Why Do We Care About Lighting?

Lighting "dis-ambiguates" 3D scenes

Lighting

Without lighting

With lighting

The Surface Normal

A *surface normal* is a vector perpendicular to the surface.

Sometimes surface normals are defined or computed *per-face*, like this.

\[ n = (P1 - P0) \times (P2 - P0) \]

Sometimes they are defined *per-vertex*, like this, to best approximate the underlying surface that the face is representing.

Setting a Per-Face Surface Normal in OpenGL

```c
glMatrixMode(GL_MODELVIEW);
glTranslatef(tx, ty, tz);
glScalef(sx, sy, sz);
glNormal3f(nx, ny, nz);
glColor3f(r, g, b);
gBegin(GL_TRIANGLES);
gVertex3f(x0, y0, z0);
gVertex3f(x1, y1, z1);
gVertex3f(x2, y2, z2);
gEnd();
```
Setting Per-Vertex Surface Normals in OpenGL

```c
glMatrixMode( GL_MODELVIEW );
glTranslatef( tx, ty, tz );
glRotatef( degrees, ax, ay, az );
glScalef( sx, sy, sz );
glColor3f( r, g, b );
gBegin(GL_TRIANGLES );
  glNormal3f( nx0, ny0, nz0 );
  glVertex3f( x0, y0, z0 );
  glNormal3f( nx1, ny1, nz1 );
  glVertex3f( x1, y1, z1 );
  glNormal3f( nx2, ny2, nz2 );
  glVertex3f( x2, y2, z2 );
gEnd( );
```

Per-vertex

Flat Shading (Per-face)

```c
glMatrixMode( GL_MODELVIEW );
glTranslatef( tx, ty, tz );
glRotatef( degrees, ax, ay, az );
glScalef( sx, sy, sz );

```glShadeModel( GL_FLAT );
```glNormal3f( nx, ny, nz );
```
```

Flat Shading (Per-face)

```c

```glShadeModel( GL_SMOOTH );
```glColor3f( r, g, b );
gBegin(GL_TRIANGLES );
  glNormal3f( nx0, ny0, nz0 );
  glVertex3f( x0, y0, z0 );
  glNormal3f( nx1, ny1, nz1 );
  glVertex3f( x1, y1, z1 );
  glNormal3f( nx2, ny2, nz2 );
  glVertex3f( x2, y2, z2 );
gEnd( );
```

Smooth Shading (Per-vertex)

```c

```glShadeModel( GL_SMOOTH );
```glColor3f( r, g, b );
gBegin(GL_TRIANGLES );
  glNormal3f( nx0, ny0, nz0 );
  glVertex3f( x0, y0, z0 );
  glNormal3f( nx1, ny1, nz1 );
  glVertex3f( x1, y1, z1 );
  glNormal3f( nx2, ny2, nz2 );
  glVertex3f( x2, y2, z2 );
gEnd( );
```

Smooth Shading (Per-vertex)
OpenGL Surface Normals Need to be Unitized by Someone

```c
glTranslatef( tx, ty, tz );
glRotatef( degrees, ax, ay, az );
glScalef( sx, sy, sz );
glNormal3f( nx, ny, nz );
```

OpenGL expects the normal vector to be a **unit vector**, that is: $nx^2 + ny^2 + nz^2 = 1$

If it is not, or if you are using scaling transformations, you can force OpenGL to do the unitizing for you with:

```c
glEnable( GL_NORMALIZE );
```

The OpenGL “built-in” Lighting Model

![The OpenGL “built-in” Lighting Model](image)

| P | Point being illuminated |
| I | Light intensity |
| L | Unit vector from point to light |
| n | Unit vector surface normal |
| R | Perfect reflection unit vector |
| E | Unit vector to eye position |

You are all familiar with the Diffuse Lighting effects

1. **Ambient** = a constant  
   Accounts for light bouncing “everywhere”

2. **Diffuse** = $I \cdot \cos \Theta$  
   Accounts for the angle between the incoming light and the surface normal

3. **Specular** = $I \cdot \cos^S \phi$  
   Accounts for the angle between the “perfect reflector” and the eye. The exponent, $S$, accounts for surface shininess

Note that $\cos \Theta$ is just the dot product between unit vectors $L$ and $n$

Note that $\cos \phi$ is just the dot product between unit vectors $R$ and $E$
Diffuse Lighting actually works because of spreading out the same amount of light energy across more surface area

\[ \text{Diffuse} = I \cdot \cos \theta \]

You are all familiar with the Specular Lighting effects

These all have metallic-looking surfaces. What tells you that?

It’s the shiny-reflection spots.

You are all familiar with the Specular Lighting effects

These are not actually metal. They are wood with special paint that mimics the metallic reflection highlights. We can mimic the same effects digitally!

The Specular Lighting equation is a heuristic that approximates reflection from a rough surface

\[ \text{Specular} = I \cdot \cos \phi \]

\[ S = \text{"shininess"} \]

\[ 1/S = \text{"roughness"} \]
The Three Elements of Built-in OpenGL Lighting

Ambient + Diffuse + Specular = Total Lighting Effect

Types of Light Sources
- Point
- Directional (Parallel, Sun)
- Spotlight

Lighting Examples
- Point Light at the Eye
- Point Light at the Origin
- Spot Lights
Colored Lights Shining on Colored Objects

What the light can produce

What the material can reflect

What the eye sees

\[
\begin{align*}
E_R &= L_R \cdot M_R \\
E_G &= L_G \cdot M_G \\
E_B &= L_B \cdot M_B
\end{align*}
\]

Too Many Lighting Options

If there is one light and one material, the following things can be set independently:

- Global scene ambient red, green, blue
- Light position: x, y, z
- Light ambient red, green, blue
- Light diffuse red, green, blue
- Light specular red, green, blue
- Material reaction to ambient red, green, blue
- Material reaction to diffuse red, green, blue
- Material reaction to specular red, green, blue
- Material specular shininess

This makes for 25 things that can be set for just one light and one material! While many combinations are possible, some make more sense than others.

Ways to Simplify Too Many Lighting Options

1. Set the ambient light globally using, for example,
   \[
   \text{glLightModelfv( GL_LIGHT_MODEL_AMBIENT, MulArray3( .3f, White ) )}
   \]
   I.e., set it to some low intensity of white.
2. Set the light's ambient component to zero.
3. Set the light's diffuse and specular components to the full color of the light.
4. Set each material's ambient and diffuse to the full color of the object.
5. Set each material's specular component to some fraction of white.

float White[] = { 1., 1., 1., 1. };

float * Array3( float a, float b, float c )
{
    static float array[4];
    array[0] = a;
    array[1] = b;
    array[2] = c;
    array[3] = 1.;
    return array;
}

float * MulArray3( float factor, float array0[3] )
{
    static float array[4];
    array[0] = factor * array0[0];
    array[1] = factor * array0[1];
    array[2] = factor * array0[2];
    array[3] = 1.;
    return array;
}

The 4th element of the array being set to 1.0 is there on purpose. The reason for that is coming up soon!
### Setting the Material Characteristics

```c
void SetMaterial( float r, float g, float b, float shininess ) {
    glMaterialfv( GL_BACK, GL_AMBIENT, MulArray3( .4f, White ) );
    glMaterialfv( GL_BACK, GL_DIFFUSE, MulArray3( 1.0f, White ) );
    glMaterialfv( GL_BACK, GL_SPECULAR, Array3( 0., 0., 0. ) );
    glMaterialf ( GL_BACK, GL_SHININESS, 5. );
    glMaterialfv( GL_BACK, GL_EMISSION, Array3( 0., 0., 0. ) );
    glMaterialfv( GL_FRONT, GL_AMBIENT, Array3( r, g, b ) );
    glMaterialfv( GL_FRONT, GL_DIFFUSE, Array3( r, g, b ) );
    glMaterialfv( GL_FRONT, GL_SPECULAR, MulArray3( .8f, White ) );
    glMaterialf ( GL_FRONT, GL_SHININESS, shininess );
}
```

You can also set the front and back characteristics to be the same value at the same time:

```c
glMaterialfv( GL_FRONT_AND_BACK, . . . );
```

### How Does OpenGL Define GL_FRONT and GL_BACK?

- **GL_FRONT**
  - Vertices are CCW from the point of view of the eye
  - Vertices are CW from the point of view of the eye

### Setting the Light Characteristics

You can have multiple lights, nominally 0-7.

#### Light Model Parameters

- Linear Attenuation: \( \alpha_1 \)
- Quadratic Attenuation: \( \alpha_2 \)
- Constant Attenuation: \( \alpha_3 \)

#### Attenuation Formula

\[
\text{Attenuation} = \frac{1}{C + Ld + Qd^2}
\]

where \( d \) is the distance from the light to the point being lit.

```c
// this is here because we are going to do object (and thus normal) scaling:
glEnable( GL_NORMALIZE );
```
Light Attenuation

\[ \text{Attenuation} = \frac{1}{C + Ld + Qd^2} \]

where \( d \) is the distance from the light to the point being lit.

Physics tells us that light energy decreases with the inverse square of the distance, \( \frac{1}{d^2} \). To emulate this, we would set \( C=0., L=0., Q=1. \). Streetlights and car headlights are good uses for this.

Often, we don’t want any attenuation, that is, we want to see everything. In that case, set \( C=1., L=0., Q=0. \).

And sometimes you might want to attenuate linearly. Why? Well, because you can! In that case, set \( C=0., L=1., Q=0. \).

\[ \text{glLightf} \ (\ GL\_LIGHT0, \ GL\_CONSTANT\_ATTENUATION, \ 1. ); \]
\[ \text{glLightf} \ (\ GL\_LIGHT0, \ GL\_LINEAR\_ATTENUATION, \ 0. ); \]
\[ \text{glLightf} \ (\ GL\_LIGHT0, \ GL\_QUADRATIC\_ATTENUATION, \ 0. ); \]

Setting the Light Position

The light position gets transformed by the ModelView matrix at the moment the \( \text{glLightf} \ (\ ..., \ GL\_POSITION, \ ...) \) function is called. It is really important to remember this!

// 1. if we do this, then the light will be wrt the scene at XLIGHT, YLIGHT, ZLIGHT:
\[ \text{glLightf} \ (\ GL\_LIGHT0, \ GL\_POSITION, \ Array3(XLIGHT, YLIGHT, ZLIGHT) ); \]

// translate the object into the viewing volume:
\[ \text{glLookAt} \ (\ XEYE, \ YEYE, \ ZEYE, \ 0., \ 0., \ 0., \ 0., \ 1., \ 0. ); \]

// 2. if we do this, then the light will be wrt the eye at XLIGHT, YLIGHT, ZLIGHT:
\[ \text{glLightf} \ (\ GL\_LIGHT0, \ GL\_POSITION, \ Array3(XLIGHT, YLIGHT, ZLIGHT) ); \]

Setting the Light Position

The light position gets transformed by the ModelView matrix at the moment the \( \text{glLightf} \ (\ ..., \ GL\_POSITION, \ ...) \) function is called. It is really important to remember this!

// 1. if we do this, then the light will be wrt the scene at XLIGHT, YLIGHT, ZLIGHT:
\[ \text{glLightf} \ (\ GL\_LIGHT0, \ GL\_POSITION, \ Array3(XLIGHT, YLIGHT, ZLIGHT) ); \]

// translate the object into the viewing volume:
\[ \text{glLookAt} \ (\ XEYE, \ YEYE, \ ZEYE, \ 0., \ 0., \ 0., \ 0., \ 1., \ 0. ); \]

// 2. if we do this, then the light will be wrt the eye at XLIGHT, YLIGHT, ZLIGHT:
\[ \text{glLightf} \ (\ GL\_LIGHT0, \ GL\_POSITION, \ Array3(XLIGHT, YLIGHT, ZLIGHT) ); \]

Sidebar: Why are Light Positions 4-element arrays where the 4th element is 1.0? Homogeneous Coordinates!

You can enable and disable lighting "at all". (This toggles between using what the lighting equations say and what \( \text{glColor3f} \) says.)

You can enable and disable each light independently.

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You can enable and disable each light independently.

We usually think of a 3D point as being represented by a triple: \( (x,y,z) \). Using homogeneous coordinates, we add a 4th number: \( (x,y,z,w) \). Graphics systems take \( (x,y,z,w) \), perform all transformations, and then divide \( x, y, \) and \( z \) by \( w \) before using them.

\[
\begin{align*}
X &= \frac{x}{w}, \\
Y &= \frac{y}{w}, \\
Z &= \frac{z}{w}
\end{align*}
\]

Thus \( (1,2,3,1) \), \( (2,4,6,2) \), \( (-1,-2,-3,1) \) all represent the same 3D point.
Homogeneous Coordinates let us Represent Points at Infinity

This is useful to be able specify a **parallel light source** by placing the light source **position** at infinity.

The point (1,2,3,1) represents the 3D point (1,2,3).
The point (1,2,3,5) represents the 3D point (2,4,6).
The point (1,2,0,1) represents the point (100,200,300).

So, (1,2,3,0) represents a point at infinity, along the ray from the origin through (1,2,3).

**Points-at-infinity are used for parallel light sources** (and some shadow algorithms).

Additional Parameters for Spotlights

```c
void SetPointLight(int ilight, float x, float y, float z, float r, float g, float b ) {
    glLightfv( ilight, GL_POSITION,  Array3( x, y, z ) );
    glLightfv( ilight, GL_AMBIENT,  Array3( 0., 0., 0. ) );
    glLightfv( ilight, GL_DIFFUSE,  Array3( r, g, b ) );
    glLightfv( ilight, GL_SPECULAR,  Array3( r, g, b ) );
    glLightf ( ilight, GL_CONSTANT_ATTENUATION, 1. );
    glLightf ( ilight, GL_LINEAR_ATTENUATION, 0. );
    glLightf ( ilight, GL_QUADRATIC_ATTENUATION, 0. );
    glEnable( ilight );
}
```

```c
void SetSpotLight(int ilight, float x, float y, float z, float xdir, float ydir, float zdir, float r, float g, float b ) {
    glLightfv( ilight, GL_POSITION,  Array3( x, y, z ) );
    glLightfv( ilight, GL_SPOT_DIRECTION,  Array3(xdir,ydir,zdir) );
    glLightf( ilight, GL_SPOT_EXPONENT, 1. );
    glLightf( ilight, GL_SPOT_CUTOFF, 45. );
    glLightfv( ilight, GL_AMBIENT,  Array3( 0., 0., 0. ) );
    glLightfv( ilight, GL_DIFFUSE,  Array3( r, g, b ) );
    glLightfv( ilight, GL_SPECULAR,  Array3( r, g, b ) );
    glLightf ( ilight, GL_CONSTANT_ATTENUATION, 1. );
    glLightf ( ilight, GL_LINEAR_ATTENUATION, 0. );
    glLightf ( ilight, GL_QUADRATIC_ATTENUATION, 0. );
    glEnable( ilight );
}
```

Two Light-setting Helper Functions I Like

```c
void SetPointLight(int ilight, float x, float y, float z, float r, float g, float b ) {
    glLightfv( ilight, GL_POSITION,  Array3( x, y, z ) );
    glLightfv( ilight, GL_AMBIENT,  Array3( 0., 0., 0. ) );
    glLightfv( ilight, GL_DIFFUSE,  Array3( r, g, b ) );
    glLightfv( ilight, GL_SPECULAR,  Array3( r, g, b ) );
    glLightf ( ilight, GL_CONSTANT_ATTENUATION, 1. );
    glLightf ( ilight, GL_LINEAR_ATTENUATION, 0. );
    glLightf ( ilight, GL_QUADRATIC_ATTENUATION, 0. );
    glEnable( ilight );
}
```

Sidebar: Note that we are computing the light intensity at each vertex first, and then interpolating that intensity across the polygon second.

That is, you are only using the lighting model at each vertex.
You can do an even better job if you interpolate the normal across the polygon first, and then compute the light intensity with the lighting model at each fragment second:

Per-vertex Per-fragment
But, for per-fragment, you will need shaders (coming up soon!)

**Per-vertex**

**Per-fragment**

**Sidebar: Smooth Shading can also interpolate vertex colors, not just the results of the lighting model**

Before, when we talked about normal vectors, we did this:

```gl
    glMatrixMode(GL_MODELVIEW);
    glTranslatef(tx, ty, tz);
    glRotatef(degrees, ax, ay, az);
    glScalef(sx, sy, sz);
    glShadeModel(GL_SMOOTH);
    glBegin(GL_TRIANGLES);
    glColor3f(r0, g0, b0);
    glVertex3f(x0, y0, z0);
    glColor3f(r1, g1, b1);
    glVertex3f(x1, y1, z1);
    glColor3f(r2, g2, b2);
    glEnd();
```

We can also provide per-vertex colors to do this:

```gl
    glMatrixMode(GL_MODELVIEW);
    glTranslatef(tx, ty, tz);
    glRotatef(degrees, ax, ay, az);
    glScalef(sx, sy, sz);
    glShadeModel(GL_SMOOTH);
    glBegin(GL_TRIANGLES);
    glColor3f(r0, g0, b0);
    glVertex3f(x0, y0, z0);
    glColor3f(r1, g1, b1);
    glVertex3f(x1, y1, z1);
    glColor3f(r2, g2, b2);
    glEnd();
```

This is especially useful when using colors for scientific visualization:

**Smooth Shading can also interpolate vertex colors, not just the results of the lighting model**

Tricky Lighting Situations

- Hair
- Fur
- Feathers

Watch for these in movies!
Tricky Lighting Situations

Notice the lighting in the fur!

Disney

Sony/Columbia Pictures

Sidebar: Beware of Mach Banding

Notice how these vertical stripes look “scalloped”, like a Greek column. But, they are solid-color stripes. What is going on?

Beware of Mach Banding

Our vision systems can’t handle abrupt changes in intensity.

Our Perceived Intensity Changes

Actual Intensity Changes

In fact, our vision systems can’t even handle abrupt changes in the slope of intensity.

Flat shading

Smooth shading

This “white line” doesn’t really exist – it is an artifact of our vision system!
Beware of Mach Banding

Think of the Mach Banding problem as being similar to trying to round second base at a 90° angle.