Programmable Shaders

Based on the Slides from
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Objectives

- Introduce programmable pipelines
  - Vertex shaders
  - Fragment shaders
- Shader programming with GLSL
- Related materials
  - Angel: Chapter 2

Programming with OpenGL
Part 1: Basic Concepts

Modified from the Slides from

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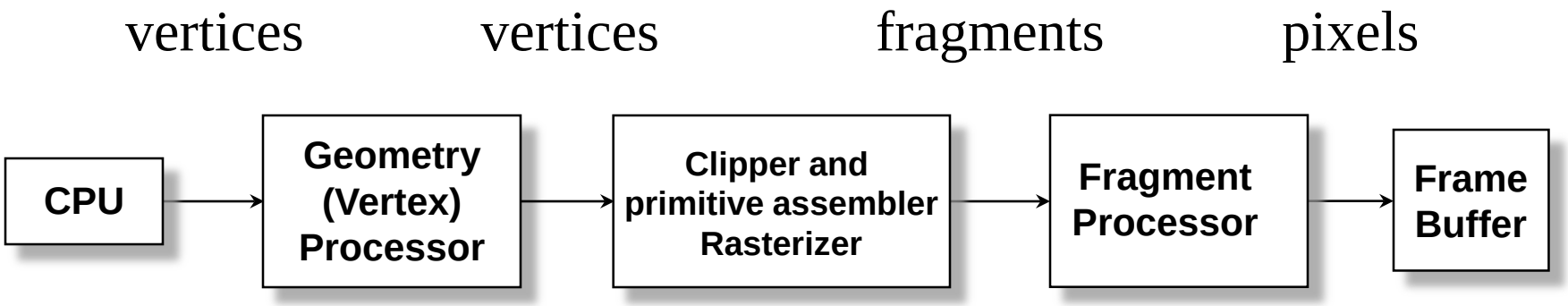
Graphics Pipeline

- OpenGL architecture
  - OpenGL as a state machine
  - OpenGL as a data flow machine



Geometric Calculations

- Geometric data: set of vertices + type
  - Can come from program
  - Type: point, line, polygon
  - Vertex data can be
    - (x,y,z,w) coordinates of a vertex (glVertex)
    - Normal vector
    - Texture Coordinates
    - RGBA color
    - Other data: color indices, edge flags
    - Additional user-defined data in GLSL

Per-Vertex Operations

- Vertex locations are transformed by the model-view matrix into eye coordinates
- Normals must be transformed with the inverse transpose of the model-view matrix so that $v \cdot n = v' \cdot n'$ in both spaces
- Textures coordinates are generated if autotexture enabled and the texture matrix is applied

Primitive Assembly

- Vertices are next assembled into objects
  - Polygons
  - Line Segements
  - Points
- Transformation by projection matrix
- Clipping
  - Against user defined planes
  - View volume, $x=\pm w$, $y=\pm w$, $z=\pm w$
  - Polygon clipping can create new vertices
- Perspective Division
- Viewport mapping

Rasterization

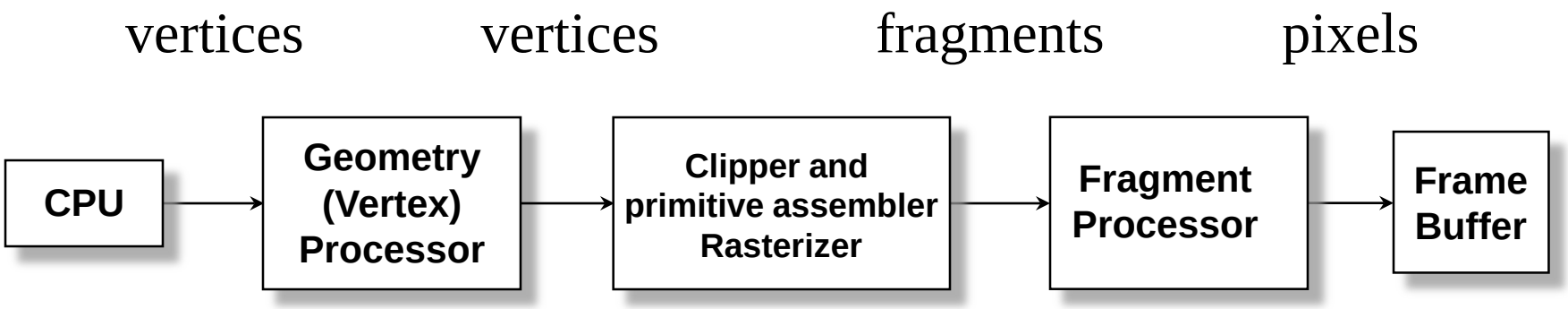
- Geometric entities are rasterized into **fragments**
- Each fragment corresponds to a point on an integer grid: a displayed pixel
- Hence each fragment is a *potential pixel*
- Each fragment has
  - A color
  - Possibly a depth value
  - Texture coordinates

Fragment Operations

- Texture generation
- Fog
- Antialiasing
- Scissoring
- Alpha test
- Blending
- Dithering
- Logical Operation
- Masking

OpenGL Architecture

- In obsolete OpenGL, every step in the pipeline is handled by the system (library)
  - OpenGL API
  - Hardware accelerated
  - Unchangeable by the application programmer



Major Changes

- Recent major advance in real time graphics is a programmable pipeline
  - First introduced by NVIDIA GForce 3
  - Supported by high-end commodity cards
    - NVIDIA, ATI, 3D Labs
  - Software Support
    - Direct X 8 , 9, 10, 11
    - OpenGL Extensions
    - OpenGL Shading Language (GLSL)
    - High-Level Shading Language (HLSL)
    - Cg

Programmable Shaders

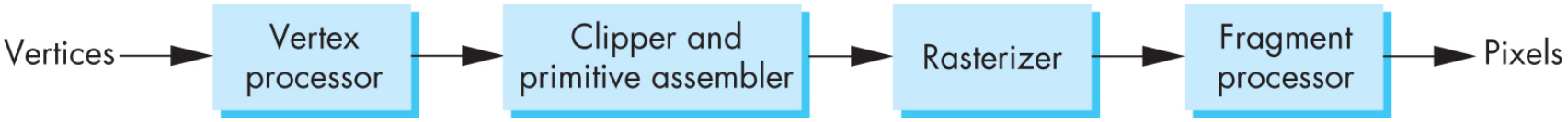
- Replace fixed function vertex and fragment processing by programmable processors called **shaders**
- If we use a programmable shader, we must do all required functions of the fixed function processor

Various Shaders

- Vertex shader
- Fragment shader
- Geometry shader
- Hull shader, Tessellator, Domain shader
- Compute shader

Performance Gains

- Performance is achieved by using GPU rather than CPU
- Control GPU through shader programs
- Application's job is to send data to GPU
- GPU does all rendering and many of geometry/data processing



OpenGL 3.1

- 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
- Backward compatibility not required

Other Versions

- OpenGL ES
  - Embedded systems
  - Version 1.0 simplified OpenGL 2.1
  - Version 2.0 simplified OpenGL 3.1
    - Shader based
- WebGL
  - Javascript implementation of ES 2.0
  - Supported on newer browsers
- OpenGL 4.1 and 4.2
  - Add geometry shaders and tessellator

What about Direct X?

- Windows only
- Advantages
  - Better control of resources
  - Access to high level functionality
- Disadvantages
  - New versions not backward compatible
  - Windows only
- Recent advances in shaders are leading to convergence with OpenGL

OpenGL and GLSL

- Shader based OpenGL 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

GLSL

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

Programming with OpenGL
Part 2: Shaders

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Writing Shaders

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

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
- New OpenGL functions to compile, link and get information to shaders

Vertex Processor

- Takes in vertex data
  - Positions
- Produces
  - Position in clip coordinates

Simple Vertex Shader

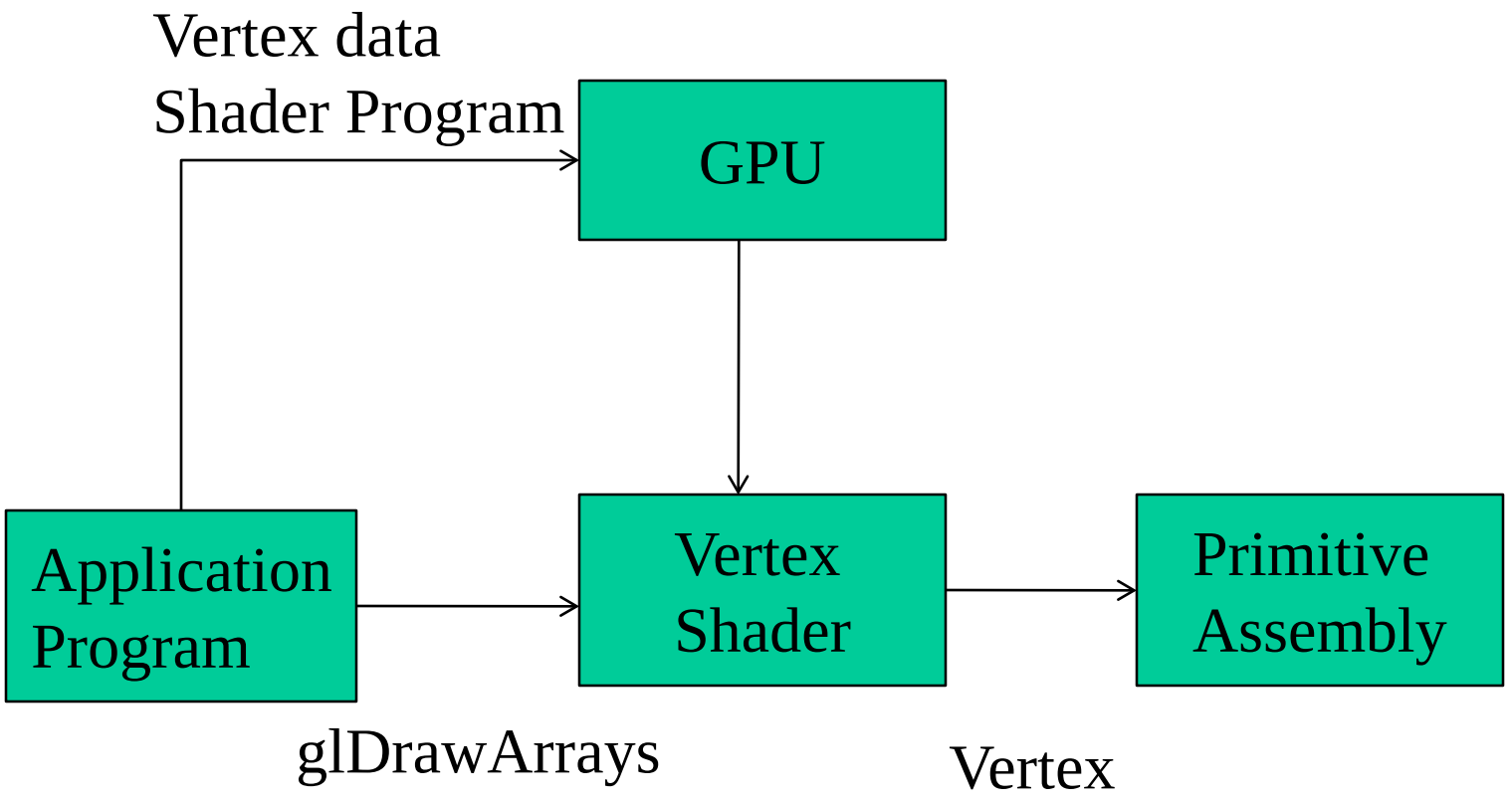
input from application

```
in vec4 vPosition;
void main(void)
{
    gl_Position = vPosition;
}
```

must link to variable in application

built-in variable

Execution Model



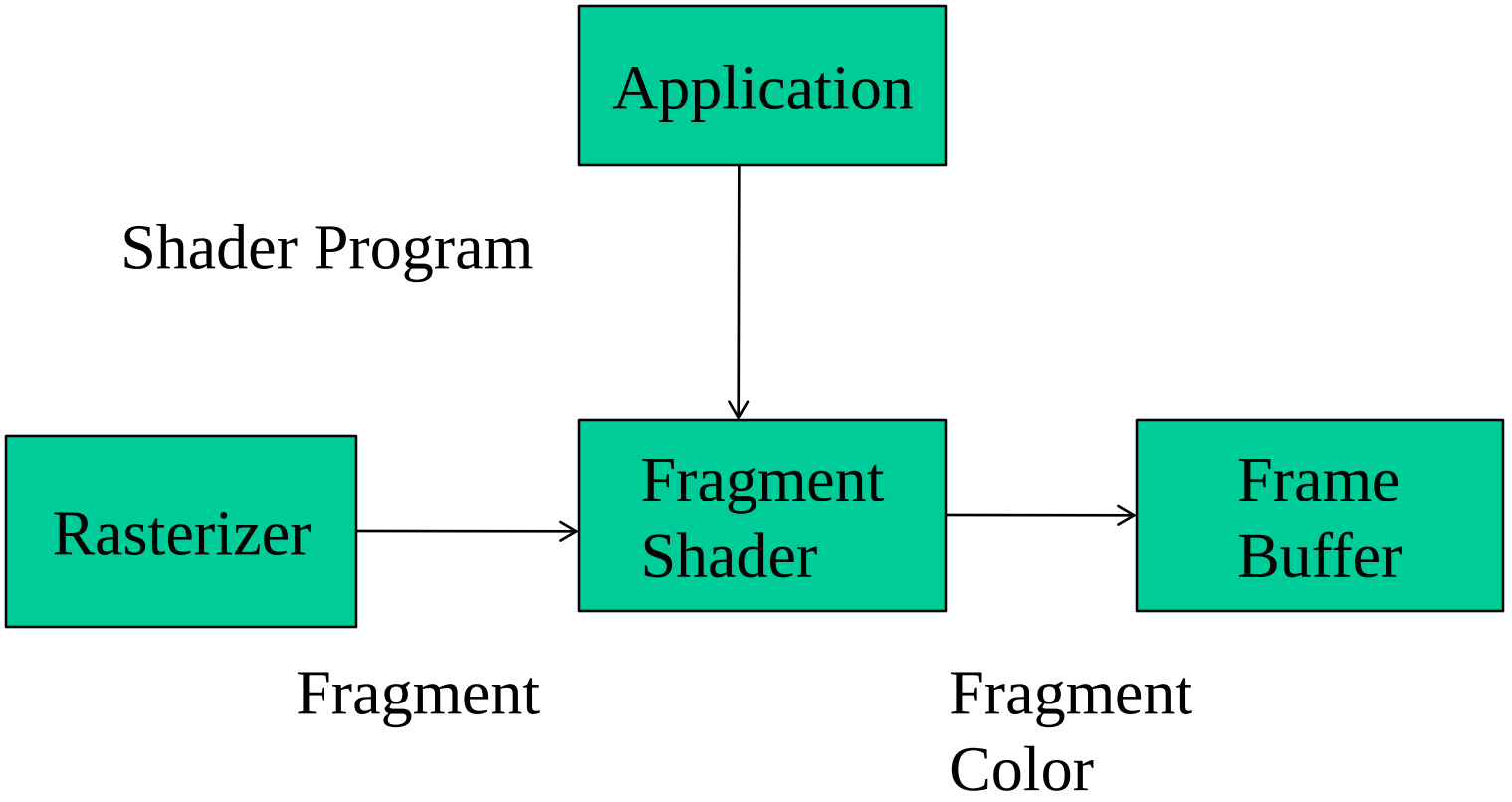
Fragment Processor

- Takes in output of rasterizer (fragments)
  - Vertex values have been interpolated over primitive by rasterizer
- Outputs a fragment
  - Color
- Fragments still go through fragment tests
  - Hidden-surface removal
  - alpha

Simple Fragment Shader

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

Execution Model



Data Types

- C types: int, float, bool
- Vectors:
  - float vec2, vec3, vec4
  - Also int (ivec) and boolean (bvec)
- 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 output from GLSL functions, e.g.

  mat3 func(mat3 a)

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
  - Per primitive (**`uniform`**)
  - Per vertex (**`in`**)
  - Per fragment (**`out`**)
  - At any time in the application
- Vertex attributes are interpolated by the rasterizer into fragment attributes

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 bounding box of a primitive

in Qualifier

- There are a few built in variables such as gl_Position but most have been deprecated

- User defined (in application program)
  - Use **`in`** qualifier to get to shader
  - **`in float temperature`**
  - **`in vec3 velocity`**

out Qualifier

- Variables that are passed from vertex shader to fragment shader
- Automatically interpolated by the rasterizer
- Old style used the varying qualifier

```
varying vec4 color;
```

- Now use **out** in vertex shader and **in** in the fragment shader

```
out vec4 color;
```

Example: Vertex Shader

```
const vec4 red = vec4(1.0, 0.0, 0.0, 1.0);
in vec4 vPosition;
out vec3 color_out;
void main(void)
{
  gl_Position = vPosition;
  color_out = red;
}
```

Required Fragment Shader

```
in vec3 color_out;
void main(void)
{
  gl_FragColor = color_out;
}
// in the latest version use form
// out vec4 fragcolor;
// fragcolor = color_out;
```

Passing values

- call by **value-return**
- Variables are copied in
- Returned values are copied back
- Three possibilities
  - **in**
  - **out**
  - **inout** (deprecated)

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;
a.yz = vec2(1.0, 2.0);
```

Programming with OpenGL
Part 3: Transformations

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Objectives

- Learn how to carry out transformations in OpenGL shaders

- Introduce mat.h and vec.h transformations
  - Model-view
  - Projection

Transformations and Viewing

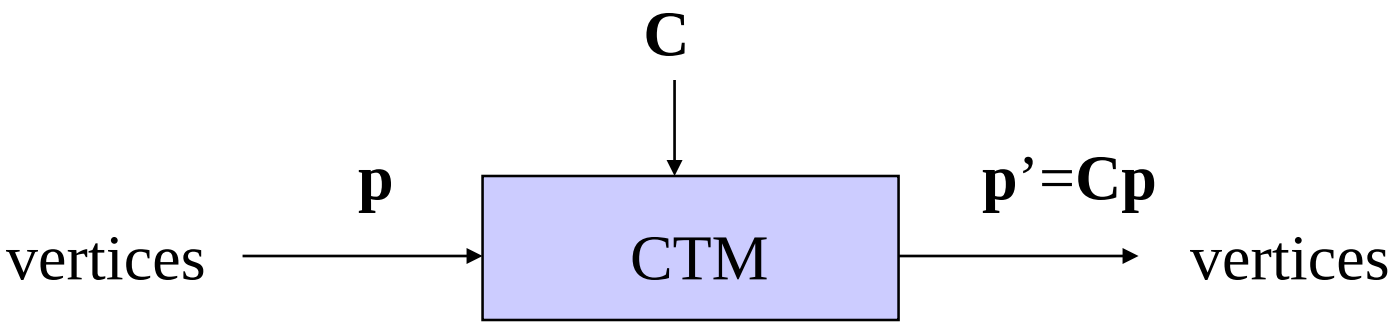
- In OpenGL, transformation functions are used for changes in coordinate systems
- Projection is also carried out by a projection matrix (transformation)
- Pre 3.0 OpenGL had a set of transformation functions which have been deprecated
- Three choices
  - Application code
  - GLSL functions
  - vec.h and mat.h (in the textbook)

Pre 3.1OpenGL Matrices

- In OpenGL matrices were part of the state
- Multiple types
  - Model-View (**GL_MODELVIEW**)
  - Projection (**GL_PROJECTION**)
  - Texture (**GL_TEXTURE**)
  - Color (**GL_COLOR**)
- Single set of functions for manipulation
- Select which to be manipulated by
  - **glMatrixMode(GL_MODELVIEW);**
  - **glMatrixMode(GL_PROJECTION);**

Current Transformation Matrix (CTM)

- Conceptually there is a 4 x 4 homogeneous coordinate matrix, the *current transformation matrix* (CTM) that is part of the state and is applied to all vertices that pass down the pipeline



Rotation, Translation, Scaling

Create an identity matrix:

```
mat4 m = Identity(); // in mat.h
```

Multiply on right by rotation matrix of **theta** in degrees where (**vx, vy, vz**) define axis of rotation

```
mat4 r = Rotate(theta, vx, vy, vz)
m = m*r;
```

Do same with translation and scaling:

```
mat4 s = Scale( sx, sy, sz)
mat4 t = Transalate(dx, dy, dz);
m = m*s*t;
```

Example

- Rotation about z axis by 30 degrees with a fixed point of (1.0, 2.0, 3.0)

```
mat 4 m = Identity();
m = Translate(1.0, 2.0, 3.0)*
  Rotate(30.0, 0.0, 0.0, 1.0)*
  Translate(-1.0, -2.0, -3.0);
```

- Remember that last matrix specified in the program is the first applied

Arbitrary Matrices

- Can load and multiply by matrices defined in the application program
- Matrices are stored as one dimensional array of 16 elements which are the components of the desired 4 x 4 matrix stored by columns
- OpenGL functions that have matrices as parameters allow the application to send the matrix or its transpose

Matrix Stacks

- In many situations we want to save transformation matrices for use later
  - Traversing hierarchical data structures (Chapter 8)
  - Avoiding state changes when executing display lists
- Pre 3.1 OpenGL maintained stacks for each type of matrix
- Easy to create the same functionality with a simple stack class

Using Transformations

- Example: use idle function to rotate a cube and mouse function to change direction of rotation
- Start with a program that draws a cube in a standard way
  - Centered at origin
  - Sides aligned with axes

main.c

```
void main(int argc, char **argv)
{
    glutInit(&argc, argv);
    glutInitDisplayMode(GLUT_DOUBLE | GLUT_RGB |
       GLUT_DEPTH);
    glutInitWindowSize(500, 500);
    glutCreateWindow("colorcube");
    glutReshapeFunc(myReshape);
    glutDisplayFunc(display);
    glutIdleFunc(spinCube);
    glutMouseFunc(mouse);
    glEnable(GL_DEPTH_TEST);
    glutMainLoop();
}
```

Idle and Mouse callbacks

```
void spinCube()
{
  theta[axis] += 2.0;
  if( theta[axis] > 360.0 ) theta[axis] -= 360.0;
  glutPostRedisplay();
}

void mouse(int btn, int state, int x, int y)
{
   if(btn==GLUT_LEFT_BUTTON && state == GLUT_DOWN)
           axis = 0;
   if(btn==GLUT_MIDDLE_BUTTON && state == GLUT_DOWN)
           axis = 1;
   if(btn==GLUT_RIGHT_BUTTON && state == GLUT_DOWN)
           axis = 2;
}
```

Display callback

We can form matrix in application and send to shader and let shader do the rotation or we can send the angle and axis to the shader and let the shader form the transformation matrix and then do the rotation

More efficient than transforming data in application and resending the data

```
void display()
{
   glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);
   glUniform(…); //or glUniformMatrix
    glDrawArrays(…);
   glutSwapBuffers();
}
```

Display callback

```
GLint matrix_loc;
matrix_loc = getUniformLocation(program, "rotation");

mat4 ctm;
void display()
{
  glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);
  ctm = RotateX(theta[0])*RotateY(theta[1])*RotateZ(theta[2]);
  glUniformMatrix4fv(matrix_loc, 1, GL_TRUE, ctm);
  glDrawArrays(GL_TRIANGLES, 0, N);
  glutSwapBuffers();
}
```

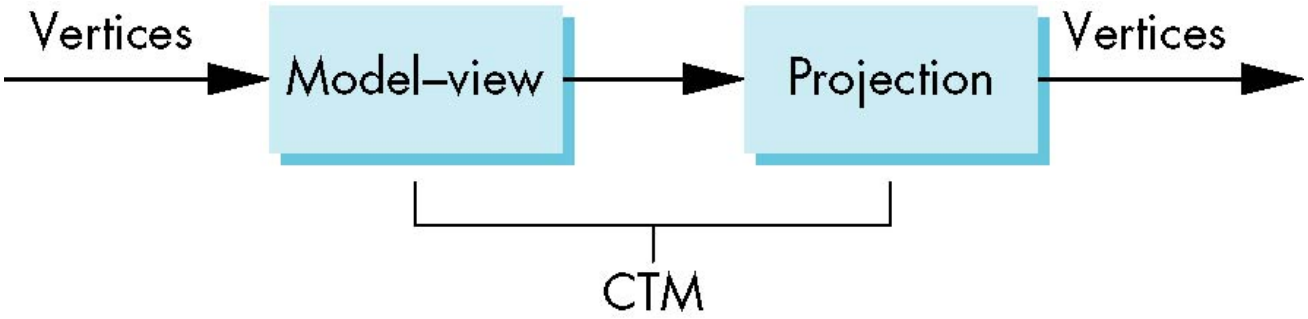
Vertex Shader

```
in vec4 vPosition;
in vec4 vColor;
out vec4 color;
uniform mat4 rotation;

void main()
{
      gl_Position = rotation*vPosition;
      color = vColor;
}
```

Transformation Process

- OpenGL had a model-view and a projection matrix in the pipeline which were concatenated together to form the CTM
- We can emulate the process in application
- Vertex shader completes transformation by way of matrix multiplication



Vertex Shader

```
in vec4 vPosition;
in vec4 vColor;
out vec4 color;
uniform mat4 model_view;
uniform mat4 projection;

void main()
{
  gl_Position = projection*model_view*vPosition;
  color = vColor;
}
```

Other Examples

- How to implement?
  - gluLookAt
  - gluOrtho2D
  - glViewport
  - Object animation
  - Camera control (navigation, zoom-in)

- Many sample codes in the textbook!

Programming with OpenGL
Part 4: Color and Attributes

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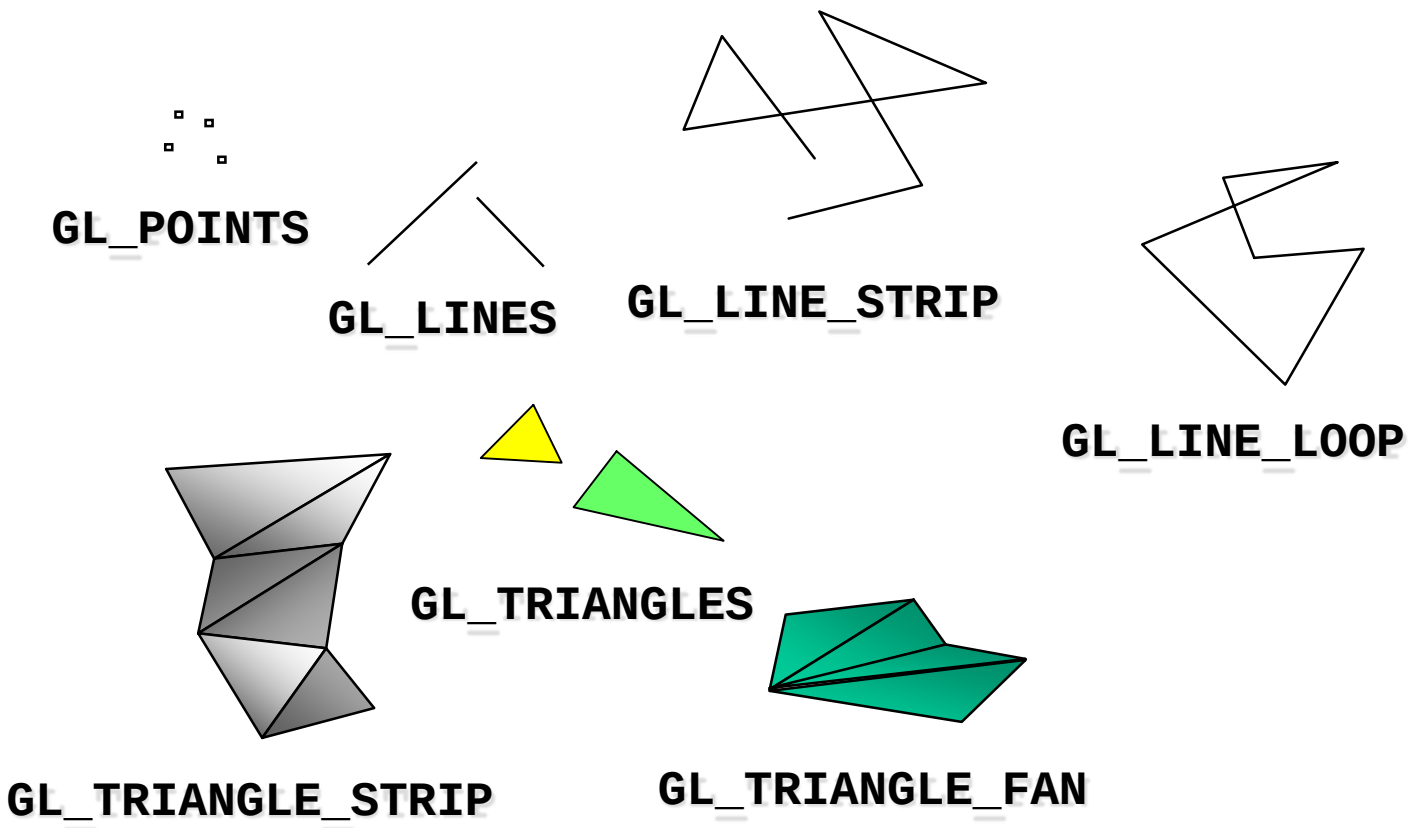
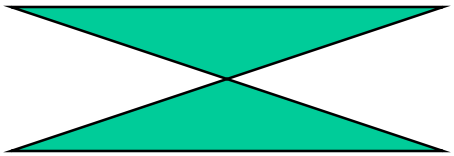
OpenGL Primitives



Polygon Issues

- OpenGL 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

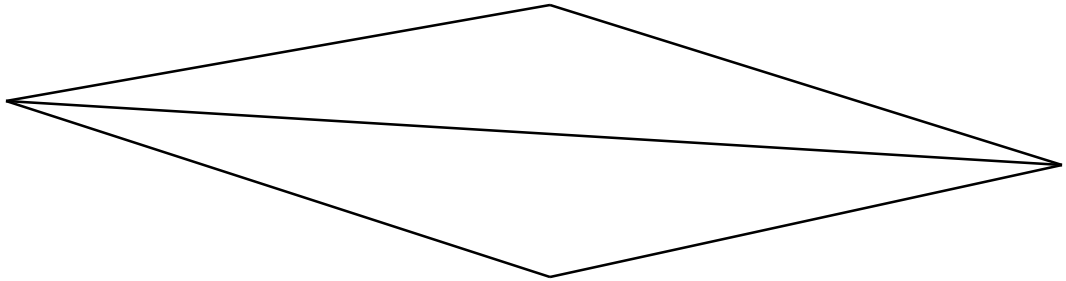


nonsimple polygon

nonconvex polygon

Good and Bad Triangles

- Long thin triangles render badly



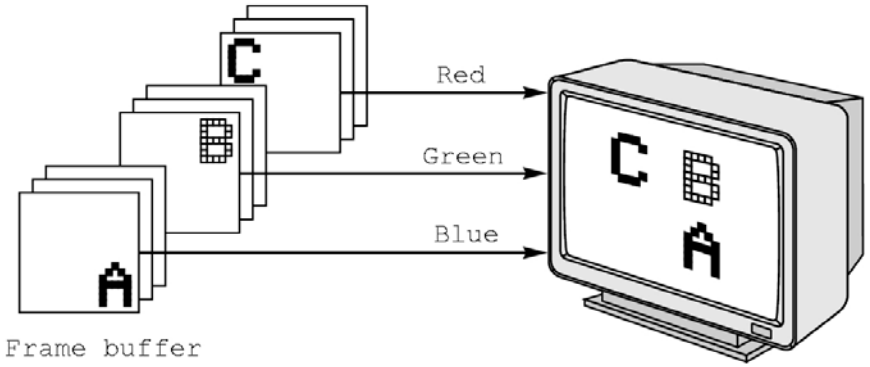
- Equilateral triangles render well
- Maximize minimum angle
- Delaunay triangulation for unstructured points

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 OpenGL functions

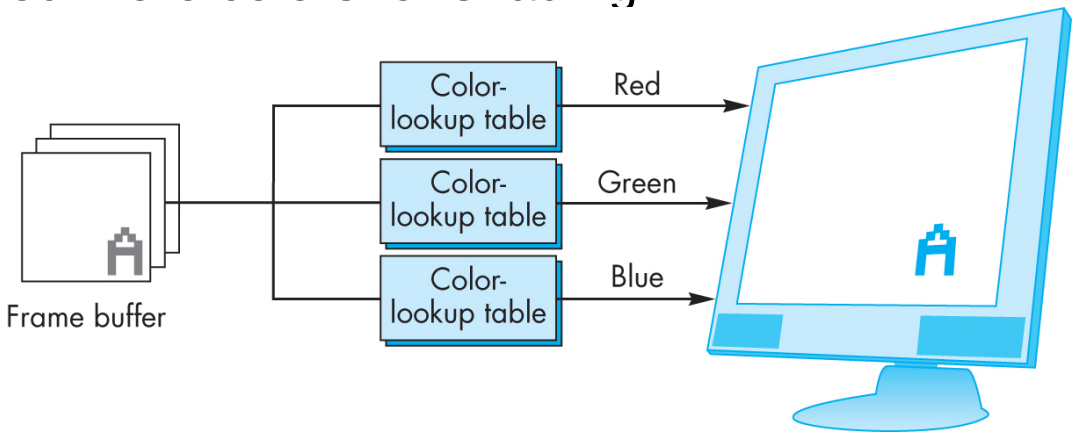
RGB color

- 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 bytels



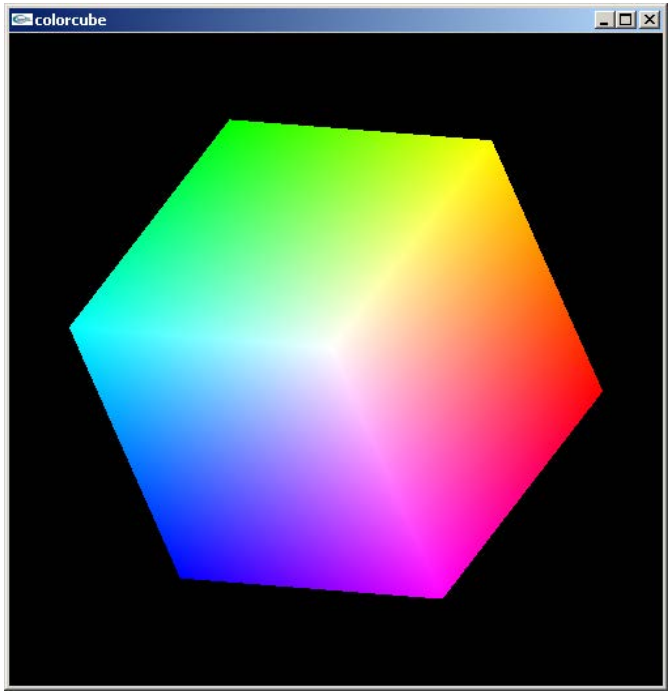
Indexed Color

- 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
  - OpenGL 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 or as a vertex attribute
- Vertex shader color: pass to fragment shader as varying variable
- Fragment color: can alter via shader code

Programming with OpenGL
Part 5: Complete Programs

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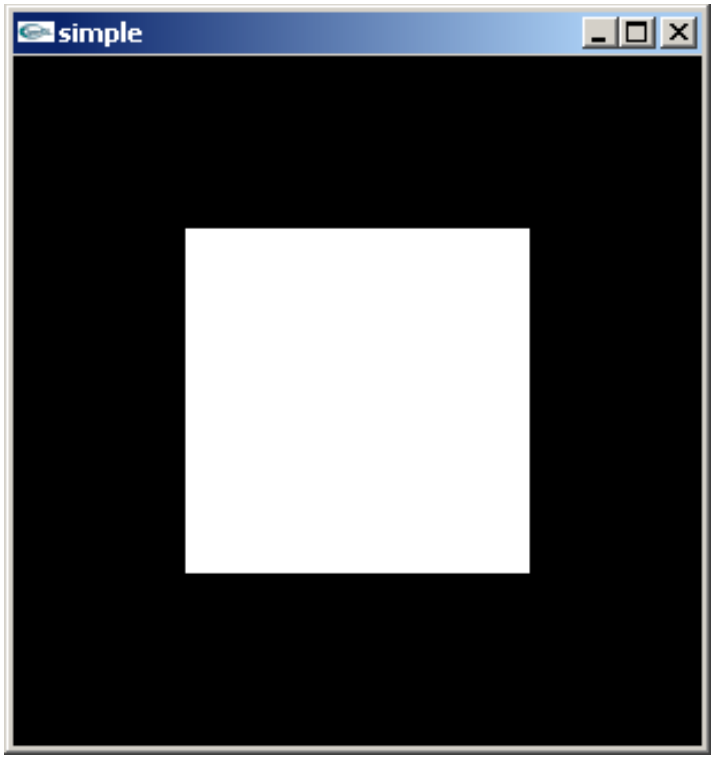
A Simple Program (?)

Generate a square on a solid background



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();
}
```

What happened

- Most OpenGL functions deprecated
- Makes heavy use of state variable default values that no longer exist
  - Viewing
  - Colors
  - Window parameters
- New version makes the defaults more explicit
- However, processing loop is the same

simple.c

```
#include <GL/glut.h>
void mydisplay(){
      glClear(GL_COLOR_BUFFER_BIT);

// need to fill in this part
// and add in shaders
}
int main(int argc, char** argv){
      glutCreateWindow("simple");
      glutDisplayFunc(mydisplay);
      glutMainLoop();
}
```

Immediate Mode Graphics

- Geometry specified by vertices
  - Locations in space (2 or 3 dimensional)
  - Points, lines, circles, polygons, curves, surfaces
- Immediate mode
  - Each time a vertex is specified in application, its location is sent to the GPU
  - Old style uses **`glVertex`**
  - Creates bottleneck between CPU and GPU
  - Removed from OpenGL 3.1

Retained Mode Graphics

- Put all vertex and attribute data in array
- Send array to GPU to be rendered immediately
- Almost OK but problem is we would have to send array over each time we need another render of it
- Better to send array over and store on GPU for multiple renderings

Display Callback

- Once we get data to GPU, we can initiate the rendering with a simple callback

```
void mydisplay()
{
   glClear(GL_COLOR_BUFFER_BIT);
   glDrawArrays(GL_TRIANGLES, 0, 3);
   glFlush();
}
```

- Arrays are buffer objects that contain vertex arrays

Vertex Arrays

- Vertices can have many attributes
  - Position
  - Color
  - Texture Coordinates
  - Application data
- A vertex array holds these data
- Using types in **`vec.h`**

```
point2 vertices[3] = {point2(0.0, 0.0),
      point2(0.0, 1.0), point2(1.0, 1.0)};
```

Vertex Array Object

- Bundles all vertex data (positions, colors, ..,)
- Get name for buffer then bind

```
Glunit abuffer;
glGenVertexArrays(1, &abuffer);
glBindVertexArray(abuffer);
```

- At this point we have a current vertex array but no contents
- Use of glBindVertexArray lets us switch between VBOs

Buffer Object

- Buffer objects allow us to transfer large amounts of data to the GPU
- Need to create, bind and identify data

```
Gluint buffer;
glGenBuffers(1, &buffer);
glBindBuffer(GL_ARRAY_BUFFER, buffer);
glBufferData(GL_ARRAY_BUFFER,
             sizeof(points), points);
```

- Data in current vertex array is sent to GPU

More Information

- VAOs (Vertex Array Objects)
- glBindVertexArrays vs glBindBuffer

Initialization

- Vertex array objects and buffer objects can be set up on **init()**
- Also set clear color and other OpeGL parameters
- Also set up shaders as part of initialization
  - Read
  - Compile
  - Link

Linking Shaders with Application

- Read shaders
- Compile shaders
- Create a program object
- Link everything together
- Link variables in application with variables in shaders
  - Vertex attributes
  - Uniform variables

Program Object

- Container for shaders
  - Can contain multiple shaders
  - Other GLSL functions

```
GLuint myProgObj;
myProgObj = glCreateProgram();
 /* define shader objects here */
glUseProgram(myProgObj);
glLinkProgram(myProgObj);
```

Reading a Shader

- Shaders are added to the program object and compiled
- Usual method of passing a shader is as a null-terminated string using the function **`glShaderSource`**
- If the shader is in a file, we can write a reader to convert the file to a string
- Sample code in the textbook

Adding a Vertex Shader

```
GLuint vShader;
GLunit myVertexObj;
GLchar vShaderfile[] = “my_vertex_shader”;
GLchar* vSource =
        readShaderSource(vShaderFile);
myVertexObj =
        glCreateShader(GL_VERTEX_SHADER);
glShaderSource(myVertexObj, 1,
        &vSource, NULL);
glCompileShader(myVertexObj);
glAttachObject(myProgObj, myVertexObj);
```

Vertex Attributes

- Vertex attributes are named in the shaders
- Linker forms a table
- Application can get index from table and tie it to an application variable
- Similar process for uniform variables

Vertex Attribute Example

```
#define BUFFER_OFFSET( offset )
   ((GLvoid*) (offset))

GLuint loc =
  glGetAttribLocation( program, "vPosition" );
glEnableVertexAttribArray( loc );
glVertexAttribPointer( loc, 2, GL_FLOAT,
    GL_FALSE, 0, BUFFER_OFFSET(0) );
```

Uniform Variable Example

```
GLint angleParam;
angleParam = glGetUniformLocation(myProgObj,
     "angle");
/* angle defined in shader */

/* my_angle set in application */
GLfloat my_angle;
my_angle = 5.0 /* or some other value */

glUniform1f(angleParam, my_angle);
```

Adding Color

- If we set a color in the application, we can send it to the shaders as a vertex attribute or as a uniform variable depending on how often it changes
- Let's associate a color with each vertex
- Set up an array of same size as positions
- Send to GPU as a vertex buffer object

Setting Colors

```
typedef  vec3 color3;
color3 base_colors[4] = {color3(1.0, 0.0. 0.0), ….
color3 colors[NumVertices];
vec3 points[NumVertices];

//in loop setting positions

colors[i] = basecolors[color_index]
position[i] = …….
```

Setting Up Buffer Object

```
//need larger buffer

glBufferData(GL_ARRAY_BUFFER, sizeof(points) +
   sizeof(colors), NULL, GL_STATIC_DRAW);

//load data separately

glBufferSubData(GL_ARRAY_BUFFER, 0,
   sizeof(points), points);
glBufferSubData(GL_ARRAY_BUFFER, sizeof(points),
   sizeof(colors), colors);
```

Second Vertex Array

```
// vPosition and vColor identifiers in vertex shader


loc = glGetAttribLocation(program, “vPosition”);
glEnableVertexAttribArray(loc);
glVertexAttribPointer(loc, 3, GL_FLOAT, GL_FALSE, 0,
    BUFFER_OFFSET(0));

loc2 = glGetAttribLocation(program, “vColor”);
glEnableVertexAttribArray(loc2);
glVertexAttribPointer(loc2, 3, GL_FLOAT, GL_FALSE, 0,
    BUFFER_OFFSET(sizeofpoints));
```

Shader Applications

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Vertex Shader Applications

- Moving vertices
  - Wave motion
  - Particle system
  - Morphing
  - Fractals
- Lighting
  - More realistic models
  - Cartoon shaders

Wave Motion Vertex Shader

```
in vec4 vPosition;
uniform float xs, zs; // frequencies
uniform float h; // height scale
void main()
{
  vec4 t = vPosition;
  t.y = vPosition.y
     + h*sin(time + xs*vPosition.x)
     + h*sin(time + zs*vPosition.z);
  gl_Position = t;
}
```

Particle System

```
in vec3 vPosition;
uniform mat4 ModelViewProjectionMatrix;
uniform vec3 init_vel;
uniform float g, m, t;

void main()
{
    vec3 object_pos;
    object_pos.x = vPosition.x + vel.x*t;
    object_pos.y = vPosition.y + vel.y*t
           + g/(2.0*m)*t*t;
    object_pos.z = vPosition.z + vel.z*t;
    gl_Position = ModelViewProjectionMatrix
            *vec4(object_pos,1);
}
```

Pass Through Fragment Shader

```
/* pass-through fragment shader */

in vec4 color;
void main(void)
{
    gl_FragColor = color;
}
```

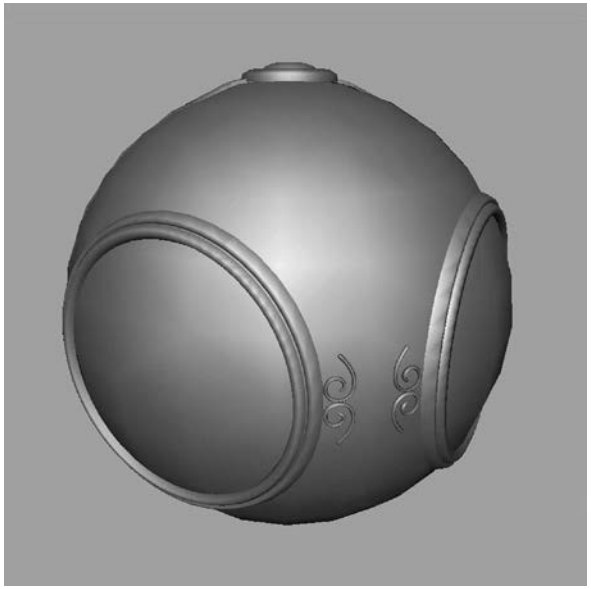
Vertex vs Fragment Lighting

per vertex lighting

per fragment lighting

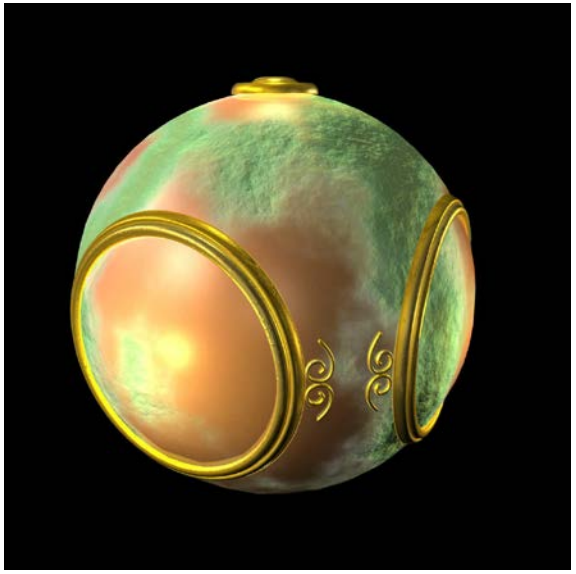
Fragment Shader Applications

Texture mapping



smooth shading

environment mapping



bump mapping

Summary

- Programmable graphics pipeline
- Vertex processing → vertex shader
- Fragment process →fragment shader
- Binding shaders to application program
- Transferring values to shaders

- Many sample codes in the textbook!
  - vec.h and mat.h in the book web page

Summary

- Lots of advanced features of shaders
- Geometry/Tessellation/Compute shaders
- Multiple passes of shaders

- Massive parallelism → high performance
- Used for a variety of applications
- GPGPU (General-Purpose GPU)
  - CUDA, OpenCL

Supplementary Slides

OpenGL Libraries

- OpenGL core library
  - OpenGL32 on Windows
  - GL on most unix/linux systems (libGL.a)
- OpenGL Utility Library (GLU)
  - Provides functionality in OpenGL core but avoids having to rewrite code
  - Will only work with legacy code
- Links with window system
  - GLX for X window systems
  - WGL for Windows
  - AGL for Macintosh

GLUT

- OpenGL Utility Toolkit (GLUT)
  - Provides functionality common to all window systems
    - Open a window
    - Get input from mouse and keyboard
    - Menus
    - Event-driven
  - Code is portable but GLUT lacks the functionality of a good toolkit for a specific platform
    - No slide bars

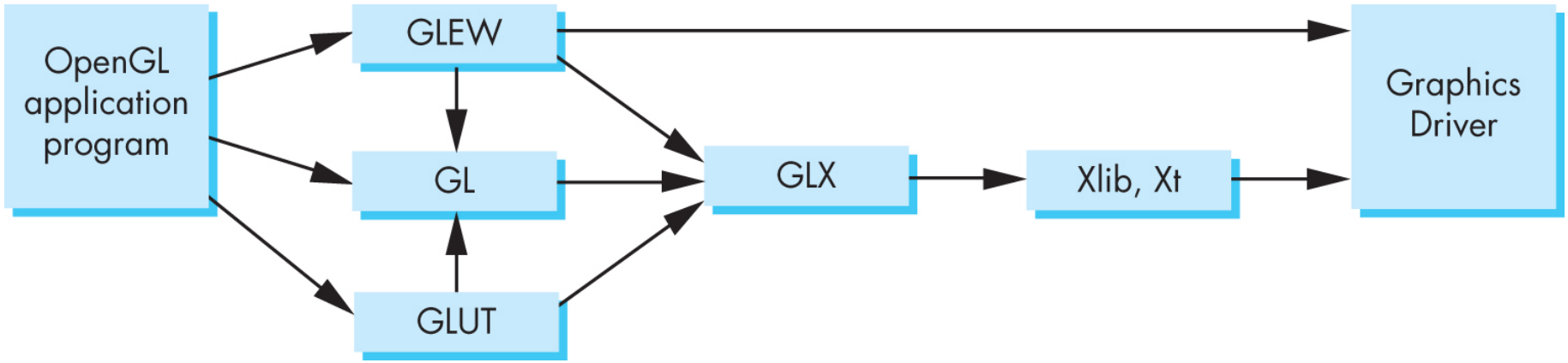
freeglut

- GLUT was created long ago and has been unchanged
  - Amazing that it works with OpenGL 3.1
  - Some functionality can’t work since it requires deprecated functions
- freeglut updates GLUT
  - Added capabilities
  - Context checking

GLEW

- OpenGL Extension Wrangler Library
- Makes it easy to access OpenGL extensions available on a particular system
- Avoids having to have specific entry points in Windows code
- Application needs only to include glew.h and run a glewInit()

Software Organization



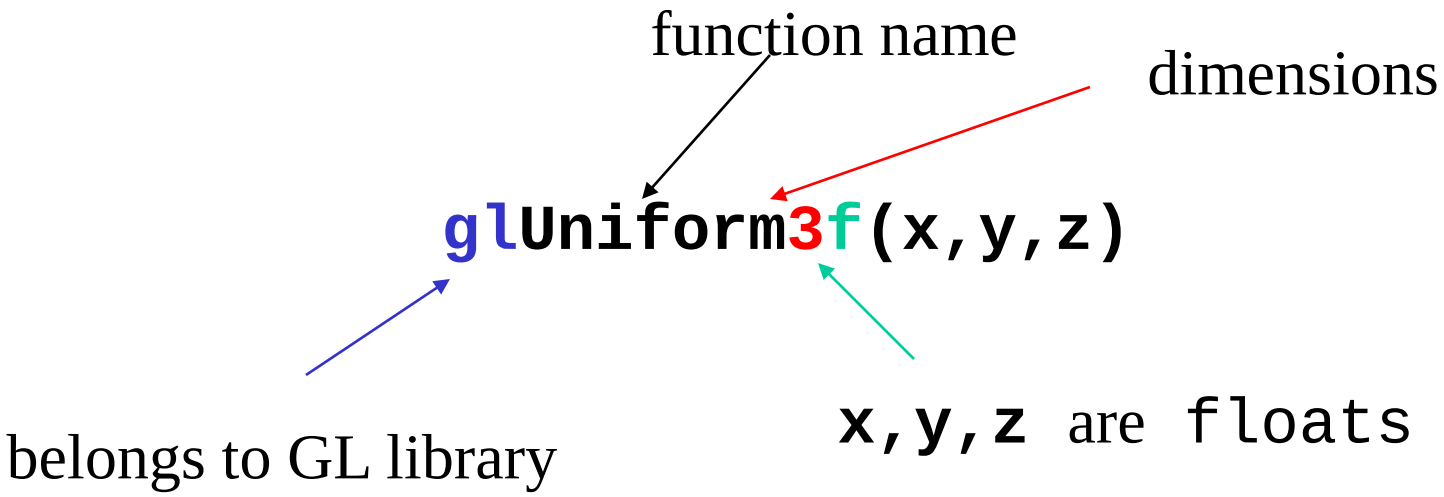
OpenGL #defines

- Most constants are defined in the include files **`gl.h`**, **`glu.h`** and **`glut.h`**
  - Note **`#include <GL/glut.h>`** should automatically include the others
  - Examples
  - **`glEnable(GL_DEPTH_TEST)`**
  - **`glClear(GL_COLOR_BUFFER_BIT)`**
- include files also define OpenGL data types: **`GLfloat`**, **`GLdouble`**,….

OpenGL Functions

- Primitives
  - Points
  - Line Segments
  - Triangles
- Attributes
- Transformations
  - Viewing
  - Modeling
- Control (GLUT)
- Input (GLUT)
- Query

OpenGL function format




```
glUniform3fv(p)
```

p is a pointer to an array

Lack of Object Orientation

- OpenGL is not object oriented so that there are multiple functions for a given logical function
  - **`glUniform3f`**
  - **`glUniform2i`**
  - **`glUniform3dv`**
- Easy to create overloaded functions in C++ but issue is efficiency

OpenGL State

- OpenGL is a state machine
- OpenGL functions are of two types
  - Primitive generating
    - Can cause output if primitive is visible
    - Vertices are processed and appearance of primitive are controlled by the state
  - State changing
    - Transformation functions
    - Attribute functions
    - Under 3.1 most state variables are defined by the application and sent to the shaders

main.c

```
#include <GL/glew.h>
#include <GL/glut.h>

int main(int argc, char** argv)
{
 glutInit(&argc,argv);
 glutInitDisplayMode(GLUT_SINGLE|GLUT_RGB);
 glutInitWindowSize(500,500);
 glutInitWindowPosition(0,0);
 glutCreateWindow("simple");
 glutDisplayFunc(mydisplay);
 glewInit();
 init();
 glutMainLoop();
}
```

includes **gl.h**

specify window properties

display callback

set OpenGL state and initialize shaders

enter event loop

GLUT functions

- **`glutInit`** allows application to get command line arguments and initializes system
- **`gluInitDisplayMode`** requests properties for the window (the *rendering context*)
  - RGB color
  - Single buffering
  - Properties logically ORed together
- **`glutWindowSize`** in pixels
- **`glutWindowPosition`** from top-left corner of display
- **`glutCreateWindow`** create window with title “simple”
- **`glutDisplayFunc`** display callback
- **`glutMainLoop`** enter infinite event loop

Double Buffering

- Updating the value of a uniform variable opens the door to animating an application
  - Execute glUniform in display callback
  - Force a redraw through glutPostRedisplay()
- Need to prevent a partially redrawn frame buffer from being displayed
- Draw into back buffer
- Display front buffer
- Swap buffers after updating finished

Adding Double Buffering

- Request a double buffer
  - glutInitDisplayMode(GLUT_DOUBLE)
- Swap buffers

```
void mydisplay()
{
        glClear(……);
        glDrawArrays();
        glutSwapBuffers();
}
```

Event Loop

- Note that the program specifies a *display callback* function named **`mydisplay`**
  - Every glut program must have a display callback
  - The display callback is executed whenever OpenGL decides the display must be refreshed, for example when the window is opened
  - The **`main`** function ends with the program entering an event loop

Idle Callback

- Idle callback specifies function to be executed when no other actions pending
  - glutIdleFunc(myIdle);

```
void myIdle()
{
    // recompute display
    glutPostRedisplay();
}
```

Program Structure

- Most OpenGL programs have a similar structure that consists of the following functions
  - **`main()`**:
    - specifies the callback functions
    - opens one or more windows with the required properties
    - enters event loop (last executable statement)
  - **`init()`**: sets the state variables
    - Viewing
    - Attributes
  - **`initShader():`** read, compile and link shaders
  - callbacks
    - Display function
    - Input and window functions

simple.c revisited

- **`main()`** function similar to last lecture
  - Mostly GLUT functions
- init() will allow more flexible colors
- initShader() will hides details of setting up shaders for now
- Key issue is that we must form a data array to send to GPU and then render it

Shader Reader

```
#include <stdio.h>

static char*
readShaderSource(const char* shaderFile)
{
    FILE* fp = fopen(shaderFile, "r");

    if ( fp == NULL ) { return NULL; }

    fseek(fp, 0L, SEEK_END);
    long size = ftell(fp);
```

Shader Reader (cont)

```
    fseek(fp, 0L, SEEK_SET);
    char* buf = new char[size + 1];
    fread(buf, 1, size, fp);

    buf[size] = '\0';
    fclose(fp);

    return buf;
}
```

Attribute and Varying Qualifiers

- Starting with GLSL 1.5 attribute and varying qualifiers have been replaced by in and out qualifiers
- No changes needed in application
- Vertex shader example:

```
#version 1.4
attribute vec3 vPosition;
varying vec3 color;
```

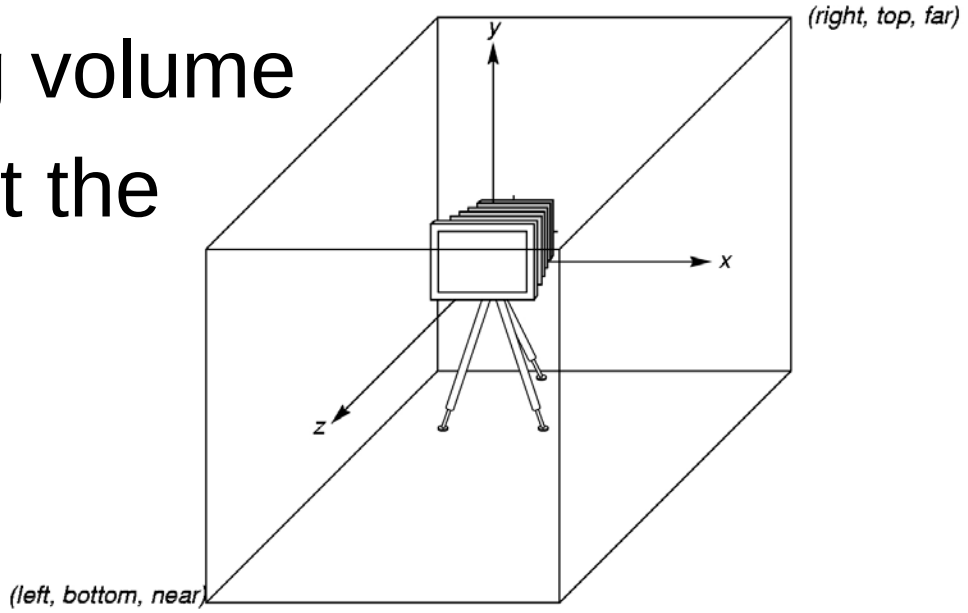
```
#version 1.5
in vec3 vPosition;
out vec3 color;
```

Coordinate Systems

- The units in **`points`** are determined by the application and are called *world, object, model* or *problem coordinates*
- Viewing specifications usually are also in object coordinates
- Eventually pixels will be produced in *device, window coordinates*
- OpenGL also uses some internal representations that usually are not visible to the application but are important in the shaders

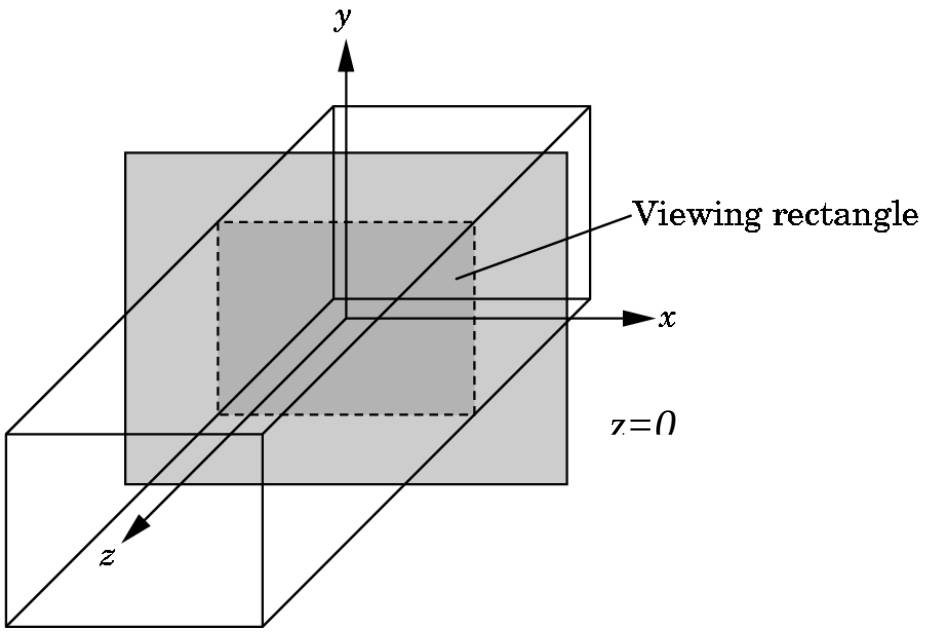
OpenGL Camera

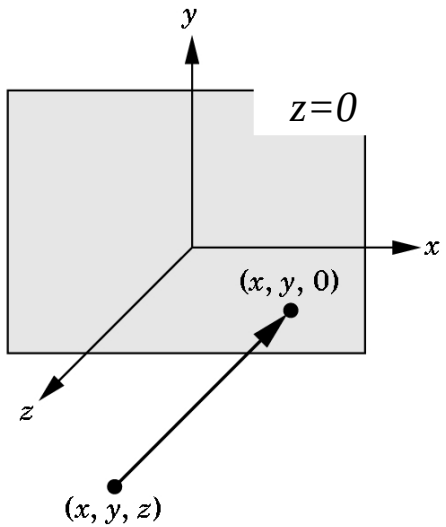
- OpenGL places a camera at the origin in object space pointing in the negative z direction
- The default viewing volume is a box centered at the origin with sides of length 2



Orthographic Viewing

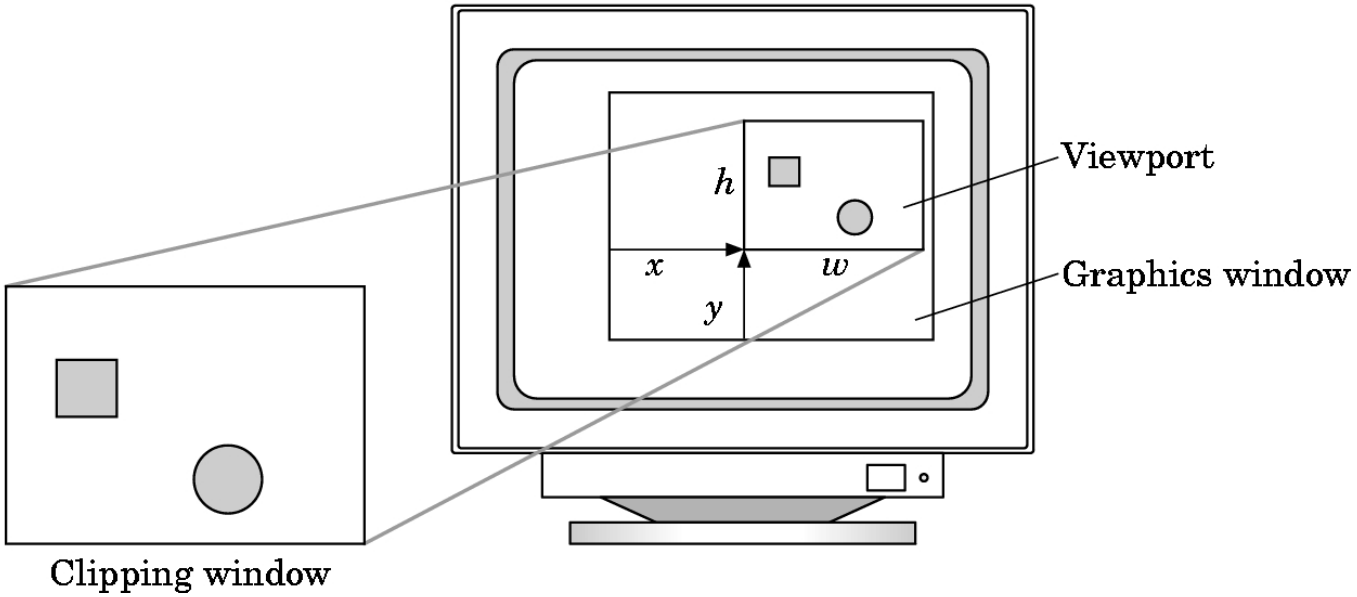
In the default orthographic view, points are projected forward along the z axis onto the plane $z=0$





Viewports

- Do not have to use the entire window for the image: **`glViewport(x,y,w,h)`**
- Values in pixels (device coordinates)

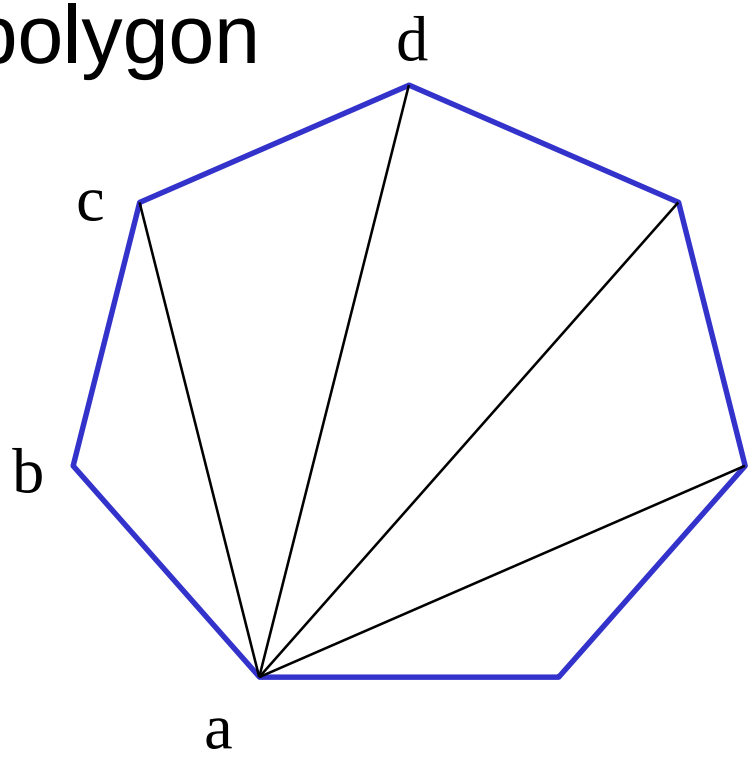


Polygon Testing

- 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

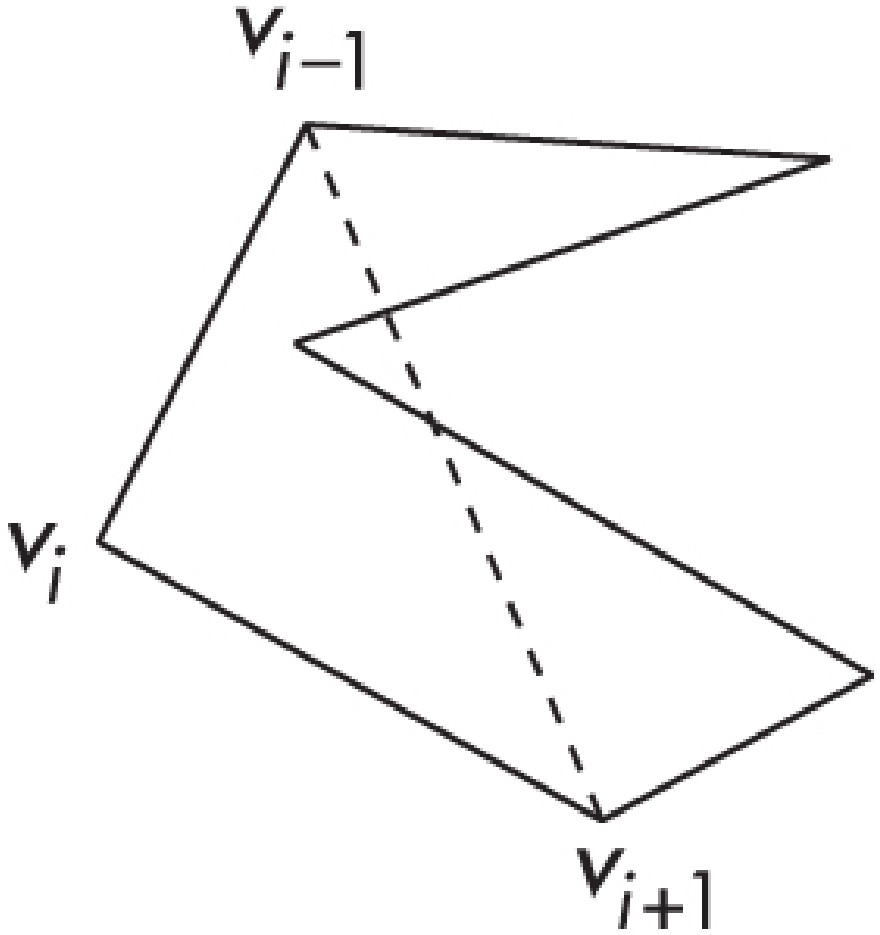
Triangularization

- Convex polygon



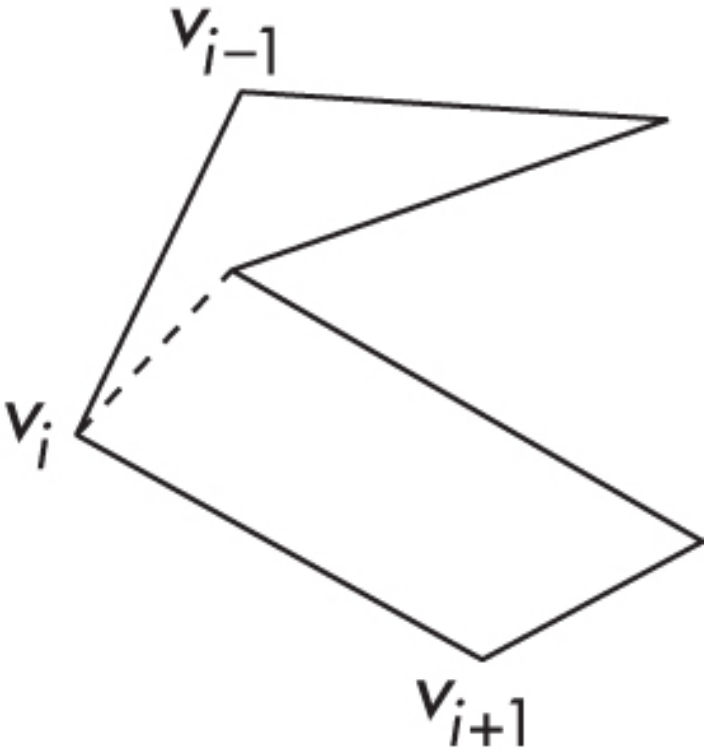
- Start with abc, remove b, then acd, ….

Non-convex (concave)



Recursive Division

- Find leftmost vertex and split



CTM operations

- The CTM can be altered either by loading a new CTM or by postmutiplication

  Load an identity matrix: **C** ← **I**
  Load an arbitrary matrix: **C** ← **M**

  Load a translation matrix: **C** ← **T**
  Load a rotation matrix: **C** ← **R**
  Load a scaling matrix: **C** ← **S**

  Postmultiply by an arbitrary matrix: **C** ← **CM**
  Postmultiply by a translation matrix: **C** ← **CT**
  Postmultiply by a rotation matrix: **C** ← **C R**
  Postmultiply by a scaling matrix: **C** ← **C S**

Rotation about a Fixed Point

Start with identity matrix: $\mathbf{C} \leftarrow \mathbf{I}$
Move fixed point to origin: $\mathbf{C} \leftarrow \mathbf{CT}$
Rotate: $\mathbf{C} \leftarrow \mathbf{CR}$
Move fixed point back: $\mathbf{C} \leftarrow \mathbf{CT}^{-1}$

Result: $\mathbf{C} = \mathbf{TR}\,\mathbf{T}^{-1}$ which is **backwards**.

This result is a consequence of doing postmultiplications.
Let's try again.

Reversing the Order

We want $\mathbf{C} = \mathbf{T}^{-1}\,\mathbf{R}\,\mathbf{T}$
so we must do the operations in the following order

$\mathbf{C} \leftarrow \mathbf{I}$
$\mathbf{C} \leftarrow \mathbf{C}\mathbf{T}^{-1}$
$\mathbf{C} \leftarrow \mathbf{C}\mathbf{R}$
$\mathbf{C} \leftarrow \mathbf{C}\mathbf{T}$

Each operation corresponds to one function call in the program.

Note that the last operation specified is the first executed in the program