

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

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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

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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)

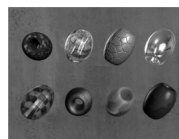
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OpenGL 2.0 Added Shaders

- 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)

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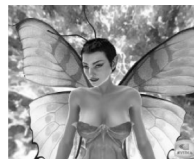
Shaders Enable Many New Effects



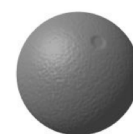
Complex materials



Shadows



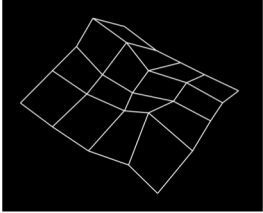
Lighting environments



Advanced mapping

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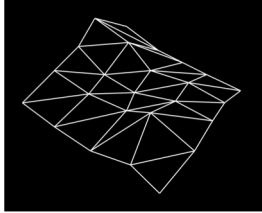
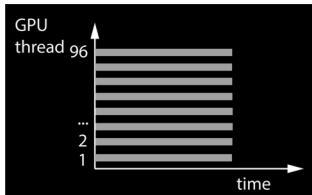
Vertex Shader



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

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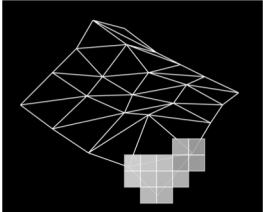
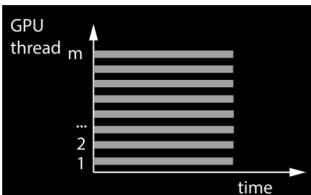
Vertex Shader

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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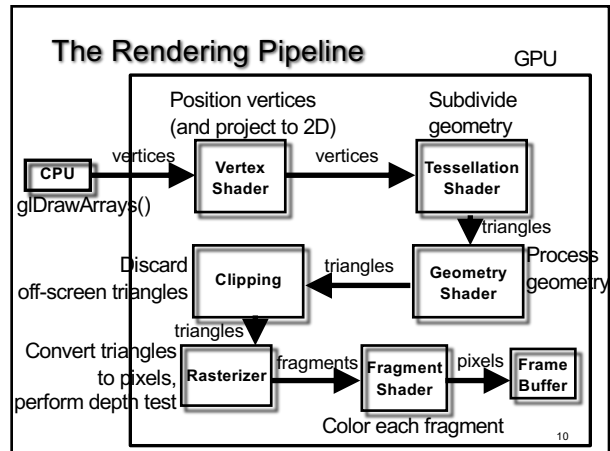
Fragment Shader

Rasterization
 rasterizes into 13 pixels

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

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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 shaderExample: Vertex Color
- Uniform
 - Constant information passed to vertex/fragment shader
 - Cannot be written to in a shaderExample: 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 shaderExample: Vertex Color
Texture Coords
- Const
 - To declare non-writable, constant variablesExample: 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** keyword¹⁸

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
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

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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);
```

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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");

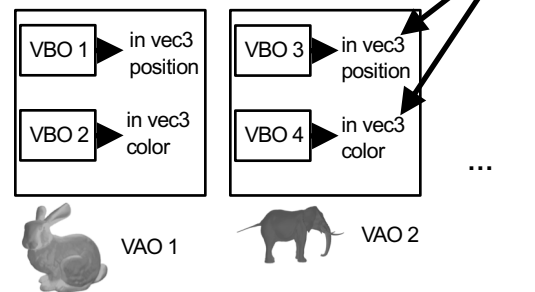
float p[16]; // column-major
// here, must fill p... (use our OpenGLMatrix class)
// (missing code to fill p)

// upload p to the GPU
GLboolean isRowMajor = GL_FALSE;
glUniformMatrix4fv(h_projectionMatrix, 1, isRowMajor, p);
```

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Vertex Array Objects (VAOs)

- A container to collect the VBOs of each object



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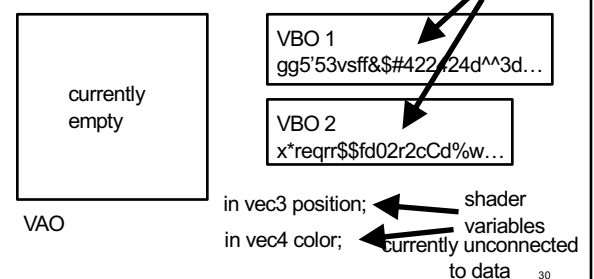
Vertex Array Objects (VAOs)

- 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), and place the VBOs into the proper VAOs
- At render time: bind the VAO, then call `glDrawArrays()`, then unbind

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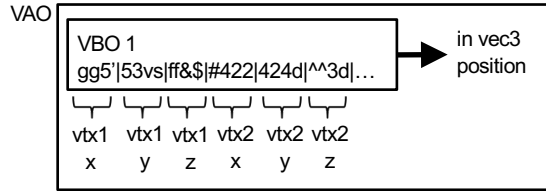
Step 1: Create the VAO

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



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



```
GLuint loc = glGetAttribLocation(program, "position");
glVertexAttribPointer(loc, 3, GL_FLOAT,
    GL_FALSE, stride, offset);
```

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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 = glGetAttribLocation(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);
```

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VAO code ("color" shader variable)

```
// get the location index of the "color" shader variable
loc = glGetAttribLocation(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);

glBindVertexArray(0); // unbind the VAO
```

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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
```

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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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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
- Uniform Variables
 - Matrices (ModelViewMatrix, ProjectionMatrix, inverses, transposes)
 - Materials (in MaterialParameters struct, ambient, diffuse, etc.)
 - Lights (in LightSourceParameters struct, specular, position, etc.)
- Varying Variables
 - FrontColor for colors
 - TexCoord[] for texture coordinates

These do not work
in the core profile!

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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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