# Shading

CS 537 Interactive Computer Graphics

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# Lessons Learned from HW4

- Only have an idle() function if something is animated
- Set idle function to NULL, when animation is not running
- If an interaction (keyboard, mouse or menu) changes something that requires a screen update, put glutPostRedisplay at the end of the associated callback function
- Only send geometry (vertices & colors) when it changes
- IOW, If geometry never changes, only send it once
- Make sure your transformation matrices are applied in the correct order

# Objectives

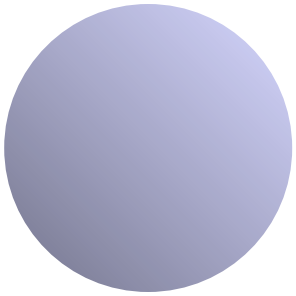
- Learn to shade objects so their images appear three-dimensional
- Introduce the types of light-material interactions
- Build a simple reflection model---the Phong model--- that can be used with real time graphics hardware

# Why we need shading

- Suppose we build a model of a sphere using many polygons and color it with one color. We get something like

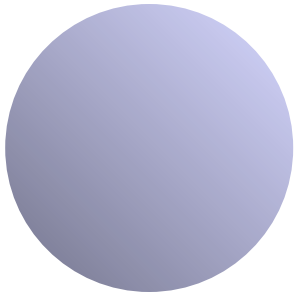


- But we want



# Shading

- Why does the image of a real sphere look like this?

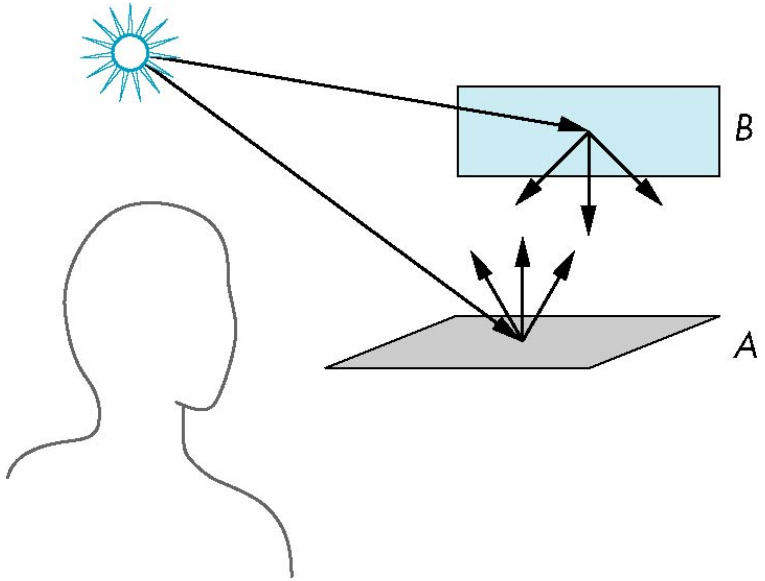


- Light-material interactions cause each point to have a different color or shade
- Need to consider
  - Light sources
  - Material properties
  - Location of viewer
  - Surface orientation

# Scattering

- Light strikes A
  - Some scattered
  - Some absorbed
- Some of scattered light strikes B
  - Some scattered
  - Some absorbed
- Some of this scattered light strikes A

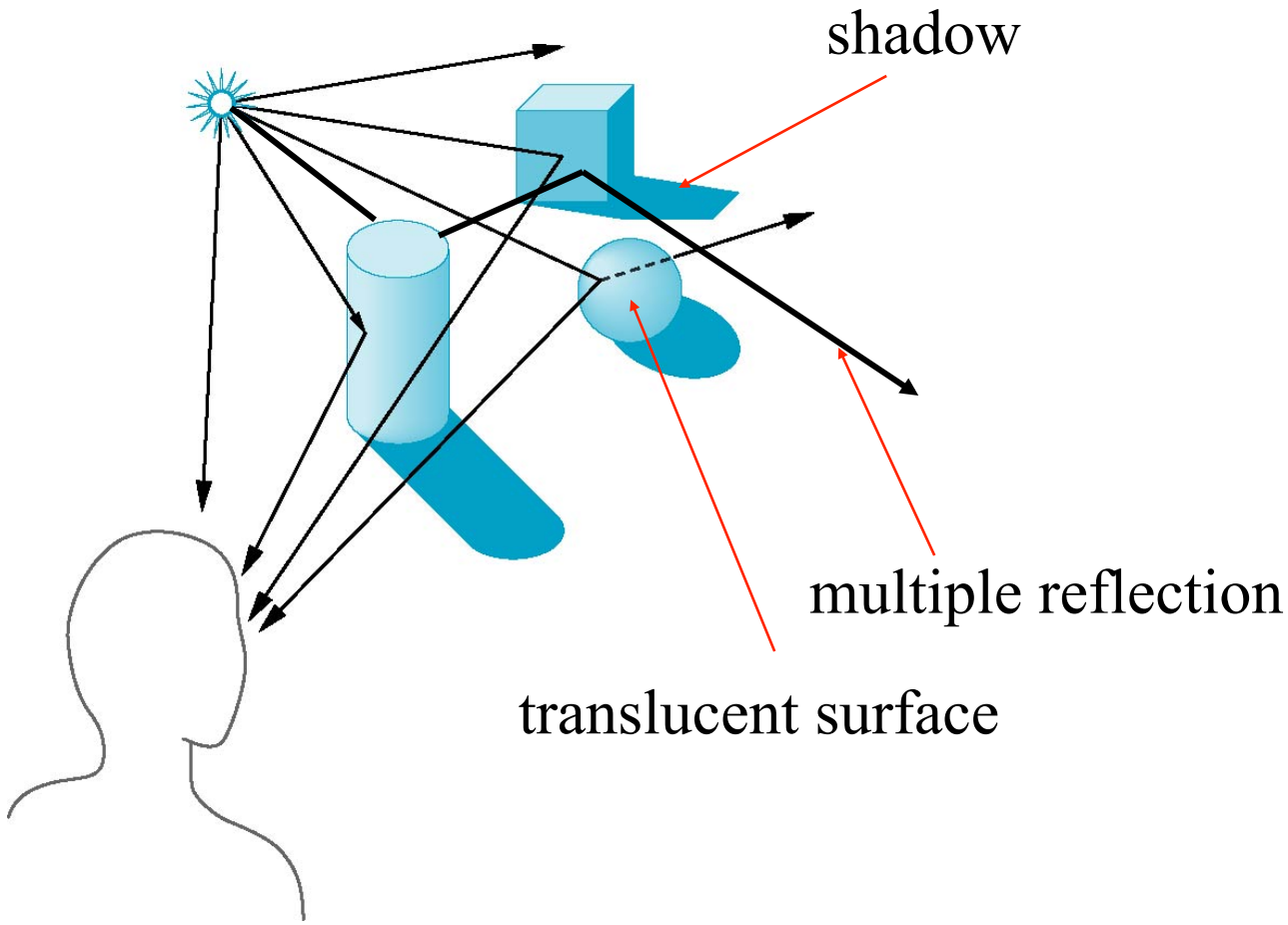
  and so on



# Rendering Equation

- The infinite scattering and absorption of light can be described by the *rendering equation*
  - Cannot be solved in general
  - Ray tracing is a special case for perfectly reflecting surfaces
- Rendering equation is global and includes
  - Shadows
  - Multiple scattering from object to object

# Global Effects



# Local vs Global Rendering

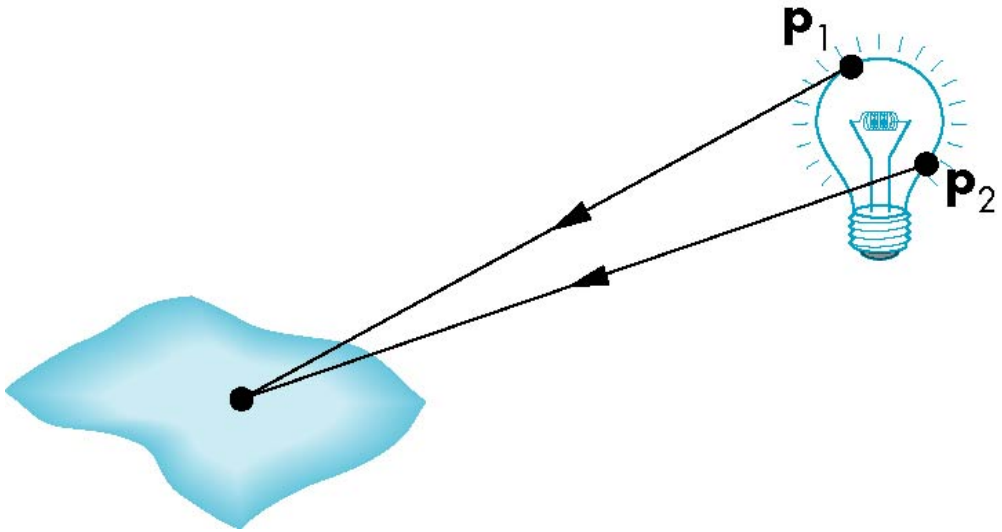
- Correct shading requires a global calculation involving all objects and light sources
  - Incompatible with pipeline model which shades each polygon independently (local rendering)
- However, in computer graphics, especially real time graphics, we are happy if things "look right"
  - There are many techniques for approximating global effects

# Light-Material Interaction

- Light that strikes an object is partially absorbed and partially scattered (reflected)
- The amount reflected determines the color and brightness of the object
  - A surface appears red under white light because the red component of the light is reflected and the rest is absorbed
- The reflected light is scattered in a manner that depends on the smoothness and orientation of the surface

# Light Sources

General light sources are difficult to work with because we must integrate light coming from all points on the source

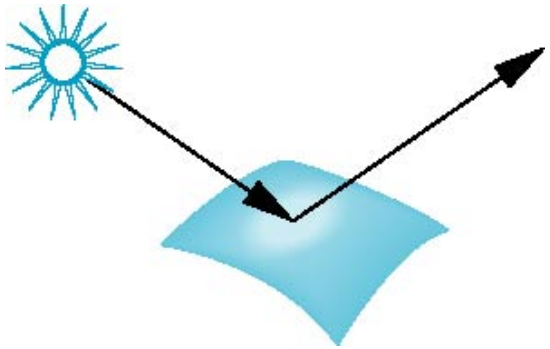


# Simple Light Sources

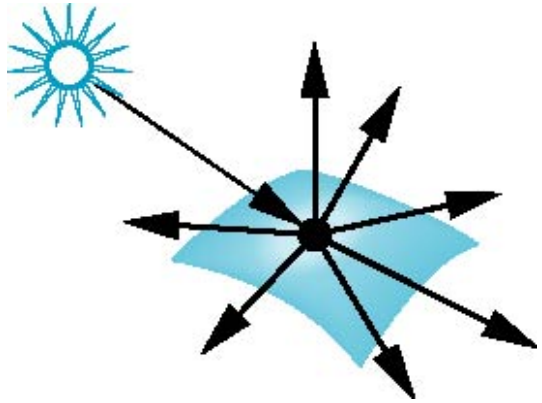
- Point source
  - Model with position and color
  - Distant source = infinite distance away (parallel)
- Spotlight
  - Restrict light from ideal point source
- Ambient light
  - Same amount of light everywhere in scene
  - Can model contribution of many sources and reflecting surfaces

# Surface Types

- The smoother a surface, the more reflected light is concentrated in the direction a perfect mirror would reflected the light
- A very rough surface scatters light in all directions



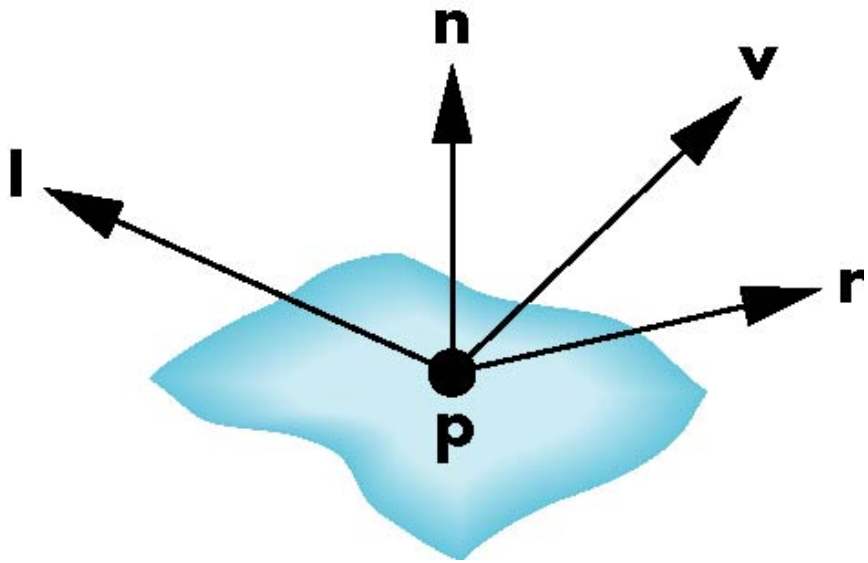
smooth surface



rough surface

# Phong Shading Model

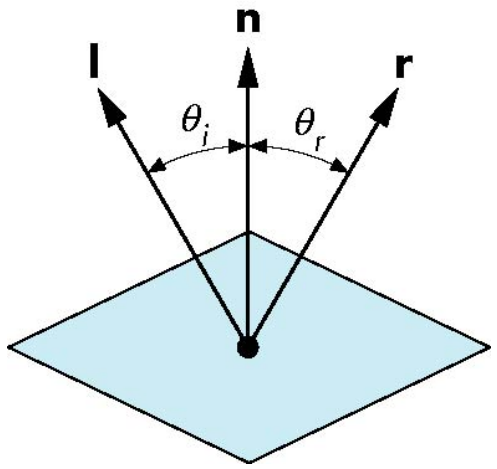
- A simple model that can be computed rapidly
- Has three components
  - Diffuse
  - Specular
  - Ambient
- Uses four vectors
  - To light source
  - To viewer
  - Normal
  - Perfect reflector



# Ideal Reflector

- Normal is determined by local orientation
- Angle of incidence = angle of reflection
- The three vectors must be coplanar

$$\mathbf{r} = 2\,(\mathbf{l} \cdot \mathbf{n})\,\mathbf{n} - \mathbf{l}$$

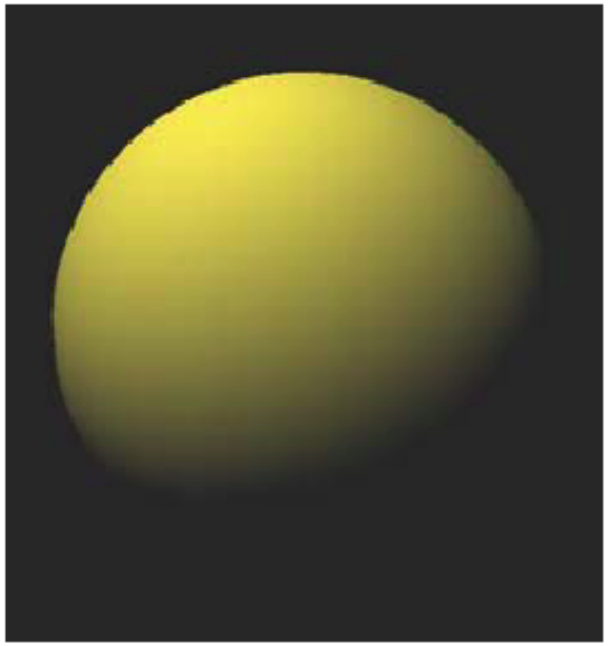


# Lambertian Surface

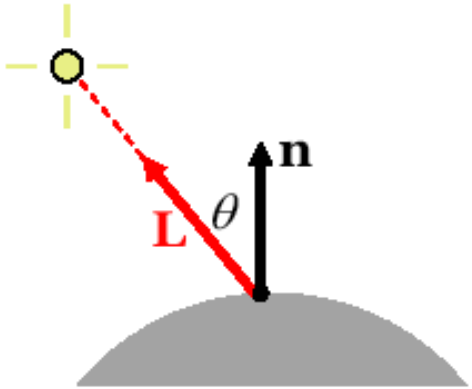
- Perfectly diffuse reflector
- Light scattered equally in all directions
- Amount of light reflected is proportional to the vertical component of incoming light
  - reflected light ~$\cos \theta_i$
  - $\cos \theta_i = \mathbf{l} \cdot \mathbf{n}$ if vectors normalized
  - There are also three coefficients, $k_r$, $k_b$, $k_g$ that show how much of each color component is reflected

# Lambert's Law for Diffuse Reflection

*Purely diffuse object*



$$I = I_L k_d \cos\theta$$
$$= I_L k_d (\mathbf{n} \cdot \mathbf{L})$$




$I$ : resulting intensity

$I_L$ : light source intensity

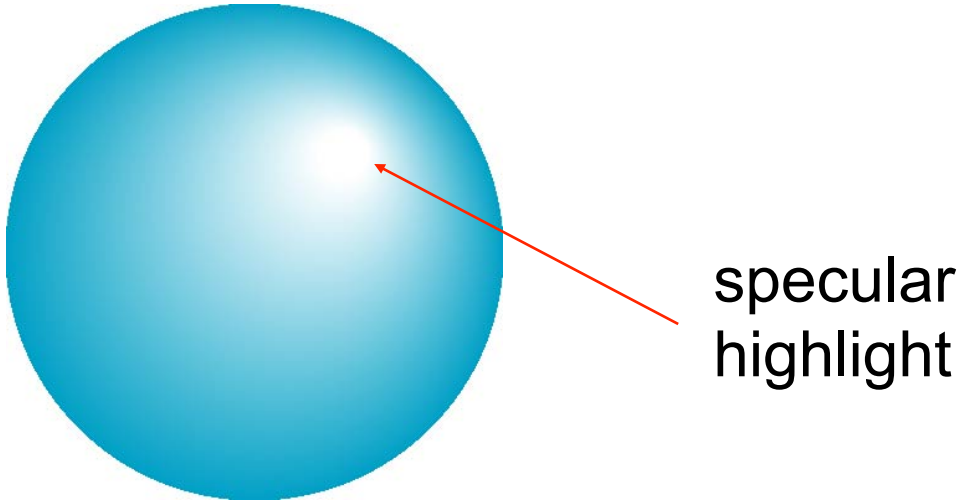
$k_d$ : (diffuse) surface reflectance coefficient

$k_d \in [0,1]$

$\theta$ : angle between normal & light direction

# Specular Surfaces

- Most surfaces are neither ideal diffusers nor perfectly specular (ideal reflectors)
- Smooth surfaces show specular highlights due to incoming light being reflected in directions concentrated close to the direction of a perfect reflection



# Modeling Specular Relections

- Phong proposed using a term that dropped off as the angle between the viewer and the ideal reflection increased

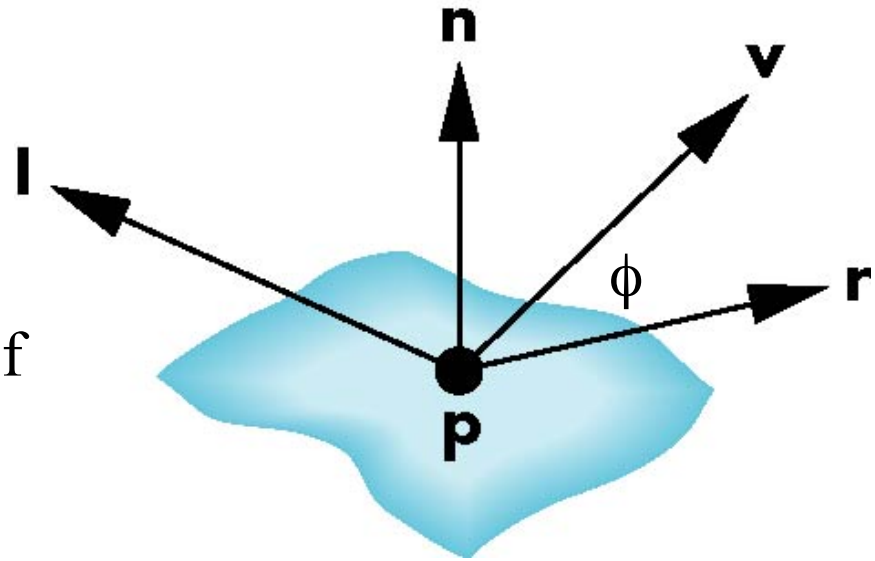
$$\mathbf{I}_r \sim k_s \mathbf{I} \cos^{\alpha}\phi$$

reflected intensity

absorption coef

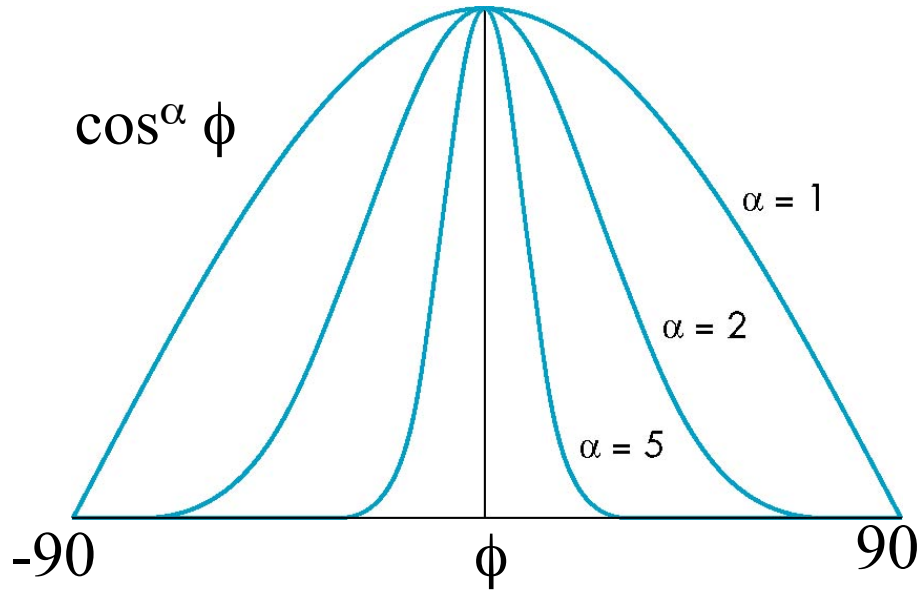
incoming intensity

shininess coef



# The Shininess Coefficient

- Values of $\alpha$ between 100 and 200 correspond to metals
- Values between 5 and 10 give surface that look like plastic



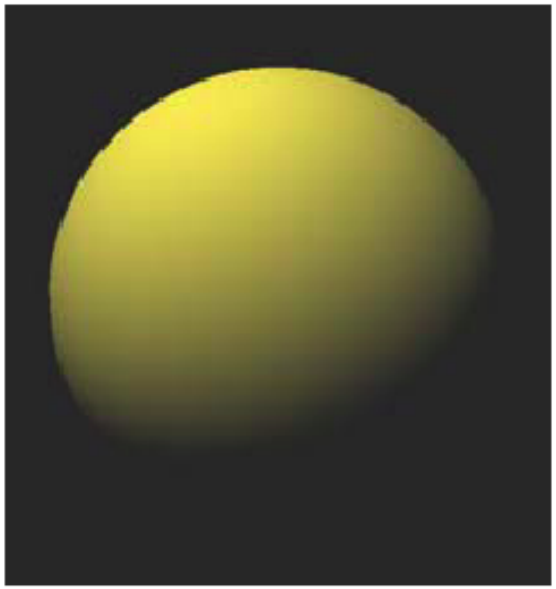
# Ambient Light

- Ambient light is the result of multiple interactions between (large) light sources and the objects in the environment
- Amount and color depend on both the color of the light(s) and the material properties of the object
- Add $k_a I_a$ to diffuse and specular terms

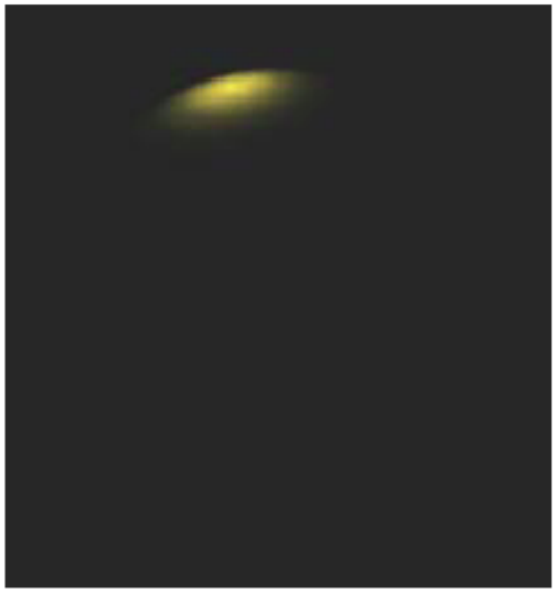
reflection coef

intensity of ambient light

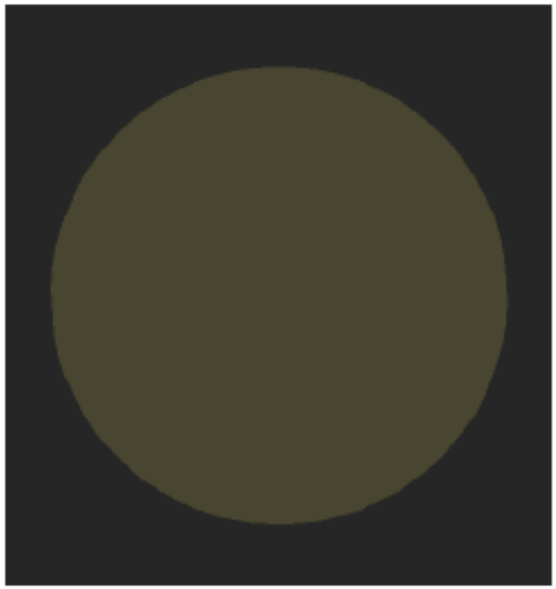
# Our Three Basic Components of Illumination



Diffuse

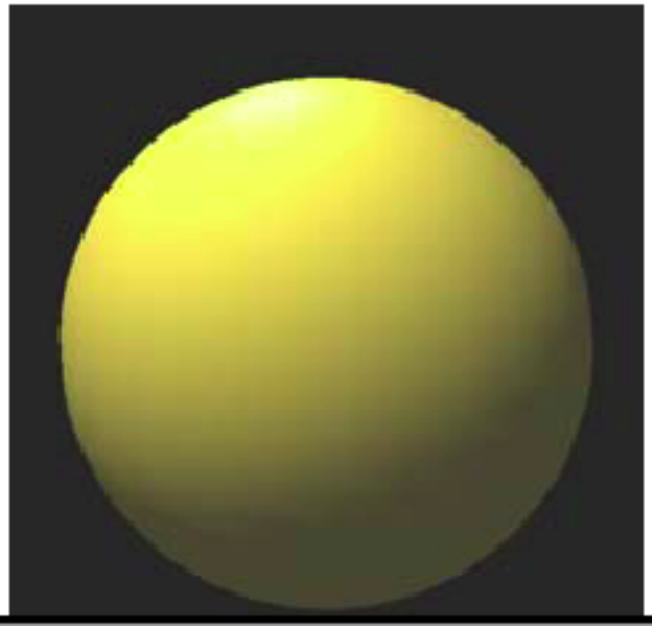


Specular



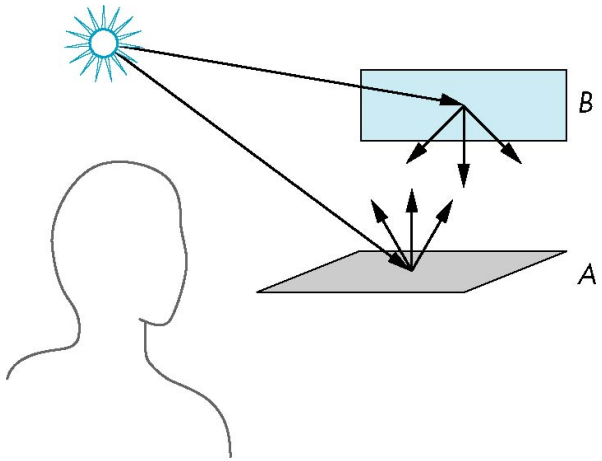
Ambient

# Combined for the Final Result



# Distance Terms

- The light from a point source that reaches a surface is inversely proportional to the square of the distance between them
- We can add a factor of the form $1/(a + bd + cd^2)$ to the diffuse and specular terms
- The constant and linear terms soften the effect of the point source



# Light Sources

- In the Phong Model, we add the results from each light source
- Each light source has separate diffuse, specular, and ambient terms to allow for maximum flexibility even though this form does not have a physical justification
- Separate red, green and blue components
- Hence, 9 coefficients for each point source
  - $I_{dr}$, $I_{dg}$, $I_{db}$, $I_{sr}$, $I_{sg}$, $I_{sb}$, $I_{ar}$, $I_{ag}$, $I_{ab}$

# Material Properties

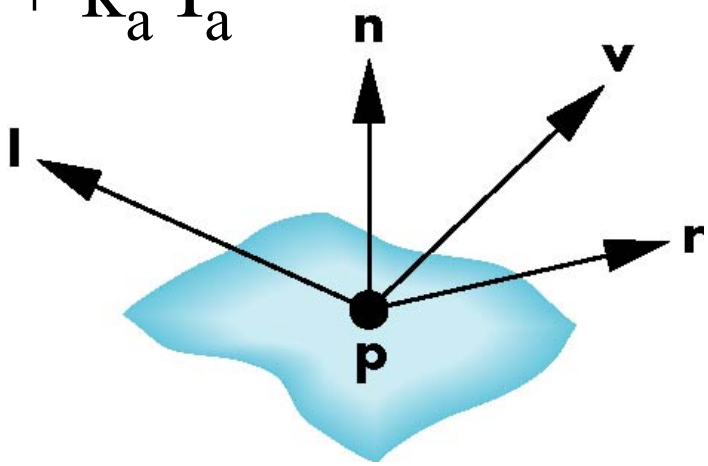
- Material properties match light source properties
  - Nine absorbtion coefficients
    - $k_{dr}$, $k_{dg}$, $k_{db}$, $k_{sr}$, $k_{sg}$, $k_{sb}$, $k_{ar}$, $k_{ag}$, $k_{ab}$
  - Shininess coefficient $\alpha$

# Adding up the Components

For each light source and each color component, the Phong model can be written (without the distance terms) as

$$I = k_d I_d \, \mathbf{l} \cdot \mathbf{n} + k_s I_s (\mathbf{v} \cdot \mathbf{r})^{\alpha} + k_a I_a$$

For each color component we add contributions from all light sources



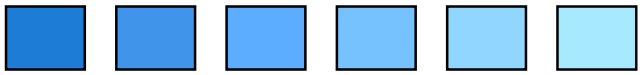
# Too Intense

**With multiple light sources, it is easy to generated values of I > 1**

**One solution is to set the color value to be *MIN(I, 1)***

- **An object can change color, saturating towards white**

  **Ex. (0.1, 0.4, 0.8) + (0.5, 0.5, 0.5) = (0.6, 0.9, 1.0)**



**Another solution is to renormalize the intensities to vary from 0 to 1 if one I > 1.**

- **Requires calculating all I's before rendering anything.**
- **No over-saturation, but image may be too bright, and contrasts a little off.**

**Image-processing on image to be rendered (with original I's) will produce better results, but is costly.**

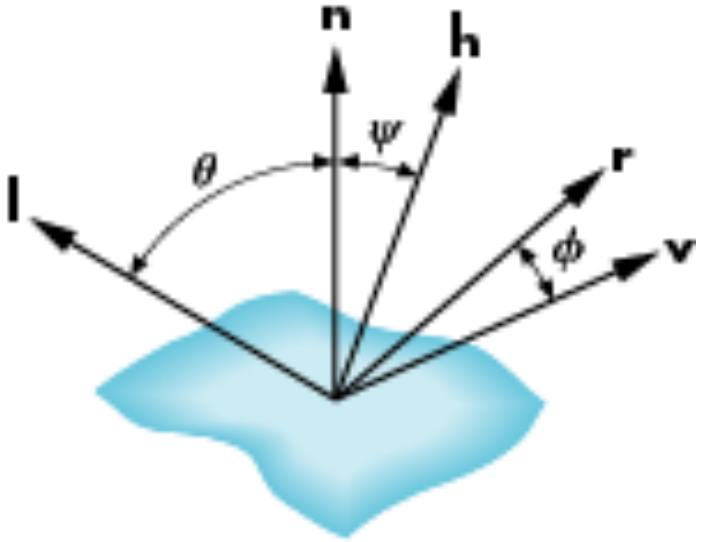
# Modified Phong Model

- The specular term in the Phong model is problematic because it requires the calculation of a new reflection vector and view vector for each vertex
- Blinn suggested an approximation using the halfway vector that is more efficient

# The Halfway Vector

- **h** is normalized vector halfway between **l** and **v**

$$\mathbf{h} = (\mathbf{l} + \mathbf{v})/|\mathbf{l} + \mathbf{v}|$$

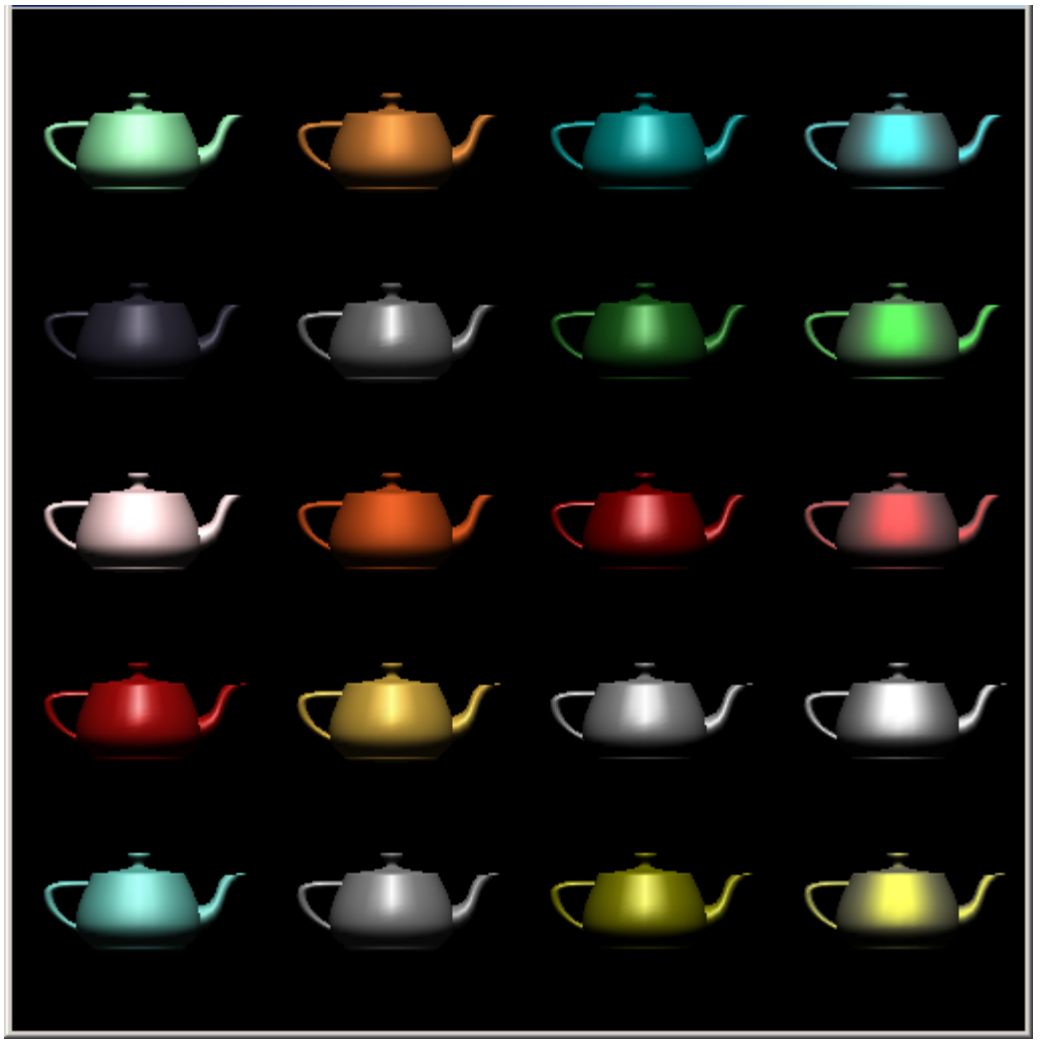


# Using the halfway vector

- Replace $(\mathbf{v} \cdot \mathbf{r})^{\alpha}$ by $(\mathbf{n} \cdot \mathbf{h})^{\beta}$
- $\beta$ is chosen to match shineness
- Note that halfway angle is half of angle between $\mathbf{r}$ and $\mathbf{v}$ if vectors are coplanar
- Resulting model is known as the modified Phong or Blinn lighting model
  - Specified in OpenGL standard

# Example

Only differences in these teapots are the parameters in the modified Phong model



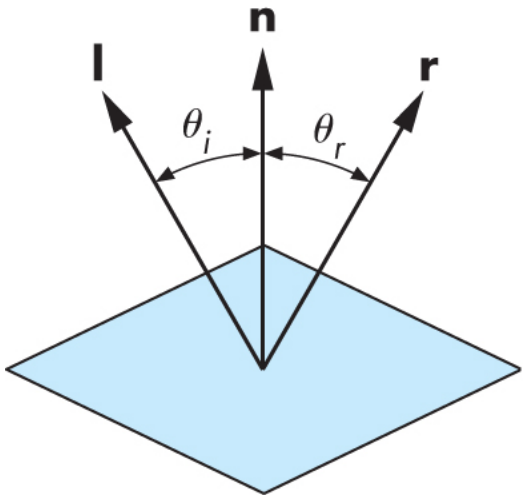
# Computation of Vectors

- **l** and **v** are specified by the application
- Can compute **r** from **l** and **n**
- Problem is determining **n**
- For simple surfaces **n** can be determined, but how we determine **n** differs depending on underlying representation of surface
- OpenGL leaves determination of normal to application
  - Exception for GLU quadrics and Bezier surfaces which are deprecated

# Computing Reflection Direction

- Angle of incidence = angle of reflection
- Normal, light direction and reflection direction are coplaner
- Want all three to be unit length

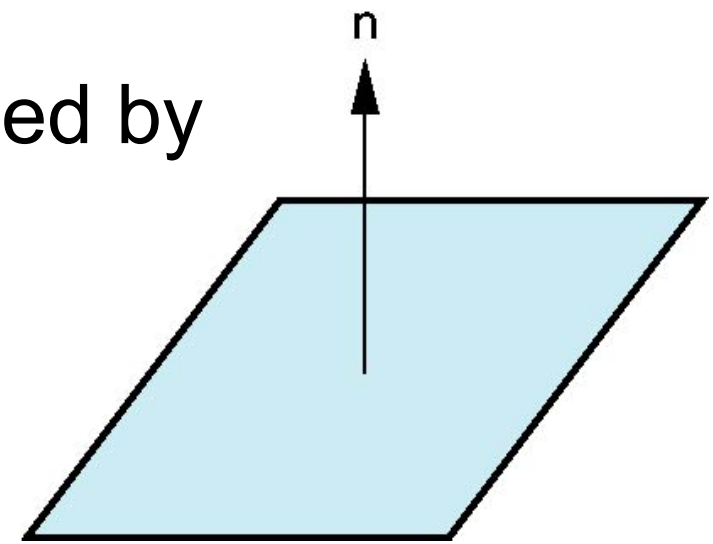
$$r = 2(l \bullet n)n - l$$



# Plane Normals

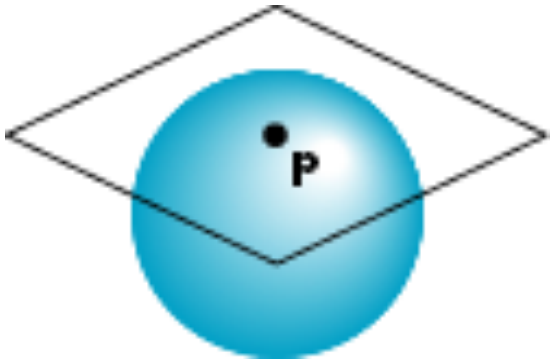
- Equation of plane: $ax+by+cz+d = 0$
- From Chapter 3 we know that plane is determined by three points $p_0$, $p_2$, $p_3$ or normal $\mathbf{n}$ and $p_0$
- Normal can be obtained by

$$\mathbf{n} = (p_2-p_0) \times (p_1-p_0)$$



# Normal to Sphere

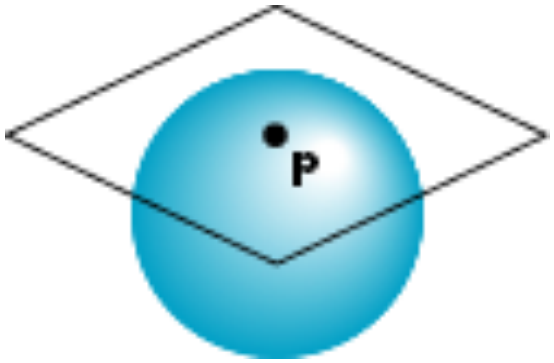
- Implicit function $f(x,y,z)=0$
- Normal given by gradient
- Sphere $f(\mathbf{p})=\mathbf{p}\cdot\mathbf{p}-1$
- $n = [\partial f/\partial x, \partial f/\partial y, \partial f/\partial z]^T=\mathbf{p}$



# Parametric Form

- For sphere

$$x=x(u,v)=\cos u \sin v$$
$$y=y(u,v)=\cos u \cos v$$
$$z= z(u,v)=\sin u$$




- Tangent plane determined by vectors

$$\partial \mathbf{p}/\partial u = [\partial x/\partial u, \partial y/\partial u, \partial z/\partial u]^T$$
$$\partial \mathbf{p}/\partial v = [\partial x/\partial v, \partial y/\partial v, \partial z/\partial v]^T$$

- Normal given by cross product

$$\mathbf{n} = \partial \mathbf{p}/\partial u \times \partial \mathbf{p}/\partial v$$

# General Case

- We can compute parametric normals for other simple cases
  - Quadrics
  - Parameteric polynomial surfaces
    - Bezier surface patches (Chapter 10)

# Shading in OpenGL

CS 537 Interactive Computer Graphics

Prof. David E. Breen

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# Objectives

- Introduce the OpenGL shading methods
  - per vertex vs per fragment shading
  - Where to carry out
- Discuss polygonal shading
  - Flat
  - Smooth
  - Gouraud

# OpenGL shading

- Need
  - Normals
  - Material properties
  - Lights
- State-based shading functions have been deprecated (glNormal, glMaterial, glLight)
- Get computed in application or send attributes to shaders

# Normalization

- Cosine terms in lighting calculations can be computed using dot product
- Unit length vectors simplify calculation
- Usually we want to set the magnitudes to have unit length but
  - Length can be affected by transformations
  - Note that scaling does not preserved length
- GLSL has a normalization function

# Specifying a Point Light Source

- For each light source, we can set its position and an RGBA for the diffuse, specular, and ambient components

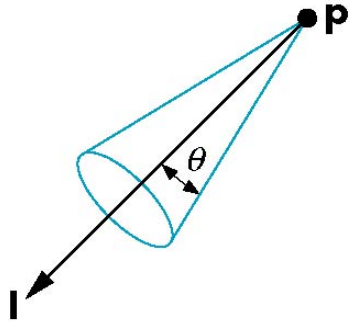
```
vec4 diffuse0 = vec4(1.0, 0.0, 0.0, 1.0);
vec4 ambient0 = vec4(1.0, 0.0, 0.0, 1.0);
vec4 specular0 = vec4(1.0, 0.0, 0.0, 1.0);
vec4 light0_pos =vec4(1.0, 2.0, 3,0, 1.0);
```

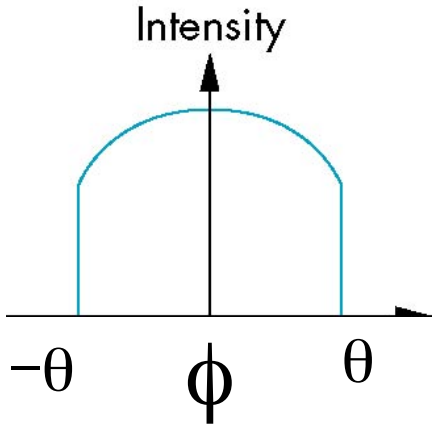
# Distance and Direction

- The source colors are specified in RGBA
- The position is given in homogeneous coordinates
  - If w =1.0, we are specifying a finite location
  - If w =0.0, we are specifying a parallel source with the given direction vector
- The coefficients in distance terms are usually quadratic (1/(a+b*d+c*d*d)) where d is the distance from the point being rendered to the light source

# Spotlights

- Derive from point source
  - Direction
  - Cutoff
  - Attenuation  Proportional to $\cos^{\alpha}\phi$



# Global Ambient Light

- Ambient light depends on color of light sources
  - A red light in a white room will cause a red ambient term that disappears when the light is turned off
- A global ambient term is often helpful for testing

# Moving Light Sources

- Light sources are geometric objects whose positions or directions are affected by the model-view matrix
- Depending on where we place the position (direction) setting function, we can
  - Move the light source(s) with the object(s)
  - Fix the object(s) and move the light source(s)
  - Fix the light source(s) and move the object(s)
  - Move the light source(s) and object(s) independently

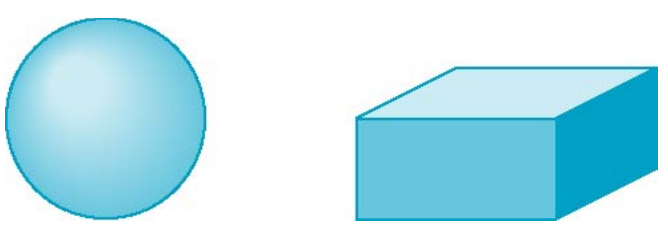
# Material Properties

- Material properties should match the terms in the light model
- Reflectivities
- w component gives opacity (alpha)

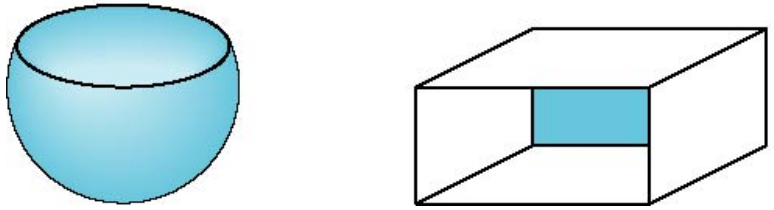
```
vec4 ambient = vec4(0.2, 0.2, 0.2, 1.0);
vec4 diffuse = vec4(1.0, 0.8, 0.0, 1.0);
vec4 specular = vec4(1.0, 1.0, 1.0, 1.0);
GLfloat shine = 100.0
```

# Front and Back Faces

- Every face has a front and back
- For many objects, we never see the back face so we don't care how or if it's rendered
- If it matters, we can handle in shader



back faces not visible



back faces visible

# Transparency

- Material properties are specified as RGBA values
- The A value can be used to make the surface translucent
- The default is that all surfaces are opaque regardless of A
- Later we will enable blending and use this feature

# Polygonal Shading

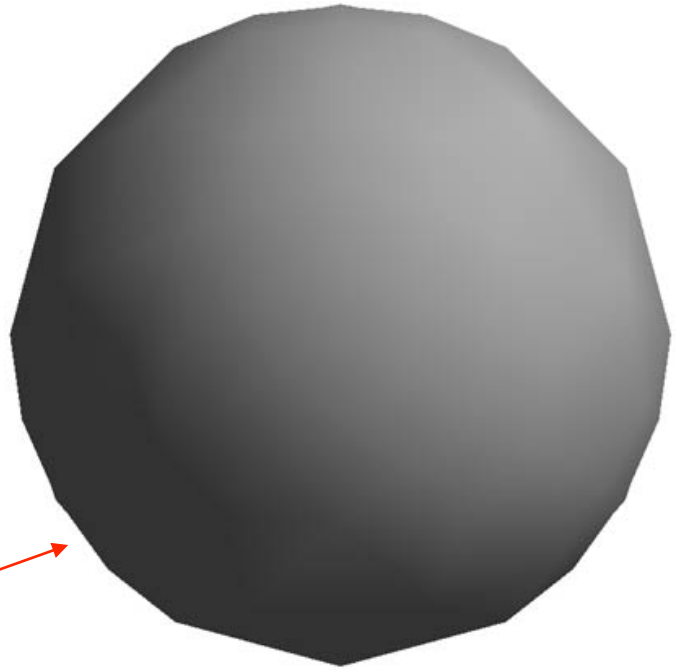
- In per vertex shading, shading calculations are done for each vertex
  - Vertex colors become vertex shades and can be sent to the vertex shader as a vertex attribute
  - Alternately, we can send the parameters to the vertex shader and have it compute the shade
- By default, vertex shades are interpolated across an object if passed to the fragment shader as a varying variable (smooth shading)
- We can also use uniform variables to shade with a single shade (flat shading)

# Polygon Normals

- Triangles have a single normal
  - Shades at the vertices as computed by the Phong model can almost be the same
  - Identical for a distant viewer (default) or if there is no specular component
- Consider model of sphere
- Want different normals at each vertex

# Smooth Shading

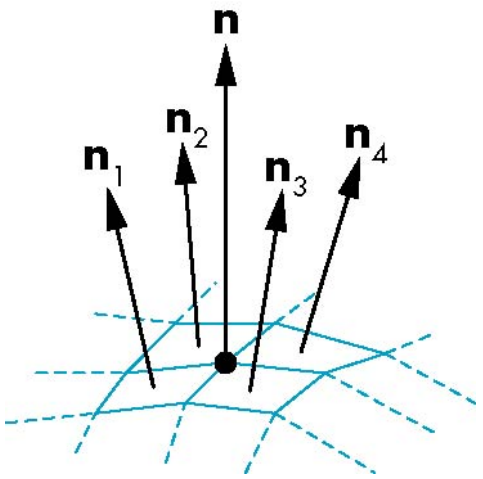
- We can set a new normal at each vertex
- Easy for sphere model
  - If centered at origin $\mathbf{n} = \mathbf{p}$
- Now smooth shading works
- Note *silhouette edge*



# Mesh Shading

- The previous example is not general because we knew the normal at each vertex analytically
- For polygonal models, Gouraud proposed we use the average of the normals around a mesh vertex

$$\mathbf{n} = (\mathbf{n}_1+\mathbf{n}_2+\mathbf{n}_3+\mathbf{n}_4)/\ |\mathbf{n}_1+\mathbf{n}_2+\mathbf{n}_3+\mathbf{n}_4|$$

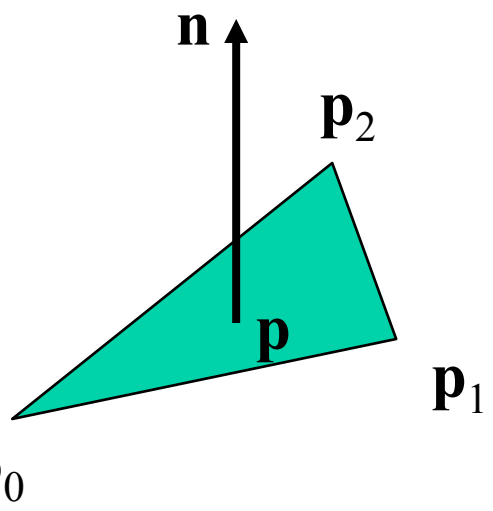


# Normal for Triangle

plane $\quad \mathbf{n} \cdot (\mathbf{p} - \mathbf{p}_0) = 0$

$\mathbf{n} = (\mathbf{p}_2 - \mathbf{p}_0) \times (\mathbf{p}_1 - \mathbf{p}_0)$

normalize $\mathbf{n} \leftarrow \mathbf{n} / |\mathbf{n}|$




Note that right-hand rule determines outward face

# Simple Mesh Format (SMF)

- Michael Garland http://graphics.cs.uiuc.edu/~garland/

- Triangle data
- List of 3D vertices
- List of references to vertex array define faces (triangles)

- Vertex indices begin at 1

```
#$SMF 1.0
#$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
```

# Calculating Normals

vertices

```
v -1 -1 -1
v  1 -1 -1
v -1  1 -1
v  1  1 -1
v -1 -1  1
v  1 -1  1
v -1  1  1
v  1  1  1
```

triangles

```
f 1 3 4
f 1 4 2
f 5 6 8
f 5 8 7
f 1 2 6
f 1 6 5
f 3 7 8
f 3 8 4
f 1 5 7
f 1 7 3
f 2 4 8
f 2 8 6
```

- Create vector structure (for normals) same size as vertex structure
- For each face
  - Calculate unit normal
  - Add to normals structure using vertex indices
- Normalize all the normals

# Gouraud and Phong Shading

- Gouraud Shading
  - Find average normal at each vertex (vertex normals)
  - Compute modified Phong shading model at each vertex
  - Interpolate vertex shades across each polygon
- Phong Shading
  - Find averaged vertex normals
  - Interpolate vertex normals across polygon
  - Compute modified Phong model at each fragment

# Comparison

- If the polygon mesh approximates surfaces with a high curvatures, Phong shading may look smooth while Gouraud shading may show edges
- Phong shading requires much more work than Gouraud shading
  - Until recently not available in real time systems
  - Now can be done using fragment shaders
- Both need data structures to represent meshes so we can obtain vertex normals

# Comparison

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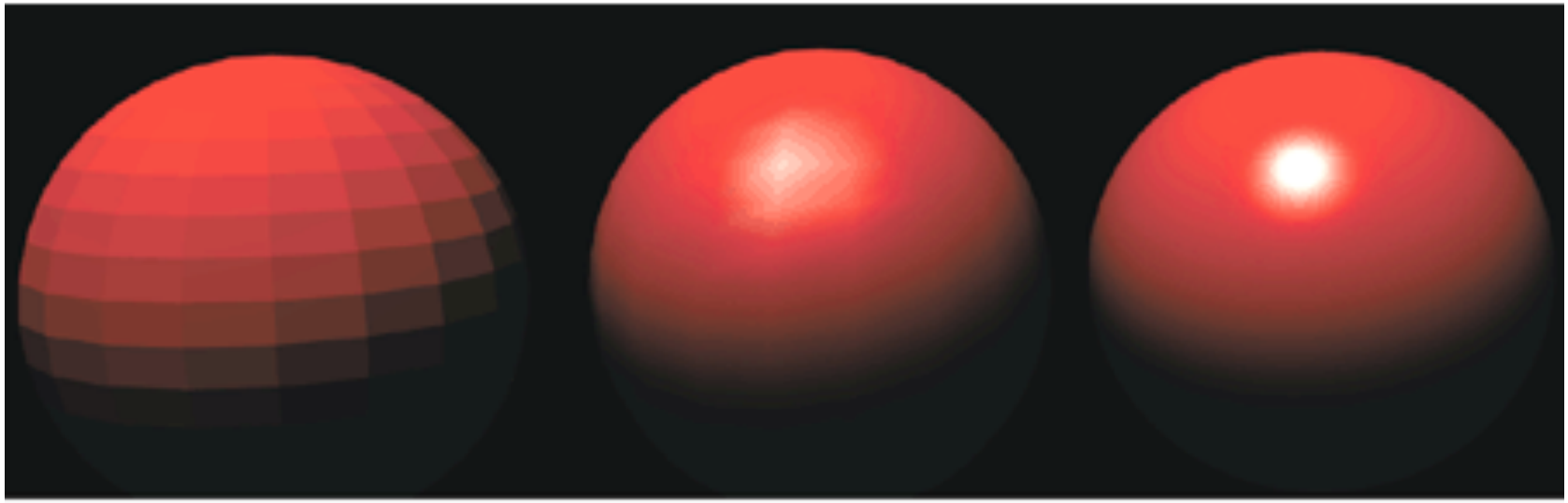


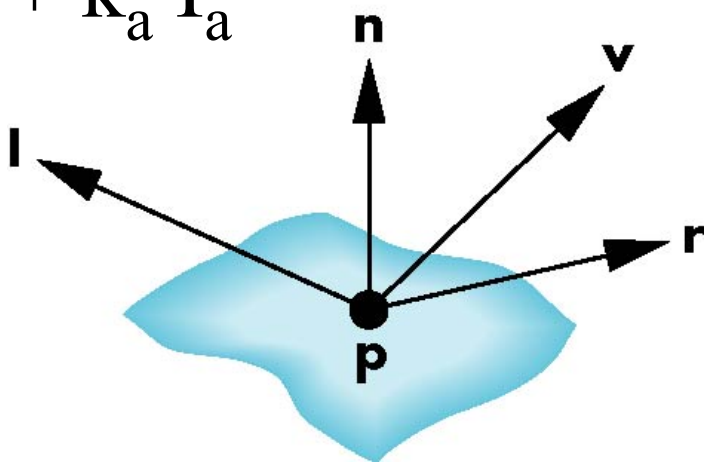
Flat Gouraud Phong

# Adding up the Components

For each light source and each color component, the Phong model can be written (without the distance terms) as

$$I = k_d I_d \, \mathbf{l} \cdot \mathbf{n} + k_s I_s (\mathbf{v} \cdot \mathbf{r})^{\alpha} + k_a I_a$$

For each color component we add contributions from all light sources



# Vertex Lighting Shaders I (Gouraud shading)

```
// vertex shader
in vec3 vPosition;
in vec3 vNormal;
out vec3 color;  //vertex shade

// Light and material properties. Light color * surface color
uniform vec3 AmbientProduct, DiffuseProduct, SpecularProduct;
uniform mat4 ModelView;
uniform mat4 Projection;
uniform vec3 LightPosition;
uniform float Shininess;
```

# Vertex Lighting Shaders II

```
void main()
{
   // Transform vertex  position into eye coordinates
   vec3 pos = (ModelView * vec4(vPosition,1.0)).xyz;

   // Light defined in camera frame
   vec3 L = normalize( LightPosition - pos );
   vec3 E = normalize( -pos );
   vec3 H = normalize( L + E );

   // Transform vertex normal into eye coordinates
   vec3 N = normalize( ModelView*vec4(vNormal, 0.0) ).xyz;
```

# Vertex Lighting Shaders III

```
// Compute terms in the illumination equation
    vec3 ambient = AmbientProduct;

    float dTerm = max( dot(L, N), 0.0 );
    vec3  diffuse = dTerm*DiffuseProduct;
    float sTerm = pow( max(dot(N, H), 0.0), Shininess );
    vec3  specular = sTerm * SpecularProduct;
    if( dot(L, N) < 0.0 )  specular = vec4(0.0, 0.0, 0.0, 1.0);
    gl_Position = Projection * ModelView * vPosition;

    color = ambient + diffuse + specular;
}
```

# Vertex Lighting Shaders IV

```
// fragment shader

in vec3 color;
out vec4 frag_color;

void main()
{
    frag_color = vec4(color, 1.0);
}
```

# Fragment Lighting Shaders I (Phong Shading)

```
// vertex shader
in vec3 vPosition;
in vec3 vNormal;

// output values that will be interpolated per-fragment
out vec3 fN;
out vec3 fE;
out vec3 fL;

uniform vec4 LightPosition;
uniform vec3 EyePosition;
uniform mat4 ModelView;
uniform mat4 Projection;
```

# Fragment Lighting Shaders II

```
void main()
{
    fN = vNormal;
    fE = EyePosition - vPosition.xyz;

    //  Light defined in world coordinates
    if ( LightPosition.w != 0.0 ) {
        fL = LightPosition.xyz - vPosition.xyz;
    } else {
        fL = LightPosition.xyz;
    }
    gl_Position = Projection*ModelView*vPosition;
}
```

# Fragment Lighting Shaders III

```
// fragment shader

// per-fragment interpolated values from the vertex shader
in vec3 fN;
in vec3 fL;
in vec3 fE;
out frag_color;

uniform vec3 AmbientProduct, DiffuseProduct, SpecularProduct;
uniform mat4 ModelView;
uniform float Shininess;
```

# Fragment Lighting Shaders IV

```
void main()
{
   // Normalize the input lighting vectors

  vec3 N = normalize(fN);
   vec3 E = normalize(fE);
   vec3 L = normalize(fL);

   vec3 H = normalize( L + E );
   vec3 ambient = AmbientProduct;
```

# Fragment Lighting Shaders V

```
    float dTerm = max(dot(L, N), 0.0);
    vec3 diffuse = dTerm*DiffuseProduct;

    float sTerm = pow(max(dot(N, H), 0.0), Shininess);
    vec3 specular = sTerm*SpecularProduct;

    // discard the specular highlight if the light's behind the vertex
    if( dot(L, N) < 0.0 )
        specular = vec3(0.0, 0.0, 0.0);

    frag_color = vec4(ambient + diffuse + specular, 1.0);
}
```

# HW6 Suggestions

- Write code for computing average surface normal per vertex
- Use normal as color (don't forget the absolute value) and interpolate across your model. This should look like your HW5 output, but with interpolated colors
- Implement Phong shading model in vertex shader with one light. This is produces Gouraud shading algorithm.

# HW6 Suggestions

- Light and specular color should be white
- First light should be in camera coordinates and placed above camera (e.g. (0,3,0))
- Test with sphere model and shininess of 100. Should get good results with a distinct specular highlight
- Try the lo-res and hi-res bunny models and note the differences in the specular highlights between the two.

# HW6 Suggestions

- Next implement Phong shading algorithm in fragment shader
- Be sure to use the same material and lighting values for both shading algorithms
- Provide a way to switch between the two
- Provide interface for changing the object's material properties. The three choices should be significantly different.
- Add a second light

# HW6 Suggestions

- 2nd light will need its own transformation
- Allow user to move light
- Keep track of which coordinate system you are calculating your surface colors in. Is it in world coordinates or camera coordinates?