Computer Graphics Seminar

MTAT.03.296

Spring 2014
Computer Graphics

- Graphical illusion via the computer
- Displaying something meaningful (inc art)
Math

• Computers are good at... computing.
• To do computer graphics, we need math for the computer to compute.
• Geometry, algebra, calculus.
Point

- Simplest geometry primitive
- In homogeneous coordinates: $(x, y, z, w), w \neq 0$
- Usually you can put $w = 1$
- Actual division will be done by GPU later
Line (segment)

- Consists of:
  - 2 endpoints
  - *Infinite* number of points between
- Defined by the endpoints
- Interpolated in GPU

\((x_1, y_1, z_1, 1)\)
\((x_2, y_2, z_2, 1)\)
Triangle

- Consists of:
  - 3 points called vertices
  - 3 lines called edges
  - 1 face

- Defined by 3 vertices

- Lines and face will be interpolated in GPU

- Counter-clockwise order defines front face
Why triangles?

• They are in many ways the simplest polygons
  • 3 different points always form a plane
  • Easy to rasterize (fill the face with points)
  • Every other polygon can be converted to triangles

• OpenGL used to support other polygons too
  • Must have been:
    - Simple – No edges intersect each other
    - Convex – All points between any two points are inner points
Examples of polygons
OpenGL < 3.1 primitives

Figure 2-7  Geometric Primitive Types

OpenGL Programming Guide 7th edition, p49
After OpenGL 3.1

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**Figure 3.1** Vertex layout for a triangle strip

**Figure 3.2** Vertex layout for a triangle fan

In the beginning there were points

- Now that we can define our geometric objects, what next?
- We want to move our objects!

Luckily GPU will do this work for us.
Transformations

- It turns out that homogeneous coordinates allows us to easily do:
  - Linear transformations
    - Scaling, reflection
    - Rotation
    - Shearing
  - Affine transformations
    - Translation (shifting)
  - Projection transformations
    - Perspective
    - Orthographic

Actually these we could do without homogeneous coordinates...

This too...
Transformations

- Every transformation is a function
- As you remember from Algebra, linear functions can be represented as matrices

\[
f(v) = (2x, y, z) = \begin{pmatrix} 2 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} x \\ y \\ z \end{pmatrix}
\]

\[v \in \mathbb{R}^3\]

\[v = (x, y, z)\]

You should transpose the result later
Transformations

- GPU-s are built for doing transformations with matrices.
- Remember, computers are made for computing.
- Let's look at some linear transformations...

\[ f(a_1 x_1 + \ldots + a_n x_n) = a_1 f(x_1) + \ldots + a_n f(x_n) \]

We don't use homogeneous coordinates at the moment, don't worry, they'll be back...
Scaling

- Redefines the basis vectors as some multiple of the previous basis vectors.

\[
\begin{pmatrix}
2 & 0 \\
0 & 1
\end{pmatrix} \cdot \begin{pmatrix} x \\ y \end{pmatrix} \quad \begin{pmatrix}
2 & 0 \\
0 & 1
\end{pmatrix} \cdot \begin{pmatrix} 1.5 \\ 1.5 \end{pmatrix} = \begin{pmatrix} 3 \\ 1.5 \end{pmatrix}
\]
Scaling

- In general we could scale each axis

\[
\begin{pmatrix}
  a_x & 0 & 0 \\
  0 & a_y & 0 \\
  0 & 0 & a_z
\end{pmatrix}
\]

\(a_x\) – x-axis scale factor

\(a_y\) – y-axis scale factor

\(a_z\) – z-axis scale factor

- If some factor is negative, this matrix will reflect the points from that axis. Thus we get reflection.
Shearing

- Not much used by itself, but remember it for translations later.
- Rotates only one axis.
- Squares become parallelograms.

\[
\begin{pmatrix}
1 & 0 \\
1 & 1
\end{pmatrix}
\begin{pmatrix}
0 \\
2
\end{pmatrix} =
\begin{pmatrix}
0 \\
2
\end{pmatrix}
\]

\[
\begin{pmatrix}
1 & 0 \\
1 & 1
\end{pmatrix}
\begin{pmatrix}
1 \\
2
\end{pmatrix} =
\begin{pmatrix}
1 \\
3
\end{pmatrix}
\]
Shearing

- Shear-x, we rotate x basis vector by angle $\phi$ counter-clockwise
  \[
  \begin{pmatrix}
    1 & 0 \\
    \tan(\phi) & 1
  \end{pmatrix}
  \begin{pmatrix}
    x \\
    y
  \end{pmatrix} =
  \begin{pmatrix}
    x \\
    y + \tan(\phi) \cdot x
  \end{pmatrix}
  \]

- Shear-y, we rotate y basis vector by angle $\phi$ clockwise
  \[
  \begin{pmatrix}
    1 & \tan(\phi) \\
    0 & 1
  \end{pmatrix}
  \begin{pmatrix}
    x \\
    y
  \end{pmatrix} =
  \begin{pmatrix}
    x + \tan(\phi) \cdot y \\
    y
  \end{pmatrix}
  \]
Rotation

- Shearing rotated only one axis
- Also changed the size of the basis vector
- Can we do better?

Did you notice that the columns of the transformation matrix show the coordinates of the new basis vectors?
\[ e'_0 = (|a|, |b|) = (\cos(\alpha), \sin(\alpha)) \]
\[ e'_1 = (|a'|, |b'|) = (-\sin(\alpha), \cos(\alpha)) \]

\[ \cos(\alpha) = \frac{|a|}{|e'_0|} = \frac{|a|}{1} = |a| \]
Rotation

• So if we rotate by $\alpha$ in counter-clockwise order in 2D, the transformation matrix is:

$$
\begin{pmatrix}
\cos(\alpha) & -\sin(\alpha) \\
\sin(\alpha) & \cos(\alpha)
\end{pmatrix}
$$

• In 3D we can do rotations in each plane (xy, xz, yz), so there can be 3 different matrices.
Rotation

- To do a rotation around an arbitrary axis, we can:
  - Rotate that axis to be the x-axis
  - Rotate around the new x-axis
  - Invert the first rotations (move the old x-axis back)

- OpenGL provides a command for rotating around a given axis.

- Sometimes quaternions are used for rotations.

Quaternions are elements of a number system that extend the complex numbers...
Do we have everything now?

- We can scale, share and rotate our geometry around the origin...

What if we have an object not centered in the origin?
Translation

- Imagine that our 1D world is located at $y=1$ line in 2D space.

- Notice that all the points are in the form: $(x, 1)$
Translation

• What happens if we do shear-y(45°) operation on the 2D world?

• Everything in our world has moved magically one x-coordinate to the right...

\[ \tan(45°) = 1 \]
Translation

- What if we do shear-y(63.4°)?

\[ \tan(63.4°) = 2 \]

- Everything has now moved 2 x-coordinates to the right from the original position.

- We can do translation / shift!
Translation

- When we represent our points in one dimension higher space, where the extra coordinate is 1, we get to the **homogeneous** space.

\[
\begin{pmatrix}
1 & x_t \\
0 & 1
\end{pmatrix} \cdot \begin{pmatrix} x \\ 1 \end{pmatrix} = \begin{pmatrix} x + x_t \\ 1 \end{pmatrix}
\]

\[
\begin{pmatrix}
1 & 0 & x_t \\
0 & 1 & y_t \\
0 & 0 & 1
\end{pmatrix} \cdot \begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = \begin{pmatrix} x + x_t \\ y + y_t \\ z + z_t \end{pmatrix}
\]
Transformations

- This together gives us a very good toolset to transform our geometry as we wish.

\[
\begin{pmatrix}
  a & b & c & x_t \\
  d & e & f & y_t \\
  g & h & i & z_t \\
  0 & 0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
  x \\
  y \\
  z \\
  1
\end{pmatrix}
= \begin{pmatrix}
  ax + by + cz + x_t \\
  dx + ey + fz + y_t \\
  gx + hy + iz + z_t \\
  1
\end{pmatrix}
\]

Used for perspective projection...
Multiple transformations

- Everything starts from the origin!
- To apply multiple transformations, just multiply matrices.
Multiple transformations

Our initial geometry defined by vertices: (-1, -1), (1, -1), (1, 1), (-1, 1)
Multiple transformations

\[
\begin{pmatrix}
\cos(45^\circ) & -\sin(45^\circ) & 0 \\
\sin(45^\circ) & \cos(45^\circ) & 0 \\
0 & 0 & 1
\end{pmatrix}
\]
Multiple transformations

\[
\begin{pmatrix}
1 & 0 & 4 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{pmatrix}
\]
Multiple transformations

• We can combine the transformations to a single matrix.

\[
\begin{pmatrix}
\cos(45^\circ) & -\sin(45^\circ) & 0 \\
\sin(45^\circ) & \cos(45^\circ) & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
1 & 0 & 4 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{pmatrix}
= 
\begin{pmatrix}
\cos(45^\circ) & -\sin(45^\circ) & 4 \\
\sin(45^\circ) & \cos(45^\circ) & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

• This also works for combining different linear transformations, but the resulting matrix isn't that clear...

• Order of transformations / matrices is important!

Now we know how it's supposed to go...
OpenGL

- GPU API
- I.e a set of commands that program can give to GPU
- Supported in many languages

Vertices a, b, c → Transformations A, B, C → Draw!
WebGL

- GPU API in JavaScript
- Supported by major browsers
- THREE.js – Higher level library to ease your coding: [http://threejs.org/docs/](http://threejs.org/docs/)
Forward is backward

• Actually you need to tell GPU commands in this order:
  • Transformations
  • Vertices

```c
glTranslatef(0.0, 0.0, -1.0);
glRotatef(60, 1.0, 0.0, 0.0);
glRotatef(-20, 0.0, 0.0, 1.0);

 glBegin(GL_QUADS);
  glVertex3fv(...);
  glVertex3fv(...);
  glVertex3fv(...);
  glVertex3fv(...);
 glEnd();
```

Prior to OpenGL 3
State machine

- GPU acts like a state machine

Prior to OpenGL 3
Multiple objects in the scene?

- Each object has its own geometry
- And its own transformations for that geometry
- OpenGL has a single ModelView matrix

Prior to OpenGL 3

```c
.glTranslatef(0.0, 0.0, -1.0);
.glRotatef(60, 1.0, 0.0, 0.0);
.glRotatef(-20, 0.0, 0.0, 1.0);
.glBegin(GL_QUADS);
.glVertex3fv(...);
.glVertex3fv(...);
.glVertex3fv(...);
.glVertex3fv(...);
.glEnd();
```
Multiple objects in the scene

- OpenGL has a matrix stack
- We can push a copy to the stack (save)
- We can pop the top matrix from the stack (load)

```c
// Prior to OpenGL 3

glPushMatrix();  
  glTranslatef(10.0, 0.0, -1.0);  
  drawCube();  
  glPopMatrix();  

glPushMatrix();  
  glTranslatef(-10.0, 0.0, -1.0);  
  drawSphere();  
  glPopMatrix();
```
Multiple objects in the scene

- More complex geometry for a single object

```c
// Prior to OpenGL 3

glPushMatrix();

// Translation
glTranslatef(10.0, 0.0, -1.0);

drawPalm();

// Saved matrices here

glPushMatrix();

// Translation
glTranslatef(-1.0, 0.0, 0.0);

drawFingers();

glPopMatrix();

// MV

// MV*A

// MV*A*B

// MV

// MV*A

// MV
```
Old and new OpenGL?

- Lot has changed from OpenGL 3.
- Everything old still works in compatibility mode.

**Prior to OpenGL 3**

- `glBegin(...)`
- `glVertex(...)`
- `glEnd(...)`
- `glTranslate(...)`
- `glRotate(...)`
- `glScale(...)`
- `glMaterial(...)`

**OpenGL 3+**

- Vertex Array Object (VAO)
- Vertex Buffer Object (VBO)
- Use other Matrix library
- Send your matrices to shaders
- Vertex Buffer Object

Good tutorials: [http://antongerdelan.net/opengl/](http://antongerdelan.net/opengl/)
Multiple objects in the scene

• Useful to think of the scene as a tree
Next time…

- Graphics pipeline in more detail
- How to define color for our geometry?
- Vertex and fragment shaders
- What else could be done?

Our geometry defined by 4 vertices
A parallelogram…