Computer Graphics Lighting

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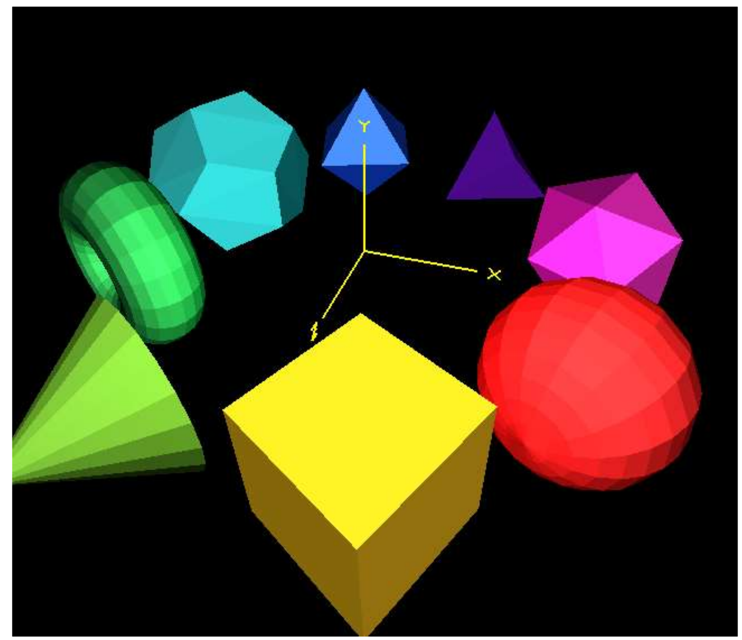
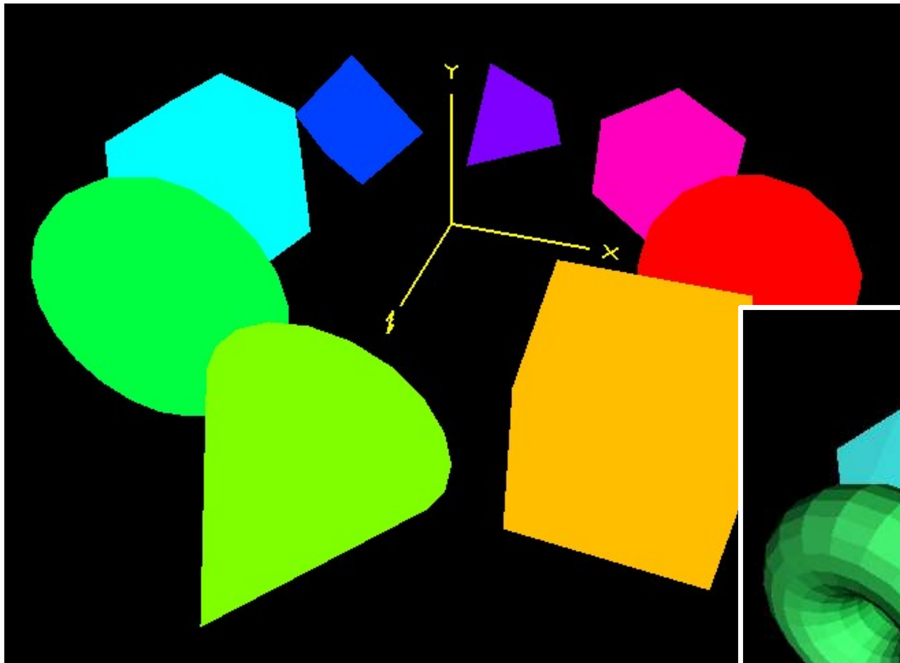
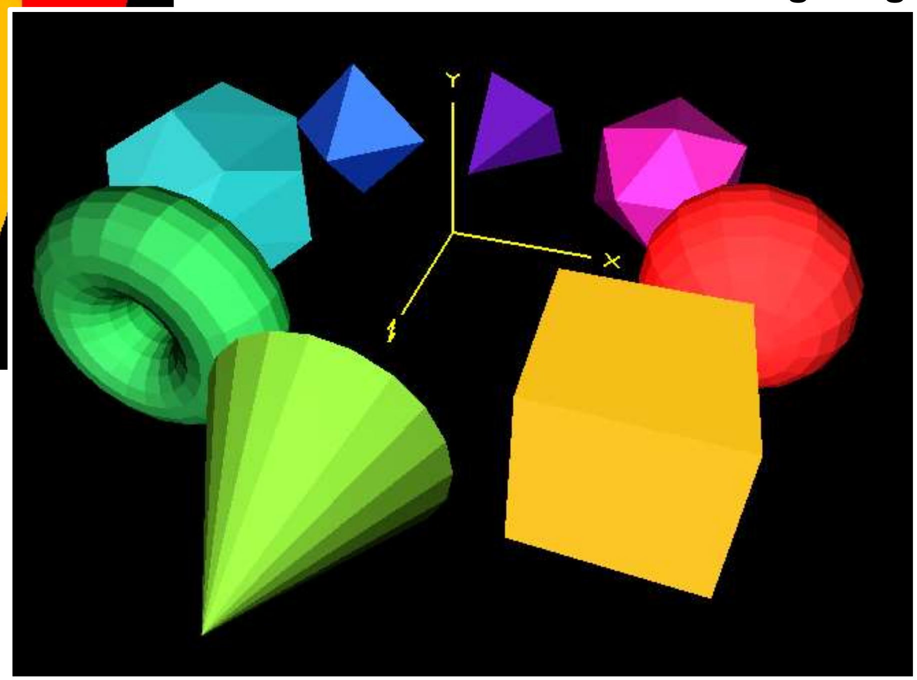


Why Do We Care About Lighting?



Lighting "dis-ambiguates" 3D scenes

With lighting

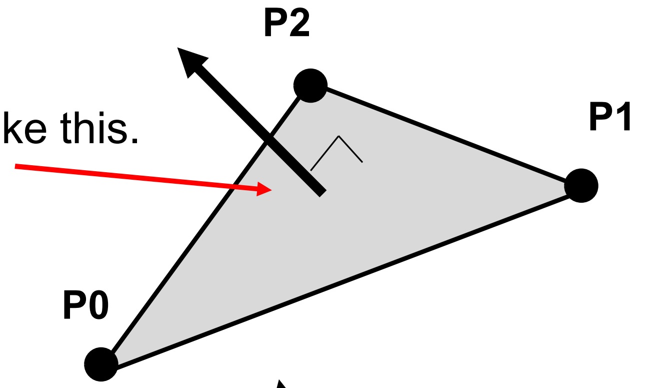


Without lighting

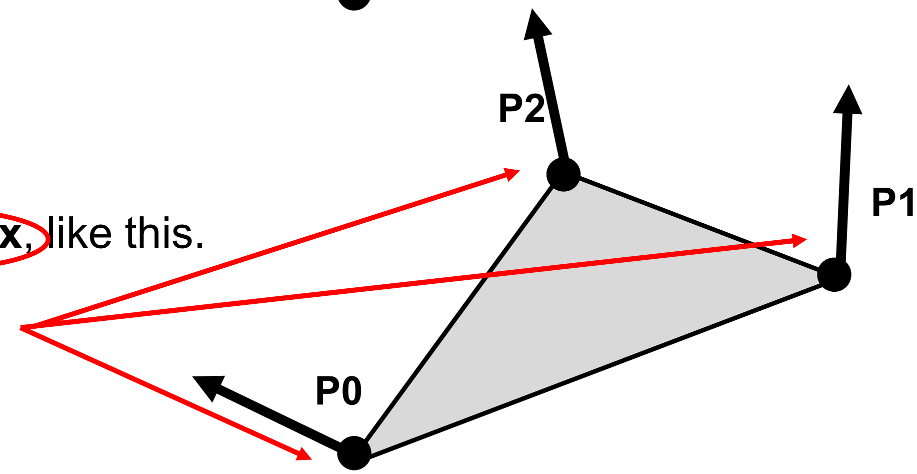
The Surface Normal Vector

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

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

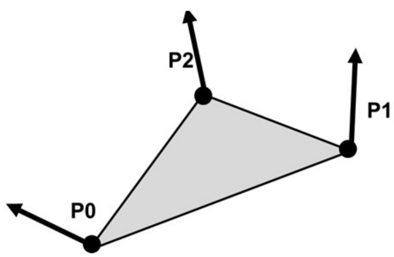


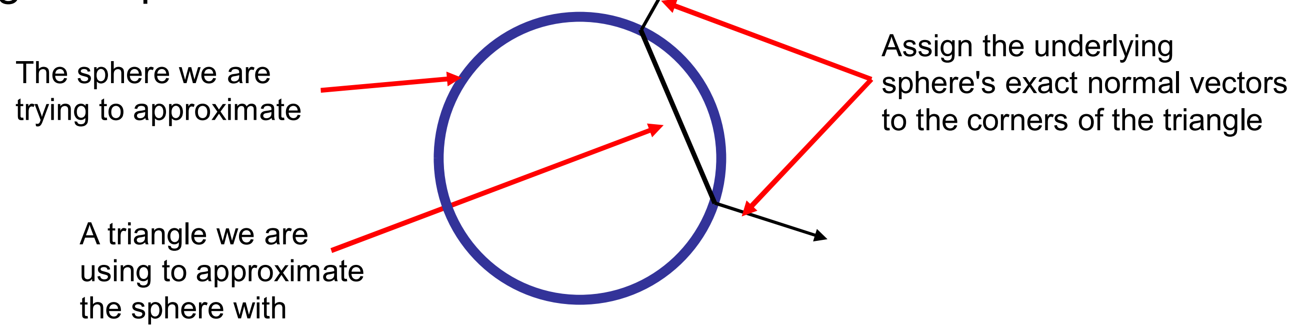
Sometimes they are defined or computed **per-vertex**, like this.

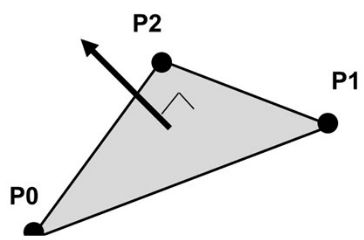


Where Do Surface Normal Vectors Come From?

When the triangle is approximating an underlying smooth surface that we know the equation of, we can get them by knowing what the exact normal of the smooth surface would have been. A good example is looking at a sphere from the side:







When the triangle is part of an arbitrary polyhedron for which we do not have an underlying exact equation, we use vector cross products of the edge vectors to get a vector that is perpendicular to the surface:

$$n = (P1 - P0) \times (P2 – P0)$$

vector cross product

Setting a Per-Face Surface Normal Vector 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( );
```

Per-face normal is set *before* the face is drawn

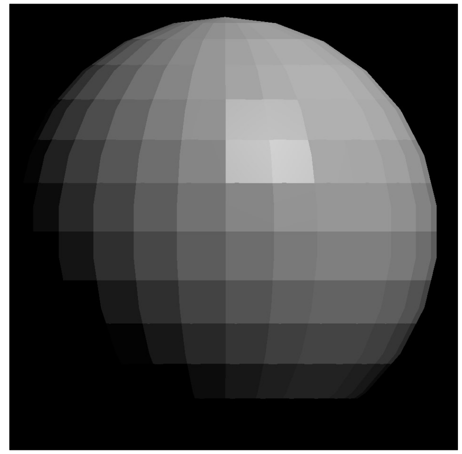
Setting Per-Vertex Surface Normal Vectors in OpenGL

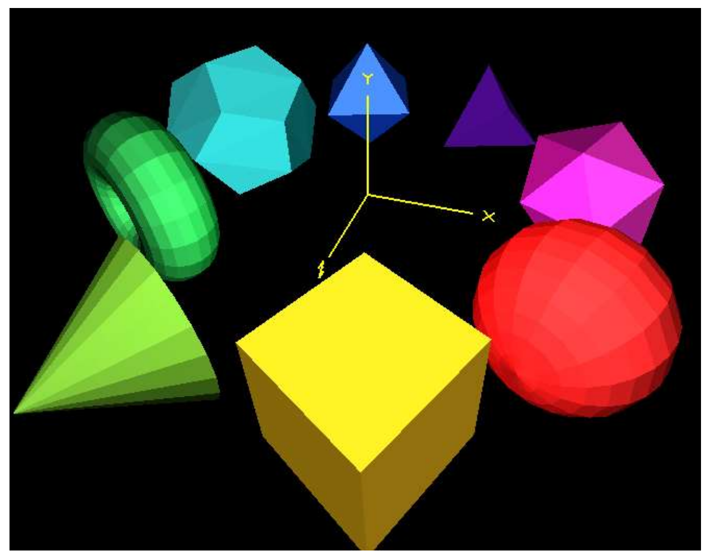
```
glMatrixMode( GL_MODELVIEW );

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

glColor3f( r, g, b );
glBegin(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 );
glEnd( );
```

Per-vertex normal is set *while* the face is being drawn

Flat Shading (Per-face)

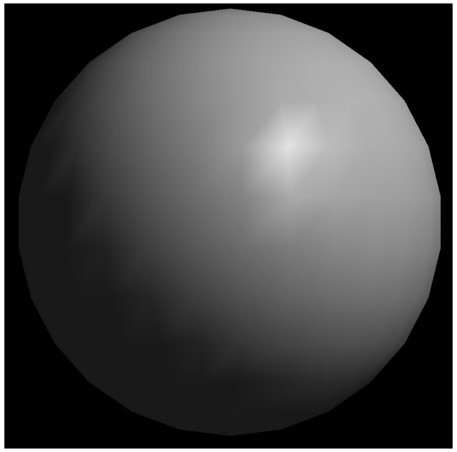
```
glMatrixMode( GL_MODELVIEW );

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( );
```

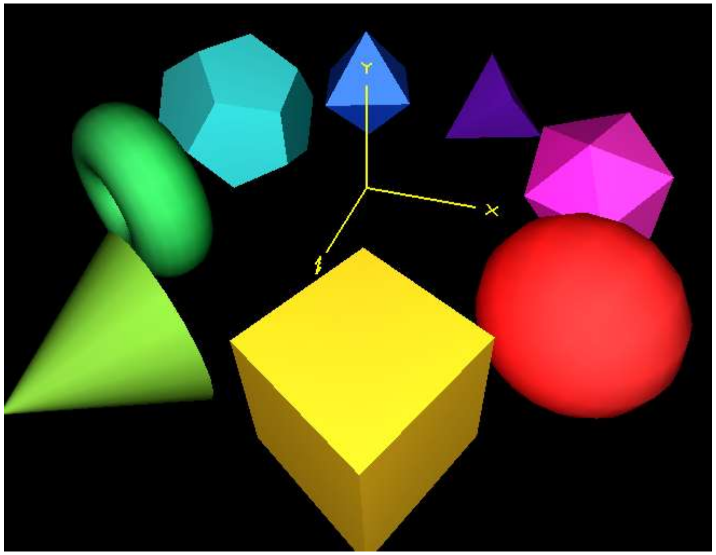




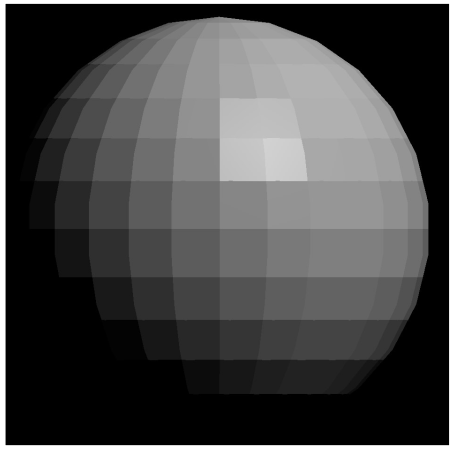
Smooth Shading (Per-vertex)

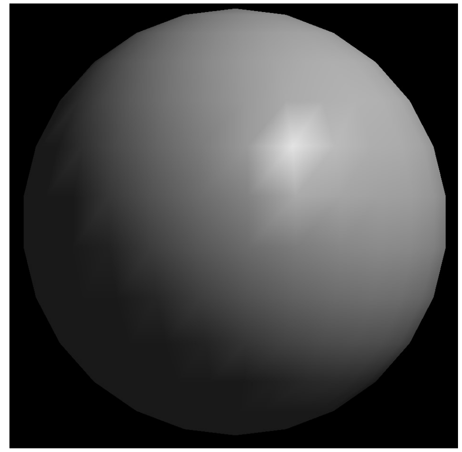

```
glMatrixMode( GL_MODELVIEW );

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

glShadeModel( GL_SMOOTH );

glColor3f( r, g, b );
glBegin(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 );
glEnd( );
```



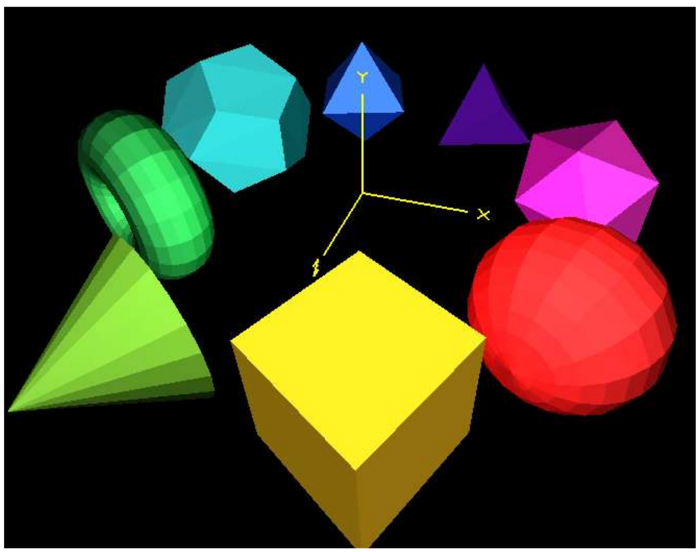


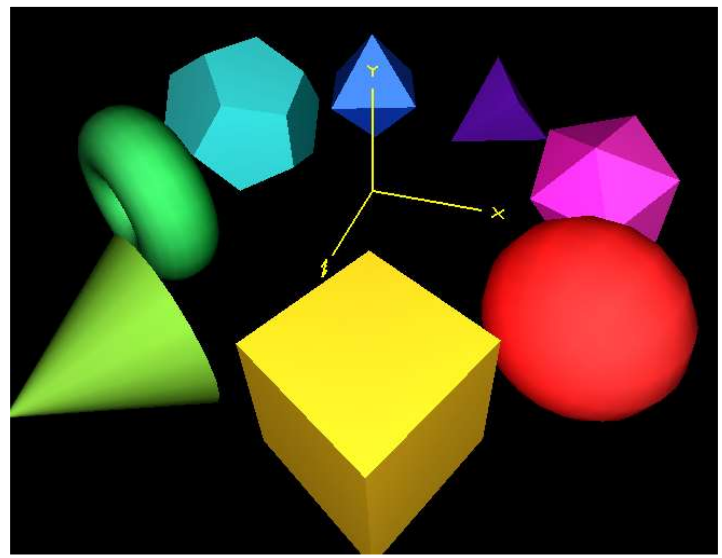
GL_FLAT





GL_SMOOTH





OpenGL Surface Normal Vectors Need to be Unitized by Someone

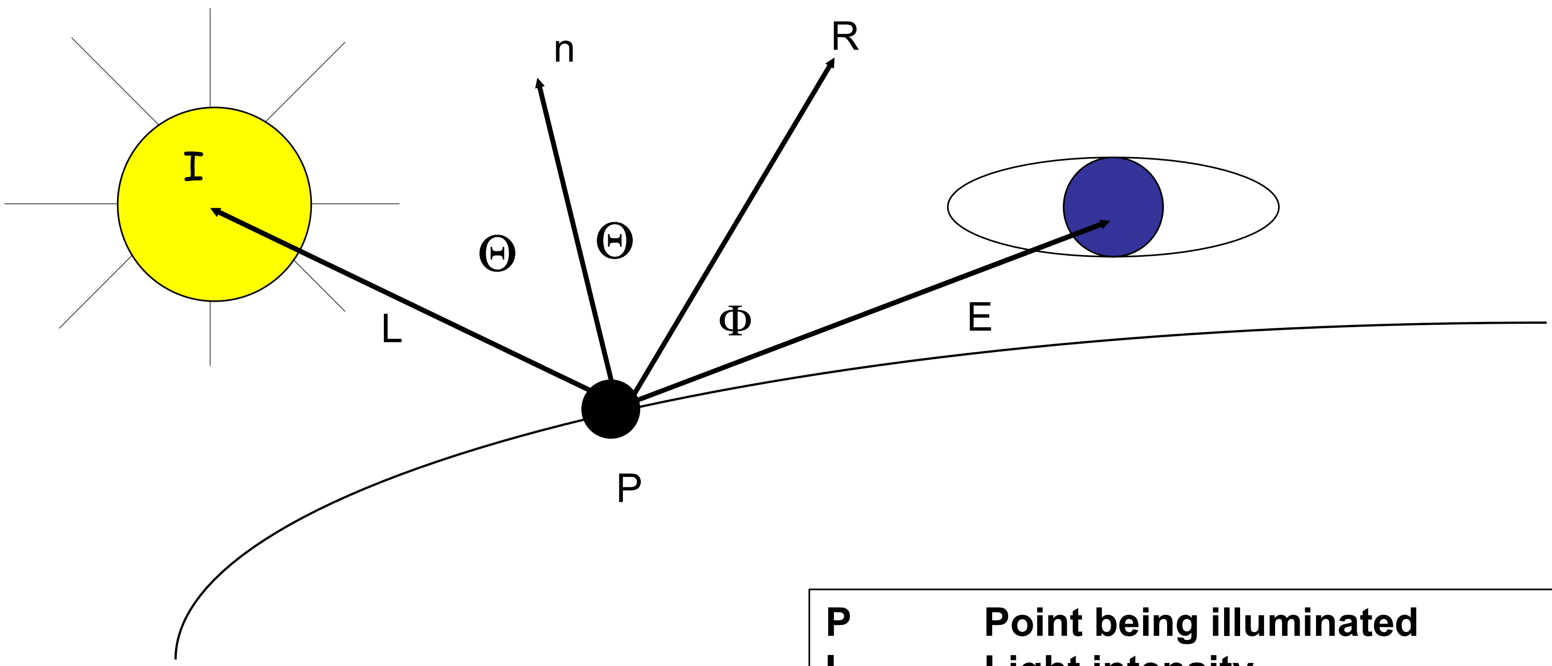
```
glTranslatef( tx, ty, tz );
glRotatef( degrees,  ax, ay, az );
glScalef( sx, sy, sz );

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, you can force OpenGL to do the unitizing for you with:

glEnable(GL_NORMALIZE);

The OpenGL "built-in" Lighting Model



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**

The OpenGL "built-in" Lighting Model

1. **Ambient** = a constant

Accounts for light bouncing "everywhere"

2. **Diffuse** = $I * \cos\Theta$

Accounts for the angle between the incoming light and the surface normal

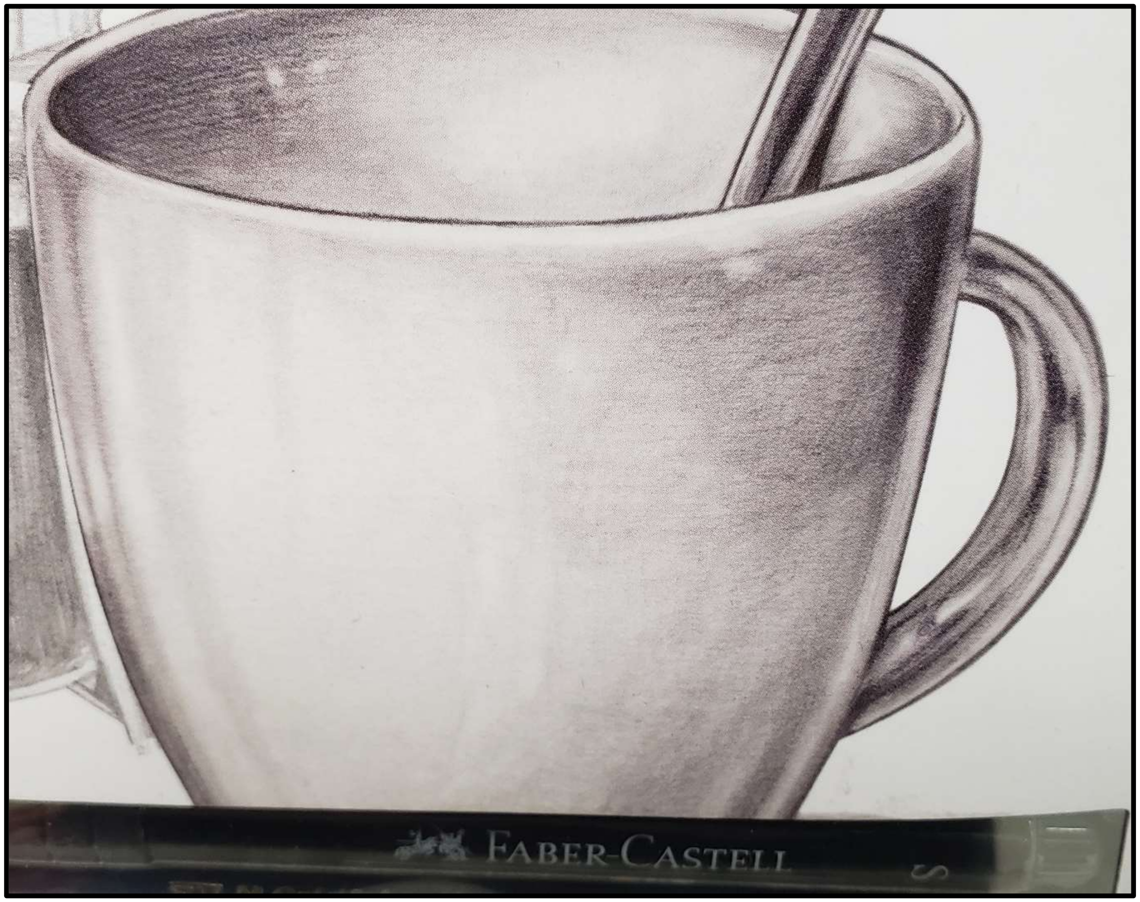
3. **Specular** = $I * \cos^{S}\phi$

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**

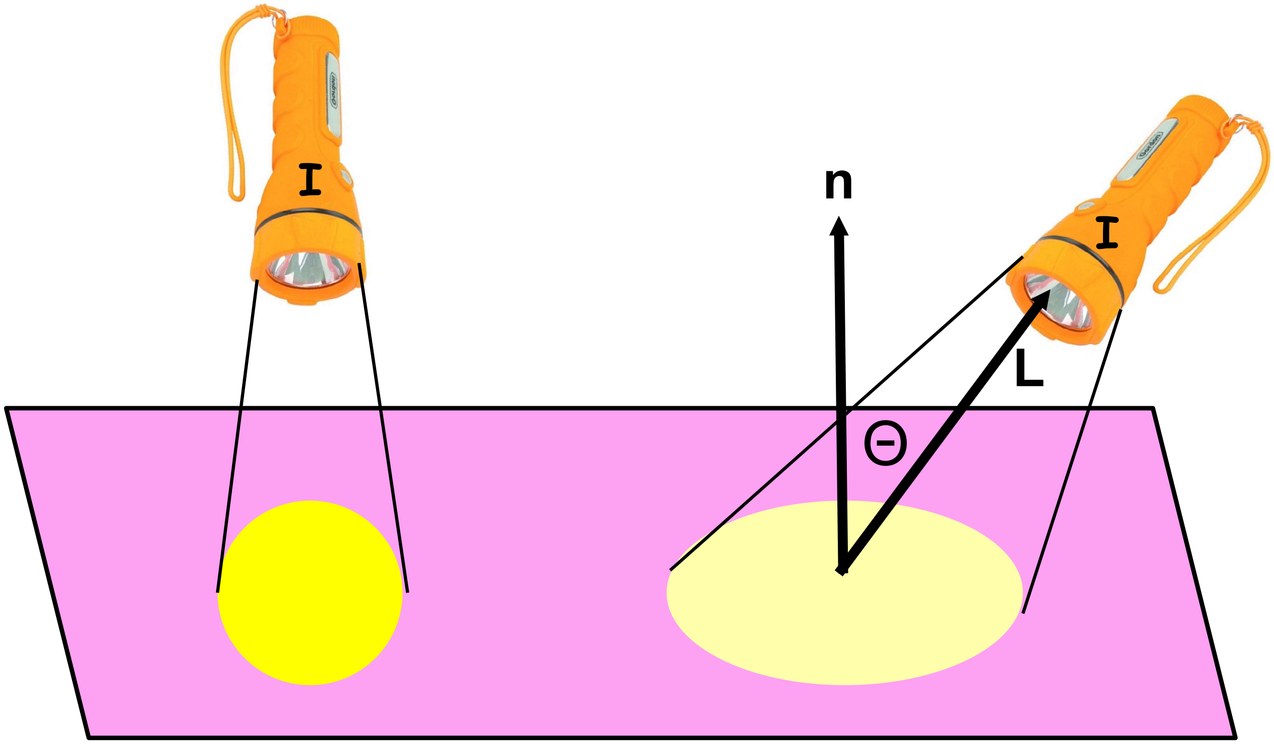
Note that $\cos\phi$ is just the dot product between unit vectors **R** and **E**

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

Diffuse = I*cosΘ



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

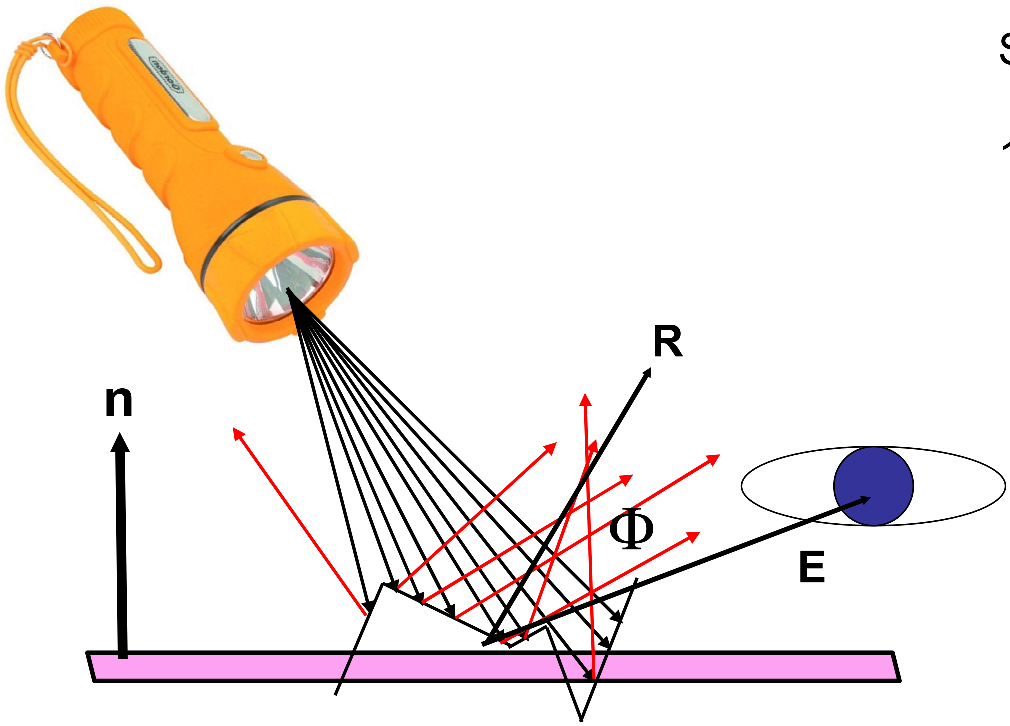
These are not actually metal. They are wood with special paint that mimics the metallic reflection highlights. We can mimic the same effects digitally!

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

$$\textbf{Specular} = I^* \cos^S \phi$$

S ≈ "shininess"

1/S ≈ "roughness"



The Three Elements of Built-in OpenGL Lighting

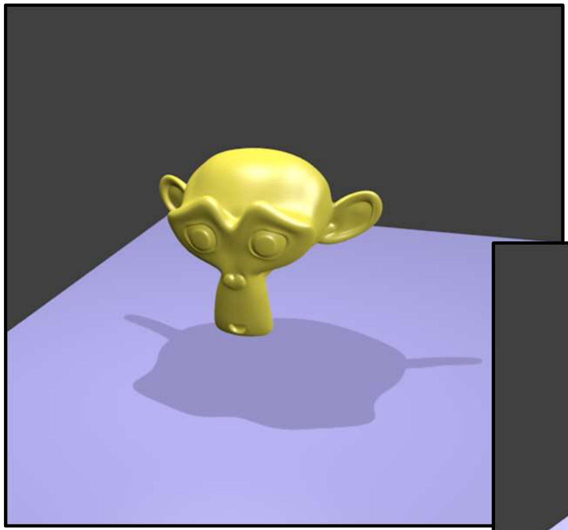
+

+

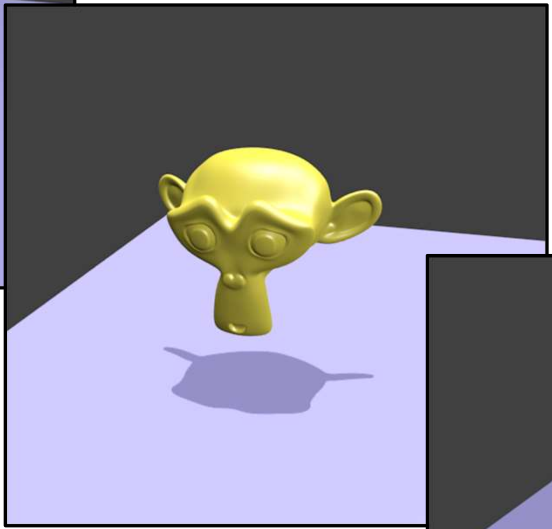
=

Types of Light Sources

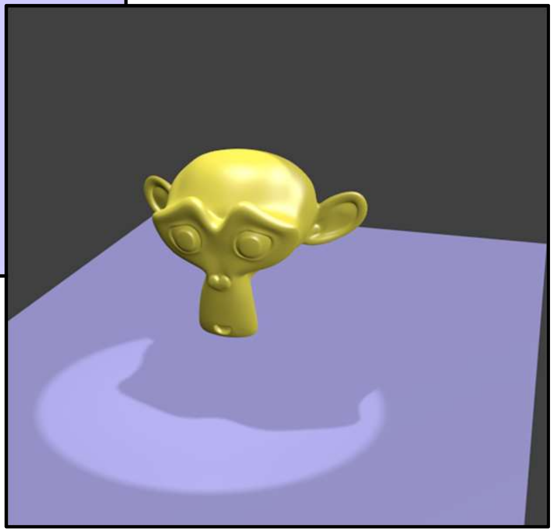
Point



Directional (Parallel, Sun)

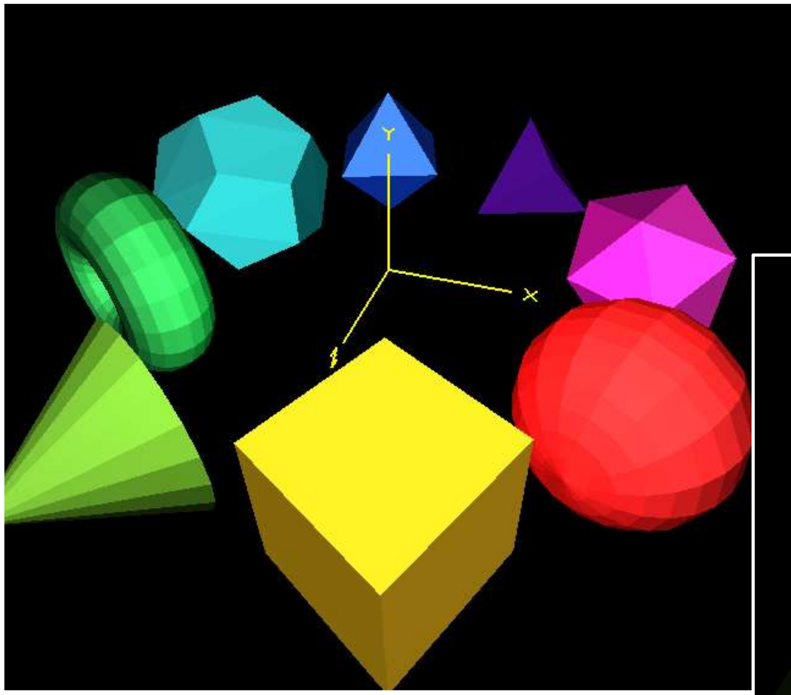


Spotlight

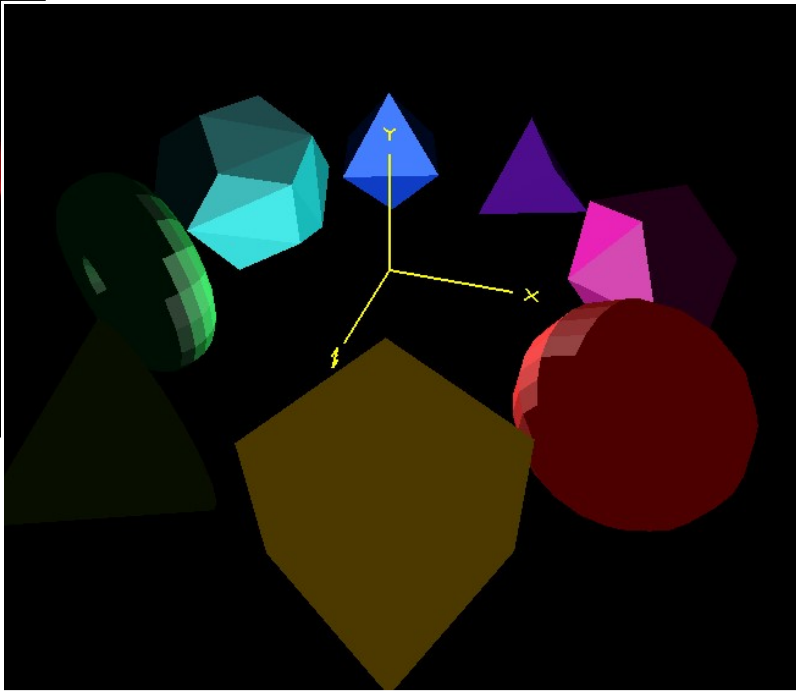


Lighting Examples

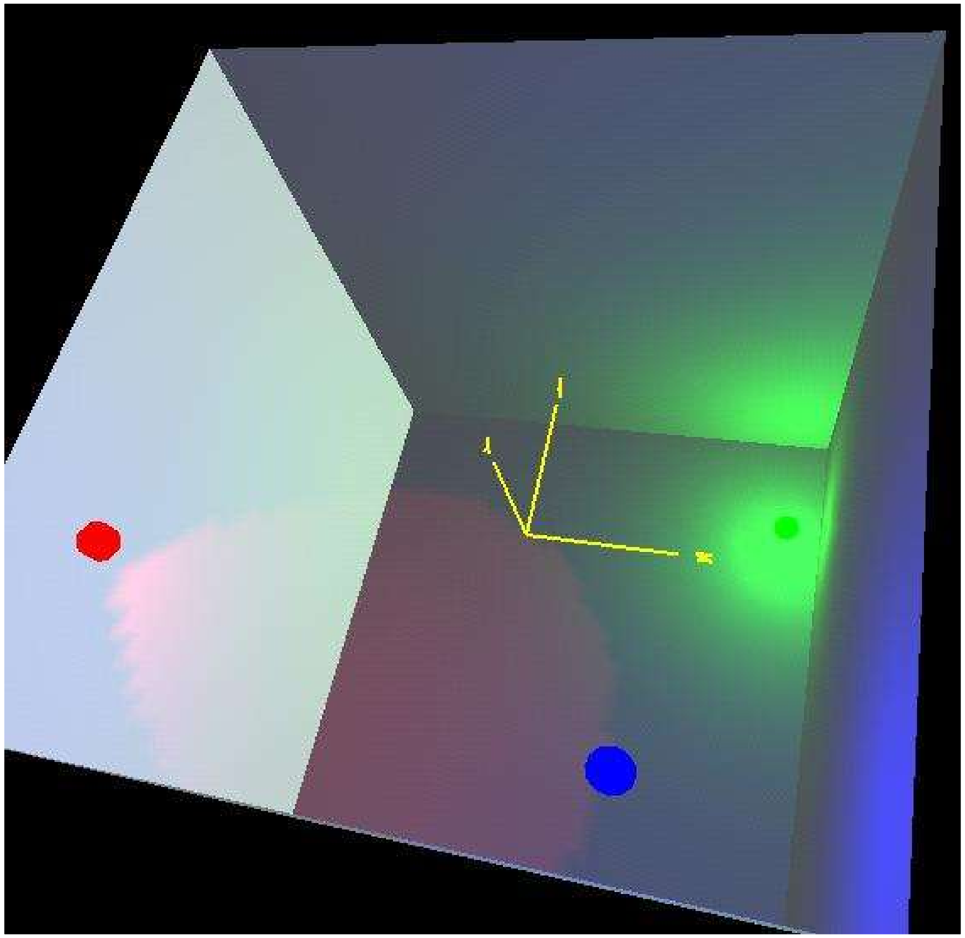
Point Light at the Eye



Point Light at the Origin



Lighting Examples



Spot Lights

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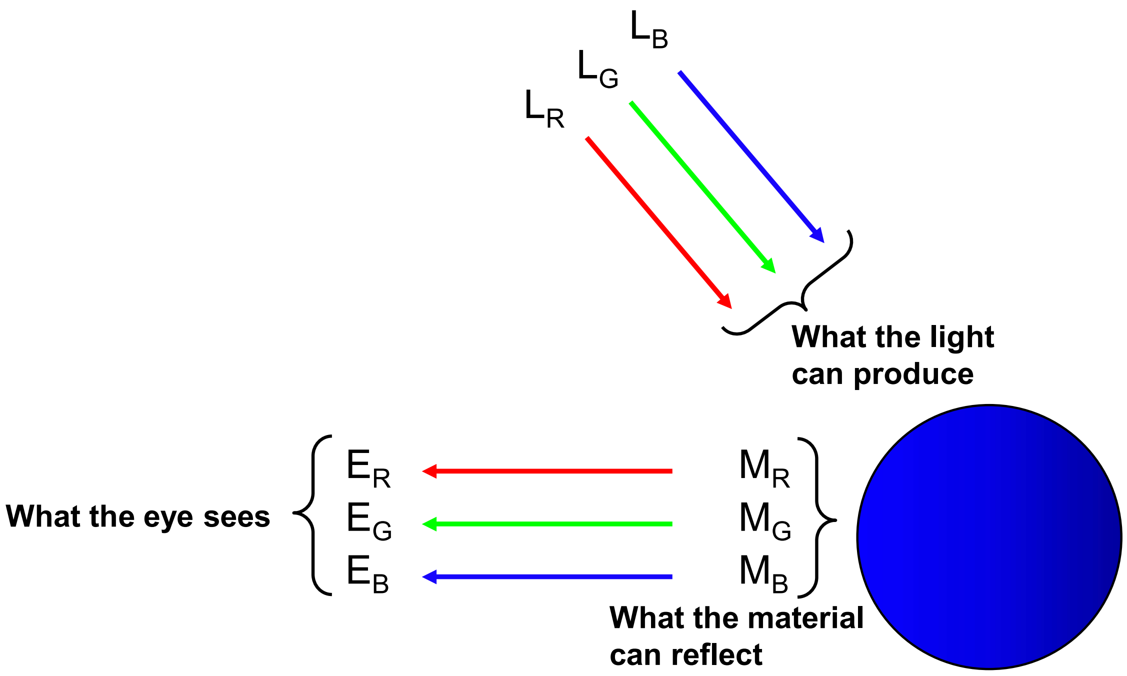
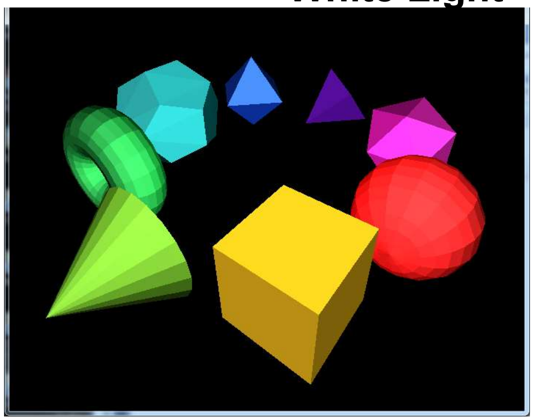
Colored Lights Shining on Colored Objects

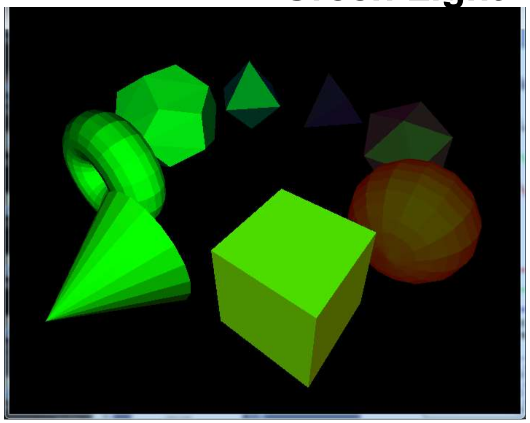


$$E_R = L_R * M_R$$
$$E_G = L_G * M_G$$
$$E_B = L_B * M_B$$

White Light



Green Light



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.

```
const float  WHITE[ ] = { 1.,1.,1.,1. };

// utility to create an array from 3 separate values:

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;
}

// utility to create an array from a multiplier and an 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

```
glMaterialfv( GL_BACK,  GL_AMBIENT,    MulArray3( .4, WHITE ) );
glMaterialfv( GL_BACK,  GL_DIFFUSE,     MulArray3( 1., 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,    MulArray3( 1., rgb ) );
glMaterialfv( GL_FRONT, GL_DIFFUSE,     MulArray3( 1., rgb ) );
glMaterialfv( GL_FRONT, GL_SPECULAR, MulArray3( .7, WHITE ) );
glMaterialf (  GL_FRONT, GL_SHININESS, 8. );
glMaterialfv( GL_FRONT, GL_EMISSION,   Array3( 0., 0., 0. ) );
```

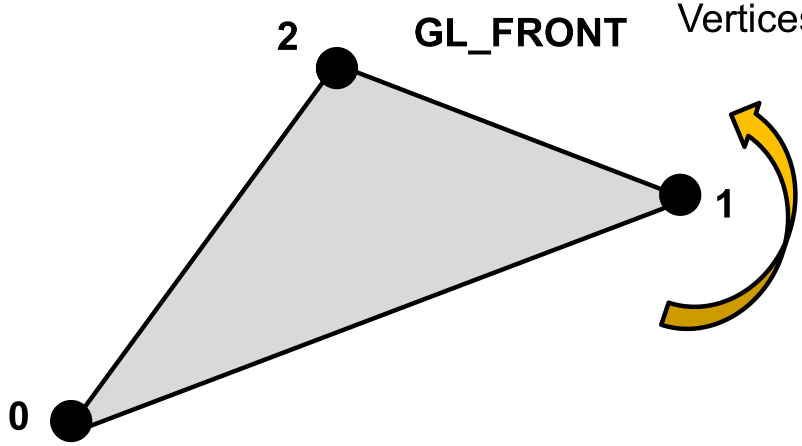
Characteristics for the back-facing surfaces

Characteristics for the front-facing surfaces

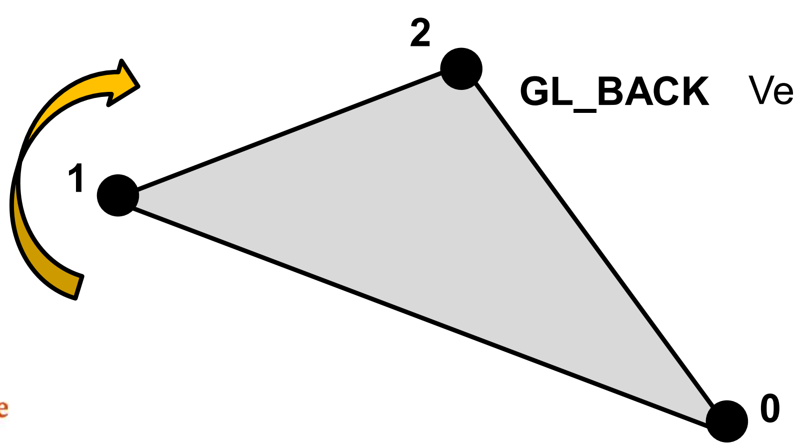
```
glMaterialfv( GL_FRONT_AND_BACK, . . . );
```

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

How Does OpenGL Define GL_FRONT and GL_BACK?



Vertices are CCW from the point of view of the eye



Vertices are CW from the point of view of the eye

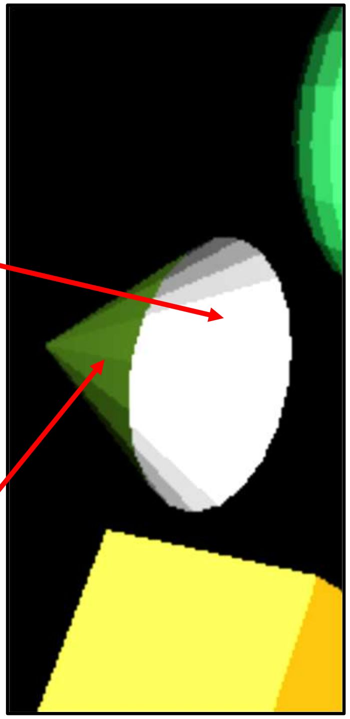
A Material-setting Helper Function I Like to Use

```
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 );
}
```

Back-facing= gray

Front-facing = (r,g,b)



This code is in your sample code folder in the file *setmaterial.cpp*

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Setting the Light Characteristics

```
glEnable( GL_LIGHTING );
glEnable( GL_LIGHT0 );
glLightModelfv( GL_LIGHT_MODEL_AMBIENT, MulArray3( .2, WHITE ) );
glLightModeli (  GL_LIGHT_MODEL_TWO_SIDE, GL_TRUE );


glLightfv( GL_LIGHT0, GL_AMBIENT,   Array3( 0., 0., 0. ) );
glLightfv( GL_LIGHT0, GL_DIFFUSE,     LightColor );
glLightfv( GL_LIGHT0, GL_SPECULAR,  LightColor );


glLightf (  GL_LIGHT0, GL_CONSTANT_ATTENUATION,  1. );
glLightf (  GL_LIGHT0, GL_LINEAR_ATTENUATION,        0. );
glLightf (  GL_LIGHT0, GL_QUADRATIC_ATTENUATION, 0. );

 // this is here because we are going to do object (and thus normal) scaling:

glEnable( GL_NORMALIZE );
```

You can have multiple lights, nominally 0-7

Attenuation = $\dfrac{1}{C + Ld + Qd^2}$ where *d* is the distance from the light to the point being lit

Light Attenuation

Attenuation = $\dfrac{1}{C + Ld + Qd^2}$ 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, $\dfrac{1}{d^2}$
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.**

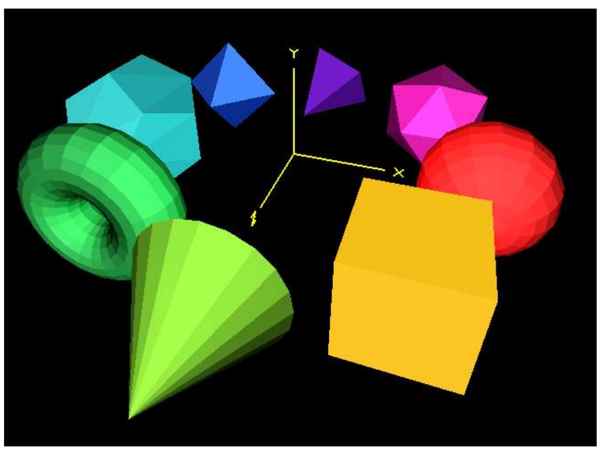
```
glLightf (  GL_LIGHT0, GL_CONSTANT_ATTENUATION,  1. );
glLightf (  GL_LIGHT0, GL_LINEAR_ATTENUATION,        0. );
glLightf (  GL_LIGHT0, GL_QUADRATIC_ATTENUATION, 0. );
```

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

Should OpenGL Use the Lighting Equations or Use glColor3f?

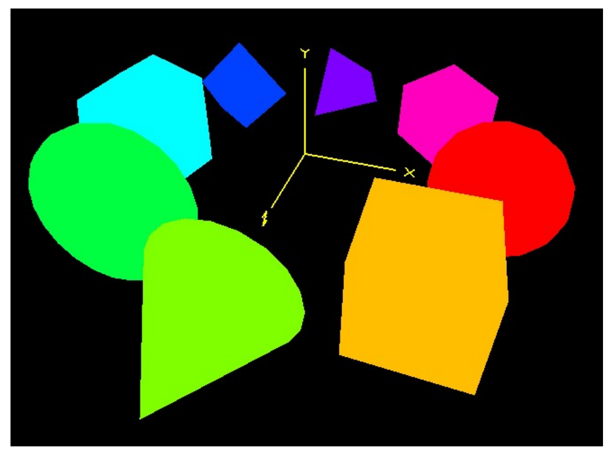
If your code has most recently said:
glEnable(GL_LIGHTING);

OpenGL will use the most recent Lighting values
OpenGL will use the most recent Material values



If your code has most recently said:
glDisable(GL_LIGHTING);

OpenGL will use the most recent glColor3f values



Setting the Light Position

The light position gets transformed by the **ModelView matrix** at the moment the **glLghtfv(…, GL_POSITION, …)** function is encountered. It is *really important* to remember this!

```
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) );
```

```
// perform the rotations and scaling about the origin:

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:

// glLightfv( GL_LIGHT0, GL_POSITION,  Array3(XLIGHT, YLIGHT, ZLIGHT) );


// specify the shading model:

glShadeModel( GL_SMOOTH );


// enable lighting:
glEnable( GL_LIGHTING );

glEnable( GL_LIGHT0 );


// draw the objects:
    . . .
glDisable( GL_LIGHTING );
```

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

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

```
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;
}
```

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.

$$X = \frac{x}{w}, Y = \frac{y}{w}, Z = \frac{z}{w}$$

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**.

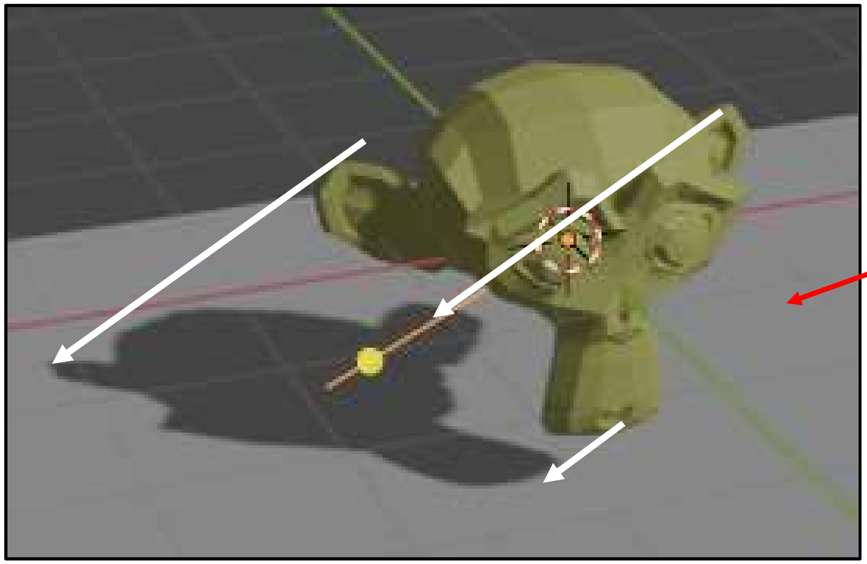
The point (1,2,3,1) represents the 3D point (1,2,3)

The point (1,2,3,.5) represents the 3D point (2,4,6)

The point (1,2,3,.01) 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

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

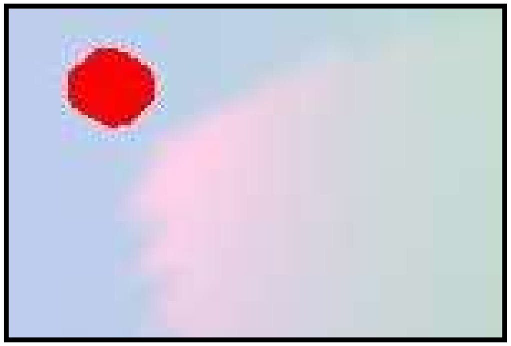
Specifies the spotlight-pointing direction. This gets transformed by the current value of the ModelView matrix.

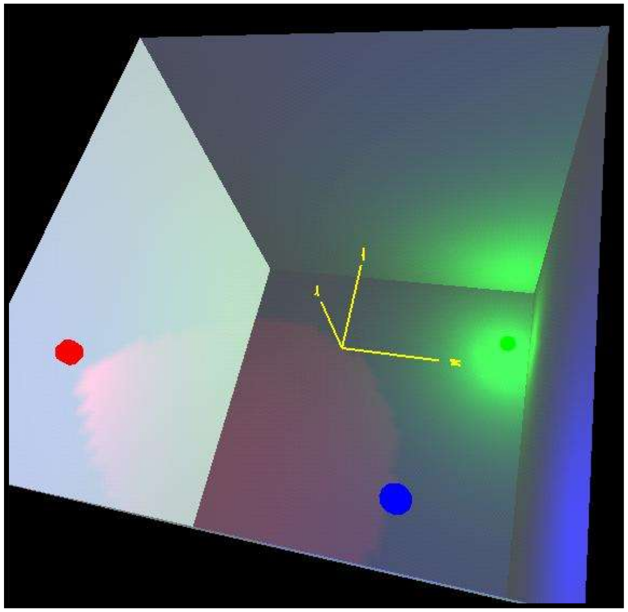
glLightf(GL_LIGHT0, GL_SPOT_EXPONENT, e);

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

glLightf(GL_LIGHT0, GL_SPOT_CUTOFF, deg);

Specifies the spotlight maximum spread angle. A cutoff angle of 180° indicates that this is really a point light.





Three bouncing spotlights

Two Light-setting Helper Functions I Like to Use

```
void
SetPointLight( int ilight, float x, float y, float z,  float r, float g, float b )
{
        glLightfv( ilight, GL_POSITION,  Array3( x, y, z ) );
        glLightf(  ilight, GL_SPOT_CUTOFF, 180.f );
        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.f );
        glLightf ( ilight, GL_LINEAR_ATTENUATION, 0.f );
        glLightf ( ilight, GL_QUADRATIC_ATTENUATION, 0.f );
        glEnable( ilight );
}
```

ilight would be GL_LIGHT0, for example

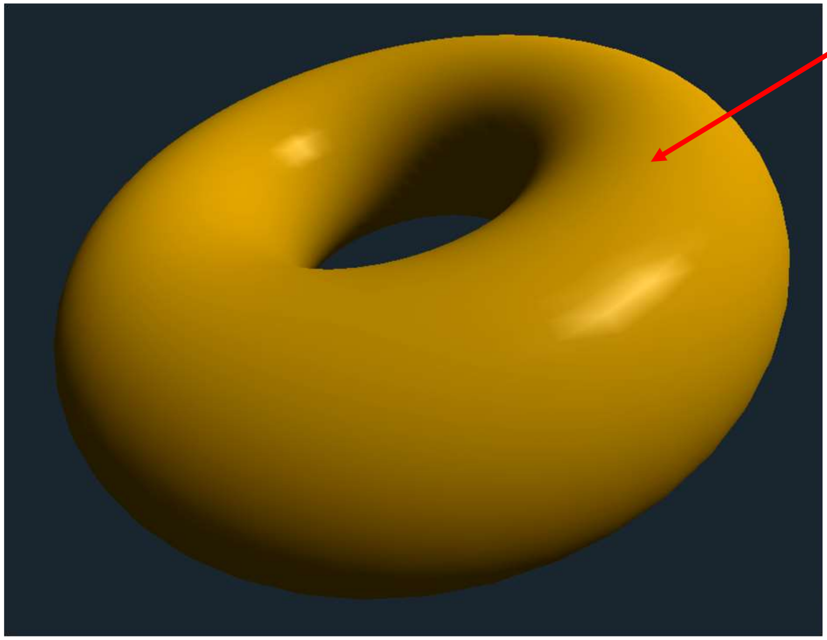
```
void
SetSpotLight( int ilight, float x, float y, float z,  float xdir, float ydir, float zdir, float r, float g, float b )
{
        glLightfv( ilight, GL_POSITION,  Array3( x, y, z ) );
        glLightfv( ilight, GL_SPOT_DIRECTION,  Array3(xdir,ydir,zdir) );
        glLightf(  ilight, GL_SPOT_EXPONENT, 1.f );
        glLightf(  ilight, GL_SPOT_CUTOFF, 30.f );
        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.f );
        glLightf ( ilight, GL_LINEAR_ATTENUATION, 0.f );
        glLightf ( ilight, GL_QUADRATIC_ATTENUATION, 0.f );
        glEnable( ilight );
}
```

This code is in your sample code folder in the file *setlight.cpp*

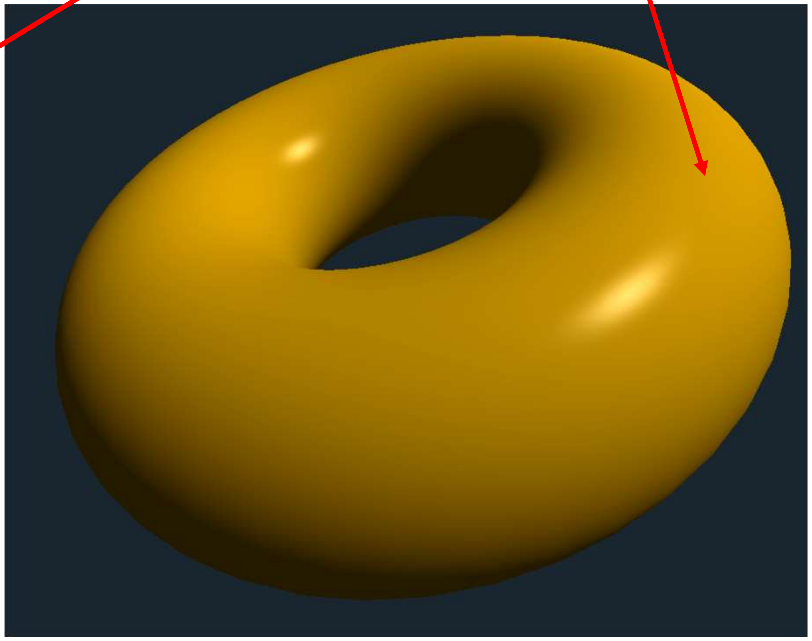
Sidebar: Note that we are computing the light intensity at each vertex first, and then interpolating that intensity across the polygon second

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:



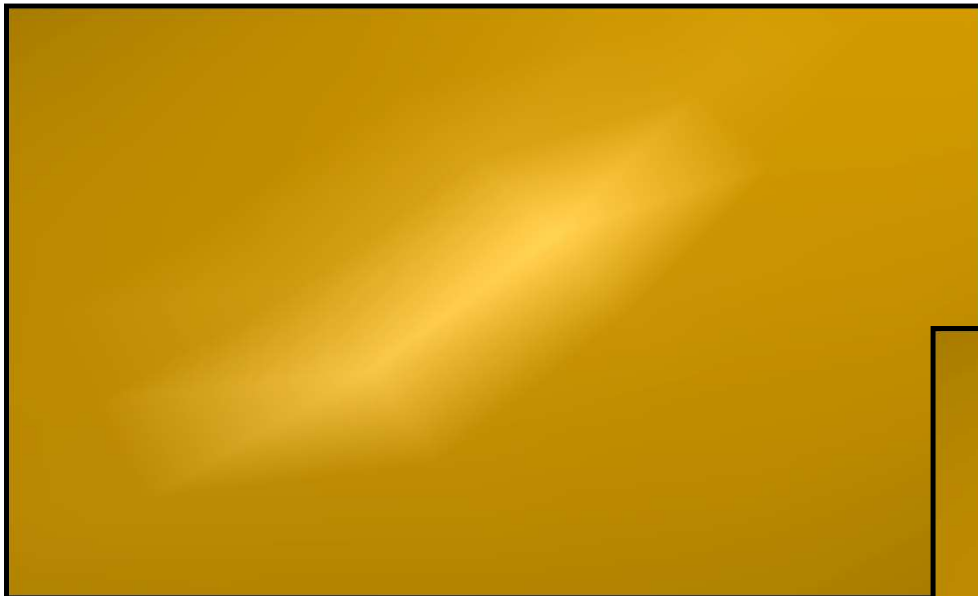
Per-vertex

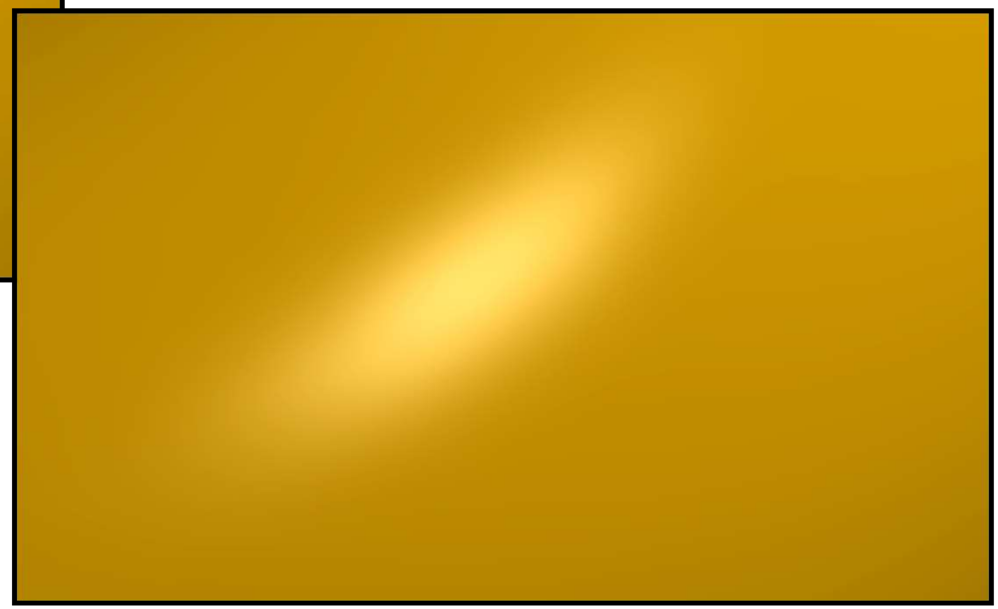


Per-fragment

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

Per-vertex





Per-fragment

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

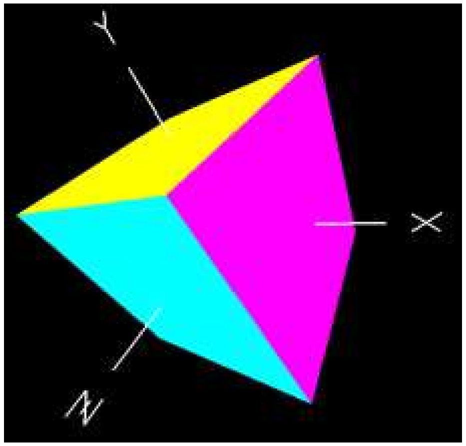
Before, when we talked about per-vertex normal vectors, we did this:

```
glMatrixMode( GL_MODELVIEW );

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

glShadeModel( GL_SMOOTH );

glColor3f( r, g, b );
glBegin(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 );
glEnd( );
```

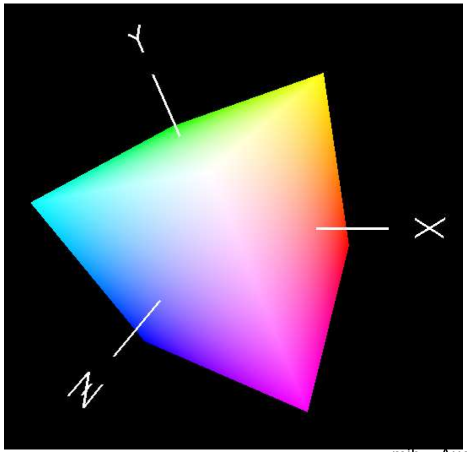
We can also provide per-vertex *colors* to do this:

```
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 );
        glVertex3f( x2, y2, z2 );
glEnd( );
```

Flat

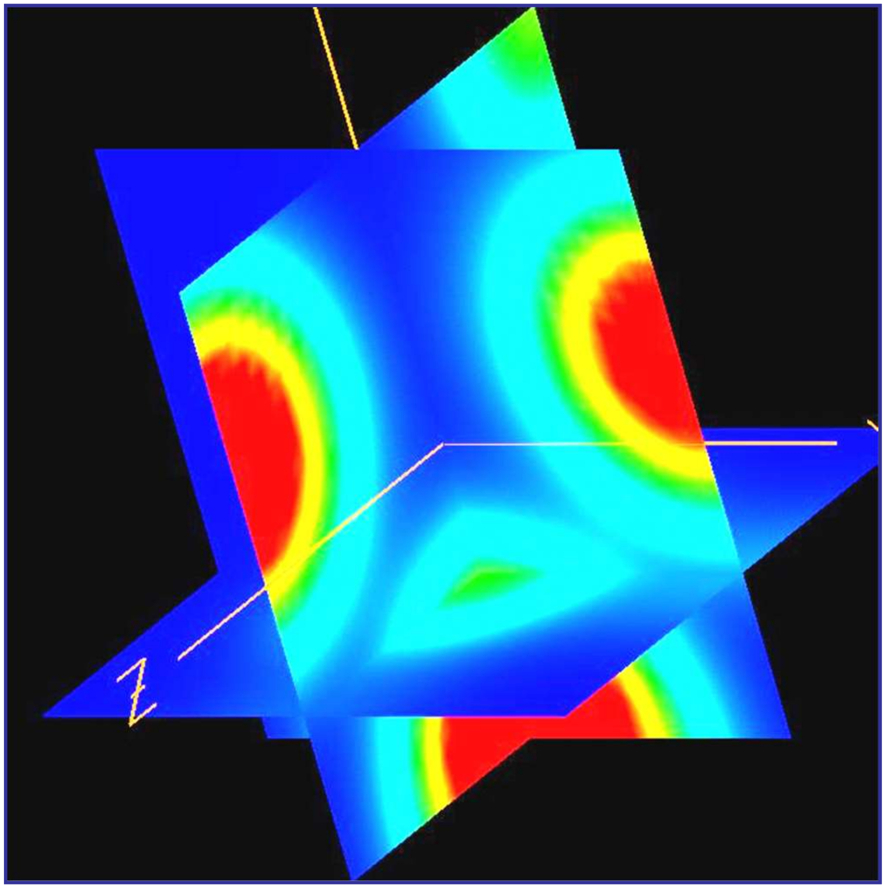


Smooth



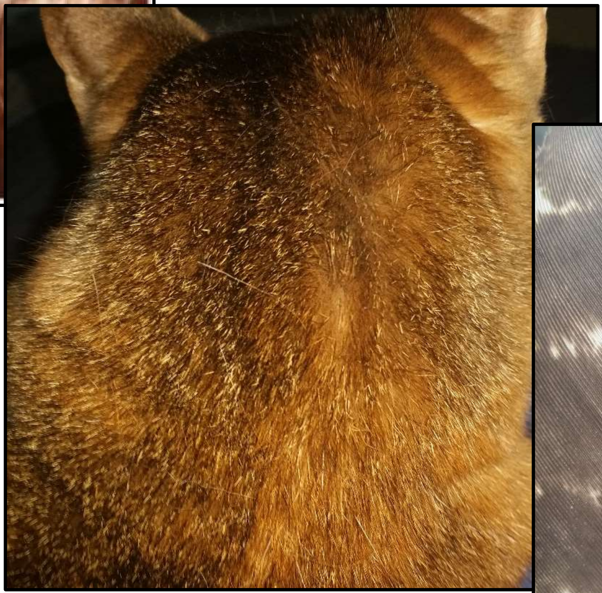
Smooth Shading can also interpolate vertex colors, not just the results of the lighting model

This is especially useful when using colors for scientific visualization:



Tricky Lighting Situations

Hair



Fur

Feathers

Watch for these in movies!

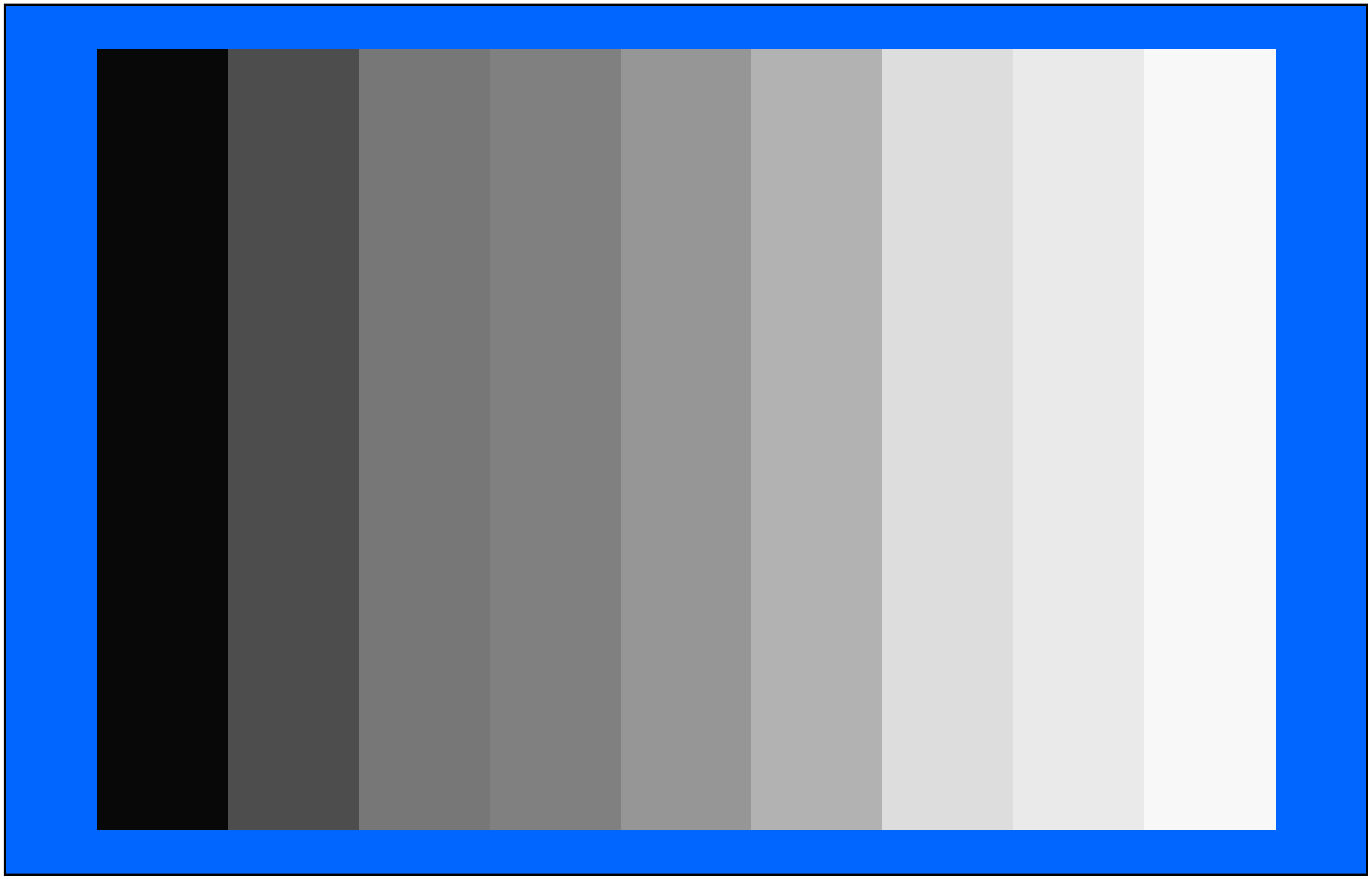
Tricky Lighting Situations

Disney

Sony/Columbia Pictures

Notice the lighting in the fur!

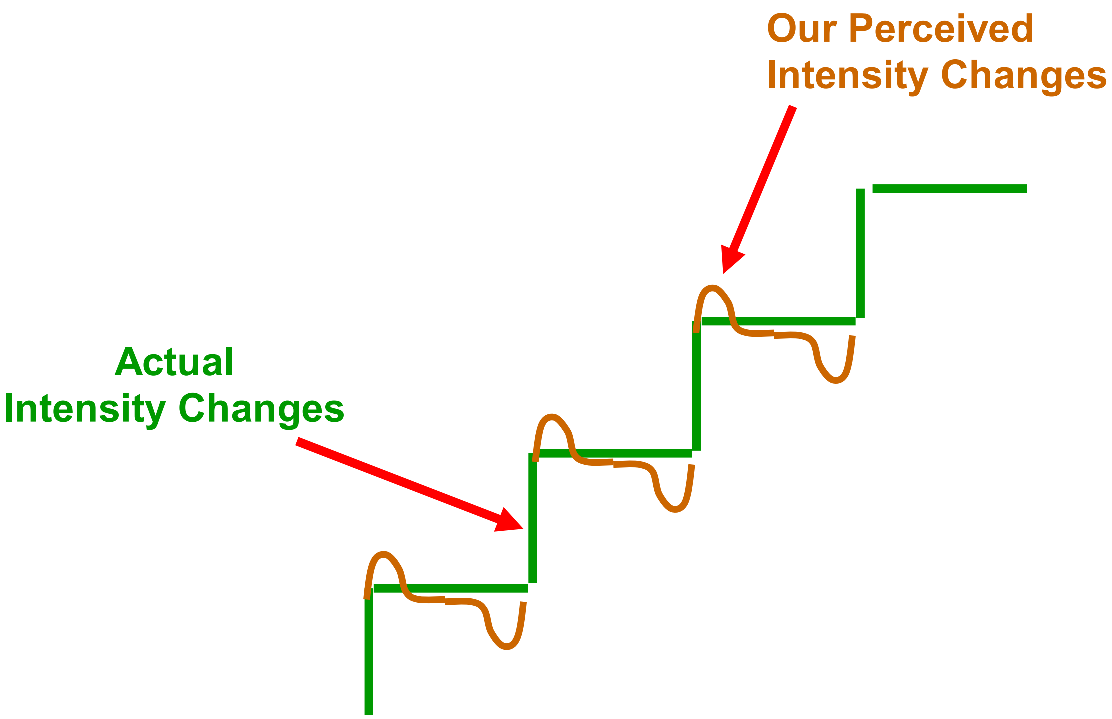
Sidebar: Beware of Mach Banding



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

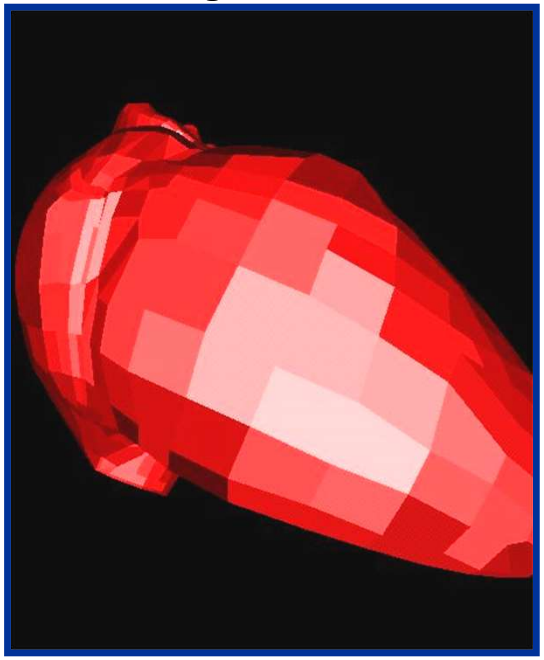
Our vision systems can't handle abrupt changes in intensity.



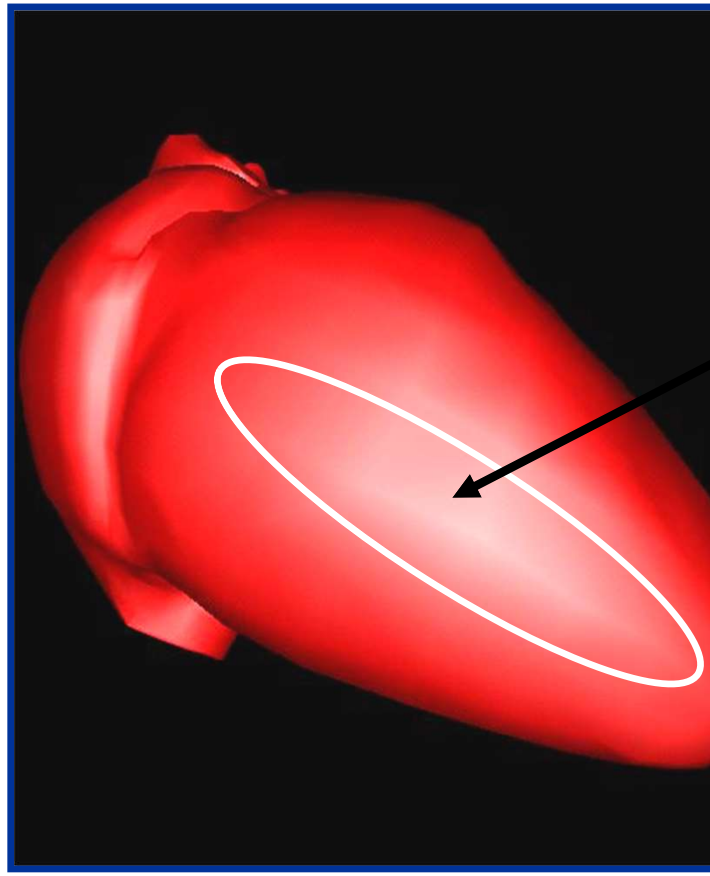
Beware of Mach Banding

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

Flat shading



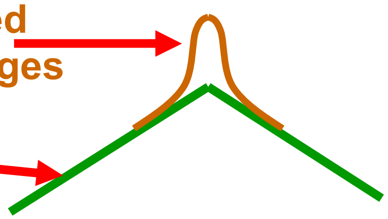
Smooth shading



This "white line" doesn't really exist – it is an artifact of our vision system!

Our Perceived Intensity Changes

Actual Intensity Changes



Beware of Mach Banding

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