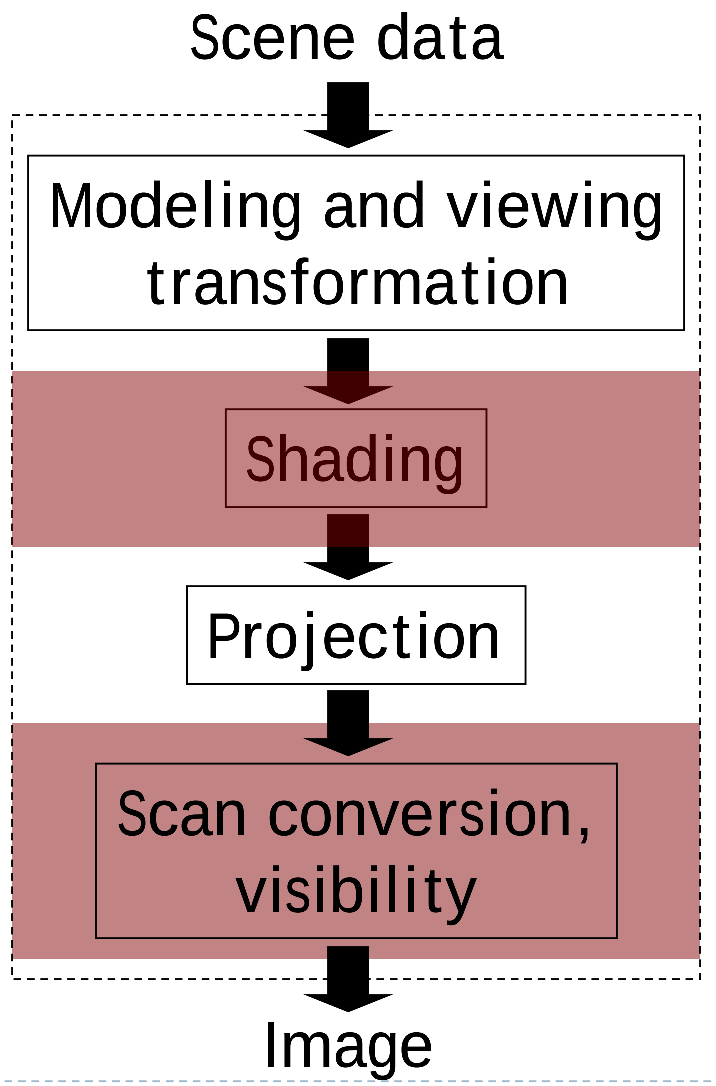
Global Illumination

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

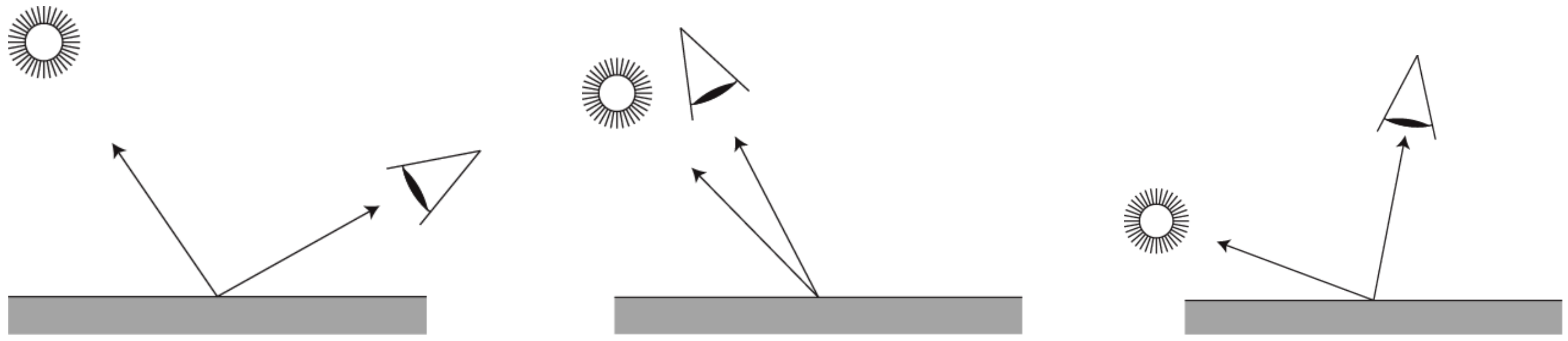
- Position object in 3D
- Determine colors of vertices
  - Per vertex shading
- Map triangles to 2D
- Draw triangles
  - Per pixel shading

Local Illumination

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

Local Illumination

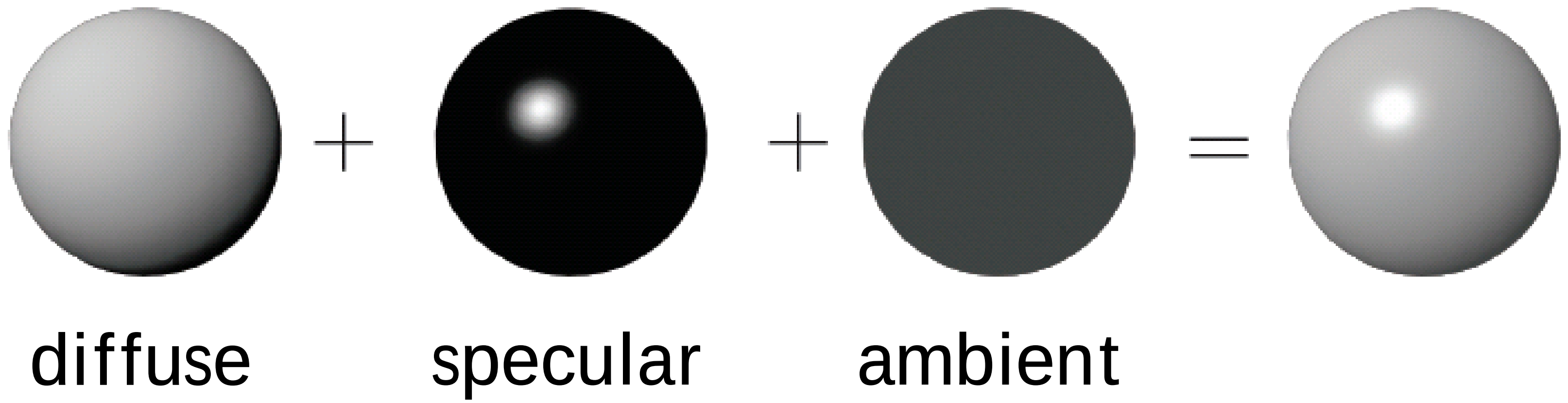
- Model reflection of light at surfaces
  - Assumption: no subsurface scattering
- Bidirectional reflectance distribution function (BRDF)
  - Given light direction, viewing direction, how much light is reflected towards the viewer
  - For any pair of light/viewing directions!



Local Illumination

Simplified model

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



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Local Illumination

Simplified model

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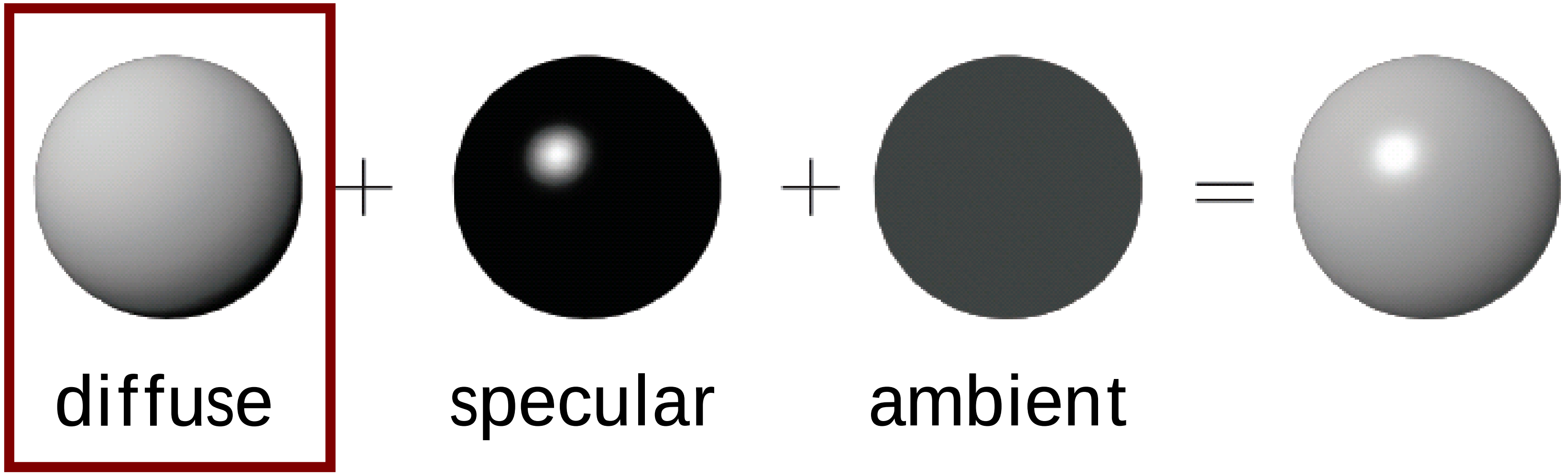
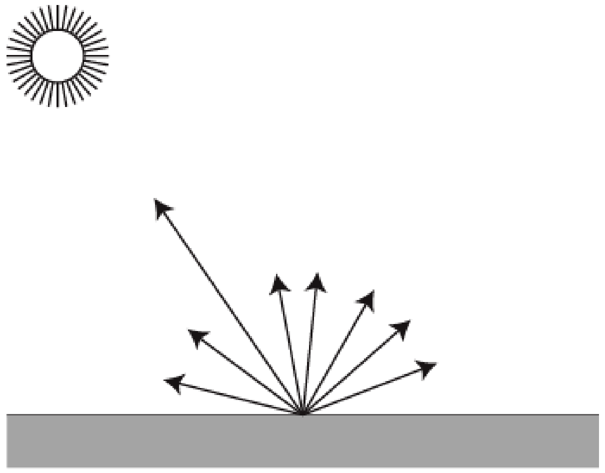
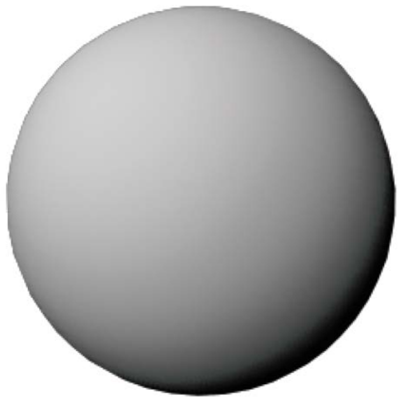


Diffuse Reflection

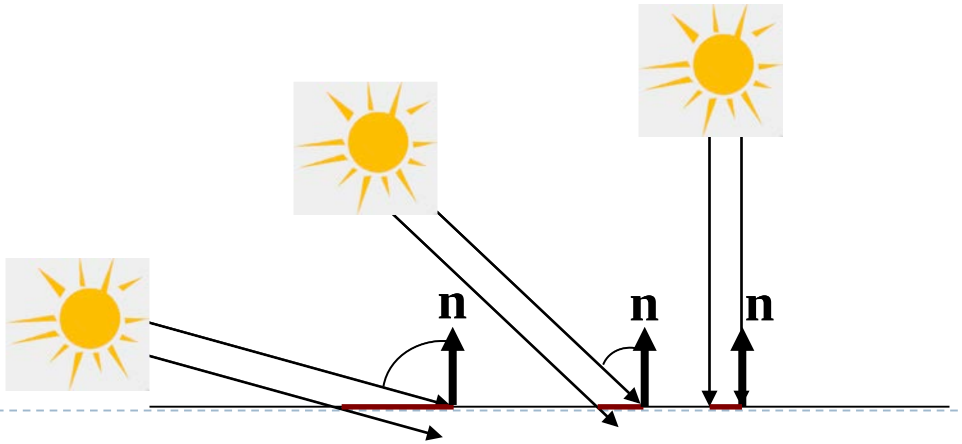
- Ideal diffuse material reflects light equally in all directions
- View-independent
- Matte, not shiny materials
  - Paper
  - Unfinished wood
  - Unpolished stone





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

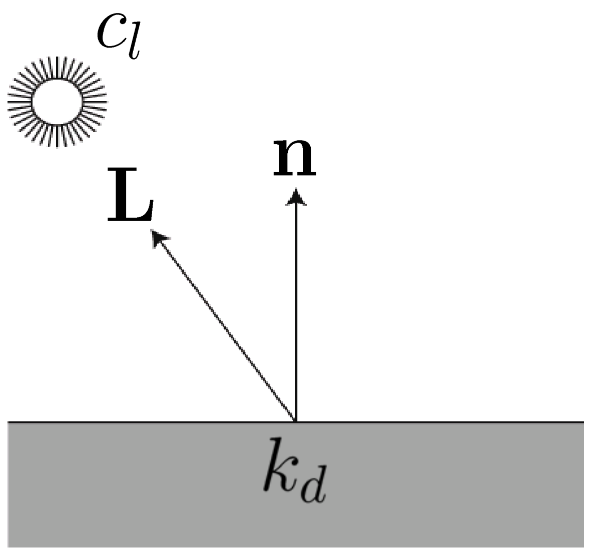


Diffuse Reflection

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

- Diffuse color c_d is:

$$c_d = c_l k_d \underbrace{(\mathbf{n} \cdot \mathbf{L})}_{\text{Proportional to cosine between normal and light}}$$



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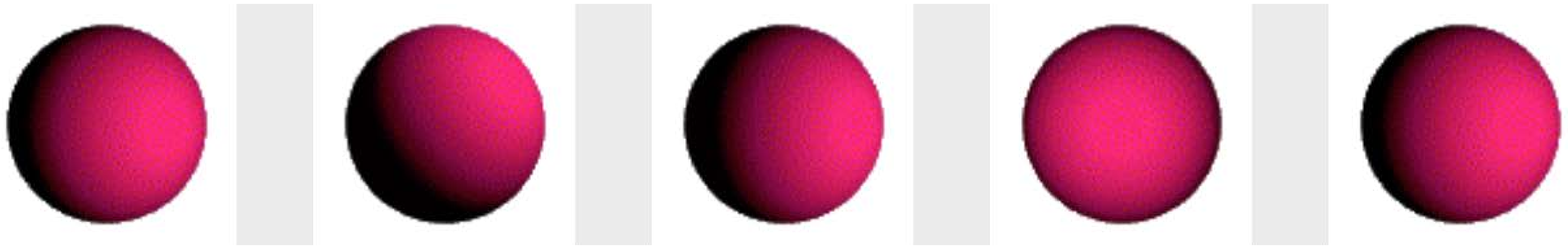
Diffuse Reflection

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

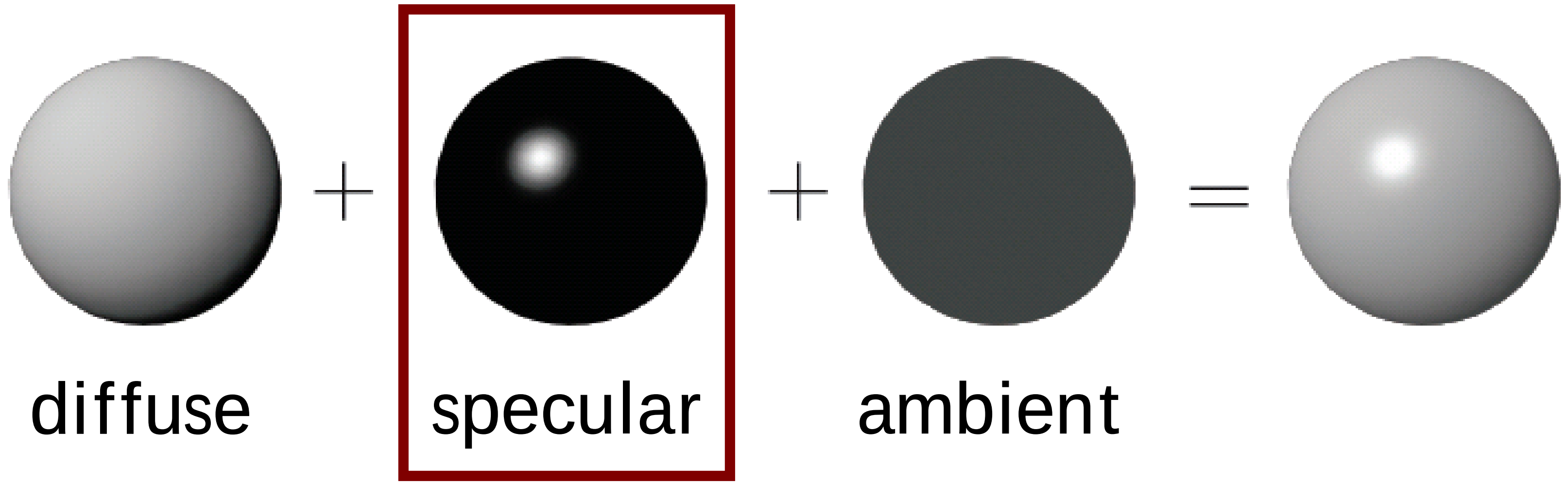


Lambertian (diffuse) sphere under different lighting directions

Local Illumination

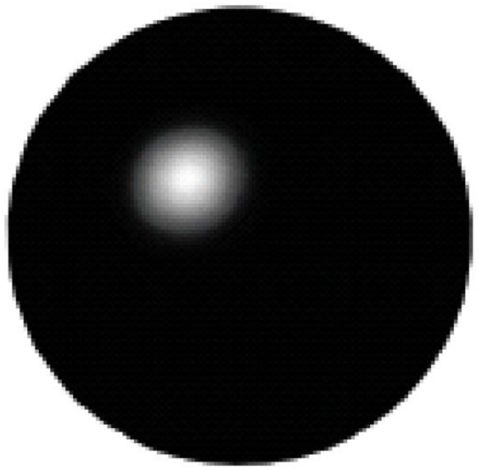
Simplified model

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



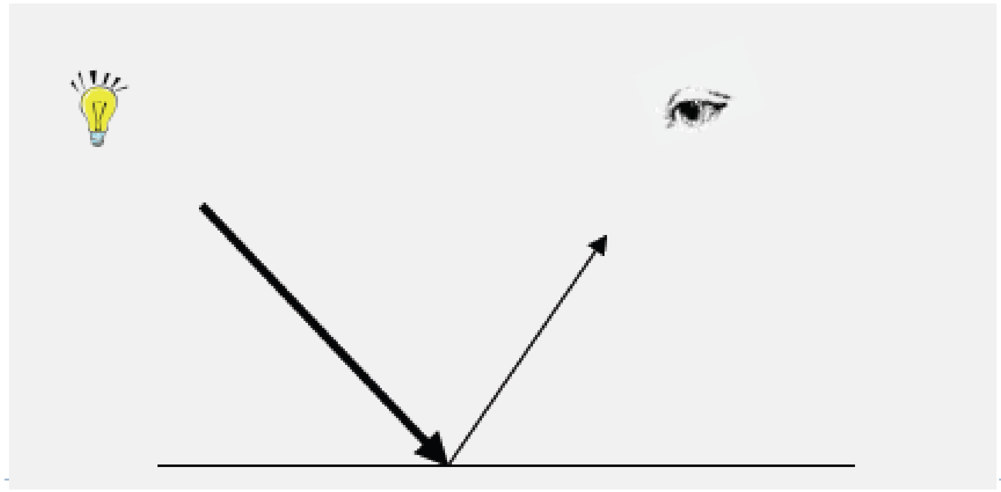
Specular Reflection

- Shiny surfaces
  - Polished metal
  - Glossy car finish
  - Plastics
- Specular highlight
  - Blurred reflection of the light source
  - Position of highlight depends on viewing direction

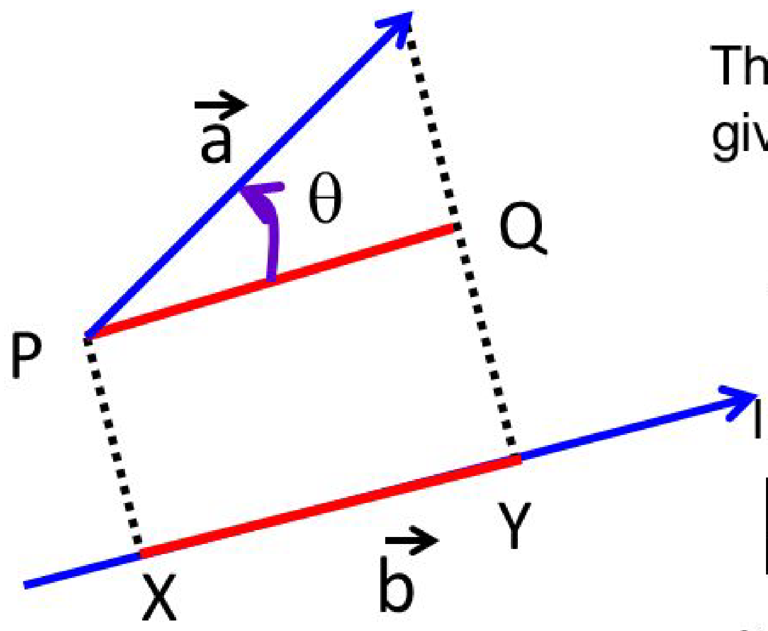

Specular highlight

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 **a** onto **b** will be given by:

$$proj_b a = |a| \cos\theta \frac{\mathrm{b}}{|\mathrm{b}|}$$

In summary, the proj$_a$ b has length

$|a| \cos\theta$, and direction $\frac{b}{|b|}$

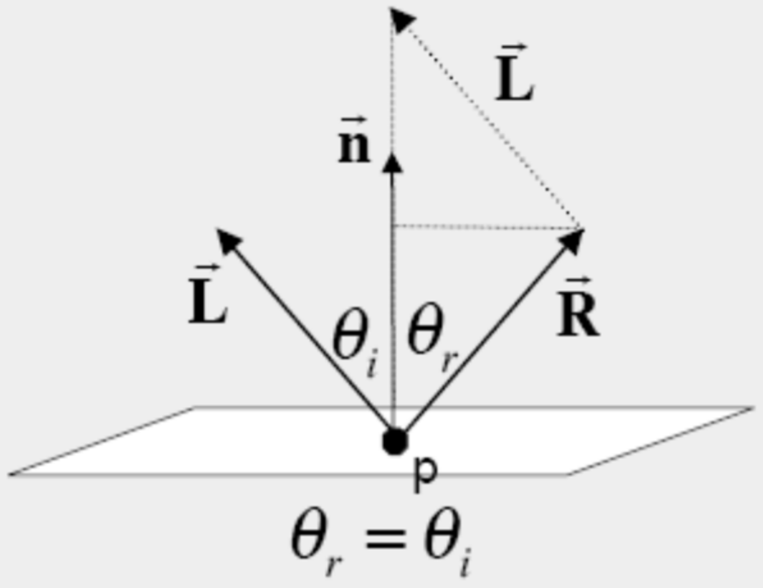
It is called the scalar component of **a** in the direction of **b**

Law of Reflection

- Angle of incidence equals angle of reflection

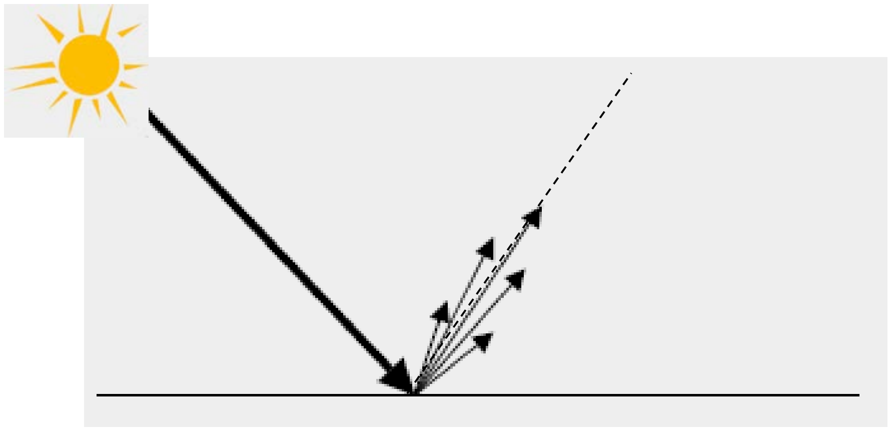
$$\vec{\mathbf{R}} + \vec{\mathbf{L}} = 2\cos\theta\ \vec{\mathbf{n}} = 2\left(\vec{\mathbf{L}} \cdot \vec{\mathbf{n}}\right)\vec{\mathbf{n}}$$

$$\vec{\mathbf{R}} = 2\left(\vec{\mathbf{L}} \cdot \vec{\mathbf{n}}\right)\vec{\mathbf{n}} - \vec{\mathbf{L}}$$



Specular Reflection

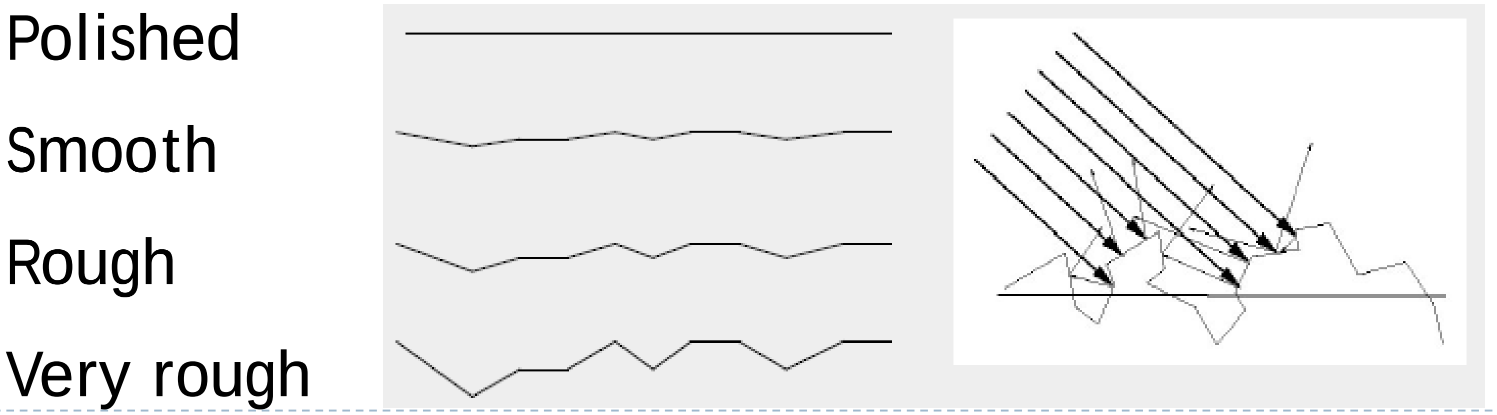
- Many materials are not perfect mirrors
  - Glossy materials



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

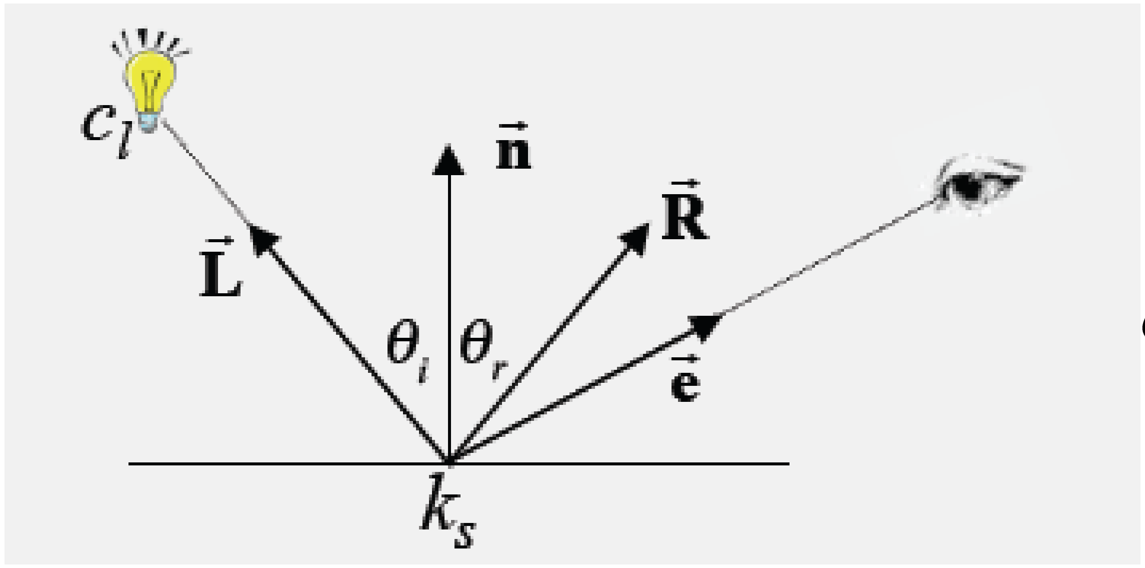


Glossy Surfaces

- 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

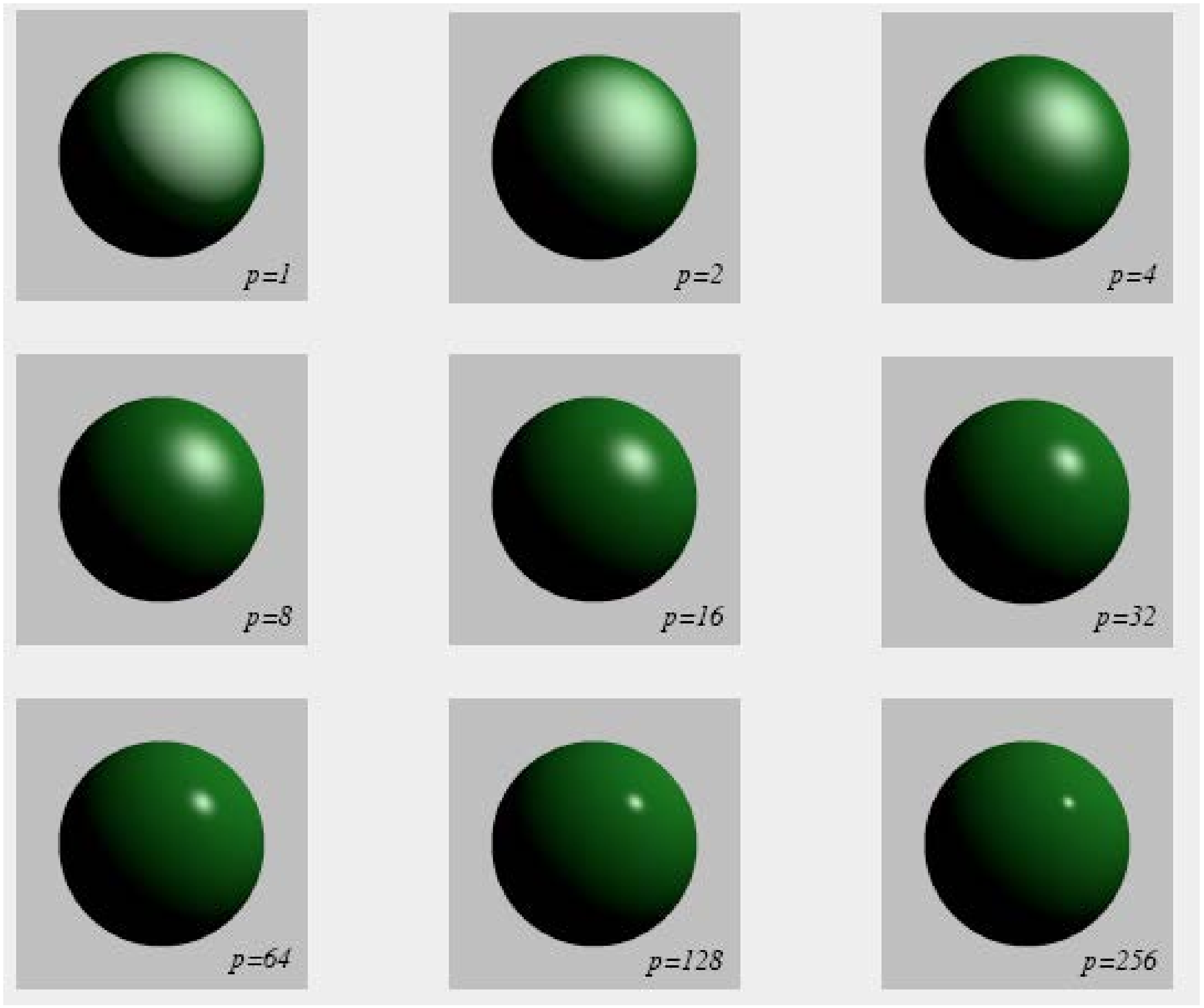
Phong Shading Model

- Developed by Bui Tuong Phong in1973
- Specular reflectance coefficient k_s
- Phong exponent p
  - Greater p means smaller (sharper) highlight



$$c = k_s c_l \left(\mathbf{R} \cdot \mathbf{e}\right)^p$$

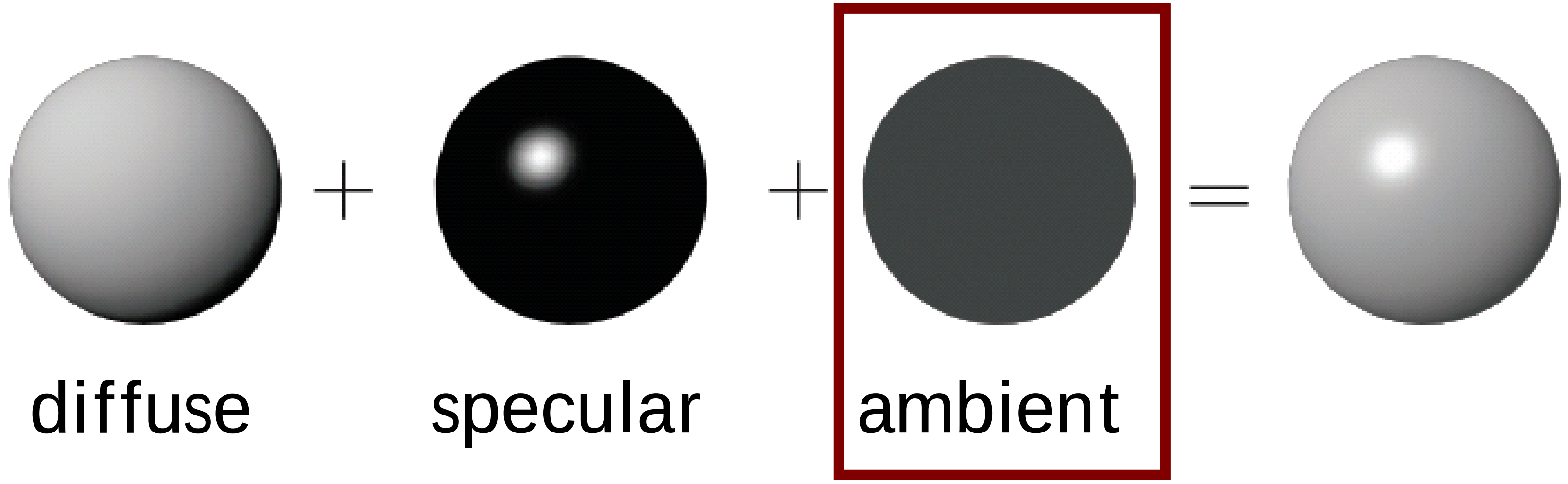
Phong Shading Model



Local Illumination

Simplified model

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



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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

$$c = \sum_i c_{l_i}(k_d(L_i \cdot n) + k_s(R \cdot e)^p + k_a)$$

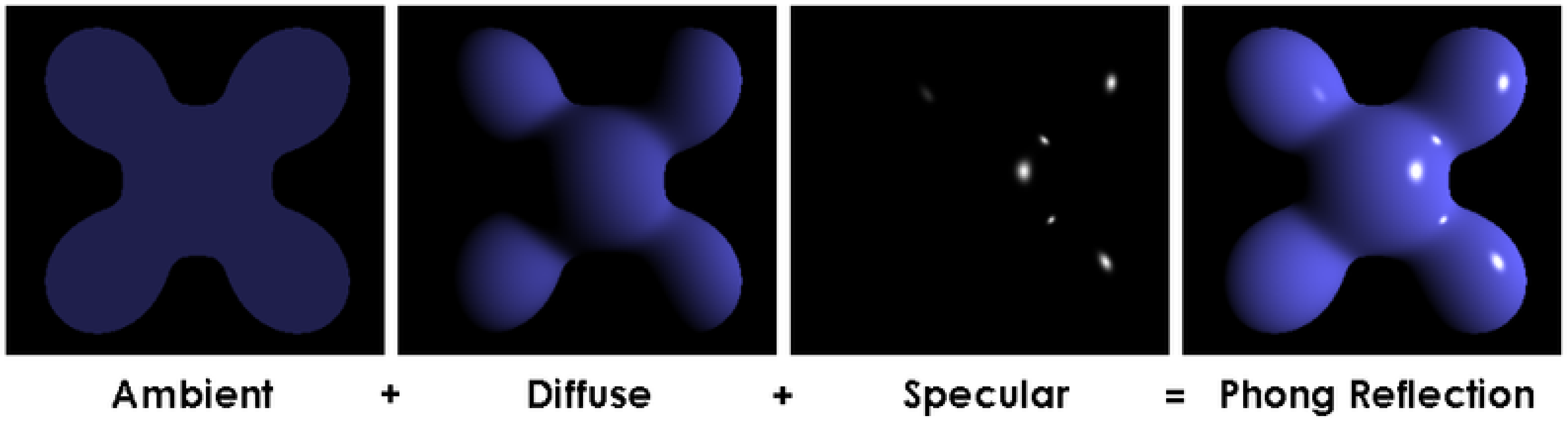


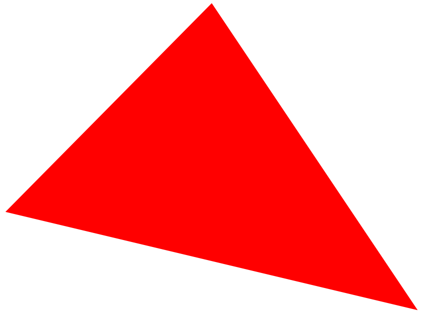
Image by Brad Smith

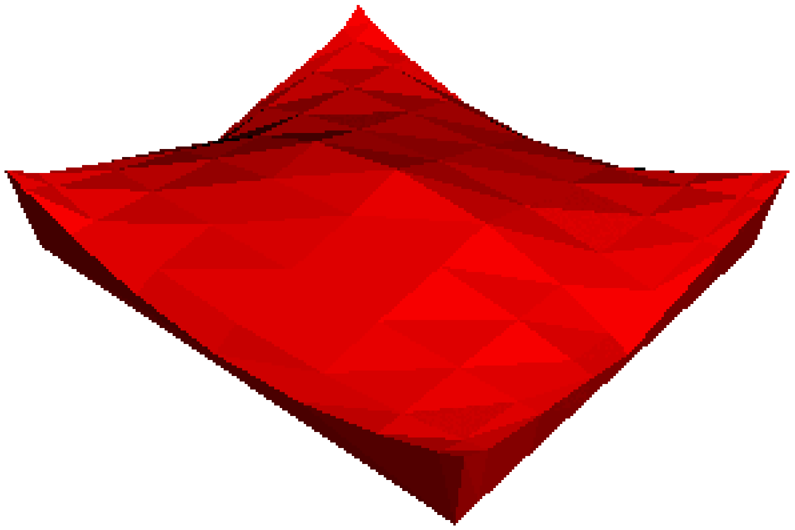
Types of Shading

- Per-triangle
- Per-vertex
- Per-pixel

Per-Triangle Shading

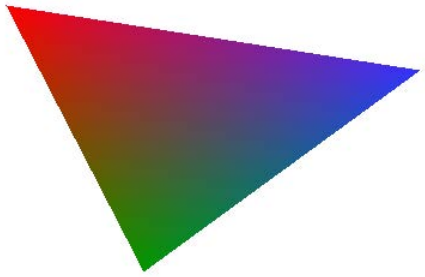
- A.k.a. *flat shading*
- Evaluate shading once per triangle, based on normal vector
- Advantage
  - Fast
- Disadvantage
  - Faceted appearance

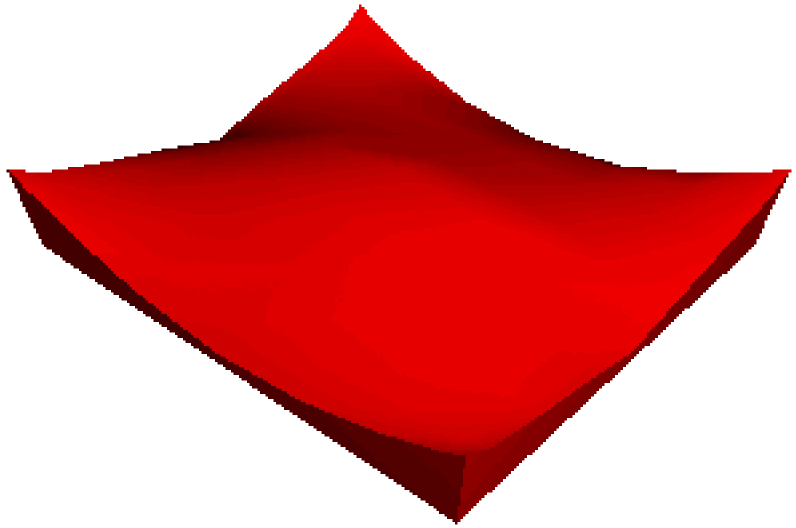




Per-Vertex Shading

- 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





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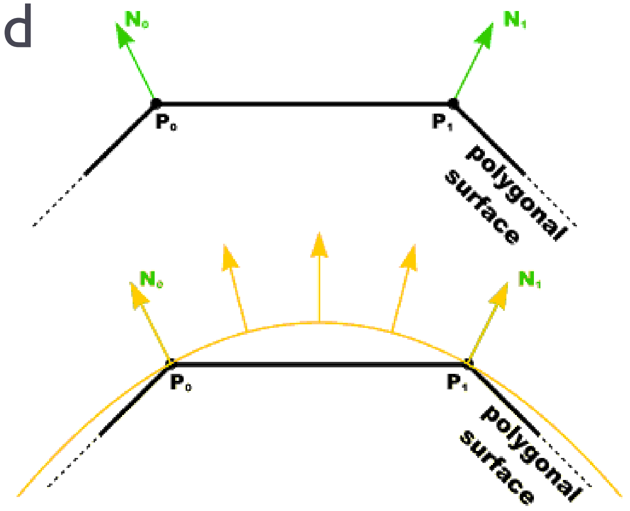
Per-Pixel Shading

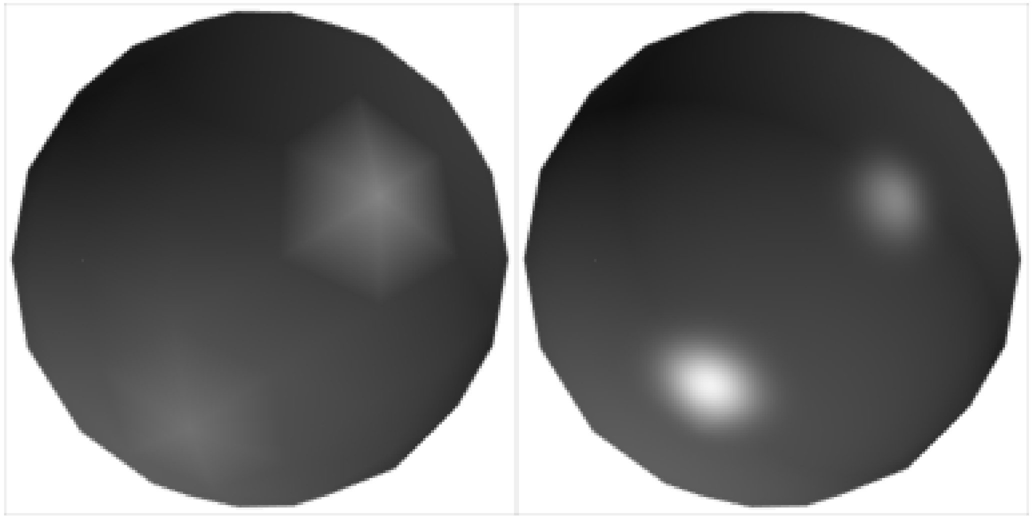
- A.k.a. *Phong Interpolation* (not to be confused with *Phong Illumination Model*)
  - Rasterizer interpolates <u>normals</u> (instead of colors) across triangles
  - Illumination model is evaluated at each pixel
  - Simulates shading with normals of a curved surface
- Advantage
  - Highest rendering 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=FI5i-UnIQps&feature=youtu.be



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

Lights

Light Sources

- Real light sources can have complex properties
  - Geometric area over which light is produced
  - Anisotropy (directionally dependent)
  - Reflective surfaces act as light sources (indirect light)

- Need to use simplified model for real-time rendering

Types of Light Sources

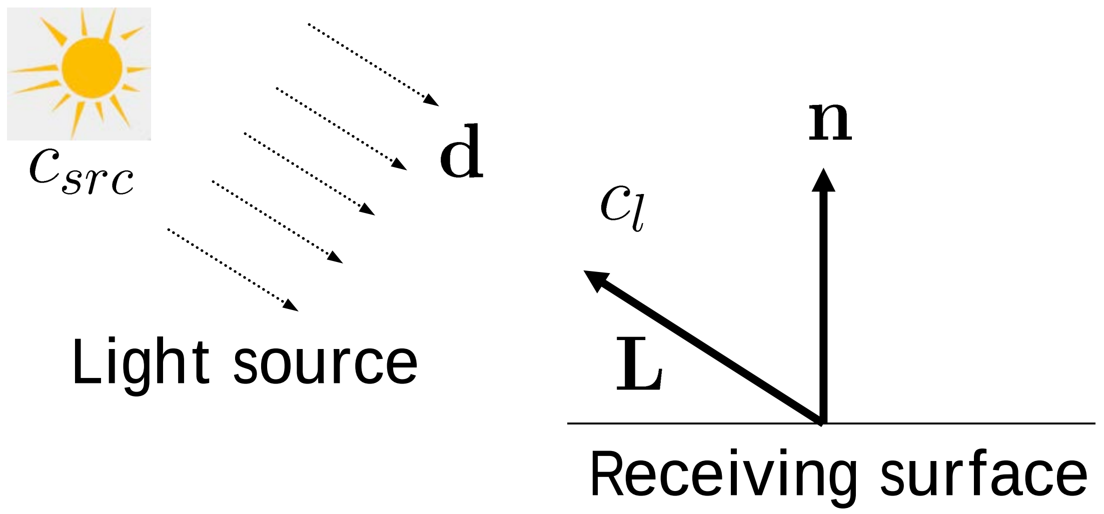
- At each point on surfaces we need to know
  - Direction of incoming light (the $\mathbf{L}$ vector)
  - Intensity of incoming light (the c_l values)
- Three light types:
  - Directional: from a specific direction
  - Point light: from a specific point
  - Spotlight: from a specific point with intensity that depends on direction

Lecture Overview

- Light Sources
  - Directional Lights
  - Point Lights
  - Spot Lights

Directional Light

- Light from a distant source
  - Light rays are parallel
  - Direction and intensity are the same everywhere
  - As if the source were infinitely far away
  - Good approximation of sunlight
- Specified by a unit length direction vector, and a color



$$\mathbf{L} = -\mathbf{d}$$

$$c_l = c_{src}$$

Lecture Overview

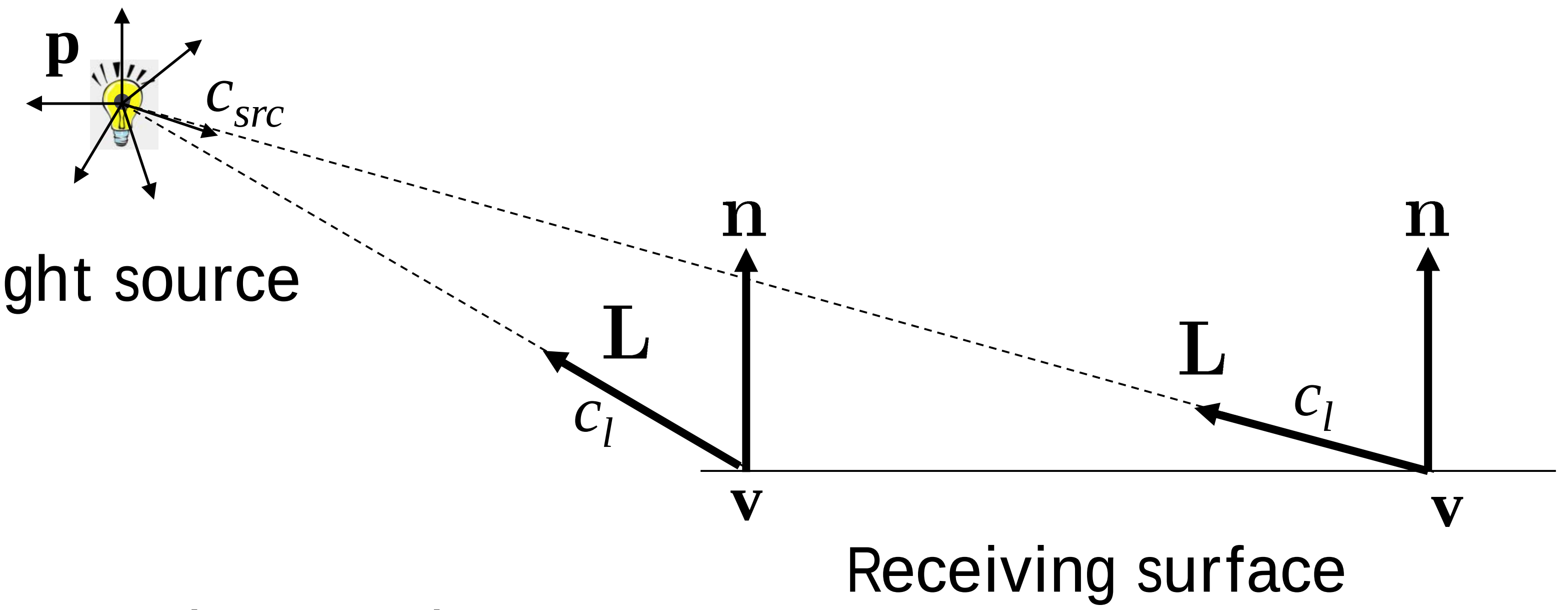
- Light Sources
  - Directional Lights
  - Point Lights
  - Spot Lights

Point Lights

- Similar to light bulbs
- Infinitely small point radiates light equally in all directions
  - Light vector varies across receiving surface
  - What is light intensity over distance proportional to?
  - Intensity drops off proportionally to the inverse square of the distance from the light
    - Reason for inverse square falloff: Surface area A of sphere:

      $A = 4 \pi r^2$

Point Light Math



At any point v on the surface:

$$\mathbf{L} = \frac{\mathbf{p} - \mathbf{v}}{\|\mathbf{p} - \mathbf{v}\|}$$

Attenuation: $$c_l = \frac{c_{src}}{\|\mathbf{p} - \mathbf{v}\|^2}$$

Light Attenuation

- Adding constant factor k to denominator for better control
- Quadratic attenuation: $k*(p-v)^2$
  - Most computationally expensive, most physically correct
- Linear attenuation: $k*(p-v)$
  - Less expensive, less accurate
- Constant attenuation: k
  - Fastest computation, least accurate

Lecture Overview

- Light Sources
  - Directional Lights
  - Point Lights
  - Spot Lights

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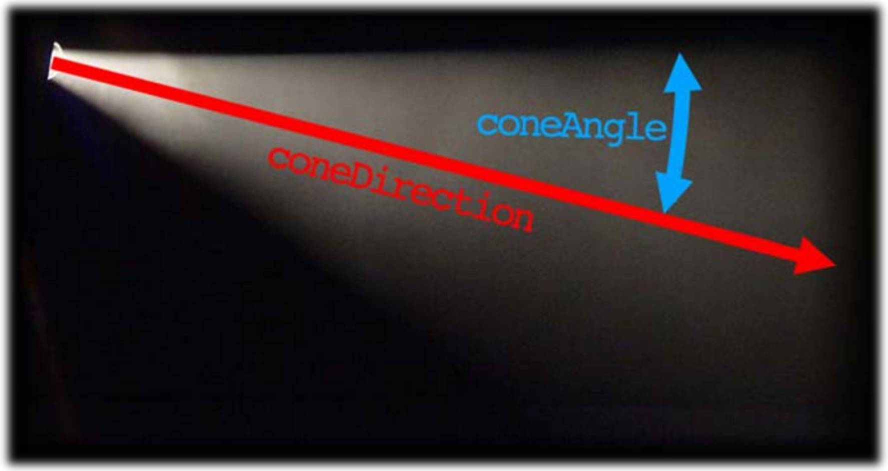
Spotlights

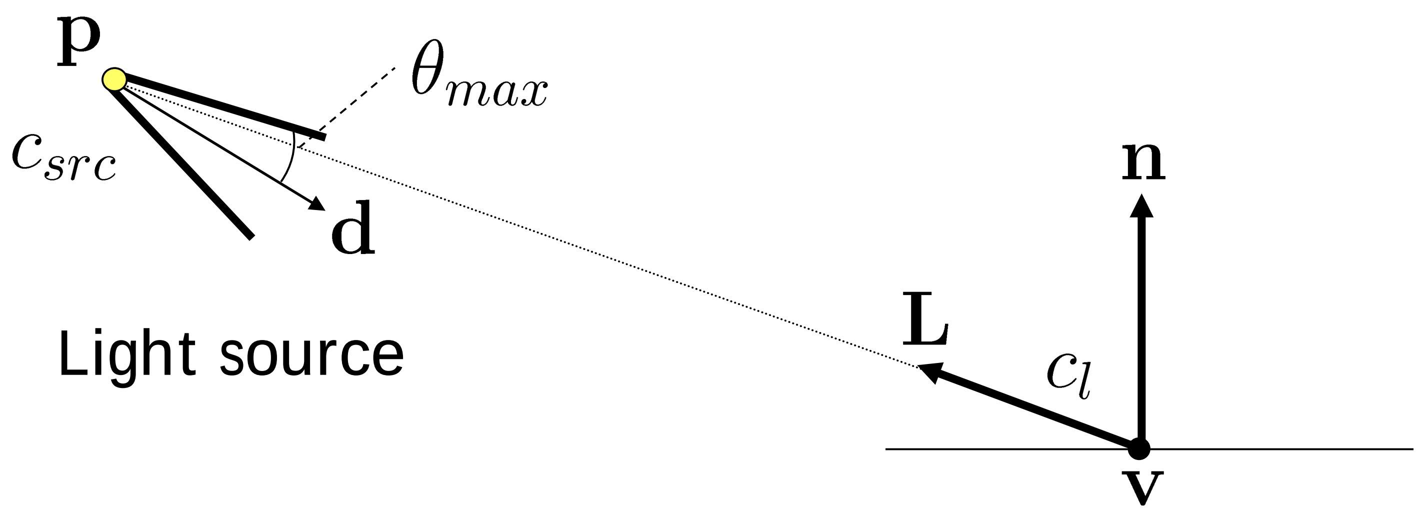
- Like point light, but intensity depends on direction



Parameters

- Position: location of light source
- Cone direction *d*: center axis of light source
- Intensity falloff:
  - Beam width (cone angle θ_{max})
  - The way the light tapers off at the edges of the beam (cosine exponent *f*)

Spotlights



Light source

Receiving surface

$$\mathbf{L} = \frac{\mathbf{p} - \mathbf{v}}{\|\mathbf{p} - \mathbf{v}\|}$$

$$c_l = \begin{cases} 0 & \text{if} \quad -\mathbf{L} \cdot \mathbf{d} \leq \cos(\theta_{max}) \\ c_{src}\,(-\mathbf{L} \cdot \mathbf{d})^f & \text{otherwise} \end{cases}$$

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Vertex Shader

```
#version 150

uniform mat4 camera;
uniform mat4 model;

in vec3 vert;
in vec2 vertTexCoord;
in vec3 vertNormal;

out vec3 fragVert;
out vec2 fragTexCoord;
out vec3 fragNormal;

void main()
{
    // Pass some variables to the fragment shader
    fragTexCoord = vertTexCoord;
    fragNormal = vertNormal;
    fragVert = vert;

    // Apply all matrix transformations to vert
    gl_Position = camera * model * vec4(vert, 1);
}
```

Source: Tom Dallling's OpenGL Tutorial

Fragment Shader for Diffuse Reflection

```
#version 150

uniform mat4 model;
uniform sampler2D tex;

uniform struct Light
{
   vec4 position; // if w component=0 it’s directional
   vec3 intensities; // a.k.a the color of the light
   float attenuation; // only needed for point and spotlights
   float ambientCoefficient;
   float coneAngle;  // only needed for spotlights
   vec3 coneDirection; // only needed for spotlights
   float exponent;  // cosine exponent for how light tapers off
} light;

in vec2 fragTexCoord;
in vec3 fragNormal;
in vec3 fragVert;

out vec4 finalColor;
```

Source: Tom Dallling’s OpenGL Tutorial

Fragment Shader Part 2

```
void main()
{
    // calculate normal in world coordinates
    mat3 normalMatrix = transpose(inverse(mat3(model)));
    vec3 normal = normalize(normalMatrix * fragNormal);

    // calculate the location of this fragment (pixel) in world coordinates
    vec3 fragPosition = vec3(model * vec4(fragVert, 1));

    // calculate the vector from this pixels surface to the light source
    vec3 surfaceToLight = light.position - fragPosition;

    // calculate the cosine of the angle of incidence
    float brightness = dot(normal, surfaceToLight) / (length(surfaceToLight) * length(normal));
    brightness = clamp(brightness, 0, 1);

    // calculate final color of the pixel, based on:
    // 1. The angle of incidence: brightness
    // 2. The color/intensities of the light: light.intensities
    // 3. The texture and texture coord: texture(tex, fragTexCoord)
    vec4 surfaceColor = texture(tex, fragTexCoord);
    finalColor = vec4(brightness * light.intensities * surfaceColor.rgb, surfaceColor.a);
}
```

Source: Tom Dallling’s OpenGL Tutorial