Programming with WebGL
Part 1: Background

CS 432 Interactive Computer Graphics
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Objectives

• Development of the OpenGL API
• OpenGL Architecture
  - OpenGL as a state machine
  - WebGL as a data flow machine
• Functions
  - Types
  - Formats
• Simple program
Retained vs. Immediate Mode Graphics

- **Immediate**
  - Geometry is drawn when CPU sends it to GPU
  - All data needs to be resent even if little changes
  - Once drawn, geometry on GPU is discarded
  - Requires major bandwidth between CPU and GPU
  - Minimizes memory requirements on GPU

- **Retained**
  - Geometry is sent to GPU and stored
  - It is displayed when directed by CPU
  - CPU may send transformations to move geometry
  - Minimizes data transfers, but GPU now needs enough memory to store geometry
Early History of APIs

• IFIPS (1973) formed two committees to come up with a standard graphics API
  - Graphical Kernel System (GKS)
    • 2D but contained good workstation model
  - Core
    • Both 2D and 3D
  - GKS adopted as ISO and later ANSI standard (1980s)

• GKS not easily extended to 3D (GKS-3D)
  - Far behind hardware development
PHIGS and X

- Programmers Hierarchical Graphics System (PHIGS)
  - Arose from CAD community
  - Database model with retained graphics (structures)
- X Window System
  - DEC/MIT effort
  - Client-server architecture with graphics
- PEX combined the two
  - Not easy to use (all the defects of each)
SGI and GL

• Silicon Graphics (SGI) revolutionized the graphics workstation by implementing the graphics pipeline in hardware (1982)

• To access the system, application programmers used a library called GL

• With GL, it was relatively simple to program three dimensional interactive applications
The success of GL lead to OpenGL (1992), a platform-independent API that was

- Easy to use
- Close enough to the hardware to get excellent performance
- Focused on rendering
- Omitted windowing and input to avoid window system dependencies
- An immediate mode system, that later added retained mode functionality
OpenGL Evolution

• Originally controlled by an Architectural Review Board (ARB)
  - Members included SGI, Microsoft, Nvidia, HP, 3DLabs, IBM,…….
  - Now Khronos Group
  - Was relatively stable (through version 2.5)
    • Backward compatible
    • Evolution reflected new hardware capabilities
      – 3D texture mapping and texture objects
      – Vertex and fragment programs
  - Allows platform specific features through extensions
Modern OpenGL

- Performance is achieved by using GPU rather than CPU
- Control GPU through programs called shaders
- Application’s job is to send data to GPU
- GPU does all rendering
OpenGL 3.1 (2009)

• Totally shader-based
  - No default shaders
  - Each application must provide both a vertex and a fragment shader

• No immediate mode

• Few state variables

• Most 2.5 functions deprecated
  - *deprecate* in CS - To mark (a component of a software standard) as obsolete to warn against its use in the future, so that it may be phased out.

• Backward compatibility not required
Other Versions

• OpenGL ES
  - Embedded systems
  - Version 1.0 simplified OpenGL 2.1
  - Version 2.0 simplified OpenGL 3.1
    • Shader based
  - Version 3.0 simplified OpenGL 4.3

• WebGL 1.0
  - Javascript implementation of ES 2.0
  - Supported on newer browsers

• OpenGL 4.1 ➔ 4.5
  - Added geometry & compute shaders and tessellator
What About Other Low-Level Graphics Libraries?

- **Direct3D**
  - Part of DirectX, Windows-only
- **Mantle**
  - Developed by AMD
- **Metal**
  - Developed by Apple
- **Vulkan**
  - “next-gen” OpenGL
  - Derived from Mantle
OpenGL Architecture

Application program → Graphics library (API) → Drivers

Keyboard → Mouse → Display
A Simple Program (?)

Generate a square on a solid background
It used to be easy

#include <GL/glut.h>
void mydisplay(){
    glClear(GL_COLOR_BUFFER_BIT);
    glBegin(GL_QUAD);
    glVertex2f(-0.5, -0.5);
    glVertex2f(-0.5, 0.5);
    glVertex2f(0.5, 0.5);
    glVertex2f(0.5, -0.5);
    glEnd();
}
int main(int argc, char** argv){
    glutCreateWindow("simple");
    glutDisplayFunc(mydisplay);
    glutMainLoop();
}
What happened

• Most OpenGL functions deprecated
• Made heavy use of state variable default values that no longer exist
  - Viewing
  - Colors
  - Window parameters
• Current version makes the defaults more explicit
• However, processing loop is the same
Execution in Browser

[Diagram showing the flow of data from Browser to Web Server, through JS Engine, CPU/GPU, and Framebuffer to Canvas]
Event Loop

• Remember that the sample program specifies a render function which is an event listener or callback function
  - Every program should have a render callback
  - For a static application we need only execute the render function once
  - In a dynamic application, the render function can call itself recursively but each redrawing of the display must be triggered by an event
Lack of Object Orientation

• All versions of OpenGL are not object oriented so that there are multiple functions for a given logical function

• Example: sending values to shaders
  - `glUniform3f`
  - `glUniform2i`
  - `glUniform3dv`

• Underlying storage mode is the same
WebGL function format

```
gl.uniform3f(x, y, z)
```

function name

dimension

belongs to WebGL canvas

\(x, y, z\) are float variables

```
gl.uniform3fv(p)
```

\(p\) is an array
WebGL constants

• Most constants are defined in the canvas object
  - In desktop OpenGL, they were in #include files such as gl.h

• Examples
  – desktop OpenGL
    • glEnable(GL_DEPTH_TEST);
  – WebGL
    • gl.enable(gl.DEPTH_TEST)
    – gl.clear(gl.COLOR_BUFFER_BIT)
WebGL and GLSL

• WebGL requires shaders and is based less on a state machine model than a data flow model
• Most state variables, attributes and related pre-3.1 OpenGL functions have been deprecated
• Action happens in shaders
• Job of application is to get data to GPU
GLSL

• OpenGL Shading Language
• C-like with
  - Matrix and vector types (2, 3, 4 dimensional)
  - Overloaded operators
  - C++ like constructors
• Similar to Nvidia’s Cg and Microsoft HLSL
• Code sent to shaders as source code
• WebGL functions compile, link and get information to shaders
Programming with OpenGL
Part 2: Complete Programs
Objectives

• Build a complete first program
  - Introduce shaders
  - Introduce a standard program structure

• Simple viewing
  - Two-dimensional viewing as a special case of three-dimensional viewing

• Initialization steps and program structure
Coding in WebGL

• Example: Draw a square
  - Each application consists of (at least) two files
  - HTML file and a JavaScript file

• HTML
  - describes page
  - includes utilities
  - includes shaders

• JavaScript
  - contains the graphics code
Coding in WebGL

• Can run WebGL on any recent browser
  - Chrome
  - Firefox
  - Safari
  - Edge

• Code written in JavaScript

• JS runs within browser
  - Use local resources
Square Program
WebGL

• Five steps
  - Describe page (HTML file)
    • request WebGL Canvas
    • read in necessary files
  - Define shaders (HTML file)
    • could be done with a separate file (browser dependent)
  - Compute or specify data (JS file)
  - Send data to GPU (JS file)
  - Render data (JS file)
square.html

<!DOCTYPE html>
<html>
<script id="vertex-shader" type="x-shader/x-vertex">
#version 300 es
in vec2 aPosition;

void main()
{
    gl_Position = vec4(aPosition, 0.0, 1.0);
}
</script>

<script id="fragment-shader" type="x-shader/x-fragment">
#version 300 es
precision mediump float;

out vec4 fColor;

void main()
{
    fColor = vec4( 1.0, 1.0, 1.0, 1.0 );
}
</script>

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attribute vec4 vPosition;
void main()
{
    gl_Position = vPosition;
}
</script>

<script id="fragment-shader" type="x-shader/x-fragment">
precision mediump float;

void main()
{
    gl_FragColor = vec4( 1.0, 1.0, 1.0, 1.0 );
}
</script>
Shaders

• We assign names to the shaders that we can use in the JS file

• These are trivial pass-through (do nothing) shaders which set the
  - one required built-in variable (gl_Position) in the vertex shader
  - assign an output color for the fragment

• Note both shaders are full programs

• Note vector types vec2 and vec4

• Must set precision in fragment shader

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<script type="text/javascript" src="../Common/initShaders.js"></script>
<script type="text/javascript" src="../Common/MV.js"></script>
<script type="text/javascript" src="square.js"></script>
</head>

<body>
<canvas id="gl-canvas" width="512" height="512">
Oops ... your browser doesn't support the HTML5 canvas element
</canvas>
</body>
</html>
Files

- ../Common/initShaders.js: contains JS and WebGL code for reading, compiling and linking the shaders
- ../Common/MV.js: our matrix-vector package
- square.js: the application file
var canvas;
var gl;

window.onload = function init(){
  canvas = document.getElementById( "gl-canvas" );

  gl = canvas.getContext('webgl2');
  if ( !gl ) { alert( "WebGL 2.0 isn't available" ); } 

  // Four Vertices

  var vertices = [
    vec2( -0.5, -0.5 ),
    vec2( -0.5, 0.5 ),
    vec2( 0.5, 0.5 ),
    vec2( 0.5, -0.5 )
  ];
}
Notes

- **onload**: determines where to start execution when all code is loaded
- canvas gets WebGL context from HTML file
- vertices use vec2 type in MV.js
- JS array is not the same as a C or Java array
  - object with methods
  - vertices.length // 4
- Values in clip coordinates

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// Configure WebGL

gl.viewport( 0, 0, canvas.width, canvas.height );
gl.clearColor( 0.0, 0.0, 0.0, 1.0 );

// Load shaders and initialize attribute buffers

var program = initShaders( gl, "vertex-shader", "fragment-shader" );
gl.useProgram( program );

// Load the data into the GPU

var bufferId = gl.createBuffer();
gl.bindBuffer( gl.ARRAY_BUFFER, bufferId );
gl.bufferData( gl.ARRAY_BUFFER, flatten(vertices), gl.STATIC_DRAW );

// Associate our shader variables with our data buffer

var aPosition = gl.getAttribLocation( program, "aPosition" );
gl.vertexAttribPointer( aPosition, 2, gl.FLOAT, false, 0, 0 );
gl.enableVertexAttribArray( aPosition );
Notes

• `initShaders` used to load, compile and link shaders to form a program object

• Load data onto GPU by creating a `vertex buffer object` on the GPU
  - Note use of `flatten()` to convert JS array to an array of float32’s

• Finally we must connect variable in program with variable in shader
  - need name, type, location in buffer
```javascript
render();
}

function render() {
  gl.clear( gl.COLOR_BUFFER_BIT );
  gl.drawArrays( gl.TRIANGLE_FAN, 0, 4 );
}
```

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Triangles, Fans or Strips

```
gl.drawArrays( gl.TRIANGLE_FAN, 0, 4 ); // 0, 1, 2, 3

gl.drawArrays( gl.TRIANGLES, 0, 6 ); // 0, 1, 2, 0, 2, 3

gl.drawArrays( gl.TRIANGLE_STRIP, 0, 4 ); // 0, 1, 3, 2
```

```
1

2

0

3
```

```
1

2

0

3
```

```
gl.drawArrays( gl.TRIANGLE_STRIP, 0, 4 ); // 0, 1, 3, 2
```

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JavaScript Notes

• JavaScript (JS) is the language of the Web
  - All browsers will execute JS code
  - JavaScript is an interpreted object-oriented language

• References
  - Flanagan, JavaScript: The Definitive Guide, O’Reilly
  - Crockford, JavaScript, The Good Parts, O’Reilly
  - Many Web tutorials
JS Notes

• Is JS slow?
  - JS engines in browsers are getting much faster
  - Not a key issues for graphics since once we get the data to the GPU it doesn’t matter how we got the data there

• JS is a (too) big language
  - We don’t need to use it all
  - Choose parts we want to use
  - Don’t try to make your code look like C or Java
• Very few native types:
  - numbers
  - strings
  - booleans

• Only one numerical type: 64 bit float
  - var x = 1;
  - var x = 1.0; // same
  - potential issue in loops
  - two operators for equality == and ===

• Dynamic typing
Scoping

• Different from other languages
• Function scope
• Variables are *hoisted* within a function
  - can use a variable before it is declared
• Note functions are first class objects in JS
JS Arrays

JS arrays are objects

- inherit methods
- var a = [1, 2, 3];
  
  is not the same as in C++ or Java
- a.length   // 3
- a.push(4); // length now 4
- a.pop();  // 4
- avoids use of many loops and indexing
- Problem for WebGL which expects C-style arrays
Typed Arrays

JS has typed arrays that are like C arrays

```javascript
var a = new Float32Array(3)
var b = new Uint8Array(3)
```

Generally, we prefer to work with standard JS arrays and convert to typed arrays only when we need to send data to the GPU with the flatten function in MV.js
A Minimalist Approach

• We will use only core JS and HTML
  - no extras or variants
• No additional packages
  - CSS
  - JQuery
• Focus on graphics
  - examples may lack beauty
Buffer Object

• Buffers objects allow us to transfer large amounts of data to the GPU
• Need to create, bind (make current) and identify/specify data

```javascript
var buffer_id;
buffer_id = gl.createBuffer();
gl.bindBuffer(gl.ARRAY_BUFFER, buffer_id);
gl.bufferData(gl.ARRAY_BUFFER, data,
             gl.STATIC_DRAW);
```

• Data in current buffer is sent to GPU
Why use Buffer Objects?

Only Advantages

• The memory manager in the buffer object will put the data into the best memory locations based on user's hints

• Memory manager can optimize the buffers by balancing between 3 kinds of memory:
  - system, GPU and video memory
gl.createBuffer()

- creates a buffer object and returns the buffer object

WebGLBuffer gl.createBuffer()

- Returns a WebGLBuffer for storing data such as vertices or colors.
gl.bindBuffer()

- Once the buffer object has been created, we need to bind it to a target.
- Also makes the buffer “current”

```c
void gl.bindBuffer(GLenum target, WebGLBuffer buffer)
```

- Target can be
  - gl.ARRAY_BUFFER: Any vertex attribute, such as vertex coordinates, texture coordinates, normals and color component arrays
  - gl.ELEMENT_ARRAY_BUFFER: Index array which is used for `glDraw[Range]Elements()`

- Once first called, the buffer is initialized with a zero-sized memory buffer and sets the initial states
gl.bufferData()

- You can initialize and copy the data into the buffer object with gl.bufferData().

```c
void gl.bufferData(GLenum target, GLsizeiptr size,
                    GLenum usage);
void gl.bufferData(GLenum target, ArrayBuffer data,
                    GLenum usage);
```

- target is either GL_ARRAY_BUFFER or GL_ELEMENT_ARRAY_BUFFER.
- size is the number of bytes of data to transfer.
- Data is the array holding the data to be copied.
- "usage" flag is a performance hint to provide how the buffer object is going to be used: static, dynamic or stream, and read, copy or draw.
Usage Flags

- **gl.STATIC_DRAW**
  - Contents of the buffer are likely to be used often and not change often.

- **gl.DYNAMIC_DRAW**
  - Contents of the buffer are likely to be used often and change often.

- **gl.STREAM_DRAW**
  - Contents of the buffer are likely to not be used often.

- All contents are written to the buffer, but not read.
void gl.bufferSubData(GLenum target, GLintptr offset, ArrayBuffer data)

- Like gl.bufferData(),
  - used to copy data into BO
- It only replaces a range of data into the existing buffer, starting from the given offset.
- The total size of the buffer must be set by gl.bufferData() before using gl.bufferSubData().
gl.deleteBuffer()

void gl.deleteBuffers(WebGLBuffer buffer)

- You can delete a BO with gl.deleteBuffer(), if it is no longer needed. After a buffer object is deleted, its contents will be lost.
Program Execution

• WebGL runs within the browser
  - complex interaction among the operating system, the window system, the browser and your code (HTML and JS)

• Simple model
  - Start with HTML file
  - files read in asynchronously
  - start with onload function
    • event driven input
Coordinate Systems

- The units in vertices are determined by the application and are called object, world, model or problem coordinates
- Viewing specifications usually are also in object coordinates
- GL_Positions are passed to clipping volume
  - Most important is clip coordinates
- Eventually pixels will be produced in window coordinates
- WebGL also uses some internal representations that usually are not visible to the application but are important in the shaders

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Coordinate Systems and Shaders

- Vertex shader must output vertices in clip coordinates.
- Input to fragment shader from rasterizer is in window coordinates (pixels).
- Application can provide vertex data in any coordinate system, but vertex shader must eventually produce `gl_Position` in clip coordinates.
- Simple example uses clip coordinates.
WebGL Camera

- WebGL places a camera at the origin in camera space pointing in the negative $z$ direction
- The view/clipping volume is a box centered at the origin with sides of length 2
- $(-1, -1, -1) \rightarrow (1, 1, 1)$
Orthographic Viewing

In the default orthographic (parallel) view, all points in the view volume are projected along the $z$ axis onto the plane $z = 0$. 

![Diagram showing orthographic viewing with points projected along the z axis onto the plane z = 0.](image-url)
WebGL View Volume

• Only geometry (gl_Positions) inside of view volume will be rendered!
• Doesn’t matter if they are in front of or behind camera (origin)
• The viewing/clipping volume is a box centered at the origin with sides of length 2
• \((-1,-1,-1) \rightarrow (1,1,1)\)
Objects in the Viewing Rectangle are mapped into the Viewport
Note the window’s coordinate frame!
• Do not have to use the entire canvas for the image: `gl.viewport(x,y,w,h)`
• Values in pixels (window coordinates)
• `w` and `h` should and `x` and `y` are recommended to be non-negative
• Specified in square.js
Transformations and Viewing

- In WebGL, projection is carried out by a projection matrix (transformation)
- Transformation functions are also used for changes in coordinate systems
- Pre 3.0 OpenGL had a set of transformation functions which have been deprecated
- Three choices
  - Application code
  - GLSL functions
  - MV.js
First Programming Assignment

• Get example code from HW1 web page
• Get test code running
• Make minor modifications to it
• Change color in square.html
First Programming Assignment

• Modify square.js
  - Draw a red pentagon, rather than a white square
  - Change viewport
• Add vertex/vertices to define another triangle
• Modify gl.drawArrays()