Fragment Tests, Images and Buffers

CS 432 Interactive Computer Graphics
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Fragment Tests
Objectives

• Introduce fragment tests and operations
• Learn to use blending
• Introduce additional WebGL buffers
• Reading and writing buffers
• Buffers and Images
• After the fragment shader is executed a series of tests and operations are performed on the fragment

• Determine how and whether a fragment color is drawn into the frame buffer
Fragment Tests and Operations

- Determine how and whether a fragment color is drawn into the frame buffer.
- This is where the depth test is being performed.
Fragment Tests and Operations

- Tests and operations are performed in the following order
  - Scissor test
  - Stencil test
  - Depth test
  - Blending
  - Dithering

- On/off `gl.enable()`, `gl.disable()`
Pixel Tests

• Scissor
  - Only draw in a rectangular portion of screen
  - `gl.scissor()` – Specify rectangle
  - Default rectangle matches window

• Depth
  - Draw based on depth value and comparison function
  - `gl.depthFunc()` – Specify comparison function
  - Default is `gl.LESS`
Pixel Tests

• Stencil
  - Draw based on values in stencil buffer, if available and enabled
  - Used for drawing into an irregular region of color buffer
    - `gl.stencilFunc()` – Specifies comparison function, reference value and mask
    - `gl.stencilOp()` – Specifies how fragments can modify stencil buffer
  - Used for reflections, capping and stippling
Dithering

- Dithering may be enabled (\texttt{gl.DITHER}) on some systems with limited color resolution
- System/hardware-dependent
Opacity and Transparency using Blending

- Opaque surfaces permit no light to pass through
- Transparent surfaces permit all light to pass
- Translucent surfaces pass some light

\[
\text{translucency} = 1 - \text{opacity} (\alpha)
\]

opaque surface $\alpha = 1$
Physical Models

- Dealing with translucency in a physically correct manner is difficult due to:
  - the complexity of the internal interactions of light and matter
  - Using a pipeline renderer
Writing Model for Blending

- Use a component of RGBA (or RGB\(_{\alpha}\)) color to store opacity
- During rendering we can expand our writing model to use RGBA values

![Diagram showing the writing model for blending]

- **source blending factor**
- **destination blending factor**
- **Color Buffer**
- **source component**
- **destination component**
- **blend**
Blending Equation

- We can define source and destination blending factors for each RGBA component

\[ s = [s_r, s_g, s_b, s_\alpha] \]
\[ d = [d_r, d_g, d_b, d_\alpha] \]

Suppose that the source and destination colors are

\[ b = [b_r, b_g, b_b, b_\alpha] \]
\[ c = [c_r, c_g, c_b, c_\alpha] \]

Blend as \[ c' = s \ast b + d \ast c \]

\[ c' = [b_r s_r + c_r d_r, b_g s_g + c_g d_g, b_b s_b + c_b d_b, b_\alpha s_\alpha + c_\alpha d_\alpha] \]
WebGL Blending

- Must enable blending and set source and destination factors

  ```javascript
  gl.enable(gl.BLEND)
  gl.blendFunc(source_factor, destination_factor)
  ```

- Only certain factors supported
  - `gl.ZERO`, `gl.ONE`
  - `gl.SRC_ALPHA`, `gl.ONE_MINUS_SRC_ALPHA`
  - `gl.DST_ALPHA`, `gl.ONE_MINUS_DST_ALPHA`

- See WebGL spec for complete list
Example

• Suppose that we start with the opaque background color \((R_0, G_0, B_0, 1)\)
  - This color becomes the initial destination color
• We now want to blend in a translucent polygon with color \((R_1, G_1, B_1, \alpha_1)\)
• Select `gl.SRC_ALPHA` and `gl.ONE_MINUS_SRC_ALPHA` as the source and destination blending factors
  \[
  R'_0 = \alpha_1 R_1 + (1- \alpha_1) R_0, \quad \ldots
  \]
• Note this formula is correct if polygon is either opaque or transparent
Clamping and Accuracy

- All the components (RGBA) are clamped and stay in the range (0,1)
- However, in a typical system, RGBA values are only stored to 8 bits
  - Can easily lose accuracy if we add many components together
  - Example: add together n images
    - Divide all color components by n to avoid clamping
    - Blend with source factor = 1, destination factor = 1
    - But division by n loses bits
Order Dependency

- Is this image correct?
  - Probably not
  - Polygons are rendered in the order they pass down the pipeline
  - Blending functions are order dependent
Correct Blending
Opaque and Translucent Polygons

• Suppose that we have a group of polygons some of which are opaque and some translucent
• How do we use hidden-surface removal?
• Opaque polygons block all polygons behind them and affect the depth buffer
• Translucent polygons should not affect depth buffer
  - Render with `gl.depthMask(false)` which makes depth buffer read-only
• Sort polygons first to remove order dependency!
• Draw back to front
Blending and HTML

• In desktop OpenGL, the A component has no effect unless blending is enabled
• In WebGL, an A other than 1.0 has an effect because WebGL works with the HTML5 Canvas element
• A = 0.5 will cut the RGB values by $\frac{1}{2}$ when the pixel is displayed
• Allows other applications to be blended into the canvas along with the graphics
Fragment Tests and Operations

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  - Scissor test
  - Stencil test
  - Depth test
  - Blending
  - Dithering

• On/off `gl.enable()`, `gl.disable()`
Imaging Applications
Objectives

• Use the fragment shader to do image processing
  - Image filtering
  - Pseudo Color

• Use multiple textures
  - matrix operations

• Introduce GPGPU
Accumulation Techniques

• Compositing and blending are limited by resolution of the frame buffer
  - Typically 8 bits per color component
• The *accumulation buffer* was a high resolution buffer (16 or more bits per component) that avoided this problem
• Could write into it or read from it with a scale factor
• Slower than direct compositing into the frame buffer
• Now deprecated but can do techniques with floating point frame buffers
Multirendering

- Composite multiple images
- Image Filtering (convolution)
  - add shifted and scaled versions of an image
- Whole scene antialiasing
  - move primitives a little for each render
- Depth of Field
  - move viewer a little for each render keeping one plane unchanged
- Motion effects
Suppose that we send a rectangle (two triangles) to the vertex shader and render it with an $n \times m$ texture map.

Suppose that in addition we use an $n \times m$ canvas.

There is now a one-to-one correspondence between each texel and each fragment.

Hence we can regard fragment operations as imaging operations on the texture map.
• Looking back at these examples, we can note that the only purpose of the geometry is to trigger the execution of the imaging operations in the fragment shader.

• Consequently, we can look at what we have done as large matrix operations rather than graphics operations.

• Leads to the field of General Purpose Computing with a GPU (GPGPU).
Examples

• Add two matrices
• Multiply two matrices
• Fast Fourier Transform
• Uses speed and parallelism of GPU
• But how do we get out results?
  - Floating point frame buffers
  - OpenCL (WebCL)
  - Compute shaders
Using Multiple Texels

• Suppose we have a 1024 x 1024 texture in the texture object “image”

\[
sampler2D(image, \text{vec2}(x,y)) \text{ returns the value of the texture at } (x,y)
\]

\[
sampler2D(image, \text{vec2}(x+1.0/1024.0, y)) \text{; returns the value of the texel to the right of } (x,y)
\]

We can use any combination of texels surrounding \((x, y)\) in the fragment shader.
precision mediump float;
varying vec2 fTexCoord;
uniform sampler2D texture;
void main()
{
    float d = 1.0/256.0;  // spacing between texels
    float x = fTexCoord.x;
    float y = fTexCoord.y;

    gl_FragColor = 10.0*abs( texture2D( texture, vec2(x+d, y))
        - texture2D( texture, vec2(x-d, y)))
    + 10.0*abs( texture2D( texture, vec2(x, y+d))
        - texture2D( texture, vec2(x, y-d)));
    gl_FragColor.w = 1.0;
}
Honolulu Image

original

enhanced
Sobel Edge Detector

- Nonlinear
- Find approximate gradient at each point
- Compute smoothed finite difference approximations to x and y components separately
- Display magnitude of approximate gradient
- Simple with fragment shader
Sobel Edge Detector

vec4 gx = 3.0*texture2D( texture, vec2(x+d, y))
+ texture2D( texture, vec2(x+d, y+d))
+ texture2D( texture, vec2(x+d, y-d))
- 3.0*texture2D( texture, vec2(x-d, y))
- texture2D( texture, vec2(x-d, y+d))
- texture2D( texture, vec2(x-d, y-d));

vec4 gy = 3.0*texture2D( texture, vec2(x, y+d))
+ texture2D( texture, vec2(x+d, y+d))
+ texture2D( texture, vec2(x-d, y+d))
- 3.0*texture2D( texture, vec2(x, y-d))
- texture2D( texture, vec2(x+d, y-d))
- texture2D( texture, vec2(x-d, y-d));

mag = sqrt(gx*gx + gy*gy);

gl_FragColor = vec4(mag, mag, mag, 1.0);
Sobel Edge Detector
Using Multiple Textures

• Example: matrix addition
• Create two samplers, texture1 and texture2, that contain the data
• In fragment shader

\[
\text{gl\_FragColor} = \text{sampler2D(texture1, vec2(x, y))} + \text{sampler2D(texture2, vec2(x,y))};
\]
Indexed and Pseudo Color

- Display luminance (2D) image as texture map
- Treat pixel value as independent variable for separate functions for each color component

```c
void main()
{
    vec4 color = texture2D(texture, fTexCoord);
    if(color.g<0.5) color.g = 2.0*color.g;
    else color.g = 2.0 - 2.0*color.g;
    color.b = 1.0-color.b;
    gl_FragColor = color;
}
```
Top View of 2D Sinc
The Next Step

• Need more storage for most GPGPU calculations
• Example: filtering
• Example: iteration
• Need shared memory
• Solution: Use texture memory and off-screen rendering
Computing the Mandelbrot Set
Objectives

• Introduce the most famous fractal object
  - more about fractal curves and surfaces later

• Imaging calculation
  - Must compute value for each pixel on display
  - Shows power of fragment processing
Sierpinski Gasket

Rule based:

Repeat \( n \) times. As \( n \to \infty \)

Area\( \to 0 \)

Perimeter \( \to \infty \)

Not a normal geometric object
Complex Arithmetic

- Complex number defined by two scalars
  \[ z = x + iy \]
  \[ i^2 = -1 \]

- Addition and Subtraction
  \[ z_1 + z_2 = x_1 + x_2 + i(y_1 + y_2) \]
  \[ z_1 * z_2 = x_1 * x_2 - y_1 * y_2 + i(x_1 * y_2 + x_2 * y_1) \]

- Magnitude
  \[ |z|^2 = x^2 + y^2 \]
Iteration in the Complex Plane

\[ z_0 \rightarrow z_1 = F(z_0) \rightarrow z_2 = F(z_1) \rightarrow z_3 = F(z_2) \]
iterate on \( z_{k+1} = z_k^2 + c \)
with \( z_0 = 0 + i0 \)

Two cases as \( k \to \infty \)

\[
|z_k| \to \infty
\]
\[
|z_k| \text{ remains finite}
\]

If for a given \( c \), \( |z_k| \) remains finite, then \( c \) belongs to the Mandelbrot set
Computing the Mandelbrot Set

• Pick a rectangular region
• Map each pixel to a value in this region
• Do an iterative calculation for each pixel
  - If magnitude is greater than 2, we know sequence will diverge and point does not belong to the set
  - Stop after a fixed number of iterations
  - Points with small magnitudes should be in set
  - Color each point based on its magnitude
Mandelbrot Set
Exploring the Mandelbrot Set

• Most interesting parts are centered near (-0.5, 0.0)
• Really interesting parts are where we are uncertain if points are in or out of the set
• Repeated magnification these regions reveals complex and beautiful patterns
• We use color maps to enhance the detail
Mandelbrot Set
• Form a texture map of the set and map to a rectangle

```javascript
var height = 0.5; var width = 0.5; // size of window in complex plane
var cx = -0.5; var cy = 0.5; // center of window in complex plane
var max = 100; // number of iterations per point

var n = 512;
var m = 512;
var texImage = new Uint8Array(4*n*m);
```
for ( var i = 0; i < n; i++ )
    for ( var j = 0; j < m; j++ ) {
        var x = i * ( width / (n - 1) ) + cx - width / 2;
        var y = j * ( height / ( m - 1 ) ) + cy - height / 2;
        var c = [ 0.0, 0.0 ];
        var p = [ x, y ];

        for ( var k = 0; k < max; k++ ) {
            // compute c = c^2 + p
            c = [c[0]*c[0]-c[1]*c[1], 2*c[0]*c[1]];
            c = [c[0]+p[0],  c[1]+p[1]];
            v = c[0]*c[0]+c[1]*c[1];
            if ( v > 4.0 ) break;  /* assume not in set if mag > 2 */
        }
    }
// assign gray level to point based on its magnitude */
if ( v > 1.0 ) v = 1.0;      /* clamp if > 1 */
texImage[4*i*m+4*j] = 255*v;
texImage[4*i*m+4*j+1] =
    255*( 0.5* (Math.sin( v*Math.PI/180 ) + 1.0));
texImage[4*i*m+4*j+2] = 255*(1.0 - v);
texImage[4*i*m+4*j+3] = 255;
}

• Set up two triangles to define a rectangle
• Set up texture object with the set as data
• Render the triangles
Example
Our first implementation is incredibly inefficient and makes no use of the power of the fragment shader. Note the calculation is “embarrassingly parallel”:

- computation for the color of each fragment is completely independent
- Why not have each fragment compute membership for itself?
- Each fragment would then determine its own color
Interactive Program

- JS file sends window parameters obtained from sliders to the fragment shader as uniforms
- Only geometry is a rectangle
- No need for a texture map since shader will work on individual pixels
precision mediump float;
uniform float cx;
uniform float cy;
uniform float scale;
float height;
float width;

void main() {

const int max = 100; /* number of iterations per point */
const float PI = 3.14159;
float n = 1000.0;
float m = 1000.0;
float v;
float x = gl_FragCoord.x / (n*scale) + cx - 1.0 / (2.0*scale);
float y = gl_FragCoord.y / (m*scale) + cy - 1.0 / (2.0*scale);
float ax=0.0, ay=0.0;
float bx, by;
for ( int k = 0; k < max; k++ ) {
    // compute c = c^2 + p
    bx = ax*ax-ay*ay;
    by = 2.0*ax*ay;
    ax = bx+x;
    ay = by+y;
    v = ax*ax+ay*ay;
    if ( v > 4.0 ) break;     // assume not in set if mag > 2
}
// assign gray level to point based on its magnitude //

// clamp if > 1

v = min(v, 1.0);
gl_FragColor.r = v;

gl_FragColor.g = 0.5* sin( 3.0*PI*v) + 1.0;

// gl_FragColor.b = 1.0-v;
gl_FragColor.b = 0.5* cos( 19.0*PI*v) + 1.0;
gl_FragColor.a = 1.0;

}
Analysis

• This implementation will use as many fragment processors as are available concurrently.

• Note that if an iteration ends early, the GPU will use that processor to work on another fragment.

• Note also the absence of loops over x and y.
Buffers
Define a buffer by its spatial resolution \((n \times m)\) and its depth (or precision) \(k\), the number of bits/pixel.
WebGL Frame Buffer

Stencil buffer
Depth buffer
Back buffer
Front buffer

\{ Color buffers \}

m
n
Where are the Buffers?

- **HTML5 Canvas**
  - Default front and back color buffers
  - Under control of local window system
  - Physically on graphics card
- **Depth buffer also on graphics card**
- **Stencil buffer**
  - Holds masks
- **Most RGBA buffers 8 bits per component**
- **Latest are floating point (IEEE)**
Other Buffers

• Desktop OpenGL supported other buffers
  - auxiliary color buffers
  - accumulation buffer
  - these were on application side
  - now deprecated

• GPUs have their own or attached memory
  - texture buffers
  - off-screen buffers
    • not under control of window system
    • may be floating point
Images

- Framebuffer contents are unformatted
  - usually RGB or RGBA
  - one byte per component
  - no compression
- Standard Web Image Formats
  - jpeg, gif, png
- WebGL has no conversion functions
  - Understands standard Web formats for texture images
Writing into Buffers

- WebGL does not contain a function for writing bits into frame buffer
  - Use texture functions instead
- We can use the fragment shader to do bit level operations on graphics memory
- Bit Block Transfer (BitBlt) operations act on blocks of bits with a single instruction
BitBlt

- Conceptually, we can consider all of memory as a large two-dimensional array of pixels.
- We read and write rectangular block of pixels
  - *Bit block transfer (bitblt) operations*
- The frame buffer is part of this memory.

```
memory -> source
writing into the frame buffer
frme buffer (destination)
```
The (Old) Pixel Pipeline

• OpenGL has a separate pipeline for pixels
  - Writing pixels involves
    • Moving pixels from processor memory to the frame buffer
    • Format conversions
    • Mapping, Lookups, Tests
  - Reading pixels
    • Format conversion
Packing and Unpacking

• Compressed or uncompressed
• Indexed or RGB
• Bit Format
  - little or big endian
• WebGL (and shader-based OpenGL) lacks most functions for packing and unpacking
  - use texture functions instead
  - can implement desired functionality in fragment shaders
Buffer Reading

- WebGL can read pixels from the current framebuffer with `gl.readPixels`
- Returns only 8 bit RGBA values
- In general, the format of pixels in the frame buffer is different from that of processor memory and these two types of memory reside in different places
  - Need packing and unpacking
  - Reading can be slow
- Drawing through texture functions and off-screen memory (frame buffer objects)
WebGL Pixel Function

```javascript
var myimage[512*512*4];

gl.readPixels(0, 0, 512, 512, gl.RGBA,
                    gl.UNSIGNED_BYTE, myimage);
```
Formats & Types

• `gl.RGBA`
• `gl.RGB`
• `gl.ALPHA`

• `gl.UNSIGNED_BYTE`
• `gl.UNSIGNED_SHORT_5_6_5`
• `gl.UNSIGNED_SHORT_4_4_4_4`
• `gl.UNSIGNED_SHORT_5_5_5_2`
• `gl.FLOAT`
Clearing Buffers

• A clear (default) value may be set for each buffer
  - `gl clearColor()`
  - `gl clearDepth()`
  - `gl clearStencil()`

• `gl clear(Glbitfield mask)`

• Clears the specified buffer
  - `gl.COLOR_BUFFER_BIT, gl.DEPTH_BUFFER_BIT, gl.STENCIL_BUFFER_BIT`
  - Can be or’ed together in one `clear()` call
Masking Buffers

- A buffer may be masked, i.e. enabled or disabled
  - `gl.colorMask(red, green, blue, alpha)`
    - Arguments are booleans
  - `gl.depthMask(flag)`
  - `gl.stencilMask(mask)`
  - `gl.stencilMaskSeparate(face, mask)`
    - Stencil specific sides (front & back) of triangles
Render to Texture

- GPUs now include a large amount of texture memory that we can write into
- Advantage: fast (not under control of window system)
- Using frame buffer objects (FBOs) we can render into texture memory instead of the frame buffer and then read from this memory
  - Image processing
  - GPGPU
Framebuffer Objects
Objectives

• Look at methods that use memory on the graphics card
• Introduce off screen rendering
• Learn how to create framebuffer objects
  - Create a renderbuffer
  - Attach resources
Discrete Processing in WebGL

- Recent GPUs contain large amounts of memory
  - Texture memory
  - Framebuffer
  - Floating point
- Fragment shaders support discrete operations at the pixel level
- Separate pixel (texel) pipeline
• Pre 3.1 OpenGL had functions that allowed access to the framebuffer and other OpenGL buffers
  - Draw Pixels
  - Read Pixels
  - Copy Pixels
  - BitBlt
  - Accumulation Buffer functions

• All deprecated
Going between CPU and GPU

• We will see that we can write pixels as texels to texture memory
• Texture objects reduce transfers between CPU and GPU
• Transfer of pixel data back to CPU slow
• Want to manipulate pixels without going back to CPU
  - Image processing
  - GPGPU
Framebuffer Objects

• Framebuffer Objects (FBOs) are buffers that are created by the application
  - Not under control of window system
  - Cannot be displayed
  - Can attach a renderbuffer to a FBO and can render off screen into the attached buffer
  - Attached buffer can then be detached and used as a texture map for an on-screen render to the default frame buffer
Render to Texture

- Textures are shared by all instances of the fragment shader
- If we render to a texture attachment we can create a new texture image that can be used in subsequent renderings
- Use a double buffering strategy for operations such as convolution
Steps

• Create an empty texture object
• Create an FBO
• Bind FBO
• Attach renderbuffers to create texture image
• Attach texture object to store rendered image
• Render scene to texture object
• Detach renderbuffer
• Bind window system frame buffer
• Bind texture
• Render with generated texture image
Empty Texture Object

texture1 = gl.createTexture();
gl.activeTexture( gl.TEXTURE0 );
gl.bindTexture( gl.TEXTURE_2D, texture1 );

gl.texImage2D(gl.TEXTURE_2D, 0, gl.RGBA, 512, 512, 0, gl.RGBA, gl.UNSIGNED_BYTE, null);

gl.generateMipmap(gl.TEXTURE_2D);
gl.texParameteri( gl.TEXTURE_2D, gl.TEXTURE_MIN_FILTER, gl.NEAREST_MIPMAP_LINEAR );
gl.texParameteri( gl.TEXTURE_2D, gl.TEXTURE_MAG_FILTER, gl.NEAREST );
Creating a FBO

- We create a framebuffer object in a similar manner to other objects.
- Creating an FBO creates an empty FBO.
- Must add needed resources:
  - Can add a renderbuffer to render into.
  - Can add a texture which can also be rendered into.
  - For hidden surface removal we must add a depth buffer attachment to the renderbuffer.
  - Can also add a stencil buffer to FBO.
Frame Buffer Object

```javascript
var framebuffer = gl.createFramebuffer();
gl.bindFramebuffer(gl.FRAMEBUFFER, framebuffer);
framebuffer.width = 512;
framebuffer.height = 512;
renderbuffer = gl.createRenderbuffer();
gl.bindRenderbuffer(gl.RENDERBUFFER, renderbuffer);
gl.renderbufferStorage(gl.RENDERBUFFER,
  gl.DEPTH_COMPONENT16, 512, 512);
gl.framebufferRenderbuffer(gl.FRAMEBUFFER, gl.DEPTH_ATTACHMENT,
  gl.RENDERBUFFER, renderbuffer);

// Attach color buffer
gl.framebufferTexture2D(gl.FRAMEBUFFER, gl.COLOR_ATTACHMENT0,
  gl.TEXTURE_2D, texture1, 0);

// check for completeness
var status = gl.checkFramebufferStatus(gl.FRAMEBUFFER);
if (status !== gl.FRAMEBUFFER_COMPLETE) alert('Frame Buffer Not Complete');
```
Rest of Initialization

• Same as previous examples
  - Allocate VAO
  - Fill VAO with data for render to texture

• Initialize two program objects with different shaders
  - First for render to texture
  - Second for rendering with created texture
Render to Texture
Objectives

• Examples of render-to-texture
• Render a triangle to texture, then use this texture on a rectangle
• Introduce buffer pingponging
Program Objects and Shaders

- For most applications of render-to-texture, we need multiple program objects and shaders:
  - One set for creating a texture
  - Second set for rendering with that texture
- Applications that we consider later such as buffer pingponging may require additional program objects.
// pass through vertex shader:
in  vec4 vPosition;
void main()
{
    gl_Position = vPosition;
}

// fragment shader to produce a red triangle:
precision mediump float;
out vec4 fColor;
void main()
{
    fColor = vec4(1.0, 0.0, 0.0, 1.0);
}
Program Object 2 Shaders

// vertex shader

in vec4 vPosition;
in vec2 vTexCoord;
out vec2 fTexCoord;

void main()
{
    gl_Position = vPosition;
    fTexCoord = vTexCoord;
}

// fragment shader

precision mediump float;

in vec2 fTexCoord;
uniform sampler2D texture;
out vec4 fColor;

void main()
{
    fColor = texture2D( texture, fTexCoord);
}
First Render (to Texture)

```javascript
// Initialize the vertex position attribute from the vertex shader
var vPosition = gl.getAttribLocation( program1, "vPosition" );
gl.vertexAttribPointer( vPosition, 2, gl.FLOAT, false, 0, 0 );
gl.enableVertexAttribArray( vPosition );

// Render one triangle to an FBO

gl.viewport(0, 0, 64, 64);
gl clearColor(0.5, 0.5, 0.5, 1.0);
gl.clear(gl.COLOR_BUFFER_BIT);
gl.drawArrays(gl.TRIANGLES, 0, 3);       // Draws red triangle to texture object
```

```javascript
// First Render (to Texture)

var buffer1 = gl.createBuffer();
gl.bindBuffer( gl.ARRAY_BUFFER, buffer1 );
gl.bufferData( gl.ARRAY_BUFFER, flatten(pointsArray), gl.STATIC_DRAW );
```

```javascript
// Initialize the vertex position attribute from the vertex shader
```
Set Up Second Render

// Bind to default window system framebuffer

    gl.bindFramebuffer(gl.FRAMEBUFFER, null);
    gl.bindRenderbuffer(gl.RENDERBUFFER, null);
    gl.disableVertexAttribArray(vPosition);
    gl.useProgram(program2);

// Assume we have already set up a texture object with null texture image

    gl.activeTexture(gl.TEXTURE0);
    gl.bindTexture(gl.TEXTURE_2D, texture1);

// set up vertex attribute arrays for texture coordinates and rectangle as usual
Data for Second Render

```javascript
var buffer2 = gl.createBuffer();
gl.bindBuffer( gl.ARRAY_BUFFER, buffer2);
gl.bufferData( gl.ARRAY_BUFFER, flatten(vertices), gl.STATIC_DRAW);

var vPosition = gl.getAttribLocation( program2, "vPosition" );
gl.vertexAttribPointer( vPosition, 2, gl.FLOAT, false, 0, 0 );
gl.enableVertexAttribArray( vPosition );

var buffer3 = gl.createBuffer();
gl.bindBuffer( gl.ARRAY_BUFFER, buffer3);
gl.bufferData( gl.ARRAY_BUFFER, flatten(texCoord), gl.STATIC_DRAW);

var vTexCoord = gl.getAttribLocation( program2, "vTexCoord" );
gl.vertexAttribPointer( vTexCoord, 2, gl.FLOAT, false, 0, 0 );
gl.enableVertexAttribArray( vTexCoord );
```
Render a Quad with Texture

```glsl
gl.uniform1i(gl.getUniformLocation(program2, "texture"), 0);

gl.viewport(0, 0, 512, 512);
gl clearColor(0.0, 0.0, 1.0, 1.0);
gl clear(gl.COLOR_BUFFER_BIT);

gl drawArrays(gl.TRIANGLES, 0, 6);
```
Buffer Applications
Anti-aliasing

- Aliasing – artifacts produced from inadequate sampling
  - Jagged edges
  - Missing thin objects/features

- Anti-aliasing – removing artifacts via super-sampling, filtering, blurring, smoothing

- OpenGL offers a number of ways to perform anti-aliasing

- More limited in WebGL
Line Aliasing

• Ideal raster line is one pixel wide
• All line segments, other than vertical and horizontal segments, partially cover pixels
• Simple algorithms color only whole pixels
• Lead to the “jaggies” or aliasing
• Similar issue for polygons
Antialiasing

• Color a pixel by adding in a fraction of the fragment’s color
  - Fraction depends on percentage of pixel covered by object
  - Fraction depends on whether there is overlap

no overlap

overlap
Area Averaging

- Use average area $\alpha_1 + \alpha_2 - \alpha_1 \alpha_2$ as blending factor
Area Averaging
OpenGL Antialiasing

• Not (yet) supported in WebGL
• Can enable separately for points, lines, or polygons

```c
// Compute fractional alpha values along edges
// Based on pixel coverage
glEnable(GL_POINT_SMOOTH);
glEnable(GL_LINE_SMOOTH);
glEnable(GL_POLYGON_SMOOTH);

glEnable(GL_BLEND);
glBlendFunc(GL_SRC_ALPHA, GL_ONE_MINUS_SRC_ALPHA);
```

• Note most hardware will automatically antialias
WebGL Antialiasing

• Full-screen antialiasing
• Multiple renderings with texture ping-pong
• Jitter view
• Average several jittered images together
Fog

- We can blend with a fixed color and have the blending factors depend on depth
  - Simulates a fog effect
- Blend source color $C_s$ and fog color $C_f$ by
  \[ C'_s = f C_s + (1-f) C_f \]
- $f$ is the fog factor based on depth
  - Exponential
  - Gaussian
  - Linear (depth cueing)
- Hard-coded fog deprecated but can recreate
Fog Functions

\[ e^{-z^2} \]

\[ 1 - 0.5z \]

Distance

Attenuation

Angel and Shreiner: Interactive Computer Graphics 7E © Addison-Wesley 2015
Fog Effect

http://www.engin.swarthmore.edu/~jshin1
Interactive Depth-of-Field

- Jitter camera
- Each frustum has common plane “in focus”
- Accumulate & blend images
Interactive Depth-of-Field

http://www.cs.stevens.edu/~quynh
Reflections

- One of the most noticeable effects of inter-object lighting
- Direct calculation of the physics (ray tracing) is too expensive
- Our focus is to capture the most significant reflection while minimizing the overhead via rendering the “virtual object”
Image vs. Object Space Methods

• Image space methods: create a texture from a view of the reflected objects and apply it to the reflector
  - Advantage: does not depend on the object geometry
  - Disadvantage: sampling issue and also only an approximation (environment mapping as an example)

• Object space methods: create the actual geometry of the object to be reflected and render it to the reflector
  - Disadvantage: Limited to planar reflections
  - Advantage: more accurate reflection (for nearby objects)

• Both methods need to create the virtual objects
Planar Reflections

• The most common reflection – flat mirror, floor, wall, etc
• Creating virtual objects (or reflected objects) is much easier
• A view independent operation – only consider the relative position of the object and the reflector
• The virtual object is created by transforming the object across the reflector plane
Planar Reflections

Figure 54. Mirror Reflection of the Viewpoint

Figure 55. Mirror Reflection of the Scene
Render the Reflected Geometry

- An important task: clip the reflected geometry so it is only visible on the reflector surface
  - Beyond the reflector boundaries and in front of reflector
Clipping using the stencil

- The key is you only want the reflected geometry to appear on the reflector surface.
- Use stencil buffer:
  - Clear the stencil buffer
  - Render the reflector and set the stencil
  - Render the reflected geometry only where the stencil pixels have been set.
- The above algorithm uses the stencil buffer to control where to draw the reflection.
Clipping using the stencil

- Another method: render the reflected object first, and then render the reflector to set the stencil buffer, then clear the color buffer everywhere except where the stencil is set.

- This method is to use the stencil buffer to control where to erase the incorrect reflection.

- Advantage: when it is faster to use stencil to control clearing the scene than drawing the entire scene with stencil tests.
The stencil erase algorithm

Figure 57. Stencil Reflection Steps
Reflection Effect
Motion Effects
Agent Based Models
Objectives

• Introduce a powerful form of simulation
• Use render-to-texture for dynamic simulations using agent-based models
• Example of diffusion
Agent Based Models (ABMs)

• Consider a particle system in which particle can be programmed with individual behaviors and properties
  - different colors
  - different geometry
  - different rules

• Agents can interact with each other and with the environment
Simulating Ant Behavior

• Consider ants searching for food
• At the beginning, an ant moves randomly around the terrain searching for food
  - The ant can leave a chemical marker called a pheromone to indicate the spot was visited
  - Once food is found, other ants can trace the path by following the pheromone trail
• Model each ant as a point moving over a surface
• Render each point with arbitrary geometry
Diffusion Example I

• Two types of agents
  - no interaction with environment
  - differ only in color
• All move randomly
• Leave position information
  - need render-to-texture
• Diffuse position information
  - need buffer pingponging
Initialization

• We need two program objects
  - One for rendering points in new positions
  - One for diffusing texture map
• Initialization is standard otherwise
  - setup texture objects
  - setup framebuffer object
  - distribute particles in random locations
Vertex Shader 1

```cpp
attribute vec4 vPosition1;
attribute vec2 vTexCoord;
varying vec2 fTexCoord;
void main()
{
    gl_Position = vPosition1;
    fTexCoord = vTexCoord;
}
```
precision mediump float;
uniform sampler2D texture;
uniform float d;
uniform float s;
varying vec2 fTexCoord;
void main()
{
  float x = fTexCoord.x;
  float y = fTexCoord.y;
  gl_FragColor = (texture2D( texture, vec2(x+d, y))
                   +texture2D( texture, vec2(x, y+d))
                   +texture2D( texture, vec2(x-d, y))
                   +texture2D( texture, vec2(x, y-d)))/s;
}
attribute vec4 vPosition2;
uniform float pointSize;
void main()
{
    gl_PointSize = pointSize;
    gl_Position = vPosition2;
}
precision mediump float;
uniform vec4 color;
void main()
{
    gl_FragColor = color;
}

var render = function(){
  // render to texture
  // first a rectangle that is texture mapped
  gl.useProgram(program1);
  gl.bindFramebuffer( gl.FRAMEBUFFER, framebuffer);
  if (flag) {
    gl.bindTexture( gl.TEXTURE_2D, texture1);
    gl.framebufferTexture2D( gl.FRAMEBUFFER, gl.COLOR_ATTACHMENT0, gl.TEXTURE_2D, texture2, 0);
  }
  else {
    gl.bindTexture( gl.TEXTURE_2D, texture2);
    gl.framebufferTexture2D( gl.FRAMEBUFFER, gl.COLOR_ATTACHMENT0, gl.TEXTURE_2D, texture1, 0);
  }
  gl.drawArrays( gl.TRIANGLE_STRIP, 0, 4 );
}
// render points
gl.useProgram(program2);
gl.vertexAttribPointer(vPosition2, 2, gl.FLOAT, false, 0, 0);
gl.uniform4f(gl.getUniformLocation(program2, "color"), 0.9, 0.0, 0.9, 1.0);
gl.drawArrays(gl.POINTS, 4, numPoints/2);
gl.uniform4f(gl.getUniformLocation(program2, "color"), 0.0, 9.0, 0.0, 1.0);
gl.drawArrays(gl.POINTS, 4+numPoints/2, numPoints/2);

// render to display
gl.useProgram(program1);
gl.vertexAttribPointer(texLoc, 2, gl.FLOAT, false, 0, 32+8*numPoints);
gl.generateMipmap(gl.TEXTURE_2D);
gl.bindFramebuffer(gl.FRAMEBUFFER, null);

// pick texture
if (flag) gl.bindTexture(gl.TEXTURE_2D, texture2);
else gl.bindTexture(gl.TEXTURE_2D, texture1);
Rendering Loop III

```javascript
var r = 1024/texSize;
gl.viewport(0, 0, r*texSize, r*texSize);
gl.clear( gl.COLOR_BUFFER_BIT );
gl.drawArrays( gl.TRIANGLE_STRIP, 0, 4 );

// move particles in a random direction with wrap around
for(var i=0; i<numPoints; i++) {
    vertices[4+i][0] += 0.01*(2.0*Math.random()-1.0);
    vertices[4+i][1] += 0.01*(2.0*Math.random()-1.0);
    if (vertices[4+i][0]>1.0) vertices[4+i][0]= 2.0;
    if (vertices[4+i][0]<-1.0) vertices[4+i][0]+= 2.0;
    if (vertices[4+i][1]>1.0) vertices[4+i][1]= 2.0;
    if (vertices[4+i][1]<-1.0) vertices[4+i][1]+= 2.0;
}
gl.bufferSubData(gl.ARRAY_BUFFER, 0, flatten(vertices));
```
// swap textures
    flag = !flag;
    requestAnimFrame(render);
}
Snapshots
Add Agent Behavior

- Move randomly
- Check color where particle is located
- If green particle sees a green component over 128 move to (0.5, 0.5)
- If magenta particle sees a red component over 128 move to (-0.5, -0.5)
var color = new Uint8(4);
for(var i=0; i<numPoints/2; i++) {
    var x = Math.floor(511*(vertices[4+i][0]));
    var y = Math.floor(511*(vertices[4+i][1]));
    gl.readPixels(x, y, 1, 1, gl.RGBA, gl.UNSIGNED_BYTE, color);
    if (color[0]>128) {
        vertices[4+i][0] = 0.5;
        vertices[4+i][1] = 0.5;
    }
}
for(var i=numPoints/2; i<numPoints; i++) {
    var x = Math.floor(511*(vertices[4+i][0]));
    var y = Math.floor(511*(vertices[4+i][1]));
    gl.readPixels(x, y, 1, 1, gl.RGBA, gl.UNSIGNED_BYTE, color);
    if (color[1]>128) {
        vertices[4+i][0] = -0.5;
        vertices[4+i][1] = -0.5;
    }
}
Snapshots

without reading color  

with reading color
Picking by Color
Objectives

• Use off-screen rendering for picking
• Example: rotating cube with shading
  - indicate which face is clicked on with mouse
  - normal rendering uses vertex colors that are interpolated across each face
  - Vertex colors could be determined by lighting calculation or just assigned
  - use console log to indicate which face (or background) was clicked
Algorithm

• Assign a unique color to each object
• When the mouse is clicked:
  - Do an off-screen render using these colors and no lighting
  - use gl.readPixels to obtain the color of the pixel where the mouse is located
  - map the color to the object id
  - do a normal render to the display
Shaders

• Only need one program object
• Vertex shader: same as in previous cube examples
  - includes rotation matrices
  - gets angle as uniform variable
• Fragment shader
  - Stores face colors for picking
  - Gets vertex color for normal render from rasterizer
• Send uniform integer to fragment shader as index for desired color
precision mediump float;

uniform int i;
in vec4 vColor;
out vec4 fColor
void main()
{
    vec4 c[7];
c[0] = vColor;
c[1] = vec4(1.0, 0.0, 0.0, 1.0);
c[2] = vec4(0.0, 1.0, 0.0, 1.0);
c[3] = vec4(0.0, 0.0, 1.0, 1.0);
c[4] = vec4(1.0, 1.0, 0.0, 1.0);
c[5] = vec4(0.0, 1.0, 1.0, 1.0);
c[6] = vec4(1.0, 0.0, 1.0, 1.0);
Fragment Shader

// no case statement in GLSL

if (i==0) fColor = c[0];
else if (i==1) fColor = c[1];
else if (i==2) fColor = c[2];
else if (i==3) fColor = c[3];
else if (i==4) fColor = c[4];
else if (i==5) fColor = c[5];
else if (i==6) fColor = c[6];
}
Setup

// Allocate a frame buffer object
framebuffer = gl.createFramebuffer();
gl.bindFramebuffer( gl.FRAMEBUFFER, framebuffer );
// Attach color buffer
// Must first define empty texture object “texture”
gl.framebufferTexture2D( gl.FRAMEBUFFER,
    gl.COLOR_ATTACHMENT0, gl.TEXTURE_2D, texture, 0 );
gl.bindFramebuffer( gl.FRAMEBUFFER, null );
canvas.addEventListener("mousedown", function() {
    gl.bindFramebuffer(gl.FRAMEBUFFER, framebuffer);
    gl.clear( gl.COLOR_BUFFER_BIT);
    for(var i=0; i<6; i++) {
        gl.uniform1i(gl.getUniformLocation(program, "i"), i+1);
        gl.drawArrays(gl.TRIANGLES, 6*i, 6);
    }
    var x = event.clientX;
    var y = canvas.height - event.clientY; // Flipping y !!!!
    gl.readPixels(x, y, 1, 1, gl.RGBA,
                  gl.UNSIGNED_BYTE, color);
if(color[0]==255)
    if(color[1]==255) console.log("yellow");
    else if(color[2]==255) console.log("magenta");
    else console.log("red");

else if(color[1]==255)
    if(color[2]==255) console.log("cyan");
    else console.log("green");

else if(color[2]==255) console.log("blue");
else console.log("background");
// return to default framebuffer
    gl.bindFramebuffer(gl.FRAMEBUFFER, null);
// send index 0 to fragment shader
    gl.uniform1i(gl.getUniformLocation(program, "i"), 0);
// normal render
    gl.clear( gl.COLOR_BUFFER_BIT );
    gl.drawArrays(gl.TRIANGLES, 0, 36);
Picking by Selection

• Possible with render-to-texture
• When mouse clicked do an off-screen rendering with new viewing conditions that render only a small area around mouse
• Or render full scene and just sample off-screen image at mouse click position
• Keep track of what gets rendered to this off-screen buffer
• Know what was picked by returned color
HW9 Suggestions

• Create an off-screen frame buffer
  - With color(texture) and depth buffers
• Draw your three objects to this frame buffer, with each object having a unique, constant color
  - This color will act as the object’s ID
• Draw normally to on-screen frame buffer
• Allow user to click in the graphics window
HW9 Suggestions

• Read color at click point out of the off-screen frame buffer
• The color will tell you if an object was selected and which one
• Randomly change the diffuse color of the picked object
• Your EventListener should draw to both the off-screen and on-screen buffers