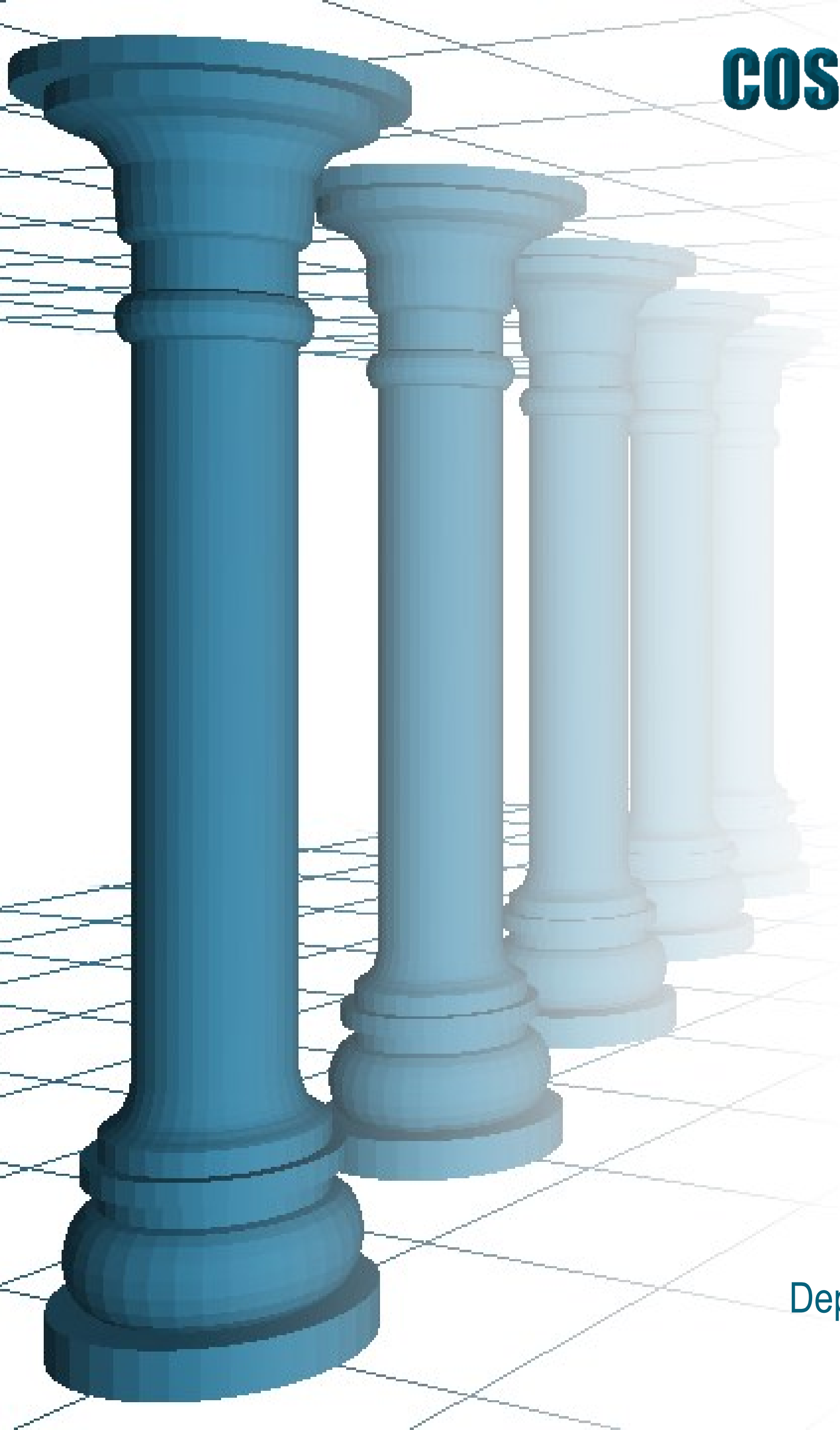

COSC363 Computer Graphics

10

OpenGL- 4

You are in charge (of everything!)

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Changes in OpenGL

- OpenGL 1.0 designed for the fixed-function pipeline is not optimal for today's hardware.
- Users must be able to choose a rendering context based on a specific OpenGL version.
- A thorough overhaul of the API began in 2007, with the design of OpenGL 3.0 in 2008, and OpenGL 4.0 in 2010
  - Fundamental changes in the rendering paradigm, suitable for hardware optimisation.
  - GPU processing given utmost importance. Allows you to create functions (**shaders**) that graphics hardware can execute.

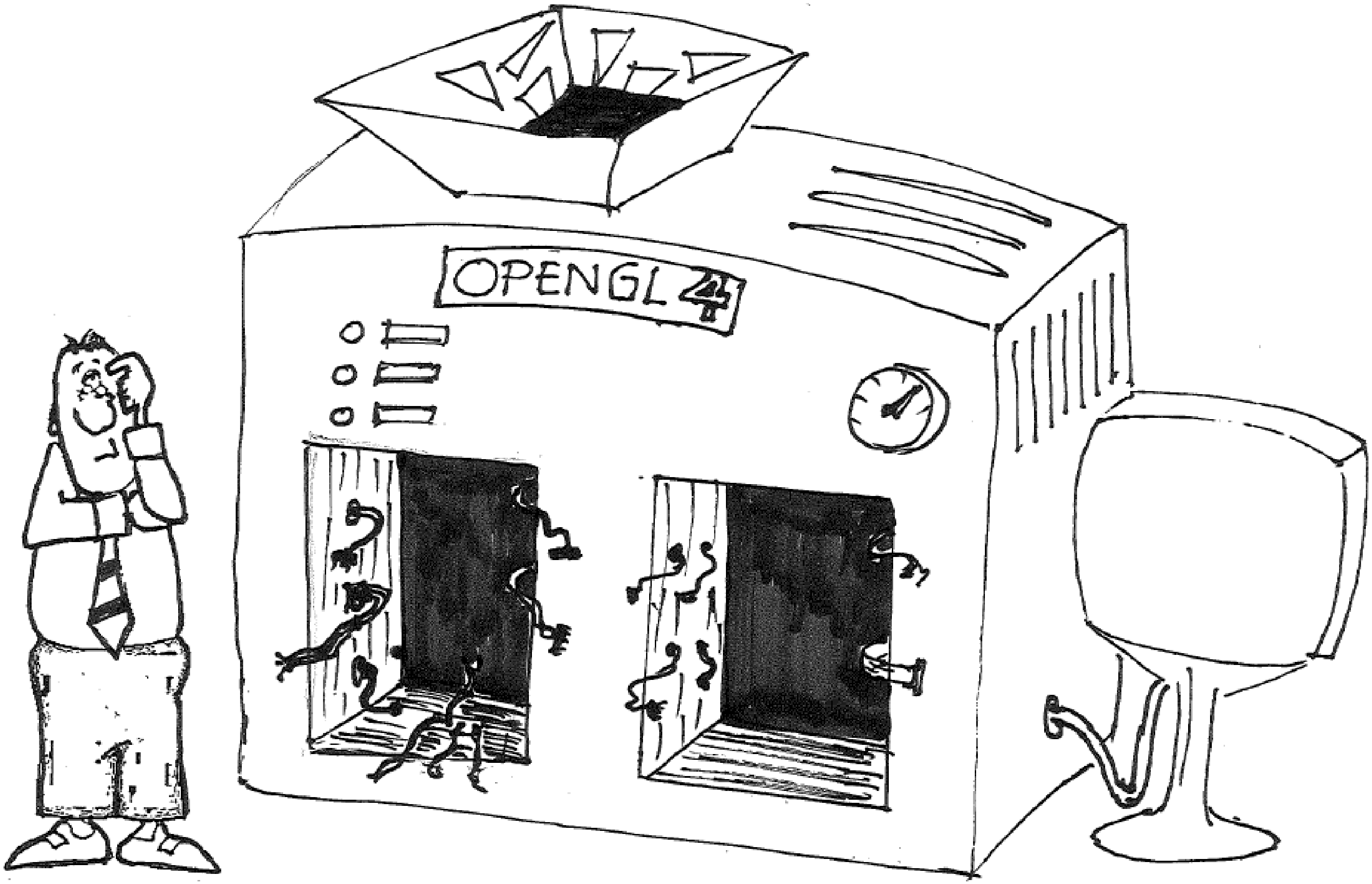
More Shader/GPU Functionality

- OpenGL 3.0 introduced a deprecation model with several functions marked for deletion in future versions.
  - All **fixed-function mode** vertex and fragment processing routines were deprecated.
  - **Immediate mode** rendering using `glBegin()-glEnd()` blocks also deprecated.
- OpenGL 3.2 divided the specification into two profiles:
  - Compatibility profile: Backward compatible, allowing access to old APIs
  - Core profile: The core API specification.

Motivation

- The ability to program the graphics hardware allows you to achieve a wider range of rendering effects that give optimal performance.
- Traditional lighting functions and the fixed functionality of the graphics pipeline are fine only for ‘common things’. They have now been removed from the core profile.
- Developers have more freedom to define the actions to be taken at different stages of processing.
- Downside: The user needs to specify the computations to be done at each stage.

OpenGL 4 State Machine



OpenGL Context: Example

```
#include <iostream>
#include <GL/glew.h>
#include <GL/freeglut.h>
using namespace std;
...

int main(int argc, char** argv)
{
  glutInit(&argc, argv);
  glutInitDisplayMode(GLUT_RGB);
  glutInitWindowSize(500, 500);
  glutCreateWindow("A Triangle");
  glutInitContextVersion (4, 2);
  glutInitContextProfile (GLUT_CORE_PROFILE);
   ...
```

Getting Version Info

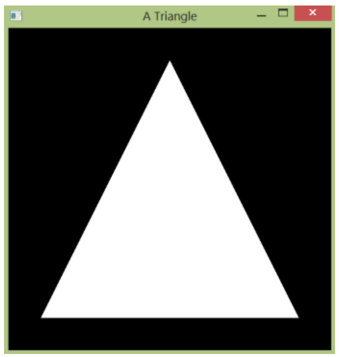
Version.cpp

```
const GLubyte *version = glGetString(GL_VERSION);
const GLubyte *renderer = glGetString(GL_RENDERER);
const GLubyte *vendor = glGetString(GL_VENDOR);
```

```
OpenGL version: 4.2.0
OpenGL vendor: NVIDIA Corporation
OpenGL renderer: GeForce 710M/PCIe/SSE2
Version (ints): 4.2
```

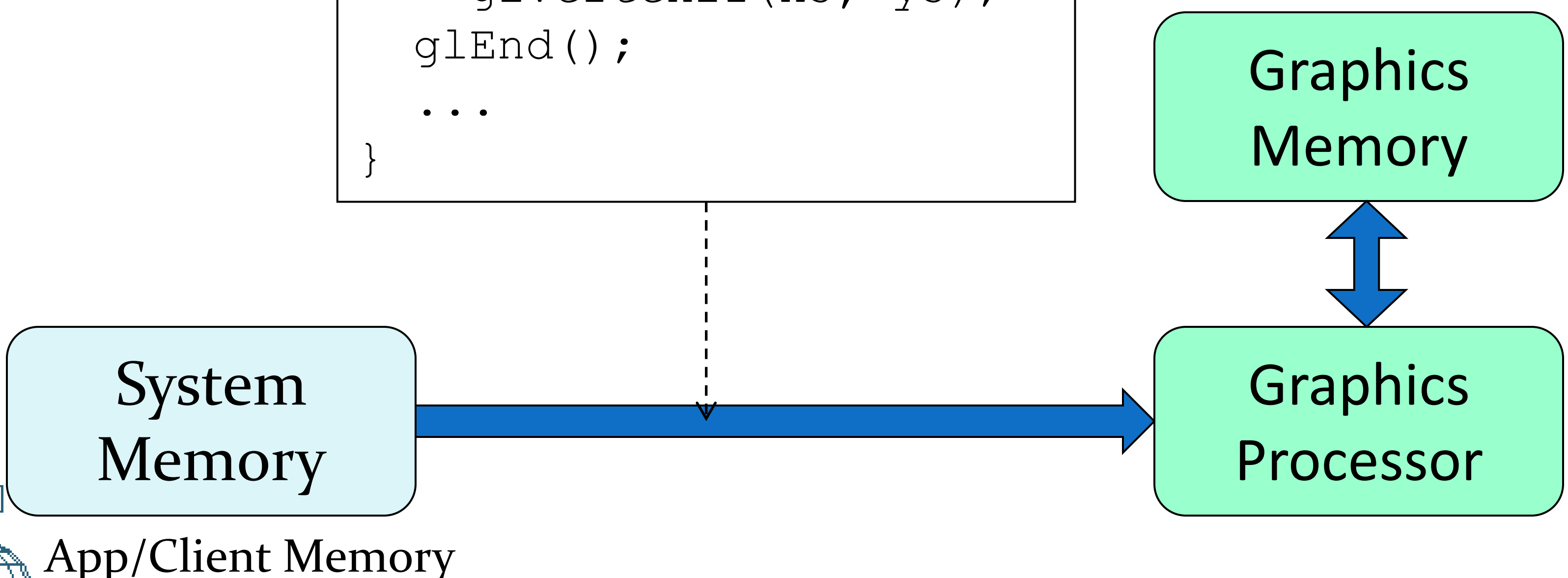
Primitive Drawing (OpenGL 1)

(Immediate Mode Rendering)




```
void display()
{
   ...
   glBegin(GL_TRIANGLES);
     glVertex2f(x1, y1);
     glVertex2f(x2, y2);
     glVertex2f(x3, y3);
   glEnd();
   ...
}
```

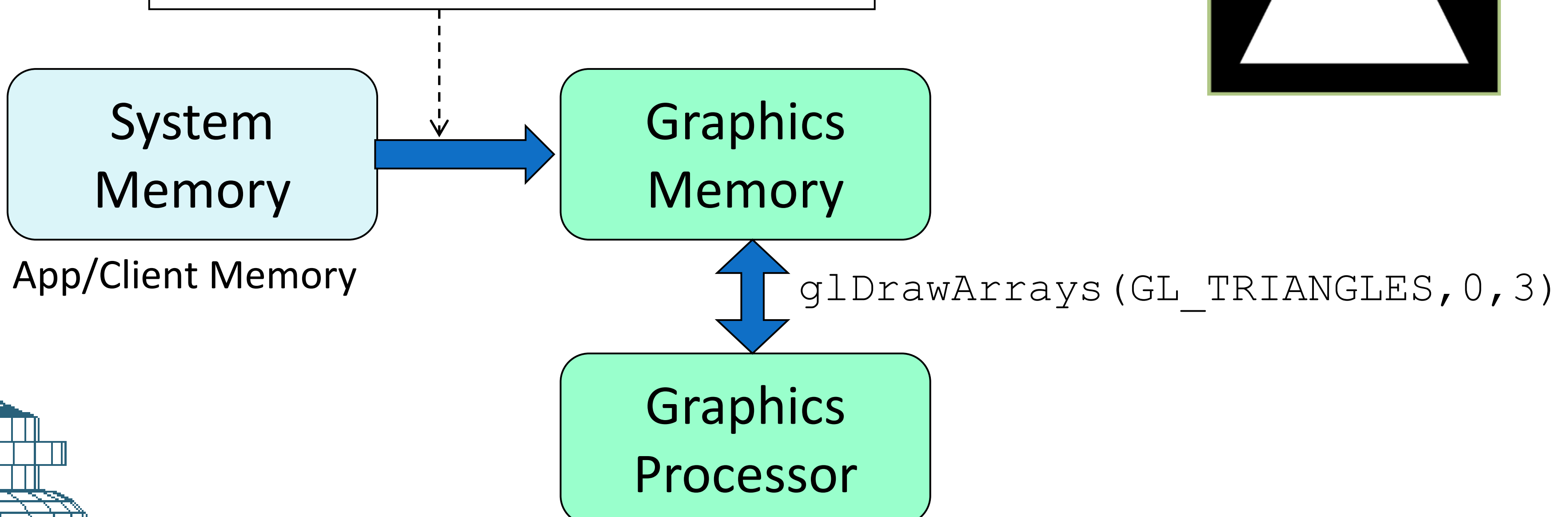
Deprecated!

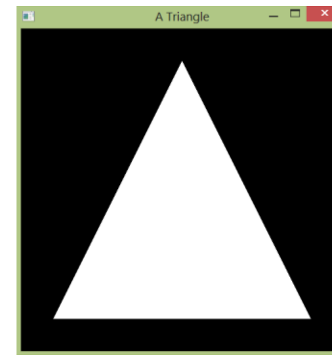


Primitive Drawing (OpenGL 4)

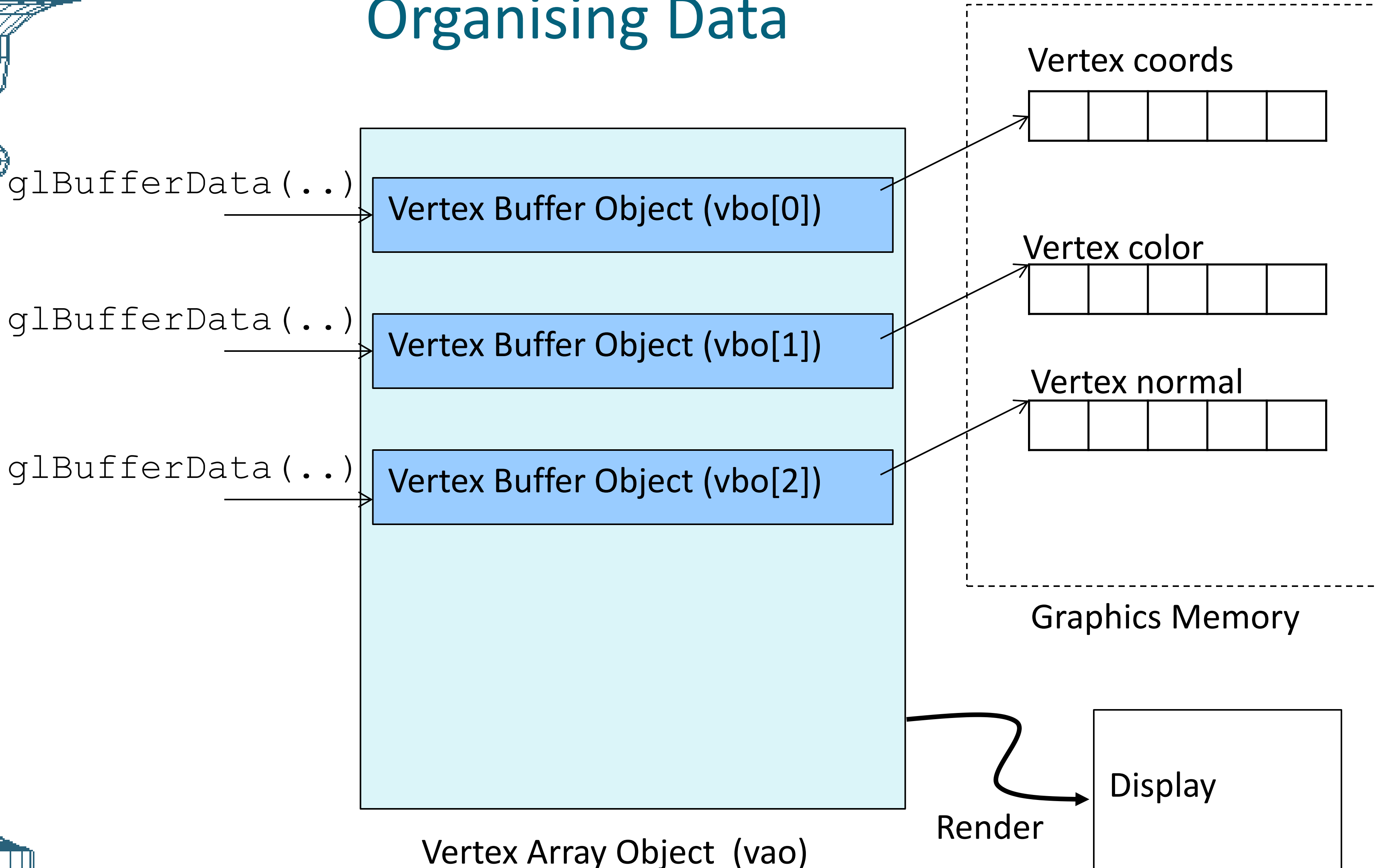
(Non-Immediate Mode Rendering)

```
void initialise()
{
    ...
    glBufferData(...);
    glBufferSubData(...);
    ...
}
```



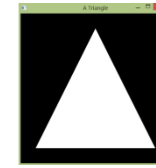


Organising Data



Vertex Buffer Objects

Draw1.cpp

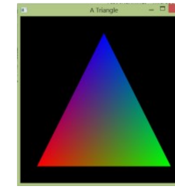


- A vertex buffer object (VBO) represents the data for a particular vertex attribute in video memory.
- Creating VBOs:
  1. Generate a new buffer object “vbo”
  2. Bind the buffer object to a target
  3. Copy vertex data to the buffer

```
  GLuint vbo;
1 glGenBuffers(1, &vbo);
2 glBindBuffer(GL_ARRAY_BUFFER, vbo);

3 glBufferData(GL_ARRAY_BUFFER, sizeof(verts), verts,
                                         GL_STATIC_DRAW);
  glEnableVertexAttribArray(0);
  glVertexAttribPointer(0, 2, GL_FLOAT, GL_FALSE, 0, NULL);
```

Multiple VBOs

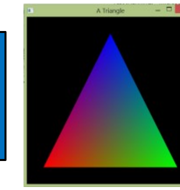
Draw2.cpp



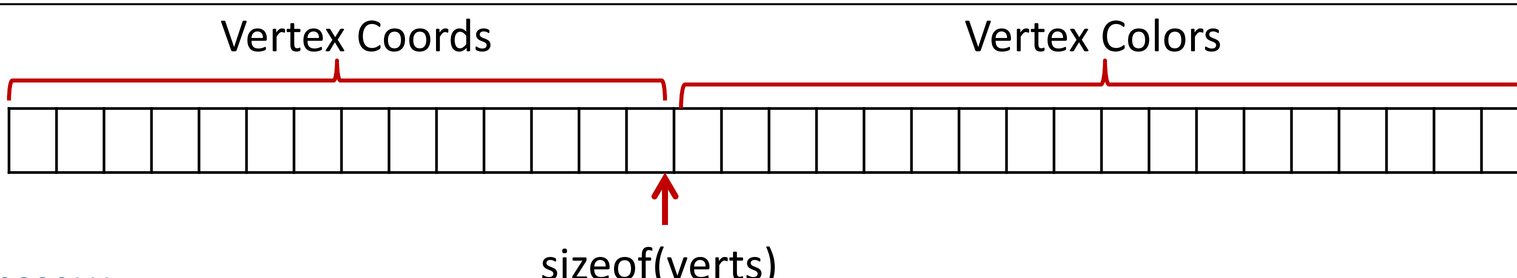
```
GLuint vbo[2];
glGenBuffers(2, vbo);     //Two VBOs

glBindBuffer(GL_ARRAY_BUFFER, vbo[0]);  //First VBO
glBufferData(GL_ARRAY_BUFFER, sizeof(verts), verts,
                                         GL_STATIC_DRAW);
glEnableVertexAttribArray(0);
glVertexAttribPointer(0, 2, GL_FLOAT, GL_FALSE, 0, NULL);

glBindBuffer(GL_ARRAY_BUFFER, vbo[1]);  //Second VBO
glBufferData(GL_ARRAY_BUFFER, sizeof(cols), cols,
                                        GL_STATIC_DRAW);
glEnableVertexAttribArray(1);
glVertexAttribPointer(1, 4, GL_FLOAT, GL_FALSE, 0, NULL);
```

Packing Several Attributes in 1 VBO

Draw3.cpp



```
GLuint vbo;
glGenBuffers(1, &vbo);    //Only 1 vbo

glBindBuffer(GL_ARRAY_BUFFER, vbo);
glBufferData(GL_ARRAY_BUFFER, sizeof(verts)+sizeof(cols),
                                     verts,  GL_STATIC_DRAW);
glBufferSubData(GL_ARRAY_BUFFER, sizeof(verts), sizeof(cols),
                                                       cols);
glEnableVertexAttribArray(0);
glVertexAttribPointer(0, 2, GL_FLOAT, GL_FALSE, 0, NULL);
glEnableVertexAttribArray(1);
glVertexAttribPointer(1, 4, GL_FLOAT, GL_FALSE, 0,
                                    (GLvoid *)sizeof(verts));
```



Vertex Array Object

- A vertex array object (VAO) encapsulates all the state needed to specify vertex data of an object.
- Creating VAOs:
  1. Generate a new vertex array object “vao”
  2. Bind the vertex array object (initially empty)
  3. Create constituent VBOs and transfer data

```
glGenVertexArrays(1, &vao);
glBindVertexArray(vao);
...
glGenBuffers(3, vbo);
...
```

Rendering

- Bind the VAO representing the vertex data
- Render the collection of primitives using `glDrawArray()` command:

```
glBindVertexArray(vao);
glDrawArrays(GL_TRIANGLES, 0, 3);
```

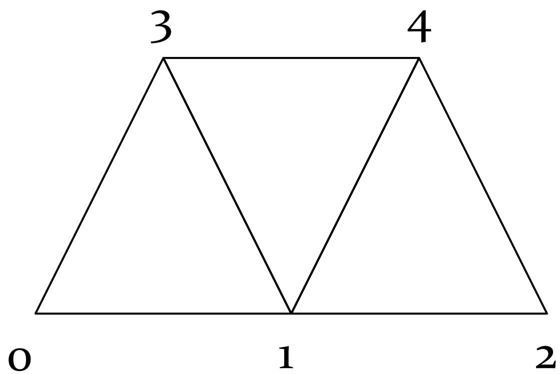
Primitive Type

Start index in the enabled arrays

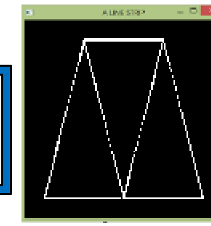
Count

Drawing Using Vertex Indices

- Mesh data is often represented using vertex indices to avoid repetition of vertices



Draw4.cpp



Polygonal Line : 3 0 1 3 4 1 2 4

- The VBO for indices is defined using `GL_ELEMENT_ARRAY` as the target.
- Rendering of the mesh is done using the command `glDrawElements(..)`

Homework!

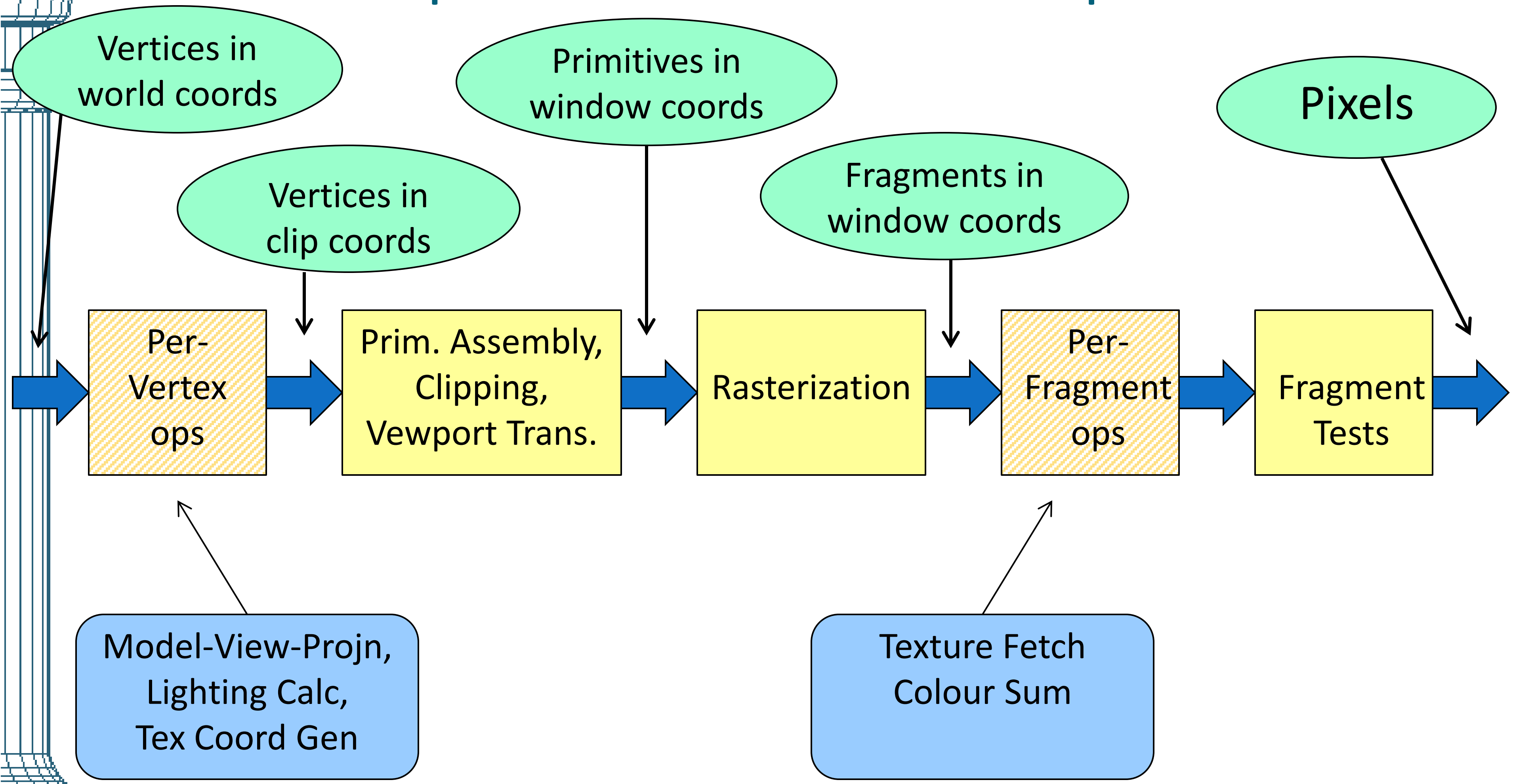
- Download and install
  - freeglut (http://freeglut.sourceforge.net) and
  - glew (http://glew.sourceforge.net)
- Run the following programs:
  - Version.cpp
  - Draw1.cpp
  - Draw2.cpp
  - Draw3.cpp
  - Draw4.cpp

Uses shader code

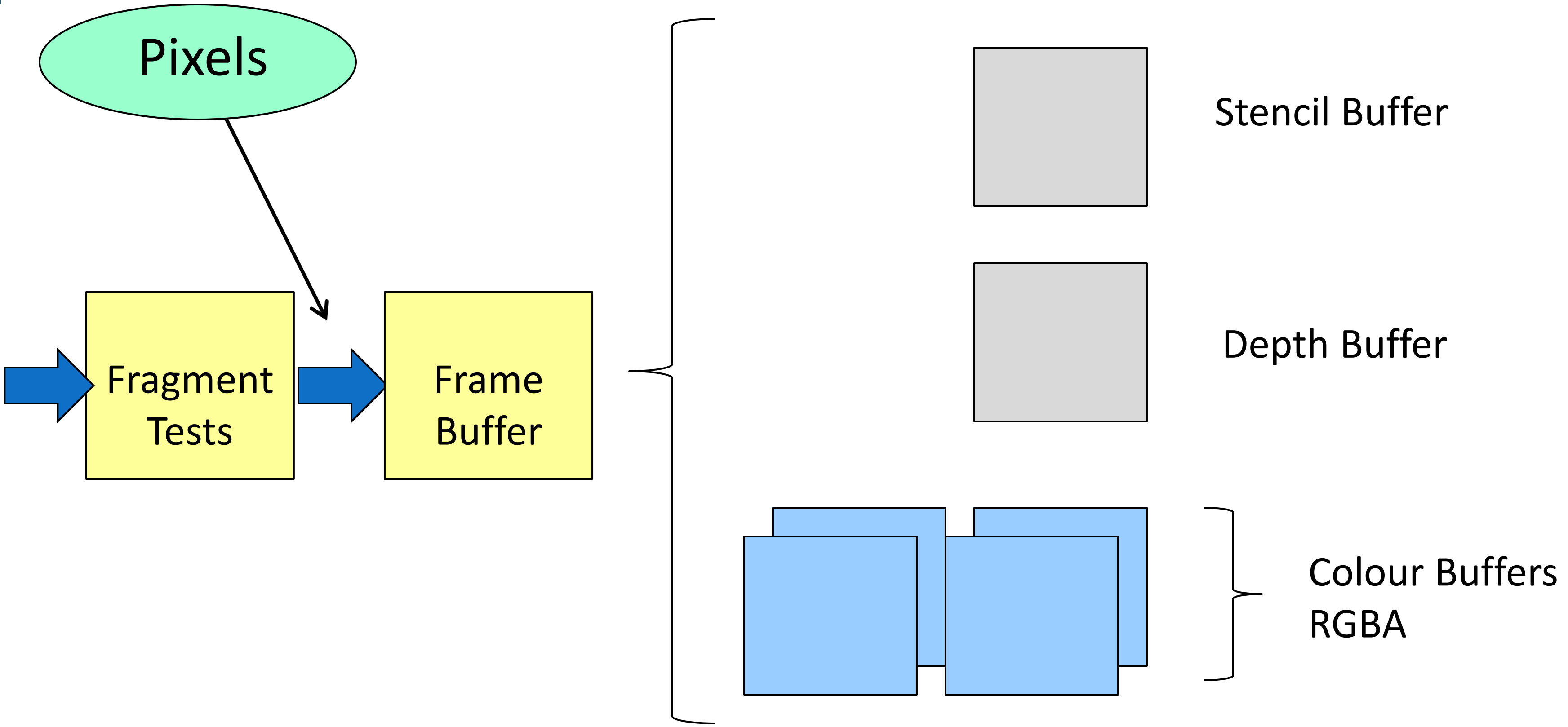
`Simple.vert, Simple.frag`

- Discuss any issues using class forum

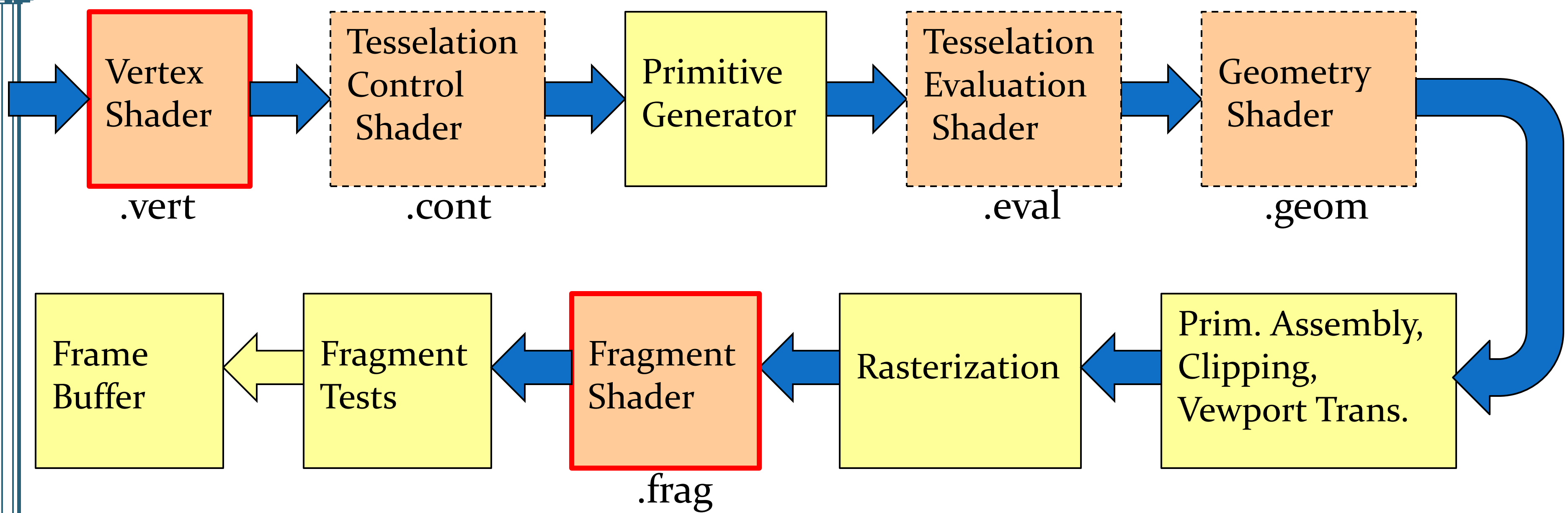
OpenGL Fixed Function Pipeline



OpenGL Fixed Function Pipeline



OpenGL-4 Shader Stages

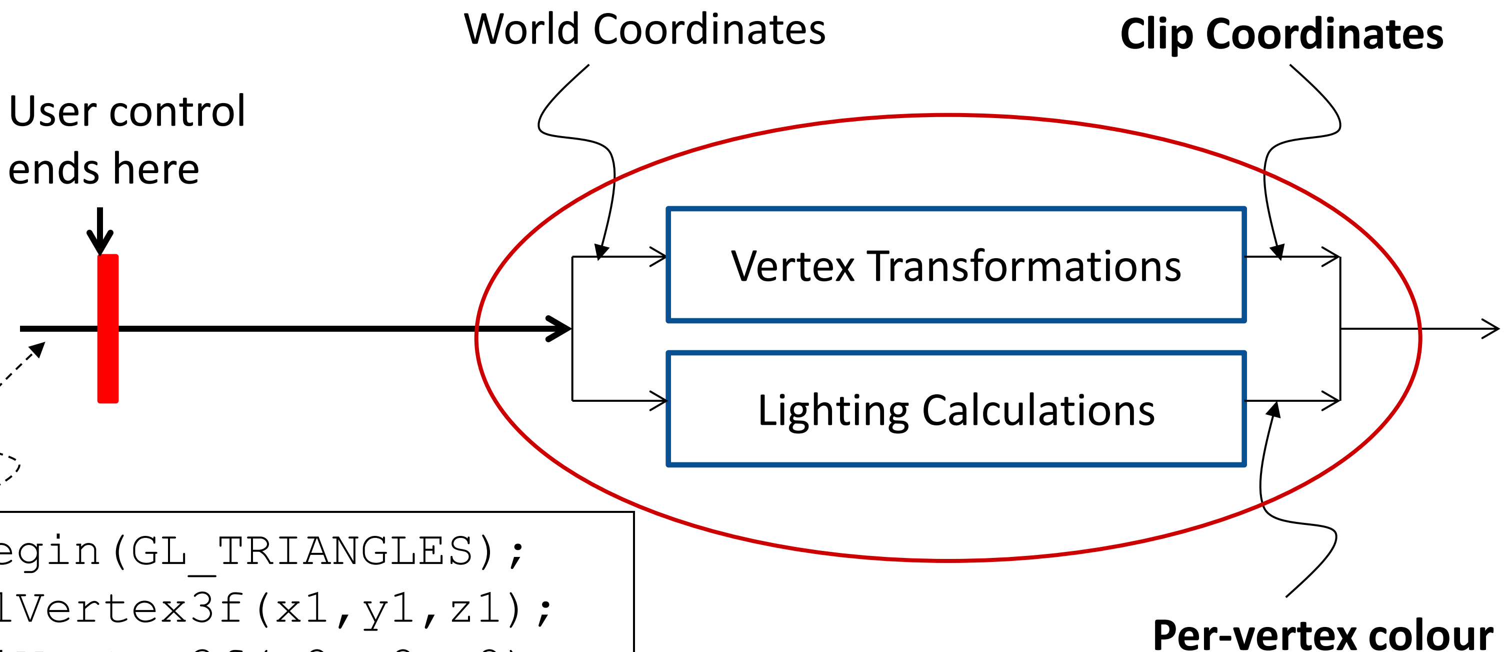


Vertex Shader

- The vertex shader will execute once of every vertex.
- The position and any other attributes (normal, colour, texture coords etc) of the *current vertex,* if specified, will be available in the shader.
- Positions and attributes of other vertices are not available.
- A vertex shader *normally* outputs the clip coordinates of the current vertex, and also performs lighting calculations on the vertex.
- **`gl_Position`** is a built-in out variable for the vertex shader. A vertex shader *must* define its value.

OpenGL Fixed Function Pipeline

The Vertex Processing Stage (T&L Stage)

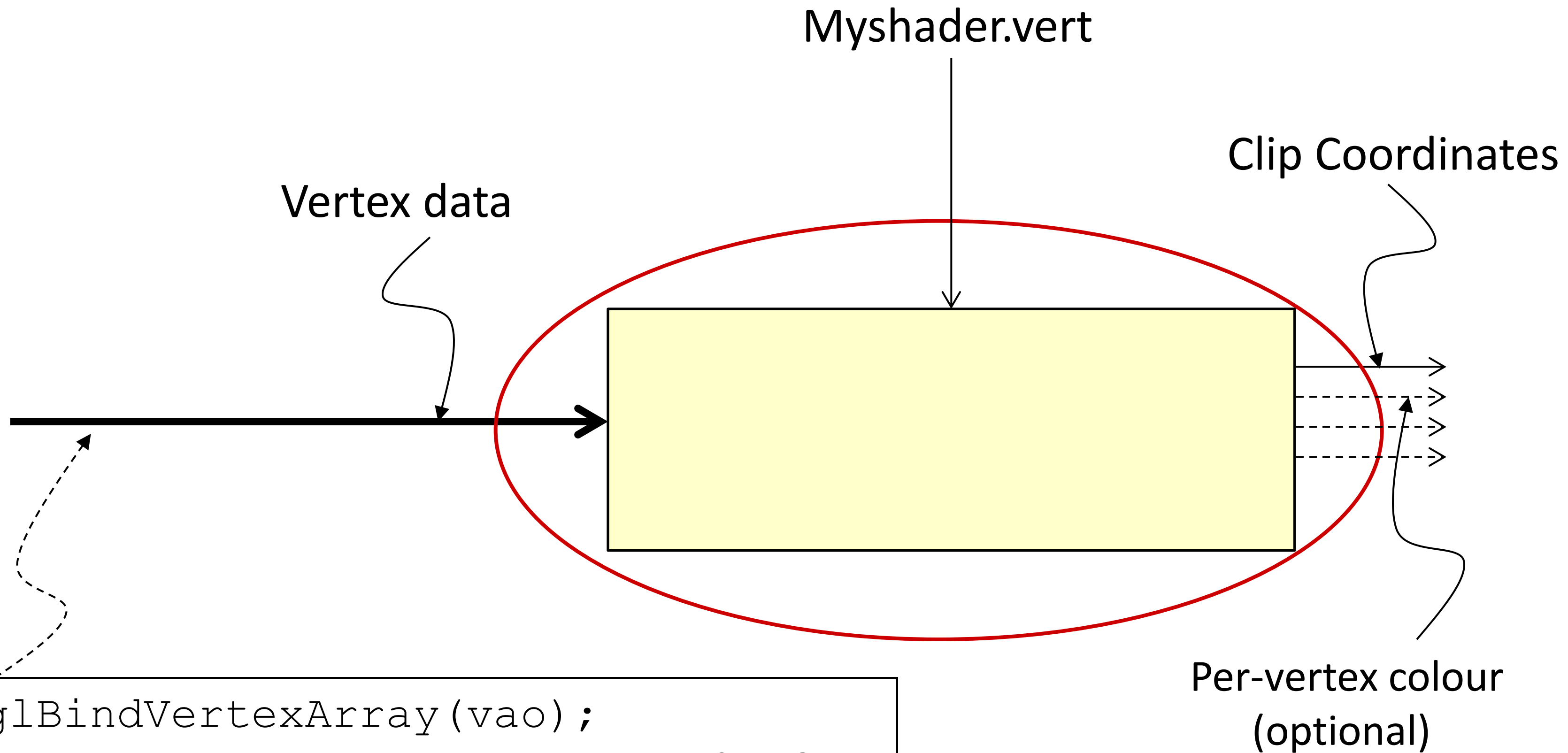



```
glBegin(GL_TRIANGLES);
  glVertex3f(x1,y1,z1);
  glVertex3f(x2,y2,z2);
  glVertex3f(x3,y3,z3);
glEnd();
```

Deprecated!

Programmable Pipeline

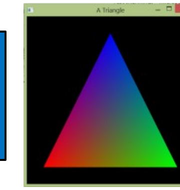
The Vertex Shader




```
glBindVertexArray(vao);
glDrawArrays(GL_TRIANGLES, 0, 3);
```

Vertex Shader: Example

Draw2.cpp



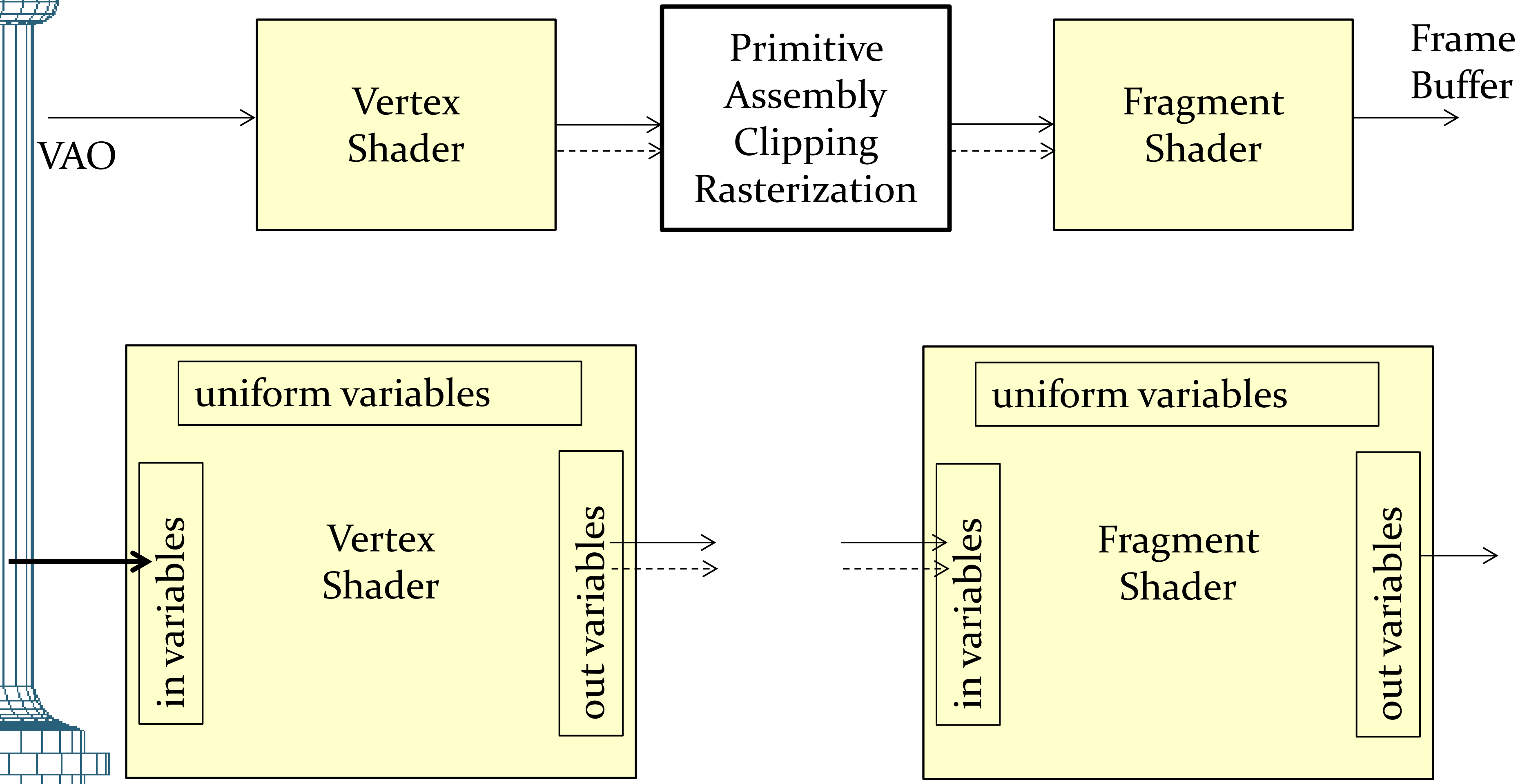
Application

```
glVertexAttribPointer(0, 2, GL_FLOAT, GL_FALSE, 0, NULL);

glVertexAttribPointer(1, 4, GL_FLOAT, GL_FALSE, 0, NULL);
```

```
#version 330

layout (location = 0) in vec4 position;
layout (location = 1) in vec4 color;

out vec4 theColor;

void main()
{
        gl_Position = position;
        theColor = color;
}
```

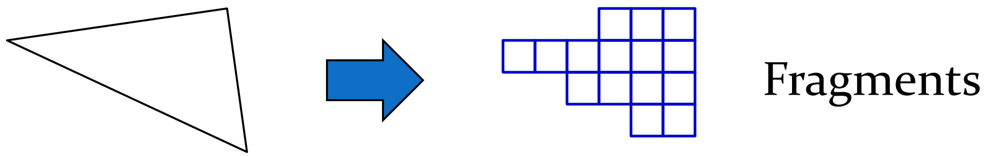
Simple.vert

Vertex and Fragment Shaders



Fragments

- Rasterization is the process of scan-converting a primitive into a set of fragments.
- A fragment is a pixel-sized element that belongs to a primitive and could be potentially displayed as a pixel.
- The number of fragments generated for a primitive depends on the projected area of the primitive in the screen coordinate space.

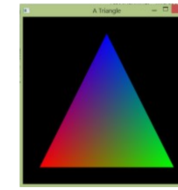


Fragment Shader

- A fragment shader is executed for each fragment generated by the rasterizer.
- A fragment shader outputs the colour of a fragment and optionally the depth value.
- Several colour computations (texture mapping, colour sum etc.), and depth offsets can be performed inside a fragment shader.
- A fragment shader can also discard a fragment.
- A fragment shader has the built-in in variable `gl_FragCoord` and built-in out variables **`gl_FragColor`** and `gl_FragDepth`

Fragment Shader: Example

Draw2.cpp



Vertex Shader
Simple.vert

```
#version 330

layout (location = 0) in vec4 position;
layout (location = 1) in vec4 color;

out vec4 theColor;

void main()
{
    gl_Position = position;
    theColor = color;
}
```

Fragment Shader
Simple.frag

```
#version 330

in vec4 theColor;

void main()
{
    gl_FragColor = theColor;
}
```

GLSL Aggregate Types

Vector Types: `vec2, vec3, vec4`

```
vec2 posn2D;
vec3 grey, norm, color, view;
vec4 posnA, posnB;
float zcoord, d;
posnA = vec4(-1, 2, 0.5, 1);
posnB = vec4(posnA.yxx, 1);  //Same as (2, -1, -1, 1)
norm = normalize(vec3(1));   //(.33, .33, .33)
view = vec3(1.6);            //(1.6, 1.6, 1.6)
d =  dot(norm, view);
zcoord = posnA.z;            //0.5
color = vec3(0.9, 0.2, 0.2);
grey = vec3(0.2, color.gb);  //(0.2, 0.2, 0.2)
```

Component Accessors: `(x,y,z,w), (r,g,b,a)`

`(s,t,p,q)`

GLSL – Aggregate Types

Matrix Types: `mat2, mat3, mat4`

```
mat2 matA, matB, matC;
mat3 scale, identity;
float det;
vec2 v1, v2, v3, v4;
v1 = vec2(-6, 4);
v2 = vec2(3);
matA = mat2(3, 0, -2, 5);       //1st Column = (3, 0)
matB = mat2(v1, v2);            //v1, v2 column vectors
matC = matA * transpose(matB);    //Product matrix
v3 = matC[1];                   //Second column of matC
v4 = matA * v3;
identity = mat3(1.0);
scale = mat3(3.0);              //3.0 along diagonal
det = determinant(matC);
matC = inverse(matC);
```

Defining Transformations

- We will need to define transformations and projections using our own functions!
- The GLM (GL Mathematics) library written by Christophe Riccio provides functionality similar to the deprecated functions.
- GLM is a header-only library that can be downloaded from http://glm.g-trunc.net

```
#include <glm/glm.hpp>
#include <glm/gtc/matrix_transform.hpp>
```

Defining Transformations

- The Model-view-projection matrix must be made available in the vertex shader for transforming vertices to clip coordinates.
- **Uniform variables** provide a mechanism for transferring matrices and other values from your application to the shader.
- Uniform variables change less frequently compared to vertex attributes. They remain constant for every primitive.
- Important matrices:
  - Model-View Matrix (*VM*)
  - Model-View-Projection Matrix (*PVM*)

Model-View-Projection Matrix

Old Version

glFrustum(...)
gluPerspective(...)
glOrtho(...)

gluLookAt(...)

glTranslatef(...)
glRotatef(...)
glScalef(...)

$$\begin{bmatrix} x_c \\ y_c \\ z_c \\ w_c \end{bmatrix} = \begin{bmatrix} \text{Projection} \\ \text{Matrix} \end{bmatrix} \begin{bmatrix} \text{View} \\ \text{Matrix} \end{bmatrix} \begin{bmatrix} \text{Transformation} \\ \text{Matrix} \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

Output

Vertex Position in Clip Coordinates

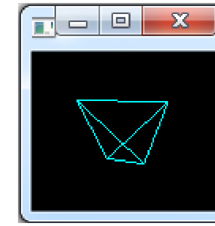
Input

Vertex Position in World Coordinates

Defining Transformations

Application

Draw5.cpp

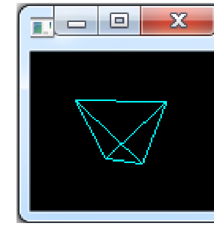


```
GLuint matrixLoc;
matrixLoc = glGetUniformLocation(program, "mvpMatrix");
```

```
void display() {
glm::mat4 proj = glm::perspective(60.0f, 1.0f, 100.0f, 1000.0f);
glm::mat4 view = glm::lookAt(glm::vec3(0.0, 0.0, 150.0),
                             glm::vec3(0.0, 0.0, 0.0),
                             glm::vec3(0.0, 1.0, 0.0));
glm::mat4 matrix = glm::mat4(1.0);     //Identity matrix
matrix = glm::rotate(matrix, angle, glm::vec3(0.0, 1.0, 0.0));
glm::mat4 prodMatrix = proj*view*matrix;
glUniformMatrix4fv(matrixLoc, 1, GL_FALSE, &prodMatrix[0][0]);
...
```

Defining Transformations

Draw5.cpp



Vertex Shader

Tetrahedron.vert

```
#version 330

layout (location = 0) in vec4 position;
uniform mat4 mvpMatrix;

void main()
{
        gl_Position = mvpMatrix * position;
}
```

Output in Clip-Coordinates

Input in World-Coordinates

Fragment Shader

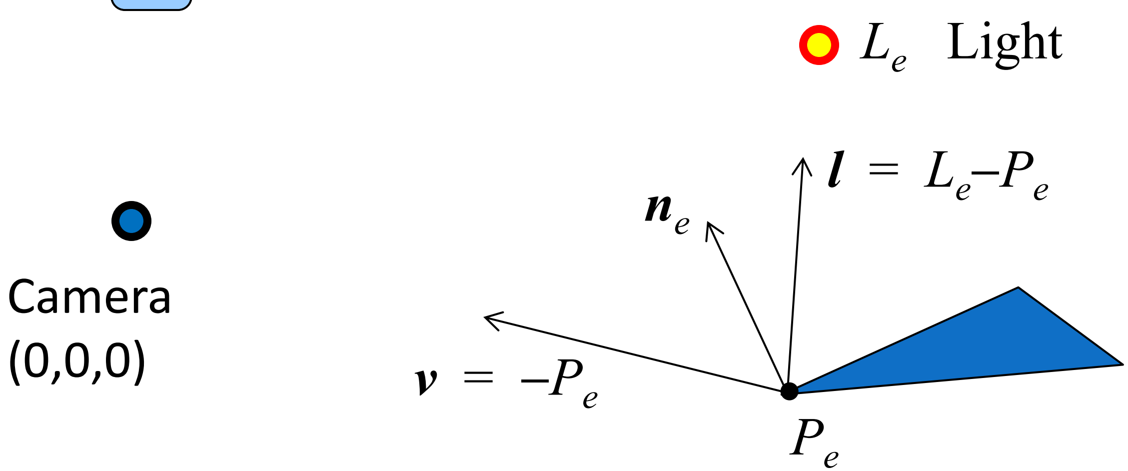
Tetrahedron.frag

```
void main()
{
    gl_FragColor = vec4(0.0, 1.0, 1.0, 1.0);
}
```

Lighting Calculations

Lighting calculations are usually performed in **eye-coordinate** space.

$$\underbrace{\begin{bmatrix}x_e\\ y_e\\ z_e\\ 1\end{bmatrix}}_{P_e} = \overbrace{\begin{bmatrix}\text{View}\\ \text{Matrix}\end{bmatrix}\begin{bmatrix}\text{Transformation}\\ \text{Matrix}\end{bmatrix}}^{\text{Model-View Matrix}}\underbrace{\begin{bmatrix}x\\ y\\ z\\ 1\end{bmatrix}}_{P}$$



Transformation of Normal Vector

Consider a vector $V = \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix}$, and its normal vector $N = \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix}$

The vectors are perpendicular: $v_x n_x + v_y n_y + v_z n_z = 0.$

In matrix notation,

$$\begin{bmatrix} v_x & v_y & v_z \end{bmatrix} \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix} = 0 \qquad V^{\mathrm{T}} N = 0.$$

Let V be transformed using matrix A, and the normal using matrix B. After the transformation, the vectors will remain perpendicular only if $(AV)^{\mathrm{T}}(BN) = 0.$

Transformation of Normal Vector

The previous equation gives $V^T A^T B N = 0$

$V^T (A^T B) N = 0.$

But, $V^T N = 0.$

Therefore, $A^T B = I$ (identity matrix).

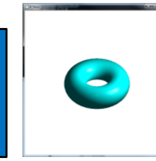
Hence, $B = (A^T)^{-1}$

The transformation applied to the normal is the ***inverse-transpose*** of the transformation applied to the vectors (or points).

For lighting calculations, we need to multiply the normal vectors by the inverse-transpose of the model-view matrix.

Lighting Calculations

TorusDraw.cpp



- Lighting calculations are performed in eye-coordinates.
- We compute the following (using GLM) in our application:
  - Model-View matrix (*VM*)
  - Light's position in eye coordinates: $L_e = VML$
  - Inverse transformation matrix for the normal $(VM)^{-T}$

```
void display() {
...
glm::mat4 prodMatrix1 = view*matrix;
glm::mat4 prodMatrix2 = proj*prodMatrix1;
glm::vec4 lightEye = view*light;
glm::mat4 invMatrix = glm::inverse(prodMatrix1);
glUniformMatrix4fv(matrixLoc1, 1, GL_FALSE, &prodMatrix1[0][0]);
glUniformMatrix4fv(matrixLoc2, 1, GL_FALSE, &prodMatrix2[0][0]);
glUniformMatrix4fv(matrixLoc3, 1, GL_TRUE, &invMatrix[0][0]);
glUniform4fv(lgtLoc, 1, &lightEye[0]);
```

Lighting Calculations (Vertex Shader)

Inside the vertex shader, we add the code to output the colour value using the Phong-Blinn model.

Vertex shader:

Torus.vert

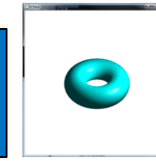
```
layout (location = 0) in vec4 position;
layout (location = 1) in vec3 normal;
uniform mat4 mvMatrix;
uniform mat4 mvpMatrix;
uniform mat4 norMatrix;
uniform vec4 lightPos;  //in eye coords

out vec4 theColour;

void main()
{
  vec4 white = vec4(1.0);  //Light’s colour (diffuse & specular)
  vec4 grey = vec4(0.2);      //Ambient light
```

Continued on next slide

Lighting Calculations (Vertex Shader)

```
vec4 posnEye = mvMatrix * position;     //point in eye coords
vec4 normalEye = norMatrix * vec4(normal, 0);
vec4 lgtVec = normalize(lightPos - posnEye);
vec4 viewVec = normalize(vec4(-posnEye.xyz, 0));
vec4 halfVec = normalize(lgtVec + viewVec);
vec4 material = vec4(0.0, 1.0, 1.0, 1.0);     //cyan
vec4 ambOut = grey * material;
float shininess = 100.0;
float diffTerm = max(dot(lgtVec, normalEye), 0);
vec4 diffOut = material * diffTerm;
float specTerm = max(dot(halfVec, normalEye), 0);
vec4 specOut = white *  pow(specTerm, shininess);

gl_Position = mvpMatrix * position;
theColour = ambOut + diffOut + specOut;
}
```

TorusDraw.cpp



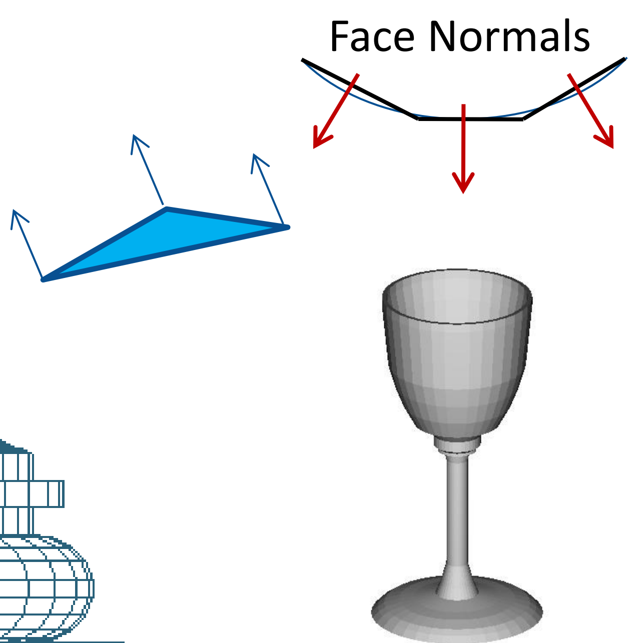
Fragment shader:

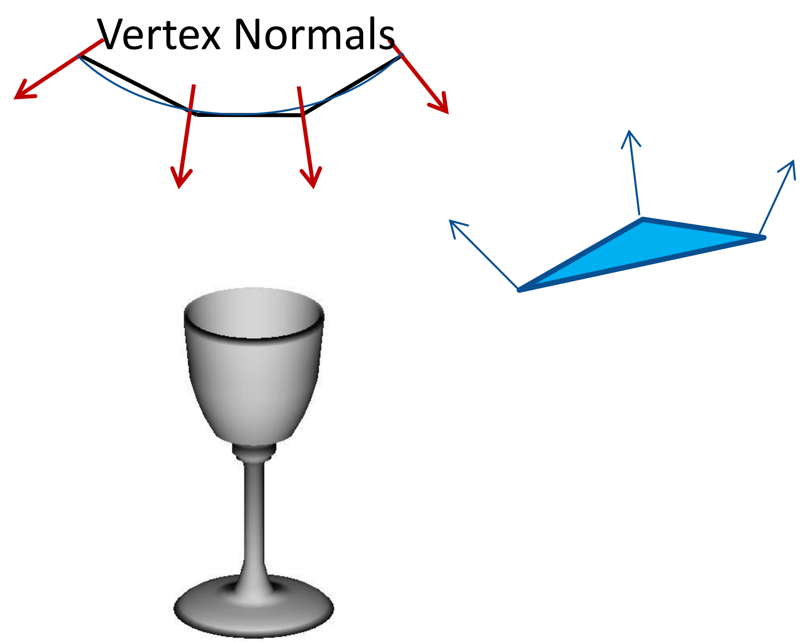
Torus.frag

```
in vec4 theColour;

void main()
{
   gl_FragColor = theColour;
}
```

Face Normals vs Vertex Normals

- Face normals: Each triangle or quad of a mesh model has a single normal vector representing the orientation of that face.
- Vertex normals: A planar element can be made to look curved, by assigning different normal vectors at the vertices that represent an underlying curved shape of the surface.





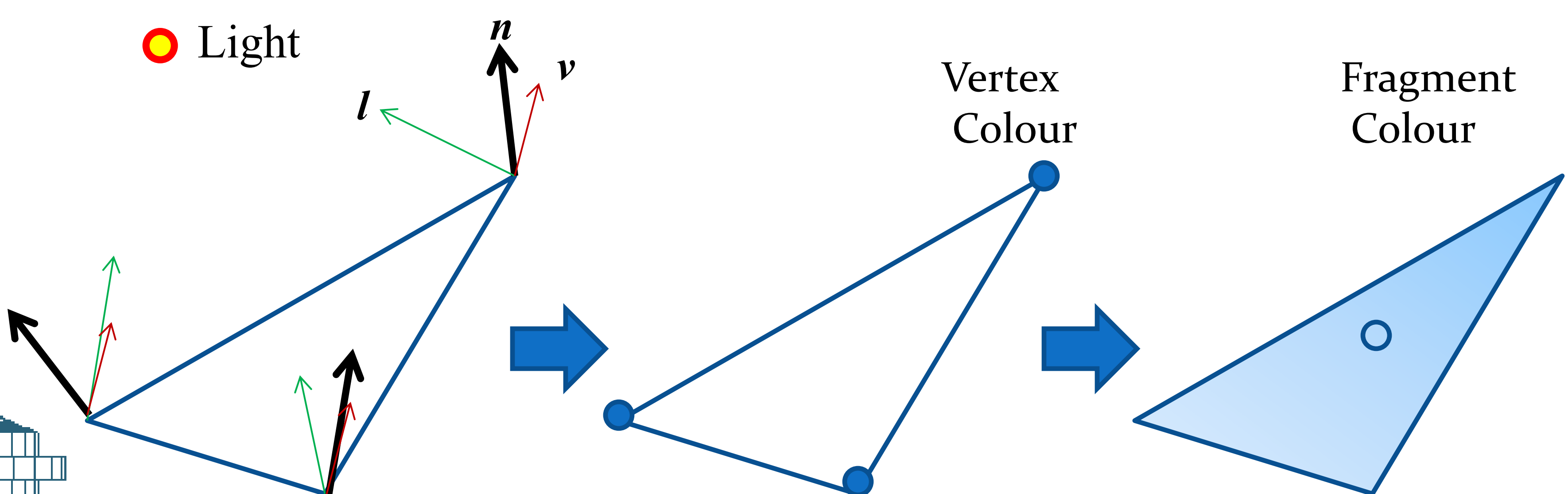
Modelling Using Vertex Normals

Torus.cpp

```
int nverts  = nsides * nrings;
nelms = nsides * nrings * 6;

float *verts = new float[nverts * 3];
float *normals = new float[nverts * 3];
unsigned int *elems = new unsigned int[nelms];
  ...
glGenBuffers(3, vboID);

glBindBuffer(GL_ARRAY_BUFFER, vboID[0]);
glBufferData(GL_ARRAY_BUFFER, indx * sizeof(float), verts,
                                              GL_STATIC_DRAW);
glEnableVertexAttribArray(0);
glVertexAttribPointer(0, 3, GL_FLOAT, GL_FALSE, 0, NULL);

glBindBuffer(GL_ARRAY_BUFFER, vboID[1]);
glBufferData(GL_ARRAY_BUFFER, indx * sizeof(float), normals,
                                               GL_STATIC_DRAW);
glEnableVertexAttribArray(1);
glVertexAttribPointer(1, 3, GL_FLOAT, GL_FALSE, 0, NULL);

glBindBuffer(GL_ELEMENT_ARRAY_BUFFER, vboID[2]);
glBufferData(GL_ELEMENT_ARRAY_BUFFER, ielndx * sizeof(unsigned int),
                                         elems, GL_STATIC_DRAW);
```

Per-Vertex (Traditional) Lighting

- The lighting calculations shown on slides 40-42 are performed for each vertex and the interpolated colour values are used in the fragment shader.
- The traditional lighting model of the fixed-function pipeline is also implemented in this way.



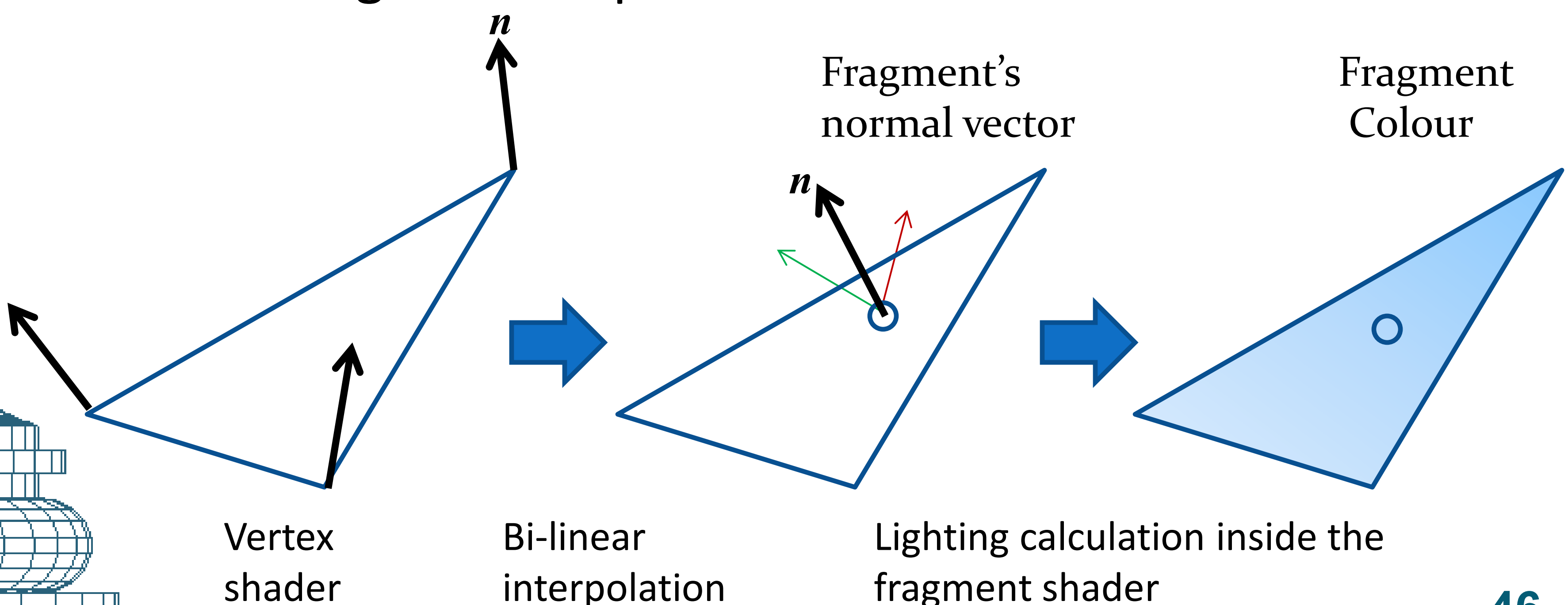
Lighting calculation inside the vertex shader

Bi-linear interpolation

Fragment shader

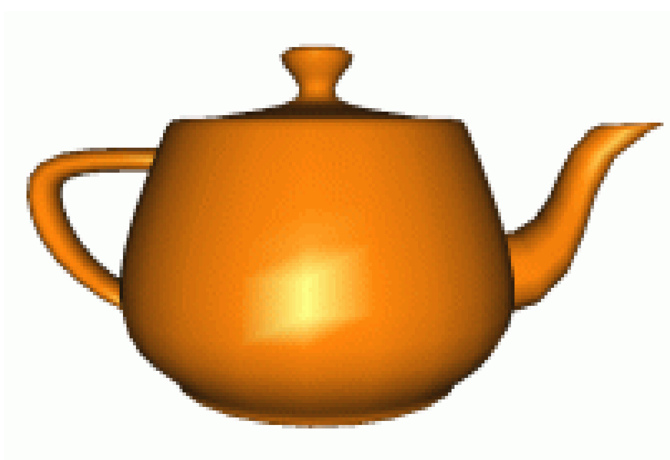
Per-Fragment Lighting (Phong Shading)

- The vertex shader outputs the normal vector to the fragment shader.
- The fragment shader receives an interpolated normal vector for each fragment.
- The lighting calculation is performed inside the fragment shader using the interpolated normal vector.

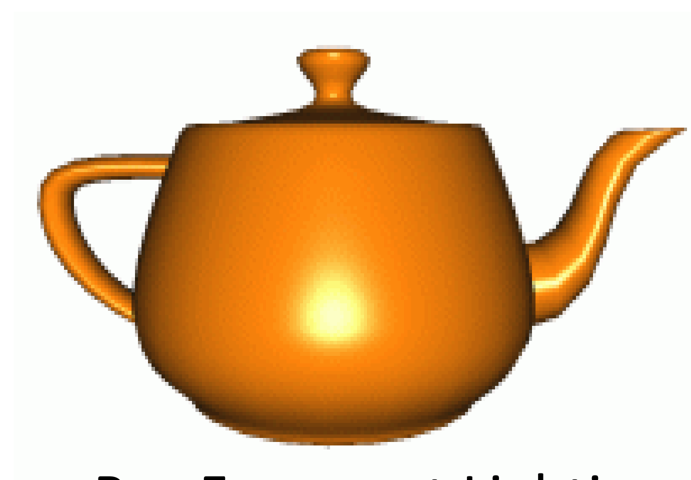


Per-Fragment Lighting

- A lighting computation implemented inside the fragment shader produces a far more accurate rendering of reflections from the surface than the traditional model.
- Per-fragment lighting is computationally very expensive compared to per-vertex lighting.



Per-Vertex Lighting



Per-Fragment Lighting

Texturing

- Select an active texture unit
- Load texture image
- Set texture parameters
- Create a Sampler2D variable in the fragment shader. Assign this uniform variable the index of the texture unit.

Application:

```
glGenTextures(1, &texID);
glActiveTexture(GL_TEXTURE0);
glBindTexture(GL_TEXTURE_2D, texID);
loadTGA("myImage.tga");

glTexParameterf(GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_LINEAR);
glTexParameterf(GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_LINEAR);
...
GLuint texLoc = glGetUniformLocation(program, "txSampler");
glUniform1i(texLoc, 0);
```

Texturing

Texture coordinates are stored in a vertex buffer object:

```
glBindBuffer(GL_ARRAY_BUFFER, vboID[0]);
glBufferData(GL_ARRAY_BUFFER, (indx) * sizeof(float), verts,
                                              GL_STATIC_DRAW);
glEnableVertexAttribArray(0);
glVertexAttribPointer(0, 3, GL_FLOAT, GL_FALSE, 0, NULL);

glBindBuffer(GL_ARRAY_BUFFER, vboID[1]);
glBufferData(GL_ARRAY_BUFFER, (indx) * sizeof(float), normals,
                                               GL_STATIC_DRAW);
glEnableVertexAttribArray(1);
glVertexAttribPointer(1, 3, GL_FLOAT, GL_FALSE, 0, NULL);

glBindBuffer(GL_ARRAY_BUFFER, vboID[2]);
glBufferData(GL_ARRAY_BUFFER, (indx) * sizeof(float), texCoords,
                                               GL_STATIC_DRAW);
glVertexAttribPointer(2, 2, GL_FLOAT, GL_FALSE, 0, NULL);
glEnableVertexAttribArray(2);  // texture coords

glBindBuffer(GL_ELEMENT_ARRAY_BUFFER, vboID[3]);
glBufferData(GL_ELEMENT_ARRAY_BUFFER, ...
```

Texturing

The vertex shader passes the texture coords of each vertex to the fragment shader.

Vertex shader:

```
layout (location = 0) in vec3 position;
layout (location = 1) in vec3 normal;
layout (location = 2) in vec2 texCoord;

...

out vec4 diffRefl;
out vec2 TexCoord;

void main()
{
        gl_Position = mvpMatrix * vec4(position, 1.0);
                    ...  //lighting calculations
         diffRefl = ...
        TexCoord = texCoord;
}
```

Texturing

The fragment shader receives the interpolated texture coordinates for each fragment, and uses a Sampler2D object to retrieve the colour values from texture memory.

Fragment shader:

```
uniform sampler2D txSampler;

in vec4 diffRefl;
in vec2 TexCoord;

void main()
{
        vec4 tColor = texture(txSampler, TexCoord);
        gl_FragColor =  diffRefl * tColor;
}
```

Multi-Texturing

Texture 1

Texture 2

Texture Unit 0

```
glActiveTexture(GL_TEXTURE0);
glBindTexture(GL_TEXTURE2D, tex[0]);
texLoc1 = glGetUniformLocation
              (program, "tex1");
glUniform1i(texLoc1, 0);
```

Texture Unit 1

```
glActiveTexture(GL_TEXTURE1);
glBindTexture(GL_TEXTURE2D, tex[1]);
texLoc2 = glGetUniformLocation
              (program, "tex2");
glUniform1i(texLoc2, 1);
```

Texture Coordinates

```
glBindBuffer(GL_ARRAY_BUFFER, vboID[2]);
glBufferData(GL_ARRAY_BUFFER, num* sizeof(float), texC, GL_STATIC_DRAW);
glVertexAttribPointer(2, 2, GL_FLOAT, GL_FALSE, 0, NULL);
glEnableVertexAttribArray(2);
```

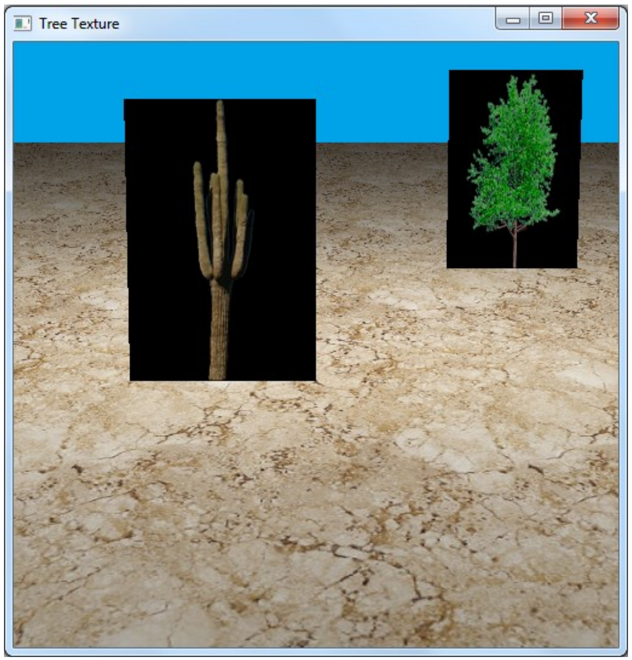
Multi-Texturing

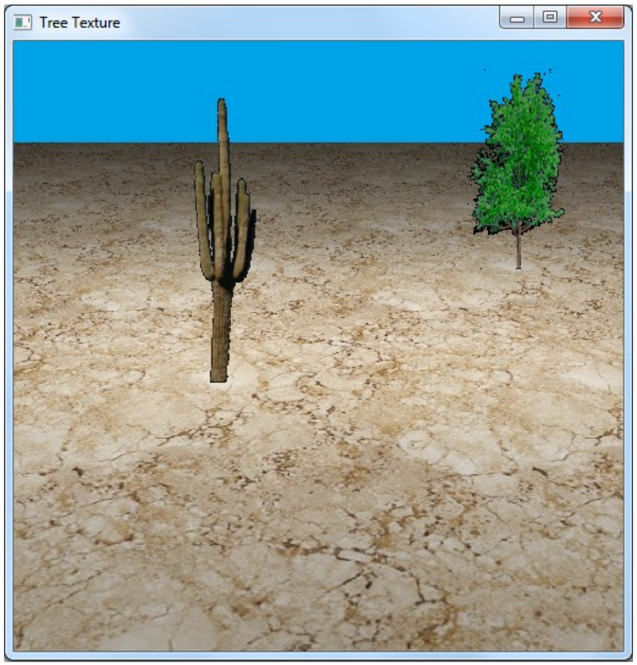
Fragment Shader:

```
uniform sampler2D tex1;
uniform sampler2D tex2;

in vec4 diffRefl;
in vec2 TexCoord;

void main()
{
        vec4 tColor1 = texture(tex1, TexCoord);
        vec4 tColor2 = texture(tex2, TexCoord);

        gl_FragColor =  diffRefl*(0.8*tColor1+ 0.2*tColor2);
}
```

Alpha Texturing

A textured image of a tree should appear as being part of the surrounding scene, and not part of a rectangular 'board'.





Alpha Texturing

Use the alpha channel of an image (if available) to transfer only those pixels on the object.

Fragment Shader

```
uniform sampler2D texTree;

in vec2 TexCoord;

void main()
{
  vec4 treeColor = texture(texTree, TexCoord);
  if(treeColor.a == 0) discard;
  gl_FragColor = treeColor;
}
```

RGB

Alpha