Computer Graphics

8 - Lighting & Shading

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Spring 2020

Topics Covered

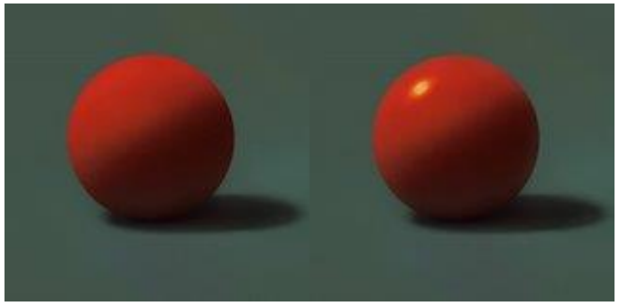
- Reflection of Light
- Phong Illumination Model
- Shading
  - Face / Vertex Normal
  - Flat / Goraud / Phong Shading
- Lighting & Shading in OpenGL

Reflection of Light

Reflection of Light

- Light can be absorbed(흡수), emitted(발산), scattered(산란), reflected(반사), or refracted(굴절) by objects.

- Scattering and reflection are the main factors in the visual characteristics of a object surface.
  - such as surface color, highlight on surface



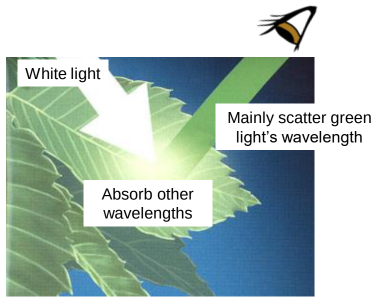
- Types of reflection:
  - Diffuse reflection
  - Specular reflection (ideal & non-ideal)

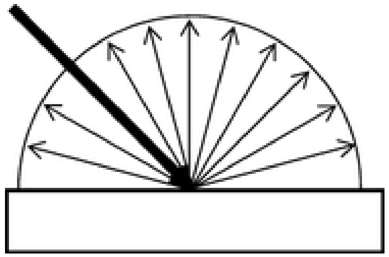
    - In computer graphics, both scattering and reflection are often referred to as "reflection"

Diffuse Reflection

- : Scattering specific light spectrum in all direction
- → Determines surface color

- **View-independent**





strongly scatters magenta's wavelengths

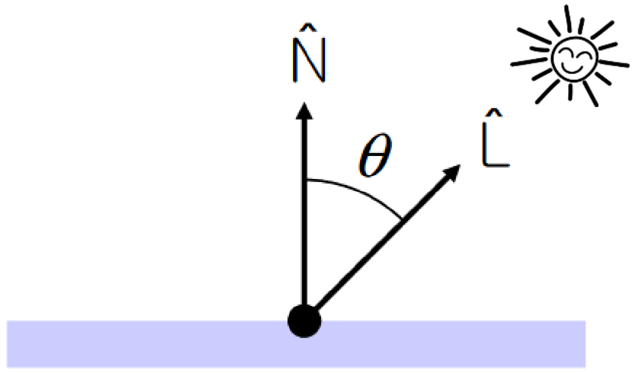
scatters wavelengths for all colors

scatters no colors (absorbs all colors)

Diffuse Reflection - Lambert’s Cosine Law

- The **reflected energy** from a small surface area is proportional to the **cosine of the angle** between **incident light direction** and the **surface normal**

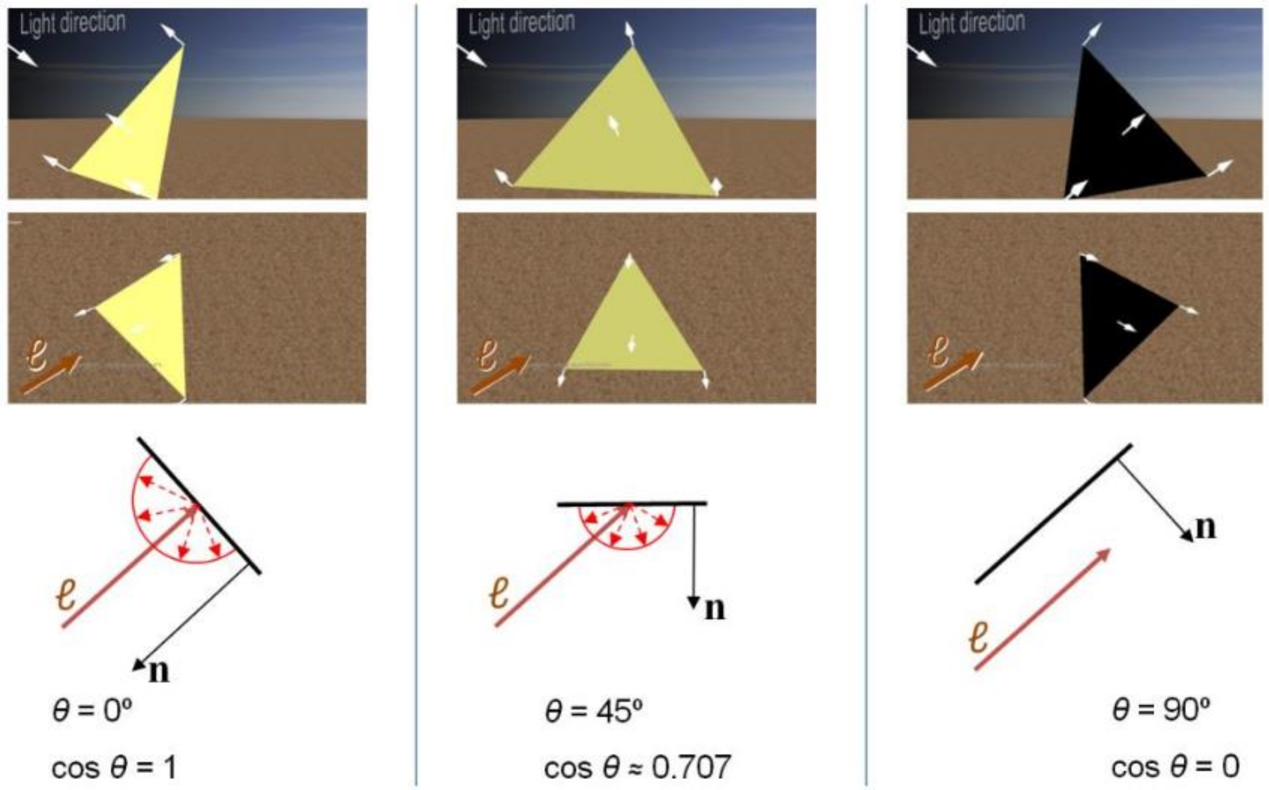
$$\begin{aligned} I_{reflected} &= I_{incident} cos\theta \\ &= I_{incident}(\hat{\mathbf{N}} \cdot \hat{\mathbf{L}}) \end{aligned}$$



$I_{reflected}$	intensity of reflected ray
$I_{incident}$	intensity of incident ray
$\hat{\mathbf{N}}$	normal to the reflection surface at the point of the incidence
$\hat{\mathbf{L}}$	normalized light direction vector

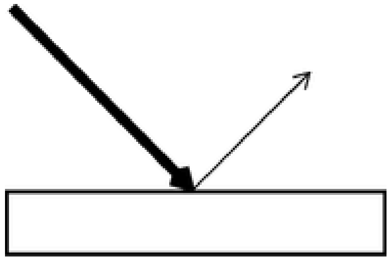
Diffuse Reflection - Lambert’s Cosine Law

- Visualization of Lambert's law in 2D
-



Ideal Specular Reflection

- : Mirror-like reflection of light from smooth, polished surface
- → Generate mirrored images

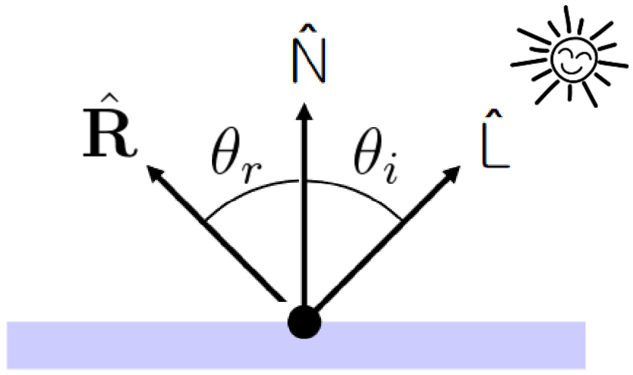


- **View-dependent**

Ideal Specular Reflection - Laws of Reflection (Special case of Snell's Law)

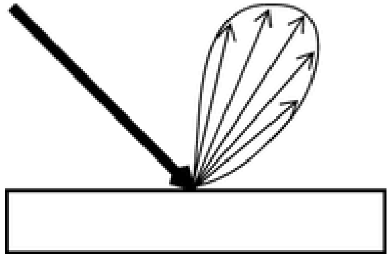
- $\hat{\mathbf{N}}, \hat{\mathbf{L}}, \hat{\mathbf{R}}$ lie in the same plane
- $\theta_r = \theta_i$
- ($\hat{\mathbf{L}}$ and $\hat{\mathbf{R}}$ are on the opposite sides of $\hat{\mathbf{N}}$)

$\hat{\mathbf{N}}$	normal to the reflection surface at the point of the incidence
$\hat{\mathbf{L}}$	normalized indicent ray direction vector
$\hat{\mathbf{R}}$	normalized reflected ray direction vector



Non-Ideal Specular Reflection (a.k.a. Glossy Reflection)

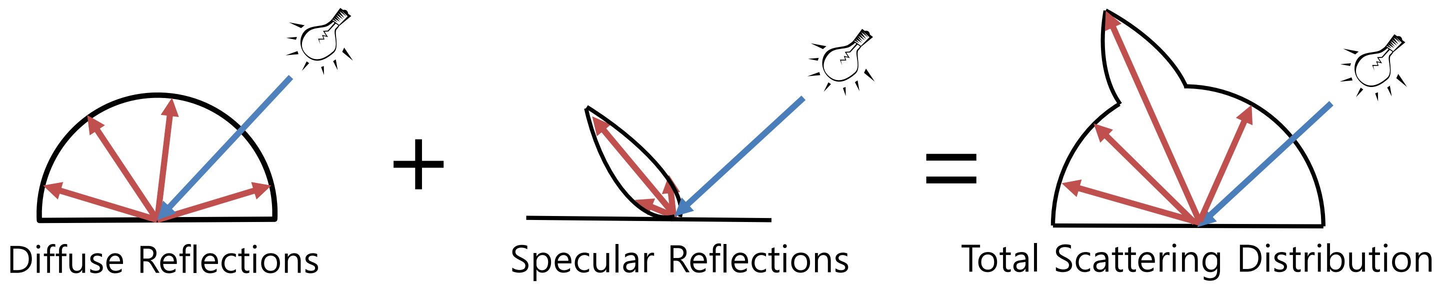
- : Reflection on shiny & glossy surface, but not as smooth as a mirror
- Reflected rays are “spread out” due to surface roughness
- → Generate bright highlights



- **View-dependent**

Reflection of General Materials

- Many materials' surface have both diffuse reflection and specular reflection.



Quiz #1

- Go to https://www.slido.com/
- Join #cg-hyu
- Click "Polls"

- Submit your answer in the following format:
  - **Student ID: Your answer**
  - **e.g. 2017123456: 4)**

- Note that you must submit all quiz answers in the above format to be checked for "attendance".

Phong Illumination Model

Lighting (or Illumination)

- **Lighting** (or **Illumination**): Process of computing effects of lights
- → Computing surface color and highlights of objects.

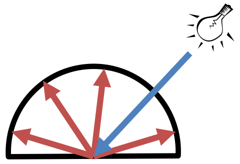
Phong Illumination Model

- One of the most commonly used "classical" illumination models in computer graphics
  - Empirical model, not physically based

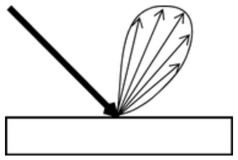
Bùi Tường Phong
(1942 – 1975)

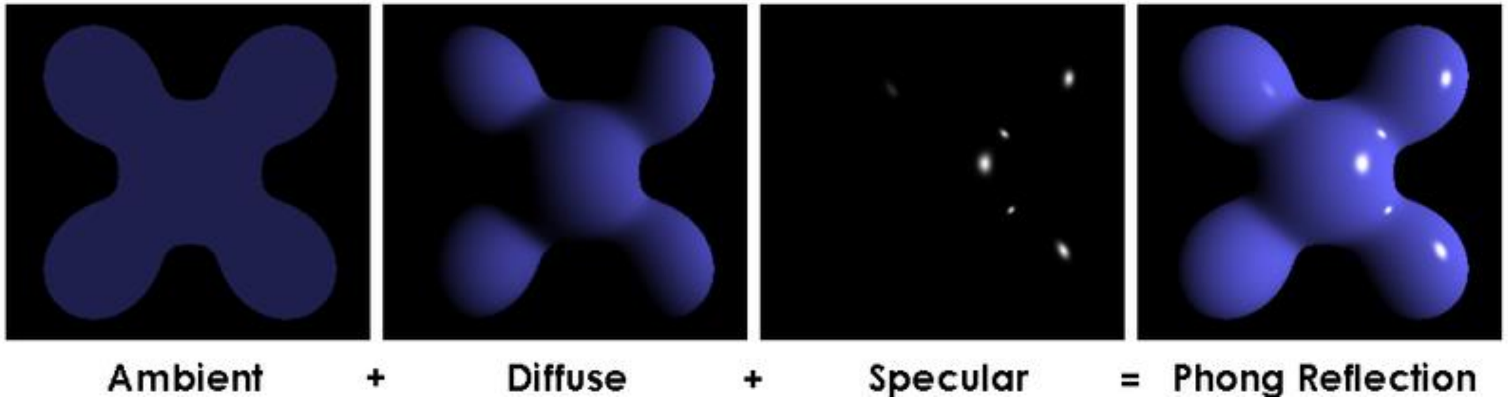
Phong Illumination Model

- Three components:
- **Ambient**
  - Non-specific constant global lighting
  - Crudest approximation for indirect lighting
- **Diffuse**
  - Color of object under normal conditions using Lambert's model



- **Specular**
  - Highlights on shiny objects
  - Approximation for glossy reflection using $\cos^n(\alpha)$





Ambient Light

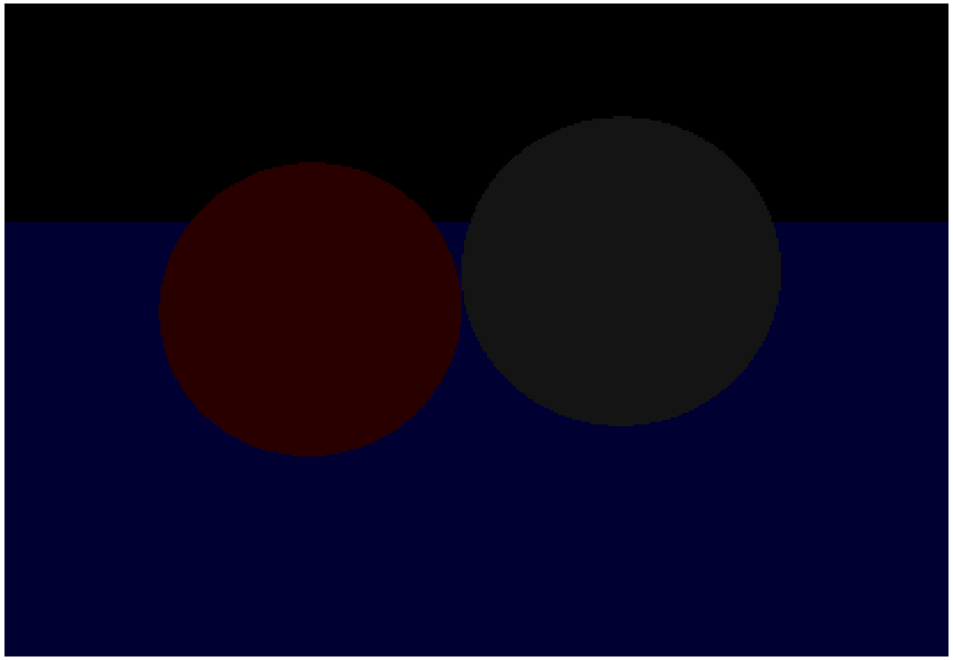
$$I = k_a C_a$$

- C_a =intensity of ambient light
- k_a=ambient reflection coefficient

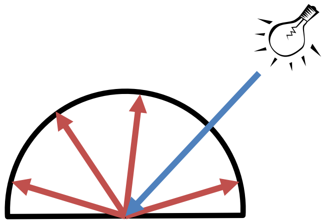
- Actually 3 equations for 3 C_as! (C_a^r, C_a^g, C_a^b for Red, Green, Blue)

Total Illumination

$$I = k_a C_a$$



Diffuse Light

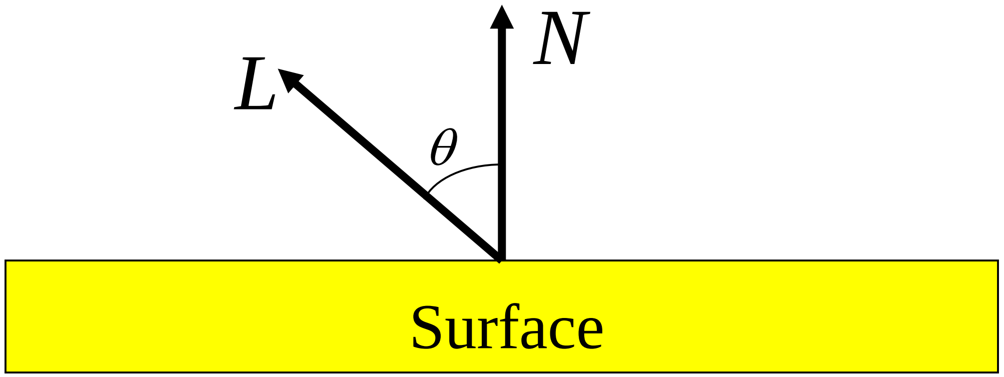


Lambert's Cosine Law

$$I = C_d k_d \boxed{\cos(\theta)} = C_d k_d (L \cdot N)$$

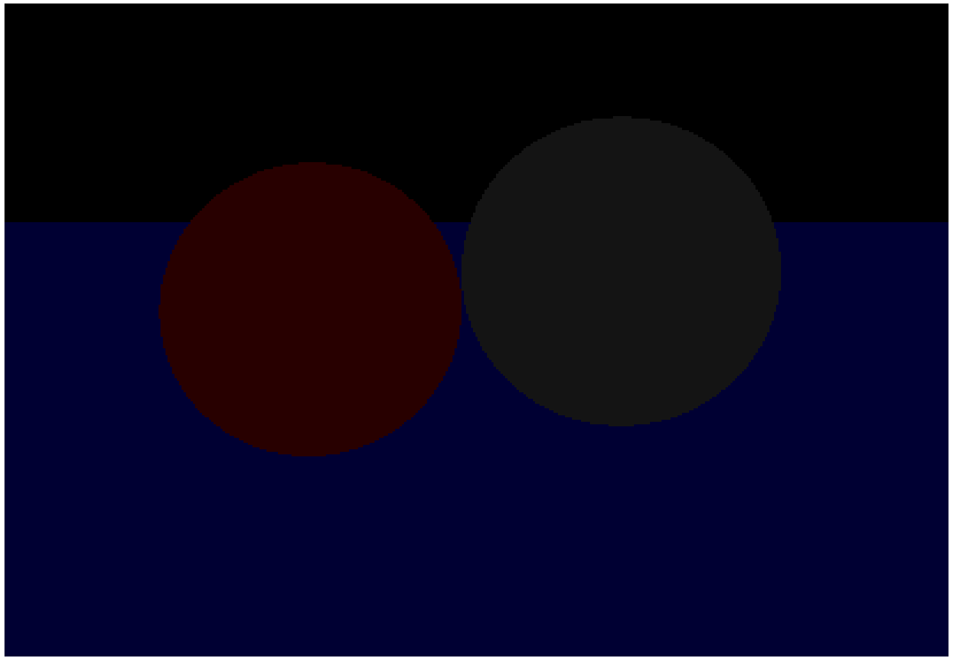
- C_d = intensity of light source (actually 3 equations for C_d^r, C_d^g, C_d^b)
- k_d = diffuse reflection coefficient
- θ = angle between normal and direction to light

$$\cos(\theta) = L \cdot N$$



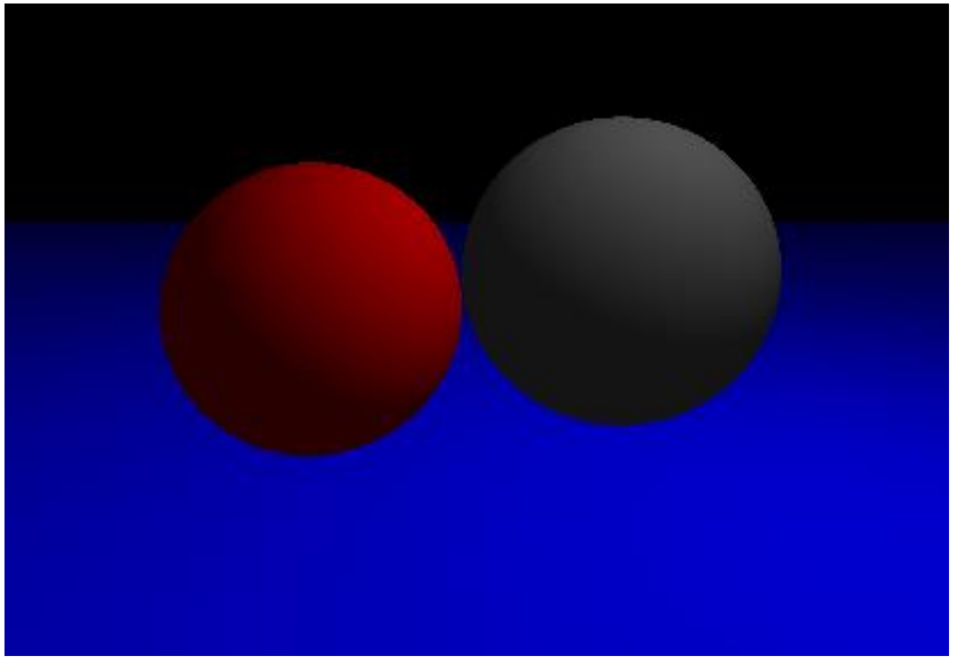
Total Illumination

$$I = k_a C_a$$



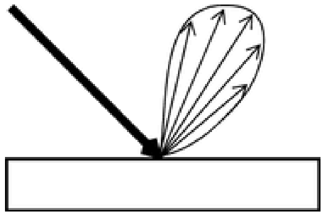
Total Illumination

$$I = k_a C_a + k_d C_d (L \cdot N)$$



Specular Light

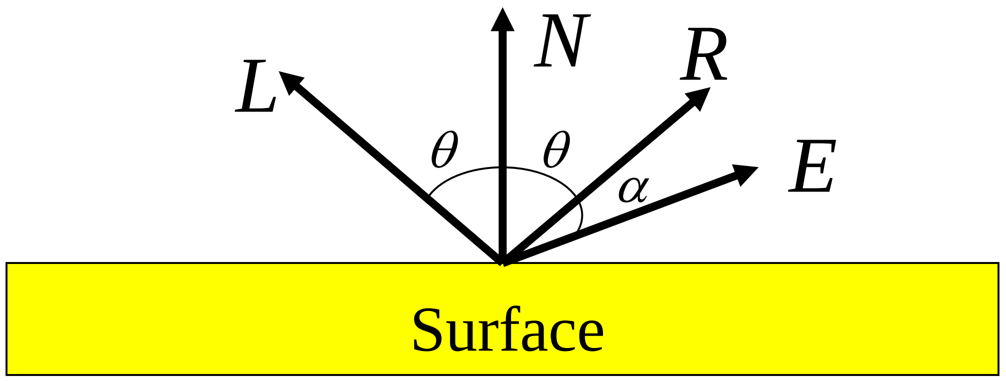
approximation for glossy reflection



$$I = C_s k_s \boxed{\cos^n(\alpha)} = C_s k_s (R \cdot E)^n$$

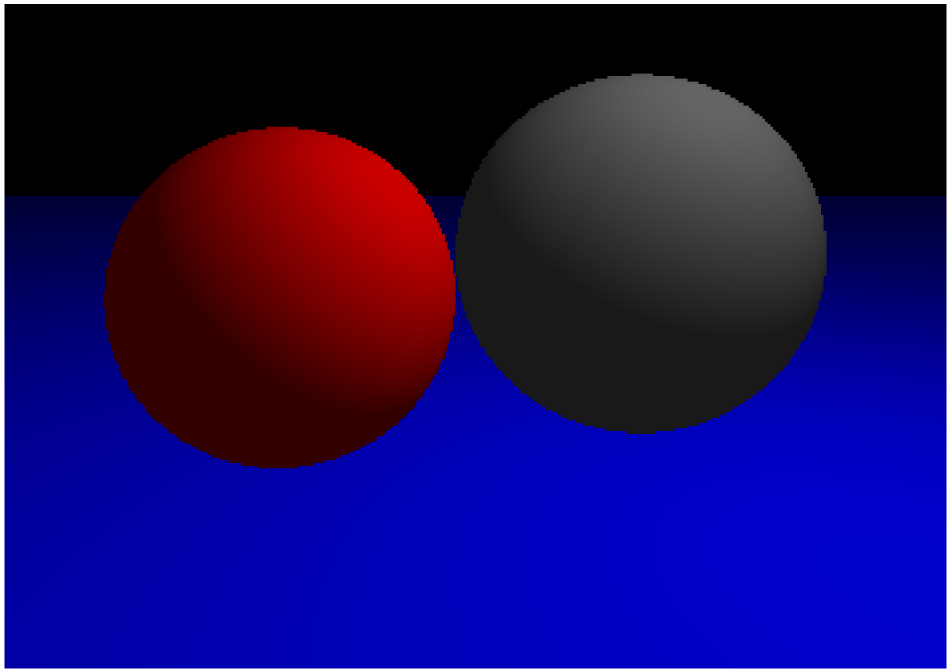
- C_s = intensity of light source (actually 3 eq: C_s^r, C_s^g, C_s^b)
- k_s = specular reflection coefficient
- α = angle between reflected vector (R) and eye (E)
- n = shininess coefficient

$$\cos(\alpha) = R \cdot E$$



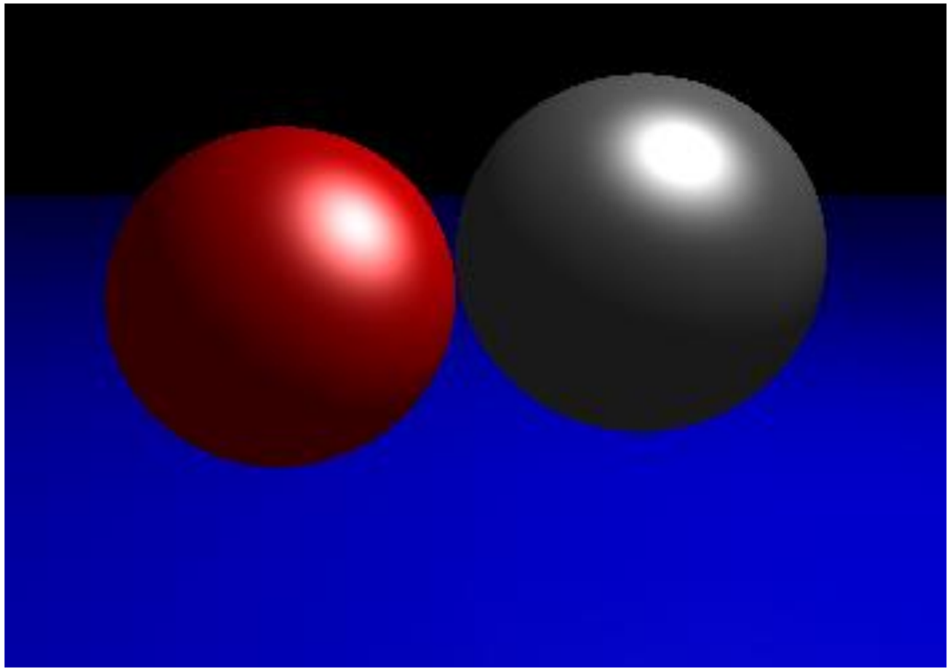
Total Illumination

$$I = k_a C_a + k_d C_d (L \cdot N)$$



Total Illumination

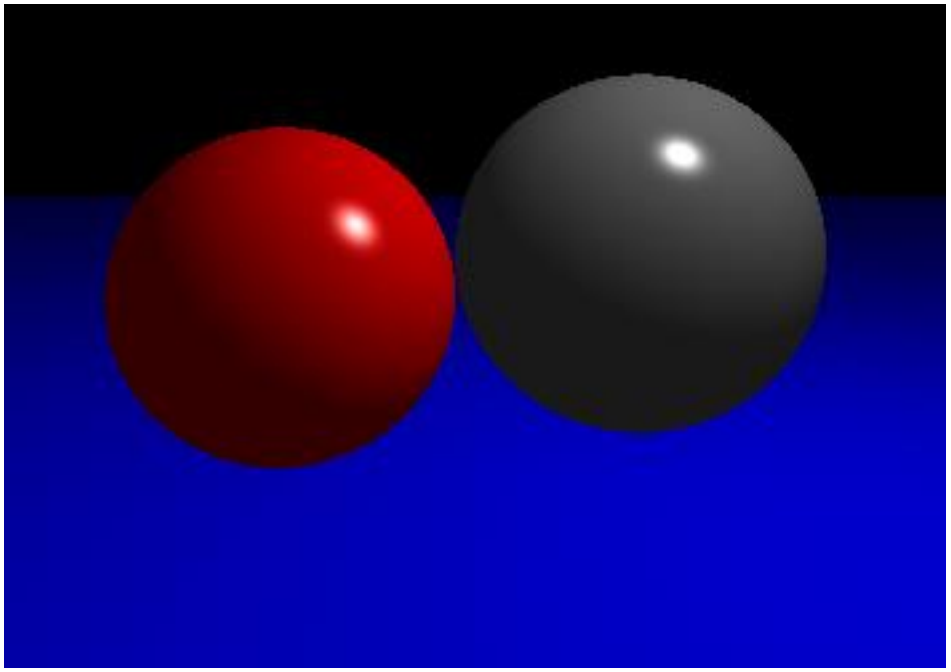
$$I = k_a C_a + k_d C_d (L \cdot N) + k_s C_s (R \cdot E)^n$$



$n=5$

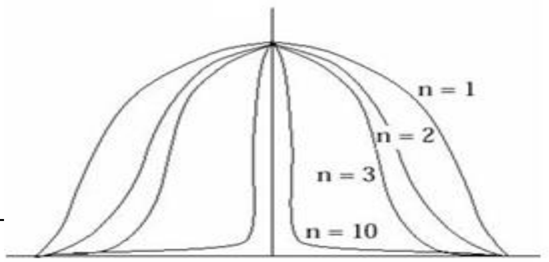
Total Illumination

$$I = k_a C_a + k_d C_d (L \cdot N) + k_s C_s (R \cdot E)^n$$



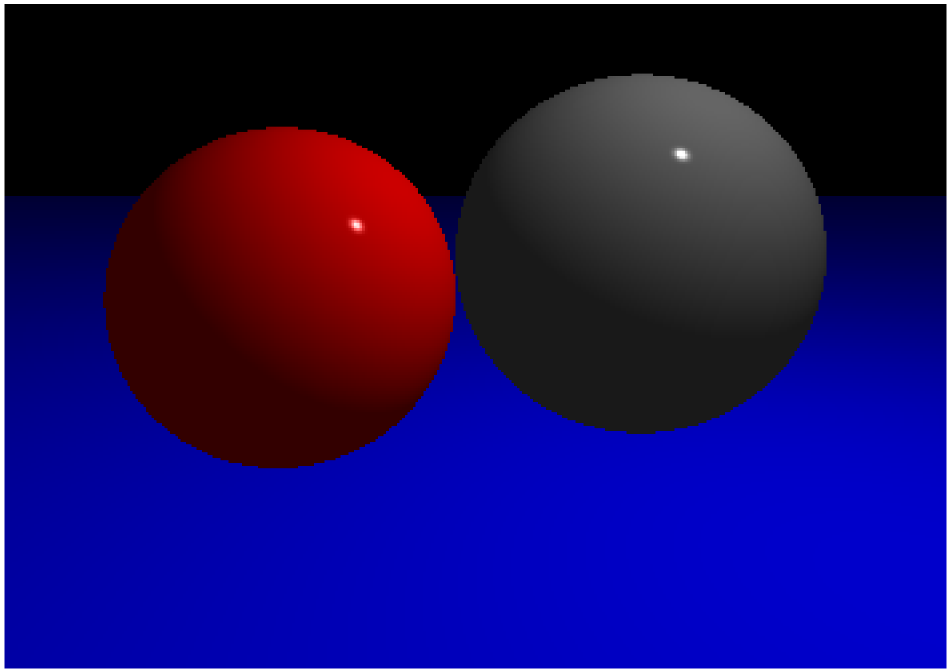
$$n = 50$$

Total Illumination



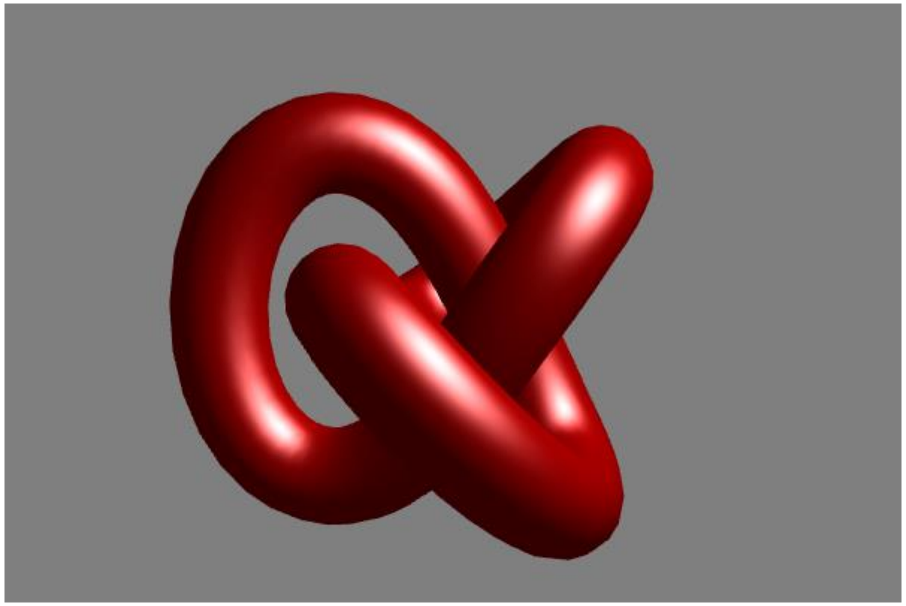
Specular falloff of $(\cos \delta)^n$

$$I = k_a C_a + k_d C_d (L \cdot N) + k_s C_s (R \cdot E)^n$$



$n = 500$

[Practice] Phong Illumination Demo



http://www.cs.toronto.edu/~jacobson/phong-demo/

- First set the value of the first drop down box to “Phong Shading”
- Try to change
  - reflection coefficient and color of ambient, diffuse, and specular
  - specular shininess
  - you can also change object type, light position and background color

Quiz #2

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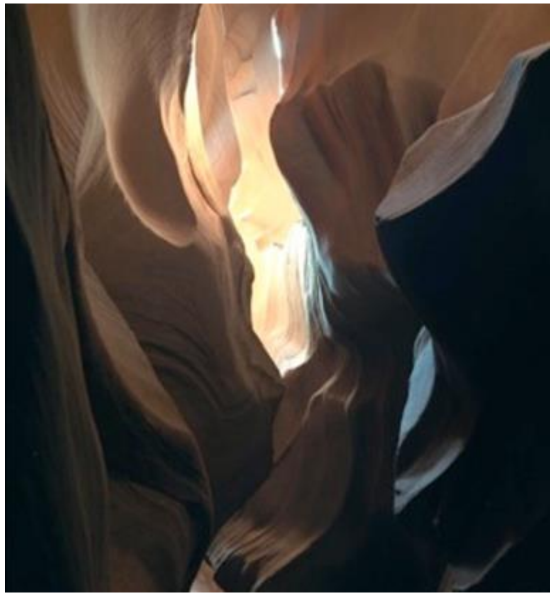
Shading

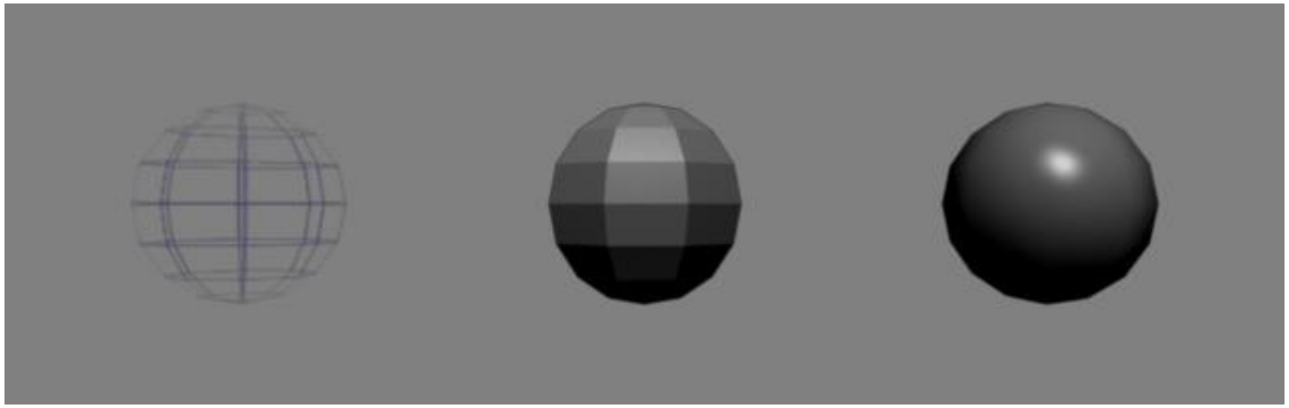
Shading - General Meaning

- Variation in observed color across an object
  - Strongly affected by lighting



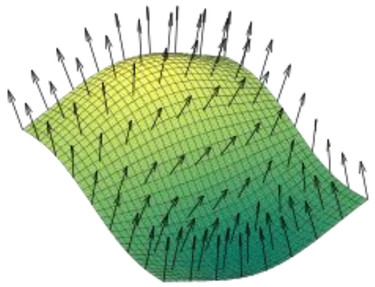
Shading - Meaning in Computer Graphics

- The process of determining **each pixel color in a polygon** based on a illumination model



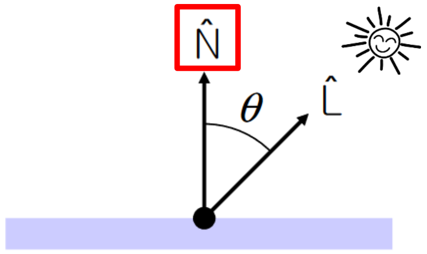
Surface Normal

- A vector that is perpendicular to the surface at a given point
  - A unit normal vector (of length 1) is generally used



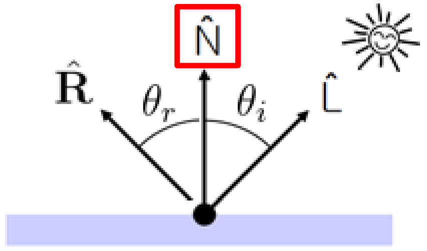
- Plays a key role in shading & illumination process

- Diffuse reflection
  - Lambert's Cosine Law



$$I_{reflected} = I_{incident} cos\theta$$

- Specular reflection
  - Laws of Reflection



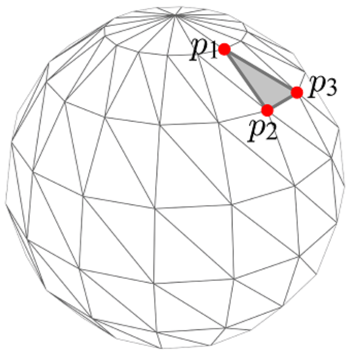
$$\theta_r = \theta_i$$

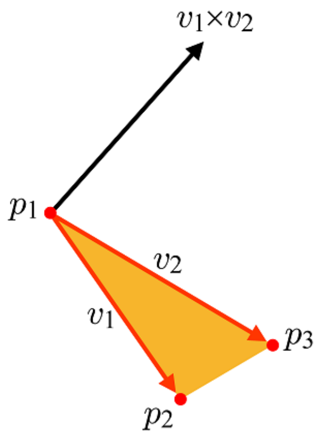
Face Normal

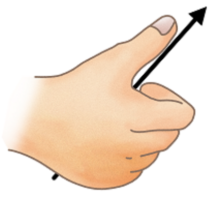
- How to get <u>the surface normal of a polygonal face</u>?

The order does matter! $\xrightarrow{\qquad}$

- The normal of a triangle **<p1, p2, p3>** is computed as v1×v2
  - v1 is the vector connecting p1 and p2, v2 connects p1 and p3





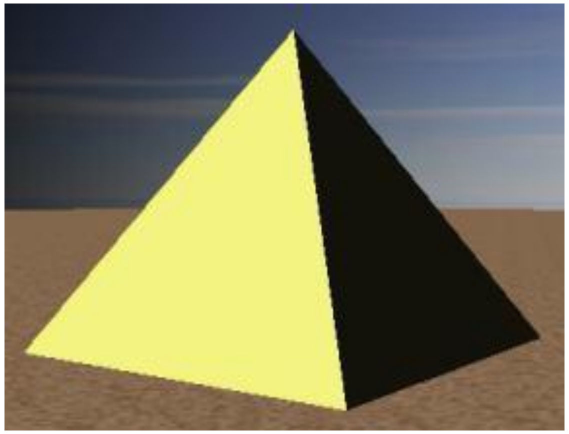


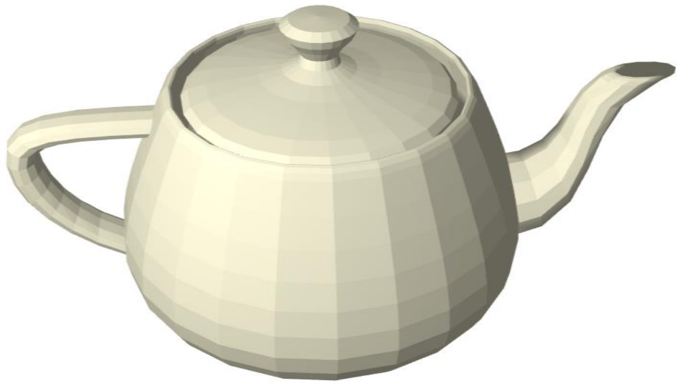
$$\frac{v_1 \times v_2}{||v_1 \times v_2||}$$

- That's why we need **counterclockwise** vertex ordering
  - The direction of a face normal determines "outside" of the face

Flat Shading

- Use a single face normal for each polygon
- Calculate color (by illumination) once per polygon
  - Typically use center of polygon
- Fast, but not very desirable for curved shapes
  - Even if we increase the number of polygons, it’s still “faceted“

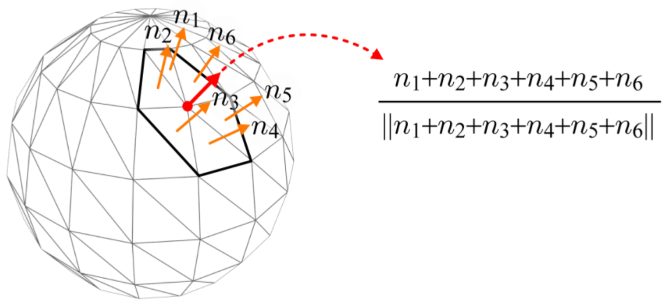




Smooth Shading

- Shading methods for curved shapes
  - Smooth color transition between two adjacent polygons

- Two methods:
  - Gouraud shading
  - Phong shading



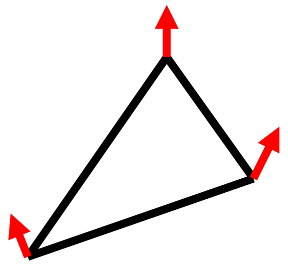
n_1
n_2
n_6
n_5
n_3
n_4
$\frac{n_1+n_2+n_3+n_4+n_5+n_6}{||n_1+n_2+n_3+n_4+n_5+n_6||}$

- Use a vertex normal for each vertex
  - For smooth shading, a vertex normal is commonly set to the average of normals of all faces sharing the vertex.

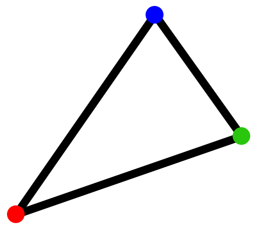
Gouraud Shading

Henri Gouraud
(1944~)

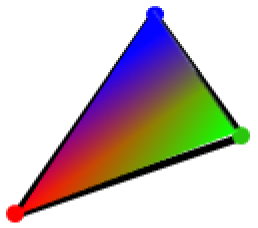
- Use a single vertex normal for each vertex



- Calculate color (by illumination) at each vertex

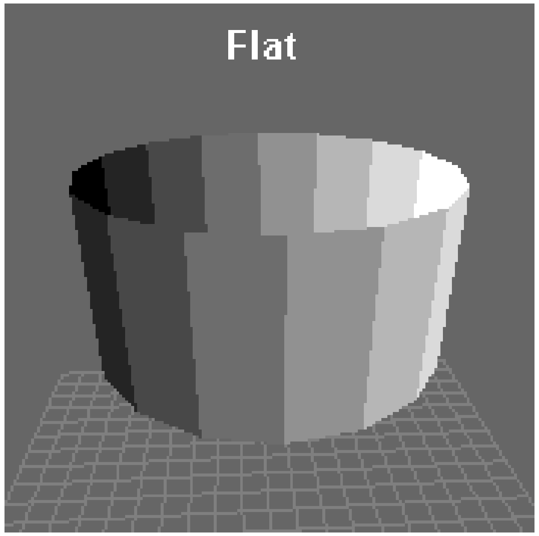


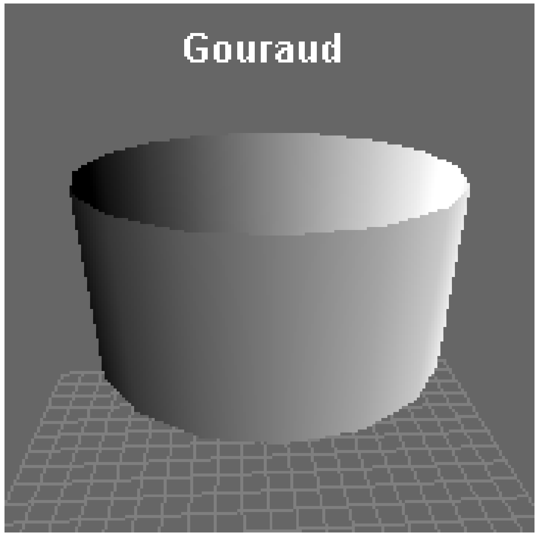
- Interpolate colors from vertices across polygon
  - Barycentric interpolation



See more for barycentric interpolation:
https://www.scratchapixel.com/lessons/3d-basic-rendering/ray-tracing-rendering-a-triangle/barycentric-coordinates

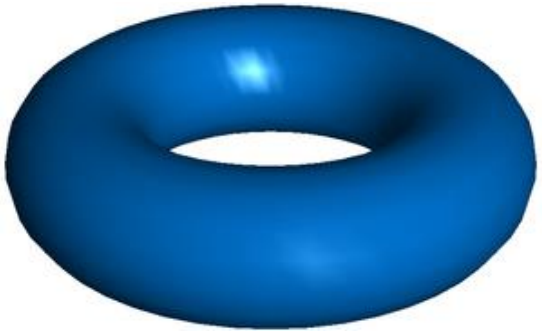
Gouraud Shading

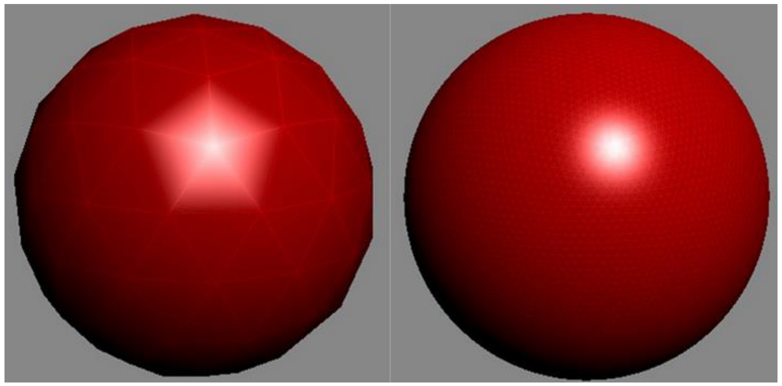




Gouraud Shading

- Problem: poor specular highlight
  - Specular highlights may be distorted or averaged away altogether



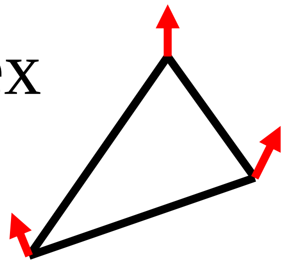


Higher polygon count
reduces this artifact

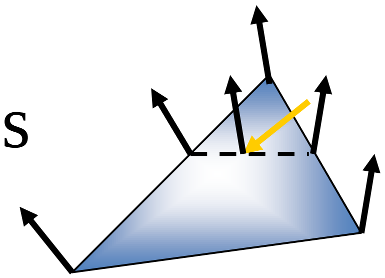
Phong Shading

Bùi Tường Phong
(1942 – 1975)

- Use a single vertex normal for each vertex

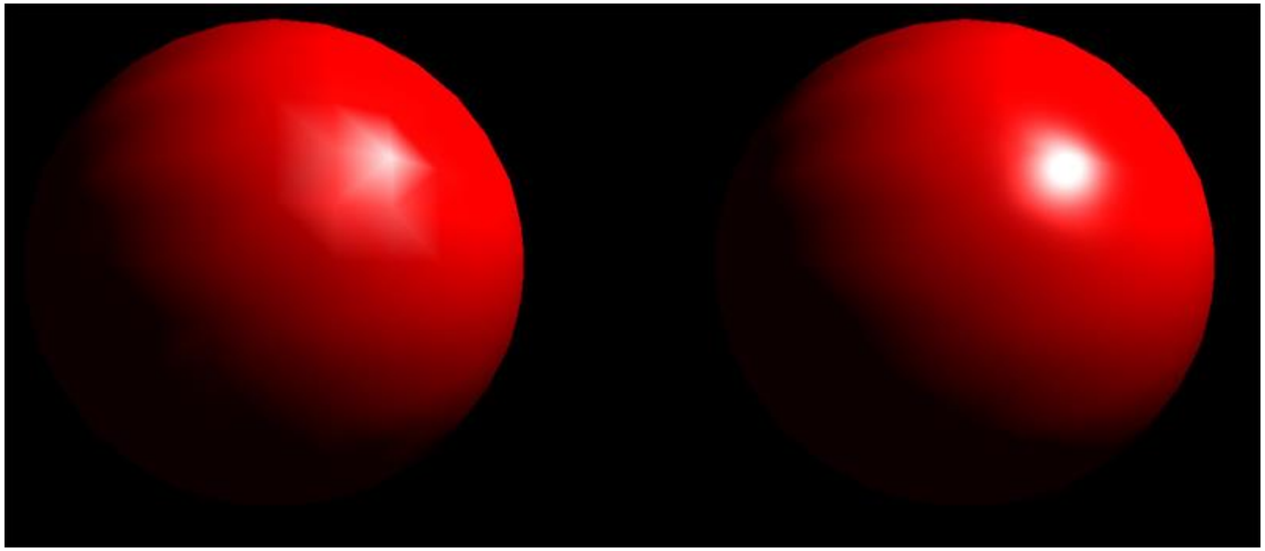


- Interpolate normals from vertices across polygon



- Calculate color (by illumination) at each pixel in polygon

Phong Shading



Gouraud shading Phong shading

Phong Shading

- Captures highlights much better
  - The interpolated normal at each interior pixel is more accurate representation of true surface normal at each point
  - Higher quality, but needs more computation

- Not to be confused with Phong's illumination model (developed by the same person)

[Practice] Online Shading Demos

- Flat & Gouraud shading
  - http://math.hws.edu/graphicsbook/demos/c4/smooth-vs-flat.html
- Gouraud & Phong shading
  - http://www.cs.toronto.edu/~jacobson/phong-demo/

Lighting & Shading in OpenGL

To do Lighting & Shading in OpenGL,

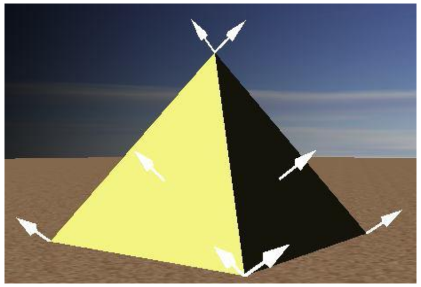
- First, you need to set vertex normal.

- Recall from 2-IntroNumPyOpenGL slides, a vertex has these attributes:
  - Vertex coordinate : specified by glVertex*()
  - Vertex color : specified by glColor*()
  - **Normal vector : specified by glNormal*()**
  - Texture coordinate : specified by glTexCoord*()

Shading in OpenGL

- The shading method is determined by the vertex normal vectors you specify.

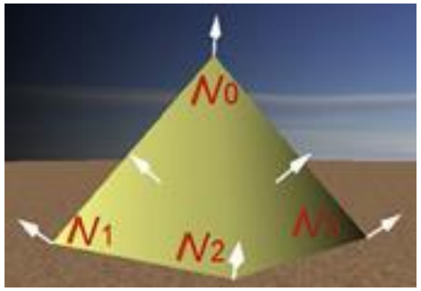
- Flat shading: Set each vertex normal to the face normal the vertex belongs to.



The normal at a vertex is the same as the plane normal. Therefore, each vertex has as many normals as the number of planes it belongs

Shading in OpenGL

- Gouraud shading: Set each vertex normal to the average of normals of all faces sharing the vertex.



Only one vertex normal per vertex; average of face normals of the faces the vertex is part of

- Phong shading is not available in legacy OpenGL.

Setting Vertex Normals in OpenGL

- You can specify normals using glNormal*() or a vertex array

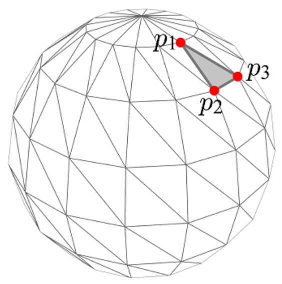
```
glBegin(GL_TRIANGLES)

glNormal3f(0,0,1) # v0,v2,v1,v0,v3,v2 normal
glVertex3f( -1 ,  1 ,  1 ) # v0 position
glVertex3f(  1 , -1 ,  1 ) # v2 position
glVertex3f(  1 ,  1 ,  1 ) # v1 position

glVertex3f( -1 ,  1 ,  1 ) # v0 position
glVertex3f( -1 , -1 ,  1 ) # v3 position
glVertex3f(  1 , -1 ,  1 ) # v2 position

glNormal3f(0,0,-1)
glVertex3f( -1 ,  1 , -1 ) # v4
glVertex3f(  1 ,  1 , -1 ) # v5
glVertex3f(  1 , -1 , -1 ) # v6

glVertex3f( -1 ,  1 , -1 ) # v4
glVertex3f(  1 , -1 , -1 ) # v6
glVertex3f( -1 , -1 , -1 ) # v7
```

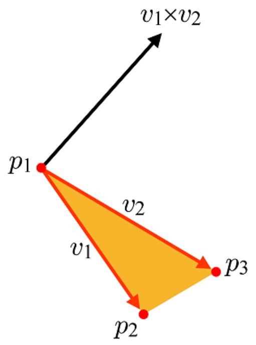
```
 varr = np.array([
         (0,0,1),             # v0 normal
         ( -1 ,  1 ,  1 ), # v0 position
         (0,0,1),             # v2 normal
         (  1 , -1 ,  1 ), # v2 position
         (0,0,1),             # v1 normal
         (  1 ,  1 ,  1 ), # v1 position

         (0,0,1),             # v0 normal
         ( -1 ,  1 ,  1 ), # v0 position
         (0,0,1),             # v3 normal
         ( -1 , -1 ,  1 ), # v3 position
         (0,0,1),             # v2 normal
         (  1 , -1 ,  1 ), # v2 position

         (0,0,-1),
         ( -1 ,  1 , -1 ), # v4
         (0,0,-1),
         (  1 ,  1 , -1 ), # v5
         (0,0,-1),
         (  1 , -1 , -1 ), # v6
# ...
], 'float32')
```

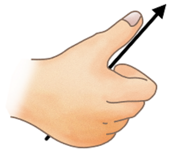
Setting Vertex Normals in OpenGL

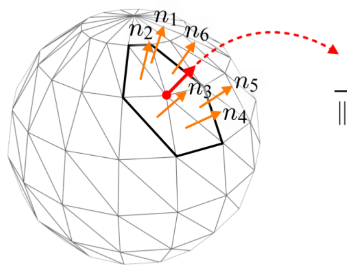
- You can hard-code normals like prev. page

- or compute normals from vertex positions









$$\frac{n_1+n_2+n_3+n_4+n_5+n_6}{||n_1+n_2+n_3+n_4+n_5+n_6||}$$

- or read normals from a model file such as .obj files (most common case)

Lighting in OpenGL

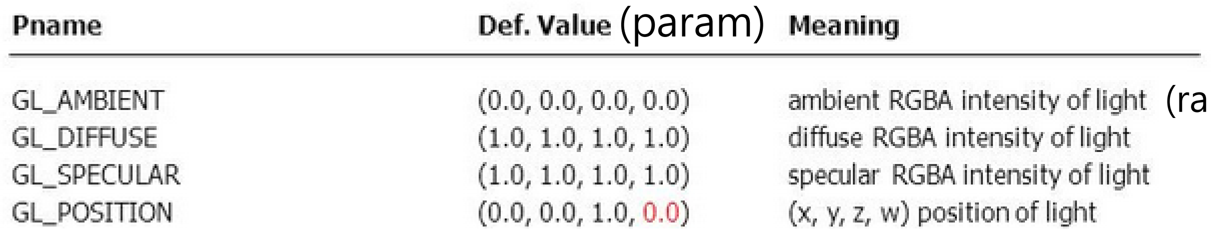
- Lighting in legacy OpenGL is too restrictive.
  - Only Blinn-Phong illumination model is available.

- **glEnable(GL_LIGHTING)**
  - Enable lighting

- **glEnable(GL_LIGHT0)**
  - Enable 0th light. You can use eight lights in legacy OpenGL (GL_LIGHT0 ~ GL_LIGHT7)

glLightfv()

- **glLightfv(light, pname, param)**
  - **light**: The light to assign
    - GL_LIGHT0 ~ GL_LIGHT7
  - **pname**, **param**: light properties including light intensity for each color channel, etc



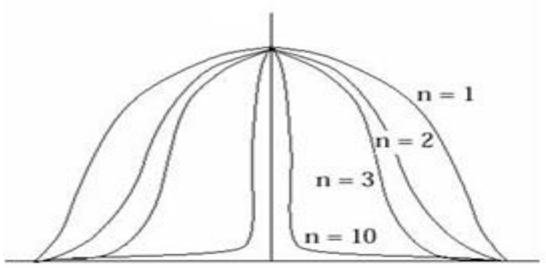
Pname	Def. Value (param)	Meaning
GL_AMBIENT	(0.0, 0.0, 0.0, 0.0)	ambient RGBA intensity of light (ranging from 0.0 to 1.0)
GL_DIFFUSE	(1.0, 1.0, 1.0, 1.0)	diffuse RGBA intensity of light
GL_SPECULAR	(1.0, 1.0, 1.0, 1.0)	specular RGBA intensity of light
GL_POSITION	(0.0, 0.0, 1.0, 0.0)	(x, y, z, w) position of light

w=0: directional light
w=1: point light
(homogeneous coordinates)

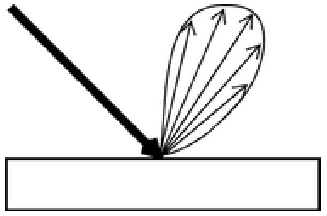
glMaterialfv()

- **glMaterialfv(face, pname, param)**
  - **face**: The face type to assign
    - GL_FRONT, GL_BACK, or GL_FRONT_AND_BACK
  - **pname**, **param**: material reflectance for each color channel
    - GL_AMBIENT, GL_DIFFUSE, GL_SPECULAR
    - GL_AMBIENT_AND_DIFFUSE
    - GL_SHININESS: Specular exponent (shininess coefficient) (0 ~ 128)

$$I = C_s k_s \cos^{\boxed{n}}(\alpha)$$



Specular falloff of (cos δ) ^{n}



Good Settings for glLightfv() & glMaterialfv()

- glLightfv()
  - GL_DIFFUSE & GL_SPECULAR: Color of the light source
  - GL_AMBIENT: The same color, but at much reduced intensity (about 10%)

- glMaterialfv()
  - GL_DIFFUSE & GL_AMBIENT: Color of the object
  - GL_SPECULAR: White (1,1,1,1)

- Final polygon color is the sum of ambient, diffuse, specular components, each of which is formed by multiplying the glMaterial color by the glLight color.

Reference: https://www.khronos.org/opengl/wiki/How_lighting_works#glMaterial_and_glLight

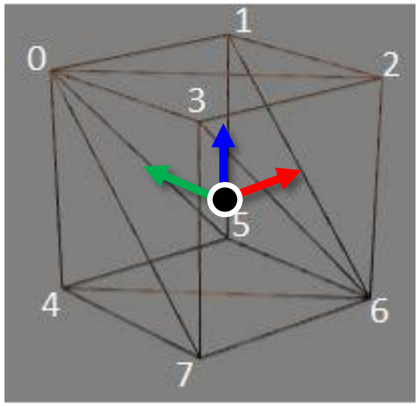
Normals with Lighting

- In OpenGL, normal vectors should have *unit length*.

- Normal vectors are transformed by GL_MODELVIEW matrix, so they may not have unit length, especially if scaling are included.

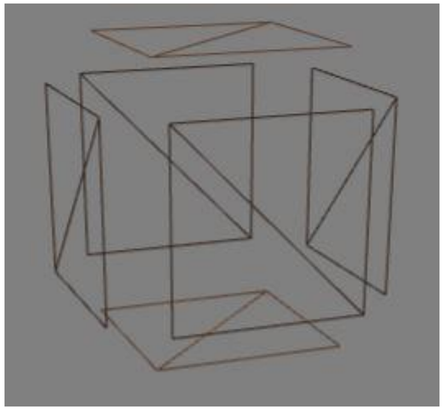
- You need to use one of these:
  - **glEnable(GL_NORMALIZE)**
    - Automatically normalize normal vectors after model-view transformation
  - **glEnable(GL_RESCALE_NORMAL)**
    - More efficient, but normal vectors must be initially supplied as unit vectors and only works for uniform scaling

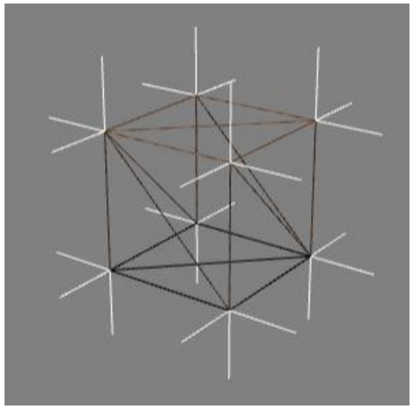
Example: a cube of length 2 again

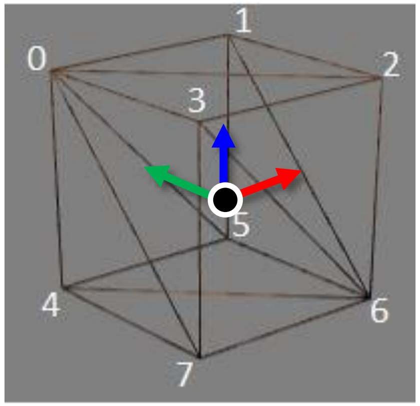


vertex index	position
0	(-1 , 1 , 1)
1	(1 , 1 , 1)
2	(1 , -1 , 1)
3	(-1 , -1 , 1)
4	(-1 , 1 , -1)
5	(1 , 1 , -1)
6	(1 , -1 , -1)
7	(-1 , -1 , -1)

Normals of the Cube for Flat Shading







vertex index	position	**normal**
0	(-1 , 1 , 1)	**(0,0,1)**
2	(1 , -1 , 1)	**(0,0,1)**
1	(1 , 1 , 1)	**(0,0,1)**
0	(-1 , 1 , 1)	**(0,0,1)**
3	(-1 , -1 , 1)	**(0,0,1)**
2	(1 , -1 , 1)	**(0,0,1)**
4	(-1 , 1 , -1)	**(0,0,-1)**
5	(1 , 1 , -1)	**(0,0,-1)**
6	(1 , -1 , -1)	**(0,0,-1)**
4	(-1 , 1 , -1)	**(0,0,-1)**
6	(1 , -1 , -1)	**(0,0,-1)**
7	(-1 , -1 , -1)	**(0,0,-1)**
0	(-1 , 1 , 1)	**(0,1,0)**
1	(1 , 1 , 1)	**(0,1,0)**
5	(1 , 1 , -1)	**(0,1,0)**
0	(-1 , 1 , 1)	**(0,1,0)**
5	(1 , 1 , -1)	**(0,1,0)**
4	(-1 , 1 , -1)	**(0,1,0)**
3	(-1 , -1 , 1)	**(0,-1,0)**
6	(1 , -1 , -1)	**(0,-1,0)**
2	(1 , -1 , 1)	**(0,-1,0)**
3	(-1 , -1 , 1)	**(0,-1,0)**
7	(-1 , -1 , -1)	**(0,-1,0)**
6	(1 , -1 , -1)	**(0,-1,0)**
1	(1 , 1 , 1)	**(1,0,0)**
2	(1 , -1 , 1)	**(1,0,0)**
6	(1 , -1 , -1)	**(1,0,0)**
1	(1 , 1 , 1)	**(1,0,0)**
6	(1 , -1 , -1)	**(1,0,0)**
5	(1 , 1 , -1)	**(1,0,0)**
0	(-1 , 1 , 1)	**(-1,0,0)**
7	(-1 , -1 , -1)	**(-1,0,0)**
3	(-1 , -1 , 1)	**(-1,0,0)**
0	(-1 , 1 , 1)	**(-1,0,0)**
4	(-1 , 1 , -1)	**(-1,0,0)**
7	(-1 , -1 , -1)	**(-1,0,0)**

[Practice] OpenGL Lighting

```python
import glfw
from OpenGL.GL import *
from OpenGL.GLU import *
import numpy as np
from OpenGL.arrays import vbo
import ctypes

gCamAng = 0.
gCamHeight = 1.

def drawCube_glVertex():
    glBegin(GL_TRIANGLES)

    glNormal3f(0,0,1) # v0, v2, v1, v0, v3, v2 normal
    glVertex3f( -1 ,  1 ,  1 ) # v0 position
    glVertex3f(  1 , -1 ,  1 ) # v2 position
    glVertex3f(  1 ,  1 ,  1 ) # v1 position

    glVertex3f( -1 ,  1 ,  1 ) # v0 position
    glVertex3f( -1 , -1 ,  1 ) # v3 position
    glVertex3f(  1 , -1 ,  1 ) # v2 position

    glNormal3f(0,0,-1)
    glVertex3f( -1 ,  1 , -1 ) # v4
    glVertex3f(  1 ,  1 , -1 ) # v5
    glVertex3f(  1 , -1 , -1 ) # v6

    glVertex3f( -1 ,  1 , -1 ) # v4
    glVertex3f(  1 , -1 , -1 ) # v6
    glVertex3f( -1 , -1 , -1 ) # v7
```

```python
    glNormal3f(0,1,0)
    glVertex3f( -1 ,  1 ,  1 ) # v0
    glVertex3f(  1 ,  1 ,  1 ) # v1
    glVertex3f(  1 ,  1 , -1 ) # v5

    glVertex3f( -1 ,  1 ,  1 ) # v0
    glVertex3f(  1 ,  1 , -1 ) # v5
    glVertex3f( -1 ,  1 , -1 ) # v4

    glNormal3f(0,-1,0)
    glVertex3f( -1 , -1 ,  1 ) # v3
    glVertex3f(  1 , -1 , -1 ) # v6
    glVertex3f(  1 , -1 ,  1 ) # v2

    glVertex3f( -1 , -1 ,  1 ) # v3
    glVertex3f( -1 , -1 , -1 ) # v7
    glVertex3f(  1 , -1 , -1 ) # v6

    glNormal3f(1,0,0)
    glVertex3f(  1 ,  1 ,  1 ) # v1
    glVertex3f(  1 , -1 ,  1 ) # v2
    glVertex3f(  1 , -1 , -1 ) # v6

    glVertex3f(  1 ,  1 ,  1 ) # v1
    glVertex3f(  1 , -1 , -1 ) # v6
    glVertex3f(  1 ,  1 , -1 ) # v5

    glNormal3f(-1,0,0)
    glVertex3f( -1 ,  1 ,  1 ) # v0
    glVertex3f( -1 , -1 , -1 ) # v7
    glVertex3f( -1 , -1 ,  1 ) # v3

    glVertex3f( -1 ,  1 ,  1 ) # v0
    glVertex3f( -1 ,  1 , -1 ) # v4
    glVertex3f( -1 , -1 , -1 ) # v7
    glEnd()
```

```
def createVertexArraySeparate():
    varr = np.array([
            (0,0,1),         # v0 normal
            ( -1 ,  1 ,  1 ), # v0 position
            (0,0,1),         # v2 normal
            (  1 , -1 ,  1 ), # v2 position
            (0,0,1),         # v1 normal
            (  1 ,  1 ,  1 ), # v1 position

            (0,0,1),         # v0 normal
            ( -1 ,  1 ,  1 ), # v0 position
            (0,0,1),         # v3 normal
            ( -1 , -1 ,  1 ), # v3 position
            (0,0,1),         # v2 normal
            (  1 , -1 ,  1 ), # v2 position

            (0,0,-1),
            ( -1 ,  1 , -1 ), # v4
            (0,0,-1),
            (  1 ,  1 , -1 ), # v5
            (0,0,-1),
            (  1 , -1 , -1 ), # v6

            (0,0,-1),
            ( -1 ,  1 , -1 ), # v4
            (0,0,-1),
            (  1 , -1 , -1 ), # v6
            (0,0,-1),
            ( -1 , -1 , -1 ), # v7

            (0,1,0),
            ( -1 ,  1 ,  1 ), # v0
            (0,1,0),
            (  1 ,  1 ,  1 ), # v1
            (0,1,0),
            (  1 ,  1 , -1 ), # v5

            (0,1,0),
            ( -1 ,  1 ,  1 ), # v0
            (0,1,0),
            (  1 ,  1 , -1 ), # v5
            (0,1,0),
            ( -1 ,  1 , -1 ), # v4

            (0,-1,0),
            ( -1 , -1 ,  1 ), # v3
            (0,-1,0),
            (  1 , -1 , -1 ), # v6
            (0,-1,0),
            (  1 , -1 ,  1 ), # v2

            (0,-1,0),
            ( -1 , -1 ,  1 ), # v3
            (0,-1,0),
            ( -1 , -1 , -1 ), # v7
            (0,-1,0),
            (  1 , -1 , -1 ), # v6

            (1,0,0),
            (  1 ,  1 ,  1 ), # v1
            (1,0,0),
            (  1 , -1 ,  1 ), # v2
            (1,0,0),
            (  1 , -1 , -1 ), # v6

            (1,0,0),
            (  1 ,  1 ,  1 ), # v1
            (1,0,0),
            (  1 , -1 , -1 ), # v6
            (1,0,0),
            (  1 ,  1 , -1 ), # v5

            (-1,0,0),
            ( -1 ,  1 ,  1 ), # v0
            (-1,0,0),
            ( -1 , -1 , -1 ), # v7
            (-1,0,0),
            ( -1 , -1 ,  1 ), # v3

            (-1,0,0),
            ( -1 ,  1 ,  1 ), # v0
            (-1,0,0),
            ( -1 ,  1 , -1 ), # v4
            (-1,0,0),
            ( -1 , -1 , -1 ), # v7
            ], 'float32')
    return varr
```

```
def drawCube_glDrawArray():
    global gVertexArraySeparate
    varr = gVertexArraySeparate
    glEnableClientState(GL_VERTEX_ARRAY)
    glEnableClientState(GL_NORMAL_ARRAY)
    glNormalPointer(GL_FLOAT, 6*varr.itemsize, varr)
    glVertexPointer(3, GL_FLOAT, 6*varr.itemsize,
ctypes.c_void_p(varr.ctypes.data + 3*varr.itemsize))
    glDrawArrays(GL_TRIANGLES, 0, int(varr.size/6))
```

```
def render():
    global gCamAng, gCamHeight

glClear(GL_COLOR_BUFFER_BIT|GL_DEPTH_BUFFER_BIT)

    glEnable(GL_DEPTH_TEST)

    glMatrixMode(GL_PROJECTION)
    glLoadIdentity()
    gluPerspective(45, 1, 1,10)

    glMatrixMode(GL_MODELVIEW)
    glLoadIdentity()

gluLookAt(5*np.sin(gCamAng),gCamHeight,5*np.cos(
gCamAng), 0,0,0, 0,1,0)

    drawFrame()

    glEnable(GL_LIGHTING)   # try to uncomment:
no lighting
    glEnable(GL_LIGHT0)

    glEnable(GL_RESCALE_NORMAL)  # try to
uncomment: lighting will be incorrect if you
scale the object
    # glEnable(GL_NORMALIZE)

    # light position
    glPushMatrix()

    # glRotatef(t*(180/np.pi),0,1,0)  # try to
uncomment: rotate light
    lightPos = (3.,4.,5.,1.)    # try to change
4th element to 0. or 1.
    glLightfv(GL_LIGHT0, GL_POSITION, lightPos)
    glPopMatrix()

 # light intensity for each color channel
    lightColor = (1.,1.,1.,1.)
    ambientLightColor = (.1,.1,.1,1.)
    glLightfv(GL_LIGHT0, GL_DIFFUSE,
lightColor)
    glLightfv(GL_LIGHT0, GL_SPECULAR,
lightColor)
    glLightfv(GL_LIGHT0, GL_AMBIENT,
ambientLightColor)

    # material reflectance for each color
channel
    objectColor = (1.,0.,0.,1.)
    specularObjectColor = (1.,1.,1.,1.)
    glMaterialfv(GL_FRONT,
GL_AMBIENT_AND_DIFFUSE, objectColor)
    glMaterialfv(GL_FRONT, GL_SHININESS, 10)
    glMaterialfv(GL_FRONT, GL_SPECULAR,
specularObjectColor)

    glPushMatrix()
    # glRotatef(t*(180/np.pi),0,1,0)    # try
to uncomment: rotate object
    # glScalef(1.,.2,1.)    # try to uncomment:
scale object

    glColor3ub(0, 0, 255) # glColor*() is
ignored if lighting is enabled

    # drawCube_glVertex()
    drawCube_glDrawArray()
    glPopMatrix()

    glDisable(GL_LIGHTING)
```

```
def drawFrame():
    glBegin(GL_LINES)
    glColor3ub(255, 0, 0)
    glVertex3fv(np.array([0.,0.,0.]))
    glVertex3fv(np.array([1.,0.,0.]))
    glColor3ub(0, 255, 0)
    glVertex3fv(np.array([0.,0.,0.]))
    glVertex3fv(np.array([0.,1.,0.]))
    glColor3ub(0, 0, 255)
    glVertex3fv(np.array([0.,0.,0]))
    glVertex3fv(np.array([0.,0.,1.]))
    glEnd()

def key_callback(window, key, scancode, 
action, mods):
    global gCamAng, gCamHeight
    if action==glfw.PRESS or 
action==glfw.REPEAT:
        if key==glfw.KEY_1:
            gCamAng += np.radians(-10)
        elif key==glfw.KEY_3:
            gCamAng += np.radians(10)
        elif key==glfw.KEY_2:
            gCamHeight += .1
        elif key==glfw.KEY_W:
            gCamHeight += -.1
```

```
gVertexArraySeparate = None
def main():
    global gVertexArraySeparate

    if not glfw.init():
        return
    window = 
glfw.create_window(640,640,'Lecture13', 
None,None)
    if not window:
        glfw.terminate()
        return
    glfw.make_context_current(window)
    glfw.set_key_callback(window, 
key_callback)
    glfw.swap_interval(1)

    gVertexArraySeparate = 
createVertexArraySeparate()

    while not 
glfw.window_should_close(window):
        glfw.poll_events()
        render()
        glfw.swap_buffers(window)

    glfw.terminate()

if __name__ == "__main__":
    main()
```

glNormalPointer()

- **glNormalPointer(type, stride, pointer)**
- : specifies the location and data format of an array of normals
  - **type**: The data type of each coordinate value in the array. GL_FLOAT, GL_SHORT, GL_INT or GL_DOUBLE.
  - **stride**: The number of bytes to offset to the next normal
  - **pointer**: The pointer to the first coordinate of the first normal in the array

- **c.f.) glVertexPointer(size, type, stride, pointer)**
- : specifies the location and data format of an array of vertex coordinates
  - **size**: The number of vertex coordinates, 2 for 2D points, 3 for 3D points
  - **type**: The data type of each coordinate value in the array. GL_FLOAT, GL_SHORT, GL_INT or GL_DOUBLE.
  - **stride**: The number of bytes to offset to the next vertex
  - **pointer**: The pointer to the first coordinate of the first vertex in the array

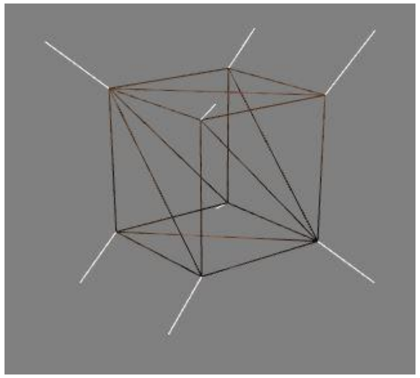
Quiz #3

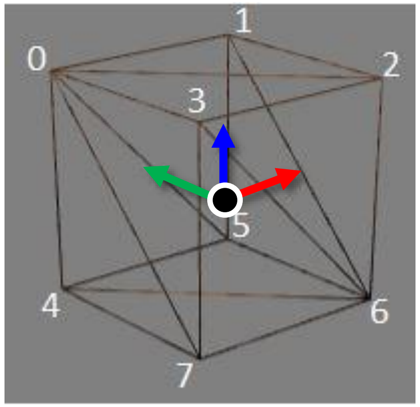
- Go to https://www.slido.com/
- Join #cg-hyu
- Click “Polls”

- Submit your answer in the following format:
  - **Student ID: Your answer**
  - **e.g. 2017123456: 4)**

- Note that you must submit all quiz answers in the above format to be checked for “attendance”.

Normals of the Cube for Smooth Shading





vertex index	position	normal
0	(-1 , 1 , 1)	(-0.5773502691896258 , 0.5773502691896258 , 0.5773502691896258)
1	(1 , 1 , 1)	(0.8164965809277261 , 0.4082482904638631 , 0.4082482904638631)
2	(1 , -1 , 1)	(0.4082482904638631 , -0.4082482904638631 , 0.8164965809277261)
3	(-1 , -1 , 1)	(-0.4082482904638631 , -0.8164965809277261 , 0.4082482904638631)
4	(-1 , 1 , -1)	(-0.4082482904638631 , 0.4082482904638631 , -0.8164965809277261)
5	(1 , 1 , -1)	(0.4082482904638631 , 0.8164965809277261 , -0.4082482904638631)
6	(1 , -1 , -1)	(0.5773502691896258 , -0.5773502691896258 , -0.5773502691896258)
7	(-1 , -1 , -1)	(-0.8164965809277261 , -0.4082482904638631 , -0.4082482904638631)

Lighting in Modern OpenGL

- Legacy OpenGL
  - Only allows Gouraud shading & Blinn-Phong illumination model.
  - Rendering quality is not good.

- Modern OpenGL:
  - No specific lighting & shading model in modern OpenGL
  - Programmers have to implement Phong or other illumination model in vertex shader or fragment shader.
  - Example: the shader code in this online demo http://www.cs.toronto.edu/~jacobson/phong-demo/

Next Time

- Lab in this week:
  - Lab assignment 8

- Next lecture:
  - 9 - Orientation & Rotation

- Acknowledgement: Some materials come from the lecture slides of
  - Prof. Andy van Dam, Brown Univ., http://cs.brown.edu/courses/csci1230/lectures.shtml
  - Prof. Jinxiang Chai, Texas A&M Univ., http://faculty.cs.tamu.edu/jchai/csce441_2016spring/lectures.html
  - Prof. Steve Marschner, Cornell Univ., http://www.cs.cornell.edu/courses/cs4620/2014fa/index.shtml
  - Prof. JungHyun Han, Korea Univ., http://media.korea.ac.kr/book/