Computer Graphics

T6 - Lighting & Shading

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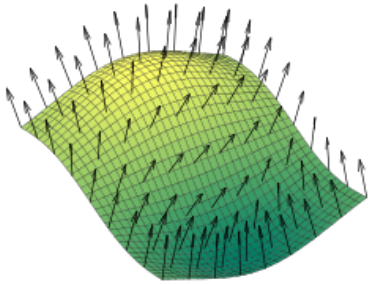
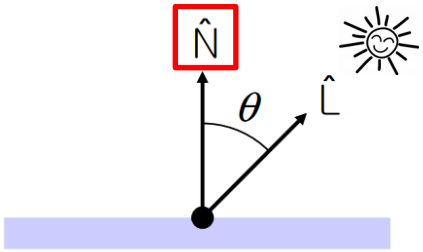
Surface Normal

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

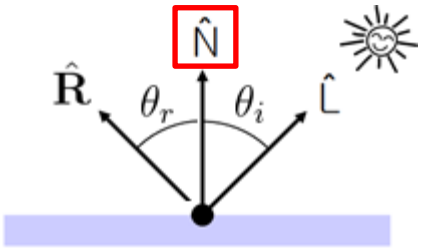


- Plays a key role in shading & illumination process
- Diffuse reflection
  - Lambert's Cosine Law



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

- Specular reflection
  - Laws of Reflection



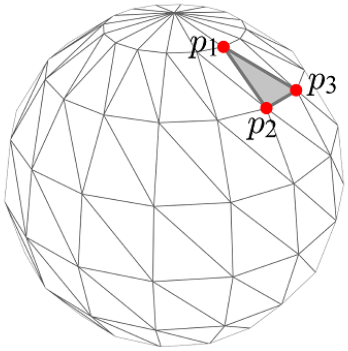
$$\theta_r = \theta_i$$

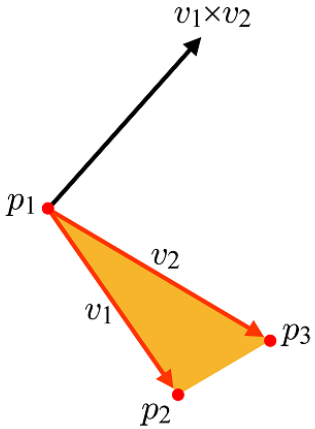
Face Normal

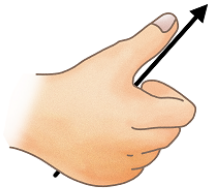
- How to get the surface normal of a polygonal face?

The order does matter!

- 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





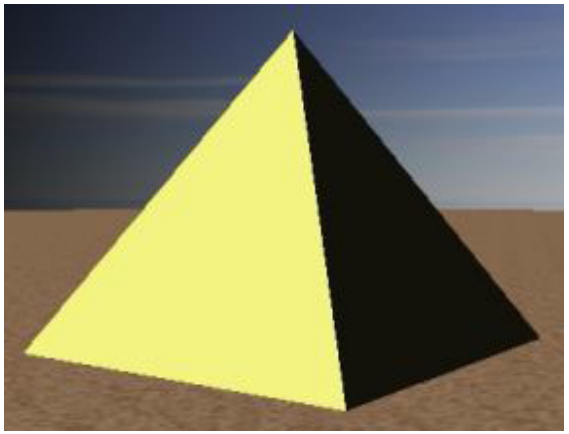


$$\frac{v_1 \times v_2}{||v_1 \times v_2||}$$

- That's why we need **counterclockwise** vertex ordering
  -

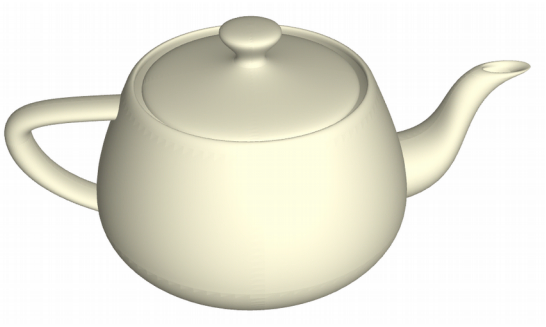
Flat Shading

- 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 polygon

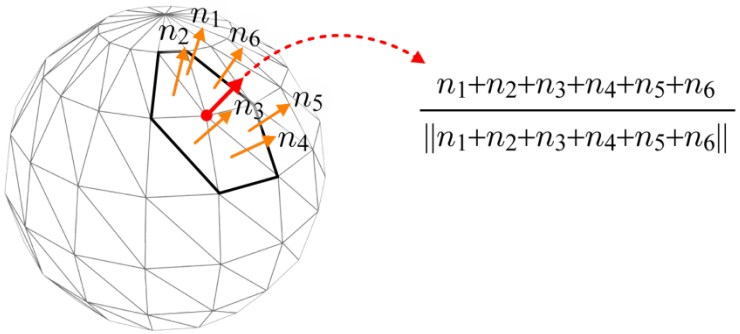


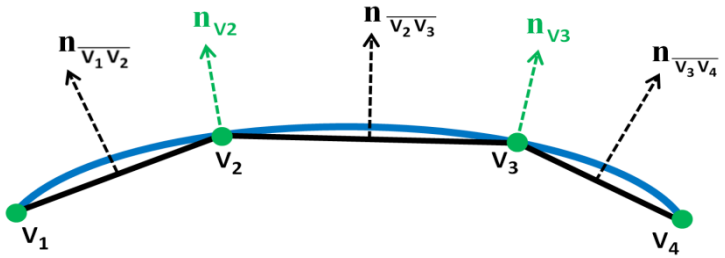
- Two methods:
  - Gouraud shading
  - Phong shading

Vertex Normal

- Let's assume each vertex has its own normal
  - Although the normal is mathematically undefined since a vertex is a discontinuity

- For smooth shading, a vertex normal is commonly set to the average of normals of all faces sharing the vertex
  - Decent approximation to the normal of curved surface closest to that vertex





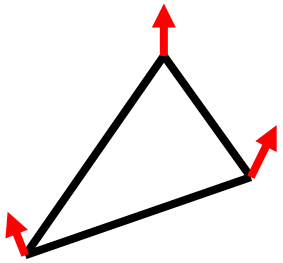
- *Blue lines: Real curved surface*
- *Black lines: Polygonal approximation of the surface*

- *Black arrows: Face normals*
- *Green arrows: Vertex normals (average of adjacent face normals)*

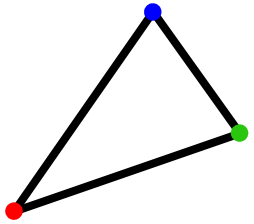
Gouraud Shading

Henri Gouraud
(1944~)

- Use a single vertex normal for each vertex



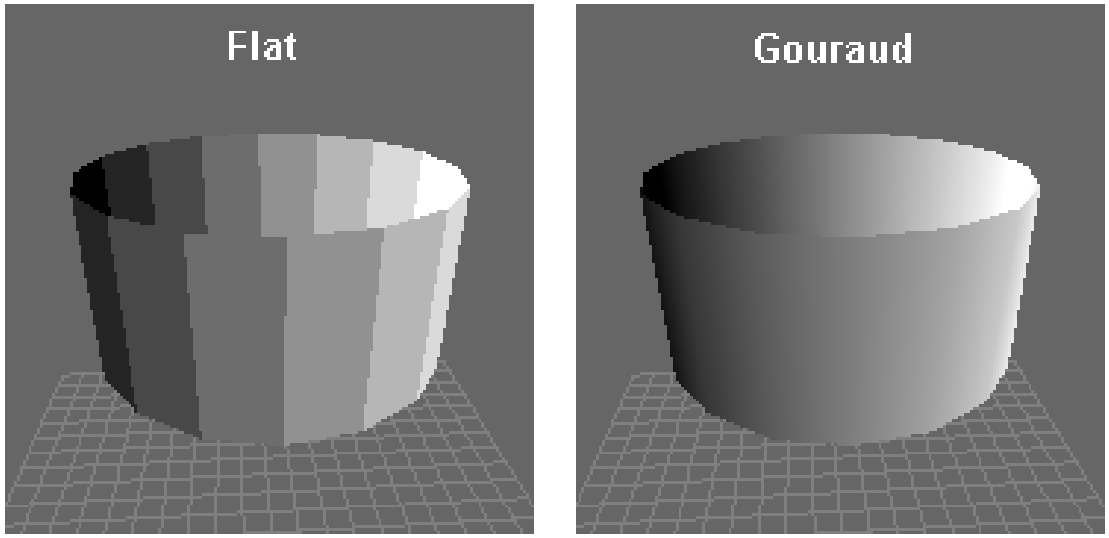
- Calculate color (by illumination) at each vertex



- Interpolate colors from vertices across polygon
  - Barycentric interpolation

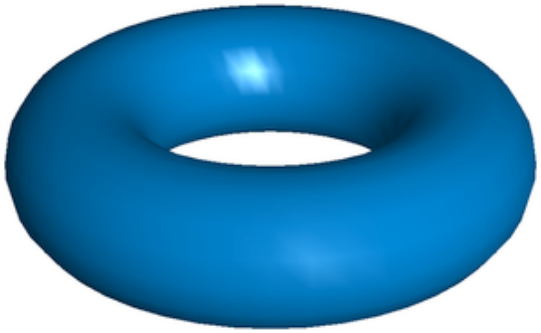
See more for barycentric interpolation:
https://www.scratchapixel.com/lessons/3d-basic-rendering/ray-tracing-rendering-a-triangle/barycentric-coordinates

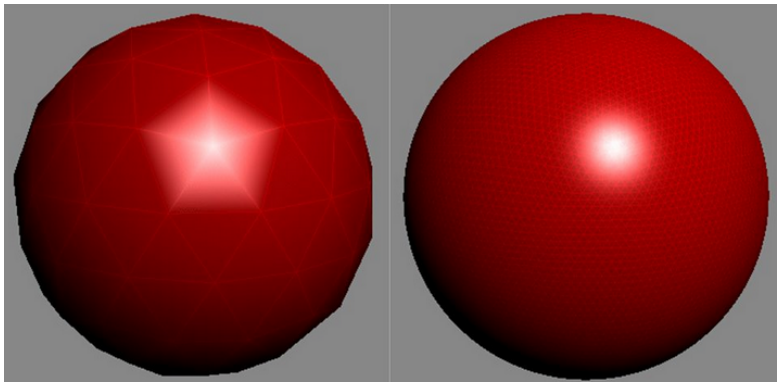
Gouraud Shading



Gouraud Shading

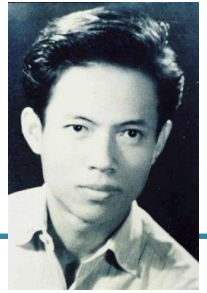
- Problem: poor specular highlight
  - Specular highlights may be distorted or averaged away altogether





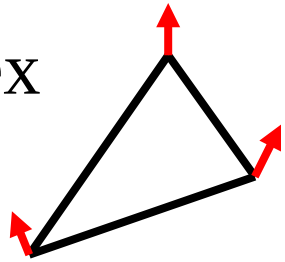
Higher polygon count reduces this artifact

Phong Shading

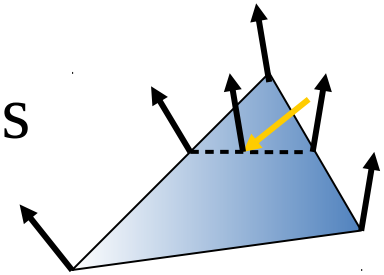


Bùi Tường Phong
(1942 – 1975)

- Use a single vertex normal for each vertex

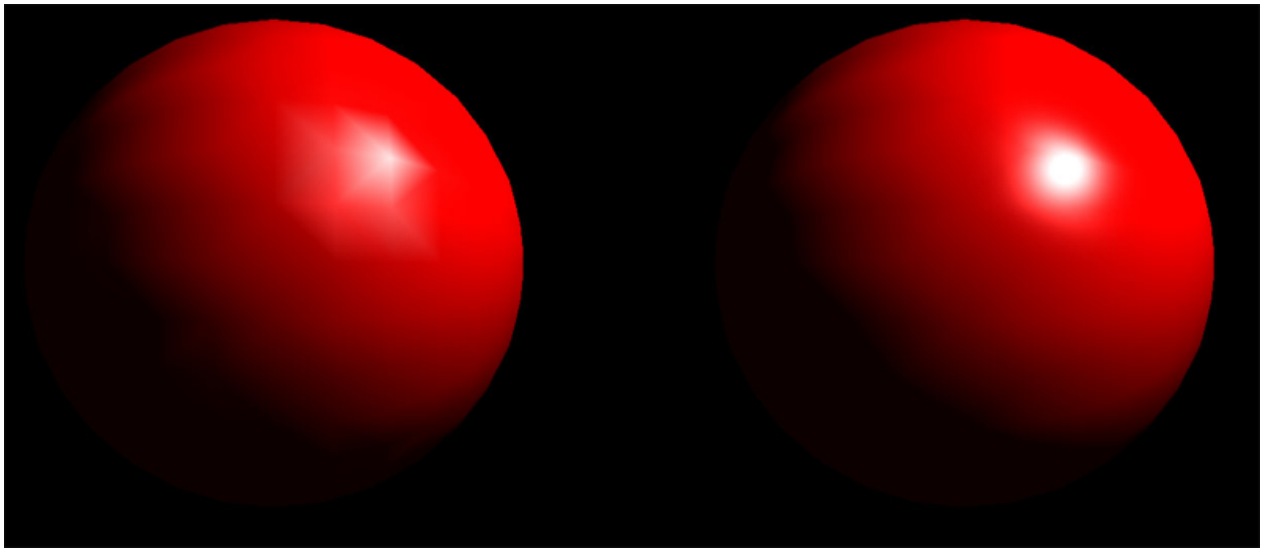


- Interpolate normals from vertices across polygon



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

Phong Shading



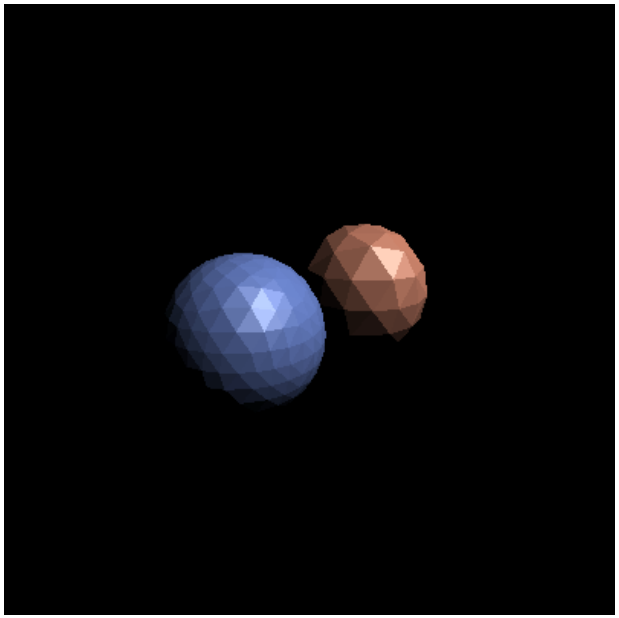
Gouraud shading Phong shading

Phong Shading

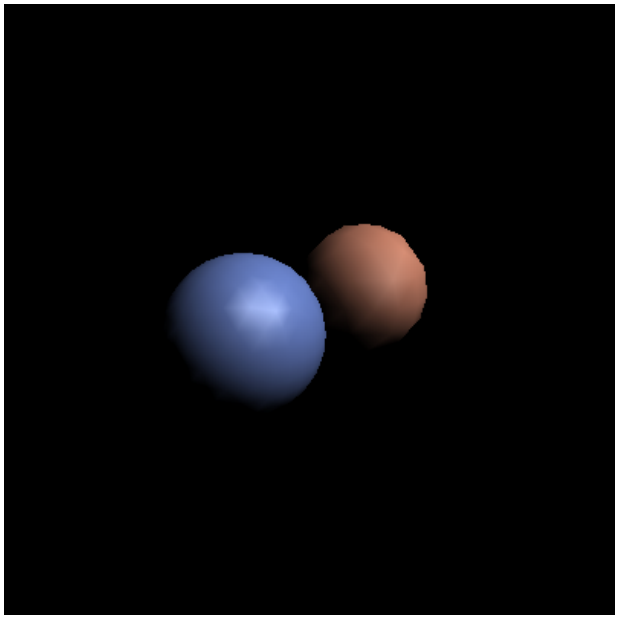
- Captures highlights much better
  - The interpolated normal at each interior pixel is more accurate representation of true surface normal at each point
  - Higher quality, but needs more computation

- Not to be confused with Phong's illumination

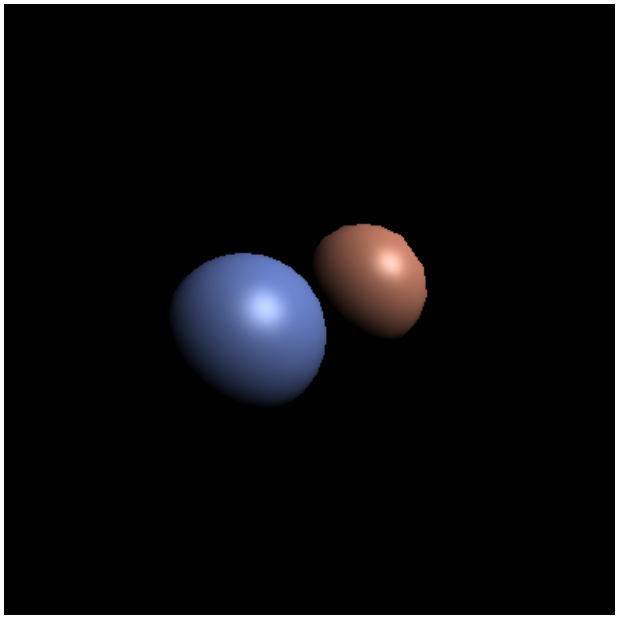
An Example



flat shading



Gouraud shading



Phong shading

[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,

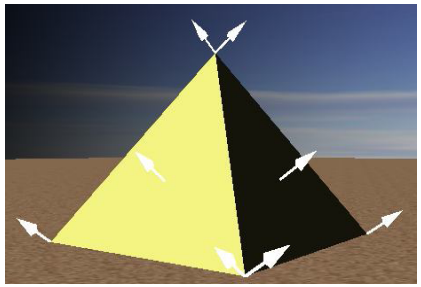
- First, you need to set vertex normal.

- 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.

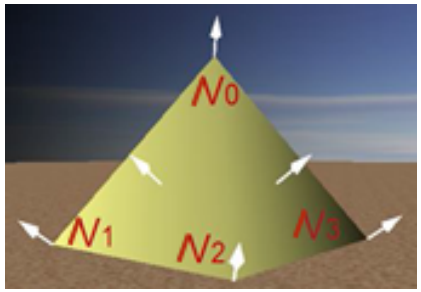
- Flat shading: Set each vertex normal to the face normal the vertex belongs to



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.
  - - Use shaders instead!

Setting Vertex Normals in OpenGL

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

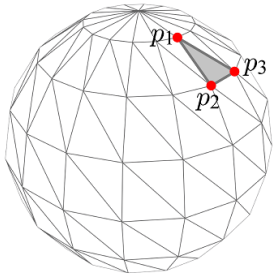
```
glBegin(GL_TRIANGLES)

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
```

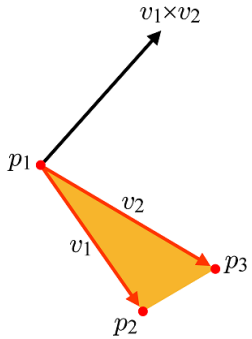
```
varr = np.array([
(0,0,1),          # v0 normal
( -1 ,  1 ,  1 ), # v0 position
(0,0,1),          # v2 normal
(  1 , -1 ,  1 ), # v2 position
(0,0,1),          # v1 normal
(  1 ,  1 ,  1 ), # v1 position

(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')
```

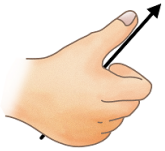
Setting Vertex Normals in OpenGL

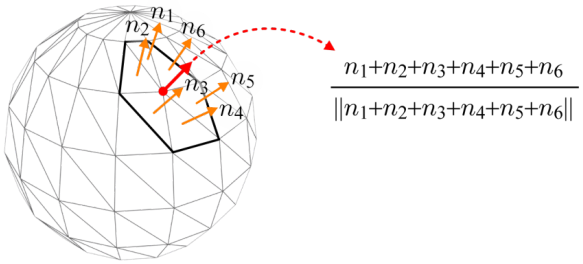
- You can hard-code normals like prev. page

- or compute normals from vertex positions









- or read normals from a model file such as .obj

Lighting in OpenGL

- Lighting in legacy OpenGL is very restrictive.
  - Blinn-Phong illumination model is available.
  - Texture mapping & alpha blending is available.
  - You can configure how the vertex colors, shading results, and texture colors are blended.
  - That’s about it.

Enabling Light

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

- **glEnable(GL_LIGHT0)**
  - Enable 0^{th}

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
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

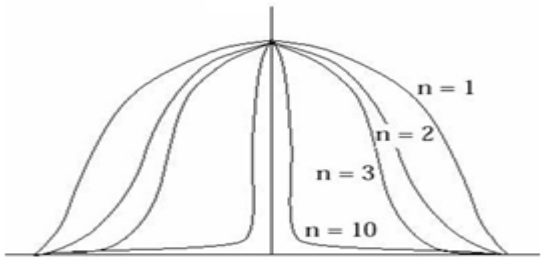
(ranging from 0.0 to 1.0)

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

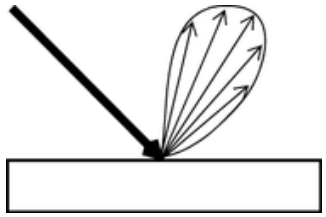
glMaterialfv()

- **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 (0 ~ 128)

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



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



Normals with Lighting

- In OpenGL, normal vectors should have *unit length*.
- Normal vectors are transformed by GL_MODELVIEW matrix, so they need to be renormalized after scaling transformation
- You need to use one of these:
  - **glEnable(GL_NORMALIZE)**
  - **glEnable(GL_RESCALE_NORMAL)**
    - To use this, normal vectors must be initially supplied as unit vectors.

Good Settings for glLightfv() & glMaterialfv()

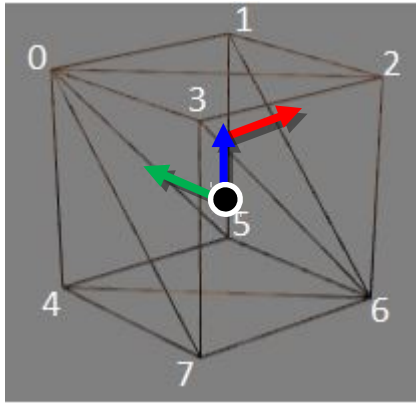
- glLightfv()
  - GL_DIFFUSE & GL_SPECULAR: Color of the light source
  - GL_AMBIENT: The same color, but at much reduced intensity (about 10%)

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

- The color of a rendered polygon will be the sum of ambient, diffuse, and specular components, each of which is calculated by multiplying the material color and the light color

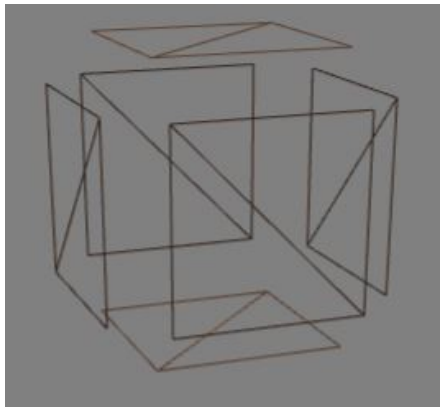
Reference: https://www.khronos.org/opengl/wiki/How_lighting_works#glMaterial_and_glLight

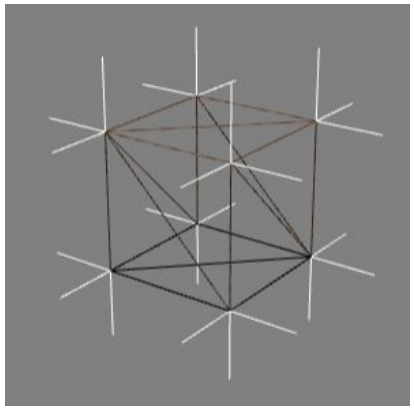
Example: a cube of length 2 again

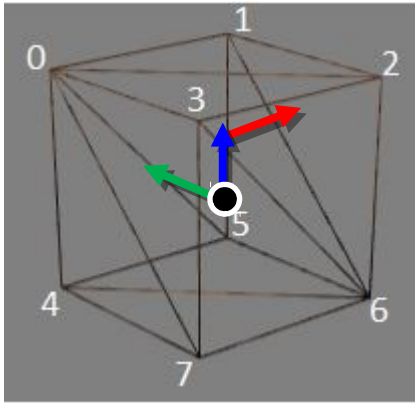


vertex index	position
0	(-1 , 1 , 1)
1	(1 , 1 , 1)
2	(1 , -1 , 1)
3	(-1 , -1 , 1)
4	(-1 , 1 , -1)
5	(1 , 1 , -1)
6	(1 , -1 , -1)
7	(-1 , -1 , -1)

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)**

[Practice] OpenGL Lighting

```
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
```

```
    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(g
CamAng), 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
```

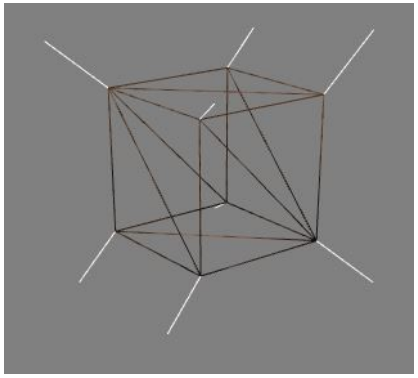
```
gVertexArraySeparate = None
def main():
    global gVertexArraySeparate

    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()
```

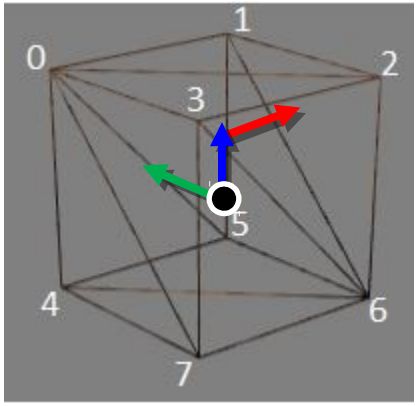
glNormalPointer()

- **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

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.

- 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

- Acknowledgement: Some materials come from the lecture slides of
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  - 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/

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