CSCI 420 Computer Graphics
Lecture 11

Lighting and Shading

Light Sources
Phong Illumination Model
Normal Vectors
[Angel Ch. 5]

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Outline

- Global and Local Illumination
- Normal Vectors
- Light Sources
- Phong Illumination Model
- Polygonal Shading
- Example

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Global Illumination

- Ray tracing
- Radiosity
- Photon Mapping

Tobias R. Metoc

- Follow light rays through a scene
- Accurate, but expensive (off-line)

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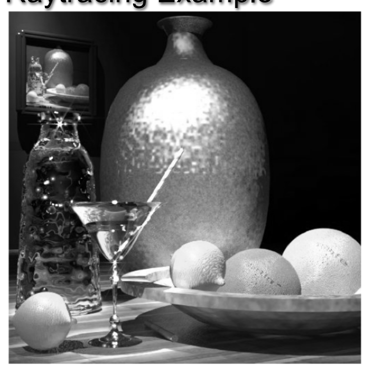
Raytracing Example



Martin Moeck,
Siemens Lighting

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Radiosity Example

Restaurant Interior. Guillermo Leal, Evolucion Visual

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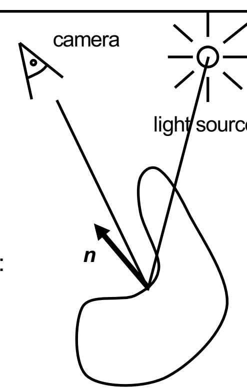
Local Illumination



- Approximate model
- Local interaction between light, surface, viewer
- Phong model (this lecture): fast, supported in OpenGL
- GPU shaders
- Pixar Renderman (offline)

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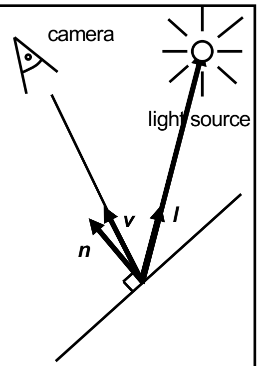
Local Illumination

- Approximate model
- Local interaction between light, surface, viewer
- Color determined only based on surface normal, relative camera position and relative light position
- What effects does this ignore?



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Normal Vectors

- Must calculate and specify the normal vector
  - Even in OpenGL!
- Two examples: plane and sphere

Normals of a Plane, Method I

- Method I: given by ax + by + cz + d = 0
- Let p_0 be a known point on the plane
- Let p be an arbitrary point on the plane
- Recall: $u \cdot v = 0$ if and only if u orthogonal to v
- $n \cdot (p - p_0) = n \cdot p - n \cdot p_0 = 0$
- Consequently $n_0 = [a \;\; b \;\; c]^T$
- Normalize to $n = n_0/|n_0|$

Normals of a Plane, Method II

- Method II: plane given by p_0, p_1, p_2
- Points must not be collinear
- Recall: u x v orthogonal to u and v
- $n_0 = (p_1 - p_0) \times (p_2 - p_0)$
- Order of cross product determines orientation
- Normalize to $n = n_0/|n_0|$

Normals of Sphere

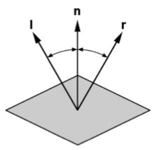
- Implicit Equation $f(x, y, z) = x^2 + y^2 + z^2 - 1 = 0$
- Vector form: $f(p) = p \cdot p - 1 = 0$
- Normal given by gradient vector

$$n_0 = \begin{bmatrix} \frac{\partial f}{\partial x} \\ \frac{\partial f}{\partial y} \\ \frac{\partial f}{\partial z} \end{bmatrix} = \begin{bmatrix} 2x \\ 2y \\ 2z \end{bmatrix} = 2p$$

- Normalize $n_0/|n_0| = 2p/2 = p$

Reflected Vector

- Perfect reflection: angle of incident equals angle of reflection
- Also: ***l***, ***n***, and ***r*** lie in the same plane
- Assume |***l***| = |***n***| = 1, guarantee |***r***| = 1



$\boldsymbol{l} \cdot \boldsymbol{n} = \cos(\theta) = \boldsymbol{n} \cdot \boldsymbol{r}$

$\boldsymbol{r} = \alpha\, \boldsymbol{l} + \beta\, \boldsymbol{n}$

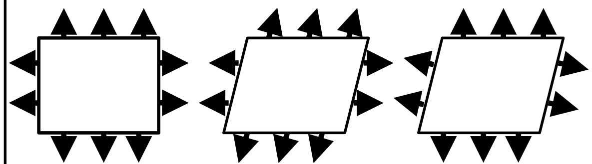
Solution: $\alpha = -1$ and $\beta = 2\,(\boldsymbol{l} \cdot \boldsymbol{n})$

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

Normals Transformed by Modelview Matrix

Modelview matrix *M* (shear in this example)

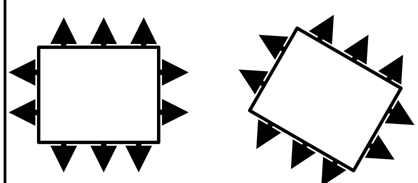
Only keep linear transform in *M* (discard any translation).



Undeformed | Transformed with *M* (incorrect) | Transformed with $(M^{-1})^T$ (correct)

Normals Transformed by Modelview Matrix

When M is rotation, $M = (M^{-1})^T$



Undeformed | Transformed with $M = (M^{-1})^T$ (correct)

Normals Transformed by Modelview Matrix (proof of $(M^{-1})^T$ *transform)*

Point (x,y,z,w) is on a plane in 3D (homogeneous coordinates) if and only if

$a x + b y + c z + d w = 0$, or $[a\ b\ c\ d]\ [x\ y\ z\ w]^T = 0$.

Now, let's transform the plane by *M*.

Point (x,y,z,w) is on the transformed plane if and only if $M^{-1}\ [x\ y\ z\ w]^T$ is on the original plane:
$[a\ b\ c\ d]\ M^{-1}\ [x\ y\ z\ w]^T = 0$.

So, equation of transformed plane is
$[a'\ b'\ c'\ d']\ [x\ y\ z\ w]^T = 0$, for
$[a'\ b'\ c'\ d']^T = (M^{-1})^T\ [a\ b\ c\ d]^T$.

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Light Sources and Material Properties

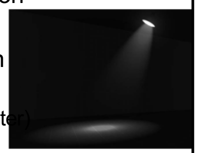
- Appearance depends on
  - Light sources, their locations and properties
  - Material (surface) properties:



  - Viewer position

Types of Light Sources

- Ambient light: no identifiable source or direction
- Point source: given only by point
- Distant light: given only by direction
- Spotlight: from source in direction
  - Cut-off angle defines a cone of light
  - Attenuation function (brighter in center)



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Point Source

- Given by a point p_0
- Light emitted equally in all directions
- Intensity decreases with square of distance

$$I \propto \frac{1}{|p - p_0|^2}$$

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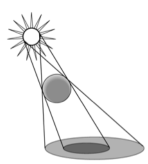
Limitations of Point Sources

- Shading and shadows inaccurate
- Example: penumbra (partial "soft" shadow)
- Similar problems with highlights
- Compensate with attenuation

$$\frac{1}{a + bq + cq^2}$$ q = distance $|p - p_0|$; a, b, c constants



- Softens lighting
- Better with ray tracing
- Better with radiosity

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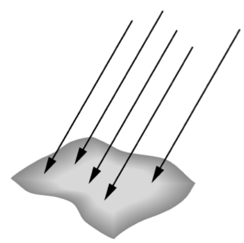
Distant Light Source

- Given by a direction vector [x y z]



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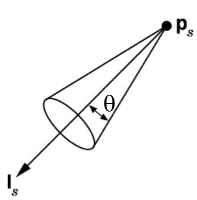
Spotlight

- Light still emanates from point
- Cut-off by cone determined by angle θ



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Global Ambient Light

- Independent of light source
- Lights entire scene
- Computationally inexpensive
- Simply add $[G_R\ G_G\ G_B]$ to every pixel on every object
- Not very interesting on its own.
  A cheap hack to make the scene brighter.

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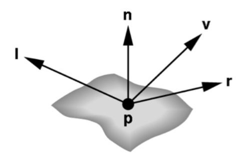
Phong Illumination Model

- Calculate color for arbitrary point on surface
- Compromise between realism and efficiency
- Local computation (no visibility calculations)
- Basic inputs are material properties and **l**, **n**, **v**:

l = unit vector to light source
n = surface normal
v = unit vector to viewer
r = reflection of **l** at **p**
(determined by **l** and **n**)



Phong Illumination Overview

1. Start with global ambient light $[G_R\ G_G\ G_B]$
2. Add contributions from each light source
3. Clamp the final result to [0, 1]

- Calculate each color channel (R,G,B) **separately**
- Light source contributions decomposed into
  - Ambient reflection
  - Diffuse reflection
  - Specular reflection
- Based on ambient, diffuse, and specular lighting and material properties

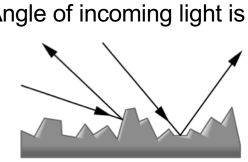
Ambient Reflection

$$I_a = k_a L_a$$

- Intensity of ambient light is uniform at every point
- Ambient reflection coefficient $k_a \geq 0$
- May be different for every surface and r,g,b
- Determines reflected fraction of ambient light
- L_a = ambient component of light source
  (can be set to different value for each light source)
- Note: L_a is not a physically meaningful quantity

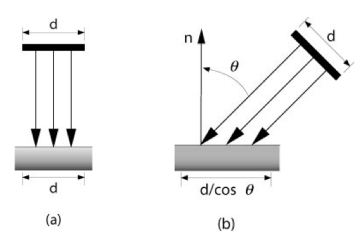
Diffuse Reflection

- Diffuse reflector scatters light
- Assume equally all direction
- Called Lambertian surface
- Diffuse reflection coefficient $k_d \geq 0$
- Angle of incoming light is important



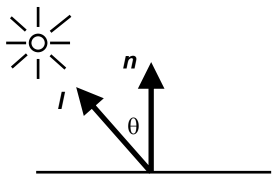
Lambert's Law

Intensity depends on angle of incoming light.



Diffuse Light Intensity Depends On Angle Of Incoming Light

- Recall
  - ***l*** = unit vector to light
  - ***n*** = unit surface normal
  - θ = angle to normal
- $\cos\theta = \boldsymbol{l} \cdot \boldsymbol{n}$



- $I_d = k_d L_d (\boldsymbol{l} \cdot \boldsymbol{n})$
- With attenuation:

$$I_d = \frac{k_d L_d}{a + bq + cq^2}(l \cdot n)$$

q = distance to light source,
L_d = diffuse component of light

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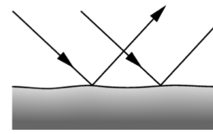
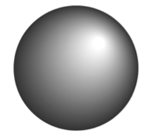
Specular Reflection

- Specular reflection coefficient $k_s \geq 0$
- Shiny surfaces have high specular coefficient
- Used to model specular highlights
- Does not give the mirror effect (need other techniques)



specular reflection



specular highlights

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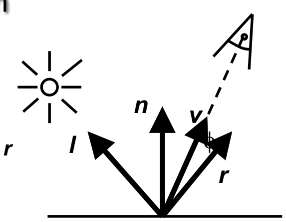
Specular Reflection

- Recall
  - ***v*** = unit vector to camera
  - ***r*** = unit reflected vector
  - ϕ = angle between ***v*** and ***r***
- $\cos\phi = \boldsymbol{v} \cdot \boldsymbol{r}$



- $I_s = k_s L_s (\cos\phi)^\alpha$
- L_s is specular component of light
- α is shininess coefficient
- Can add distance term as well

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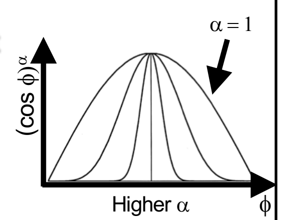
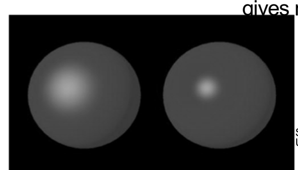
Shininess Coefficient

- $I_s = k_s L_s (\cos\phi)^\alpha$
- α is the shininess coefficient





low α high α

Source: Univ. of Calgary

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Summary of Phong Model

- Light components for each color:
  - Ambient (L_a), diffuse (L_d), specular (L_s)
- Material coefficients for each color:
  - Ambient (k_a), diffuse (k_d), specular (k_s)
- Distance q for surface point from light source

$$I = \frac{1}{a + bq + cq^2}(k_d L_d (l \cdot n) + k_s L_s (r \cdot v)^\alpha) + k_a L_a$$

l = unit vector to light
n = surface normal
r = ***l*** reflected about ***n***
v = vector to viewer

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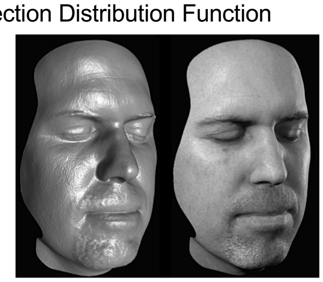
BRDF

- Bidirectional Reflection Distribution Function
- Must measure for real materials
- Isotropic vs. anisotropic
- Mathematically complex
- Implement in a fragment shader



Lighting properties of a human face were captured and face re-rendered; Institute for Creative Technologies

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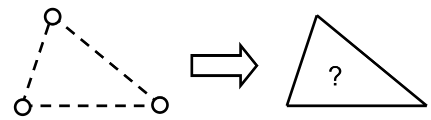
Polygonal Shading

- Now we know vertex colors
  - either via OpenGL lighting,
  - or by setting directly via glColor3f if lighting disabled
- How do we shade the interior of the triangle ?



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Polygonal Shading

- Curved surfaces are approximated by polygons
- How do we shade?
  - Flat shading
  - Interpolative shading
  - Gouraud shading
  - Phong shading (different from Phong illumination!)

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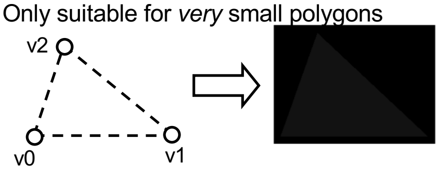
Flat Shading

- Shading constant across polygon
- Core profile: Use interpolation qualifiers in the fragment shader
- Compatibility profile: Enable with glShadeModel(GL_FLAT);
- Color of last vertex determines interior color
- Only suitable for *very* small polygons



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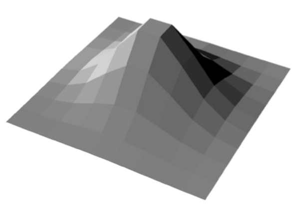
Flat Shading Assessment

- Inexpensive to compute
- Appropriate for objects with flat faces
- Less pleasant for smooth surfaces



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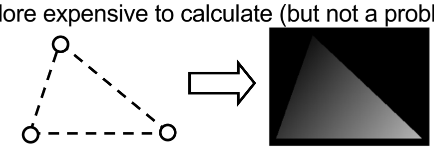
Interpolative Shading

- Interpolate color in interior
- Computed during scan conversion (rasterization)
- Core profile: enabled by default
- Compatibiltiy profile: enable with glShadeModel(GL_SMOOTH);
- Much better than flat shading
- More expensive to calculate (but not a problem)



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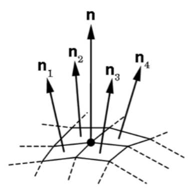
Gouraud Shading

Invented by Henri Gouraud, Univ. of Utah, 1971

- Special case of interpolative shading
- How do we calculate vertex normals for a polygonal surface? Gouraud:
  1. average all adjacent face normals

$$n = \frac{n_1 + n_2 + n_3 + n_4}{|n_1 + n_2 + n_3 + n_4|}$$

  2. use *n* for Phong lighting
  3. interpolate vertex colors into the interior



- Requires knowledge about which faces share a vertex

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Data Structures for Gouraud Shading

- Sometimes vertex normals can be computed directly (e.g. height field with uniform mesh)
- More generally, need data structure for mesh
- Key: which polygons meet at each vertex

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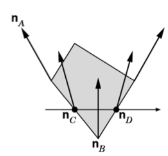
Phong Shading ("per-pixel lighting")

Invented by Bui Tuong Phong, Univ. of Utah, 1973

- *At each pixel* (as opposed to at each vertex) :
  1. Interpolate *normals* (rather than colors)
  2. Apply Phong lighting to the interpolated normal
- Significantly more expensive
- Done off-line or in GPU shaders (not supported in OpenGL directly)



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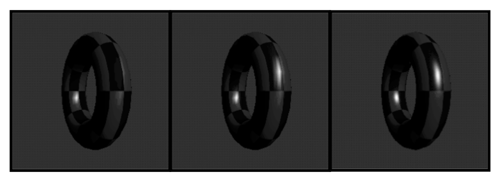
Phong Shading Results

Michael Gold, Nvidia



Single light Phong Lighting Gouraud Shading	Two lights Phong Lighting Gouraud Shading	Two lights Phong Lighting Phong Shading

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Phong Shader: Vertex Program

```
#version 150

in vec3 position;
in vec3 normal;

out vec3 viewPosition;
out vec3 viewNormal;

uniform mat4 modelViewMatrix;
uniform mat4 normalMatrix;
uniform mat4 projectionMatrix;
```

- `in vec3 position; in vec3 normal;` } input vertex position and normal, in world-space
- `out vec3 viewPosition; out vec3 viewNormal;` } vertex position and normal, in view-space } these will be passed to fragment program (interpolated by hardware)
- `uniform mat4 modelViewMatrix; uniform mat4 normalMatrix; uniform mat4 projectionMatrix;` } transformation matrices

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Phong Shader: Vertex Program

```
void main()
{
  // view-space position of the vertex
  vec4 viewPosition4 = modelViewMatrix * vec4(position, 1.0f);
  viewPosition = viewPosition4.xyz;

  // final position in the normalized device coordinates space
  gl_Position = projectionMatrix * viewPosition4;
  // view-space normal
  viewNormal = normalize((normalMatrix*vec4(normal, 0.0f)).xyz);
}
```

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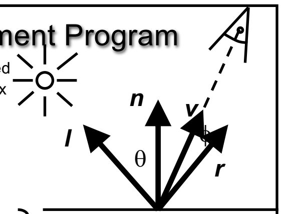
Phong Shader: Fragment Program

```
in vec3 viewPosition;  } interpolated from vertex
in vec3 viewNormal;    } program outputs

out vec4 c; // output color

uniform vec4 La; // light ambient        }
uniform vec4 Ld; // light diffuse        } properties of the
uniform vec4 Ls; // light specular       } directional light
uniform vec3 viewLightDirection;         }   <- In view space

uniform vec4 ka; // mesh ambient         }
uniform vec4 kd; // mesh diffuse         } mesh optical
uniform vec4 ks; // mesh specular        } properties
uniform float alpha; // shininess        }
```



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Phong Shader: Fragment Program

```
void main()
{
  // camera is at (0,0,0) after the modelview transformation
  vec3 eyedir = normalize(vec3(0, 0, 0) - viewPosition);
  // reflected light direction
  vec3 reflectDir = -reflect(viewLightDirection, viewNormal);
  // Phong lighting
  float d = max(dot(viewLightDirection, viewNormal), 0.0f);
  float s = max(dot(reflectDir, eyedir), 0.0f);
  // compute the final color
  c = ka * La + d * kd * Ld + pow(s, alpha) * ks * Ls;
}
```

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VBO Layout: positions and normals

VBO

gg5'|53vs|ff&$|#422|424d|^^3d|aa7y|oarT|J^23|Gr/%|fryu|*xpP

vtx1	vtx1	vtx1	vtx2	vtx2	vtx2	nor1	nor1	nor1	nor2	nor2	nor2
x	y	z	x	y	z	x	y	z	x	y	z

in vec3 position (vtx1 x … vtx2 z)

in vec3 normal (nor1 x … nor2 z)

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VAO code ("normal" shader variable)

During initialization:

```
glBindVertexArray(vao); // bind the VAO

// bind the VBO "buffer" (must be previously created)
glBindBuffer(GL_ARRAY_BUFFER, buffer);

// get location index of the "normal" shader variable
GLuint loc = glGetAttribLocation(program, "normal");
glEnableVertexAttribArray(loc); // enable the "normal" attribute
const void * offset = (const void*) sizeof(positions);  GLsizei stride = 0;
GLboolean normalized = GL_FALSE;
// set the layout of the "normal" attribute data
glVertexAttribPointer(loc, 3, GL_FLOAT, normalized, stride, offset);
```

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Upload the light direction vector to GPU

```
void display()
{
  glClear (GL_COLOR_BUFFER_BIT|GL_DEPTH_BUFFER_BIT);
  openGLMatrix->SetMatrixMode(OpenGLMatrix::ModelView);
  openGLMatrix->LoadIdentity();
  openGLMatrix->LookAt(ex, ey, ez,  fx, fy, fz,  ux, uy, uz);

  float view[16];
  openGLMatrix->GetMatrix(view); // read the view matrix

  // get a handle to the program
  GLuint program = pipelineProgram->GetProgramHandle();
  // get a handle to the viewLightDirection shader variable
  GLint h_viewLightDirection =
    glGetUniformLocation(program, "viewLightDirection");
```

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Upload the light direction vector to GPU

```
float lightDirection[3] = { 0, 1, 0 }; // the “Sun” at noon
float viewLightDirection[3]; // light direction in the view space
// the following line is pseudo-code:
viewLightDirection = (view * float4(lightDirection, 0.0)).xyz;

// upload viewLightDirection to the GPU
glUniform3fv(h_viewLightDirection, 1, viewLightDirection);

// continue with model transformations
openGLMatrix->Translate(x, y, z);
...

renderBunny(); // render, via VAO
glutSwapBuffers();
}
```

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Upload the normal matrix to GPU

```
// in the display function:

// get a handle to the program
GLuint program = pipelineProgram->GetProgramHandle();
// get a handle to the normalMatrix shader variable
GLint h_normalMatrix =
  glGetUniformLocation(program, “normalMatrix”);

float n[16];
matrix->SetMatrixMode(OpenGLMatrix::ModelView);
matrix->GetNormalMatrix(n); // get normal matrix

// upload n to the GPU
GLboolean isRowMajor = GL_FALSE;
glUniformMatrix4fv(h_normalMatrix, 1, isRowMajor, n);
```

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- Phong Illumination Model
- Polygonal Shading
- Example

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