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

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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

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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 IS0 and later ANSI standard (1980s)
- GKS not easily extended to 3D (GKS-3D)
  - Far behind hardware development

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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)

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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

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OpenGL

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

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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

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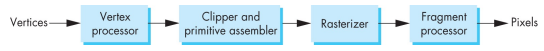
Modern OpenGL

- 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



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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

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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

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What About Other Low-Level Graphics Libraries?

- Direct3D
  - Part of DirectX, Windows-only
- Mantle (discontinued)
  - Developed by AMD
- Metal
  - Developed by Apple
- Vulkan
  - "next-gen" OpenGL
  - Derived from Mantle

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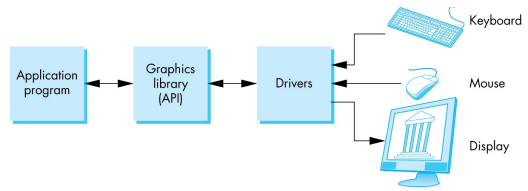
OpenGL Architecture



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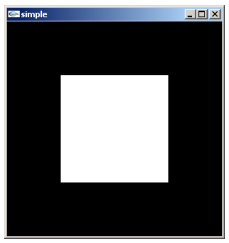
A Simple Program (?)

Generate a square on a solid background



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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();
}
```


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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

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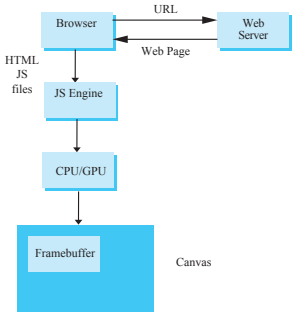
Execution in Browser



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Event Loop

- Remember that the sample program specifies a render function which is a *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

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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

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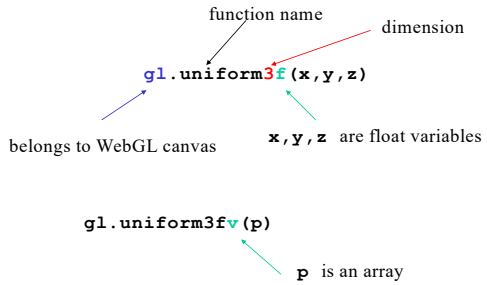
WebGL function format



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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)`

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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

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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

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Programming with OpenGL Part 2: Complete Programs

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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

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Coding in WebGL

- Example: Draw a square
  - Each application consists of three types of files
- HTML (index.html)
  - describes canvas, i.e. page layout
  - includes utility scripts
  - includes application scripts
- JavaScript
  - contains the actual graphics code
- GLSL
  - contains shader code

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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

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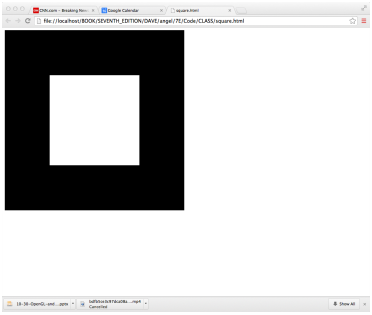
Square Program



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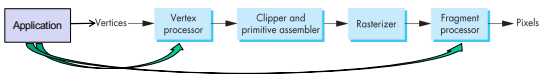
WebGL

- Five steps
  - Describe page (HTML file)
    - request WebGL Canvas
    - read in necessary files
  - Define shaders (GLSL file)
  - Compute or specify data (JS file)
  - Send data to GPU (JS file)
  - Render data (JS file)



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index.html

```
<!DOCTYPE HTML>
<html>
<head>
<script src="https://greggman.github.io/webgl-lint/webgl-lint.js"
crossorigin></script>
<script type="text/javascript" src="./Common/initShaders2.js"></script>
<script type="text/javascript" src="./Common/MVnew.js"></script>
<script type="text/javascript" src="./square.js"></script>
<script type="text/javascript" src="./app.js"></script>

</head>
<body>
<canvas id="gl-canvas" width="512" height="512">
Not supported
</canvas>
</body>
</html>
```


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Utility Files

- **`webgl-lint.js`**: checks for common WebGL errors
  - See https://github.com/greggman/webgl-lint
- **`../Common/initShaders2.js`**: contains JS and WebGL code for reading, compiling and linking the shaders
- **`../Common/MVnew.js`**: matrix-vector package

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Application Files

- **`square.js`**: contains JS & WebGL code for
  - defining square geometry
  - setting up shader programs
  - initializing buffers and pointers
  - drawing square
- **`app.js`**: contains JS & WebGL code for
  - initializing canvas and WebGL
  - render() function
  - instantiating square and rendering it

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Shaders

- We access shaders through their filenames 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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Notes

- **`onload`**: determines where to start execution when all code is loaded
- canvas gets WebGL context from HTML file
- vertices use vec2 type in MVnew.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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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

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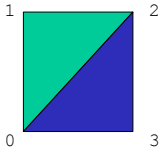
Drawing the square

```
function render() {
    gl.clear( gl.COLOR_BUFFER_BIT );
    sq.draw();
}

draw() {
    ...
    gl.drawArrays( gl.TRIANGLE_FAN, 0, 4 );
    ...
}
```



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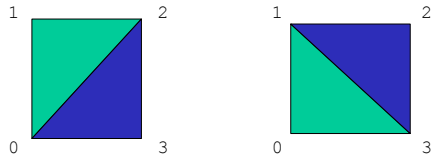
Triangles, Fans or Strips

```
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
```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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

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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

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JS Notes

- 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

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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

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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

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Typed Arrays

JS has typed arrays that are like C arrays

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 MVnew.js

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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

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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

```
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

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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

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gl.createBuffer()

- 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.

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gl.bindBuffer()

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

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

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gl.bufferData()

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

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.

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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.

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gl.bufferSubData()

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().

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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.

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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

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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_Position`**s 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`s in clip coordinates
- Simple example uses clip coordinates

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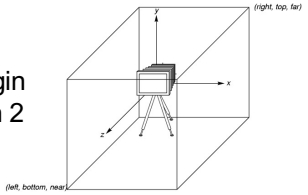
WebGL Camera

- 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) ➔ (1,1,1)



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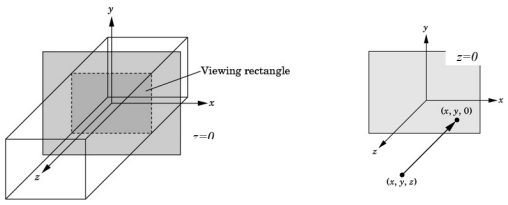
Orthographic Viewing

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



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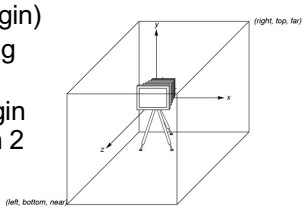
WebGL View Volume

- Only geometry (`gl_Position`s) 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) ➔ (1,1,1)



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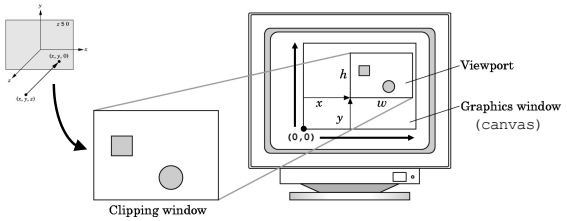
Viewing Rectangle Maps to Viewport

Objects in the Viewing Rectangle are mapped into the Viewport
Note the window's coordinate frame!



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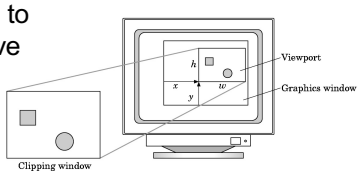
Viewports

- 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 be and `x` and `y` are recommended to be non-negative
- Specified in square.js



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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
  - MVnew.js

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First Programming Assignment

- Get example code from HW1 web page
- Get test code running
- Make minor modifications to it
- Draw red pentagon, instead of a white square

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First Programming Assignment

- Change viewport (app.js)
- Add vertex/vertices to define another triangle (square.js)
- Modify gl.drawArrays() (square.js)
- Change output color (vshader.glsl)

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