CSCI 420 Computer Graphics  
Lecture 3

Graphics Pipeline

Primitives: Points, Lines, Triangles  
[Angel Ch. 2]

The Framebuffer

• Special memory on the graphics card
• Stores the current pixels to be displayed on the monitor
• Monitor has no storage capabilities
• The framebuffer is copied to the monitor at each refresh cycle

Rendering with OpenGL

• Application generates the geometric primitives (polygons, lines)
• System draws each one into the framebuffer
• Entire scene redrawn anew every frame
• Compare to: off-line rendering  
  (e.g., Pixar Renderman, ray tracers)

The pipeline is implemented by OpenGL, graphics driver and the graphics hardware

OpenGL programmer does not need to implement the pipeline.

However, pipeline is reconfigurable  
⇒ “shaders”

Graphics Pipeline

• Efficiently implementable in hardware  
  (but not in software)
• Each stage can employ multiple specialized processors, working in parallel, buses between stages
• #processors per stage, bus bandwidths are fully tuned for typical graphics use
• Latency vs throughput

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**Vertices (compatibility profile)**

- Vertices in world coordinates
  
  ```c
  void glVertex3f(GLfloat x, GLfloat y, GLfloat z)
  
  – Vertex (x, y, z) is sent down the pipeline.
  – Function call then returns.
  ```

- Use GLtype for portability and consistency
- `glVertex{234}{sfid}{v}(TYPE coords)`

**Vertices (core profile)**

- Vertices in world coordinates
- Store vertices into a Vertex Buffer Object (VBO)
- Upload the VBO to the GPU during program initialization (before rendering)
- OpenGL renders directly from the VBO

**Transformer (compatibility profile)**

- Transformer in world coordinates
- Must be set before object is drawn!
  
  ```c
  glRotatef(45.0, 0.0, 0.0, -1.0);
  glVertex2f(1.0, 0.0);
  ```

- Complex [Angel Ch. 3]

**Transformer (core profile)**

- Transformer in world coordinates
- 4x4 matrix
- Created manually by the user
- Transmitted to the shader program before rendering

**Clipper**

- Mostly automatic (must set viewing volume)

**Projector**

- Complex transformation [Angel Ch. 4]
Rasterizer

• Interesting algorithms [Angel Ch. 6]
• To window coordinates
• Antialiasing

Geometric Primitives

• Suppose we have 8 vertices: P₀, P₁, P₂, P₃, P₄, P₅, P₆, P₇
• Then, one can interpret them as:

Triangles

• Can be any shape or size
• Well-shaped triangles have advantages for numerical simulation
• Shape quality makes little difference for basic OpenGL rendering

Geometric Primitives

(compatibility profile)

• Specified via vertices
• General schema
  
  \[
  \text{glBegin}(\text{type});
  \text{glVertex3f}(x_1, y_1, z_1);
  \ldots
  \text{glVertex3f}(x_N, y_N, z_N);
  \text{glEnd}();
  \]

  • type determines interpretation of vertices
  • Can use \text{glVertex2f}(x, y) in 2D

Example: Draw Two Square Edges (compatibility profile)

• Type = GL_LINES
  
  \[
  \text{glBegin}(\text{GL_LINES});
  \text{glVertex3f}(0.0, 0.0, -1.0);
  \text{glVertex3f}(1.0, 0.0, -1.0);
  \text{glVertex3f}(1.0, 1.0, -1.0);
  \text{glVertex3f}(0.0, 1.0, -1.0);
  \text{glEnd}();
  \]

  • Calls to other functions are allowed between \text{glBegin(type)} and \text{glEnd}();

Geometric Primitives

(core profile)

• Specified via vertices
• Stored in a Vertex Buffer Object (VBO)

\[
\text{int numVertices} = 300;
\text{float vertices}[3 * \text{numVertices}];
\]

// (fill the "vertices" array ...)

// create the VBO:
\text{GLuint buffer};
\text{glGenBuffers}(1, &buffer);
\text{glBindBuffer(GL_ARRAY_BUFFER, buffer)};
\text{glBufferData(GL_ARRAY_BUFFER, sizeof(vertices), vertices, GL_STATIC_DRAW});


Render Points and Line Segments (compatibility profile)

```c
 glBegin(GL_POINTS); // or GL_LINES to render lines
 glVertex3f(...);
 ...
 glVertex3f(...);
 glEnd();
```

Main difference between the two profiles

**Compatibility:**

- **Rendering:**
  - `glBegin(type);`
  - `glVertex3f(x1, y1, z1);`
  - `...`
  - `glVertex3f(xN, yN, zN);`
  - `glEnd();`

**Core:**

- **Initialization:**
  - `int numVertices = 300;`
  - `float vertices[3 * numVertices];`
  - `... fill the "vertices" array ...`
  - `... create the VBO: GLUInt buffer;` `glGenBuffers(1, &buffer);` `glBindBuffer(GL_ARRAY_BUFFER, buffer);` `glBufferData(GL_ARRAY_BUFFER, sizeof(vertices), vertices, GL_STATIC_DRAW);`
- **Rendering:**
  - `glDrawArrays(type, 0, numVertices);`

Common Bug

```c
int numVertices = 50000;
float *vertices = (float*) malloc(sizeof(float) * 3 * numVertices);
... fill the "vertices" array ...
glBufferData(GL_ARRAY_BUFFER, sizeof(vertices), vertices, GL_STATIC_DRAW);
```

What is wrong?

- Polygons enclose an area
- Rendering of area (fill) depends on attributes
- All vertices must be in one plane in 3D
- GL_POLYGON and GL_QUADS are only available in the compatibility profile (removed in core profile since OpenGL 3.1)
Polygon Restrictions (relevant for compatibility profile only)

- OpenGL Polygons must be simple
- OpenGL Polygons must be convex

(a) simple, but not convex
(b) non-simple
(c) convex

Why Polygon Restrictions?
- Non-convex and non-simple polygons are expensive to process and render
- Convexity and simplicity is expensive to test
- Behavior of OpenGL implementation on disallowed polygons is "undefined"
- Some tools in GLU for decomposing complex polygons (tessellation)
- Triangles are most efficient
- Polygons removed since OpenGL 3.1

Triangle Strips

- Efficiency in space and time
- Reduces visual artefacts

Summary

1. Graphics pipeline
2. Primitives: vertices, lines, triangles