Foundations of Computer Graphics

Online Lecture 6: OpenGL 1

Overview and Motivation

Ravi Ramamoorthi

This Lecture

- Introduction to OpenGL and simple demo code
  - mytest1.cpp ; you compiled mytest3.cpp for HW 0
- I am going to show (and write) actual code
  - Code helps you understand HW 2 better
- Simple demo of mytest1
- This lecture deals with very basic OpenGL setup. Next 2 lectures will likely be more interesting

Outline

- *Basic idea about OpenGL*
- Basic setup and buffers
- Matrix modes
- Window system interaction and callbacks
- Drawing basic OpenGL primitives
- Initializing Shaders

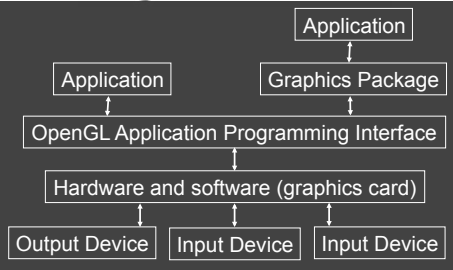
Introduction to OpenGL

- OpenGL is a graphics *API*
  - Portable software library (platform-independent)
  - Layer between programmer and graphics hardware
  - Uniform instruction set (hides different capabilities)
- OpenGL can fit in many places
  - Between application and graphics system
  - Between higher level API and graphics system

Why OpenGL?

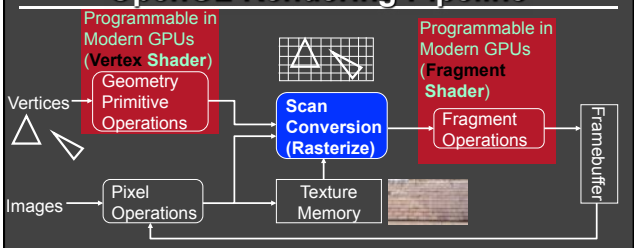
- Why do we need OpenGL or an API?
  - Encapsulates many basic functions of 2D/3D graphics
  - Think of it as high-level language (C++) for graphics
  - History: Introduced SGI in 92, maintained by Khronos
  - Precursor for DirectX, WebGL, Java3D etc.

Programmer's View



Slide inspired by Greg Humphreys

OpenGL Rendering Pipeline



Traditional Approach: Fixed function pipeline (state machine)
New Development (2003-): Programmable pipeline

GPUs and Programmability

- Since 2003, can write vertex/pixel shaders
- Fixed function pipeline special type of shader
- Like writing C programs (see GLSL book)
- Performance >> CPU (even used for non-graphics)
- Operate *in parallel* on all vertices or fragments

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Basic Setup and Buffers, Matrix Modes

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Buffers and Window Interactions

- Buffers: Color (front, back, left, right), depth (z), accumulation, stencil. When you draw, you write to some buffer (most simply, front and depth)
- Buffers also used for vertices etc. Buffer data and buffer arrays (will see in creating objects)
- No window system interactions (for portability)
  - But can use GLUT (or Motif, GLX, Tcl/Tk)
  - Callbacks to implement mouse, keyboard interaction

Basic setup (can copy; slight OS diffs)

```
int main(int argc, char** argv)
{
   glutInit(&argc, argv);
   // Requests the type of buffers (Single, RGB).
   // Think about what buffers you would need...
   glutInitDisplayMode (GLUT_SINGLE | GLUT_RGB);
   // Need to add GLUT_3_2_CORE_PROFILE for Apple/Mac OS
   glutInitWindowSize (500, 500);
   glutInitWindowPosition (100, 100);
   glutCreateWindow ("Simple Demo with Shaders");
   // glewInit(); // GLEW related stuff for non-Apple systems
   init (); // Always initialize first

   // Now, we define callbacks and functions for various tasks.
   ...
}
```

Basic setup (can copy; slight OS diffs)

```
int main(int argc, char** argv)
{
   ...

   // Now, we define callbacks and functions for various tasks.
   glutDisplayFunc(display);
   glutReshapeFunc(reshape) ;
   glutKeyboardFunc(keyboard);
   glutMouseFunc(mouse) ;
   glutMotionFunc(mousedrag) ;
   glutMainLoop(); // Start the main code
   deleteBuffers(); //Termination. Delete buffers generated in init()
   return 0;   /* ANSI C requires main to return int. */
}
```

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Viewing in OpenGL

- *Inspired by old OpenGL. Now, only best practice, not requirement*
  - *You could do your own thing, but this is still the best way to develop viewing*
- Viewing consists of two parts
  - Object positioning: *model view* transformation matrix
  - View projection: *projection* transformation matrix
- Old OpenGL (no longer supported/taught in 167x), two matrix stacks
  - GL_MODELVIEW_MATRIX, GL_PROJECTION_MATRIX
  - Can push and pop matrices onto stacks
- New OpenGL: Use C++ STL templates to make stacks as needed
  - e.g. stack <mat4> modelview ; modelview.push(mat4(1.0)) ;
  - GLM libraries replace many deprecated commands. Include mat4

Viewing in OpenGL

- Convention: camera always at the origin, pointing in the –z direction
- Transformations move objects relative to the camera
- In old OpenGL, *Matrices are column-major and right-multiply top of stack*. (Last transform in code is first actually applied). In new GLM, similarly (read the assignment notes and documentation).

Basic initialization code for viewing

```
#include <GL/glut.h> //also <GL/glew.h>; <GLUT/glut.h> for Mac OS
#include <stdlib.h>  //also stdio.h, assert.h, glm, others

int mouseoldx, mouseoldy ; // For mouse motion
GLfloat eyeloc = 2.0 ; // Where to look from; initially 0 -2, 2
glm::mat4 projection, modelview; // The mvp matrices themselves

void init (void) {
/* select clearing color      */
   glClearColor (0.0, 0.0, 0.0, 0.0);
/* initialize viewing values  */
   projection = glm::mat4(1.0f); // The identity matrix
   // Think about this.  Why is the up vector not normalized?
   modelview = glm::loakAt(glm::vec3(0,-eyeloc,eyeloc),
                           glm::vec3(0,0,0), glm::vec3(0,1,1)) ;
   // (To be cont'd).  Geometry and shader set up later ...
```

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Window System Interaction and Callbacks

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Window System Interaction

- Not part of OpenGL
  - Toolkits (GLUT) available (also freeglut)
- Callback functions for events (similar to X, Java,)
  - Keyboard, Mouse, etc.
  - Open, initialize, resize window
- Our main func included

```
glutDisplayFunc(display);
glutReshapeFunc(reshape) ;
glutKeyboardFunc(keyboard);
glutMouseFunc(mouse) ;
glutMotionFunc(mousedrag) ;
```

Basic window interaction code

```
/* Defines what to do when various keys are pressed */
void keyboard (unsigned char key, int x, int y)
{
  switch (key) {
  case 27:  // Escape to quit
    exit(0) ;
    break ;
  default:
    break ;
  }
}
```

Basic window interaction code

```
/* Reshapes the window appropriately */
void reshape(int w, int h)
{
   glViewport (0, 0, (GLsizei) w, (GLsizei) h);
   // Note that the field of view takes in a radian angle
   projection = glm::perspective(30.0f / 180.0f * glm::pi<float>(),
            (GLfloat)w / (GLfloat)h, 1.0f, 10.0f);
   glUniformMatrix4fv(projectionPos,1, GL_FALSE, &projection[0][0]);
   // To send the projection matrix to the shader
}
```

Mouse motion (demo)

```
void mouse(int button, int state, int x, int y) {
  if (button == GLUT_LEFT_BUTTON) {
    if (state == GLUT_UP) {// Do Nothing ;}
    else if (state == GLUT_DOWN) {
      mouseoldx = x ; mouseoldy = y ; // so we can move wrt x , y
    }
  }
  else if (button == GLUT_RIGHT_BUTTON && state == GLUT_DOWN)
    { // Reset gluLookAt
      eyeloc = 2.0 ;
      modelview = glm::lookAt(glm::vec3(0, -eyeloc, eyeloc),
                  glm::vec3(0, 0, 0), glm::vec3(0, 1, 1));
        // Send the updated matrix to the shader
      glUniformMatrix4fv(modelviewPos,1,GL_FALSE,&modelview[0][0]);
      glutPostRedisplay() ; // Redraw scene
    }
}
```

Mouse drag (demo)

```
void mousedrag(int x, int y) {
  int yloc = y - mouseoldy   ;    // We will use the y coord to
zoom in/out
  eyeloc  += 0.005*yloc ;         // Where do we look from
  if (eyeloc < 0) eyeloc = 0.0 ;
  mouseoldy = y ;


  /* Set the eye location */
  modelview = glm::lookAt(glm::vec3(0, -eyeloc, eyeloc),
       glm::vec3(0, 0, 0), glm::vec3(0, 1, 1));
  // Send the updated matrix over to the shader
  glUniformMatrix4fv(modelviewPos,1,GL_FALSE,&modelview[0][0]);

  glutPostRedisplay() ; }
```

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Drawing Basic OpenGL Primitives

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Outline

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- *Drawing basic OpenGL primitives*
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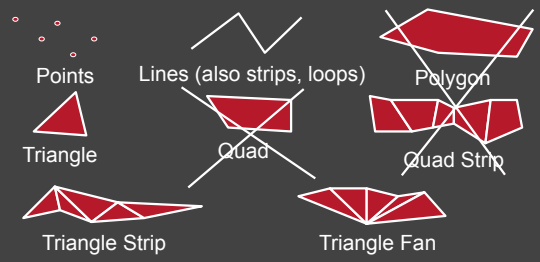
New OpenGL Primitives (fewer)



Geometry

- Points (GL_POINTS)
  Stored in Homogeneous coordinates
- Line segments (GL_LINES)
  - Also (GL_LINE_STRIP, GL_LINE_LOOP)
- Triangles (GL_TRIANGLES)
  - Also strips, fans (GL_TRIANGLE_STRIP, GL_TRIANGLE_FAN)
- More complex primitives (GLUT): Sphere, teapot, cube,…
  - Must now be converted into triangles (which is what skeleton does)

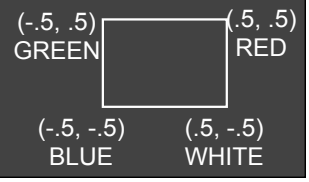
Old OpenGL: Drawing

- Enclose vertices between glBegin() … glEnd() pair
  - Can include normal C code and attributes like the colors
  - Inside are commands like glVertex3f, glColor3f
  - Attributes must be set ***before*** the vertex
- Assembly line (pass vertices, transform, shade)
  - These are vertex, fragment shaders on current GPUs
  - *Immediate Mode*: Sent to server and drawn

Old OpenGL: Drawing *(not used)*

```
void display(void) {
   glClear (GL_COLOR_BUFFER_BIT);
   // draw polygon (square) of unit length centered at the origin
   // This code draws each vertex in a different color.

   glBegin(GL_POLYGON);
      glColor3f (1.0, 0.0, 0.0);
      glVertex3f (0.5, 0.5, 0.0);
      glColor3f (0.0, 1.0, 0.0);
      glVertex3f (-0.5, 0.5, 0.0);
      glColor3f (0.0, 0.0, 1.0);
      glVertex3f (-0.5, -0.5, 0.0);
      glColor3f (1.0, 1.0, 1.0);
      glVertex3f (0.5, -0.5, 0.0);
   glEnd();
   glFlush () ;
}
```



Old OpenGL: Drawing

- Client-Server model (client generates vertices, server draws) even if on same machine
  - glFlush() forces client to send network packet
  - glFinish() waits for ack, sparingly use synchronization
- New OpenGL: **Vertex Array Objects** (next)

Modern OpenGL: Floor Specification

```
const GLfloat floorverts[4][3] = {
  {0.5, 0.5, 0.0},{-0.5, 0.5, 0.0},{-0.5, -0.5, 0.0}, {0.5, -0.5, 0.0}} ;
const GLfloat floorcol[4][3] = {
  {1.0, 0.0, 0.0},{0.0, 1.0, 0.0},{0.0, 0.0, 1.0},{1.0, 1.0, 1.0}} ;
const GLubyte floorinds[1][6] = { {0, 1, 2, 0, 2, 3} } ;  //triangles
const GLfloat floorverts2[4][3] = {
  {0.5, 0.5, 1.0},{-0.5, 0.5, 1.0},{-0.5, -0.5, 1.0},{0.5, -0.5, 1.0}} ;
const GLfloat floorcol2[4][3] = {
  {1.0, 0.0, 0.0},{1.0, 0.0, 0.0},{1.0, 0.0, 0.0},{1.0, 0.0, 0.0}} ;
const GLubyte floorinds2[1][6] = { {0, 1, 2, 0, 2, 3} };
//triangles
```

Modern OpenGL: Vertex Array Objects

```
const int numobjects = 2 ;  // number of objects for buffer
const int numperobj  = 3 ;  // Vertices, colors, indices
GLuint VAOs[numobjects];    // A Vertex Array Object per object
GLuint buffers[numperobj*numobjects]; // List of buffers geometric data
GLuint objects[numobjects]; // For each object
GLenum PrimType[numobjects];// Primitive Type (triangles, strips)
GLsizei NumElems[numobjects] ; // Number of geometric elements

// Floor Geometry is specified with a vertex array
enum {Vertices, Colors, Elements} ; // For arrays for object
enum {FLOOR, FLOOR2} ; // For objects, for the floor

//------In init below (creates buffer objects for later use)------
```

Modern OpenGL: Vertex Array Objects

```
const int numobjects = 2 ;  // number of objects for buffer
const int numperobj  = 3 ;  // Vertices, colors, indices
GLuint VAOs[numobjects];    // A Vertex Array Object per object
GLuint buffers[numperobj*numobjects] ; // List of buffers geometric data
//...
//------In init below (creates buffer objects for later use)------
 glGenVertexArrays(numobjects, VAOs); //create unique identifiers
 glGenBuffers(numperobj*numobjects, buffers); //and for buffers

 void deleteBuffers() { // Like a destructor
   glDeleteVertexArrays(numobjects, VAOs);
   glDeleteBuffers(numperobj*numobjects, buffers);
 }
```

Modern OpenGL: Initialize Buffers

```
void initobject (GLuint object, GLfloat * vert, GLint sizevert, GLfloat *
   col, GLint sizecol, GLubyte * inds, GLint sizeind, GLenum type) {
  int offset = object * numperobj;
  glBindVertexArray(VAOs[object]);
  glBindBuffer(GL_ARRAY_BUFFER, buffers[Vertices+offset]) ;
  glBufferData(GL_ARRAY_BUFFER, sizevert, vert,GL_STATIC_DRAW);
  // Use layout location 0 for the vertices
  glEnableVertexAttribArray(0);
  glVertexAttribPointer(0, 3, GL_FLOAT, GL_FALSE, 3 * sizeof(GLfloat), 0);
  glBindBuffer(GL_ARRAY_BUFFER, buffers[Colors+offset]) ;
  glBufferData(GL_ARRAY_BUFFER, sizecol, col,GL_STATIC_DRAW);
  // Use layout location 1 for the colors
  //...
}
```

Modern OpenGL: Initialize Buffers

```
void initobject (GLuint object, GLfloat * vert, GLint sizevert, GLfloat *
    col, GLint sizecol, GLubyte * inds, GLint sizeind, GLenum type) {
 // ...
 // Use layout location 1 for the colors
   glEnableVertexAttribArray(1);
   glVertexAttribPointer(1, 3, GL_FLOAT, GL_FALSE, 3 * sizeof(GLfloat), 0);
   glBindBuffer(GL_ELEMENT_ARRAY_BUFFER, buffers[Elements+offset]) ;
   glBufferData(GL_ELEMENT_ARRAY_BUFFER, sizeind, inds,GL_STATIC_DRAW);
   PrimType[object] = type;
   NumElems[object] = sizeind;
   // Prevent further modification of this VAO by unbinding it
   glBindVertexArray(0);
 }
```

Modern OpenGL: Draw Vertex Object

```
void drawobject(GLuint object) {
  glBindVertexArray(VAOs[object]);
  glDrawElements(PrimType[object], NumElems[object],
                 GL_UNSIGNED_BYTE, 0);
  glBindVertexArray(0); //unbind
}
void display(void) {
   glClear (GL_COLOR_BUFFER_BIT); // clear all pixels
   drawobject(FLOOR) ;
   drawobject(FLOOR2) ;
   glFlush ();
   // start processing buffered OpenGL commands
}
```

Initialization for Drawing, Shading

```
#include "shaders.h"
GLuint vertexshader, fragmentshader, shaderprogram ; // shaders
   // Initialization in init() for Drawing
   glGenVertexArrays(numobjects, VAOs) ;
   glGenBuffers(numperobj*numobjects, buffers) ;
   initobject(FLOOR, (GLfloat *) floorverts, sizeof(floorverts), (GLfloat
   *) floorcol, sizeof (floorcol), (GLubyte *) floorinds, sizeof
   (floorinds), GL_TRIANGLES) ;
   initobject(FLOOR2, (GLfloat *) floorverts2, sizeof(floorverts2),
   (GLfloat *) floorcol2, sizeof (floorcol2), (GLubyte *) floorinds2,
   sizeof (floorinds2), GL_TRIANGLES) ;
   // In init() for Shaders, discussed next
   vertexshader = initshaders(GL_VERTEX_SHADER, "shaders/nop.vert") ;
   fragmentshader = initshaders(GL_FRAGMENT_SHADER, "shaders/nop.frag") ;
   shaderprogram = initprogram(vertexshader, fragmentshader) ;
```

Demo (change colors)

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Initializing Shaders

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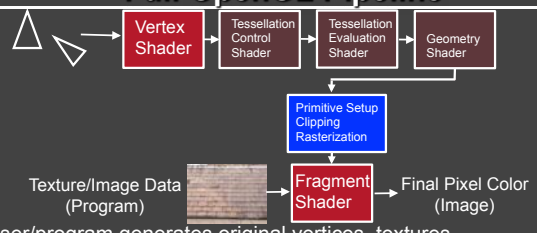
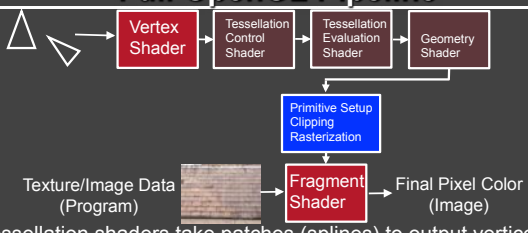
Full OpenGL Pipeline



User/program generates original vertices, textures
We cover programmable vertex and fragment shaders in course
OpenGL primitive setup, clipping, rasterization not programmable

Full OpenGL Pipeline



Tessellation shaders take patches (splines) to output vertices
Geometry shaders process primitives, can add/remove geometry
Not covered in this course

Simplified OpenGL Pipeline

- User specifies vertices (via vertex arrays)
- For each vertex in parallel
  - OpenGL calls user-specified vertex shader:
    Transform vertex (ModelView, Projection), other ops
- For each primitive, OpenGL rasterizes
  - Generates a *fragment* for each pixel the primitive covers
- For each fragment in parallel
  - OpenGL calls user-specified fragment shader:
    Shading and lighting calculations
  - OpenGL handles z-buffer depth test unless overwritten

Shader Setup

Initializing (shader itself discussed later)

1. Create shader (Vertex and Fragment)
2. Compile shader
3. Attach shader to program
4. Link program
5. Use program

Shader Setup

- Shader source is just sequence of strings
- Similar steps to compile a normal program

Shader Initialization Code

```
GLuint initshaders (GLenum type, const char *filename) {
  // Using GLSL shaders, OpenGL book, page 679 of 7th edition
  GLuint shader = glCreateShader(type) ; GLint compiled ;
  string str = textFileRead (filename) ;
  const GLchar * cstr = str.c_str() ;
  glShaderSource (shader, 1, &cstr, NULL) ;
  glCompileShader (shader) ;
  glGetShaderiv (shader, GL_COMPILE_STATUS, &compiled) ;
  if (!compiled) {
    shadererrors (shader) ;
    throw 3 ; }
return shader ;
}
```

Linking Shader Program

```
GLuint initprogram (GLuint vertexshader, GLuint fragmentshader) {
  GLuint program = glCreateProgram() ;
  GLint linked ;
  glAttachShader(program, vertexshader) ;
  glAttachShader(program, fragmentshader) ;
  glLinkProgram(program) ;
  glGetProgramiv(program, GL_LINK_STATUS, &linked) ;
  if (linked) glUseProgram(program) ;
  else {
    programerrors(program) ;
    throw 4 ; }
 cout<<"Shader program successfully attached and linked." << endl;
 return program ; }
```

Basic (nop) vertex shader

- In shaders/ nop.vert.glsl nop.frag.glsl
  - Written in GLSL (GL Shading Language)
  - Vertex Shader (out values interpolated to fragment)

```
# version 330 core
// Do not modify the above version directive to anything older.
// Shader inputs
layout (location = 0) in vec3 position;
layout (location = 1) in vec3 color;
// Shader outputs, if any
out vec3 Color;
// Uniform variables
uniform mat4 modelview;
uniform mat4 projection;
void main() {
    // ...
```

Basic (nop) vertex shader

- In shaders/ nop.vert.glsl nop.frag.glsl
  - Written in GLSL (GL Shading Language)
  - Vertex Shader (out values interpolated to fragment)

```
# version 330 core
layout (location = 0) in vec3 position;
layout (location = 1) in vec3 color;
// Shader outputs, if any
out vec3 Color;
// Uniform variables
uniform mat4 modelview;
uniform mat4 projection;
void main() {
    gl_Position = projection * modelview * vec4(position, 1.0f);
    Color = color; // Just forward this color to the fragment shader
}
```

Basic (nop) fragment shader

```
# version 330 core
// Do not modify the version directive to anything older than 330.
// Fragment shader inputs are outputs of same name from vertex shader
in vec3 Color;
// Uniform variables (none)

// Output
out vec4 fragColor;
void main (void)
{
   fragColor = vec4(Color, 1.0f);
}
```