CSE 167 (FA22) Computer Graphics: OpenGL

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Graphics API

- Our goals are
  1. Some programming interface to command the graphics card.
  2. Some programming interface to create window and interact with mouse & keyboard etc.

**Open GL**

**GLUT (OpenGL Utility Toolkit)**
**GLFW**
**OS specific language Win32, X11, Cocoa**
Overview

- What are the APIs OpenGL and GLUT?
- Hello Window (GLUT)
- OpenGL: a state machine
- OpenGL: graphics factory analogy
- OpenGL: code structure
- Draw a square
  - Set up geometry
  - Set up shader
  - Draw
  - Uniform variable
- Abstraction
OpenGL

- OpenGL is a graphics Application Programming Interface (API)
- OpenGL consists of a list of functions that can command the graphics card to do certain things.
- There are many other graphics card APIs.
OpenGL

• OpenGL consists of a list of functions that can command the graphics card to do certain things.

• These functions enable a rasterization pipeline.

• OpenGL is just a specification of what functions should exist.

• The actual implementation of OpenGL is done by the graphics card manufacturer.
  
  ▶ OpenGL is usually not open-source.
  
  ▶ OpenGL binaries come with the graphics card driver.
OpenGL Utility Toolkit (GLUT)

- GLUT has a list of functions that control window and monitor mouse & keyboard events cross platform.
- GLUT was written by Mark J. Kilgard in the 90’s with the goal of making learning OpenGL programming easier.
  - Only a few lines of code is required to open a window.
  - Does not require knowledge of OS’s windowing system.
- GLUT was no-longer maintained. Open-source replica freeglut is available.

Kilgard 1996
Where is OpenGL & GLUT?

**Windows**

GL and its extensions come with **Windows SDK**

- Need the GL extension wrangler library (GLEW) to properly include modern OpenGL cross-platform and cross-hardware.
- Need to install GLUT or FreeGLUT

```c
#include <GL/glew.h>  
#include <GL/glut.h>  
```

**Linux**

GL and its extensions come with **Mesa**

```c
#include <GL/glew.h>  
#include <GL/glut.h>  
```

**Mac**

GL and GLUT come with **ComandLineTools**

- Apple implements OpenGL, not the graphics card party. GLEW is not needed.

```c
#include <OpenGL/gl3.h>  
#include <GLUT/glut.h>  
```
GLUT HelloWindow

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Video game logic

Declare global variables

```c
init( ){
    // initialize global variables
}
```

```c
main( ){
    Call init( );
    While ( True )
        Check keyboard & mouse events
        Draw graphics if needed
    EndWhile
}
```

- Define the state
- Initialize the state
- If certain key is pressed, modify the state.
  Turn on “Redisplay” flag.
```cpp
// HelloGL.cpp

#include <OpenGL/gl3.h>
#include <GLUT/glut.h>

#include <GL/glew.h>
#include <GL/glut.h>

static const int width = 400;
static const int height = 300;

void display(void)
{
    glClear(GL_COLOR_BUFFER_BIT);
    glutSwapBuffers();
    glFlush();
}

void keyboard(unsigned char key, int x, int y)
{
    switch(key){
        case 27: // Escape to quit
            exit(0);
            break;
    }
}

int main(int argc, char** argv)
{
    glutInit(&argc, argv);
    glutInitContextVersion(3,1);
    glutInitDisplayMode(GLUT_DOUBLE | GLUT_RGB | GLUT_DEPTH);
    glutInitWindowSize(width, height);
    glutCreateWindow("Hello Window");

    glClearColor (0.0, 0.2, 0.5, 1.0);
    glViewport(0,0,width,height);

    glutDisplayFunc(display);
    glutKeyboardFunc(keyboard);

    glutMainLoop();
    return 0;
}
```
OpenGL is a state machine

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The Draw command

• There is one single OpenGL command

        glDrawElements( ... );

That will

  ▶ Take the geometric data that is activated;
  ▶ Produce pixel colors stored in a frame buffer.
The Draw command

- There is one single OpenGL command

```c
glDrawElements( ... );
```

That will

- Take the geometric data that is activated;
- Produce pixel colors stored in a frame buffer.

**graphic pipeline**

**the pipeline is fixed**

**state**

**shader programs that are activated**
OpenGL is a state machine

- OpenGL is a state machine
  - The pipeline already knows how to process an in-coming data and draw something on the screen.
  - What determines the final image boils down to the state given by which buffers and which shaders are selected.

**A buffer** is a part of memory for storing data for later access.

**A shader** is a program (a piece of code) that runs on GPU.
OpenGL is a state machine

- Simplified picture:

- Most OpenGL functions are for switching states
- Navigate to the right state, and call the draw function.
OpenGL Pipeline

- Vertex attributes are stored in an array in a vertex buffer.
- Vertex shader takes this array and apply coordinate transformations (and other things).
- With IndexBuffer they are assembled into primitives.
- (There is a Geometry Shader before rasterization that runs over primitives.)
- Clipping and culling away geometries outside the viewing box.
- Rasterization turns 3D geometries into fragments, which will be assigned to pixels.
- Fragment shader computes the pixel color.
- Pixel colors are placed into some frame buffer (or discarded according to depth test).
CPU v.s. GPU

• OpenGL API allows us to use this pipeline to access GPU

• The rest of our C++ program is performed by CPU

• Type of tasks:
  ▶ Single instruction single data (SISD). CPU is good at SISD.
  ▶ Single instruction multiple data (SIMD). GPU is good at SIMD.

• Examples
  ▶ Host CPU C++ program: manage usr input, physics, … output set of vertices
  ▶ GPU: coordinate transformation (world, camera, perspective, device coordinate), vertex computation, shading, clipping & culling. Limitation the pipeline is still fixed, vertex computation then linearly interpolated.
- Manipulating buffers and shaders are like operating a factory.
OpenGL Graphics Factory

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Output storage & delivery

- Double buffering
- There are several other frame buffers (depth, RGB, transparency)
There are 3 main stages:
- Pre-rasterization (per-vertex computation)
- Rasterization
- Post-rasterization (per-fragment computation)

In each stage, the workers execute the same arithmetics; but they are handed in with different input data.

Uniform variables are data that are constant for all workers.
Objects to deal with

- **Geometry spreadsheet (a.k.a. Vertex array object)**
  - A table of vertex attributes (data per vertex), and a table of vertex indices per triangle.

- **Buffer object**
  - The geo spreadsheet is actually pointers to this actual storage device
Objects to deal with

- **Shader object**
  - Where we type the shader source code.

- **Program object**
  - A binder that collects all shader objects.
Vending center
Machines where we can write numbers into a buffer object.

The geometry spreadsheet remembers which buffer corresponds to which attribute.

When the “draw” command is called, the source data are read from these machines.
Shaders needed to be typed in, compiled, and linked into a program.
Overall code structure

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Recall: graphics pipeline

- **Vertex array object**
  is a spreadsheet listing the input data for the vertex shader.

- **Vertex shader**
  is a function that is evaluated for each vertex.

- **Rasterization**
  turns triangles into fragments.
  Inputs of the f-shader are the interpolated v-shader outputs.

- **Fragment shader**
  is a function that is evaluated for each fragment.
C++ code using OpenGL code structure

Global variables
- Vertex array object, buffer objects
- Program object
- Uniform variable locations

Initialization
1. Build vertex array objects.
   - Write values into buffer objects.
   - Configure buffer objects as vertex attributes.
2. Write & compile shader programs.
   - Declare in, out, uniform variables.
   - Write a GLSL program, like C with many math types and functions available.

Display
- Select a vao & a shader program, set uniform.
  - glDrawElements( . . . );
Draw a Square

- What are the APIs OpenGL and GLUT?
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Goal

(Code available in HelloSquare.cpp)
Step 0: Declare global variables

```cpp
static GLuint program;
static GLuint square_vao;
static GLuint buffers[3];
```

- **shader program**
- **geometry spreadsheet**
- **actual storage for geometric data**
- **global variable only within this C++ file.**
1. Geometry Spreadsheet

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GLfloat positions[] = {
    -0.5f, -0.5f, // pt0
    0.5f, -0.5f, // pt1
    0.5f, 0.5f,  // pt2
    -0.5f, 0.5f  // pt3
};
GLfloat colors[] = {
    1.0f, 0.0f, 0.0f, // pt0: red
    1.0f, 1.0f, 0.0f, // pt1: yellow
    0.0f, 1.0f, 0.0f, // pt2: green
    0.0f, 0.0f, 1.0f  // pt3: blue
};
GLuint inds[] = {
    0, 1, 3, // first triangle
    2, 3, 1  // second triangle
};
Step 1: Define geometry

```c
glGenVertexArrays(1, &(square_vao));
glGenBuffers(3, buffers);

// activate geometry spreadsheet
glBindVertexArray(square_vao);
```
Step 1: Define geometry

0th attribute type is “2 floats”

When reading `uint` number n, view it as true: n/255? or false: n?

```
glBindBuffer(GL_ARRAY_BUFFER, buffers[0]);
glBufferData(GL_ARRAY_BUFFER, sizeof(positions), positions, GL_STATIC_DRAW);
glEnableVertexAttribArray(0);
glVertexAttribPointer(0, 2, GL_FLOAT, GL_FALSE, 0, (void*)0);
```

```
glBindBuffer(GL_ARRAY_BUFFER, buffers[1]);
glBufferData(GL_ARRAY_BUFFER, sizeof(colors), colors, GL_STATIC_DRAW);
glEnableVertexAttribArray(1);
glVertexAttribPointer(1, 3, GL_FLOAT, GL_FALSE, 0, (void*)0);
```
Step 1: Define geometry

```glsl
glEnableVertexAttribArray(0);
glVertexAttribPointer(0, 2, GL_FLOAT, GL_FALSE, 0, (void*)0);

glBindBuffer(GL_ARRAY_BUFFER, buffers[1]);
glBufferData(GL_ARRAY_BUFFER, sizeof(colors), colors, GL_STATIC_DRAW);
glEnableVertexAttribArray(1);
glVertexAttribPointer(1, 3, GL_FLOAT, GL_FALSE, 0, (void*)0);

glBindBuffer(GL_ELEMENT_ARRAY_BUFFER, buffers[2]);
glBufferData(GL_ELEMENT_ARRAY_BUFFER, sizeof(inds), inds, GL_STATIC_DRAW);
```
**Step 1: Define geometry**

```c
// Define vertex attributes

// Step 1: Define geometry

glEnableVertexAttribArray(1);
glVertexAttribPointer(1, 3, GL_FLOAT, GL_FALSE, 0, (void*)0);
```

```c
// Define element indices

// Step 1: Define geometry

glBindBuffer(GL_ELEMENT_ARRAY_BUFFER, buffers[2]);
glBufferData(GL_ELEMENT_ARRAY_BUFFER, sizeof(inds), inds, GL_STATIC_DRAW);
```
glBindBuffer(GL_ARRAY_BUFFER, buffers[1]);
glBufferData(GL_ARRAY_BUFFER, sizeof(colors), colors, GL_STATIC_DRAW);
glEnableVertexAttribArray(1);
glVertexAttribPointer(1, 3, GL_FLOAT, GL_FALSE, 0, (void*)0);

// END of setting up the square geometry.

// unbind the vao to avoid further modification to the geometry spreadsheet.

glBindVertexArray(0);

// END of setting up the square geometry.
Step 1: Define geometry

```c
glGenVertexArrays(1, &(square_vao));
glGenBuffers(3, buffers);

// activate geometry spreadsheet
glBindVertexArray(square_vao);

...  

// unbind the vao to avoid further modification to the geometry spreadsheet.

glBindVertexArray(0);

// END of setting up the square geometry.
```

- `square_vao` remembers how the 3 buffers are mapped to the desired attributes.
- Later, when we want to draw the square, we bind `square_vao` and call the draw command.
2. Shading Language (GLSL)

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  - Draw
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Step 2: Write shaders

**vertex shader**

```glsl
# version 330 core
layout (location = 0) in vec2 pos;
layout (location = 1) in vec3 color;
out vec3 vertexcolor;
out vec2 vertexpos;

void main(){
  gl_Position = vec4(pos.x, pos.y, 0.0f, 1.0f);
  vertexcolor = color;
  vertexpos = pos;
}
```

**fragment shader**

```glsl
#version 330 core
in vec3 vertexcolor;
in vec2 vertexpos;

out vec4 fragColor;

void main (void){
  fragColor = vec4(vertexcolor,1.0f);
}
```

- First line: version
- Variable declaration: in, out, uniform.
- Additional keyword: layout( location = … )
- The input of vtx shader comes from vertex array. The input of frag shader comes from the output of vtx shader.
- vtx shader needs to set gl_Position.
const char *vertShaderSrc =
R"(  
    # version 330 core
    layout (location = 0) in vec2 pos;
    layout (location = 1) in vec3 color;

    out vec3 vertexcolor;
    out vec2 vertexpos;

    void main(){
        gl_Position = vec4(pos.x, pos.y, 0.0f, 1.0f);
        vertexcolor = color;
        vertexpos = pos;
    }
)";  
const char *fragShaderSrc =
R"(    
    #version 330 core

    in vec3 vertexcolor;
)";
Step 2: Write shaders

```cpp
GLuint vs = glCreateShader(GL_VERTEX_SHADER);
GLuint fs = glCreateShader(GL_FRAGMENT_SHADER);
```

```cpp
vertexcolor = color;
vertexpos = pos;
}
);

const char *fragShaderSrc =
R"(
    #version 330 core
    in vec3 vertexcolor;
    in vec2 vertexpos;
    out vec4 fragColor;
    void main (void){
        fragColor = vec4(vertexcolor, 1.0f);
    }
)";
```
GLuint vs = glCreateShader(GL_VERTEX_SHADER);
GLuint fs = glCreateShader(GL_FRAGMENT_SHADER);
Step 2: Write shaders

```c
GLuint vs = glCreateShader(GL_VERTEX_SHADER);
GLuint fs = glCreateShader(GL_FRAGMENT_SHADER);

glShaderSource(vs, 1, &vertShaderSrc, NULL);
glShaderSource(fs, 1, &fragShaderSrc, NULL);
```
Step 2: Write shaders

glShaderSource(vs, 1, &vertShaderSrc, NULL);
glShaderSource(fs, 1, &fragShaderSrc, NULL);

glCompileShader(vs);
glCompileShader(fs);
Step 2: Write shaders

```cpp
GLuint vs = glCreateShader(GL_VERTEX_SHADER);
GLuint fs = glCreateShader(GL_FRAGMENT_SHADER);

glShaderSource(vs, 1, &vertShaderSrc, NULL);
glShaderSource(fs, 1, &fragShaderSrc, NULL);

glCompileShader(vs);
glCompileShader(fs);

program = glCreateProgram();
glAttachShader(program, vs);
glAttachShader(program, fs);
glLinkProgram(program);
glDeleteShader(vs);
glDeleteShader(fs);
// END compiling shaders
```
3. Draw Command

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  - Set up shader
  - **Draw**
  - Uniform variable
- Abstraction
void display(void){
    glClear(GL_COLOR_BUFFER_BIT);

    // BEGIN draw square
    glBindVertexArray(square_vao);
    glUseProgram(program);
    glDrawElements(GL_TRIANGLES, // cookbook
        6, // length of the array inds[]
        GL_UNSIGNED_INT,
        0
    );

    // END draw square

    glutSwapBuffers();
    glFlush();
}
void display(void) {
    glClear(GL_COLOR_BUFFER_BIT);

    // BEGIN draw square
    glBindVertexArray(square_vao);
    glUseProgram(program);
    glDrawElements(GL_TRIANGLES, // cookbook
                   6, // length of the array inds[]
                   GL_UNSIGNED_INT,  // cookbook
                   0
                   );
    // END draw square

    glutSwapBuffers();
    glFlush();
}
Uniform Variables

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Goal

(Code available in HelloSquare.cpp)
fragment shader

#version 330 core
in vec3 vertexcolor;
in vec2 vertexpos;

out vec4 fragColor;

void main (void){
   fragColor = vec4(vertexcolor, 1.0f);
}

Uniform variables
fragment shader

#version 330 core
in vec3 vertexcolor;
in vec2 vertexpos;

uniform float circleradius;
uniform vec3 circlecolor;

out vec4 fragColor;

void main (void){
    fragColor = vec4(vertexcolor, 1.0f);
}
fragment shader

#version 330 core
in vec3 vertexcolor;
in vec2 vertexpos;

uniform float circleradius;
uniform vec3 circlecolor;

out vec4 fragColor;

void main (void){
  vec4 vertexColor = vec4(vertexcolor, 1.0f);
  if (length(vertexpos)<circleradius){
    fragColor = vec4(circlecolor, 1.0f);
  }
}

# Pass uniform vars from C++ to shader

## Global variables

```cpp
static GLfloat myradius = 0.2;
static GLuint circleradius_loc;
static glm::vec3 mycolor = glm::vec3(1.0, 1.0, 1.0);
static GLuint circlecolor_loc;
```

## Fragment shader

```glsl
#version 330 core

in vec3 vertexcolor;
in vec2 vertexpos;

out vec4 fragColor;

void main (void)
{
  fragColor = vec4(vertexcolor, 1.0f);
}
```

```glsl
uniform float circleradius;
uniform vec3 circlecolor;
```

```glsl
if (length(vertexpos) < circleradius)
{
  fragColor = vec4(circlecolor, 1.0f);
}
```

## After compile program (in init)

```cpp
circleradius_loc = glGetUniformLocation(program, "circleradius");
circlecolor_loc = glGetUniformLocation(program, "circlecolor");
```

## Set uniform values (in display)

```cpp
glUseProgram(program);
glUniform1f(circleradius_loc, myradius);
glUniform3f(circlecolor_loc, mycolor[0], mycolor[1], mycolor[2]);
```

Last line is equivalent to

```cpp
glUniform3fv(circlecolor_loc, 1, &mycolor[0]);
```
What we have learned so far
What we have learned so far

• We have learned almost everything for OpenGL programming!
  ▶ Read the code from HW0.
  ▶ At low level, everything in OpenGL is to set up buffers and shaders, and call “draw” at the right time.
• One remaining thing: abstraction (make code clean)
  ▶ When there are more objects to draw, the code will be very messy. We need to group the variables and functionalities in a semantically meaningful way for a cleaner OpenGL code.
Object oriented OpenGL code

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Lots of global variables

```c
static GLuint program;
static GLuint square_vao;
static GLuint buffers[3];
static GLfloat myradius = 0.2;
static GLuint circleradius_loc;
static glm::vec3 mycolor =
    glm::vec3(1.0, 1.0, 1.0);
static GLuint circlecolor_loc;
```
Lots of global variables

```c
static GLuint program;
static GLuint square_vao;
static GLuint buffers[3];
static GLfloat myradius = 0.2;
static GLuint circleradius_loc;
static glm::vec3 mycolor = glm::vec3(1.0, 1.0, 1.0);
static GLuint circlecolor_loc;
```

owned by the “square” geometry

a special shader with a particular set of parameter interface
#include <vector>
#ifndef __GEOMETRY_H__
#define __GEOMETRY_H__
class Geometry {
	public:
		GLenum mode = GL_TRIANGLES; // the cookboook for glDrawElements
	
tint count; // number of elements to draw
		GLenum type = GL_UNSIGNED_INT; // type of the index array
		GLuint vao; // vertex array object a.k.a. geometry spreadsheet
		std::vector<GLuint> buffers; // data storage

	virtual void init(){};


tvoid draw(void){
		glBindVertexArray(vao);
		glDrawElements(mode,count,type,0);
	n}
#endif
#include "Geometry.h"
#ifndef __SQUARE_H__
define __SQUARE_H__

class Square : public Geometry {
public:

    void init(){
        ...
    }
};//
#endif
Global variable

```c
#include "Square.h"

static Square square;
```

Initialization

```c
// Initialize square
square.init();
```

Draw

```c
void display(void){
    glClear(GL_COLOR_BUFFER_BIT);
    // BEGIN draw square
    square.draw();
    // END draw square
    glutSwapBuffers();
    glutFlush();
}
```
class Shader {
public:
    GLuint program;  // the shader program
    std::string vertexshader_source;   // source code
    std::string fragmentshader_source; // source code

    void read_source(const char * vertexshader_filename,
                      const char * fragmentshader_filename);
    void compile();
    GLint getVertexShaderCompileStatus(){return compiled_vs;}
    GLint getFragmentShaderCompileStatus(){return compiled_fs;}
    GLint getLinkStatus(){return linked;}

private:
    ...
};
class Shader {
  public:
    GLuint program; // the shader program
    std::string vertexshader_source; // source code
    std::string fragmentshader_source; // source code

    void read_source(const char * vertexshader_filename,
                     const char * fragmentshader_filename);
    void compile();
    GLint getVertexShaderCompileStatus(){return compiled_vs;}
    GLint getFragmentShaderCompileStatus(){return compiled_fs;}
    GLint getLinkStatus(){return linked;}

  private:
    ...
};
class Shader {
public:
    GLuint program; // the shader program
    std::string vertexshader_source; // source code
    std::string fragmentshader_source; // source code

    void read_source(const char * vertexshader_filename,
                     const char * fragmentshader_filename);
    void compile();

    GLint getVertexShaderCompileStatus(){return compiled_vs;}
    GLint getFragmentShaderCompileStatus(){return compiled_fs;}
    GLint getLinkStatus(){return linked;}

private:
    ...
};
Inherited classes of Shader

- Specialized shaders are inherited classes of the Shader class, they have the customized uniform variables.

```cpp
class CircleShader : public Shader {
public:
    GLfloat radius = 0.2; GLuint radius_loc;
    glm::vec3 color = glm::vec3(1.0, 1.0, 1.0); GLuint color_loc;

    void initUniforms() {
        radius_loc = glGetUniformLocation(program, "circleradius");
        color_loc = glGetUniformLocation(program, "circlecolor");
    }

    void setUniforms() {
        glUniform1f(radius_loc, radius);
        glUniform3f(color_loc, color[0], color[1], color[2]);
    }
};
```
Using Square and CircleShader classes

Global variable

```
static Square square;
static CircleShader shader;
```

Initialization

```
// Initialize square
square.init();

// Initialize shader
shader.read_source(
    "shaders/hello.vert",
    "shaders/hello.frag";
shader.compile();
shuseProgram(shader.program);
shader.initUniforms();
```

Draw

```
void display(void){
    glClear(GL_COLOR_BUFFER_BIT);
    
    // BEGIN draw square
    shader.setUniforms();
    square.draw();
    
    // END draw square
    glutSwapBuffers();
    glFlush();
}
```
HW1: Mandelbrot Shader
Global variable

```cpp
static Square canvas;
static MandelbrotShader shader;
```

Initialization

```cpp
// Initialize square
square.init();

// Initialize shader
shader.read_source(
    "shaders/simple.vert",
    "shaders/Mandelbrot.frag");
shader.compile();
```

Draw

```cpp
void display(void){
    glClear(GL_COLOR_BUFFER_BIT);

    // BEGIN draw square
    shader.setUniforms();
    square.draw();

    // END draw square
    glutSwapBuffers();
    glFlush();
}
```
In the fragment shader

- For each pixel of the “canvas” evaluate a given mathematical algorithm.
- The resulting value will vary across different pixels, forming a fractal on the canvas.
Mandelbrot iteration

**Input:** \( c \in \mathbb{C}; \)

1. \( z_0 = 0 \in \mathbb{C}; \)
2. for \( k = 0, 1, 2, \ldots \) do
3. \( z_{k+1} = z_k^2 + c; \)
4. end for

- Each pixel corresponds to a complex value \( c. \)
- The color shows the **number of iteration** it takes for the iteration to produce \( |z_k| \geq 2. \)
Mandelbrot fractal