The Graphics Pipeline and OpenGL III: OpenGL Shading Language (GLSL 1.10)

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Lecture 4
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Lecture Overview

• Review of graphics pipeline
• vertex and fragment shaders
• OpenGL Shading Language (GLSL 1.10)
• Implementing lighting & shading with GLSL vertex and fragment shaders
Reminder: The Graphics Pipeline

https://www.ntu.edu.sg/home/ehchua/programming/opengl/CG_BasicsTheory.html
Reminder: The Graphics Pipeline

Raw Vertices & Primitives

Transformed Vertices & Primitives

Fragments

Processed Fragments

Pixels

Display

Vertex Processor (Programmable)

Rasterizer

Fragment Processor (Programmable)

Output Merging

3D

2D array of color-values

vertex shader

• transforms

• (per-vertex) lighting

• …

fragment shader

• texturing

• (per-fragment) lighting

• …

https://www.ntu.edu.sg/home/ehchua/programming/opengl/CG_BasicsTheory.html
Two goals:
1. determine which fragments are inside the primitives (triangles) and which ones aren’t
2. interpolate per-vertex attributes (color, texture coordinates, normals, …) to each fragment in the primitive
Vertex Shaders

vertex shader (executed for each vertex in parallel)

input
- vertex position, normal, color, material, texture coordinates
- modelview matrix, projection matrix, normal matrix
- ...

void main ()
{
    // do something here
    ...
}

output
- transformed vertex position (in clip coords), texture coordinates
- ...

https://www.ntu.edu.sg/home/ehchua/programming/opengl CG_BasicsTheory.html
Fragment Shaders

- **Input**
  - vertex position in window coords, texture coordinates
  - ...

- **Fragment Shader** (executed for each fragment in parallel)

- **Output**
  - fragment color
  - fragment depth
  - ...

```cpp
void main ()
{
    // do something here
    ...
}
```

https://www.ntu.edu.sg/home/ehchua/programming/opengl/CG_BasicsTheory.html
Why Do We Need Shaders?

- massively parallel computing
- single instruction multiple data (SIMD) paradigm \(\rightarrow\) GPUs are designed to be parallel processors
- vertex shaders are independently executed for each vertex on GPU (in parallel)
- fragment shaders are independently executed for each fragment on GPU (in parallel)
Why Do We Need Shaders?

• most important: vertex transforms and lighting & shading calculations
• shading: how to compute color of each fragment (e.g. interpolate colors)
  1. Flat shading
  2. Gouraud shading (per-vertex lighting)
  3. Phong shading (per-fragment lighting)
• other: render motion blur, depth of field, physical simulation, …

courtesy: Intergraph Computer Systems
Shading Languages

- Cg (C for Graphics – NVIDIA, deprecated)
- GLSL (GL Shading Language – OpenGL)
- HLSL (High Level Shading Language - MS Direct3D)
// variable passed in from JavaScript / three.js
uniform float deformation;

attribute vec3 position;
attribute vec3 normal;

uniform mat4 projectionMat;
uniform mat4 modelViewMat;

void main () // vertex shader
{
    // deform vertex position in object coordinates
    vec3 pos = position + deformation * normal;

    // convert to clip space
    gl_Position = projectionMat*modelViewMat*vec4(pos,1.0);

    // do lighting calculations here (in view space)
    ... 
}
Demo – Simple Fragment Shader

```glsl
// variables passed in from JavaScript / three.js
varying vec2 textureCoords;

uniform sampler2D texture;
uniform float gamma;

void main () // fragment shader
{

    // texture lookup
    vec3 textureColor = texture2D(texture, textureCoords).rgb;

    // set output color by applying gamma
    gl_FragColor.rgb = pow(textureColor.rgb, gamma);
}
```
Vertex+Fragment Shader – Gouraud Shading Template

// variable to be passed from vertex to fragment shader
varying vec4 myColor;

// variable passed in from JavaScript / three.js
uniform mat4 projectionMat;
uniform mat4 modelViewMat;
uniform mat3 normalMat;

attribute vec3 position;
attribute vec3 normal;

void main () // vertex shader - Gouraud shading
{
    // transform position to clip space
    gl_Position = projectionMat * modelViewMat * vec4(position,1.0);
    
    // transform position to view space
    vec4 positionView = modelViewMat * vec4(position,1.0);
    
    // transform normal into view space
    vec3 normalView = normalMat * normal;
    
    // do lighting calculations here (in view space)
    ...
    myColor = ...
}

// variable to be passed from vertex to fragment shader
varying vec4 myColor;

void main () // fragment shader - Gouraud shading
{
    gl_FragColor = myColor;
}
// variable to be passed from vertex to fragment shader
varying vec4 myPos;
varying vec3 myNormal;

// variable passed in from JavaScript / three.js
uniform mat4 projectionMat;
uniform mat4 modelViewMat;
uniform mat3 normalMat;

attribute vec3 position;
attribute vec3 normal;

void main () // vertex shader – Phong shading
{
  // transform position to clip space
  gl_Position = projectionMat * modelViewMat * vec4(position,1.0);

  // transform position to view space
  myPos = modelViewMat * vec4(position,1.0);

  // transform normal into view space
  myNormal = normalMat * normal;
}

// variable to be passed from vertex to fragment shader
varying vec4 myPos;
varying vec3 myNormal;

void main () // fragment shader – Phong shading
{
  // ... do lighting calculations here ...
  gl_FragColor = ...
}
Demo – General Purpose Computation Shader: Heat Equation

\[
\frac{\partial u}{\partial t} = \alpha \nabla^2 u \quad \Rightarrow \quad u^{(t+1)} = \Delta, \alpha \nabla^2 u + u^{(t)}
\]

```cpp
varying vec2 textureCoords;

// variables passed in from JavaScript / three.js
uniform sampler2D tex;
const float timestep = 1.0;

void main () // fragment shader
{
    // texture lookups
    float u = texture2D(tex, textureCoords).r;
    float u_xp1 = texture2D(tex, float2(textureCoords.x+1,textureCoords.y)).r;
    float u_xm1 = texture2D(tex, float2(textureCoords.x-1,textureCoords.y)).r;
    float u_yp1 = texture2D(tex, float2(textureCoords.x,textureCoords.y+1)).r;
    float u_ym1 = texture2D(tex, float2(textureCoords.x,textureCoords.y-1)).r;
    glFragColor.r = u + timestep*(u_xp1+u_xm1+u_yp1+u_ym1-4*u);
}
```
OpenGL Shading Language (GLSL)

• high-level programming language for shaders

• syntax similar to C (i.e. has **main** function and many other similarities)

• usually very short programs that are executed in parallel on GPU

• good introduction / tutorial:

https://www.opengl.org/sdk/docs/tutorials/TyphoonLabs/
OpenGL Shading Language (GLSL)

• versions of OpenGL, WebGL, GLSL can get confusing

• here’s what we use:
  • WebGL 1.0 - based on OpenGL ES 2.0; cheat sheet:

• GLSL 1.10 - shader preprocessor: #version 110

• reason: three.js doesn’t support WebGL 2.0 yet
GLSL – Vertex Shader Input/Output

- Input variables are either **uniform** (passed in from JavaScript, e.g. matrices) or **attribute** (values associated with each vertex, e.g. position, normal, uv, …)

- **built-in output**
  - `vec4 gl_Position` vertex position in clip coordinates
GLSL – Fragment Shader Input/Output

input variables are either **uniform** (passed in from JavaScript) or **varying** (passed in from vertex shader through rasterizer)

**Built-in output**

`vec4 gl_FragColor`  
fragment color
input variables are either \texttt{uniform} (passed in from JavaScript) or \texttt{varying} (passed in from vertex shader through rasterizer)

\begin{itemize}
\item \texttt{vec4 gl\_FragColor} \textit{fragment color}
\item \texttt{float gl\_FragDepth} \textit{value written to depth buffer, if not specified: gl\_FragCoord.z (only available in OpenGL but not WebGL)}
\end{itemize}
all of these values will be interpolated over the primitive by rasterizer
## GLSL Data Types

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boolean</td>
<td>boolean (true or false)</td>
</tr>
<tr>
<td>Signed Int</td>
<td>signed integer</td>
</tr>
<tr>
<td>Floating</td>
<td>32 bit floating point</td>
</tr>
<tr>
<td>Vectors</td>
<td>integer vector with 2, 3, or 4 elements</td>
</tr>
<tr>
<td>Matrices</td>
<td>floating point matrix with 2x2, 3x3, or 4x4 elements</td>
</tr>
<tr>
<td>Texture</td>
<td>handle to a 2D texture</td>
</tr>
</tbody>
</table>

- **Attribute**: per-vertex attribute, such as position, normal, uv, ...
**GLSL Data Types**

**uniform type** – read-only values passed in from JavaScript, e.g. `uniform float` or `uniform sampler2D`

**vertex shader**

```glsl
uniform mat4 modelViewProjectionMatrix;

varying vec2 textureCoords;

attribute vec3 position;
attribute vec2 uv;

void main ()
{
    gl_Position = modelViewProjectionMatrix * vec4(position, 1.0);
    textureCoords = uv;
}
```

**fragment shader**

```glsl
uniform sampler2D texture;

varying vec2 textureCoords;

void main ()
{
    gl_FragColor = texture2D(texture, textureCoords);
}
```
GLSL Data Types

**varying type** – variables that are passed from vertex to fragment shader (i.e. write-only in vertex shader, read-only in fragment shader)
– rasterizer interpolates these values in between shaders!

**vertex shader**
```glsl
varying float myValue;
uniform mat4 modelViewProjectionMatrix;
attribute vec3 position;
void main ()
{
    gl_Position = modelViewProjectionMatrix * vec4(position, 1.0);
    myValue = 3.14159 / 10.0;
}
```

**fragment shader**
```glsl
varying float myValue;
void main ()
{
    gl_FragColor = vec4(myValue, myValue, myValue, 1.0);
}
```
// variable passed in from JavaScript / three.js
uniform mat4 modelViewProjectionMatrix;

// vertex positions are parsed as attributes
attribute vec3 position;

void main () // vertex shader
{
    // transform position to clip space
    // this is similar to gl_Position = ftransform();
    gl_Position = modelViewProjectionMatrix * vec4(position, 1.0);
}
GLSL – Simplest Fragment Shader

```cpp
void main () // fragment shader
{
    // set same color for each fragment
    gl_FragColor = vec4(1.0,0.0,0.0,1.0);
}
```
GLSL – built-in functions

dot     dot product between two vectors
cross   cross product between two vectors
texture2D texture lookup (get color value of texture at some tex coords)
normalize normalize a vector
clamp   clamp a scalar to some range (e.g., 0 to 1)

radians, degrees, sin, cos, tan, asin, acos, atan, pow, exp, log, exp2,
log2, sqrt, abs, sign, floor, ceil, mod, min, max, length, ...

good summary of OpenGL ES (WebGL) shader functions:

Gouraud Shading with GLSL (only diffuse part) – Vertex Shader

uniform vec3 lightPositionView;
uniform vec3 lightColor;
uniform vec3 diffuseMaterial;

uniform mat4 projectionMat;
uniform mat4 modelViewMat;
uniform mat3 normalMat;

attribute vec3 position;
attribute vec3 normal;

varying vec3 vColor;

user-defined light & material properties
user-defined transformation matrices
per-vertex attributes
color computed by Phong lighting model to be interpolated by rasterizer
Gouraud Shading with GLSL (only diffuse part) – Vertex Shader

```glsl
uniform vec3 lightPositionView;
uniform vec3 lightColor;
uniform vec3 diffuseMaterial;
uniform mat4 projectionMat;
uniform mat4 modelViewMat;
uniform mat3 normalMat;
attribute vec3 position;
attribute vec3 normal;
varying vec3 vColor;

void main () // vertex shader
{
    // transform position to clip space
    gl_Position = projectionMat * modelViewMat * vec4(position,1.0);

    // transform vertex position, normal, and light position to view space
    vec3 P = ...
    vec3 L = ...
    vec3 N = ...

    // compute the diffuse term here
    float diffuseFactor = ...

    // set output color
    vColor = diffuseFactor * diffuseMaterial * lightColor;
}
```

- user-defined light & material properties
- user-defined transformation matrices
- per-vertex attributes
- color computed by Phong lighting model to be interpolated by rasterizer
varying vec3 vColor;

void main () // fragment shader
{
    // set output color
    gl_FragColor = vec4(vColor,1.0);
}
Phong Shading with GLSL (only diffuse part) – Vertex Shader

uniform mat4 modelViewMat;
uniform mat4 projectionMat;
uniform mat3 normalMat;

attribute vec3 position;
attribute vec3 normal;

varying vec3 vPosition;
varying vec3 vNormal;

user-defined transformation matrices

per-vertex attributes

vertex position & normal to be interpolated by rasterizer
Phong Shading with GLSL (only diffuse part) – Vertex Shader

```glsl
uniform mat4 modelViewMat;
uniform mat4 projectionMat;
uniform mat3 normalMat;

attribute vec3 position;
attribute vec3 normal;

varying vec3 vPosition;
varying vec3 vNormal;

void main () // vertex shader
{
    // transform position to clip space
    gl_Position = projectionMat * modelViewMat * vec4(position,1.0);

    // transform vertex position, normal, and light position to view space
    vec3 P = ...;
    vec3 N = ...

    // set output texture coordinate to vertex position in world coords
    vPosition = P;

    // set output color to vertex normal direction
    vNormal = N;
}
```
Phong Shading with GLSL (only diffuse part) – Fragment Shader

```glsl
uniform vec3 lightColor;
uniform vec3 diffuseMaterial;
uniform vec3 lightPositionWorld;

varying vec3 vPosition;
varying vec3 vNormal;

void main()
{
    // incoming color is interpolated by rasterizer over primitives!
    vec3 N = vNormal;
    // vector pointing to light source
    vec3 L = ...
    // compute the diffuse term
    float diffuseFactor = ...
    // set output color
    gl_FragColor.rgb = diffuseFactor * diffuseMaterial * lightColor;
}
```

user-defined light & material properties

vertex & normal positions interpolated to each fragment by rasterizer
Phong Shading with GLSL (only diffuse part) – Fragment Shader

```glsl
uniform vec3 lightColor;
uniform vec3 diffuseMaterial;
uniform vec3 lightPositionWorld;

varying vec3 vPosition;
varying vec3 vNormal;

void main () // fragment shader
{
    // incoming color is interpolated by rasterizer over primitives!
    vec3 N = vNormal;

    // vector pointing to light source
    vec3 L = ...

    // compute the diffuse term
    float diffuseFactor ...

    // set output color
    gl_FragColor.rgb = diffuseFactor * diffuseMaterial * lightColor;
}
```

---

**User-defined light & material properties**

**Vertex & normal positions interpolated to each fragment by rasterizer**
GLSL - Misc

- swizzling:
  ```
  vec4 myVector1;
  vec4 myVector2;
  vec3 myVector1.xxy + myVector2.zxy;
  ```

- matrices are column-major ordering

- initialize vectors in any of the following ways:
  ```
  vec4 myVector = vec4(1.0, 2.0, 3.0, 4.0);
  vec4 myVector2 = vec4(vec2(1.0, 2.0), 3.0, 4.0);
  vec4 myVector3 = vec4(vec3(1.0, 2.0, 3.0), 4.0);
  ```

- these are equivalent:
  ```
  myVector.xyzw = myVector.rgb
  ```

- we omitted a lot of details...
JavaScript & GLSL

goals:
• loading, compiling, and linking GLSL shaders (from a file) using JavaScript
• activating and deactivate GLSL shaders in JavaScript
• accessing uniforms from JavaScript

our approach (for labs and homeworks):
• use three.js to handle all of the above
• can do manually, but more work – we will shield this from you
Summary

• GLSL is your language for writing vertex and fragment shaders

• each shader is independently executed for each vertex/fragment on the GPU

• usually require both vertex and fragment shader, but can “pass-through” data
Further Reading

• GLSL tutorial: https://www.opengl.org/sdk/docs/tutorials/TyphoonLabs/

• summary of built-in GLSL functions: http://www.shaderific.com/glsl-functions/