

Shading

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CSE 457
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Reading

Required:

- Angel chapter 5.

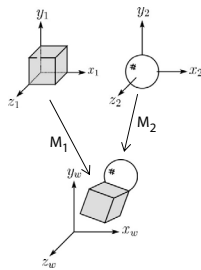
Optional:

- OpenGL red book, chapter 5.

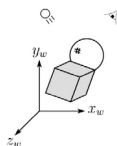
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Basic 3D graphics

With affine matrices, we can now transform virtual 3D objects in their local coordinate systems into a global (world) coordinate system:



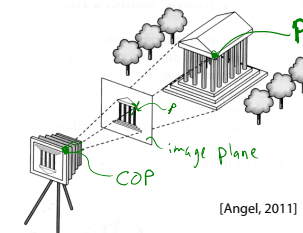
To synthesize an image of the scene, we also need to add light sources and a viewer/camera:



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Pinhole camera

To create an image of a virtual scene, we need to define a camera, and we need to model lighting and shading. For the camera, we use a **pinhole camera**.



The image is rendered onto an **image plane** (usually in front of the camera).

Viewing rays emanate from the **center of projection** (COP) at the center of the pinhole.

The image of an object point **P** is at the intersection of the viewing ray through **P** and the image plane.

But is **P** visible? This is the problem of **hidden surface removal** (a.k.a., **visible surface determination**). We'll consider this problem later.

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Shading

Next, we'll need a model to describe how light interacts with surfaces.

Such a model is called a **shading model**.

Other names:

- ♦ Lighting model
- ♦ Light reflection model
- ♦ Local illumination model
- ♦ Reflectance model
- ♦ BRDF

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An abundance of photons

Given the camera and shading model, properly determining the right color at each pixel is *extremely hard*.

Look around the room. Each light source has different characteristics. Trillions of photons are pouring out every second.

These photons can:

- ♦ interact with molecules and particles in the air ("participating media")
- ♦ strike a surface and
 - be absorbed
 - be reflected (scattered)
 - cause fluorescence or phosphorescence.
- ♦ interact in a wavelength-dependent manner
- ♦ generally bounce around and around

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Our problem

We're going to build up to a *approximations* of reality called the **Phong and Blinn-Phong illumination models**.

They have the following characteristics:

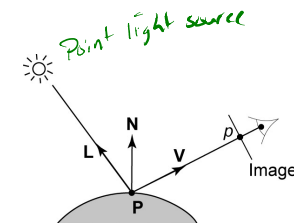
- ♦ *not* physically correct
- ♦ gives a "first-order" *approximation* to physical light reflection
- ♦ very fast
- ♦ widely used

In addition, we will assume **local illumination**, i.e., light goes: light source -> surface -> viewer.

No interreflections, no shadows.

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Setup...



Given:

- ♦ a point **P** on a surface visible through pixel *p*
- ♦ The normal **N** at **P**
- ♦ The lighting direction, **L**, and (color) intensity, I_L , at **P**
- ♦ The viewing direction, **V**, at **P**
- ♦ The shading coefficients at **P**

Compute the color, *I*, of pixel *p*.

Assume that the direction vectors are normalized:

$$\|\mathbf{N}\| = \|\mathbf{L}\| = \|\mathbf{V}\| = 1$$

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“Iteration zero”

The simplest thing you can do is...

Assign each polygon a single color:

$$I = k_e$$

where

- I is the resulting intensity
- k_e is the **emissivity** or intrinsic shade associated with the object

This has some special-purpose uses, but not really good for drawing a scene.

[Note: k_e is omitted in Angel.]

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“Iteration one”

Let’s make the color at least dependent on the overall quantity of light available in the scene:

$$I = k_e + k_a I_{La}$$

- k_a is the **ambient reflection coefficient**.
 - really the reflectance of ambient light
 - “ambient” light is assumed to be equal in all directions
- I_{La} is the **ambient light intensity**.

Physically, what is “ambient” light?

your man's interreflection

[Note: Angel uses L_a instead of I_{La} .]

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Wavelength dependence

Really, k_e , k_a , and I_{La} are functions over all wavelengths λ .

Ideally, we would do the calculation on these functions. For the ambient shading equation, we would start with:

$$I(\lambda) = k_a(\lambda) I_{La}(\lambda)$$

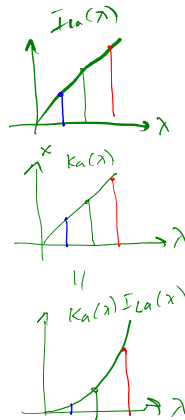
then we would find good RGB values to represent the spectrum $I(\lambda)$.

Traditionally, though, k_a and I_{La} are represented as RGB triples, and the computation is performed on each color channel separately:

$$I^R = k_a^R I_{La}^R$$

$$I^G = k_a^G I_{La}^G$$

$$I^B = k_a^B I_{La}^B$$



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Diffuse reflection

Let’s examine the ambient shading model:

- objects have different colors
- we can control the overall light intensity
 - what happens when we turn off the lights?
 - what happens as the light intensity increases?
 - what happens if we change the color of the lights?

So far, objects are uniformly lit.

- not the way things really appear
- in reality, light sources are localized in position or direction

Diffuse, or **Lambertian** reflection will allow reflected intensity to vary with the direction of the light.

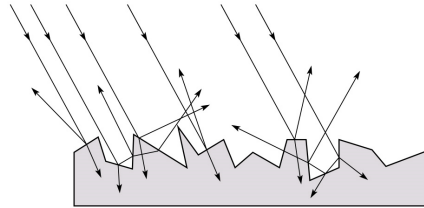
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Diffuse reflectors

Diffuse reflection occurs from dull, matte surfaces, like latex paint, or chalk.

These **diffuse** or **Lambertian** reflectors reradiate light equally in all directions.

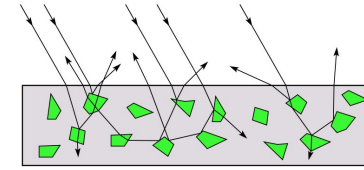
Picture a rough surface with lots of tiny **microfacets**.



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Diffuse reflectors

...or picture a surface with little pigment particles embedded beneath the surface (neglect reflection at the surface for the moment):



The microfacets and pigments distribute light rays in all directions.

Embedded pigments are responsible for the coloration of diffusely reflected light in plastics and paints.

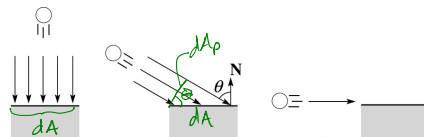
Note: the figures above are intuitive, but not strictly (physically) correct.

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Diffuse reflectors, cont.

$$L \cdot V = \|L\| \|V\| \cos\theta$$

The reflected intensity from a diffuse surface does not depend on the direction of the viewer. The incoming light, though, does depend on the direction of the light source:



$$dA_p = dA \cos\theta$$

$$I \sim \cos\theta \cdot B$$

$$B = \begin{cases} 1 & \text{if } \cos\theta \geq 0 \\ 0 & \text{else} \end{cases}$$

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"Iteration two"

The incoming energy is proportional to $\cos\theta$, giving the diffuse reflection equations:

$$I = k_e + k_a I_{La} + k_d I_L B \cos\theta$$

$$= k_e + k_a I_{La} + k_d I_L B (N \cdot L)$$

where:

- k_d is the **diffuse reflection coefficient**
- I_L is the (color) intensity of the light source
- \mathbf{N} is the normal to the surface (unit vector)
- \mathbf{L} is the direction to the light source (unit vector)
- B prevents contribution of light from below the surface:

$$B = \begin{cases} 1 & \text{if } \mathbf{N} \cdot \mathbf{L} > 0 \\ 0 & \text{if } \mathbf{N} \cdot \mathbf{L} \leq 0 \end{cases}$$

[Note: Angel uses L_d instead of I_L and f instead of B .]

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Specular reflection

Specular reflection accounts for the highlight that you see on some objects.

It is particularly important for *smooth, shiny* surfaces, such as:

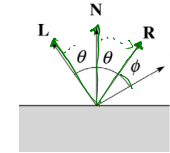
- ♦ metal
- ♦ polished stone
- ♦ plastics
- ♦ apples
- ♦ skin

Properties:

- ♦ Specular reflection depends on the viewing direction \mathbf{V} .
- ♦ For non-metals, the color is determined solely by the color of the light.
- ♦ For metals, the color may be altered (e.g., brass)

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Specular reflection “derivation”



For a perfect mirror reflector, light is reflected about \mathbf{N} , so

$$I = \begin{cases} I_L & \text{if } \mathbf{V} = \mathbf{R} \\ 0 & \text{otherwise} \end{cases}$$

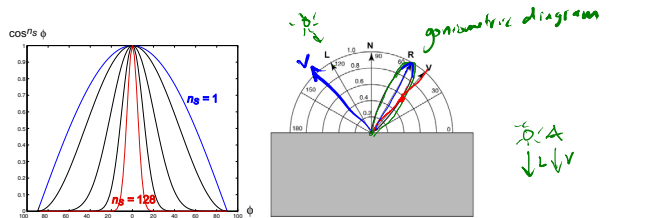
For a near-perfect reflector, you might expect the highlight to fall off quickly with increasing angle ϕ .

Also known as:

- ♦ “**rough specular**” reflection
- ♦ “**directional diffuse**” reflection
- ♦ “**glossy**” reflection

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Phong specular reflection



One way to get this effect is to take $(\mathbf{R} \cdot \mathbf{V})$, raised to a power n_s .

As n_s gets larger,

- ♦ the dropoff becomes {more,less} gradual
- ♦ gives a {larger,smaller} highlight
- ♦ simulates a {more,less} mirror-like surface

Phong specular reflection is proportional to:

$$I_{\text{specular}} \sim B(\mathbf{R} \cdot \mathbf{V})_+^{n_s}$$

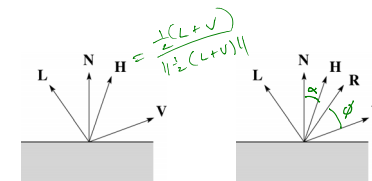
where $(x)_+ \equiv \max(0, x)$.

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Blinn-Phong specular reflection

A common alternative for specular reflection is the **Blinn-Phong model** (sometimes called the **modified Phong model**.)

We compute the vector halfway between \mathbf{L} and \mathbf{V} as:



Analogous to Phong specular reflection, we can compute the specular contribution in terms of $(\mathbf{N} \cdot \mathbf{H})$, raised to a power n_s :

$$I_{\text{specular}} \sim B(\mathbf{N} \cdot \mathbf{H})_+^{n_s}$$

where, again, $(x)_+ \equiv \max(0, x)$.

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"Iteration three"

The next update to the Blinn-Phong shading model is then:

$$I = k_e + k_a I_{La} + k_d I_L B(\mathbf{N} \cdot \mathbf{L}) + k_s I_s B(\mathbf{N} \cdot \mathbf{H})^{n_s}$$

$$= k_e + k_a I_{La} + I_L B \left[k_d (\mathbf{N} \cdot \mathbf{L}) + k_s (\mathbf{N} \cdot \mathbf{H})^{n_s} \right]$$

where:

- k_s is the **specular reflection coefficient**
- n_s is the **specular exponent** or **shininess**
- \mathbf{H} is the unit halfway vector between \mathbf{L} and \mathbf{V} , where \mathbf{V} is the viewing direction.

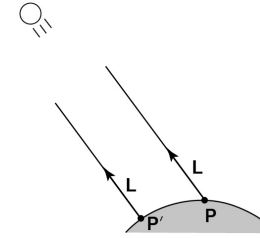
[Note: Angel uses a instead of n_s , and maintains a separate L_d and L_s , instead of a single I_L . This choice reflects the flexibility available in OpenGL.]

Directional lights

The simplest form of lights supported by renderers are ambient, directional, and point. Spotlights are also supported often as a special form of point light.

We've seen ambient light sources, which are not really geometric.

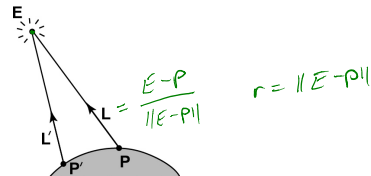
Directional light sources have a single direction and intensity associated with them.



Using affine notation, what is the homogeneous coordinate for a directional light? 0

Point lights

The direction of a **point light** sources is determined by the vector from the light position to the surface point.



Physics tells us the intensity must drop off inversely with the square of the distance:

$$f_{\text{atten}} = \frac{1}{r^2}$$

Sometimes, this distance-squared dropoff is considered too "harsh." A common alternative is:

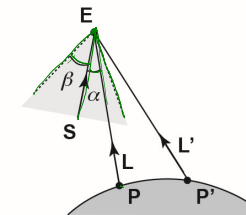
$$f_{\text{atten}} = \frac{1}{a + br + cr^2}$$

with user-supplied constants for a , b , and c .

Using affine notation, what is the homogeneous coordinate for a point light? 1

Spotlights

We can also apply a *directional attenuation* of a point light source, giving a **spotlight** effect.



A common choice for the spotlight intensity is:

$$f_{\text{spot}} = \begin{cases} \frac{(\mathbf{L} \cdot \mathbf{S})^e}{a + br + cr^2} & \alpha \leq \beta \\ 0 & \text{otherwise} \end{cases}$$

where

- \mathbf{L} is the direction to the point light.
- \mathbf{S} is the center direction of the spotlight.
- α is the angle between \mathbf{L} and \mathbf{S}
- β is the cutoff angle for the spotlight
- e is the angular falloff coefficient

Note: $\alpha \leq \beta \Leftrightarrow \cos^{-1}(\mathbf{L} \cdot \mathbf{S}) \leq \beta \Leftrightarrow \mathbf{L} \cdot \mathbf{S} \geq \cos \beta$.

“Iteration four”

Since light is additive, we can handle multiple lights by taking the sum over every light.

Our equation is now:

$$I = k_e + k_a I_{La} + \sum_j \frac{(\mathbf{L}_j \cdot \mathbf{S}_j)^{e_j}}{a_j + b_j r_j + c_j r_j^2} I_{L,j} B_j \left[k_d (\mathbf{N} \cdot \mathbf{L}_j) + k_s (\mathbf{N} \cdot \mathbf{H}_j)^{n_s} \right]$$

This is the Blinn-Phong illumination model (for spotlights).

Which quantities are spatial vectors?

Which are RGB triples?

Which are scalars?

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Shading in OpenGL

The OpenGL lighting model allows you to associate different lighting colors according to material properties they will influence.

Thus, our original shading equation (for point lights):

$$I = k_e + k_a I_{La} + \sum_j \frac{1}{a_j + b_j r_j + c_j r_j^2} I_{L,j} B_j \left[k_d (\mathbf{N} \cdot \mathbf{L}_j) + k_s (\mathbf{N} \cdot \mathbf{H}_j)^{n_s} \right]$$

becomes:

$$I = k_e + k_a I_{La} + \sum_j \frac{1}{a_j + b_j r_j + c_j r_j^2} \left[k_a I_{La,j} + B_j \{ k_d I_{Ld,j} (\mathbf{N} \cdot \mathbf{L}_j) + k_s I_{Ls,j} (\mathbf{N} \cdot \mathbf{H}_j)^{n_s} \} \right]$$

where you can have a global ambient light with intensity I_{La} in addition to having an ambient light intensity $I_{La,j}$ associated with each individual light, as well as separate diffuse and specular intensities, $I_{Ld,j}$ and $I_{Ls,j}$, respectively.

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Materials in OpenGL

The OpenGL code to specify the surface shading properties is fairly straightforward. For example:

```
GLfloat ke[] = { 0.1, 0.15, 0.05, 1.0 };
GLfloat ka[] = { 0.1, 0.15, 0.1, 1.0 };
GLfloat kd[] = { 0.3, 0.3, 0.2, 1.0 };
GLfloat ks[] = { 0.2, 0.2, 0.2, 1.0 };
GLfloat ns[] = { 50.0 };
glMaterialfv(GL_FRONT, GL_EMISSION, ke);
glMaterialfv(GL_FRONT, GL_AMBIENT, ka);
glMaterialfv(GL_FRONT, GL_DIFFUSE, kd);
glMaterialfv(GL_FRONT, GL_SPECULAR, ks);
glMaterialfv(GL_FRONT, GL_SHININESS, ns);
```

Notes:

- The `GL_FRONT` parameter tells OpenGL that we are specifying the materials for the front of the surface.
- Only the alpha value of the diffuse color is used for blending. It's usually set to 1.

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Shading in OpenGL, cont'd

In OpenGL this equation, for one light source (the 0th) is specified something like:

```
GLfloat La[] = { 0.2, 0.2, 0.2, 1.0 };
GLfloat La0[] = { 0.1, 0.1, 0.1, 1.0 };
GLfloat Ld0[] = { 1.0, 1.0, 1.0, 1.0 };
GLfloat Ls0[] = { 1.0, 1.0, 1.0, 1.0 };
GLfloat pos0[] = { 1.0, 1.0, 1.0, 0.0 };
GLfloat a0[] = { 1.0 };
GLfloat b0[] = { 0.5 };
GLfloat c0[] = { 0.25 };
GLfloat S0[] = { -1.0, -1.0, 0.0 };
GLfloat beta0[] = { 45 };
GLfloat e0[] = { 2 };

glLightModelfv(GL_LIGHT_MODEL_AMBIENT, La);
glLightfv(GL_LIGHT0, GL_AMBIENT, La0);
glLightfv(GL_LIGHT0, GL_DIFFUSE, Ld0);
glLightfv(GL_LIGHT0, GL_SPECULAR, Ls0);
glLightfv(GL_LIGHT0, GL_POSITION, pos0);
glLightfv(GL_LIGHT0, GL_CONSTANT_ATTENUATION, a0);
glLightfv(GL_LIGHT0, GL_LINEAR_ATTENUATION, b0);
glLightfv(GL_LIGHT0, GL_QUADRATIC_ATTENUATION, c0);
glLightfv(GL_LIGHT0, GL_SPOT_DIRECTION, S0);
glLightf(GL_LIGHT0, GL_SPOT_CUTOFF, beta0);
glLightf(GL_LIGHT0, GL_SPOT_EXPONENT, e0);
```

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Shading in OpenGL, cont'd

Notes:

You can have as many as `GL_MAX_LIGHTS` lights in a scene. This number is system-dependent.

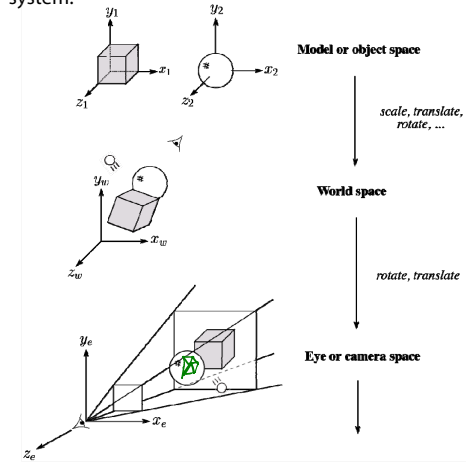
For directional lights, you specify a light direction, not position, and the attenuation and spotlight terms are ignored.

The directions of directional lights and spotlights are specified in the coordinate systems *of the lights*, not the surface points as we've been doing in lecture.

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3D Geometry in the Graphics Hardware Pipeline

Graphics hardware applies transformations to bring the objects and lighting into the camera's coordinate system:

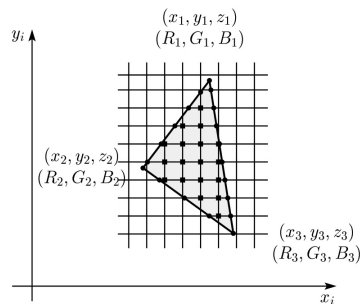


The geometry is assumed to be made of triangles, and the **vertices** are projected onto the image plane.

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Rasterization

After projecting the vertices, graphics hardware "smears" vertex properties across the interior of the triangle in a process called **rasterization**.



Smearing the z-values and using a Z-buffer will enable the graphics hardware to determine if a point inside a triangle is visible. (More on this in another lecture.)

If we have stored colors at the vertices, then we can smear these as well.

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Shading the interiors of triangles

We will be computing colors using the Blinn-Phong lighting model.

Let's assume (as graphics hardware does) that we are working with triangles.

How should we shade the interiors of triangles?

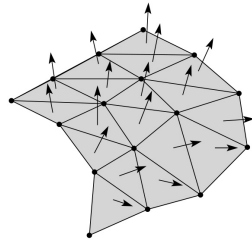
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Shading with per-face normals

$$P_i, L = \text{const.}$$

$$V = \text{const.}$$

Assume each face has a constant normal:

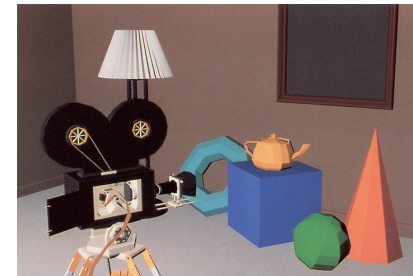
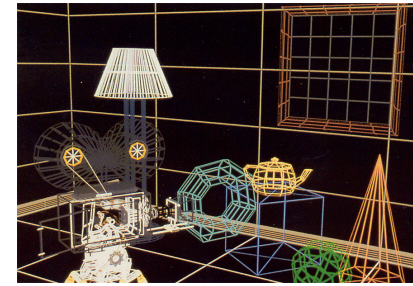


For a distant viewer and a distant light source and constant material properties over the surface, how will the color of each triangle vary?

$$I = BI_L (K_d(N \cdot L) + K_s(N \cdot H)^n)$$

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Faceted shading (cont'd)



[Williams and Siegel 1990]

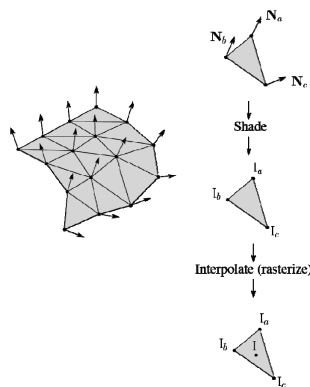
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Gouraud interpolation

To get a smoother result that is easily performed in hardware, we can do **Gouraud interpolation**.

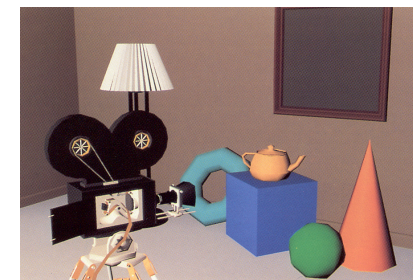
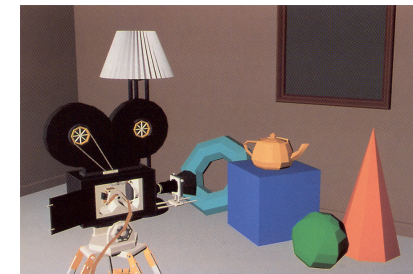
Here's how it works:

1. Compute normals at the vertices.
2. Shade only the vertices.
3. Interpolate the resulting vertex colors.



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Faceted shading vs. Gouraud interpolation



[Williams and Siegel 1990]

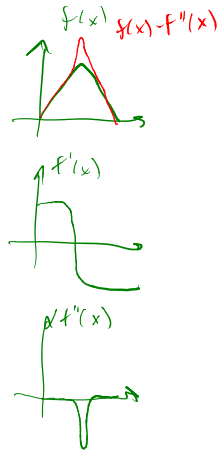
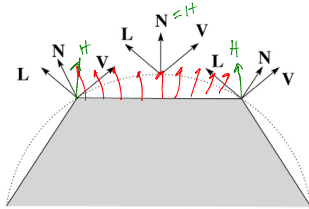
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Gouraud interpolation artifacts

R, L
AL

Gouraud interpolation has significant limitations.

1. If the polygonal approximation is too coarse, we can miss specular highlights.



2. We will encounter **Mach banding** (derivative discontinuity enhanced by human eye).

This is what graphics hardware does by default.

A substantial improvement is to do...

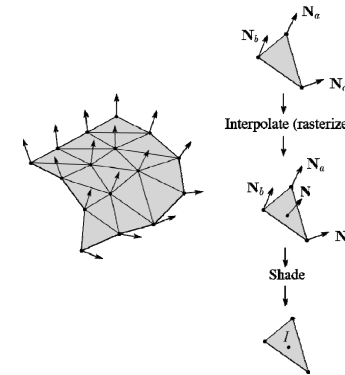
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Phong interpolation

To get an even smoother result with fewer artifacts, we can perform **Phong interpolation**.

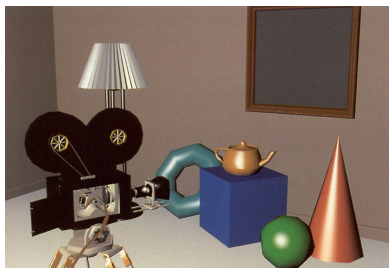
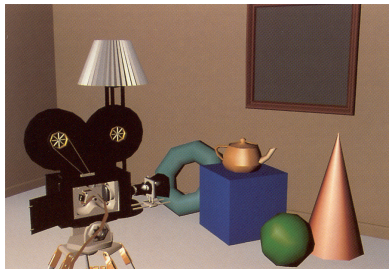
Here's how it works:

1. Compute normals at the vertices.
2. Interpolate normals and normalize.
3. Shade using the interpolated normals.



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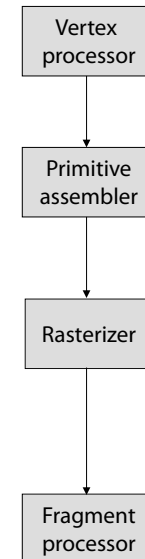
Gouraud vs. Phong interpolation



[Williams and Siegel 1990]

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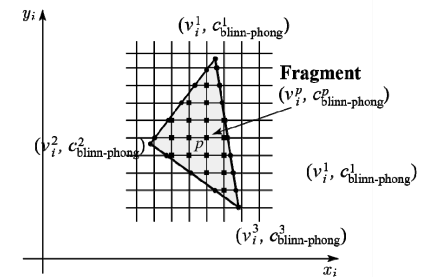
Old pipeline: Gouraud interpolation



Default vertex processing:

$L \leftarrow$ determine lighting direction
 $V \leftarrow$ determine viewing direction
 $N \leftarrow$ normalize(n_c)
 $c_{\text{blinn-phong}} \leftarrow$ shade with L, V, N, k_d, k_s, n_s
 attach $c_{\text{blinn-phong}}$ to vertex as "varying"
 $v_i \leftarrow$ project v to image

$v_i^1, v_i^2, v_i^3 \rightarrow$ triangle

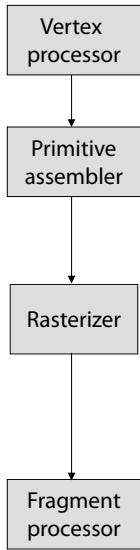


Default fragment processing:

color $\leftarrow c_{\text{blinn-phong}}^p$

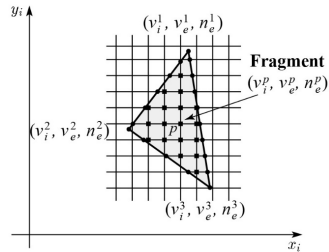
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Programmable pipeline: Phong-interpolated normals!

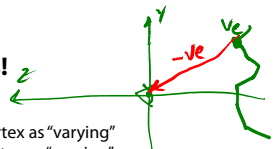


Vertex shader:
attach n_e to vertex as "varying"
attach v_e to vertex as "varying"
 $v_i \leftarrow$ project v to image

$v_i^1, v_i^2, v_i^3 \rightarrow$ triangle



Fragment shader:
 $L \leftarrow$ determine lighting direction (using v_e^p)
 $V \leftarrow$ ~~norm~~ normalize($-v_e^p$)
 $N \leftarrow$ normalize(n_e^p)
color \leftarrow shade with L, V, N, k_d, k_s, n_s



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Choosing Blinn-Phong shading parameters

Experiment with different parameter settings. To get you started, here are a few suggestions:

- Try n_s in the range $[0, 100]$
- Try $k_d + k_s < 1$
- Use a small k_d (~ 0.1)

	n_s	k_d	k_s
Metal	large	Small, color of metal	Large, color of metal
Plastic	medium	Medium, color of plastic	Medium, white
Planet	0	varying	0

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BRDF

The diffuse+specular parts of the Blinn-Phong illumination model are a mapping from light to viewing directions:

$$I = I_L B \left[k_d (\mathbf{N} \cdot \mathbf{L}) + k_s \mathbf{N} \cdot \left(\frac{\mathbf{L} + \mathbf{V}}{\|\mathbf{L} + \mathbf{V}\|} \right)_+^{n_s} \right]$$

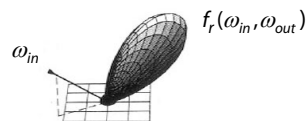
$$= I_L f_r(\mathbf{L}, \mathbf{V})$$

The mapping function f_r is often written in terms of incoming (light) directions ω_{in} and outgoing (viewing) directions ω_{out} :

$$f_r(\omega_{in}, \omega_{out}) \quad \text{or} \quad f_r(\omega_{in} \rightarrow \omega_{out})$$

This function is called the **Bi-directional Reflectance Distribution Function (BRDF)**.

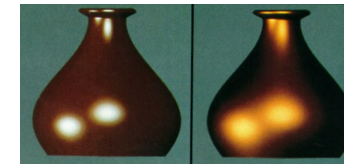
Here's a plot with ω_{in} held constant:



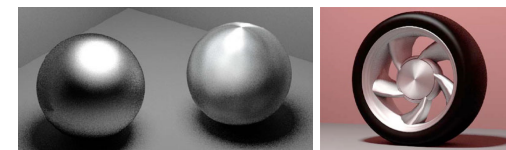
BRDF's can be quite sophisticated...

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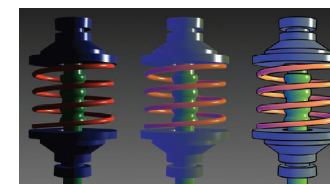
More sophisticated BRDF's



[Cook and Torrance, 1982]



Anisotropic BRDFs [Westin, Arvo, Torrance 1992]



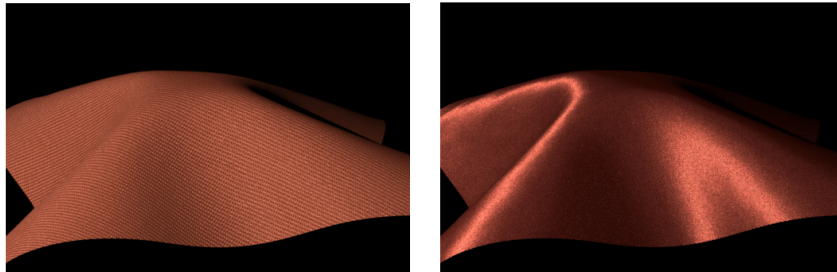
Artistics BRDFs [Gooch]

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More sophisticated BRDF's (cont'd)



Hair illuminated from different angles [Marschner et al., 2003]



Wool cloth and silk cloth [Irawan and Marschner, 2012]

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BSSRDFs for subsurface scattering



[Jensen et al. 2001]

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Summary

You should understand the equation for the Blinn-Phong lighting model described in the "Iteration Four" slide:

- ♦ What is the physical meaning of each variable?
- ♦ How are the terms computed?
- ♦ What effect does each term contribute to the image?
- ♦ What does varying the parameters do?

You should also understand the differences between faceted, Gouraud, and Phong *interpolated* shading.

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