Why Do We Care About Lighting?

Lighting “dis-ambiguates” 3D scenes

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

```
glMatrixMode(GL_MODELVIEW);
glTranslatef(tx, ty, tz);
glRotatef(degrees, ax, ay, az);
glScalef(sx, sy, sz);
glNormal3f(nx, ny, nz);
glColor3f(r, g, b);
glBegin(GL_TRIANGLES);
  glVertex3f(x0, y0, z0);
  glVertex3f(x1, y1, z1);
  glVertex3f(x2, y2, z2);
glEnd();
```

Setting Per-Vertex Surface Normals in OpenGL

```
glMatrixMode(GL_MODELVIEW);
glTranslatef(tx, ty, tz);
glRotatef(degrees, ax, ay, az);
glScalef(sx, sy, sz);
glShadeModel(GL_FLAT);
glNormal3f(nx, ny, nz);
glColor3f(r, g, b);
glBegin(GL_TRIANGLES);
  glVertex3f(x0, y0, z0);
  glVertex3f(x1, y1, z1);
  glVertex3f(x2, y2, z2);
glEnd();
```

Flat Shading (Per-face)
Smooth Shading (Per-vertex)

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

// Set shading mode
glShadeModel(GL_SMOOTH);

// Set color
glColor3f(r, g, b);

// Begin drawing
glBegin(GL_TRIANGLES);

// Set normal
glNormal3f(nx0, ny0, nz0);

// Set vertices
glVertex3f(x0, y0, z0);

// Set normal
glNormal3f(nx1, ny1, nz1);

// Set vertices
glVertex3f(x1, y1, z1);

// Set normal
glNormal3f(nx2, ny2, nz2);

// Set vertices
glVertex3f(x2, y2, z2);

// End drawing

// Enable smooth shading

```

OpenGL Surface Normals Need to be Unitized by Someone

OpenGL expects the normal vector to be a unit vector, that is: \( n_x^2 + n_y^2 + n_z^2 = 1 \)

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

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 = \( I \cdot \cos \phi \)
   - Accounts for the angle between the “perfect reflector” and the eye. The exponent, \( \phi \), accounts for surface shininess

   - Note that \( \cos \phi \) 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 \( E \)

You are all familiar with the Diffuse Lighting effects
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.

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

The Three Elements of Built-in OpenGL Lighting

Types of Light Sources

Ambient + Diffuse + Specular = Built-in OpenGL Lighting

Point

Directional (Parallel, Sun)

Spotlight
**Lighting Examples**

- **Point Light at the Eye**
- **Point Light at the Origin**

**Colored Lights Shining on Colored Objects**

What the eye sees:
- $E_R = L_R \times M_R$
- $E_G = L_G \times M_G$
- $E_B = L_B \times M_B$

What the material can reflect:
- $E_R = L_R$ (for red)
- $E_G = L_G$ (for green)
- $E_B = L_B$ (for blue)

**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, `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.
Setting the Material Characteristics

```c
void SetMaterial( float r, float g, float b, float shininess ) {
    glMaterialfv( GL_BACK, GL_EMISSION, Array3( 0., 0., 0. ) );
    glMaterialfv( GL_BACK, GL_AMBIENT, MulArray3( .4f, White ) );
    glMaterialfv( GL_BACK, GL_DIFFUSE, MulArray3( 1., White ) );
    glMaterialfv( GL_BACK, GL_SPECULAR, Array3( 0., 0., 0. ) );
    glMaterialf (  GL_BACK, GL_SHININESS, 2.f );
    glMaterialfv( GL_FRONT, 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 );
}
```

A Material-setting Helper Function I Like

```c
void SetMaterial( float r, float g, float b, float shininess ) {
    glMaterialfv( GL_BACK, GL_EMISSION, Array3( 0., 0., 0. ) );
    glMaterialfv( GL_BACK, GL_AMBIENT, MulArray3( .4f, White ) );
    glMaterialfv( GL_BACK, GL_DIFFUSE, MulArray3( 1., White ) );
    glMaterialfv( GL_BACK, GL_SPECULAR, Array3( 0., 0., 0. ) );
    glMaterialf (  GL_BACK, GL_SHININESS, 2.f );
    glMaterialfv( GL_FRONT, 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 );
}
```

How Does OpenGL Define GL_FRONT and GL_BACK?

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

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

Setting the Light Characteristics

```c
void SetLight( float x, float y, float z, float c, float l, float q, float shininess ) {
    glLightf (  GL_LIGHT0, GL_CONSTANT_ATTENUATION, 1.f );
    glLightf (  GL_LIGHT0, GL_LINEAR_ATTENUATION, 0.f );
    glLightf (  GL_LIGHT0, GL_QUADRATIC_ATTENUATION, 0.f );
    // this is here because we are going to do object (and thus normal) scaling
    glEnable( GL_NORMALIZE );
    glMatrixMode( GL_MODELVIEW );
    glLoadIdentity( );
    // 1. if we do this, then the light will be wrt the scene at XLIGHT, YLIGHT, ZLIGHT:
    glLightfv( GL_LIGHT0, GL_POSITION,  Array3(XLIGHT, YLIGHT, ZLIGHT) );
    // translate the object into the viewing volume:
    gluLookAt(  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:
    // glLightfv( GL_LIGHT0, GL_POSITION,  Array3(XLIGHT, YLIGHT, ZLIGHT) );
}
```

Light Attenuation

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

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

Setting the Light Position

```c
void SetLight( float x, float y, float z, float c, float l, float q, float shininess ) {
    glLightf (  GL_LIGHT0, GL_CONSTANT_ATTENUATION, 1.f );
    glLightf (  GL_LIGHT0, GL_LINEAR_ATTENUATION, 0.f );
    glLightf (  GL_LIGHT0, GL_QUADRATIC_ATTENUATION, 0.f );
    // this is here because we are going to do object (and thus normal) scaling
    glEnable( GL_NORMALIZE );
    glMatrixMode( GL_MODELVIEW );
    glLoadIdentity( );
    // 1. if we do this, then the light will be wrt the scene at XLIGHT, YLIGHT, ZLIGHT:
    glLightfv( GL_LIGHT0, GL_POSITION,  Array3(XLIGHT, YLIGHT, ZLIGHT) );
    // translate the object into the viewing volume:
    gluLookAt(  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:
    // glLightfv( GL_LIGHT0, GL_POSITION,  Array3(XLIGHT, YLIGHT, ZLIGHT) );
}
```

Physics tells us that light energy decreases with the inverse square of the distance:

\[
\text{Energy} \propto \frac{1}{d^2}
\]

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 \( C=1 \), \( L=0 \), \( Q=0 \). Streetlights and car headlights are good uses for this.

And sometimes you might want to attenuate linearly. Why? Well, because you can!
If we perform the rotations and scaling about the origin:

```c
    glRotatef(Xrot, 1., 0., 0.);
    glRotatef(Yrot, 0., 1., 0.);
    glScalef(Scale, Scale, Scale);
```

3. If we do this, then the light will be wrt to the object at XLIGHT, YLIGHT, ZLIGHT:

```c
    glLightfv(GL_LIGHT0, GL_POSITION, Array3(XLIGHT, YLIGHT, ZLIGHT));
```

We specify the shading model:

```c
    glShadeModel(GL_SMOOTH);
```

We enable lighting:

```c
    glEnable(GL_LIGHTING);
    glEnable(GL_LIGHT0);
```

We draw the objects:

```c
    . . .
```

We disable lighting "at all".  (This toggles between using what the lighting equations say and what glColor3f( ) says.)

You can enable and disable each light independently.  It is usually good form to disable the lighting after you are done using it.

```c
    . . .
```

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

You can enable and disable each light independently.  It is usually good form to disable the lighting after you are done using it.

```c
    . . .
```

### 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 (1,2,3,0) 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)

### 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);
    }
```

```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);
    }
```

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

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.

Thus (1,2,3,1), (2,4,6,2), (-1,-2,-3,-1) all represent the same 3D point.

#### Additional Parameters for Spotlights

```c
    glLightfv(GL_LIGHT0, GL_SPOT_DIRECTION, Array3(xdir,ydir,zdir));
```

Specifies the spotlight-pointing direction.  This gets transformed by the current value of the ModelView matrix.

```c
    glLightf(GL_LIGHT0, GL_SPOT_EXPONENT, e);
```

Specifies the spotlight directional intensity.  This acts very much like the exponent in the specular lighting equation.

```c
    glLightf(GL_LIGHT0, GL_SPOT_CUTOFF, deg);
```

Specifies the spotlight maximum spread angle.

### 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:

```c
    . . .
```
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:

\begin{verbatim}
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();
\end{verbatim}

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

\begin{verbatim}
glMatrixMode(GL_MODELVIEW);
glTranslatef(tx, ty, tz);
glRotatef(degrees, ax, ay, az);
glScalef(sx, sy, sz);
glShadeModel(GL_SMOOTH);
gBegin(GL_TRIANGLES);
gColor3f(r0, g0, b0);
gColor3f(r1, g1, b1);
gColor3f(r2, g2, b2);
gEnd();
\end{verbatim}

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

This is especially useful when using colors for scientific visualization:

Tricky Lighting Situations

Notice the lighting in the fur!

Hair

Feathers

Watch for these in movies!

Tricky Lighting Situations

Notice how these vertical stripes look “scalloped”, like a Greek column. But, they are solid-color stripes. What is going on?
Our vision systems can’t handle abrupt changes in intensity.

Beware of Mach Banding

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!

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