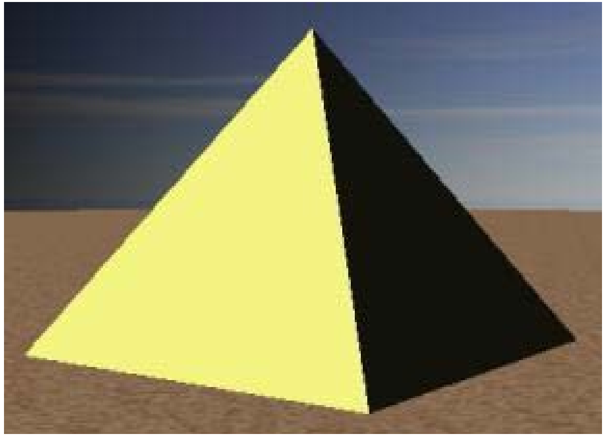
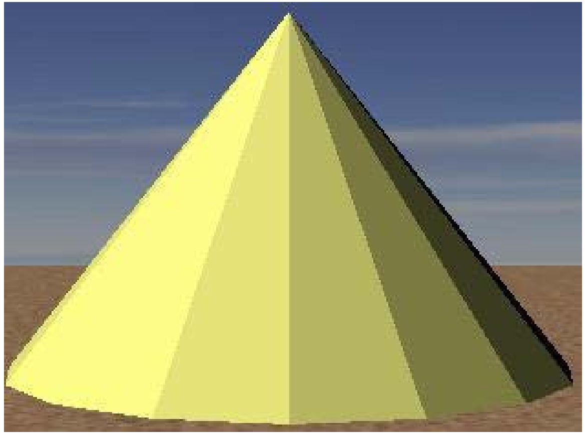




# Introduction to 3D Graphics

## Using OpenGL 3D

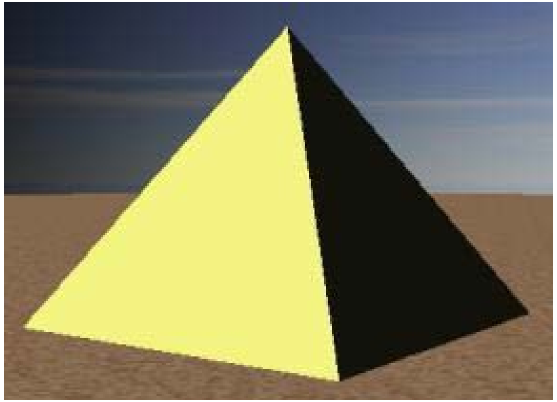
# Classical Polygon Graphics (H/W) Pipeline

- Mesh objects with 3D polygons (triangles or quads usually)
- Apply material properties to each object (for reflectance computation)
- Texture-map (i.e., superimpose an image on) polygons as needed
- Light scene
- Place camera
- Render (for each object/shape, for each polygon)
- Enjoy the view (map it to the display)

# Why OpenGL for 3D?

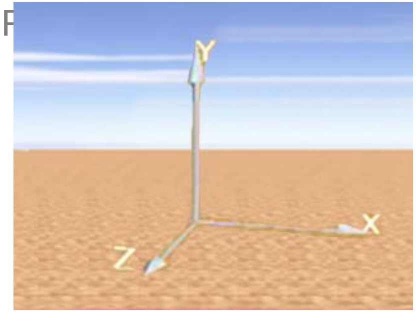
- Widely used in industry and academia for interactive or real-time 3D graphics
- Old fixed-function API (OpenGL 1.x) assisted rapid prototyping of simple 3D scenes with "classical" lighting effects
  - Experiment with simple ideas quickly
- Modern programmable API allows for more flexibility and control
  - TAs will initially provide shaders for projects/labs; you will write your own in Labs 2 and 3

# 3D Polygons (1/2)



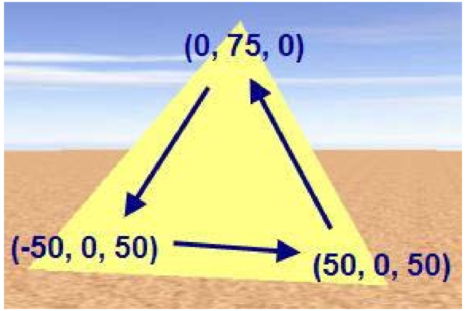
- Material specification
  - Describes the light reflecting properties of the polygon
    - Color, shininess, reflectiveness, etc.
  - Provided as input to shader
    - Provide values as **uniforms** to apply to entire shapes
    - Provide values as **attributes** to apply to individual vertices
  - Specify yellow color of triangle as (1.0, 1.0, 0.3), an RGB triple
    - Alpha (translucency) can be specified as an additional parameter, or defaulted to 1.0

# 3D Polygons (2/2)




- OpenGL defaults to a right-handed coordinate system
- Polygons are defined in a single array of vertices:

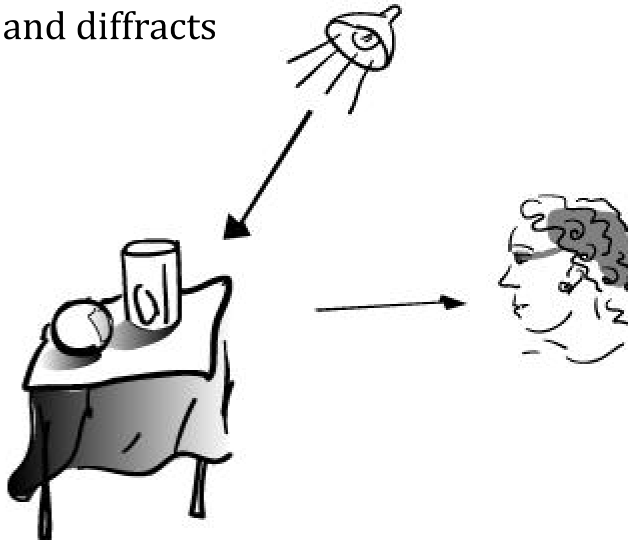
```
GLfloat vertexData[] = {
        0, 75,  0, // Vertex 1
      -50,  0, 50, // Vertex 2
       50,  0, 50, // Vertex 3
};
```




  - This defines one triangle
    - A 3D shape would have multiple triangles in one array
  - Coordinate values are arbitrary - can set virtual camera up to capture any size scene, so use convenient values
  - Remember counter-clockwise winding order!
  - Surface normal uses right-hand rule: E1 **x** E2 is normal to plane defined by edges E1, E2

# Complexities of Light Reflection from Surfaces – Need to Know

- Intensity and direction of ***all light*** that strikes a point on object's surface, whether directly from light source or after multiple bounces from other objects ( global illumination, inter-object reflection)
- How an object's surface appears to us as it reflects, absorbs, and diffracts light ("material properties")
- Location of eye/camera relative to scene
- Distribution of intensity per wavelength of incident light
- Human visual system (HVS) and its differential, highly non-linear response to light stimuli
- Lights may have geometry themselves



- **Modern lighting/illumination models address these complexities (except for HVS)**

# An Imperfect World – Model via Approximations

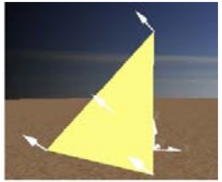
- Classic **lighting** models (also called illumination or reflection models, not to be confused with **shading** models discussed later) developed at the dawn of raster graphics in early 70s.
  - Epicenter at University of Utah in SLC where Ivan Sutherland worked with David Evans, a Mormon
  - Spawned the Evans & Sutherland flight simulator (with graphics) business
  - Other pioneers:
    - Henri Gouraud (shading model – filling in interior pixels from colors at vertices of a triangle)
    - Bui Tuong Phong (lighting and shading models)
    - Martin Newell (the Utah teapot (SIGGRAPH icon), meshing algorithms)
    - James Clark (geometry engine, Silicon Graphics, Netscape)
    - John Warnock (Hidden Surface Elimination, Adobe)
    - Ed Catmull (splines, Pixar, Disney)
    - Alvy Ray Smith (SuperPaint, HSV color space, partnered with Catmull on LucasFilm -> Pixar)
    - etc...

# An Imperfect World

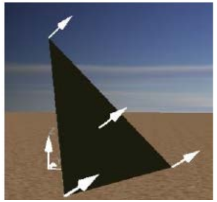
- Back then:
  - CPUs > 6 orders of magnitude less powerful, no GPU to speak of, just plot pixels
  - memory limited (measured in KB!)
- Even on today's machines, a physically accurate light simulation requires computational power beyond the capabilities of supercomputers!

# Simple Lighting (Illumination) Models (1/2)

- Color of point on surface dependent on lighting of scene and surface material
- First approximation: model diffuse reflection from a matte surface (light reflected equally in all directions, viewer-independent) based **only** on angle of surface normal to light source



**Facing light source: Maximum reflection**

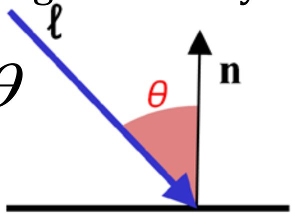


**⊥ to light source: No reflection**

**In between: Some fraction of light reflected**

- Modeling light "drop-off“ with angle to light
  - Lambert's diffuse-reflection cosine law
    - models reflected light intensity ***I***

$$I = I_{dir} \cos\theta$$




$I_{dir}$ = measure of intensity of directional light (all rays parallel) at point of contact with surface, like rays from “infinitely far away” sun

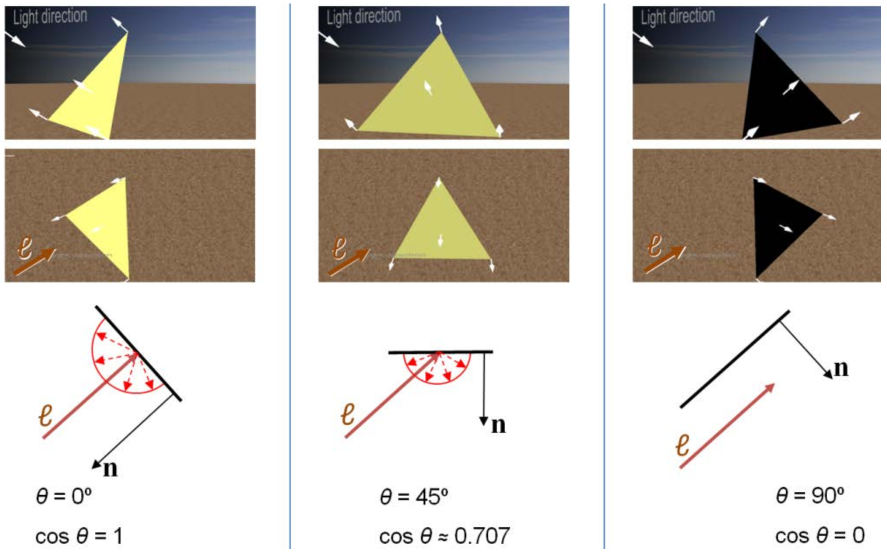
$\theta$ = angle between surface normal (**n**) and vector from light source ($\ell$)

**Note: $I_{dir}$ and other quantities are fractions in [0, 1]. These units are convenient BUT completely arbitrary and not physically-based!**

# Simple Lighting (Illumination) Models (2/2)

- Lambert light attenuation based on surface's angle to light source
- Visualization of Lambert's law in 2D

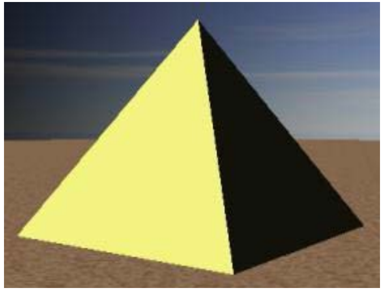
$$I = I_{dir} \cos\theta$$



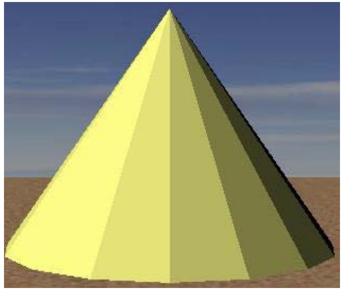

- Note: crudely approximate intrinsic material properties of object with RGB values. For example, the greater the R, the more reddish the object will appear under white light.
  - In reality, need surface (micro)geometry and wavelength-dependent reflectivity, not just RGB

# Shading Rule (1/6)

- Goal: finding color at each pixel, preferably w/o having to evaluate a full lighting model at each pixel
- First approach: Lambert's cosine law (flat/constant shading for whole facet)
  - faceted appearance, perfect for this rectangular pyramid.



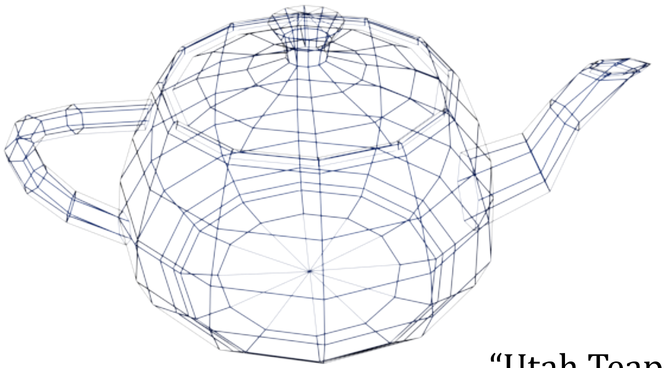
- What if we want to approximate a rounded object?
  - Lambert-shaded, faceted; appearance is no longer ideal

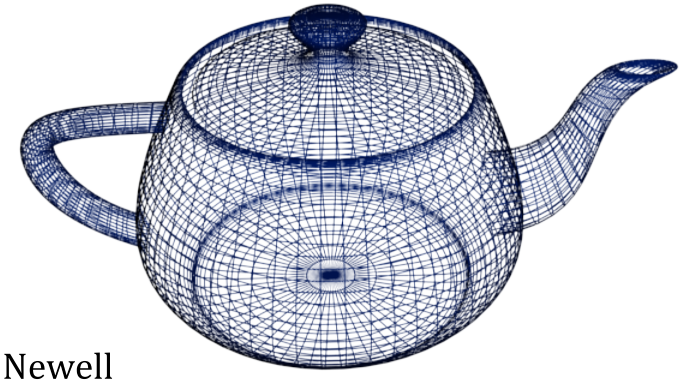


http://math.hws.edu/graphicsbook/demos/c4/smooth-vs-flat.html

# Shading Rule (2/6)

- First solution: increase the number of polygons
- Better shape approximation, more expensive to render
- Ultimately, still faceted when rendered (higher poly count **=>** less faceted)
- Adaptive meshing is an improvement - more polygons in areas of high curvature





"Utah Teapot" by Martin Newell

# Shading Rule (3/6)

- Get this:

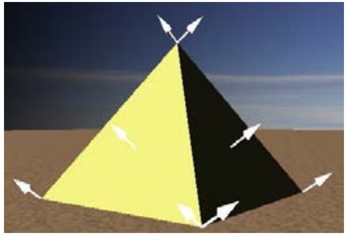
**faceted shading**

- Want this:

**smooth shading**

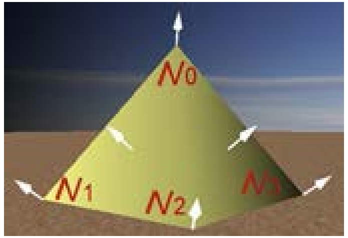
# Shading Rule (4/6)

- Gouraud smooth shading
  - compute lighting equation at each vertex of mesh (requires angle between normal, vector to light) for Lambertian diffuse reflection
  - linearly interpolate vertex color values to get colors at all points: C = C1 + **t**(C2- C1)
    - **weighted averaging**: the closer point is to a vertex, the more it is influenced by that vertex
  - **How do we determine vertex colors? Need a normal…**
    - Vertex normals are an artifice; the normal is mathematically undefined since a vertex is a discontinuity
    - Sol'n 1: use plane normal, get faceted shading
    - Sol'n 2: hack: average face/plane normals



Faceted

*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 helps define.*

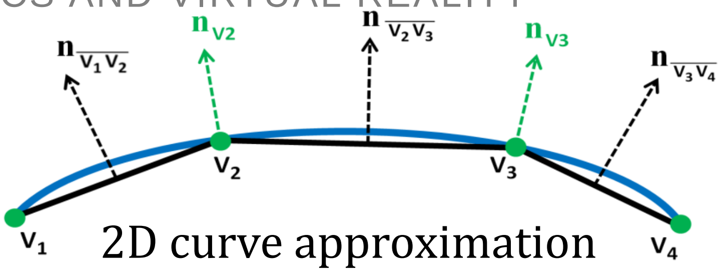



Smooth

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

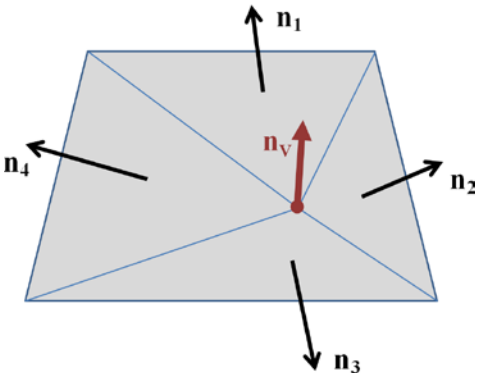
# Shading Rule (5/6)

- Vertex normals
  - if vertex used by only one face, normal is set to face's normal
    - typically computed from the face’s plane equation
  - otherwise, normal is set to average of normals of all faces sharing it
  - if mesh is not too coarse, vertex normal is a decent approximation to the normal of modeled surface closest to that vertex
  - adaptive meshing adds more triangles in areas with rapid changes in curvature
  - in assignments, you use some hacks to compute better approximations of the normal to the original surface




2D curve approximation (vertex normals in green)

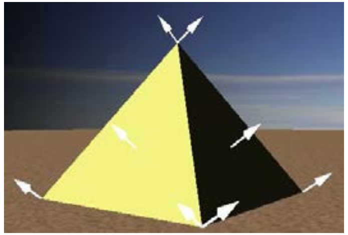
*Vertex normals shown in color, face normals in black*



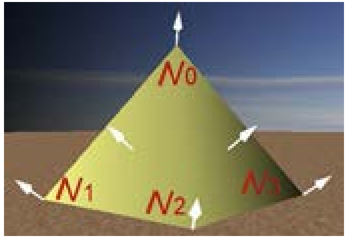

3D mesh approximation (looking down on an irregular pyramid, face normals roughly cancel each other out, hence normal points out)

# Shading Rule (6/6)

- Programmable OpenGL API doesn't provide any lighting or shading. Use shaders to implement lighting model and shading rule of your choice
  - to get flat shading, specify the same surface normal for vertices of the same facet (each vertex gets *n* normals, where *n* is the number of facets it is a part of)
  - to get smooth shading, you must specify a single shared normal for each (shared) vertex in the object

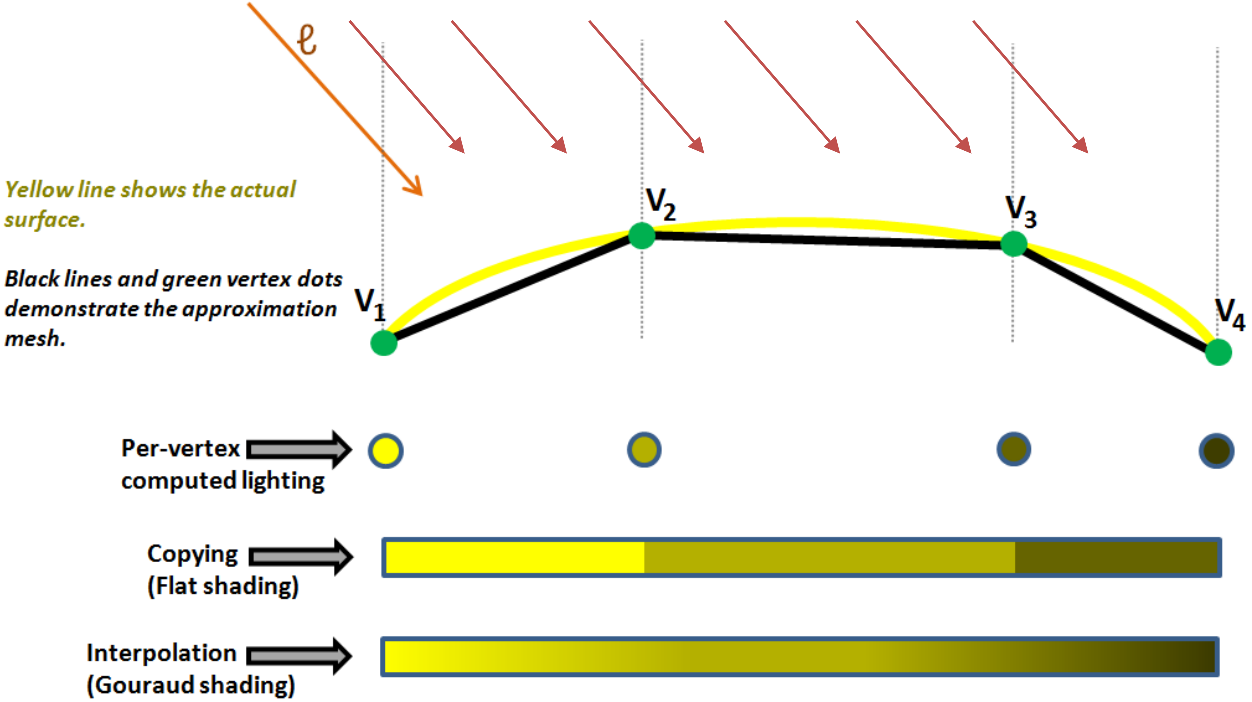


Faceted




Smooth

# Interpolation vs Flat Shading Summary



# Vertex Normals

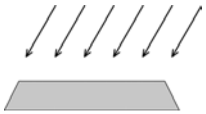
- Sending vertex normal to the shader requires a small extension to the way we specify vertices
- Each vertex is now a position plus a normal, e.g.,

```
GLfloat[] vertexData = {
       -1, 0,  0, // Position 1
        0, 0, -1, // Normal 1
        1, 0,  0, // Position 2
        1, 0,  0, // Normal 2
       … };
```

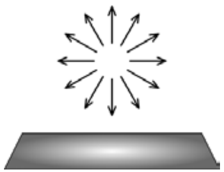
- Normals needn’t be axis-aligned, of course…
- For flat shading a shared vertex has as many (position, normal) entries as the facets it’s a part of

# Phong Reflectance (Illumination, Lighting) Model (1/7)

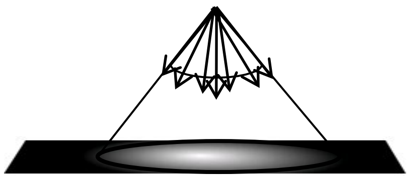
- **Non-geometric lights:**
  - Ambient: crudest approximation (i.e., total hack) to inter-object ("global") reflection - all surfaces receive same light intensity. Allows all facets to be minimally visible
  - Directional: illuminates all objects equally from a given direction; light rays are parallel (models sun, sufficiently far away)
- **Geometric lights:**
  - Point: Originates from single point, spreads outward equally in all directions
  - Spotlight: Originates from single point, spreads outward inside cone's directions



Directional



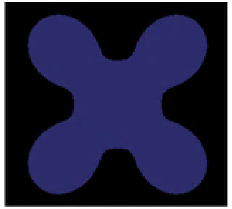
Point



Spotlight

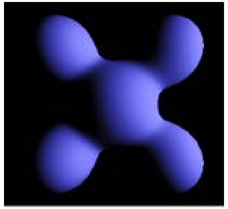
# Phong Reflectance Model (2/7)

- Many models exist to approximate lighting physics – more accurate => more computation
- Fixed-function OpenGL: Phong reflection model, survives today (though crude)
  - implemented in fixed function hardware for decades, easily implemented in shaders
  - approximates lighting by breaking down into three components: ambient, diffuse, specular
  - can think of these as coincident, independent layers, each with its own characteristics, and sum them to get the final result
  - is a non-global illumination model – no inter-object reflections, non-physically based



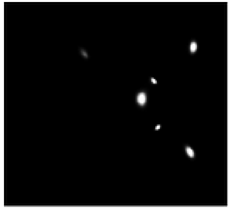
**AMBIENT**
**Effect of light that is non-directional, affecting all surfaces equally.**

+



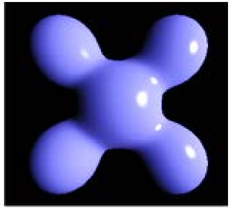
**DIFFUSE**
**Effect of directional light on a surface with a dull/rough finish.**

+



**SPECULAR**
**Effect of directional light on a shiny surface when the vector to the eye-point is closely aligned to the light's reflected rays.**

=



**THE COMPOSITE**
**The three independent reflectivity types are accumulated to produce the result.**

# Phong Reflectance Model (3/7)

- $I_{total,\lambda} =$

Ambient Component

$$\left(I_{ambient,\lambda} k_{ambient,\lambda} O_{diffuse,\lambda}\right) +$$

Diffuse Component

$$\Sigma_{directional\ lights} \left(I_{diffuse,\lambda} k_{diffuse,\lambda} O_{diffuse,\lambda} (\cos\theta)\right) + \Sigma_{geometric\ lights} \left(f_{att} I_{diffuse,\lambda} k_{diffuse,\lambda} O_{diffuse,\lambda} (\cos\theta)\right) +$$

Specular Component

$$\Sigma_{directional\ lights} \left(I_{specular,\lambda} k_{specular,\lambda} O_{specular,\lambda} (\cos\delta)^n\right) + \Sigma_{geometric\ lights} \left(f_{att} I_{specular,\lambda} k_{specular,\lambda} O_{specular,\lambda} (\cos\delta)^n\right)$$

- Equation is wavelength-dependent; approximate with separate equations for $\lambda \in (R, G, B)$
- All values unitless real numbers between 0 and 1
- Evaluates total reflected light $I_{total,\lambda}$ at a single point, based on all lights

# Phong Reflectance Model (4/7)

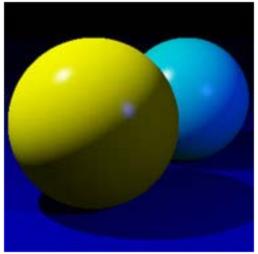
- **Variables**
  - $\lambda$ = wavelength / color component (e.g. R, G, and B)
  - $I_{total,\lambda}$ = total amount of light reflected at the point
  - $I_{ambient}$ = intensity of incident ambient light; similar for diffuse, specular incident light
  - $f_{att}$ = attenuation function for a geometric light
  - $O$ = innate color of object's material at specific point on surface (RGB approximation)
  - $k$ = object's efficiency at reflecting light
  - Since both $O$ and $k$ are dimensionless fractions we really only need one of them
- **Ambient component**
  - $(I_{ambient,\lambda} k_{ambient,\lambda} O_{diffuse,\lambda})$ -- think of $k_{ambient,\lambda}$ as the fraction of $I_{ambient}$ reflected for that $\lambda$. Note that here we use $O_{diffuse,\lambda}$ for the ambient component; in Sceneview we use distinct $O_{ambient,\lambda}$
  - effect on surface is constant regardless of orientation, no geometric information
  - total hack (crudest possible approximation to global lighting based on inter-object reflection), but makes all objects a little visible - scene looks too stark without it

# Phong Reflectance Model (5/7)

- **Diffuse component (R component shown below, same for G, B) - viewer independent!**
  - uses Lambert's diffuse-reflection cosine law
  - $\Sigma\left(I_{diffuse,R}k_{diffuse,R}O_{diffuse,R}(\cos\theta)\right)$
  - $I_{diffuse}$ = light's diffuse color
  - $k_{diffuse}$ = the efficiency of incident light reflection
  - $O_{diffuse}$ = innate color of object's diffuse material property at specific point on surface
  - $\cos\theta$ = Lambert's attenuation factor where $\theta$ is the angle between normal and light vector

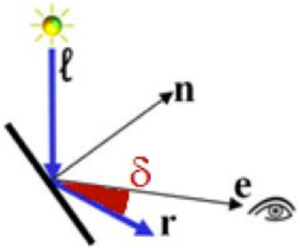
# Phong Reflectance Model (6/7)

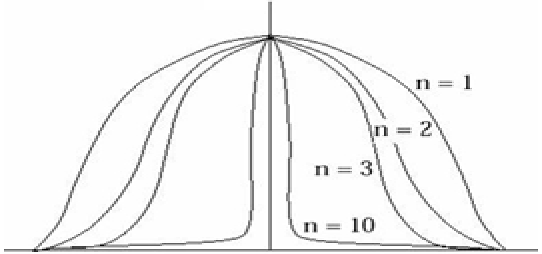
$$\Sigma_{lights}\left(I_{specular,\lambda}k_{specular,\lambda}O_{specular,\lambda}(\cos\delta)^n\right)$$



- Specular Component (for R) – viewer-dependent
  - highlights seen on shiny objects (plastic, metal, mirrors, etc.)
  - cosine-based attenuation factor ensures highlight only visible if reflected light vector and vector to viewer are closely aligned
  - $n$ = specular power, how "sharp" highlight is – the sharper, the more intense
  - specular highlight of most metals are the color of the metal but those on plastic, shiny apple, pearl, etc. are mostly the color of the light (see Materials chapter 27)

**e** = viewpoint
**r** = reflected image of light source
***ℓ*** = vector from the light source
**n** = surface normal
$\delta$ = angle between e and r
**n** = specular coefficient




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

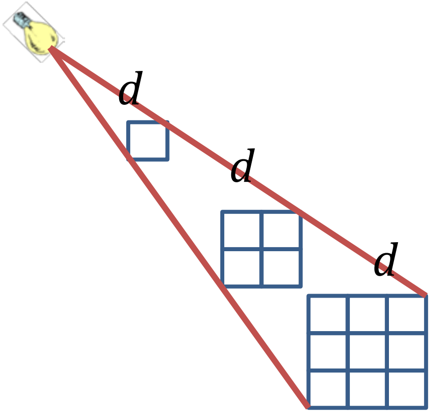
Note: Fixed-function OpenGL uses a slightly different lighting model called Blinn-Phong. See 14.9.3

# Phong Reflectance Model (7/7)

- Attenuation factor $f_{att}$
  - Used in diffuse and specular light calculation:

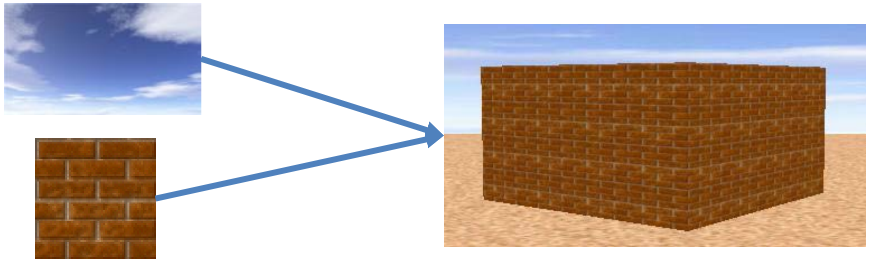
$$...+ \Sigma_{geometric\ lights}\left(f_{att} I_{diffuse,\lambda} k_{diffuse,\lambda} O_{diffuse,\lambda} (\cos\theta)\right) +...$$

  - Directional lights have no attenuation (infinitely far away)
  - Geometric lights (point lights, spot lights) get dimmer with distance
  - Inverse square law
    - area covered increases by square of distance from light
    - thus, light intensity is inversely proportional to square of distance from light
    - light twice as far away is one quarter as intense
    - though physics says inverse square law, doesn't always look good in practice so OpenGL lets you choose attenuation function (quadratic, linear, or constant)



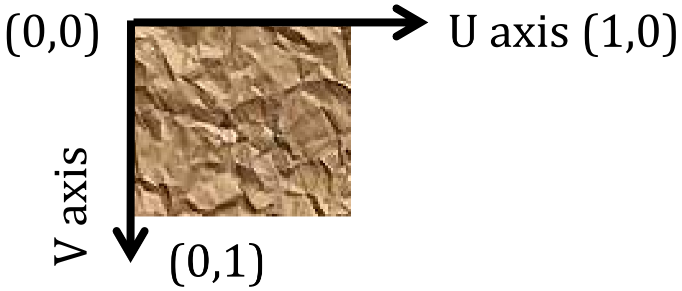
# Texture Mapping (1/2)

- **Goal:** adding more detail to geometry of scene without adding more actual polygons
- **Solution:** texture mapping
  - used extensively in video games, e.g., for backgrounds, billboards
  - also used for many other techniques such as level-of-detail management
  - cover the mesh's surface in stretchable "contact paper" with pattern or image on it
  - in general, difficult to specify mapping from contact paper to every point on an arbitrary 3D surface
  - mapping to planar polygons is easy: specify mapping for each vertex and interpolate to find mapping of interior points



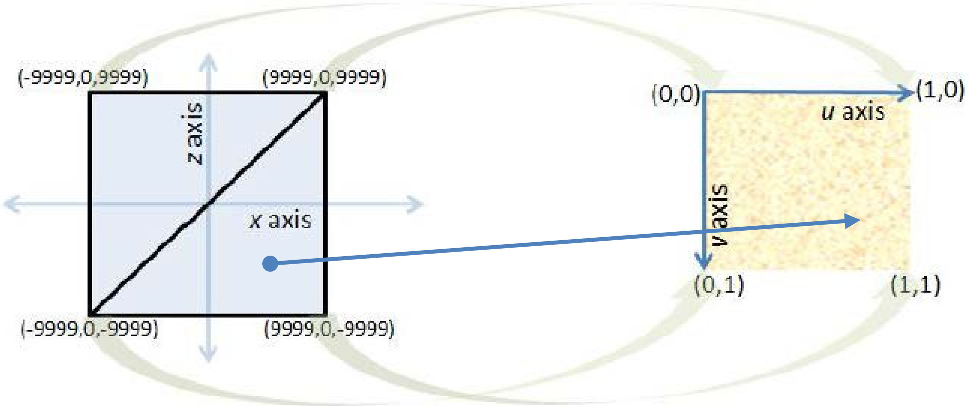
# Texture Mapping (2/2)

- Specifying "texture point" mapped to particular vertex
  - requires coordinate system for referring to positions within texture image
  - convention:
    - points on pixmap described in abstract floating-point "texture-coordinate system"
    - axes labeled u and v, range 0 to 1.
    - origin located at the upper-left corner of the pixmap



# Texture Mapping UV Coordinates

- Let's map from two coplanar triangles from a face in the 3D model to a texture map
- Texture map uses UV texture coordinates: just use ratios




Object Quad Face    Texture Map

- Texture mapping arbitrary solids is much harder – we'll study this later

# Texture Mapping Example (1/2)

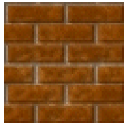
- We add texture coordinates* in the same way we added normals

```
GLfloat[] vertexData = {
      -10, 0, 0,  // Position 1
        0, 1, 0,  // Normal 1
        0, 0,     // Texture Coordinate 1
       10, 0, 0,  // Position 2
        0, 1, 0,  // Normal 2
        1, 0,     // Texture Coordinate 2
      … };
```

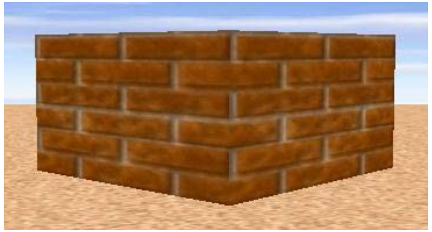
* We'll teach how to set up texture maps in Lab 3

# Texture Mapping (Tiling)

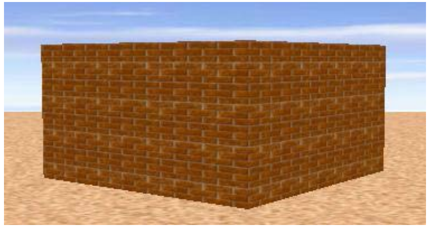
- Create a brick wall by applying brick texture to plane



- Produces realistic-looking image, but very few bricks in wall



- Tiling increases number of apparent bricks



# Texture Mapping (Stretching)

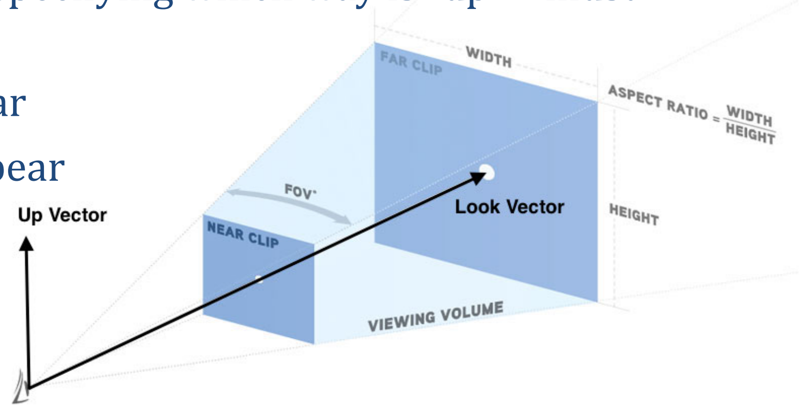
- Create a sky backdrop by applying a sky image to a plane

- Would look unnatural if tiled
- Stretch to cover whole plane

- Your texture shader can implement tiling and stretching by multiplying UV coordinates by a value >1 for tiling and <1 for stretching

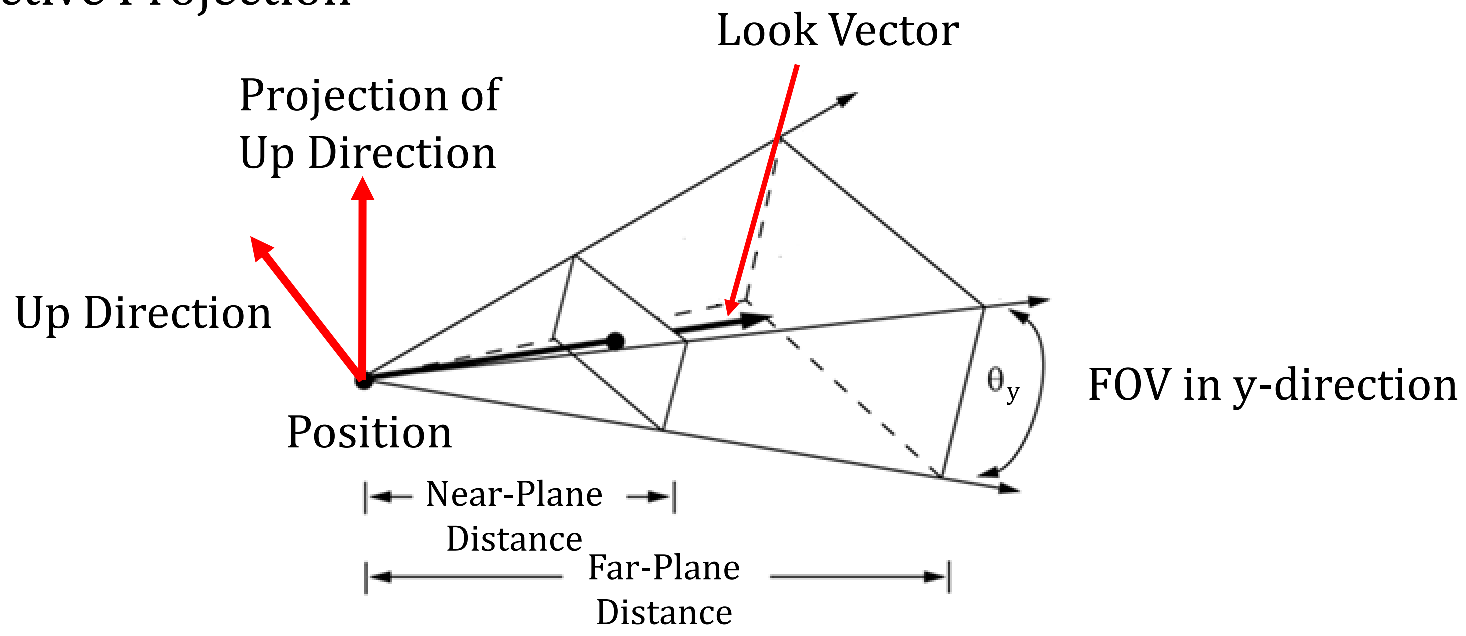
# Camera (1/3)

- Camera Properties:
  - **Perspective** or **Orthographic**
  - **Position**: placement of camera
  - **Look Direction**: direction camera is aimed (vector determining lens axis)
  - **Up Direction**: rotates camera about look vector, specifying which way is "up" – must not be collinear to the look vector
  - **Far-Plane Distance**: objects behind do not appear
  - **Near-Plane Distance**: objects in front do not appear
  - **Field Of View**: (Width, height or diagonal angle)
  - **Aspect Ratio** (Relative width and height)



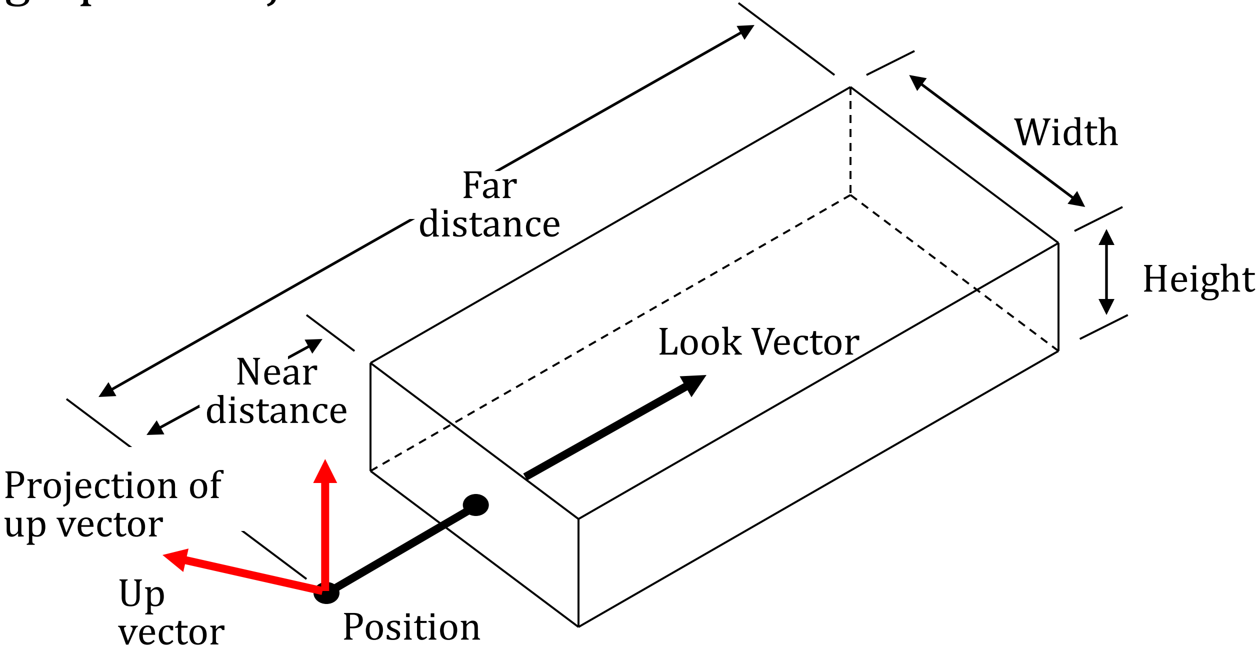
# Camera (2/3)

- Perspective Projection



# Camera (3/3)

- Orthographic Projection



# OpenGL Camera

- Fixed-function API has support for perspective and orthographic cameras
- With the Programmable API you must construct and supply all model, view, and projection matrices, and then use them in your shaders
- In the Viewing lectures you will learn how to construct these matrices yourselves, to use in the Camtrans lab (We will take care of the camera until then)
- In the shader labs you will learn how the matrices are used in shaders

# Rendering with OpenGL

- Pipeline of rendering with OpenGL
  - Calculate vertex data (position, normals, texture coords)
  - Calculate scene data (light position/type, camera position/orientation etc.)
  - Pass scene data to shader (specifying uniforms, in OGL parlance)
  - Pass vertex data to shader (specifying attributes, in OGL parlance)
  - Tell OpenGL to draw
- To be extra clear:
  - You write most code in C++
  - The C++ code involves using the OpenGL API to set up data structures for scene geometry, lights, and camera, which are then passed to the shaders for execution
  - You write the shaders in GLSL to process this data for rendering
- Easy enough, but just how do you pass data to shader?

# Passing Data to Shader (1/5)

- What kinds of data do we have in the scene?
- Vertex data (position, normal, tex coords)
  - Pass as **attributes** in a single large array
  - Requires two OpenGL objects
    - VBOs (Vertex Buffer Objects)
    - VAOs (Vertex Array Objects)
- Also have data that remains constant across vertices (e.g., camera matrices)
  - Pass as **uniforms** using a named variable

# Passing Data to Shader (2/5) -- Uniforms

- Used for data that remains constant for all vertices
  - e.g. color,* camera position, light position
- Three steps
  - 1. In GLSL shader => declare uniform variable
    - Ex: `uniform vec3 color;`
  - 2. In C++ OpenGL => Find memory address of uniform variable
    - Ex: `GLint color_loc = glGetUniformLocation(m_shaderID, "color");`
  - 3. In C++ OpenGL => Store data in memory address
    - Ex: `glUniform3f(color_loc, 0.5, 0.9, 0.8);`
      - Note: `3f` stands for 3 floats (RGB). To store 2 floats, use `glUniform2f`. To store 4 ints, use `glUniform4i`
      - See here for list of entire `glUniform` family



* Here color is constant for the whole object, but it can also be a vertex attribute

# Passing Data to Shader (3/5) – Example Uniforms

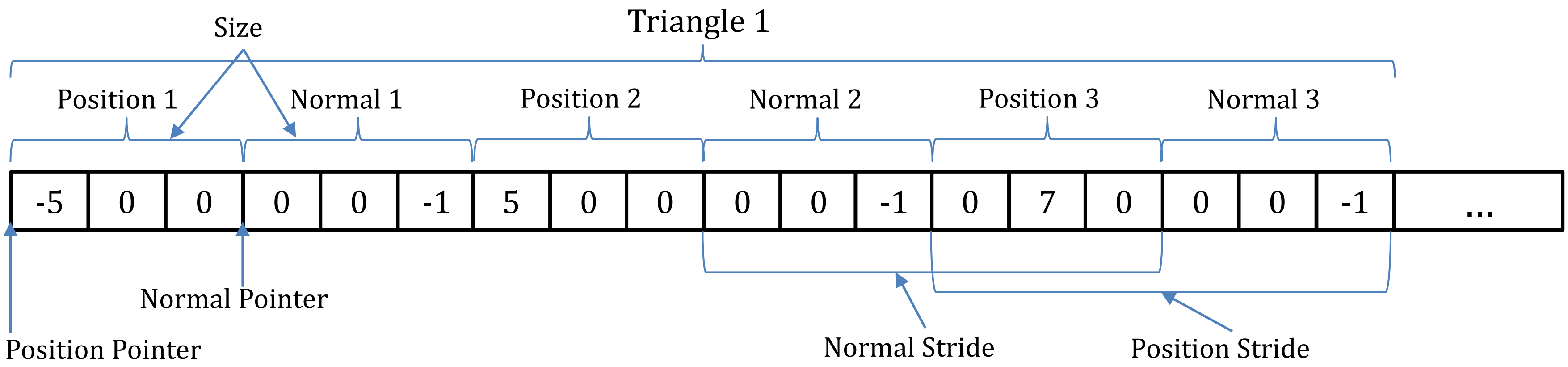
```
// passing information for color
// ambient term is specified as RGB(A). Use glUniform4f to provide optional alpha value
// this specifies a dark grey ambient “light”
glUniform4f(<Ambient Location>, 0.2, 0.2, 0.2, 1.0 ); // 4f = 4 floats

// passing information for lighting
glUniform3f(<Position Location>, 10.0, 5.0, 8.0 ); // 3f = 3 floats
glUniform3f(<Direction Location>, 1.0, 2.0, 3.0 );

// specify an integer constant to describe type of light, here a point light
glUniform1i(<Type Location>, POINT_LIGHT_TYPE); // 1i = 1 int

// To use a directional light
glUniform1i(<Type Location>, DIRECTIONAL_LIGHT_TYPE);
```

# Passing Data to Shader (4/5) – Vertex Data

- Passing vertex data is more complicated than uniform data
- Have vertex data (pos, normal, tex) in single large array
  - Note: In OGL parlance, pos, normal, tex etc. are **attributes** each vertex has
- Two steps
  - 1. Store data in Vertex Buffer Object (VBO)
  - 2. Specify attribute layout in VBO with Vertex Array Object (VAO)

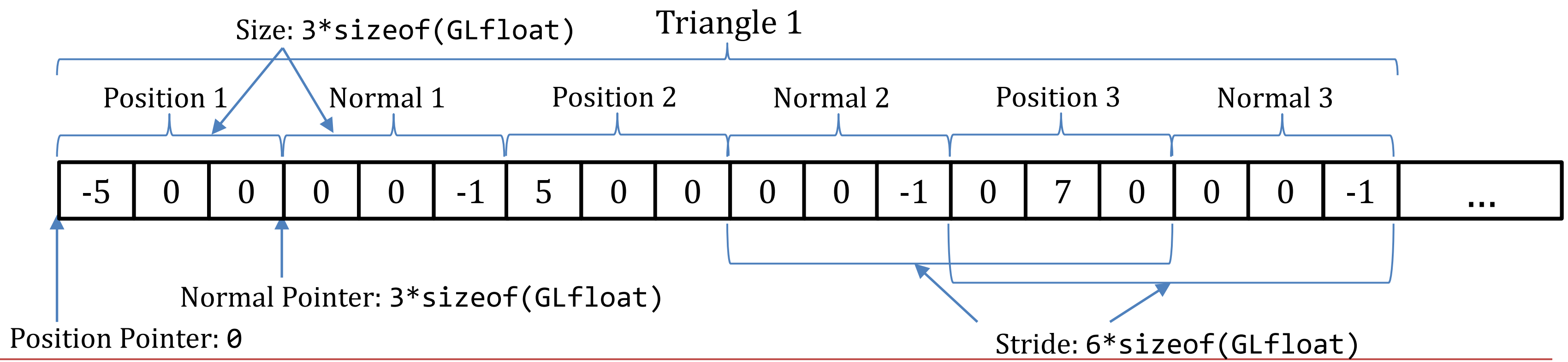
# VBOs and VAOs

- VBO (Vertex Buffer Object) stores vertex data, such as position, normal, and texture coordinates. Created in C++ program, passed to shader
  - (all numbers below are really GL_FLOATs)
- Meaningless w/o interpretation - VAO tells shader how attributes are stored



# Vertex Array Objects

- For each attribute, VAO takes three parameters, details in lab 1
  - **size** parameter is how many values an attribute has (e.g. 3 for position)
  - **stride** specifies how far apart values of the same type are in our array
  - **pointer** is a pointer to the index of the first value of that attribute
  - Because VBO is byte array, multiply parameters by `sizeof(Glfloat)`



# The CS337 Guide to OpenGL

- TA has written a guide to OpenGL:
  http://www.cs.sjtu.edu.cn/~shengbin/course/cg/course.html

**Question 1:**

- Write a program to draw a simple red cube.

**Question 2:**

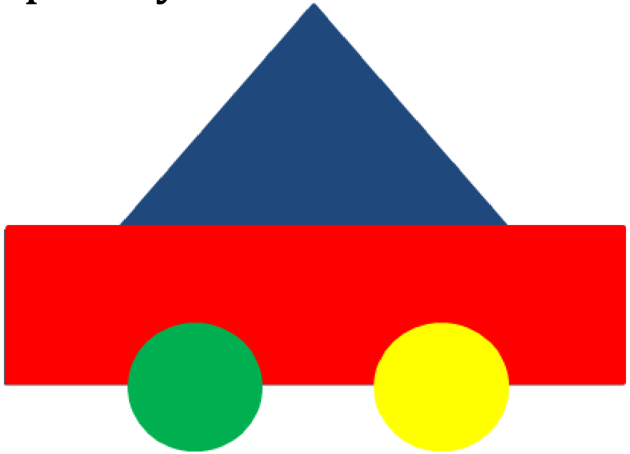
- Write a program to draw a simple blue triangle.

- **Reference:**
- http://www.opengl-tutorial.org/beginners-tutorials/tutorial-2-the-first-triangle/
- https://graphics.stanford.edu/courses/cs248-99/OpenGLSession/tri.html
- http://antongerdelan.net/opengl/hellotriangle.html

# Assignment 1- Introduction to OpenGL

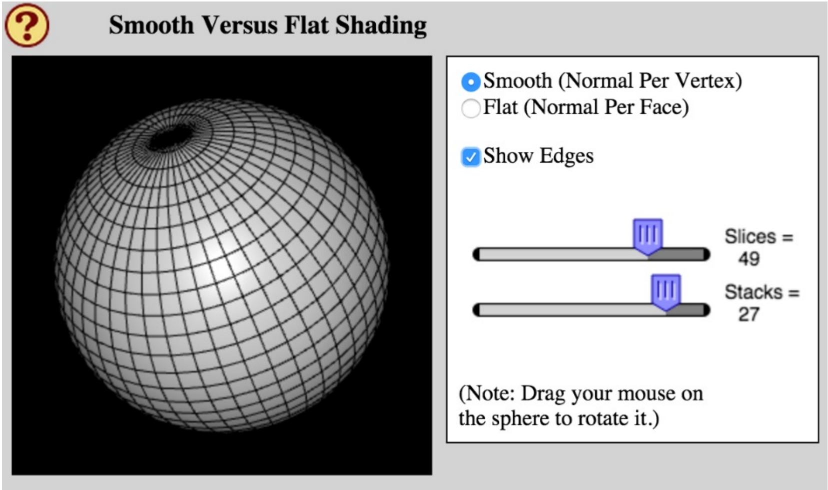
**Question 3:**

- Write a C++ class to draw and move a car using the geometrical classes. The car should be kind of similar to the one below. You can implement more complex car shapes if you want.



# Demos (1/2)

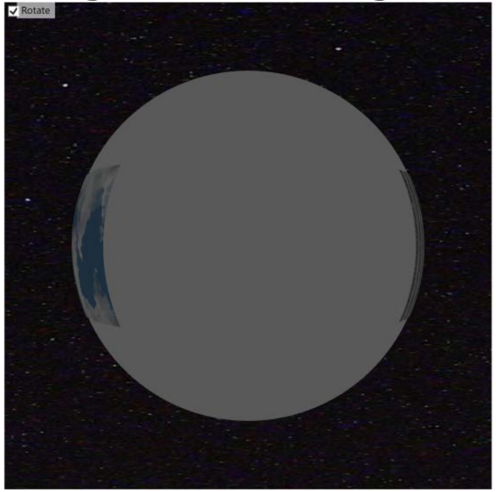
- Hands on exploration of concepts discussed in this lecture
- Modeling smooth surfaces



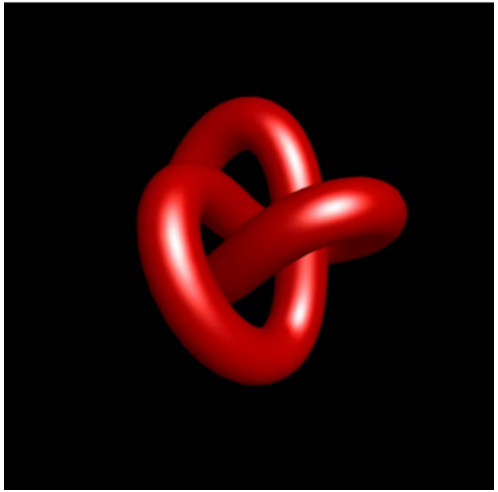

http://math.hws.edu/graphicsbook/demos/c4/smooth-vs-flat.html

# Demos (2/2)

- Lighting and shading model




http://sklardevelopment.com/graftext/ChapWPF3D/
See the "Materials and Reflectivity" part



A different one with shader code
http://www.mathematik.uni-marburg.de/~thormae/lectures/graphics1/code/WebGLShaderLightMat/ShaderLightMat.html