OpenGL Rendering Pipeline and Programmable Shaders

Topics

Rendering Pipeline

Shader Types

OpenGL Shader Language Basics

Review

Some Definitions

Primitive:
An object that can be handled by a 3D rendering system such as OpenGL.

OpenGL Primitives: **triangles**, **lines**, **points**.

Vertex:
In OpenGL, a set of information about what is usually a geometric vertex. Might include a coordinate, color, etc.

Vertex Attribute:
Information associated with an OpenGL vertex, such as color, normal, etc.

OpenGL Coordinate Spaces

Object Space:
The initial coordinate space of vertices. Chosen for the particular task.

Eye Space:
A coordinate space in which the user's eye is at the origin and the user's monitor (projection plane) faces the $-z$ direction.

Clip Space:
A coordinate space in which the view volume is within a cube centered at the origin with an edge length of 2.

Window Space:
A coordinate space in which the origin is at the lower-right of the window and units are in pixels.

Rasterization

Rasterization:
The process of finding the location of pixels covered by a primitive.

Rasterization Input:

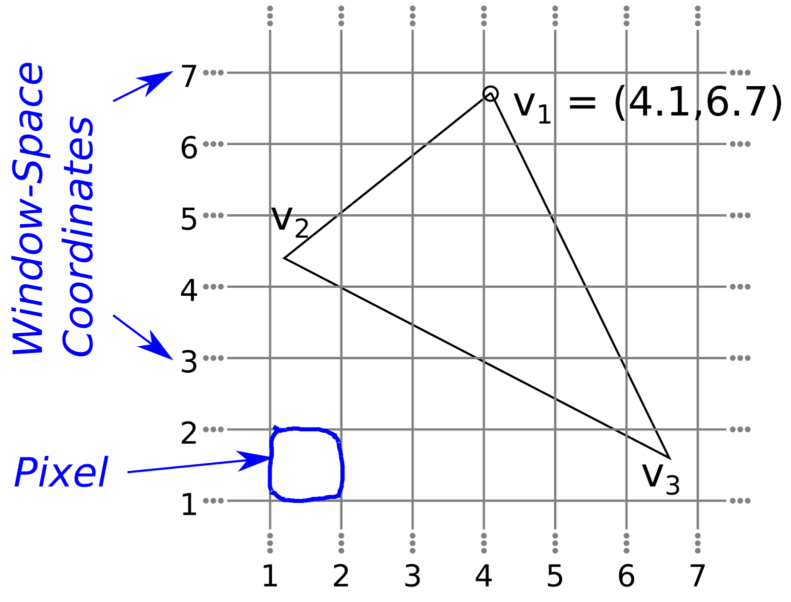
Primitive's vertices . . .
. . . with coordinates in window space.

Primitive's attributes.

Rasterization Output:

Coordinate of each pixel covered by primitive.

Interpolated attributes for each pixel.



Fragment:
Information on a pixel covered by a primitive.

Rasterization

Rasterization Question

By how much should pixel be covered by primitive?

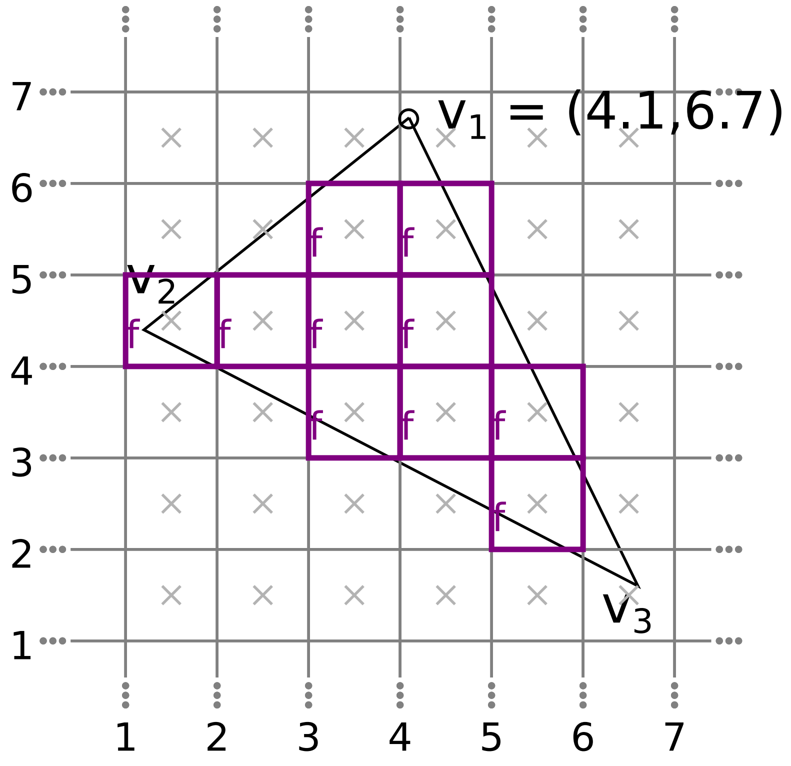
OpenGL's Answer for Triangles (Polygons)

A fragment is generated if center of pixel is inside primitive.

A special case applies if pixel center is on a shared edge.

OpenGL has rules for other primitives, and can apply antialiasing.

For course, only consider triangles without antialiasing.



Rasterization

Interpolation of Attributes

Fragment includes attributes (associated data) interpolated from primitive vertices.

Types of Interpolation (OpenGL Shader Language Terminology)

`smooth` (Perspective Correct) Interpolation:

Attribute value at point v of triangle $v_1v_2v_3$ is linearly interpolated from the attribute value at each vertex based on object space coordinates.

Computationally costly (requires division), but correct.

`noperspective` Interpolation:

Attribute value at point v of triangle $v_1v_2v_3$ is linearly interpolated from the attribute value at each vertex based on projected x and y coordinates (clip space or window space).

`flat` (no) Interpolation:

Attribute value at point v of triangle $v_1v_2v_3$ is the value of the attribute of v_3 (the provoking vertex).

Saves time when attributes are the same at all three vertices.

Rasterization

Important Point

One primitive can generate many fragments.

Fragment usually carries:

Window-space coordinates. (Exact position of pixels.)

Interpolated lighted color.

For writing to the frame buffer.

Interpolated z value.

Used to determine whether fragment is under or over another fragment.

Pipeline:

An organization for software and hardware which defines a fixed sequence of stages. Each stage carries out some operation, receiving its input data from the prior stage and providing its output data to the next stage. All data pass through the same stages in the same order.

Rendering Pipeline:

An organization for the set of steps needed to convert a set of vertices into a frame buffer image.

The term rendering pipeline might be used generically . . .

. . . or it might refer to something very specific.

"Clipping is the most tedious step in the rendering pipeline.".

OpenGL Rendering Pipeline:

The sequence of steps defined by OpenGL. . .

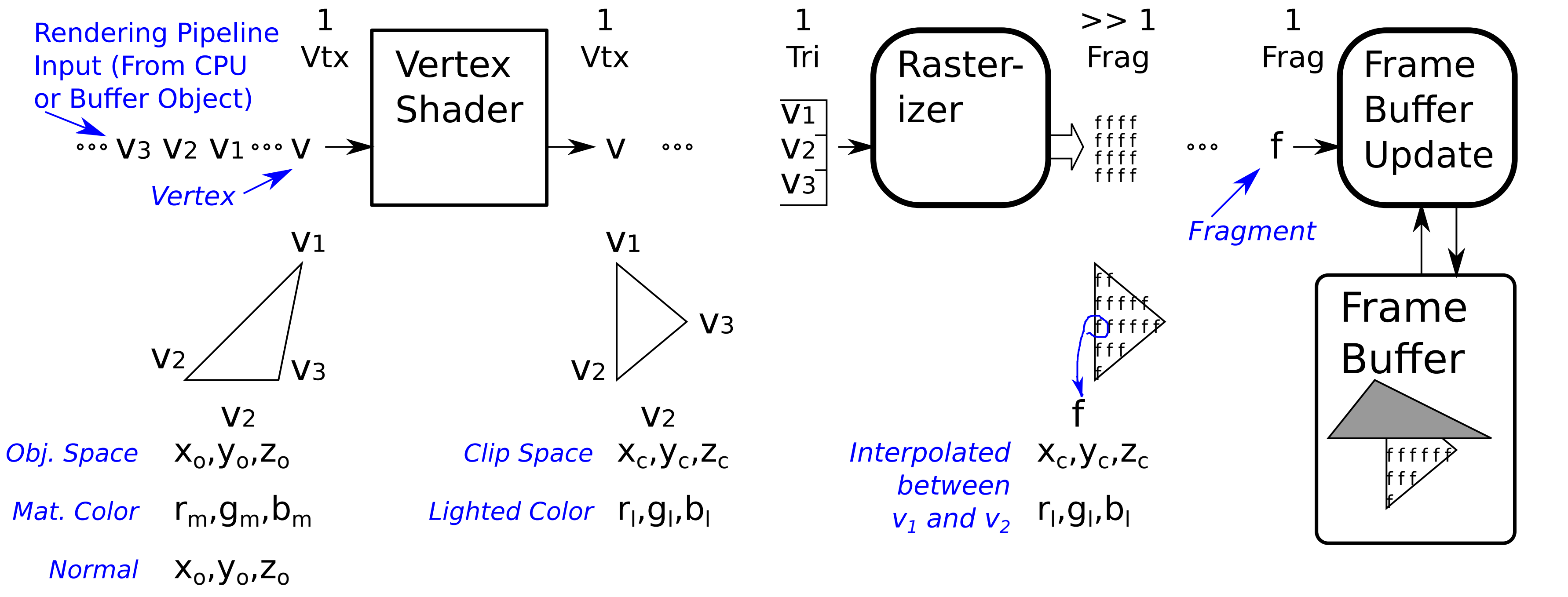
. . . that start with a vertex and its attributes . . .

. . . and usually result in the frame buffer being written.

Rendering Pass:

The use of the rendering pipeline to render some set of primitives.

Simplified OpenGL Rendering Pipeline



OpenGL Rendering Pipelines

Defined by the OpenGL standard. Current is 4.6.

Definitions

Stage:

A pipeline section.

Programmable Stage (or Unit):

An OpenGL RP stage which can perform its operation by executing user-provided software.

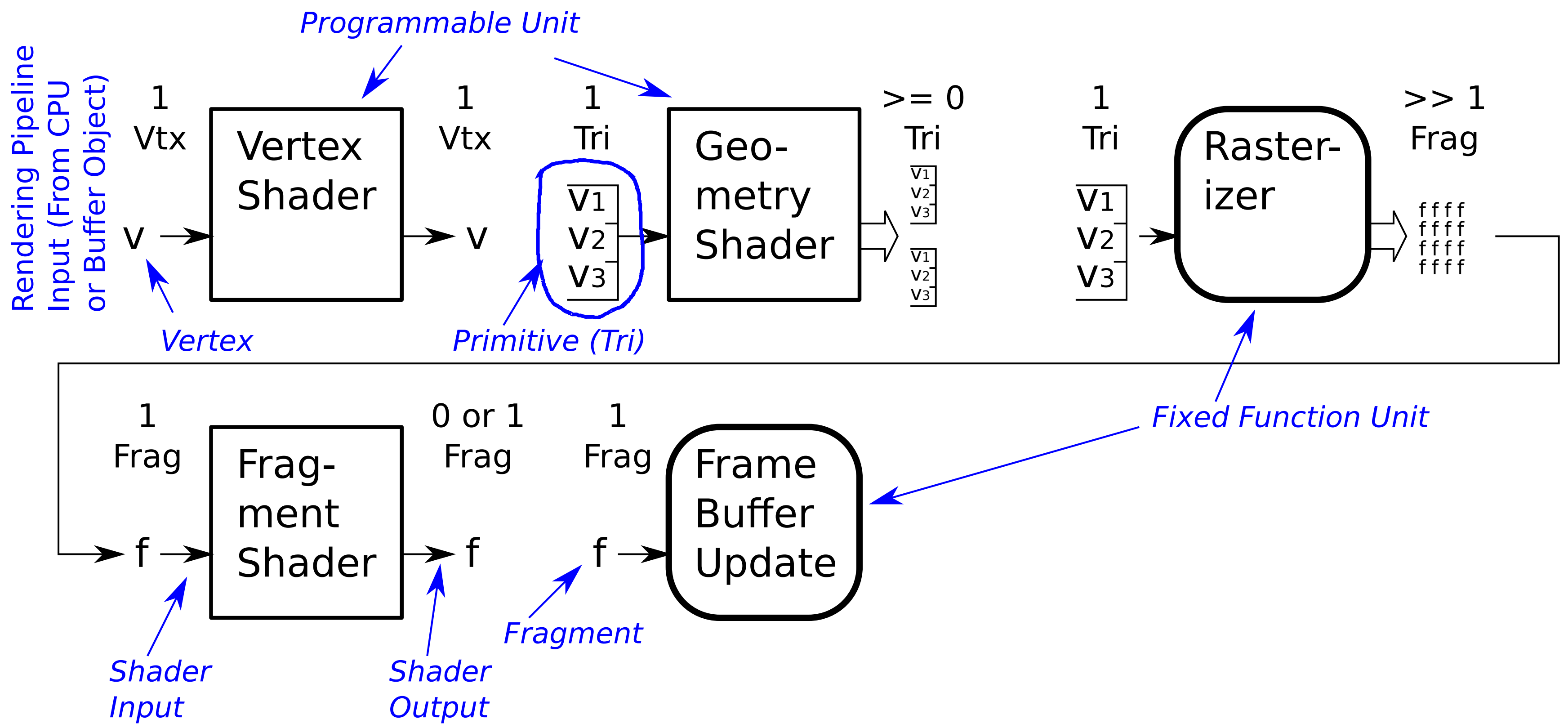
Fixed-Function Stage (or Unit):

An OpenGL RP stage which cannot be programmed, its functionality is specified by the standard and provided by the implementation.

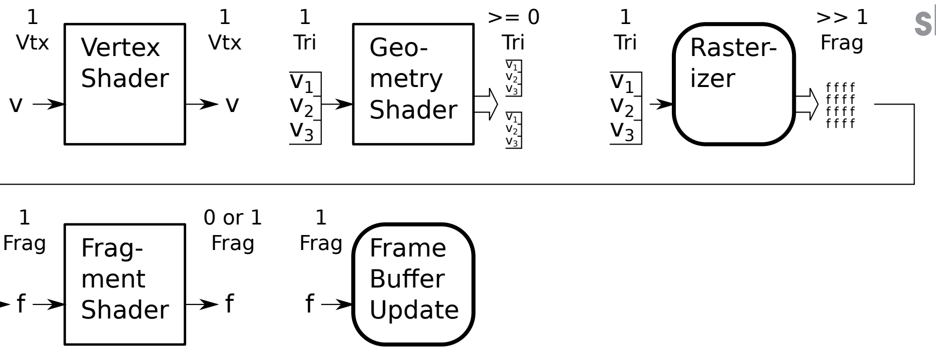
Shader:

A program set up to run in a programmable stage, or the programmable stage itself.

Less Simplified OpenGL Rendering Pipeline



Rendering Pass



```
glBegin(GL_TRIANGLE_STRIP);
glColor3fv(lsu_spirit_gold);
for ( int i=0; i<size; i++ )
    glNormal3f(norms[i].x,norms[i].y,norms[i].z);
    glVertex3f(coords[i].x,coords[i].y,coords[i].z); }
glEnd();
```

The execution of `glBegin` starts a rendering pass.

Commands such as `glDraw` also start rendering passes.

The rendering pass is complete after `glEnd` finishes.

During the rendering pass the CPU sends vertices into the rendering pipeline . . .
. . . which results in the frame buffering being updated at the RP end.

Shader Invocation

Big Difference with "Normal" Programming, Like C

C:

Must write a routine called `main`.

The routine `main` is started once each time the program is run.

This should seem obvious. How else would one do it?

OpenGL Shading Language

For each rendering pass . . .
. . . can provide a shader for each programmable unit.

Shader is run once for each item passing through pipeline.

Item can be a vertex, primitive, or fragment.

Shader Inputs and Output

Types of Storage

• `in`	Input data from a previous stage.
• `out`	Output data for a subsequent stage.
• `uniform`	Read-only data provided by CPU.
• `buffer`	A buffer object. Can be read and written.

Predefined Shader Inputs and Outputs

Each stage has predefined inputs and outputs.

Used to communicate with fixed-function hardware.

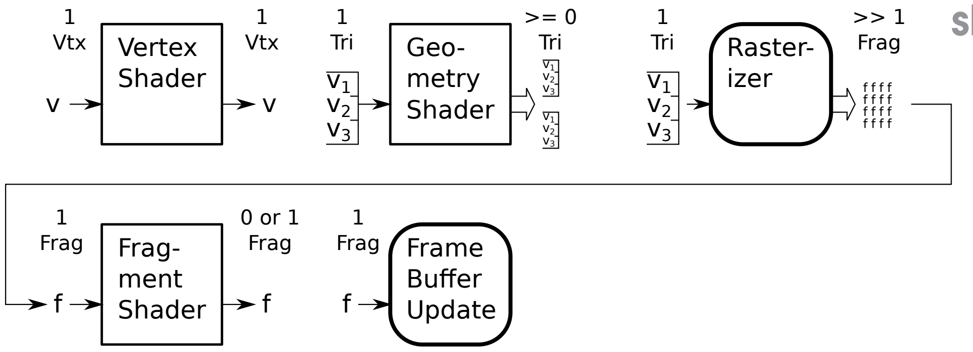
For example, `gl_Position` is used by rasterizer.

Compatibility Profile Inputs and Outputs

These are for GPUs that could not be fully programmed.

For example, `gl_Color`.

Compatibility Vertex Shader Inputs



```
glBegin(GL_TRIANGLE_STRIP);
glColor3fv(lsu_spirit_gold);
for ( int i=0; i<size; i++ )
    glNormal3f(norms[i].x,norms[i].y,norms[i].z);
    glVertex3f(coords[i].x,coords[i].y,coords[i].z); }
glEnd();
```

Each vertex in this example has the following attributes:

A coordinate (specified by `glVertex3f`).

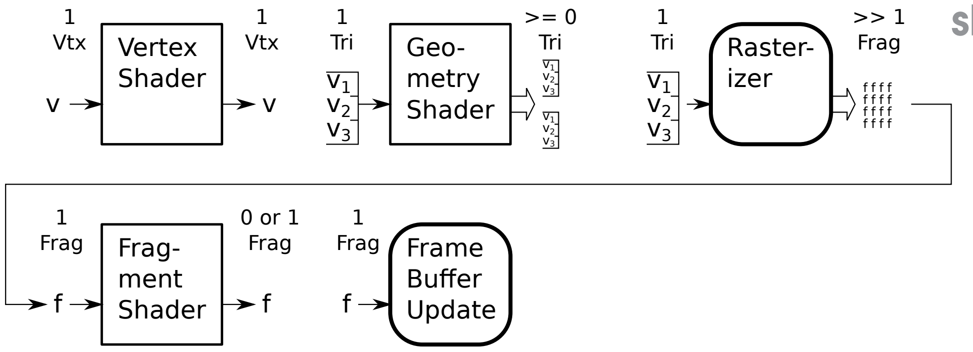
A normal (specified by `glNormal3f`).

A color (specified by `glColor3fv`).

Each execution of `glVertex3f` sends one vertex into the vertex shader.

In the diagram a vertex, including all its attributes, shown as `v`, `v1`, etc.

The Vertex Shader



Input: One vertex.

Output: One vertex.

Historical Role:

Compute lighted color of vertex.

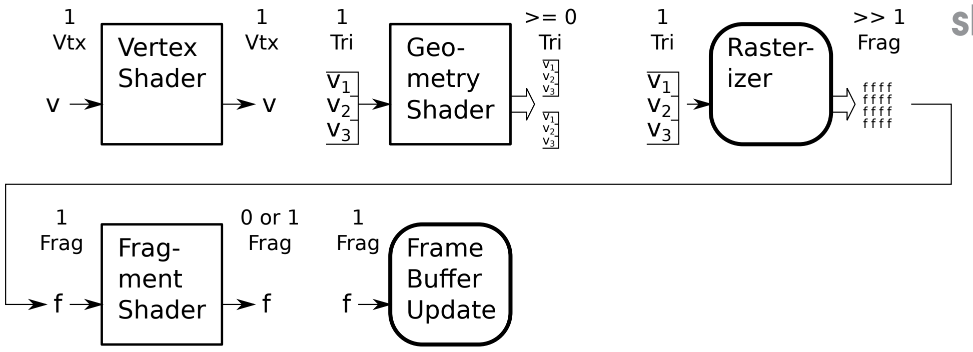
Convert object-space coordinates to clip space.

Current Role:

Provide data for geometry shader (completely user determined).

If no geometry shader, output must include clip-space coordinates.

The Geometry Shader



Input: One primitive.

Output zero or more primitives.

Input primitive type must be compatible with primitive specified by `glBegin` or `glDraw`.

Input data is an array of vertex shader outputs . . .
. . . the size of the array is determined by primitive type.

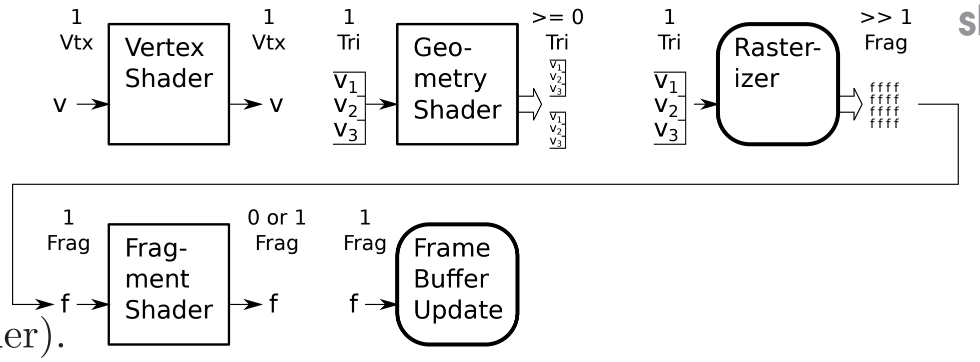
Output primitive type can be freely chosen.

Current Role:

Must write clip-space coordinates to `gl_Position`.

Also writes whatever other data fragment shader needs.

Rasterizer



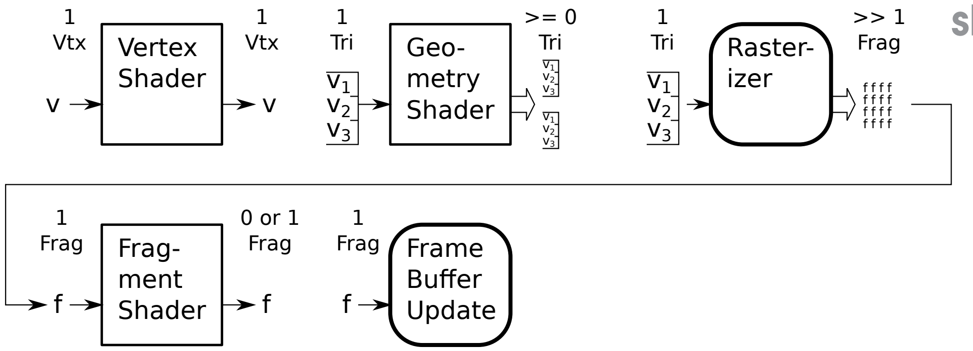
Input: One primitive . . .
. . . (type determined by geometry shader).

Output: Zero or more fragments—one fragment for each pixel that the primitive covers.

The data for each fragment is some combination of the data . . .
. . . for each vertex in the input primitive.

The rasterizer cannot be programmed.

Fragment Shader



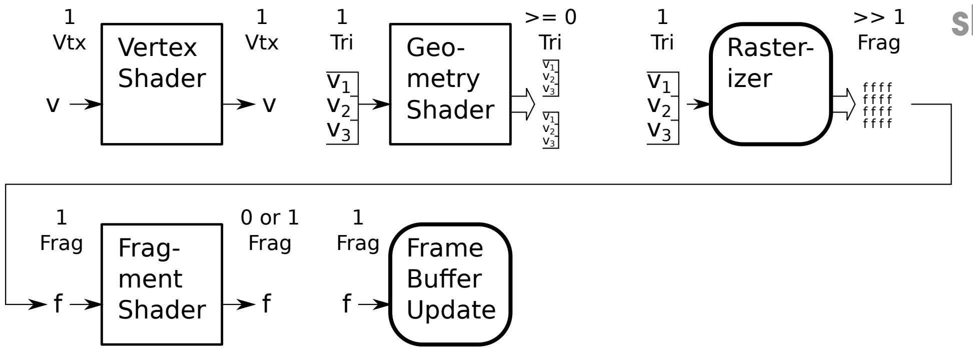
Input: One fragment.

Output: Zero or one fragments.

Typical Role:

Read texels and blend with lighted color.

Frame Buffer Update



Input one fragment. Output: None.

Typical Role

Applies depth, stencil, and other tests to fragment.

Blends or writes passing fragment to color plane of frame buffer.

Frame buffer update is not programmable.

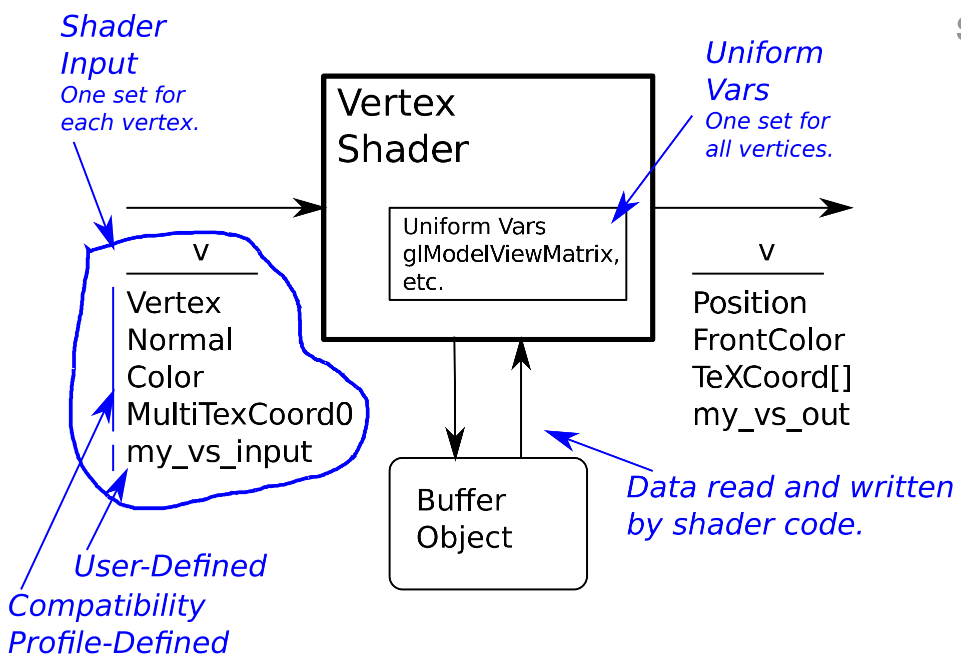
Data Access by Shaders

Categories

Shader inputs and outputs.

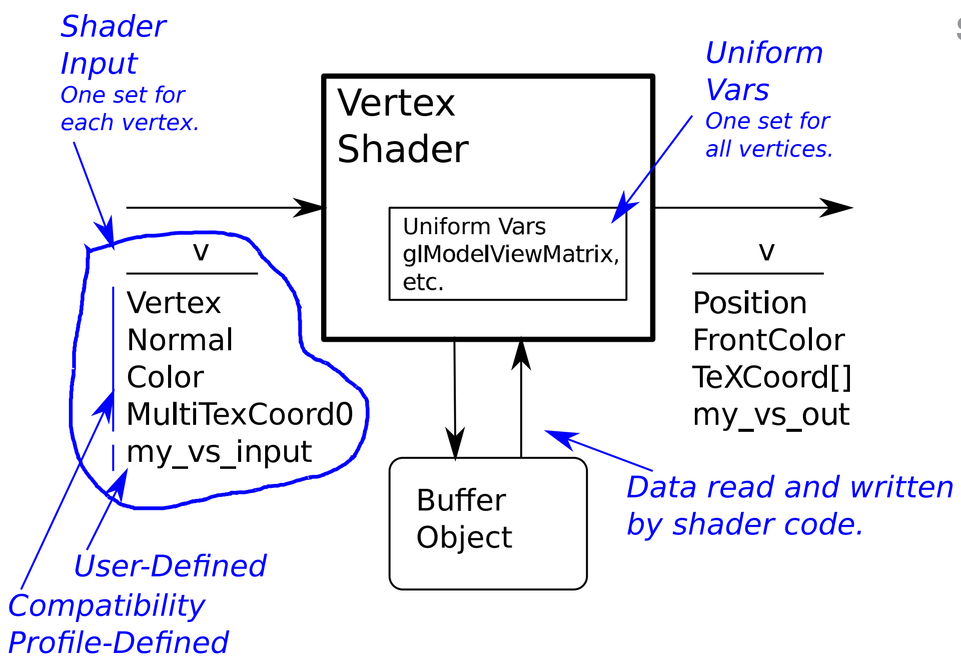
Uniform variables.

Buffer objects.



Shader Input
One set for each vertex.
Vertex Shader
Uniform Vars glModelViewMatrix, etc.
Uniform Vars
One set for all vertices.
v
Vertex
Normal
Color
MultiTexCoord0
my_vs_input
v
Position
FrontColor
TeXCoord[]
my_vs_out
Buffer Object
Data read and written by shader code.
User-Defined
Compatibility Profile-Defined

Data Access by Shaders



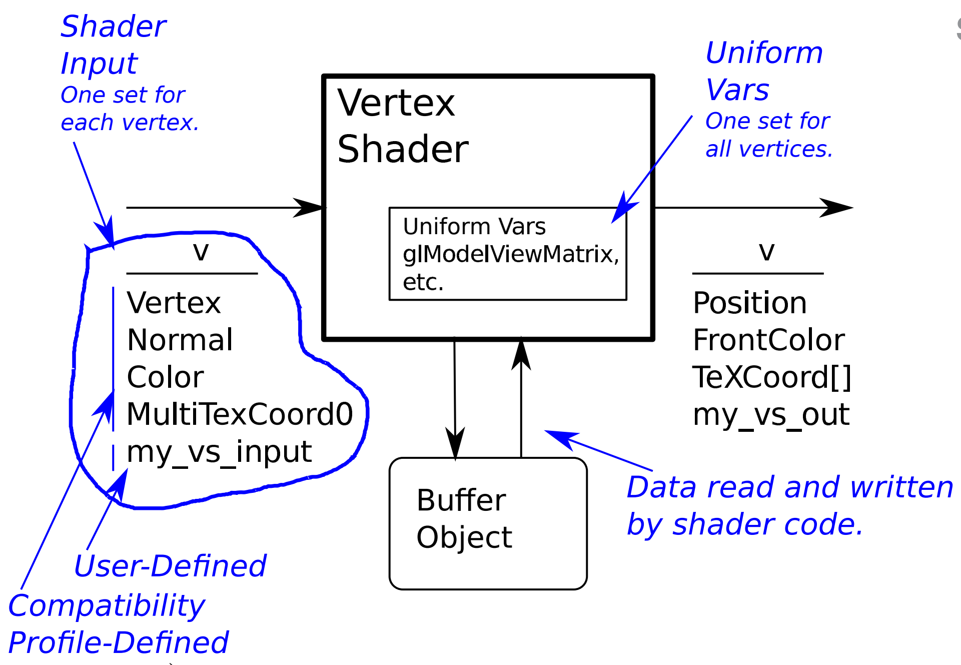
Shader Inputs and Outputs

One set of data **for each** vertex, primitive, or fragment.

To avoid waste, should not include values common to all.

For example, don't make color a shader input if all vertices are the same color, use a uniform instead.

Data Access by Shaders



Uniform Variables

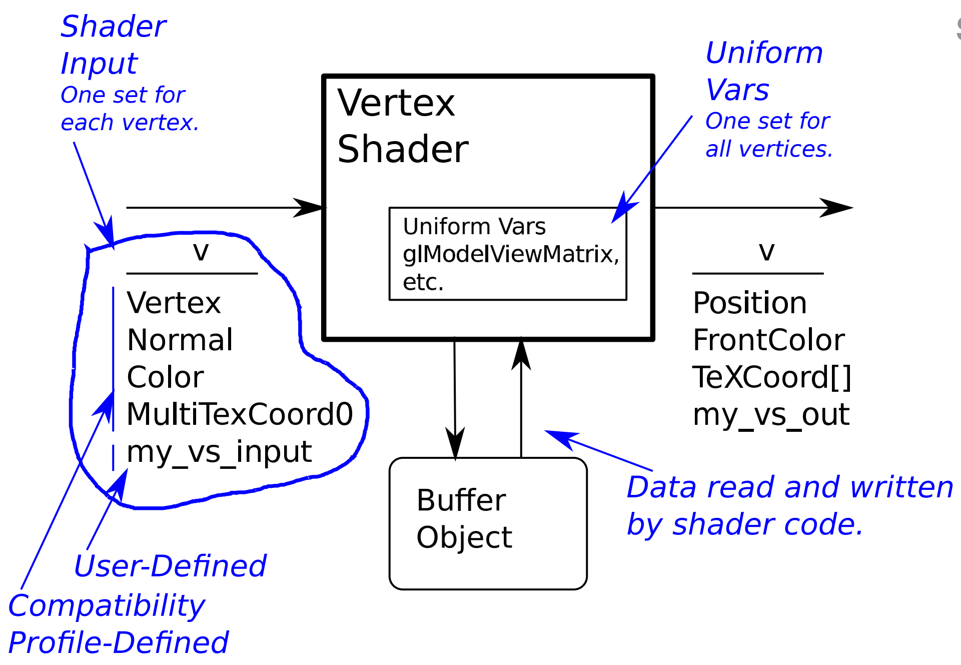
One set of data shared by all.

Read only.

Size is limited, typically 64 kiB.

Usually cached (especially if < 8 kiB accessed).

Data Access by Shaders



Buffer Objects

Shared by all. . .

. . . (vertices, primitives, fragments).

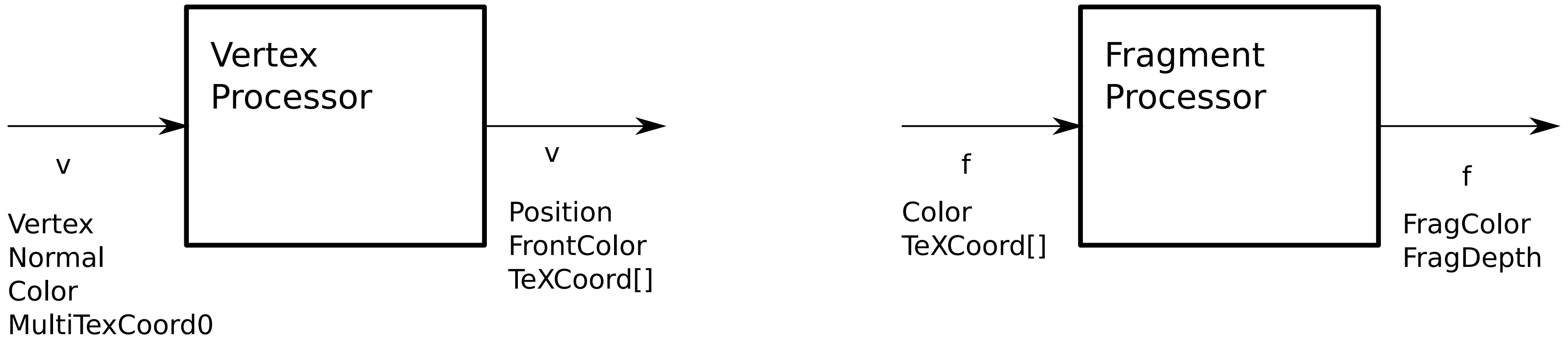
Can be read and written,. . .

. . . typically as an array.

Size is large.

Usually not cached.

OpenGL Shaders



Major Rendering Pipeline Steps

Preparation

These activities are performed before invoking pipeline.

CPU specifies transforms, material properties, etc.

Calling, say, `glTranslatef`, helps set up pipeline. . .
. . . but does not start it running or feed it data.

Feed Data to Pipeline

Data enters in a unit including a vertex and its attributes.

This initiates the steps.

Vertex Processing Steps (By GPU for each vertex.)

- *Apply modelview transform to vertex.*

  Main result is vertex coordinate in eye space.

- *Compute lighted color of vertex.*

  Main result is lighted color.

- *Apply projection transform to eye-space vertex.*

  Result is vertex coordinate in clip space.

Primitive Assembly Steps

These steps operate on a primitive (a group of primitives).

- *Primitive Assembly (Group vertices into a primitive).*

  Result is, say, a group of 3 describing a triangle.

- *Clip (remove) off-screen parts of primitive.*

  Result is fewer and maybe different primitives.

- *Rasterize*

  Result is the set of fragments (fb locations) covered by primitive.

Fragment Processing Steps

These steps operate on a fragment.

- *Fetch texels, filter and blend.*

  Result is a frame-buffer ready color.

- *Frame Buffer Update*

  If fragment passes depth and other tests, write or blend.

Programmable Units

Programmable Unit:
Part of the pipeline that can be programmed (as defined by some API).

Choice of what is and isn't programmable constrained by:

Need to allow for parallel (multithreaded, SIMD, MIMD) execution.

Simple memory access.

Major OpenGL Programmable Units

Vertex Processor:

Transform vertex and texture coordinates, compute lighting.

Geometry Processor:

Using a transformed primitive and its neighbors generates new primitives. For example, replace one triangle with many triangles to more closely match a curved surface.

Fragment Processor:

Using interpolated coordinates, read filtered texels and combine with colors.

Languages

Shader:

A programmable part of a GPU. The name “shader” is now misleading but is still in common use.

Shader Language:

An language for programming shaders.

High-Level Shader Languages

High-Level Shader Languages

OpenGL Shader Language

OpenGL standard.

Syntax very similar to C.

Language designed for vertex and fragment shaders.

Cg

Originated with ATI, adopted in Direct3D.

Syntax very similar to C.

Language designed for stream programs . . .
. . . geometry, vertex, and fragment programs can be in stream form.

OpenGL Shader Language (OGSL)

OpenGL Shader Language Important Features

C-like

CPP-like preprocessor directives.

Library of useful geometry functions.

Includes vector and matrix types and operators.

OGSL Data Types Example

Example

```
vec4 vertex_e = gl_ModelViewMatrix * o_point;
vec3 norm_e = gl_NormalMatrix * gl_Normal;
vec4 light_pos = gl_LightSource[1].position;
float phase_light = dot(norm_e, normalize(light_pos - vertex_e).xyz);
float phase_user = dot(norm_e, -vertex_e.xyz);
float phase = sign(phase_light) == sign(phase_user) ? abs(phase_light) : 0.0;
```

OGSL Storage Qualifiers

Storage Qualifiers

Used in a variable declaration, specifies where data stored.

Below, `in`, `uniform`, `constant`, `out`, and `buffer` are storage qualifiers.

```
in vec4 force;           // Input to this shader, different for each primitive.
uniform float x;         // Input to shader, value rarely changed.
const int sides = 5;     // Can never be changed.
out vec2 nudge;          // Output of this shader (input to some other).
out vec2 nudge;          // Output of this shader (input to some other).
//  Buffer object accessed from shader code as helix_coord ..
//  .. and from CPU and binding point 7.
layout ( binding = 7 ) buffer Helix_Coord  { vec4  helix_coord[];  };
```

Storage Qualifier Types

uniform:

Read-only by shader. Written by client, change is time consuming.

Typical use: transformation matrices.

in:

Input to shader. Read-only by shader that made the `in` declaration. Value is set either by client (using `glVertexAttrib` and friends) or by a prior stage shader (by writing an `out` variable.

Typical uses: vertex material properties (color), normal.

out:

Output of shader. Value is written by shader in which `out` declaration appears and read by shader in subsequent stage.

buffer:

Variable is a buffer object. Value can be read or written by shader. Variable name in declaration is used by shader code, binding point in declaration is used by CPU code.

Interpolation Qualifiers

Used for fragment shader inputs.

Specify how value should be interpolated.

flat:
No interpolation.

smooth:
Perspective-correct interpolation.

noperspective:
Linear interpolation.

Deprecated Storage Qualifiers.

These were used in earlier versions of OGSL.

They have been replaced by `in` and `out`.

attribute:
Deprecated. Like an `in` but only can be used for vertex shader.

varying:
Deprecated. When used in a vertex shader is the same as `out`, when used in a fragment shader is the same as `in`.

Storage Qualifier Example

```
// For vertex and fragment shaders:

uniform float gs_constant;
uniform vec2 ball_size;
layout ( location = 4 ) uniform vec3 gravity_force;

// Vertex Shader Only (Based on what our shader needs.)

in float step_last_time;
in vec4 position_left, position_right, position_above, position_below;
layout { location = 5 ) in vec3 ball_speed;

out vec4 out_position;
out vec3 out_velocity;

// Fragment Shader Only  (Based on what our shader needs.)
//
in vec4 out_position;
in vec3 out_velocity;
```

OGSL Functions

Function Parameters

OpenGL Shading Language 4.6 Section 6.1.1

Call by value.

Parameter Qualifiers:

in (default)

out

inout

Built In Functions

See OpenGL Shading Language 4.6 Section 8

OpenGL Shading Language Use

Steps for adding a typical shader to existing OpenGL code:

- Define what the shader is supposed to do.
- Identify appropriate programmable units (vertex, geometry, fragment, etc).
- Identify data that shaders will use.
  - If data from client (CPU) determine whether attribute or uniform.
  - For attributes and uniforms, determine if pre-defined or user-defined.
- Write shader code.
- In CPU code follow steps for installing shader. (*E.g.*, use `pShader`).
- Get names of any new uniforms and attributes.
- As necessary, initialize uniforms and attributes.
- Turn shader on and off as necessary.

Example—Phong Shader

Phong Shader:

A lighting model in which the lighted color is computed at each fragment. (Otherwise the lighted color is computed at each vertex of a primitive and those lighted colors are interpolated across the fragments.)

Phong Shader Steps

- *Define what shader does.*

  Computes lighting at fragment using interpolated normal...

- *Identify appropriate units.*

  For computing lighting: fragment shader.

  For passing along normal and color info, vertex shader.

- *Identify data that shaders use.*

  VS: Lighting data, normal. (All pre-defined.)

  FS: Normal (interpolated), eye-space vertex coordinates. User def.

OpenGL Calls, from Initialization to Use (See OGL 4.3 Chapter 7)

Create Program Object (Once)

```
pobject = glCreateProgram()
```

For Each Shader (Vertex, Geometry, Fragment, etc.):

Create Shader Object

```
sobject = glCreateShader(GL_VERTEX_SHADER)
```

Provide Source Code to Shader Object and Compile

```
glShaderSource(sobject,1,&shader_text_lines,NULL);
glCompileShader(sobject);
```

Attach

```
glAttachShader(pobject,sobject);
```

Link (Once)

```
glLinkProgram(pobject);
```

Use (Many Times, *e.g.*, once per frame.)

```
glUseProgram(pobject);
```

OGSL Use

Obtaining and Using Variable References

At run time variables identified by number.

At Initialization get **location** (index) of attributes and uniforms:

```
vsal_pos_left = glGetAttribLocation(pobject,"position_left");
sun_ball_size = glGetUniformLocation(pobject,"ball_size");
```

During Render (Infrequently) Specify Uniform Value (Using location)

```
glUniform2f(sun_ball_size,ball_size,ball_size_sq);
glUniform3fv(4,gravity_force);
```

During Render (Per Vertex Okay) Specify Attribute Value (Using location)

```
glVertexAttrib4fv(vsal_pos_left,pos_left);
glVertexAttrib3fv(5,ball_velocity);
```

Done before each glVertex.

Same options as vertex, such as client and buffer object arrays.