Shaders and OpenGL Shading Language

Professor Raymond Zavodnik

Tbilisi State University April 9, 2016

Why Shaders and OpenGL Shading Language(GLSL)?

1. OpenGL is by design a static API that offers graphics applications a fixed functionality
2. Until recently the only way to modify the API was to extend it
    - Extensions usually are there to support new graphics hardware
    - Today almost all graphics hardware is programmable
    - Vendors today must offer programmable graphics architectures
3. Over the years more than 400 extensions have been implemented by the ARB!

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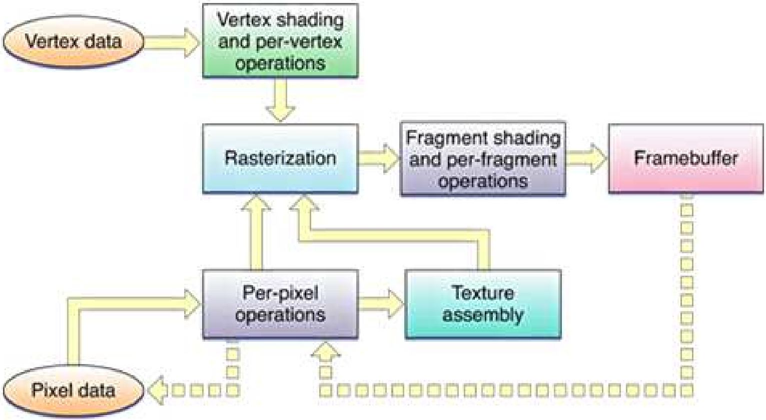
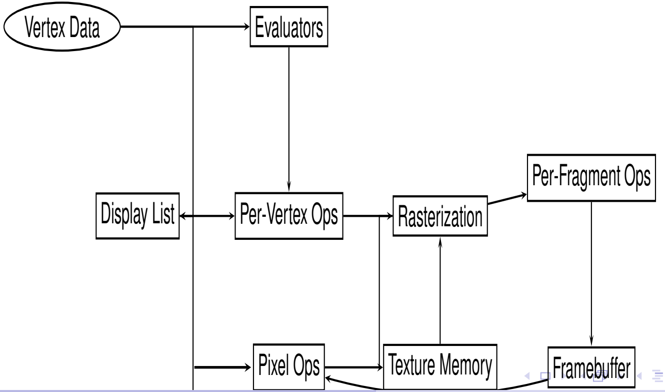
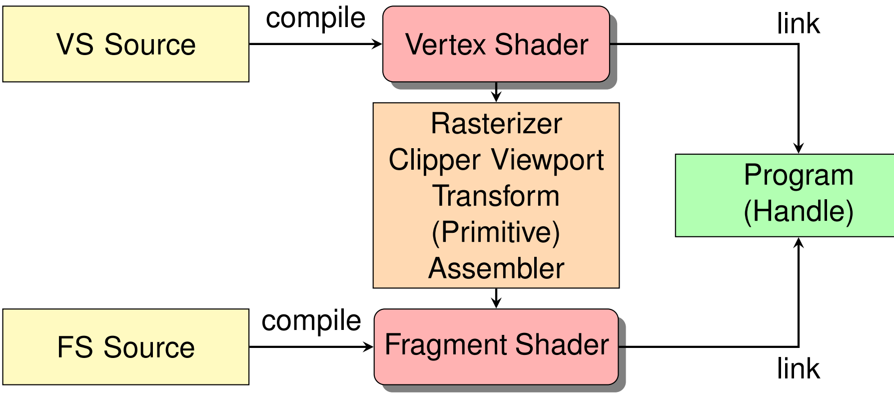

Vertex data
Vertex shading and per-vertex operations
Rasterization
Fragment shading and per-fragment operations
Framebuffer
Per-pixel operations
Texture assembly
Pixel data

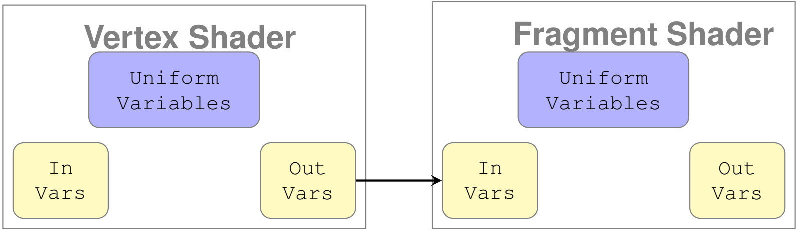
OpenGL Pipeline (Simplified)



Basic Shader Pipeline



Shader Components



Remarks

- Input for VS In Variables: Vertex Attributes from GPU
- Output for FS Output Variables: Framebuffer (for rendering)
- Role of Uniform Variables for all shaders: Share Data with main OpenGL program
- Output Vars of VS must match Input Vars of FS

Graphics Processing Pipeline

- Graphics operations in OpenGL happen in a (more or less) fixed order
- This functionality has remained fixed
  - **Per Vertex Operations**: Single vertices and their associated attributesare processed independently of one another
  - **Primitive Assembly**: Vertices are collected into graphic primitives
  - **Primitive Processing**: Primitives are clipped and perspective-projected
  - **Rasterization**: Primitives are decomposed into rasterizable units, i.e. pixels in the framebuffer. These units are called *Fragments*

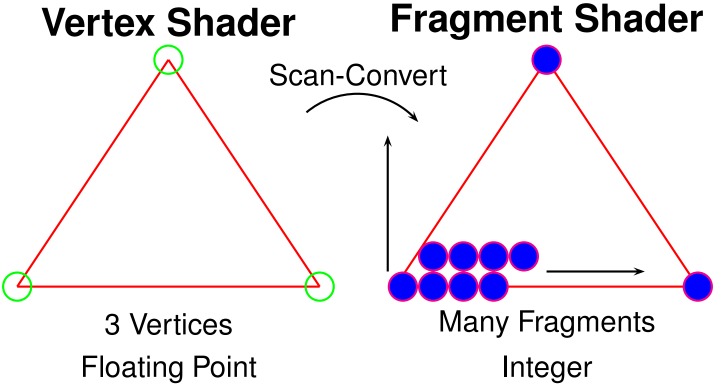
Graphics Processing Pipeline

- **Fixed Functionality Continued**
  - **Fragment Processing**: Textures, etc are combined with fragments
  - **Per-Fragment Operations**: Determine pixel visibiity, execute alpha, stencil, scissor tests
  - **Framebuffer Operations**: Determine buffers of pixel data and output them
- **The Bad News**: All of this fixed functionality has been deprecated!
- **The Good News**: The Graphics Pipeline is retained, the individual components being replaced by programmable units called *shaders*

Going From Vertices to Fragments

- 3 Floating Point Vertices are mapped to 3 Fragments
- These three Fragments are interpolated to the interior of the triangle
- Horizontally affinely interpolate from the edges, starting with the lowest vertex or side
- Vertically bump the incremented y-value by affinely interpolating between lower and higher vertex
- At any point the input variable of the Fragment Shader contains the currently scan-converted fragment (or simply, pixel)

Going from Vertices to Fragments



Compatibility Issues

- **Problem**: What about applications that use the fixed functionality?
- **Constraint**: They must run as before
- **Solution**: Although deprecated, the old features become **extensions** that are part of a complicated hierarchy of libraries that can be called apart from the new core functionality
- OpenGL3.0 introduced the *deprecation model* with features to be removed by OpenGL 4.0. Writing for a specific release the programmer would use the *core profile* for that release.
- **The Bottom Line**: Practically *all* of the old functionality has been deprecated, being replaced by the **OpenGL**

Accessing Core Functionality

- **Main problems**
  1. Obtaining the correct libraries for a specific release
  2. There are no more matrices
- Use GLEW (GL **E**xtension **W**rangler) to obtain the correct extensions automatically: just use the include
  ```
  #include <GL/glew.h>
  ```
  at the very beginning of your program
- Use the header-only **GLM** math library for vectors and matrices:
  ```
  #include <glm/glm.hpp>
  #include <glm/gtc/matrix_transform.hpp>
  #include <glm/gtx/transform2.hpp>
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  in your program using the glm namespace

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Shaders and the OpenGL Pipeline

- Per-Vertex Operations are carried out by the **Vertex Shader**. This shader is mandatory
- Primitive Assembly is carried out by the **Tesselation Shaders** *Tesselation Control Shader* and *Tesselation Evaluation Shader*. These shaders are optional. They are concerned with *patches* (later).
- Primitive Processing is done in the **Geometry Shader.** Input are all the vertices it needs to produce a primitive, e.g. a Quad. This shader is likewise optional
- Rasterization is internal producing fragments]item Fragment Processing is carried out by the **Fragment Shader**. This shader is also always required.

The Vertex Shader

Input:

- Things that change with every new vertex:
  - A single vertex
  - Its *attributes*, such as normal vector, color, texture coordinate
  - These global variables are called `IN VARIABLES` or `ATTRIBUTES GLSL 1.2`

Output: Per Vertex calculations, e.g. light intensity

The Vertex Shader

What It Does:

- Transforms vertices
- Transforms and normalize normal vectors
- Generates texture
- Calculates lighting
- Applies colors and materials

The Vertex Shader

How It Works:

- GLSL 1.2 and later: Vertices can be input via the dedicated variable `gl_Vertex`
- Normals via `gl_Normal`, Colors via `gl_Color`, etc.
- Better: Use dedicated channels associated with Vertex Attribute Objects and provide your own variables names for the `IN` or `ATTRIBUTE` variables (later).
- Use the function `glBindAttributeLocation()` to assign the channel (later)
- Use buffers on the server to store your vertex data and its attributes
- Using this data, implement the shader algorithm, e.g. calculate lighting

The Vertex Shader

How It Works (Continued):

- Export data to be used in the fragment shader using `OUT` resp. `VARYING` variables, e.g. light intensity.
- GLSL 1.2 also uses `gl_Position`, `gl_FrontColor`, etc.

A Simple Vertex Shader

```
#vertex 400   //the GLSL version
in vec3 VertexPosition;
in vec3 VertexColor;
out vec3 Color;
void main()
{
   Color = VertexColor;
   gl_Position = vec4(VertexPosition, 1.0);
}
```

Explanation

- This shader just passes through its vertex data
- Note the built-in output variable `gl_position`
- Note the two input attributes
- Values for this type must be provided via **generic vertex attributes**
- The output variable `Color` is the input for the fragment shader, which is just the contents of `VertexColor`

The Fragment Shader

Input: The `out` variablers of the vertex shader

Output: The specification of the associated fragments

- Things to be passed to the Fragment Shader:
  - The same as for fixed-function processing
  - The homogeneous coordinates of the vertex in clipping space
  - These global variables are called `OUT VARIABLES`

A Simple Fragment Shader

```
#vertex 400   //the GLSL version
in vec3 Color;
out vec4 FragColor;
void main()
{
   FragColor = vec4(Color,1.0);
}
```

Explanation

- There is just one input variable, which is identical to the output variable of the vertex shader in name and type
- The value is an interpolated value, calculated from the output vertices
- The result is the (interpolated) fragment color, given by the `out` variable
- Writing the two above shaders results in a shader program that hands the input vertices and their associated colors to the graphics pipeline, producing a shaded object

Remarks: The Vertex Shader

Remarks:

- Each vertex is processed independently
- Cannot mix vertex ops and fixed-functionality ops
- Items required by the Vertex Shader that do not vary with each vertex, such as matrices, are passed in as `UNIFORM VARIABLES`
- The standard out variable `gl_position` has been deprecated(!)

Remarks:The Fragment Shader

Input:

- User-defined in variables as results of rasterization:
  - The window coordinates for output
  - Its relevant properties such as whether it is front-facing, calculated refraction index and any other interpolated values such as color
  - These global variables are called its `IN VARIABLES`
  - These must match up in number and type with the Vertex Shader's out variables

Remarks:The Fragment Shader

What It Does:

- Realizes the shading algorithm applied to its input
- Processes each fragment independently of all others
- Does not replace the fixed-functionality per-fragment and framebuffer operations
- Automatically accepts the results of rasterization
- Deals freely with textures

Remarks:The Fragment Shader

Output:

- The results of the applied algorithm on the fragment
  - The fragment's depth, color, etc.t
  - If it is to be discarded, i.e. not written
  - These global variables are called `OUT VARIABLES`

Remarks: The Fragment Shader

- The fragment shader does not have access to the framebuffer
- The fixed functionality does pixel ownership testing, scissoring, etc
- Quantities that do not change on a per fragment basis, such as light position, density, etc. are called again `UNIFORM`
- No one-to-one correspondence with vertices: 3 vertices can produce a huge number of fragments by the fixed functionality pipeline part
- Incoming values are most often the result of interpolation, e.g. color

Shader Compilation

- The GLSL compilation system is part of OpenGL
  - There is no system compilation command
  - Shader text is submitted to the compiler as a string in a character array
  - The GLSL compiler is an OpenGL call!!
  - Error handling and debugging are problematic
- Each shader is compiled separately
- Compilation produces a "Handle" for each shader
- Compile with the OpenGL call `glCompileShader()`

Example: Compile a Vertex Shader

```
GLuint verShader;
GLint verCompiled;
const char *vShader, *fShader;
verShader = glCreateShader(GL_VERTEX_SHADER);
vShader = readShader("Verts.vert",
                     EVertexShader);
glShaderSource(verShader, 1, &vShader, NULL);
glCompileShader(verShader);
glGetShaderiv(verShader, GL_COMPILE_STATUS,
              &verCompiled);
if (verCompiled == GL_FALSE){...}
```

Remarks

- Assume the shader source has been written to the file `Verts.vert`
- Notice the distinct steps:
  - Create a vertex shader object with `glCreateShader(GL_VERTEX_SHADER)`
  - Load the shader source into a string: `readShader()`, which is written by the programmer
  - Give it a handle with `glShaderSource()`
  - Compile with `glCompileShader()`
  - Get compilation status: `glGetShaderiv()`
  - Fragment shaders are compiled analogously

How to Link Several Shaders into a Program

- All compiled shaders must be linked together into a program
- The linker must coordinate output variables from one shader to input variables of the next
- Linker must also link OpenGL variables with shaders (uniform variables)
- The linked program must be installed into the OpenGL pipeline

Link Shaders into a Program

```
GLuint programHandle, linked;
programHandle = glCreateProgram();
glAttachShader(programHandle, verShader);
glAttachShader(programHandle fragShader);
glLinkProgram(programHandle);
glDeleteShader(verShader);
glDeleteShader(fragShader);
glGetProgramiv(programHandle, GL_LINK_STATUS,
              &linked);
if (linked == GL_FALSE){ ...}
glUseProgram(programHandle);
```

Remarks about Linking

- Use `glCreateProgram()` to create the program object
- Attach the shaders to the program object with `glAttachShader()`
- Link with `glLinkProgram()`
- Delete the compiled shaders, because they have been linked
- Check the link status and react accordingly
- Install the program into the OpenGL pipeline with `glUseProgram()`
- If needed, program is available by its handle `programHandle`

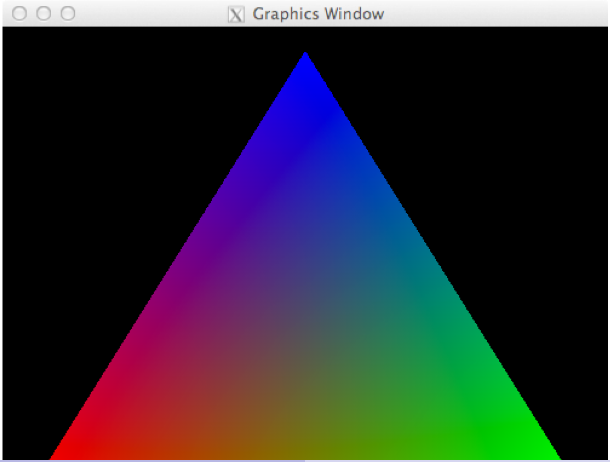
Example: Draw of Gouraud triangle

```
void redraw()
{
  glClear(GL_COLOR_BUFFER_BIT);
  glShadeModel(GL_SMOOTH);
  glBegin(GL_POLYGON);
    glColor3f(1.0,0.0,0.0);
    glVertex2f(-0.9,-0.9);
    glColor3f(0.0,1.0,0.0);
    glVertex2f(0.9,-0.9);
    glColor3f(0.0,0.0,1.0);
    glVertex2f(0.0,0.9);
  glEnd();
  if (doubleBuffer) glXSwapBuffers(display,main_wind
```

Remarks

- The OpenGL program normal with drawing taking place in `redraw()`
- There is no initialization
- Use the Vertex and Fragment Shaders above
- Write a `shader()` program that compiles. links and installs the shaders
- Run it (in X windows)
- Result: Gouraud shaded triangle

Gouraud Triangle Using Shaders



Remarks About the Gouraud Triangle

- The shaders involved use standard variable to pass the attribute variables
- The has limited value
- GLSL uses **Vertex Attribute Objects** to transfer the vertices and their attributes into the Vertex Shader
- These,in turn, are built on Buffer Objects, defined on the server
- Pointers to the attribute arrays are defined using `glVertexAttributePointer()` in the compilation process
- Consequence: You can use your own `in` resp. `attribute` variables using this preferred method

Vertex Attribute Data

- Vertex Attributes are the input variables to the Vertex Shader
- Problem: How do we pass values from our OpenGL program to these input variables?
- Early versions of GLSL used dedicated variables, e.g. `gl_position` to enable the communication
- Now this mechanism is under the control of the programmer with **Vertex Array Objects**
- Use **Vertex Buffer Objects** to store the data serverside using `GL_ARRAY_BUFFER` binding (for now)
- Tie the buffer objects together in one data structure using VAOs
- This is not specific to Vertex Attributes

Example of Vertex Array Objects: Defining

```
GLuint vaoHandle;
GLuint vertexBufferHandle = bufferID[0]; //VBO
GLuint colorBufferHandle = bufferID[0]; //VBO
glGenVertexArrays(1, &vaoHandle);
glBindVertexArray(vaoHandle);
glBindBuffer(GL_ARRAY_BUFFER, vertexBufferHandle);
glEnableClientState(GL_VERTEX_ARRAY);
glBindBuffer(GL_ARRAY_BUFFER, normalBufferHandle);
glEnableClientState(GL_NORMAL_ARRAY);
glBindVertexArray(0); //temporarily disable
```

Example of Vertex Array Objects: Using

```
void redraw()
{
  glBindVertexArray(vaoHandle);
  glDrawArrays(...);
  glBindVertexArray(0);
}
```

Using VAOs with Vertex Attributes

- Using `glBindVertexArray` makes `vaoHandle` the current VAO
- The first time used binds all of the default state of the current context
- All future calls will use that entire state
- To set the state for rendering use the important `glVertexAttribPointer()` to associate a channel for the desired data as well as a pointer to that data on the GPU
- This stores the VBO in the VAO
- Binding a new VAO does not change those buffer bindings, i.e. the current bound buffers are not stored in the VAO

Description of `glVertexAttribPointer`

- Parameter 1: The actual channel to be used for the associated data (generic attribute index)
- Parameter 2: The number of components per vertex attribute (1,2,3 or 4)
- Parameter 3: The type of each component (they are all the same)
- Parameter 4: Used for normalized data
- Parameter 5: The stride, used for tightly packed data
- Parameter 6: A pointer to the start of the data on the GPU (actually a byte offset from the beginning of the buffer)

Example: VAO that defines Vertex Attributes

```
glGenVertexArrays(1, &vaoHandle);
glBindVertexArray(vaoHandle);
glEnableVertexAttribArray(0);   //Vertices
glBindBuffer(GL_ARRAY_BUFFER, bufferID[0]);
glVertexAttribPointer((GLuint)0, 3, GL_FLOAT,
        GL_FALSE, 0, ((GLubyte *)NULL + (0)) );
glEnableVertexAttribArray(1);   //Colors
glBindBuffer(GL_ARRAY_BUFFER, bufferID[1]);
glVertexAttribPointer((GLuint)1, 3, GL_FLOAT,
        GL_FALSE, 0, ((GLubyte *)NULL + (0)) );
glBindVertexArray(0);
```

UniformVariables: Sharing Other OpenGL Data

- Importing vertices and associates attributes is only one kind of application data that is needed for use in a shader
- For example, light intensity or a ModelView transformation are also needed
- Solution: Uniform Variables–data that does change on a per-vertex basis
- Uniform variables are read-nly in a shader, i.e. their values are set by the application
- Consequence: Uniform Variables must be initialized by the application
- The GLSL linker must associate these locations with `glGetUniformLocation()` mapping shader names to actual variable locations

Rotate a Gouraud Triangle:Vertex Shader

```
#version 120

attribute vec3 VertexPosition;
attribute vec3 VertexColor;

uniform mat4 RotationMatrix;

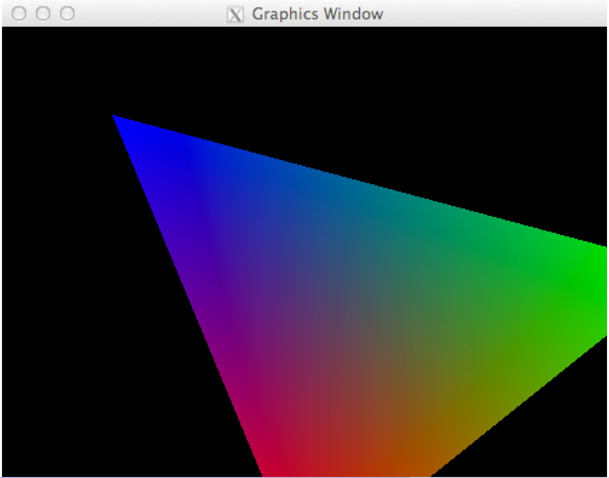
void main(void)
{
  gl_Position = RotationMatrix *
                vec4(VertexPosition, 1.0);
  gl_FrontColor = VertexColor;
}
```

Roate a Gouraud Triangle: App Code

```
int Angle = 20;
glm::mat4 rotationMatrix =
    glm::rotate(mat4(1.0f), Angle,
            vec3(0.0f, 0.0f, 1.0f));

GLuint location =
     glGetUniformLocation(prog, "RotationMatrix");
 if (location >= 0 )
  {
    glUniformMatrix4fv(location, 1, GL_FALSE,
                        &rotationMatrix[0][0]);
  }
```

Rotating a Gouraud Triangle



OpenGL Shading Language (GLSL)

- Basically the C Programming Language, with some extensions and omissions
- Easily learned by those with knowledge of C
- Omissions
    - No pointers
    - No memory management
    - No standard input and output

OpenGL Shading Language (GLSL)

- Extensions
  - VectorTypes: **vecn, ivecn, uvecn, bvecn** (n = 2,3,4)
  - Matrix Types: **matn** (n = 2,3,4) with overloaded multiplication and composition with vectors "*"
  - Shader Interfaces: **in, out, uniform, const**
  - Buffer Interfaces: **layout**
  - Texture Interfaces: **Samplers**
  - Many, many built-in functions
  - See Orange Book, pp. 65-99

References

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