CSCI 420 Computer Graphics
Lecture 7

Shaders

Shading Languages
GLSL
Vertex Array Objects
Vertex Shader
Fragment Shader
[Angel Ch. 1, 2, A]

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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

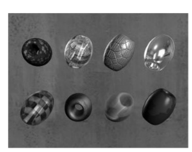
OpenGL Grows via Extensions

- 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)

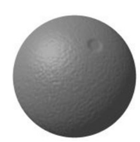
Shaders Enable Many New Effects



Complex materials

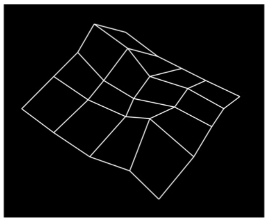
Shadows

Lighting environments



Advanced mapping

Vertex Shader



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

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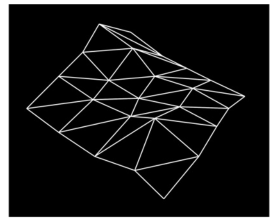
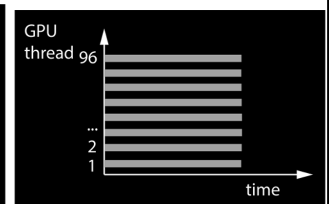
Vertex Shader





96 vertex shaders execute in parallel

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

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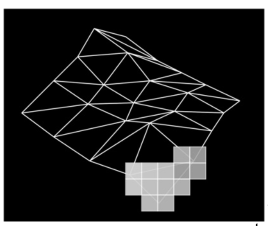
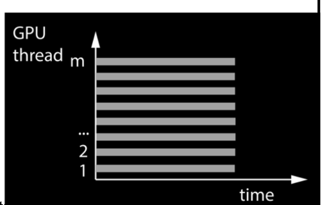
Fragment Shader





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

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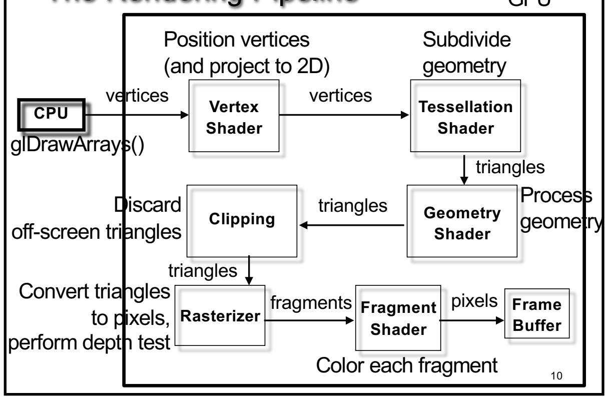
The Rendering Pipeline



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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)

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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*

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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

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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++

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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

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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

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Basic Vertex Shader in 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;
}
```

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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

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Basic Fragment Shader

```
#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;
}
```

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Another Fragment Shader

```
#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);
}
```

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Pipeline program

- Container for all the shaders
- Vertex, fragment, geometry, tessellation, 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)

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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

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Our helper library: PipelineProgram

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

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Our helper library: PipelineProgram

```
// 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);
```

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Setting up the Pipeline Program

// global variable
PipelineProgram pipelineProgram;

// during initialization:
pipelineProgram.BuildShadersFromFiles("../openGLHelper",
"vertexShader.glsl", "fragmentShader.glsl");

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

If you want to use a different pipeline program, then "Bind" that other pipeline program.

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Setting up the Uniform Variables

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

```
float m[16]; // column-major
// here, must fill m (missing code; use OpenGLMatrix class)
// …

// upload m to the GPU
pipelineProgram.Bind();
GLboolean isRowMajor = GL_FALSE;
pipelineProgram->SetUniformVariableMatrix4fv(
  "modelViewMatrix", isRowMajor, m);
```

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Setting up the Uniform Variables

Repeat the same process also for the projection matrix:

```
float p[16]; // column-major
// here, must fill p (missing code; use OpenGLMatrix class)
// …

// upload p to the GPU
pipelineProgram.Bind();
GLboolean isRowMajor = GL_FALSE;
pipelineProgram->SetUniformVariableMatrix4fv(
  "projectionMatrix", isRowMajor, p);
```

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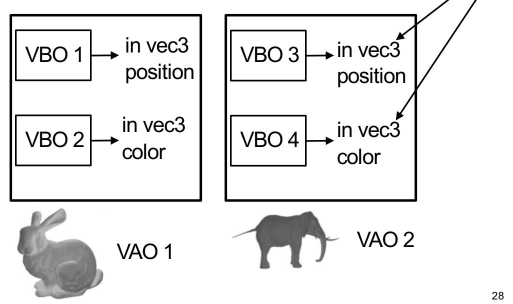
Vertex Array Objects (VAOs)

- A container to collect the VBOs of each object and connect each shader variable with a VBO



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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),
  - place the VBOs into the VAO, and connect VBOs to shader variables
- At render time: bind the VAO, then call glDrawArrays()

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VAO code (initialization)

During initialization:

```
// Create a VAO.
VAO * vao = new VAO();
// Connect the shader variables to their respective VBOs.
vao->ConnectPipelineProgramAndVBOAndShaderVariable(
  pipelineProgram, vboPositions, "position");
vao->ConnectPipelineProgramAndVBOAndShaderVariable(
  pipelineProgram, vboColors, "color");
```

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Using the VAO for rendering

In the display function:

```
// Bind the vertex and fragment shaders to use.
pipelineProgram->Bind();
// Select which object to render.
vao->Bind();

// Render the object contained in the VAO.
GLint first = 0;
GLsizei count = numVertices;
glDrawArrays(GL_TRIANGLES, first, count);
```

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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 | 3]D - to access texture images

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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;

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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
```

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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;
}
```

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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

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GLSL: Built-in Variables

- Always prefaced 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

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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)

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Summary

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

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