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Vertex Shader

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What You'll Learn in This Lecture

- How to get data from your application into the front of the graphics pipeline
- What the various OpenGL drawing commands are and what their parameters do
- How your transformed geometry is post-processed

Hint

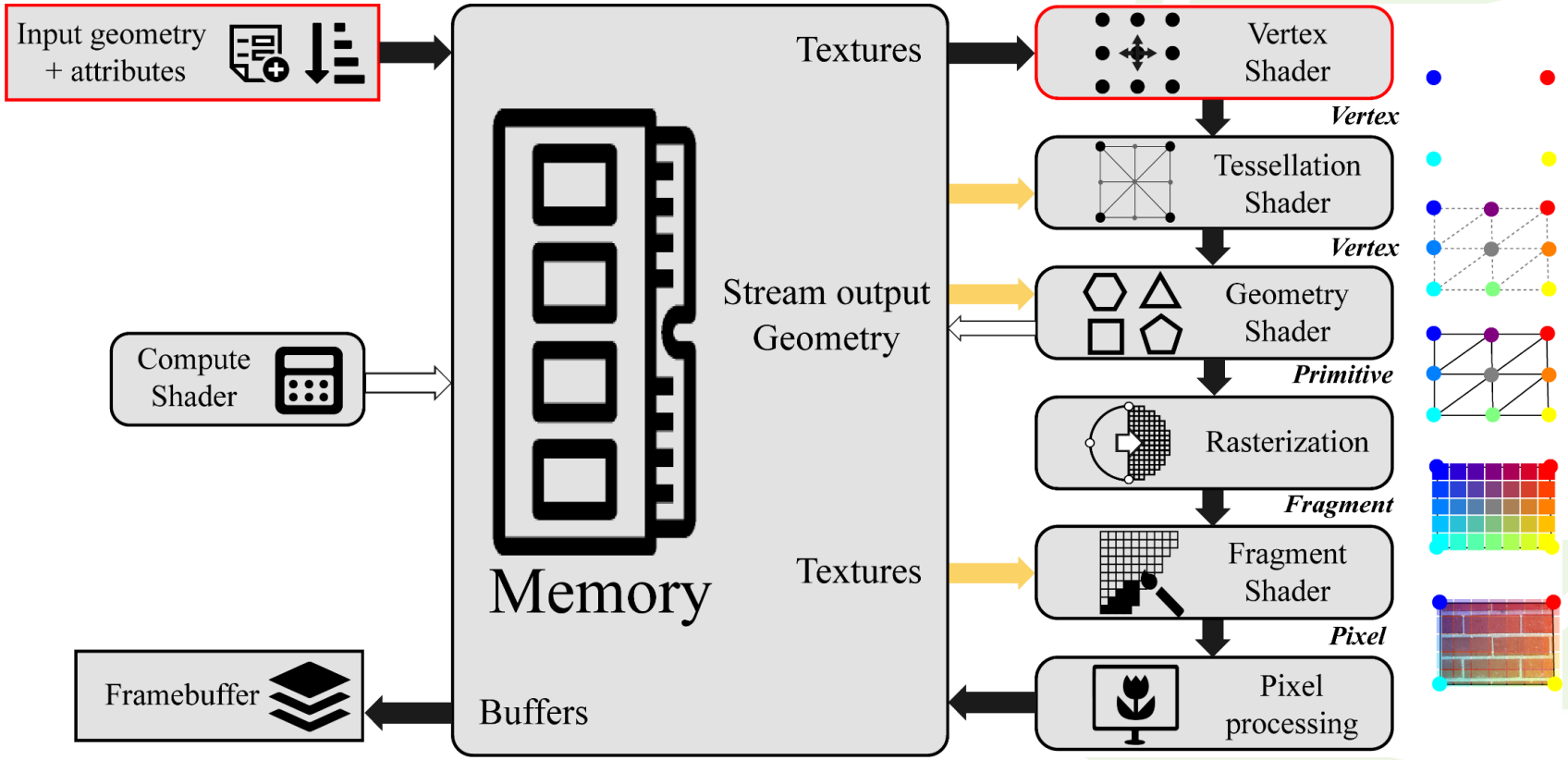
Code in yellow block => main program.

- Set up OpenGL environment.
- Maintain data or buffer objects.
- Compile, link or switch shader program.

Code in blue block => shader script.

- Rendering pipeline.
- Fetch data/texture in buffer.
- `#version 410 core` in first line.

Programmable Pipeline



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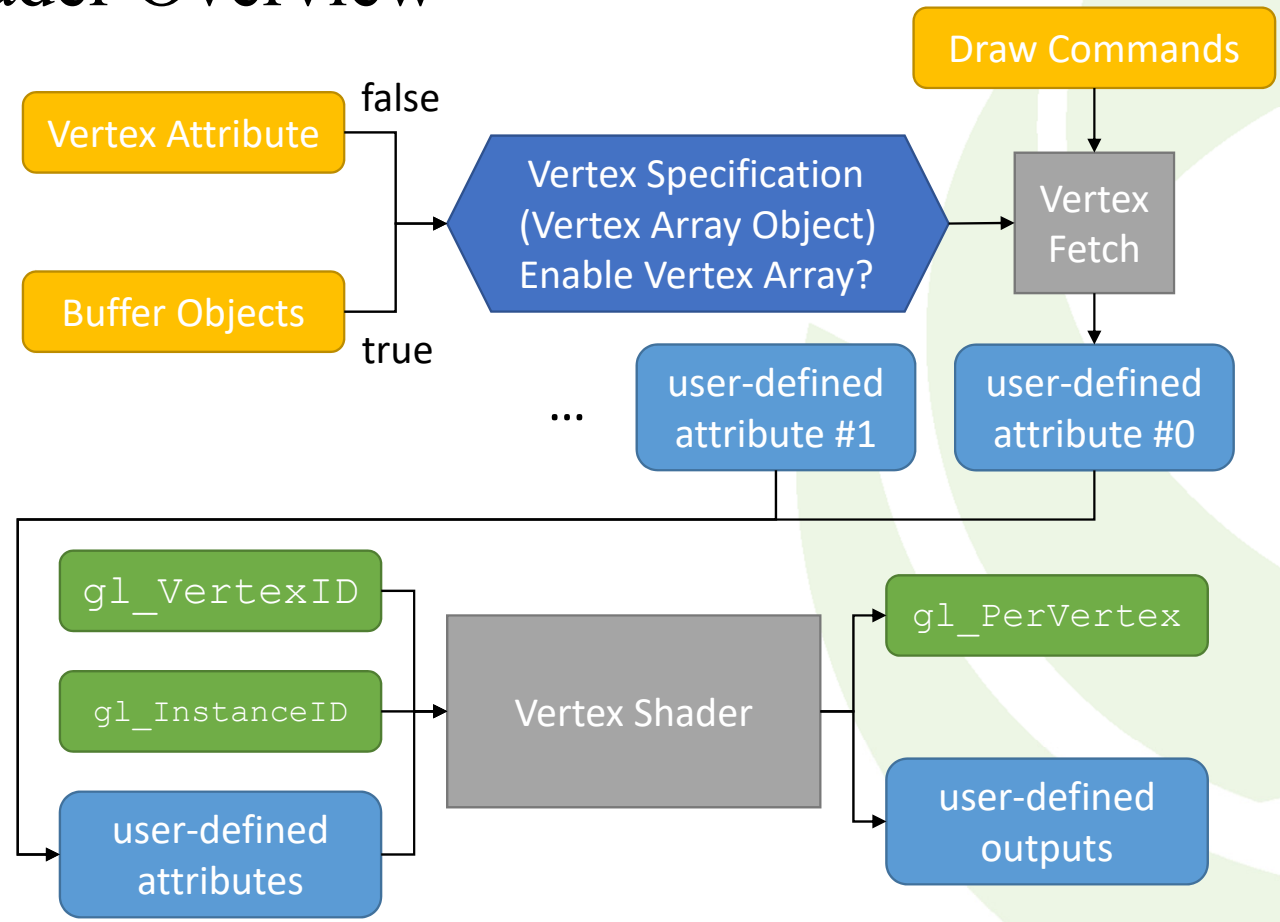
Vertex processing

Vertex Processing

- The first programmable stage, ***vertex shader***
- Vertex shader inputs are provided by binding ***vertex array objects*** and ***issuing drawing command*** calls
- Before a vertex shader runs, OpenGL fetches its inputs in the ***vertex fetch stage***
- Vertex shaders set the ***position of the vertex*** that will be fed to the next stage, and write to some other ***user-defined and built-in outputs***

Vertex Shader Overview



Vertex Shader Inputs

- Pre-defined
  - **`gl_VertexID`**
  - **`gl_InstanceID:`** range = [**0**, instancecount)
- User-defined vertex attributes
  - for example: **`in vec3 vertexPosition;`**
  - another example: **`in vec2 textureCoordinate;`**
- The value of user-defined vertex attributes are determined in the ***vertex fetch stage***

gl_VertexID

- Contains the index of the current vertex
- **Declaration**:
  - `in int gl_VertexID;`
- **Description**: `gl_VertexID` is a built-in input variable that holds an integer index for the vertex. The index is implicitly generated by `glDrawArrays` and other commands

gl_InstanceID

- Contains the index of the current primitive in an instanced draw command
- **Declaration**:
  - `in int gl_InstanceID;`
- **Description**: `gl_InstanceID` holds the integer index of the current primitive in an instanced draw command. Its value always starts at 0, even when using base instance calls. When not using instanced rendering, this value will be 0

Vertex Fetch Stage

- OpenGL determines the value of each vertex attribute in one vertex shader invocation based on its ***drawing command*** and ***vertex specification***
- Drawing command: ***how*** to fetch
- Vertex specification: ***where*** to fetch

Drawing Commands

- Drawing commands start ***vertex rendering***: the process of taking vertex data specified in ***vertex array object*** and rendering one or more ***primitives*** with this vertex data
- Drawing commands decide ***how*** vertex attribute data are fetched
- A bit complicated; Will be introduced later

Vertex Specification

- Vertex specification decides ***where*** vertex attribute data are fetched
- A ***bound*** and ***valid vertex array object*** must be present to store vertex specification settings

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Vertex specification

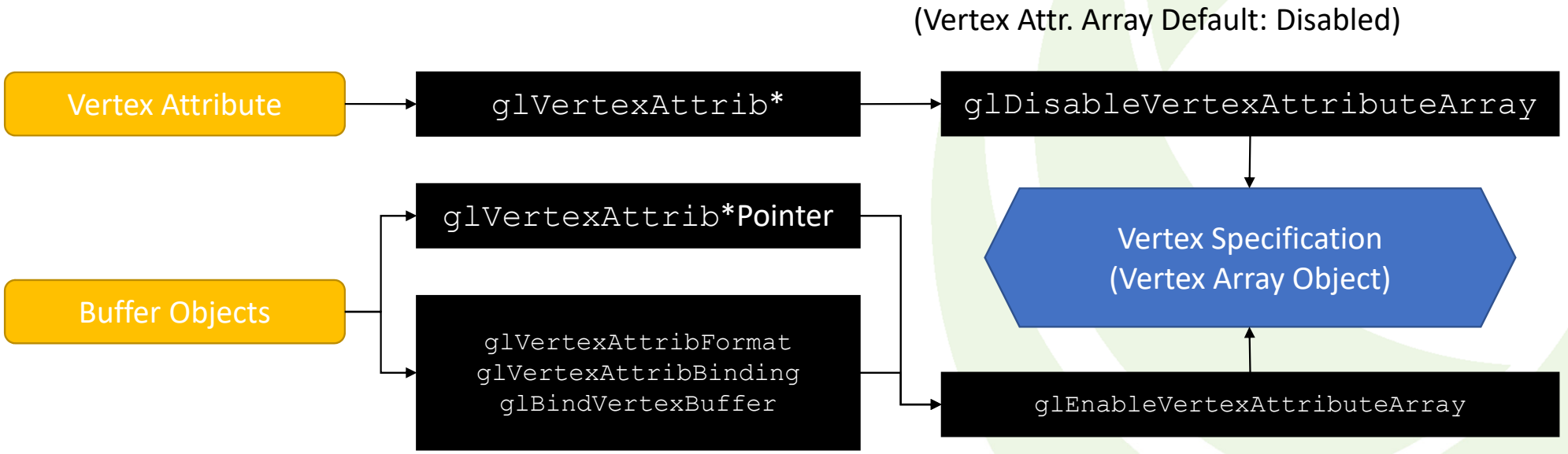
Vertex Specification

- 3 types of vertex specification APIs

1. `glVertexAttrib*`
2. `glVertexAttrib*Pointer`
3. Separate attribute format binding (GL 4.3+)
   1. `glVertexAttribFormat`
   2. `glVertexAttribBinding`
   3. `glBindVertexBuffer`

- You cannot mix type 3 with type 1 or 2!

Vertex Specification



glVertexAttrib*

```
void glVertexAttrib{1234}{fds}(GLuint index, TYPE values);
void glVertexAttrib{1234}{fds}v(GLuint index,const TYPE *values);
void glVertexAttrib4{bsifd ub us ui}v(GLuint index,const TYPE *values);
```

- **index**: Specifies the index of the generic vertex attribute to be modified.
- **values**: For the packed commands, specifies the new packed value to be used for the specified vertex attribute.

glEnableVertexAttribArray

```
void glEnableVertexAttribArray(GLuint index);
```

- **index**: Specifies the index of the generic vertex attribute to be enabled or disabled
- **Description:** ***glEnableVertexAttribArray*** enables the generic vertex attribute array specified by **index**. ***glDisableVertexAttribArray*** disables the generic vertex attribute array specified by **index**

glVertexAttribPointer

```
void glVertexAttribPointer (GLuint index, GLint size, GLenum type,
       GLboolean normalized, GLsizei stride, const GLvoid * pointer);
```

- **Description**: specify the input format of **float** type vertex attribute at location **index**. The attribute has **size** components and the input format is **type**. If **type** is an integer type and **normalized** is ***GL_TRUE***, the value is normalized into [-1, 1] for signed and [0, 1] for unsigned. The **pointer** specifies an offset of the first component of the first generic vertex attribute. The initial value is 0.

glVertexAttrib*Pointer

```
void glVertexAttribIPointer (GLuint index, GLint size, GLenum type,
GLsizei stride, const GLvoid * pointer);
```

- **Description:** specify the input format of an **integer** type vertex attribute at location **index**

```
void glVertexAttribLPointer (GLuint index, GLint size, GLenum type, GLsizei
stride, const GLvoid * pointer);
```

- **Description:** specify the input format of a **double** type vertex attribute at location **index**

glVertexAttribFormat

```
void glVertexAttribFormat(GLuint attribindex, GLint size, GLenum
type, GLboolean normalized, Gluint relativeoffset);
```

- **Description:** specify the input format of a **float** type vertex attribute at location **attribindex**. The attribute has **size** components and the input format is **type**. If **type** is an integer type and **normalized** is ***GL_TRUE***, the value is normalized into [-1, 1] for signed and [0, 1] for unsigned. The attribute is **relativeoffset** bytes from the beginning of each vertex defined in ***glBindVertexBuffer***

glVertexAttrib*Format

```
void glVertexAttribIFormat(GLuint attribindex, GLint size, GLenum
type, Gluint relativeoffset);
```

- **Description:** specify the input format of an **integer** type vertex attribute at location **attribindex**

```
void glVertexAttribLFormat(GLuint attribindex, GLint size, GLenum
type, Gluint relativeoffset);
```

- **Description:** specify the input format of a **double** type vertex attribute at location **attribindex**

glVertexAttribBinding

```
void glVertexAttribBinding(GLuint attribindex, GLuint bindingindex);
```

- **Description:** bind a vertex attribute at location **attribindex** to a binding point **bindingindex**

glBindVertexBuffer

```
void glBindVertexBuffer(GLuint bindingindex, GLuint buffer,
GLintptr offset, GLintptr stride);
```

- **Description:** bind a vertex buffer **buffer** to the binding point **bindingindex**. The data starts at **offset** bytes and the size of each vertex is **stride** bytes. If **stride** is zero, the data is assumed to be tightly-packed

6.2.Spinning_cube

```
glGenVertexArrays(1, &vao);
glBindVertexArray(vao);

glGenBuffers(1, &buffer);
glBindBuffer(GL_ARRAY_BUFFER, buffer);
glBufferData(GL_ARRAY_BUFFER, sizeof(vertex_positions), vertex_positions,
GL_STATIC_DRAW);

glVertexAttribPointer(0, 3, GL_FLOAT, GL_FALSE, 0, NULL);
glEnableVertexAttribArray(0);
```

gl_PerVertex

- Pre-defined outputs
- ***gl_PerVertex*** defines an interface block for outputs. The block is defined without an instance name, so that prefixing the names is not required

```
out gl_PerVertex
{
    vec4 gl_Position;
    float gl_PointSize;
    float gl_ClipDistance[];
};
```

gl_PerVertex

- ***gl_Position***
  - The ***clip-space*** output position of the current vertex in ***homogeneous coordinate***
  - A point in object-space is transformed by a ***model-view-project matrix*** to clip-space

gl_PerVertex

- ***gl_PointSize***
  - The pixel width/height of the point being rasterized. It only has a meaning when rendering point primitives. It will be clamped to the **GL_POINT_SIZE_RANGE**
  - If **GL_PROGRAM_POINT_SIZE** is enabled, ***gl_PointSize*** is used to determine the size of rasterized points, otherwise it is ignored by the rasterization stage

gl_PerVertex

- ***gl_ClipDistance[]***
  - Allows the shader to set the ***distance from the vertex to each user-defined clipping half-space***
  - A non-negative distance means that the vertex is inside/behind the clip plane, and a negative distance means it is outside/in front of the clip plane. Each element in the array is one clip plane
  - In order to use this variable, the user must manually ***redeclare it with an explicit size***

gl_PerVertex

- ***gl_ClipDistance[]***
  - Clipping is also a complicated topic. We will introduce this to you later in a dedicated section

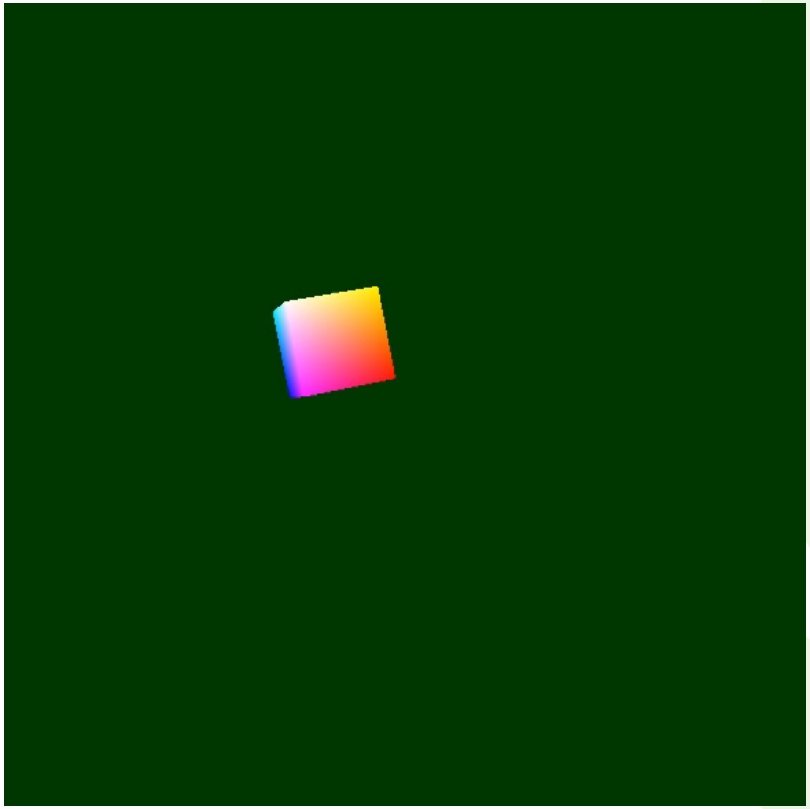
User-defined outputs

- User-defined output variables can have ***interpolation qualifiers*** (though these only matter if the output is being passed directly to the Vertex Post-Processing stage). Vertex shader outputs can also be aggregated into ***Interface Blocks***

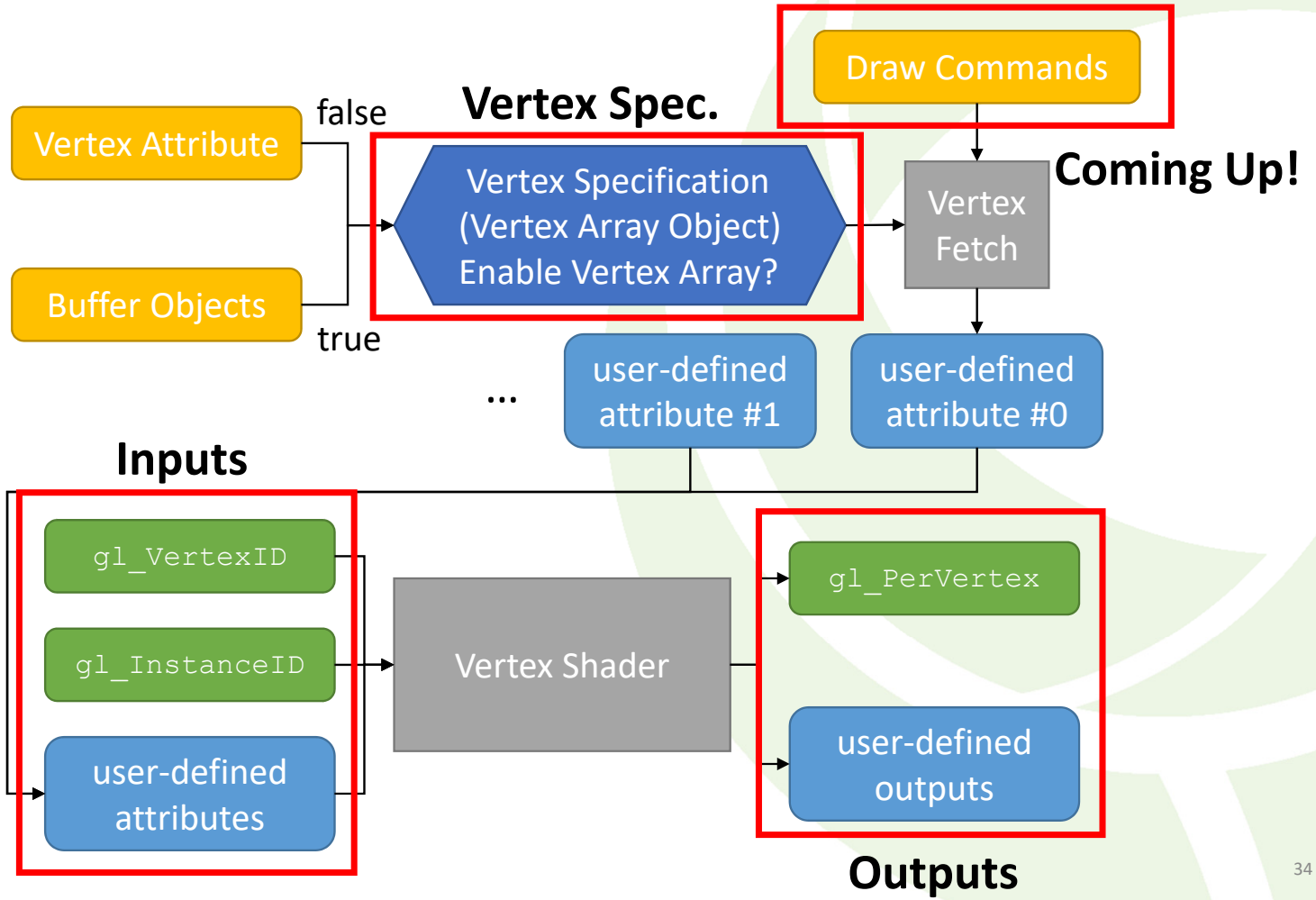
Spinning_cube.vs

```
#version 410
in vec4 position;

out VS_OUT
{
    vec4 color;
}vs_out; //(a)

uniform mat4 mv_matrix;
uniform mat4 proj_matrix; //(b)

void main(void)
{
        gl_Position = proj_matrix * mv_matrix * position; //(c)
        vs_out.color = position * 2.0 + vec4(0.5, 0.5, 0.5, 0.0); //(d)
}
```

result



Vertex Shader Overview



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Drawing commands

Drawing Commands

- Drawing commands start ***vertex rendering***: the process of taking vertex data specified in ***vertex array object*** and rendering one or more ***primitives*** with this vertex data
- Non-indexed vs. indexed
- Instanced
- Direct vs. indirect

Basic Drawing

- **`glDrawArrays`**
  - Non-indexed drawing command
  - Vertices are issued ***in order***. Vertex data stored in buffers is simply fed to the vertex shader in the order that ***it appears in the buffer***
- **`glDrawElements`**
  - Indexed drawing command
  - Includes an ***indirection*** step that treats the data in each of the buffers as an array, and uses ***another index array to index into them***
  - Bind a buffer that contains the indices of the vertices to the ***`GL_ELEMENT_ARRAY_BUFFER`*** target

glDrawArrays

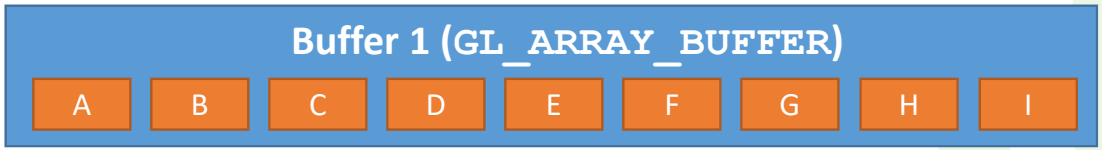
```
void glDrawArrays(GLenum mode, GLint first, GLsizei count);
```

- **Description**: ***glDrawArrays*** constructs a sequence of geometric primitives using array elements starting at **first** and ending at **first + count − 1** of each enabled array. **mode** specifies what kinds of primitives are constructed

Mode for Drawing Commands

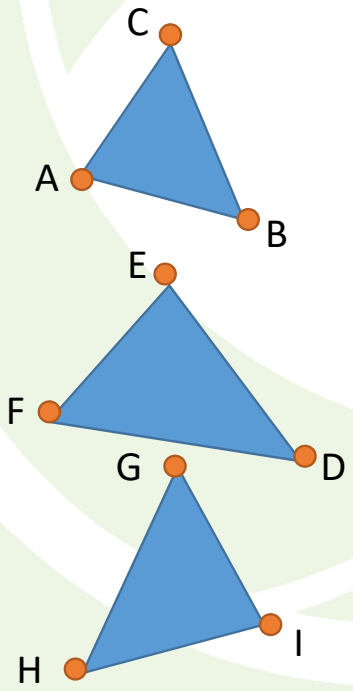
- GL_POINTS
- GL_LINE_STRIP
- GL_LINE_LOOP
- GL_LINES
- GL_LINE_STRIP_ADJACENCY
- GL_LINES_ADJACENCY
- GL_TRIANGLE_STRIP
- GL_TRIANGLE_FAN
- GL_TRIANGLES
- GL_TRIANGLE_STRIP_ADJACENCY
- GL_TRIANGLES_ADJACENCY
- GL_PATCHES

Basic Drawing




```
void render()
{
    glBindVertexArray(vao);
    glEnableVertexAttribArray(0);
    glBindBuffer(GL_ARRAY_BUFFER, buffer1);
    glVertexAttribPointer(0, 3, GL_FLOAT, GL_FALSE, 0,
0);
    glDrawArrays(GL_TRIANGLES, 0, 9);
}
```

Any Volunteers?



glDrawElements

```
void glDrawElements(GLenum mode, GLsizei count,GLenum type, const
GLvoid *offset);
```

- **Description**: **`glDrawElemets`** constructs a sequence of geometric primitives using **count** indices starting from **offset** bytes in the buffer bound to **`GL_ELEMENT_ARRAY_BUFFER`** target. **type** specifies the data type of the indices in the buffer. **mode** specifies what kinds of primitives are constructed

Create and Use Element Array

```
GLuint buffer;
static const int indices[] = { ... };

// Allocate and initialize a buffer object
glGenBuffers(1, &buffer);
glBindBuffer(GL_ELEMENT_ARRAY_BUFFER, buffer);
glBufferData(GL_ELEMENT_ARRAY_BUFFER,
             sizeof(indices), indices, GL_STATIC_DRAW);

// Bind the element array buffer and use glDrawElements()
glBindBuffer(GL_ELEMENT_ARRAY_BUFFER, buffer);
glDrawElements(GL_TRIANGLES, n, GL_UNSIGNED_INT, 0);
```

Type for Element Arrays

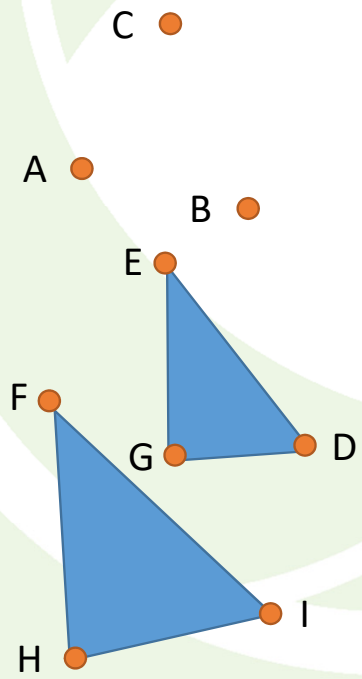
- Analyze your data for possible index range to choose the appropriate data type, saving both CPU and GPU memory

Name	Size in Bytes	Possible Values
GL_UNSIGNED_BYTE	1	[0, 255]
GL_UNSIGNED_SHORT	2	[0, 65535]
GL_UNSIGNED_INT	4	[0, 2147483647]

Basic Drawing


```
void render()
{
    glBindVertexArray(vao);
    glEnableVertexAttribArray(0);
    glBindBuffer(GL_ARRAY_BUFFER, buffer1);
    glVertexAttribPointer(0, 3, GL_FLOAT, GL_FALSE, 0, 0);
    glBindBuffer(GL_ELEMENT_ARRAY_BUFFER, buffer2);
    glDrawElements(GL_TRIANGLES, 6, GL_UNSIGNED_INT, 12);
}
```

Any Volunteers?



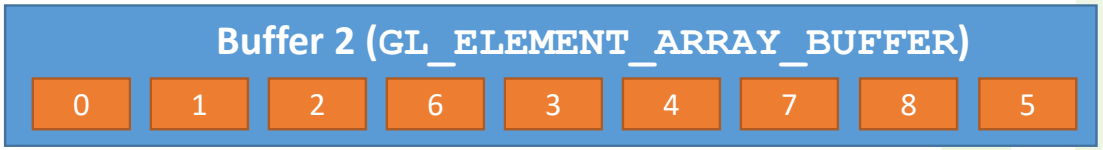
Base Index

- **`glDrawElementsBaseVertex`**
  - Index is offset by a base vertex value

```
void glDrawElementsBaseVertex(GLenum mode, GLsizei count,GLenum type,
 const GLvoid *offset, GLint basevertex);
```

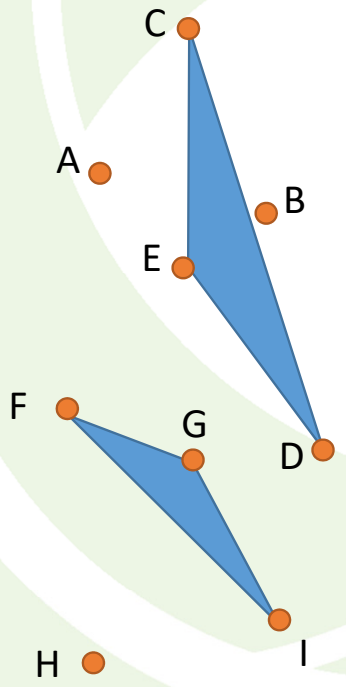
- **Description**: fetch the vertex index from the buffer bound to the ***GL_ELEMENT_ARRAY_BUFFER*** and then add **basevertex** to it before it is used to index into the array of vertices

Base Index

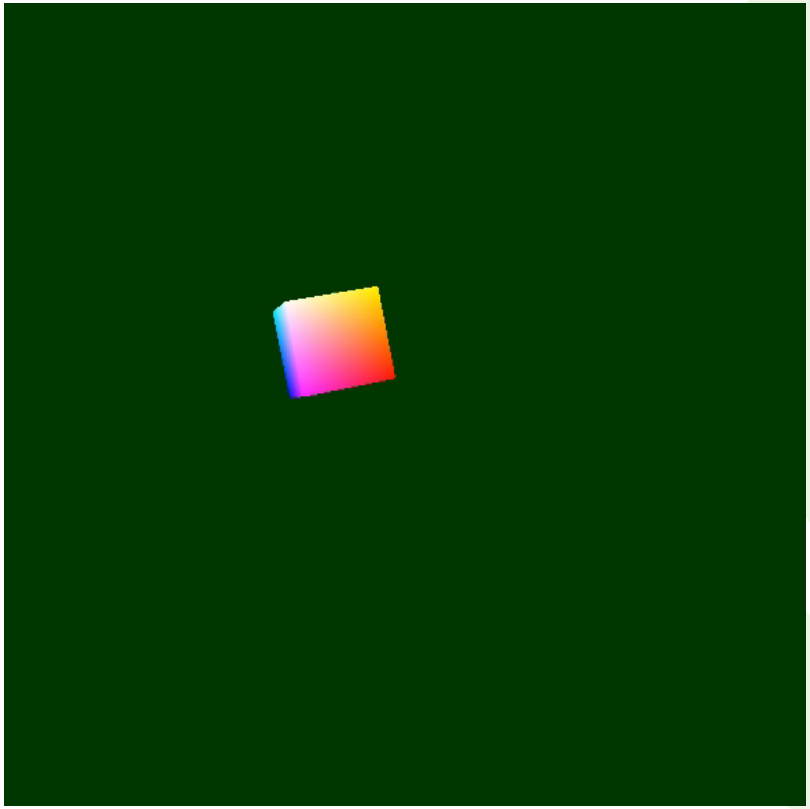



```
void render()
{
    glBindVertexArray(vao);
    glEnableVertexAttribArray(0);
    glBindBuffer(GL_ARRAY_BUFFER, buffer1);
    glVertexAttribPointer(0, 3, GL_FLOAT, GL_FALSE, 0,
0);
    glBindBuffer(GL_ELEMENT_ARRAY_BUFFER, buffer2);
    glDrawElementsBaseVertex(GL_TRIANGLES, 6,
        GL_UNSIGNED_INT, 0, 2);
}
```

Any Volunteers?



Spinning Cube



Code: Variables

```
GLuint          vao;
GLuint                  program;
GLuint                  buffer;
GLint           mv_location;
GLint           proj_location;
float           aspect;
glm::mat4       proj_matrix;
```

Code: Vertex Shader

```
#version 410 core

in vec4 position;
out VS_OUT
{
   vec4 color;
} vs_out;

uniform mat4 mv_matrix;
uniform mat4 proj_matrix;

void main(void)
{
    gl_Position = proj_matrix * mv_matrix * position;
    vs_out.color = position * 2.0 + vec4(0.5, 0.5, 0.5, 0.0);
}
```

Code: Fragment Shader

```
#version 410 core

in VS_OUT
{
    vec4 color;
} fs_in;

out vec4 color;

void main(void)
{
  color = fs_in.color;
}
```

Code: Buffer Data

```
static const GLfloat vertex_positions[] =
{
    -0.25f, -0.25f, -0.25f,
    -0.25f, 0.25f, -0.25f,
    0.25f, -0.25f, -0.25f,
    0.25f, 0.25f, -0.25f,
    0.25f, -0.25f, 0.25f,
    0.25f, 0.25f, 0.25f,
    -0.25f, -0.25f, 0.25f,
    -0.25f, 0.25f, 0.25f,
};

static const GLushort vertex_indices[] =
{
    0, 1, 2, 2, 1, 3,
    2, 3, 4, 4, 3, 5,
    4, 5, 6, 6, 5, 7,
    6, 7, 0, 0, 7, 1,
    6, 0, 2, 2, 4, 6,
    7, 5, 3, 7, 3, 1
};
```

Code: Set Up Buffer

```
glGenBuffers(1, &position_buffer);
glBindBuffer(GL_ARRAY_BUFFER, position_buffer);
glBufferData(GL_ARRAY_BUFFER, sizeof(vertex_positions),
vertex_positions, GL_STATIC_DRAW);
glVertexAttribPointer(0, 3, GL_FLOAT, GL_FALSE, 0, NULL);
glEnableVertexAttribArray(0);

glGenBuffers(1, &index_buffer);
glBindBuffer(GL_ELEMENT_ARRAY_BUFFER, index_buffer);
glBufferData(GL_ELEMENT_ARRAY_BUFFER, sizeof(vertex_indices),
vertex_indices, GL_STATIC_DRAW);
```

Code: Reshape Function

```
glm::mat4 proj_matrix;

void OnReshape(int w, int h)
{
  aspect = (float)w / (float)f;

  //should use radius in glm!!
  proj_matrix = glm::perspective(deg2rad(50.0f),aspect, 0.1f,1000.0f);

}
```

Code: Display Function

```
void My_Display()
{
    float f = (float)currentTime * 0.3f;
    glm::mat4 Identy_Init(1.0);

    glm::mat4 mv_matrix =
    glm::translate(Identy_Init, glm:: vec3(0.0f, 0.0f, -4.0f));

    mv_matrix = glm::translate(mv_matrix, glm::vec3(sinf(2.1f *f)*0.5f, cosf(1.7f * f)*0.5f,
sinf(1.3f * f)*cosf(1.5f*f)*2.0f));

    mv_matrix = glm::rotate(mv_matrix, deg2rad(currentTime*45.0f), glm::vec3(0.0f, 1.0f, 0.0f));

    mv_matrix = glm::rotate(mv_matrix, deg2rad(currentTime*81.0f), glm::vec3(1.0f, 0.0f, 0.0f));
```

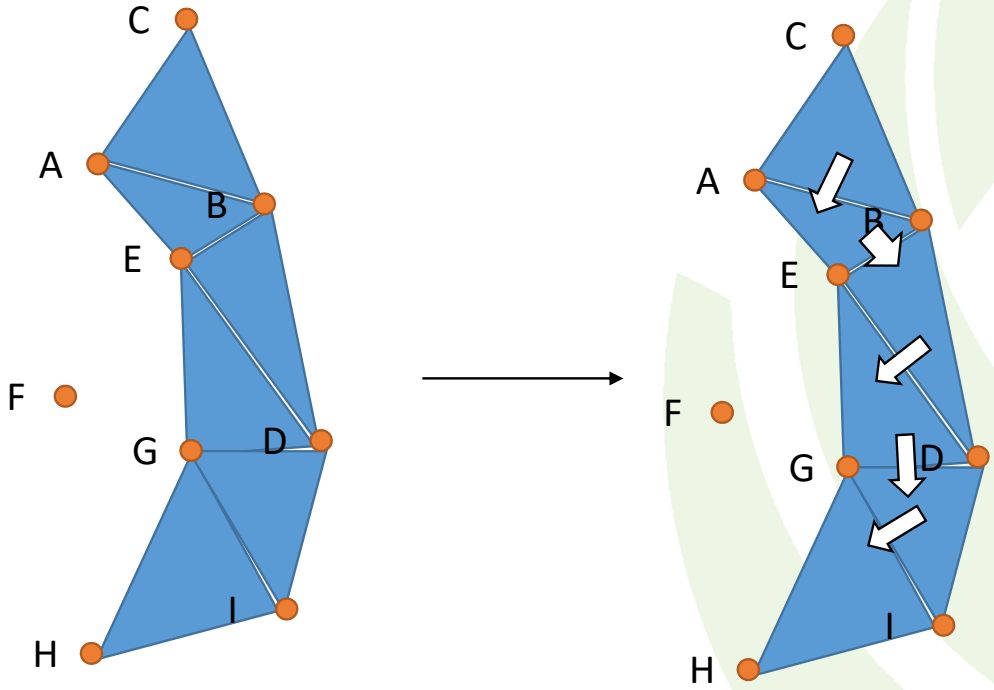
Code: Display Function (Cont'd)

```
    // Clear the framebuffer with dark green
    static const GLfloat green[] = { 0.0f, 0.25f, 0.0f, 1.0f };
    glClearBufferfv(GL_COLOR, 0, green);
    // Activate our program
    glUseProgram(program);
    // Set the model-view and projection matrices
    glUniformMatrix4fv(mv_location, 1, GL_FALSE, mv_matrix);
    glUniformMatrix4fv(proj_location, 1, GL_FALSE, proj_matrix);
    // Draw 6 faces of 2 triangles of 3 vertices each = 36 vertices
    glDrawElements(GL_TRIANGLES, 36, GL_UNSIGNED_SHORT, 0);
}
```

Drawing Triangle Strips

- Many tools are available that "***stripify***" a geometry
- The idea is that by taking "***triangle soup***," a large collection of unconnected triangles, attempt to merge it into a set of triangle strips
- Each individual triangle is represented by ***1 vertex instead of 3*** (except for the first triangle)
- By converting the geometry from triangle soup to triangle strips, there is less geometry data to process, and the system should run faster
- If the tool does a good job and produces a small number of long strips containing many triangles each, this generally works well

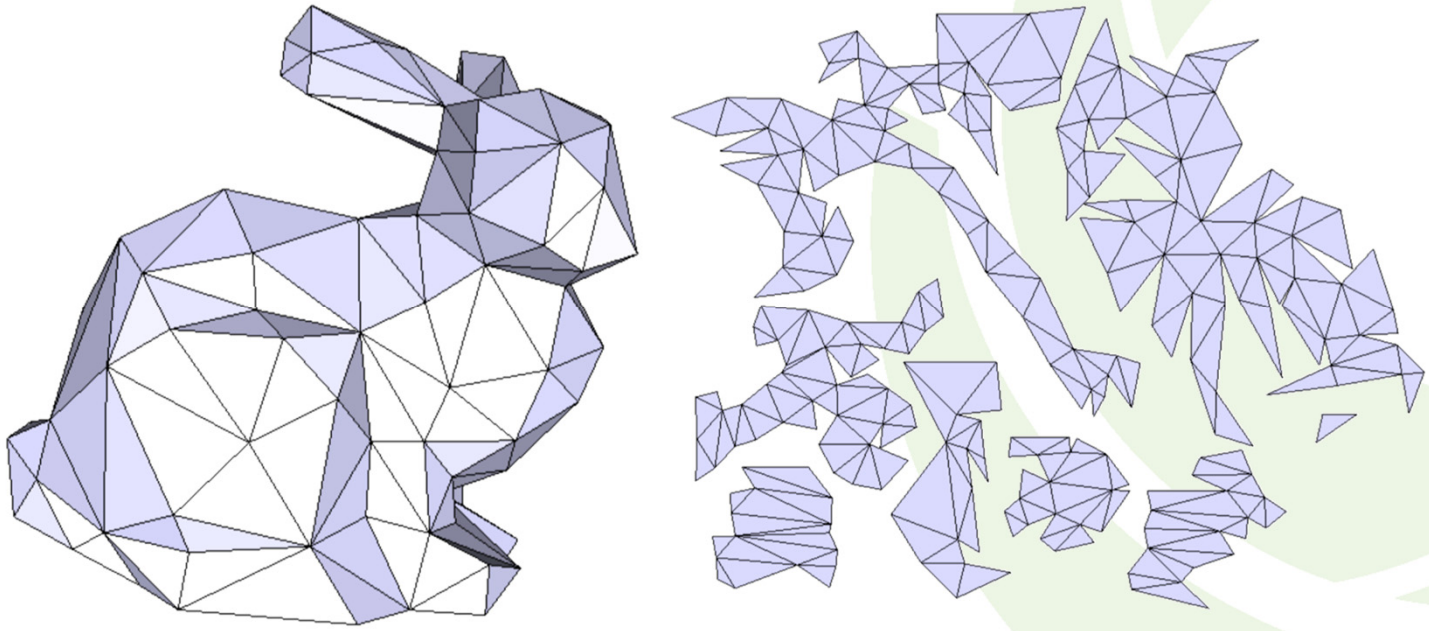
Drawing Triangle Strips



GL_TRIANGLES:
CABBAEBEDDEGDGIIGH

GL_TRIANGLE_STRIP:
CABEDGIH

Triangle Strips: Example



Instancing

- There will probably be times when you want to draw the same object many times
- A field of grass?
- There could be thousands of copies of identical sets of geometry, modified only slightly from instance to instance
- Something like this?

```
glBindVertexArray(grass_vao);
for (int n = 0; n < number_of_blades_of_grass; n++)
{
    SetupGrassBladeParameters();
    glDrawArrays(GL_TRIANGLE_STRIP, 0, 6);
}
```

Instancing (Cont'd)

- There could be thousands, millions of grass!
- Rendering each is cheap in terms of GPU cost
- The system is likely to spend most of its time sending commands to OpenGL
- Instanced rendering is a method provided by OpenGL to draw many copies of the same geometry with a single function call without system overhead
- **`glDrawArraysInstanced`**
  - Instanced version of *`glDrawArrays`*
- **`glDrawElementsInstanced`**
  - Instanced version of *`glDrawElements`*

Instancing: APIs

```
void glDrawArraysInstanced(GLenum mode, GLint first, GLsizei count,
GLsizei instancecount);
```

- **Description**: use **mode**, **first** and **count** to render **instancecount** times

```
void glDrawElementsInstanced(GLenum mode, GLsizei count,GLenum type,
const GLvoid *offset, GLsizei instancecount);
```

- **Description**: use **mode**, **count**, **type** and **offset** to render **instancecount** times

Instancing: Concepts

- How is the instanced version different from the loop one?

1. You cannot change any state between each instance rendering, while it is possible in the loop version
2. The instanced version runs faster because OpenGL only fetch state/generate command once
3. ***gl_InstanceID*** is always 0 in the loop version; while in the instanced version, its range is [0, instancecount)

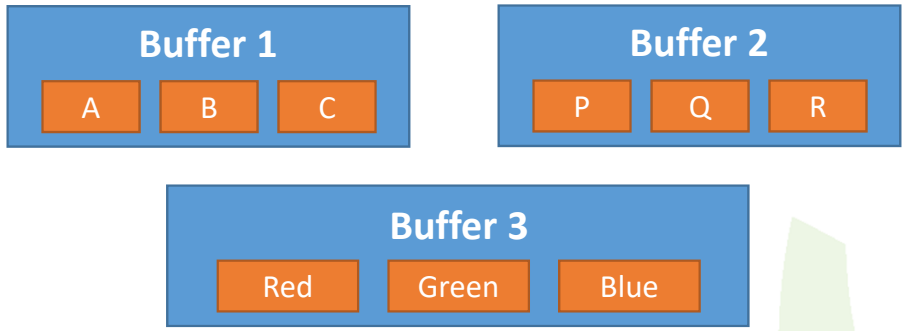
Per-Instance Data (3)

- Normally, the vertex attributes would be fetched per-vertex
- To make OpenGL read attributes once per instance, use ***glVertexAttribDivisor***

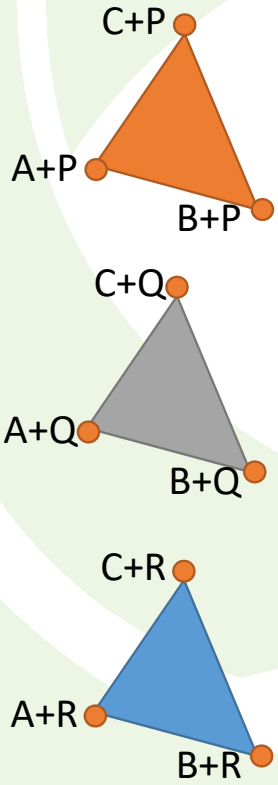
```
void glVertexAttribDivisor(GLuint index, GLuint divisor);
```

- **Description**: set the vertex fetch frequency of the vertex attribute specified by **index**. If **divisor** is zero, attribute is fetched per-vertex; If **divisor** is positive, attribute is fetched once every **divisor** instances

Per-Instance Data (3)




```
void render()
{
    glBindVertexArray(vao);
    glEnableVertexAttribArray(vertex);
    glEnableVertexAttribArray(offset);
    glEnableVertexAttribArray(color);
    ... // Bind 3 buffers
    glVertexAttribDivisor(offset, 1);
    glVertexAttribDivisor(color, 1);
    glDrawArraysInstanced(GL_TRIANGLES, 0, 3, 3);
}
```



Per-Instance Data (3)

```
void render()
{
    glBindVertexArray(vao);
    glEnableVertexAttribArray(0);
    glEnableVertexAttribArray(1);
    glVertexAttribDivisor(1, 1);
    glBindBuffer(GL_ARRAY_BUFFER, grass_vertex_buffer);
    glVertexAttribPointer(0, 3, GL_FLOAT, GL_FALSE, 0, 0);
    glBindBuffer(GL_ARRAY_BUFFER, grass_offset_buffer);
    glVertexAttribPointer(1, 3, GL_FLOAT, GL_FALSE, 0, 0);
    glBindBuffer(GL_ELEMENT_ARRAY_BUFFER, grass_index_buffer);
    glDrawElementsInstanced(GL_TRIANGLES, 9, GL_UNSIGNED_INT, 0, 10000);
}
```

```
#version 410 core

layout (location = 0) in vec3 vertex;
layout (location = 1) in vec3 offset;

void main(void)
{
    gl_Position = vec4(vertex + offset, 1.0);
}
```

Base Instance

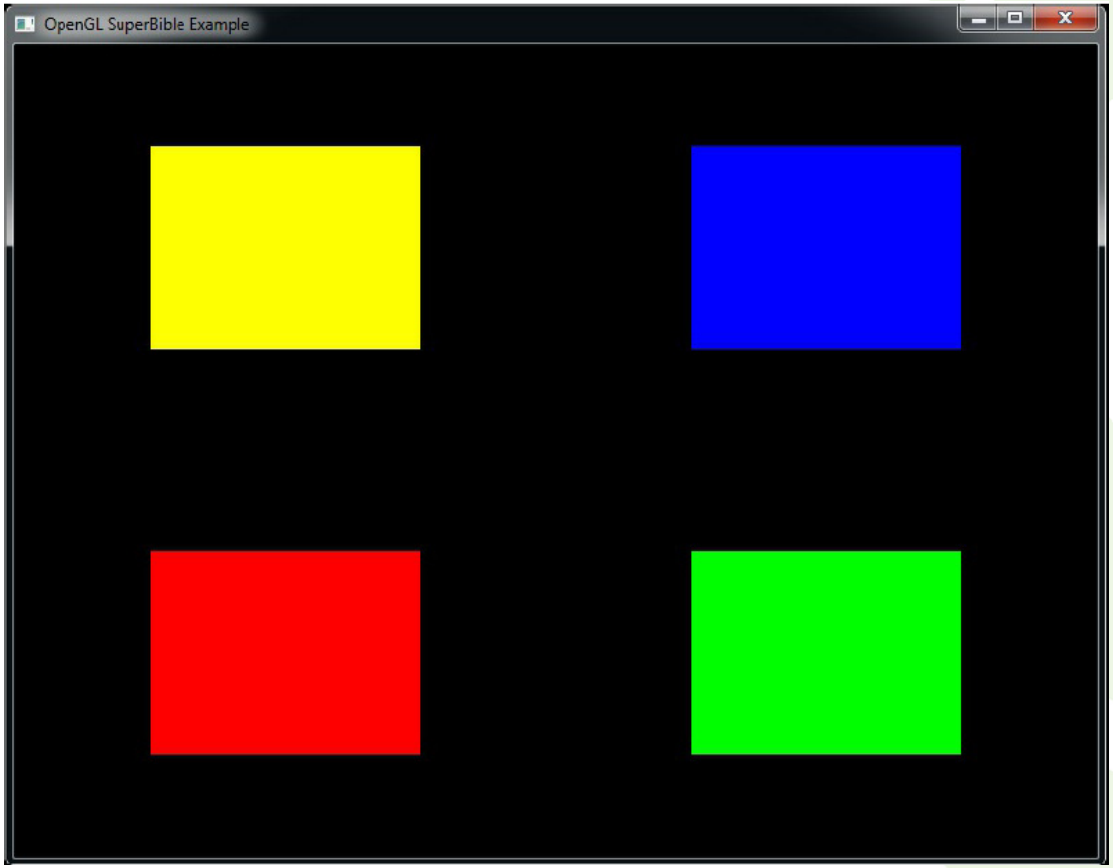
```
void glDrawArraysInstancedBaseInstance(GLenum mode, GLint first, GLsizei
count, GLsizei instancecount, GLint baseinstance);
```

- **Description**: same as ***glDrawArraysInstanced*** with additional **baseinstance** parameter

```
void glDrawElementsInstancedBaseVertexBaseInstance(
GLenum mode, GLsizei count, GLenum type, const GLvoid *offset, GLsizei
instancecount, GLint basevertex, GLint baseinstance);
```

- **Description**: same as ***glDrawElementsInstanced*** with **basevertex** and **baseinstance** parameter

Instanced Rendering



Code: Vertex Shader

```
#version 410

in vec4 position;
in vec4 instance_color;
in vec4 instance_position;

out Fragment
{
    vec4 color;
} fragment;

uniform mat4 mvp;

void main(void)
{
    gl_Position = mvp * (position + instance_position);
    fragment.color = instance_color;
}
```

Code: Fragment Shader

```
#version 410

in Fragment
{
    vec4 color;
} fragment;

out vec4 fragmentColor;

void main(void)
{
    fragmentColor = fragment.color;
}
```

Code: Buffer Data

```
static const GLfloat square_vertices[] =
{
    -1.0f, -1.0f, 0.0f, 1.0f,
    1.0f, -1.0f, 0.0f, 1.0f,
    1.0f, 1.0f, 0.0f, 1.0f,
    -1.0f, 1.0f, 0.0f, 1.0f
};
static const GLfloat instance_colors[] =
{
    1.0f, 0.0f, 0.0f, 1.0f,
    0.0f, 1.0f, 0.0f, 1.0f,
    0.0f, 0.0f, 1.0f, 1.0f,
    1.0f, 1.0f, 0.0f, 1.0f
};
static const GLfloat instance_positions[] =
{
    -2.0f, -2.0f, 0.0f, 0.0f,
    2.0f, -2.0f, 0.0f, 0.0f,
    2.0f, 2.0f, 0.0f, 0.0f,
    -2.0f, 2.0f, 0.0f, 0.0f
};
```

Code: Set Up Buffer

```
GLuint offset = 0;
glGenVertexArrays(1, &square_vao);
glGenBuffers(1, &square_vbo);
glBindVertexArray(square_vao);
glBindBuffer(GL_ARRAY_BUFFER, square_vbo);

glBufferData(GL_ARRAY_BUFFER,sizeof(square_vertices) + sizeof(instance_colors)
+sizeof(instance_positions), NULL, GL_STATIC_DRAW);

glBufferSubData(GL_ARRAY_BUFFER, offset, sizeof(square_vertices),square_vertices);
offset += sizeof(square_vertices);

glBufferSubData(GL_ARRAY_BUFFER, offset, sizeof(instance_colors), instance_colors);
offset += sizeof(instance_colors);

glBufferSubData(GL_ARRAY_BUFFER, offset, sizeof(instance_positions),
instance_positions);
offset += sizeof(instance_positions);
```

Code: Set Up Attribute

```
glVertexAttribPointer(0, 4, GL_FLOAT, GL_FALSE, 0, 0);

glVertexAttribPointer(1, 4, GL_FLOAT, GL_FALSE, 0,(GLvoid *)sizeof(square_vertices));

glVertexAttribPointer(2, 4, GL_FLOAT, GL_FALSE, 0,(GLvoid *)(sizeof(square_vertices)
+sizeof(instance_colors)));

glEnableVertexAttribArray(0);
glEnableVertexAttribArray(1);
glEnableVertexAttribArray(2);

glVertexAttribDivisor(1, 1);
glVertexAttribDivisor(2, 1);
```

Code: Display Function

```
void My_Display()
{
    static const GLfloat black[] = { 0.0f, 0.0f, 0.0f, 0.0f };

    glClearBufferfv(GL_COLOR, 0, black);

    glUseProgram(instancingProg);
    glBindVertexArray(square_vao);
    glDrawArraysInstanced(GL_TRIANGLE_FAN, 0, 4, 4);
}
```