Introduction

- The major advance in real time graphics has been the programmable pipeline:
  - First introduced by NVIDIA GeForce 3 (in 2001)
  - Supported by all modern high-end commodity cards
    - NVIDIA, AMD, Intel
  - Software Support
    - Direct3D
    - OpenGL

- This lecture: programmable pipeline and shaders

OpenGL Extensions

- Initial OpenGL version was 1.0
- Current OpenGL version is 4.6

- As graphics hardware improved, new capabilities were added to OpenGL
  - multitexturing
  - multisampling
  - non-power-of-two textures
  - shaders
  - and many more

OpenGL Grows via Extensions

- Phase 1: vendor-specific: GL_NV_multisample
- Phase 2: multi-vendor: GL_EXT_multisample
- Phase 3: approved by OpenGL’s review board GL_ARB_multisample
- Phase 4: incorporated into OpenGL (v1.3)

OpenGL 2.0 Added Shaders

- Shaders are customized programs that replace a part of the OpenGL pipeline
- They enable many effects not possible by the fixed OpenGL pipeline
- Motivated by Pixar’s Renderman (offline shader)

Shaders Enable Many New Effects

- Complex materials
- Shadows
- Lighting environments
- Advanced mapping
Vertex Shader

5x5 terrain (as in hw1)
5x5 = 25 vertices
4x4 = 16 quads

User must tessellate into triangles (in the VBO)
4 x 4 x 2 = 32 triangles
32 x 3 = 96 vertices (assuming GL_TRIANGLES)

96 vertex shaders execute in parallel

Fragment Shader

Rasterization
rasterizes into 13 pixels

m fragment shaders execute in parallel

Triangles (now in 2D) cover m pixels
Some pixels may repeat in multiple triangles

The Rendering Pipeline

CPU
vertices
(gDrawArrays)

Position vertices (and project to 2D)

Subdivide geometry

Gpu thread grid

Tessellation Shader

Triangles

CPU
vertices

Tessellation Shader

Clipping

DisCARD off-screen triangles
triangles

Geometry Shader

Process geometry

Convert triangles into pixels

Rasterizer

fragments

Fragment Shader

triangles

Color each fragment

Frame Buffer

Shaders

• Vertex shader (= vertex program)

• Tessellation control and evaluation shader
  (OpenGL 4.0; subdivide the geometry)

• Geometry shader
  (OpenGL 3.2; process, generate, replace or delete geometry)

• Fragment shader (= fragment program)

• Compute shader (OpenGL 4.3; general purpose)

Shaders

• Compatibility profile: Default shaders are provided by OpenGL (fixed-function pipeline)

• Core profile: no default vertex or fragment shader; must be provided by the programmer

• Tessellation shaders, geometry shaders and compute shaders are optional
### Shader Variables Classification

- **Attribute**
  - Information specific to each vertex/pixel passed to vertex/fragment shader
  - Example: Vertex Color

- **Uniform**
  - Constant information passed to vertex/fragment shader
  - Cannot be written to in a shader
  - Example: Light Position, Eye Position

- **Out/in**
  - Info passed from vertex shader to fragment shader
  - Interpolated from vertices to pixels
  - Write in vertex shader, but only read in fragment shader
  - Example: Vertex Color, Texture Coords

- **Const**
  - To declare non-writable, constant variables
  - Example: pi, e, 0.480

### Shaders Are Written in Shading Languages

- **Early shaders:** assembly language
- **Since ~2004:** high-level shading languages
  - OpenGL Shading Language (GLSL)
    - Highly integrated with OpenGL
  - Cg (NVIDIA and Microsoft), very similar to GLSL
  - HLSL (Microsoft), the shading language of Direct3D
  - All of these are simplified versions of C/C++

### GLSL

- The shading language of OpenGL
- Managed by OpenGL Architecture Review Board
- Introduced in OpenGL 2.0
- We use shader version 1.50:
  - #version 150
  - (a good version supporting the core profile features)
- Current shader version: 4.60

### Vertex Shader

- Input: vertices, in object coordinates, and per-vertex attributes:
  - color
  - normal
  - texture coordinates
  - many more
- Output:
  - vertex location in clip coordinates
  - vertex color
  - vertex normal
  - many more are possible

#### Basic Vertex Shader in GLSL

```glsl
#version 150
in vec3 position; // input position, in object coordinates
in vec4 color; // input color
out vec4 col; // output color
uniform mat4 modelViewMatrix; // uniform variable to store the modelview mtx
uniform mat4 projectionMatrix; // uniform variable to store the projection mtx

void main()
{
    // compute the transformed and projected vertex position (into gl_Position)
    gl_Position = projectionMatrix * modelViewMatrix * vec4(position, 1.0f);
    // compute the vertex color (into col)
    col = color;
}
```

### Fragment Shader

- Input: fragments (tentative pixels), and per-pixel attributes:
  - color
  - normal
  - texture coordinates
  - many more are possible
- Inputs are outputs from the vertex shader, interpolated (by the GPU) to the pixel location!
- Output:
  - pixel color
  - depth value
  - can discard the fragment using the `discard` keyword
### Basic Fragment Shader

```glsl
#version 150

in vec4 col; // input color (computed by the interpolator)
out vec4 c; // output color (the final fragment color)

void main()
{
    // compute the final fragment color
    c = col;
}
```

### Another Fragment Shader

```glsl
#version 150

in vec4 col; // input color (computed by the interpolator)
out vec4 c; // output color (the final fragment color)

void main()
{
    // compute the final fragment color
    c = vec4(1.0, 0.0, 0.0, 1.0);
}
```

### Pipeline program

- Container for all the shaders
- Vertex, fragment, geometry, tessellate, compute
- Can have several pipeline programs (for example, one for each rendering style)
- Must have at least one (core profile)
- At any moment of time, exactly one pipeline program is bound (active)

### Installing Pipeline Programs

- **Step 1: Create Shaders**
  - Create handles to shaders
- **Step 2: Specify Shaders**
  - Load strings that contain shader source
- **Step 3: Compiling Shaders**
  - Actually compile source (check for errors)
- **Step 4: Creating Program Objects**
  - Program object controls the shaders
- **Step 5: Attach Shaders to Programs**
  - Attach shaders to program objects via handle
- **Step 6: Link Shaders to Programs**
  - Another step similar to attach
- **Step 7: Enable Shaders**
  - Finally, let OpenGL and GPU know that shaders are ready

### Our helper library: PipelineProgram

```c
// load shaders from a file
int BuildShadersFromFile(const char * filenameBasePath,
                          const char * vertexShaderFilename,
                          const char * fragmentShaderFilename,
                          const char * geometryShaderFilename = NULL,
                          const char * tessellationControlShaderFilename = NULL,
                          const char * tessellationEvaluationShaderFilename = NULL);
```

```c
// load shaders from a C text string
int BuildShadersFromStrings(const char * vertexShaderCode,
                            const char * fragmentShaderCode,
                            const char * geometryShaderCode = NULL,
                            const char * tessellationControlShaderCode = NULL,
                            const char * tessellationEvaluationShaderCode = NULL);
```
Setting up the Pipeline Program

// global variable
BasicPipelineProgram pipelineProgram;

// during initialization:
pipelineProgram.Init("../openGLHelper-starterCode");

// before rendering, bind (activate) the pipeline program:
pipelineProgram.Bind();

If you want to change the pipeline program,
call “Bind” on the new pipeline program

Setting up the Uniform Variables

Uploading the modelview matrix transformation to the GPU
(in the display function)

// get a handle to the program
GLuint program = pipelineProgram.GetProgramHandle();
// get a handle to the modelViewMatrix shader variable
GLint h_modelViewMatrix =
glGetUniformLocation(program, "modelViewMatrix");

float m[16]; // column-major
// here, must fill m (missing code; use OpenGLMatrix class)
// upload m to the GPU
pipelineProgram.Bind(); // must do (once) before glUniformMatrix4fv
GLboolean isRowMajor = GL_FALSE;
glUniformMatrix4fv(h_modelViewMatrix, 1, isRowMajor, m);

Setting up the Uniform Variables
Repeat the same process also for the projection matrix:

// get a handle to the program
GLuint program = pipelineProgram.GetProgramHandle();
// get a handle to the projectionMatrix shader variable
GLint h_projectionMatrix =
glGetUniformLocation(program, "projectionMatrix");

float p[16]; // column-major
// here, must fill p… (use our OpenGLMatrix class)
// (missing code to fill p)
// upload p to the GPU
GLboolean isRowMajor = GL_FALSE;
glUniformMatrix4fv(h_projectionMatrix, 1, isRowMajor, p);

Vertex Array Objects (VAOs)

• A container to collect the VBOs of each object

• Usage is mandatory (by the OpenGL standard)

• During initialization: create VBOs (one or more per object), create VAOS (one per object), and place the VBOs into the proper VAOS

• At render time: bind the VAO, then call glDrawArrays(), then unbind

Step 1: Create the VAO

GLuint vao;
glGenVertexArrays(1, &vao);
glBindVertexArray(vao); // bind the VAO

Currently empty
currently unorganized bytes
currently unconnected to data

VAO

VBO 1
gg5'53vaфф&$#422424d^3d…
in vec3 position

VBO 2
x*reqr$$df022cCd%w…
in vec3 color

VBO 3
in vec3 position

VBO 4
in vec3 color

...
**Step 2: Connect VBO to VAO and the shader variable; and interpret VBO**

```
VAO 1
[gg5]53|vs|ff|&|42|42|d1|3d|...

- VBO 1
- glUseProgram(program);
- glVertexAttribPointer(loc, 3, GL_FLOAT, GL_FALSE, stride, offset);
```

**VAO code ("position" shader variable)**

During initialization:
```
GLuint vao;
glGenVertexArrays(1, &vao);
glBindVertexArray(vao); // bind the VAO

// bind the VBO "buffer" (must be previously created)
glBindBuffer(GL_ARRAY_BUFFER, vbo);
// get location index of the "position" shader variable
GLuint loc = glGetUniformLocation(program, "position");
glEnableVertexAttribArray(loc);
// enable the "position" attribute
const void * offset = (const void*)0;
GLsizei stride = 0;
GLboolean normalized = GL_FALSE;
// set the layout of the "position" attribute data
glVertexAttribPointer(loc, 3, GL_FLOAT, normalized, stride, offset);
```

**VAO code ("color" shader variable)**

```
// get the location index of the "color" shader variable
loc = glGetUniformLocation(program, "color");
glEnableVertexAttribArray(loc);
// enable the "color" attribute
offset = (const void*)sizeof(positions);
GLsizei stride = 0;
GLboolean normalized = GL_FALSE;
// set the layout of the "color" attribute data
glVertexAttribPointer(loc, 4, GL_FLOAT, normalized, stride, offset);
```

**Use the VAO**

In the display function:
```
pipelineProgram.Bind(); // bind the pipeline program
glBindVertexArray(vao); // bind the VAO
GLInt first = 0;
GLsizei count = numVertices;
glDrawArrays(GL_TRIANGLES, first, count);
glBindVertexArray(0); // unbind the VAO
```

**GLSL: Data Types**

- **Scalar Types**
  - float - 32 bit, very nearly IEEE-754 compatible
  - int - at least 16 bit
  - bool - like in C++

- **Vector Types**
  - vec[2 | 3 | 4] - floating-point vector
  - ivec[2 | 3 | 4] - integer vector
  - bvec[2 | 3 | 4] - boolean vector

- **Matrix Types**
  - mat[2 | 3 | 4] - for 2x2, 3x3, and 4x4 floating-point matrices

- **Sampler Types**
  - sampler[1 | 2 | 3D] - to access texture images

**GLSL: Operations**

- **Operators behave like in C++**
- **Component-wise for vector & matrix**
- **Multiplication on vectors and matrices**

- **Examples:**
  - Vec3 t = u * v;
  - float f = v[2];
  - v.x = u.x + f;
**GLSL: Swizzling**

- Swizzling is a convenient way to access individual vector components
  - `vec4 myVector;
    myVector.rgba; // is the same as myVector
  
  myVector.xy; // is a vec2
  myVector.b; // is a float
  myVector[2]; // is the same as myVector.b
  myVector.xb; // illegal
  myVector.xxx; // is a vec3

**GLSL: Flow Control**

- Loops
  - C++ style `if-else`
  - C++ style for, while, and do
- Functions
  - Much like C++
  - Entry point into a shader is `void main()`
  - No support for recursion
  - Call by value-return calling convention
- Parameter Qualifiers
  - `in` - copy in, but don’t copy out
  - `out` - only copy out
  - `inout` - copy in and copy out

  Example function:
  ```
  void ComputeTangent(in vec3 N, out vec3 T, inout vec3 coord) {
    if((dot(N, coord)>0))
      T = vec3(1,0,0);
    else
      T = vec3(0,0,0);
    coord = 2 * T;
  }
  ```

**GLSL: Built-in Functions**

- Wide Assortment
  - Trigonometry (`cos, sin, tan, etc.`)
  - Exponential (`pow, log, sqrt, etc.`)
  - Common (`abs, floor, min, clamp, etc.`)
  - Geometry (`length, dot, normalize, reflect, etc.`)
  - Relational (`lessThan, equal, etc.`)

  Need to watch out for common reserved keywords

  Always use built-in functions, do not implement your own

  Some functions are not implemented on some cards

**GLSL: Built-in Variables**

- Always prefixed with `gl_`

- Accessible to both vertex and fragment shaders

  Examples:
  - (input) `gl_VertexID`: index of currently processed vertex
  - (input) `gl_FrontFacing`: whether pixel is front facing or not
  - (input) `gl_FragCoord`: x,y: coordinate of pixel, z: depth
  - (output) `gl_FragDepth`: pixel depth

**GLSL: Accessing OpenGL State (Compatibility Profile Only)**

- Vertex shader: Have access to several vertex attributes:
  - `gl_Color, gl_Normal, gl_Vertex, etc.`

- Fragment shader: Write to special output variable: `gl_FragColor`

**GLSL: Accessing OpenGL State (Compatibility Profile Only)**

- Uniform Variables
  - Matrices (`ModelViewMatrix, ProjectionMatrix`, inverses, transposes)
  - Materials (`MaterialParameters`, ambient, diffuse, etc.)
  - Lights (`LightSourceParameters`, specular, position, etc.)

- Varying Variables
  - `FrontColor for colors`
  - `TexCoord[] for texture coordinates`

These do not work in the core profile!

**Debugging Shaders**

- More difficult than debugging C programs

- Common show-stoppers:
  - Typos in shader source
  - Assuming implicit type conversion (cannot convert `vec4` to `vec3`)
  - Attempting to connect VAOs to non-existent (say, due to a typo) shader variables

- Very important to check error codes; use status functions like:
  - `glGetShaderiv(GLuint shader, GLenum pname, GLint *params)`
Summary

- Shading Languages
- Program Pipeline
- Vertex Array Objects
- GLSL
- Vertex Shader
- Fragment Shader