Math Review

CS 432 Interactive Computer Graphics
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Geometric Preliminaries

• Affine Geometry
  - Scalars + Points + Vectors and their ops

• Euclidian Geometry
  - Affine Geometry lacks angles, distance
  - New op: Inner/Dot product, which gives
    • Length, distance, normalization
    • Angle, Orthogonality, Orthogonal projection

• Projective Geometry
Affine Geometry

• Affine Operations:

  - Vector addition
  - Point subtraction
  - Point-vector addition

<table>
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<tr>
<th>Operation</th>
<th>Description</th>
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<td>Vector ← scalar · vector</td>
<td>scalar-vector multiplication</td>
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<tr>
<td>Vector ← vector + vector</td>
<td>vector-vector addition</td>
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<tr>
<td>Vector ← vector − vector</td>
<td>point-point difference</td>
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<tr>
<td>Point ← point + vector</td>
<td>point-vector addition</td>
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<tr>
<td>Point ← point − vector</td>
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• Affine Combinations: $\alpha_1 v_1 + \alpha_2 v_2 + \ldots + \alpha_n v_n$

  where $v_1, v_2, \ldots, v_n$ are vectors and $\sum_i \alpha_i = 1$

Example: $R = (1 - \alpha)P + \alpha Q$

- $\alpha < 0$
- $0 < \alpha < 1$
- $\alpha > 1$
Mathematical Preliminaries

• Vector: an $n$-tuple of real numbers

• Vector Operations
  - Vector addition: $u + v = w$
    • Commutative, associative, identity element (0)
  - Scalar multiplication: $cv$

• Note: Vectors and Points are different
  - Can not add points
  - Can find the vector between two points
Linear Combinations & Dot Products

• A linear combination of the vectors $v_1, v_2, \ldots, v_n$ is any vector of the form $\alpha_1 v_1 + \alpha_2 v_2 + \ldots + \alpha_n v_n$ where $\alpha_i$ is a real number (i.e. a scalar)

• Dot Product: $u \cdot v = \sum_{k=1}^{n} u_k v_k$

a real value $u_1 v_1 + u_2 v_2 + \ldots + u_n v_n$ written as $u \cdot v$
Fun with Dot Products

• **Euclidian Distance** from \((x,y)\) to \((0,0)\)

\[
\sqrt{x^2 + y^2}
\]

in general:

\[
\sqrt{x_1^2 + x_2^2 + \ldots + x_n^2}
\]

which is just:

\[
\sqrt{\vec{x} \cdot \vec{x}}
\]

• This is also the length of vector \(\vec{v}\):

\[
||\vec{v}|| \text{ or } |\vec{v}|
\]

• **Normalization** of a vector:

\[
\hat{\vec{v}} = \frac{\vec{v}}{||\vec{v}||}.
\]

• **Orthogonal** vectors:

\[
\vec{u} \cdot \vec{v} = 0
\]
Projections & Angles

- **Angle between vectors**, \( \theta \)
  \[
  \mathbf{u} \cdot \mathbf{v} = |\mathbf{u}||\mathbf{v}| \cos(\theta)
  \]
  \[
  \theta = \text{ang}(\mathbf{u}, \mathbf{v}) = \cos^{-1} \left( \frac{\mathbf{u} \cdot \mathbf{v}}{|\mathbf{u}| |\mathbf{v}|} \right) = \cos^{-1} (\hat{\mathbf{u}} \cdot \hat{\mathbf{v}}).
  \]

- **Projection of vectors**
  \[
  \mathbf{u}_1 = \frac{(\mathbf{u} \cdot \mathbf{v})}{(\mathbf{v} \cdot \mathbf{v})} \mathbf{v}
  \]
  \[
  \mathbf{u}_2 = \mathbf{u} - \mathbf{u}_1.
  \]
Matrices and Matrix Operators

- A $n$-dimensional vector:

\[
\begin{bmatrix}
  x_1 \\
  \cdot \\
  \cdot \\
  \cdot \\
  x_n
\end{bmatrix}
\]

- Matrix Operations:
  - Addition/Subtraction
  - Identity
  - Multiplication
    - Scalar
    - Matrix Multiplication

- Implementation issue:
  Where does the index start?
  (0 or 1, it’s up to you…)

\[
\begin{align*}
A + B &= B + A \\
A + (B + C) &= (A + B) + C \\
(cd)A &= c(dA) \\
1A &= A \\
c(A + B) &= cA + cB \\
(c + d)A &= cA + dA
\end{align*}
\]
Matrix Multiplication

- \([C] = [A][B]\)
- Sum over rows & columns
- Recall: matrix multiplication is \textit{not} commutative

\begin{align*}
C_{ij} &= \sum_{s=1}^{m} A_{is} B_{sj} \\
\begin{bmatrix}
a_{11} & a_{12} & a_{13} & a_{14} \\
a_{21} & a_{22} & a_{23} & a_{24} \\
a_{31} & a_{32} & a_{33} & a_{34} \\
a_{41} & a_{42} & a_{43} & a_{44}
\end{bmatrix} \begin{bmatrix}
b_{11} & b_{12} & b_{13} & b_{14} \\
b_{21} & b_{22} & b_{23} & b_{24} \\
b_{31} & b_{32} & b_{33} & b_{34} \\
b_{41} & b_{42} & b_{43} & b_{44}
\end{bmatrix}
\end{align*}

- \textit{Identity Matrix}: 
  1s on diagonal
  0s everywhere else
Matrix Determinants

- A single real number
- Computed recursively
- Example:
  \[
  \det(A) = \sum_{j=1}^{n} A_{i,j} (-1)^{i+j} M_{i,j}
  \]
  \[
  \det\begin{bmatrix} a & c \\ b & d \end{bmatrix} = ad - bc
  \]
- Uses:
  - Find vector ortho to two other vectors
  - Determine the plane of a polygon
Cross Product

• Given two non-parallel vectors, A and B
• A x B calculates third vector C that is orthogonal to A and B
• A x B = (a_yb_z - a_zb_y, a_zb_x - a_xb_z, a_xb_y - a_yb_x)

\[
A \times B = \begin{vmatrix}
\vec{x} & \vec{y} & \vec{z} \\
\vec{a_x} & \vec{a_y} & \vec{a_z} \\
\vec{b_x} & \vec{b_y} & \vec{b_z}
\end{vmatrix}
\]
Matrix Transpose & Inverse

• **Matrix Transpose**: Swap rows and cols:
  
  $A = \begin{bmatrix} 2 \\ 8 \end{bmatrix} \quad A^T = \begin{bmatrix} 2 & 8 \end{bmatrix}$

• Facts about the transpose:
  
  $(A^T)^T = A$
  
  $(A + B)^T = A^T + B^T$
  
  $(cA)^T = c(A^T)$
  
  $(AB)^T = B^T A^T$

• **Matrix Inverse**: Given $A$, find $B$ such that
  
  $AB = BA = I \quad B \rightarrow A^{-1}$

  (only defined for square matrices)
Derivatives of Polynomials

\[ f(x) = \alpha x^n \]
\[ \frac{df(x)}{dx} = \alpha nx^{n-1} \]

\[ f(x) = 5x^3 \]
\[ \frac{df(x)}{dx} = 15x^2 \]
Partial Derivatives of Polynomials

\[ f(x, y) = \alpha x^n y^m \]
\[ \frac{\partial f(x, y)}{\partial x} = \alpha nx^{n-1} y^m \]
\[ f(x, y) = 5x^3 y^4 \]
\[ \frac{\partial f(x, y)}{\partial x} = 15x^2 y^4 \]
Programming with OpenGL
Part 3: Shaders

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Objectives

• Simple Shaders
  - Vertex shader
  - Fragment shaders

• Programming shaders with GLSL

• Finish first program
Vertex Shader Applications

• Moving vertices
  - Transformations
    • Modeling
    • Projection
  - Morphing
  - Wave motion
  - Fractals
  - Particle systems

• Lighting
  - More realistic shading models
  - Cartoon shaders
Fragment Shader Applications

Per fragment lighting calculations

per vertex lighting
(Gouraud shading)

per fragment lighting
(Phong shading)
Fragment Shader Applications

Texture mapping

Procedural textures  environment mapping  bump mapping
Writing Shaders

• First programmable shaders were programmed in an assembly-like manner
• OpenGL extensions added vertex and fragment shaders
• Cg (C for graphics) C-like language for programming shaders
  - Works with both OpenGL and DirectX
  - Interface to OpenGL complex
• OpenGL Shading Language (GLSL)
GLSL

• OpenGL Shading Language
• Part of OpenGL 2.0 and ES 1.0 and up
• High level C-like language
• New data types
  - Matrices
  - Vectors
  - Samplers
• As of OpenGL 3.1, application must provide shaders
Execution Model

Vertex data
Shader Program

glDrawArrays

Application Program

Vertex Shader

GPU

Primitive Assembly

Simple Vertex Shader

attribute vec4 vPosition;
void main(void)
{
    gl_Position = vPosition;  // Simple pass-through
}

input from application (GLSL 1.4)

Use “in vec4 vPosition” for GLSL 1.5
Execution Model

Vertices → Vertex Processor → Clipper and Primitive Assembler → Rasterizer → Fragment Processor → Pixels

Application

Uniform Variables
Shader Program

Shader Program

Rasterizer → Fragment Shader → Frame Buffer

Fragment

Color

void
main()
{
    gl_FragColor = vec4( 1.0, 0.0, 0.0, 1.0 );
}

Every fragment simply colored red
Simple (New) Fragment Program

out vec4 fragcolor;
void main(void)
{
    fragcolor = vec4(1.0, 0.0, 0.0, 1.0);
}

Every fragment simply colored red
Declaring Variables

WARNING!!!!!

• Only declare variables that you actually use in your shader programs!

• In other words, if you change your shader programs and stop using a variable, REMOVE ITS DECLARATION

• Unused declared variables will generate incomprehensible, app-killing errors
Data Types

• C types: int, float, bool, uint, double

• Vectors:
  - float vec2, vec3, vec4
  - Also int (ivec), boolean (bvec), uvec, dvec

• Matrices: mat2, mat3, mat4
  - Stored by columns
  - Standard referencing m[row][column]

• C++ style constructors
  - vec3 a = vec3(1.0, 2.0, 3.0)
  - vec2 b = vec2(a)
Pointers

- There are no pointers in GLSL
- We can use C structs which can be copied back from functions
- Because matrices and vectors are basic types they can be passed into and out from GLSL functions, e.g.
  \[
  \text{mat3 func(mat3 a)}
  \]
- Variables passed by copying
Qualifiers

• GLSL has many of the same qualifiers such as `const` as C/C++

• Need others due to the nature of the execution model

• Variables can change
  - Once per primitive
  - Once per vertex
  - Once per fragment
  - At any time in the application

• Vertex attributes are interpolated by the rasterizer into fragment attributes
Attribute Interpolation

- Vertex attributes are interpolated by the rasterizer into fragment attributes.
- For example, a color associated with a vertex will be interpolated over the fragments/pixels generated from the associated triangle.
Attribute Qualifier

• Attribute-qualified variables can change at most once per vertex
• There are a few built-in variables such as gl_Position but most have been deprecated
• User defined (in application program)
  - attribute float temperature
  - attribute vec3 velocity
- Recent versions of GLSL use in and out qualifiers to get to and from shaders
Uniform Qualifier

• Variables that are constant for an entire primitive
• Can be changed in application and sent to shaders
• Cannot be changed in shader
• Used to pass information to shader such as the time or a bounding box of a primitive
Varying Qualifier

• Variables that are passed from vertex shader to fragment shader
• Automatically interpolated by the rasterizer
• With WebGL 1.0, GLSL uses the varying qualifier in both shaders
  ```glsl
  varying vec4 color;
  ```
• More recent versions of WebGL use `out` in vertex shader and `in` in the fragment shader
  ```glsl
  out vec4 color; //vertex shader
  in vec4 color;  // fragment shader
  ```
Our Naming Convention

• Attributes passed to vertex shader have names beginning with v (vPosition, vColor) in both the application and the shader
  - Note that these are different entities with the same name

• Varying variables begin with f (fColor) in both shaders
  - must have same name

• Uniform variables are can have any/the same name in application and shaders
Example: Vertex Shader

```glsl
attribute vec4 vPosition, vColor;
varying vec4 fColor;
void main()
{
    gl_Position = vPosition;
    fColor = vColor;
}
```
Corresponding Fragment Shader

precision mediump float;

varying vec4 fColor;
void main()
{
  gl_FragColor = fColor;
}
Precision Declaration

• In GLSL for WebGL we must specify desired precision in fragment shaders
  - artifact inherited from OpenGL ES
  - ES must run on very simple embedded devices that may not support 32-bit floating point
  - All implementations must support mediump
  - No default for float in fragment shader

• Can use preprocessor directives (#ifdef) to check if highp supported and, if not, default to mediump
Pass Through Fragment Shader

```cpp
#ifdef GL_FRAGMENT_PRECISION_HIGH
    precision highp float;
#else
    precision mediump float;
#endif

varying vec4 fcolor;
void main(void)
{
    gl_FragColor = fcolor;
}
```
const vec4 red = vec4(1.0, 0.0, 0.0, 1.0);
in vec4 vPosition;
out vec4 color_out;
void main(void)
{
    gl_Position = vPosition;
    color_out = vPosition.x * red;
}
precision highp float;

in vec4 color_out;
out vec4 fragcolor;
void main(void)
{
    fragcolor = color_out;
}
Sending Colors from Application

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

var vColor = gl.getAttribLocation( program, "vColor" );
gl.vertexAttribPointer( vColor, 3, gl.FLOAT, false, 0, 0 );
gl.enableVertexAttribArray( vColor );
```
Sending a Uniform Variable

// in application

vec4 color = vec4(1.0, 0.0, 0.0, 1.0);
colorLoc = gl.getUniformLocation( program, "color" );
gl.uniform4f( colorLoc, color );

// in fragment shader (similar in vertex shader)

uniform vec4 color;
void main()
{
    gl_FragColor = color;
}

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Consistent Declaration of Variables

• Data is being passed between multiple programs (application, vertex & fragment shaders)
• Variables storing the same data in different programs must be declared consistently!
Consistent Declaration of Variables (Example)

• *attribute* and *varying* variables

• In application

```javascript
var vColor = gl.getAttribLocation(program, "vColor");
gl.vertexAttribPointer(vColor, 3, gl.FLOAT, false, 0, 0);
```

• In vertex shader

```glsl
attribute vec3 vColor;
varying vec3 fColor;
fColor = vColor;
```

• In fragment

```glsl
varying vec3 fColor;
gl_FragColor = vec4(fColor, 1.0);
```
Consistent Declaration of Variables (Example)

- **uniform** variables

- In application

  ```
  vec4 color = vec4(1.0, 0.0, 0.0, 1.0);
  colorLoc = gl.getUniformLocation( program, "color" );
  gl.uniform4f( colorLoc, color );
  ```

- In fragment shader // Same in vertex shader

  ```
  uniform vec4 color;
  gl_FragColor = color;
  ```

- Also note `gl.uniform4f`
User-defined functions

• Similar to C/C++ functions
• Except
  - Cannot be recursive
  - Specification of parameters

```
returnType MyFunction(in float inputValue,  
out int outputValue,  
inout float inAndOutValue);
```
Passing values

- call by **value-return**
- Variables are copied in
- Returned values are copied back
- Three possibilities
  - **in**
  - **out**
  - **inout**
  - No qualifier → **in**
Operators and Functions

• Standard C functions
  - Trigonometric
  - Arithmetic
  - Normalize, reflect, length

• Overloading of vector and matrix types
  mat4 a;
  vec4 b, c, d;
  c = b*a; // a column vector stored as a 1d array
  d = a*b; // a row vector stored as a 1d array
Swizzling and Selection

• Can refer to array elements by element using [] or selection (.) operator with
  - x, y, z, w
  - r, g, b, a
  - s, t, p, q
  - a[2], a.b, a.z, a.p are the same

• Swizzling operator lets us manipulate components
  
  ```
  vec4 a, b;
  a.yz = vec2(1.0, 2.0);
  a.xw = b.yy;
  b = a.yxzw;
  ```
Programming with OpenGL
Part 4: Color and Attributes
Objectives

• Expanding primitive set
• Adding color
• Vertex attributes
WebGL Primitives

GL_POINTS
GL_LINES
GL_LINE_STRIP
GL_LINE_LOOP
GL_TRIANGLES
GL_TRIANGLE_STRIP
GL_TRIANGLE_FAN
Polygon Issues

• WebGL will only display triangles
  - Simple: edges cannot cross
  - Convex: All points on line segment between two points in a polygon are also in the polygon
  - Flat: all vertices are in the same plane

• Application program must tessellate a polygon into triangles (triangulation)

• OpenGL 4.1 contains a tessellator
Polygon Testing

• Conceptually simple to test for simplicity and convexity
• Time consuming
• Earlier versions assumed both and left testing to the application
• Present version only renders triangles
• Need algorithm to triangulate an arbitrary polygon
Good and Bad Triangles

- Long thin triangles render badly
- Equilateral triangles render well
- Maximize minimum angle
- Delaunay triangulation for unstructured points
Triangularization

- Convex polygon

- Start with abc, remove b, then acd, ....
Non-convex (concave)
Recursive Division

- There are a variety of recursive algorithms for subdividing concave polygons
OpenGL Attributes

- Attributes determine the appearance of objects
  - Color (points, lines, polygons)
  - Size and width (points, lines)
  - Stipple pattern (lines, polygons)
  - Polygon mode
    - Display as filled: solid color or stipple pattern
    - Display edges
    - Display vertices
- Only a few (glPointSize) are supported by WebGL functions
RGB color

- Each color component is stored separately in the frame buffer
- Usually 8 bits per component in buffer
- Color values can range from 0.0 (none) to 1.0 (all) using floats or over the range from 0 to 255 using unsigned bytes
Indexed Color

• Colors are indices into tables of RGB values
• Requires less memory
  - indices usually 8 bits
  - not as important now
  • Memory inexpensive
  • Need more colors for shading
Smooth Color

• Default is *smooth* shading
  - Rasterizer interpolates vertex colors across visible polygons

• Alternative is *flat shading*
  - Color of first vertex determines fill color
  - Handle in shader
Setting Colors

• Colors are ultimately set in the fragment shader but can be determined in either shader or in the application

• Application color: pass to vertex shader as a uniform variable (next lecture) or as a vertex attribute

• Vertex shader color: pass to fragment shader as varying variable (next lecture)

• Fragment color: can alter via shader code