Slide Set Contents

Rendering Methods: Rasterization or Ray Tracing.

Rasterization Concepts.

The Vulkan and OpenGL Rendering Pipeline.

OpenGL Shading Language Introduction.

Programmable Shaders in the Rendering Pipeline.

Data Access by Shaders.

Some Definitions

Vertex:
In OpenGL and Vulkan, a set of information about what is usually a geometric vertex. It includes a coordinate and possibly, color, surface normal, etc.

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

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

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

Triangle Primitive

Contains three vertices.

Rendering

Rendering:
Writing an image to a frame buffer corresponding to some geometry.

Two Rendering Methods:

Rasterization:

Operate on each primitive once. (The outer loop.)

Operate on each pixel multiple times.

Ray Tracing

Operate on each pixel once. (The outer loop.)

Operate on each primitive many times.

Rasterization

See `cpu-only/demo-04-z-light.cc`.

- Transform coordinates to window space.
- Compute list of pixel coordinates covered by triangle. Call these fragments.
- For each coordinate:
    - Compute lighted color at that point.
    - Retrieve texel. Combine with lighted color.
    - Check depth buffer and discard if incumbent closer to eye.
    - Write frame buffer.

Limitations of Rasterization

Can't directly tell if light is blocked (and so a there is a shadow).

There are methods such as **shadow volumes** that require extra rendering passes.

Can't directly handle reflections and refractions.

Ray Tracing

See `cpu-only/demo-05-ray-tracing.cc`.

For each pixel in the frame buffer:

Compute a ray from the eye to the pixel. (Say in object space.)

Find the primitive. . .
. . . that is intersected by the ray. . .
. . . and is closest to the eye.

Compute a ray from the intersection point to the light.

Determine whether any primitive is intersected by that ray.

If surface is reflective, compute a ray ..

Compute lighted color based on . . .
. . . light location . . .
. . . and primitive orientation relative to light and eye.

Parallelizability and Computational Efficiency

Good: task b does not depend on task a.

Good: the memory locations that are needed are known in advance.

Easy to parallelize

```
for ( int i=0; i<10000; i++ ) b[i] = a[i] * 7;
```

Not parallelizable:

```
// Elements of a are in the range 0 to 99999.
for ( int i=0; i<10000; i++ ) idx = a[idx];
```

Rasterization:

Array of primitives.

Can divide primitives between threads.

Array of fragments for each primitive.

Can divide fragments between threads.

Ray Tracing

Ray casting: Finding the closest primitive.

Naïve: Go through the list..

Actual:

Organize primitives into a **oct-tree** or a **bounding volume hierarchy (BVH)**.

Tree-like organization. Degree 8.

Root: entire world.

Divide up into eight children.

Those in turn divided.

Put a primitive in the lowest position in which it fits in box.

Search this tree.

Coordinate Spaces

The right coordinate space can simplify a task.

For that reason OpenGL (especially compatibility mode) and Vulkan specify specific coordinate spaces for specific parts of the system.

Object Space:
The coordinate space of the vertices entering a rendering pipeline or provided for ray tracing. There is no restriction on this coordinate space.

World Space:
A coordinate space common to all objects.

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 units are in pixels. The origin is typically at the upper left or the lower left.

Rasterization

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

Rasterization Input:

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

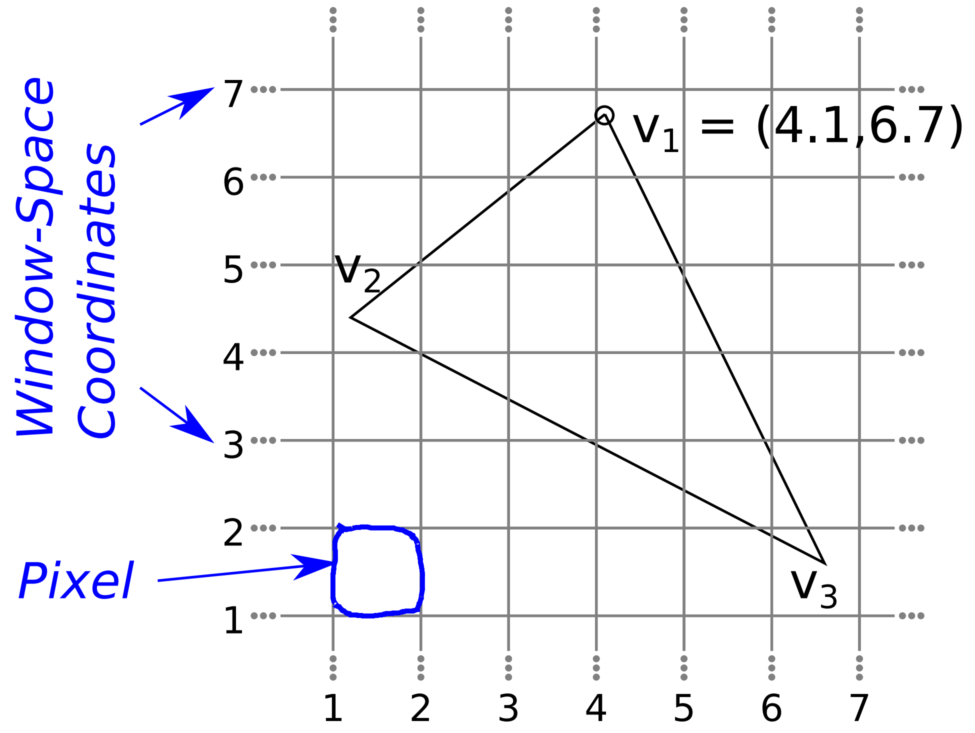
Primitive's attributes.

Rasterization Output:

Coordinate of each pixel covered by primitive.

Interpolated attributes for each pixel.

Fragment:
Information on a pixel covered by a primitive.



Rasterization Question

By how much should pixel be covered by primitive?

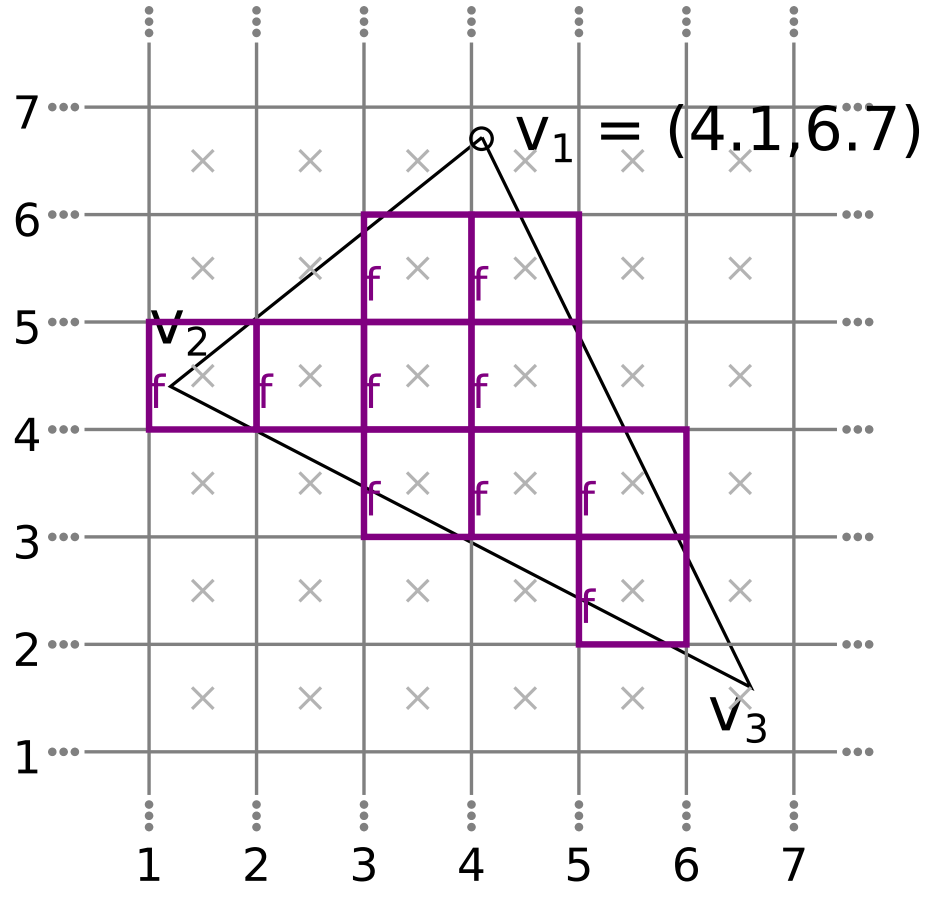
OpenGL's Answer for Triangles (Polygons)

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.



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.

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.".

Vulkan Rendering Pipeline:

The sequence of steps defined by Vulkan. . .

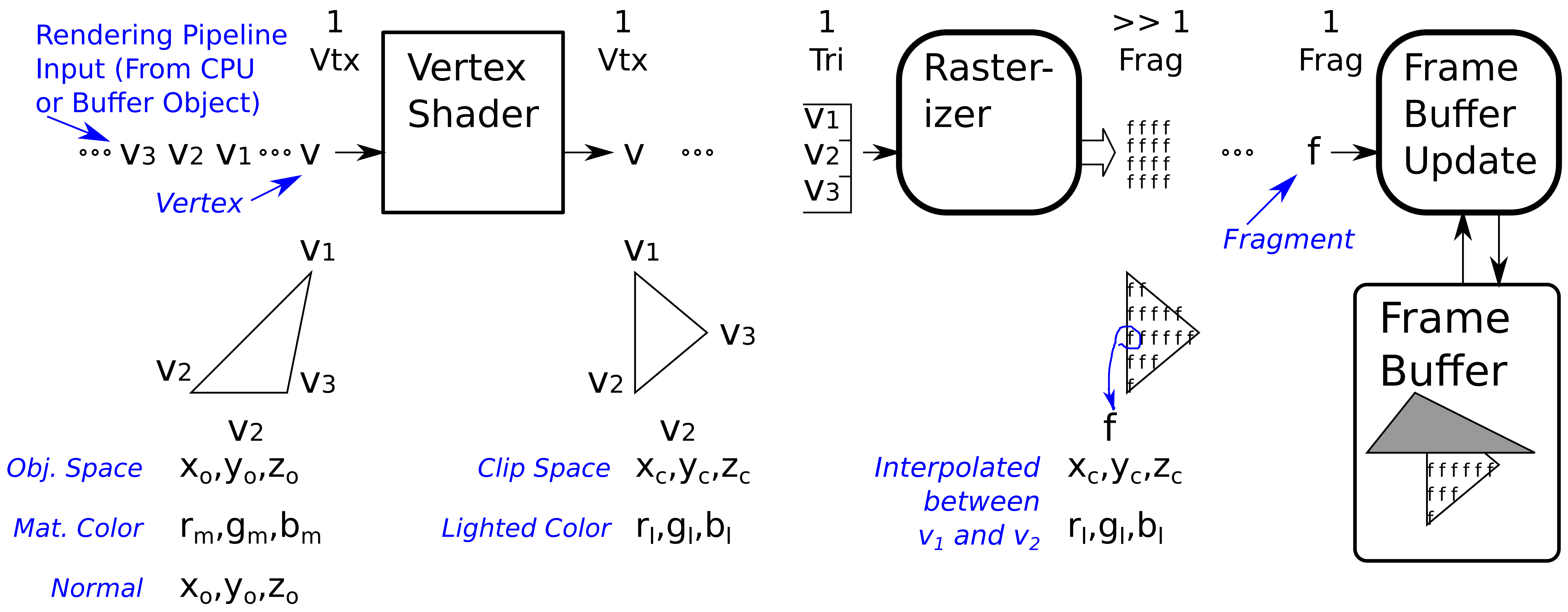
. . . that start with a vertex and its attributes . . .

. . . and usually result in the frame buffer being written. Vulkan and OpenGL rendering pipelines are very similar.

Rendering Pass:

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

Simplified Vulkan/OpenGL Rendering Pipeline



Vulkan and OpenGL Rendering Pipelines

Defined by the Vulkan (1.3) and OpenGL (4.6) standards.

Definitions

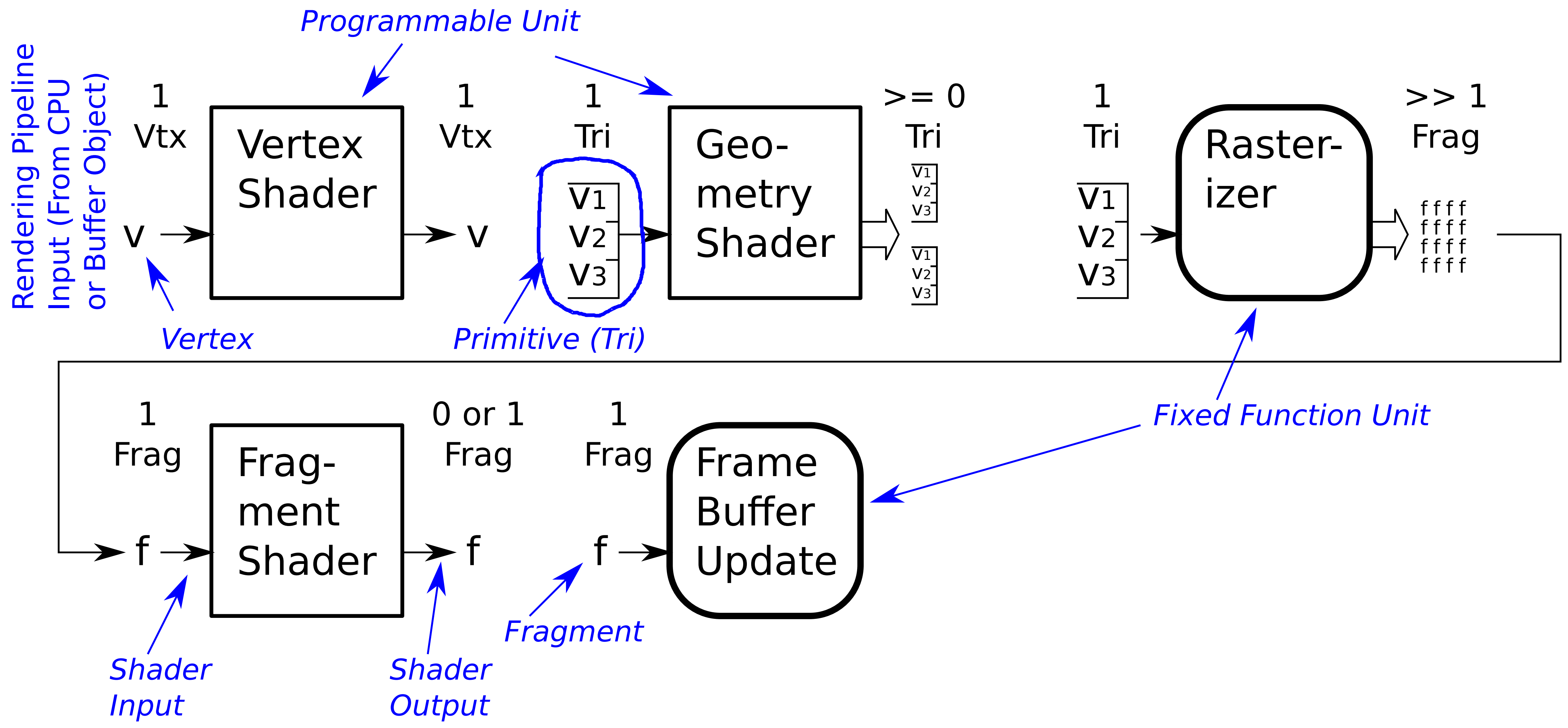
Stage:
A pipeline section.

Programmable Stage (or Unit):
A Vulkan RP stage which can perform its operation by executing user-provided software.

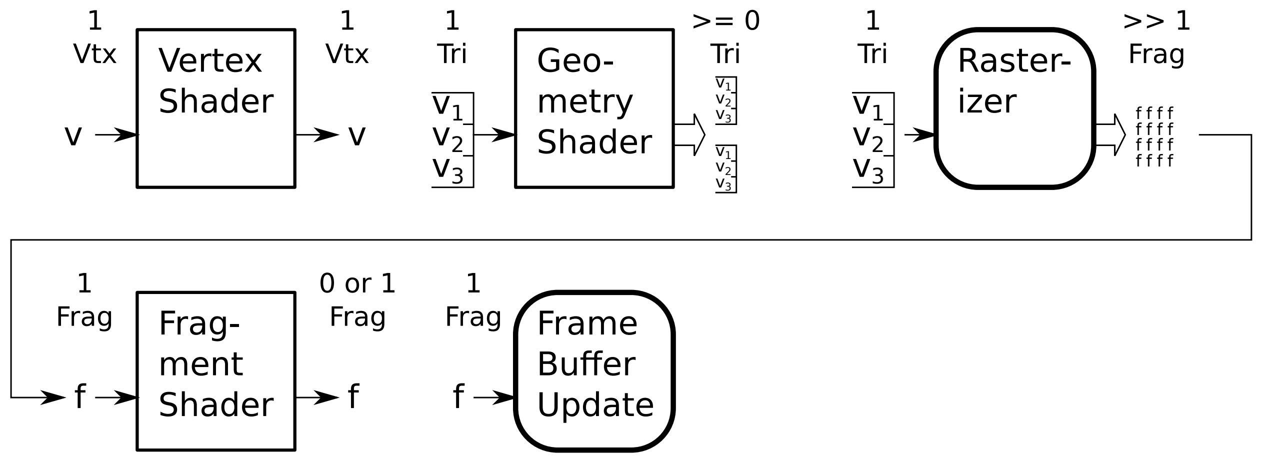
Fixed-Function Stage (or Unit):
A Vulkan RP stage which cannot be programmed, its functionality is specified by the standard and provided by the implementation.

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

Typical Vulkan Rendering Pipeline



Performing a Rendering Pass



Two Methods in OpenGL:

`glBegin(PRIMITIVE); ... glEnd();`
Slow because vertices supplied one by one.

`glDrawArray(PRIMITIVE,...)` and related commands.
Fast because vertices supplied in an array.

Example: Invoking a rendering pass using `glBegin`:

```
glBegin(GL_TRIANGLE_STRIP);    // Start rendering pass using ..
glColor3fv(lsu_spirit_gold);   // .. a rendering pipeline for triangles.
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();                      // End of rendering pass.
```

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

OpenGL Shading Language

OpenGL Shading Language (GLSL)

A C-like language for writing shaders.

Shaders in GLSL directly read by OpenGL API.

Can be used for Vulkan shaders by using a GLSL-to-SPIR-V compiler.

Basic Data Types

Section 4.1

Integer Types

Types: `bool`, `int`, `uint`

`bool`: Literal values are `true`, `false`.

`int`: 32-bit 2's complement signed number.

Arithmetic: As with C, overflow ignored, result is low 32-bits.

Unlike C need explicit cast between `bool` and `int`.

Floating-Point Types

Types: `float`, `double`.

These are similar to C equivalents.

For efficiency sake use `float` rather than `double`.

Example:

```
float dist = length(v_vtx_light);
float d_n_vl = dot(normalize(normal_e), v_vtx_light) / dist;
float phase_light = max(0,front_facing ? d_n_vl : -d_n_vl );
```

Opaque Types

Types: `sampler2D`, `sampler2DArray`, ...

Used for Vulkan or GL-managed items such as texture units.

Values are automatically set (based on CPU code).

Can be used as arguments to certain GLSL library functions.

Example:
```
// Declare variable of opaque type. (layout covered later).
layout ( binding = 1 ) uniform sampler2D tex_unit_0;

void main() {
 // Pass opaque variable tex_unit_0 to texture.
 vec4 texel = texture(tex_unit_0,gl_TexCoord[0].xy);
```

GLSL Vector Types

Section 5.5

Vector sizes: 2, 3, 4 elements.

Vector element types: Boolean, int, unsigned int, float, double.

Syntax `vec`N, where $N \in \{2, 3, 4\}$ An N-element vector of floats.

Syntax T`vec`N, where $T \in \{\texttt{b}, \texttt{u}, \texttt{i}, \texttt{d}\}$ and $N \in \{2, 3, 4\}$. A vector of Booleans, unsigned ints, ints, doubles, respectively.

Example:

```
// Straightforward declarations of vectors.
vec4 my_coord = vec4(4,2,3,1);  // Assign initial value.
dvec4 my_precise_coord;         // Vector of doubles.
ivec4 my_int_vec;               // Integer vector.
vec3 my_normal;                 // Vector of floats.
```

Access to Vector Elements

Section 5.5

Can access components of vector using a suffix starting with `.`, such as `myvec.x`,…
… or an index operator, such as `myvec[0]`.

There are *three* sets of suffixes: `xyzw`, `rgba`, `stpq` …
… any of these sets can be used, it does not depend on how the vector is declared.

Example:

```
// Demonstrate Suffix Interchangeability -- Not Good Coding Style
vec4 myvec = vec4(4,2,3,1);
// All three variables, myxa,myxb,myxc, are set to 4 (myvec.x).
float myxa = myvec.x,  myxb = myvec.r,  myxc = myvec[0];
myvec.y = myvec.q;    // Change myvec.y from 2 to 1.

// Reasonable Use of Suffixes.
vec4 my_color = vec4(0.1, 0.3, 0.7, 1);   // red, green, blue, alpha
vec3 my_velocity = vec3(10,20,30,1);      // x, y, z
vec2 my_tex_coor = vec2(0.1, 0.5);        // s, t  (s,t used for x,y in texture coords)
float gray_level = ( my_color.r + my_color.g + my_color.b ) * my_color.a / 3.0;
if ( bounce ) my_velocity.y = -my_velocity.y;
if ( my_tex_coor.s < 0.1 ) my_tex_coor.s = 0.1;
```

Multiple Component Access (Swizzling)

Vector suffixes can be made of multiple letters, such as `myvec.xy`. . .
. . . result is a vector consisting of the indicated components.

Components can be in any order, `myvec.yx`, and can be repeated, `myvec.xx`.

Example:

```
vec4 myvec = some_function_that_returns_a_vec4();
vec2 mv21 = myvec.xy;   // Assign first two components.
vec3 mv22 = myvec.yzw;  // Assign last three components.

vec2 vm23 = myvec.yx;  // Swap x and y.

vec4 mvr = myvec.yzwx; // Rotate components.

vec2 dosequis = myvec.xx;  // Duplicate a component.

float instead_of_y_g_t = myvec[1];  // Access second component.
```

GLSL Matrix Type

Matrix sizes: Up to 4×4.

Matrix element types: Boolean, int, float, double.

Syntax: `mat`N`x`M, where $N \in \{2,3,4\}$ $M \in \{2,3,4\}$. Describes an $N \times M$ matrix of floats.

Syntax: `mat`N, an $N \times N$ matrix of floats.

Syntax: T`mat`N`x`M, where $T \in \{\texttt{b}, \texttt{i}, \texttt{d}\}$. An $N \times M$ matrix of Booleans, ints, doubles.

Example:

```
mat4x4 tr;          // 4 x 4 matrix.
mat4 translation;   // 4 x 4 matrix. (Can use type mat4 or mat4x4).
mat3 rot;
mat3x2 rot2;        // 3 x 2 matrix of floats.
mat3x4 vulkan_mat; // Useful when 4th row is just 0,0,0,1. Save space.
```

Vector and Matrix Operators

Section 5.10.

Many arithmetic operators work with vector and matrix types.

The * operator does matrix/vector multiplication.

The + operator does component wise addition.

Example:

```
vec4 obj_sp = get_os_coord();
mat4 mv_matrix = get_mat();

vec4 eye_sp = mv_matrix * obj_sp;  // Matrix / vector multiplication.

vec4 transl = vec4(1,0,2,0);
vec4 moved = eye_sp + transl; // moved.x = eye_sp.x + transl.x, ...
```

Shader Data Access, Storage Qualifiers

Section 4.3

Storage Qualifier:
The part of a variable declaration that determines where the value is stored and how it can be used.

Possible Qualifications:

No qualifier: Value is local to a procedure. (This is the only easy one.)

`uniform`: For declaring uniform variables. Read-only. Value set on the CPU.

`buffer`: For declaring storage buffers. Readable and writable by everyone. Allocated on the CPU.

`shared`: Readable and writable by work group.

`in`: For declaring shader inputs. Read-only. Data written by preceding shader stage or CPU.

`out`: For declaring shader outputs. Read/write. Data read by succeeding shader stage or fixed functionality.

Each qualifier above must be used with a `layout` qualifier.

For each variable using these qualifier there must be other code somewhere that provides its value.

Uniform Variables

Uniform Variable:
A variable that uses high-speed, low-capacity storage on the GPU, and which is read-only by shaders. Uniform variables are written by code on the CPU.

Typical Use and Abuse

Uniform variables used for values that are frequently used and are small.

For example, transformation matrices and light locations.

Because uniform variable storage is limited, they **should not** be used for things like vertex coordinates.

More details to follow, but first example: (From `gp/vulkan/demo-09-shdr-code.cc`.)

```
// Declare a Uniform -- In Global Scope
layout ( binding = BIND_MAT_COLOR ) uniform Uni { vec4 material_color; };

// Use the Uniform -- In Fragment Shader
vec4 our_color = gl_FrontFacing ? material_color : vec4(1,0,0,1);
```

Uniform Variable Declaration

Section 4.4.5 (for binding)

```
// Declare Uniforms
layout ( binding = 2 ) uniform Uni_M {vec4 color_front, color_back;} ub;
// 111    22222222222   3333333 44444  555555555555555555555555555555  66

layout ( binding = 3 ) uniform Uni_L {vec4 light_location_e;};
```

1: The layout keyword.
2: A **binding location**, 2 and 3 in these cases. Must match binding from CPU code.
3: The uniform keyword. It would not be a uniform without it.
4: The **interface block** name. Can be used by host. For course assignments, choose anything.
5: The contents of the uniform. Format is similar to a C struct. Can contain multiple types, vars, etc.
6: Optional instance name. If given must be used by shader code.

Use in Shader Code:

```
vec4 our_color = gl_FrontFacing ? ub.color_front : vec4(1,0,0,1);
float l_to_v = distance( light_location_e, vertex_e );
```

```
// On CPU  (Scattered throughout from demo-09-shader.cc.)
VBufferV<vec4> uni_material_color_tri;
uni_material_color_tri = color_gray;
uni_material_color_tri.init(vh.qs, vk::BufferUsageFlagBits::eUniformBuffer );
uni_material_color_tri.to_dev();
pipe.ds_uniform_use( "BIND_MAT_COLOR", uni_material_color_tri );

// Declare a Uniform
layout ( binding = 2 ) uniform Uni_M {vec4 color_front, color_back;} ub;
// 111    2222222222   3333333 44444  5555555555555555555555555555  66
```

Input and Output Variable Declarations

Input Variable:
A variable, declared with qualifier `in`, which is an input to a shader (invocation). The value is written by the fixed functionality and is obtained from the CPU for the first programmable shader stage, or the output variable of the preceding stage for later stages.

```
// Single Variable Declaration

layout ( location = 1 ) in vec4 in_vertex;
// 111    222222222222    33 4444 555555555

 1: The "layout" keyword.

 2: Layout information.
      In general, info about where data is and how data arranged.
      In example above, indicates CPU placed the data in location 1.

 3: The "in" storage qualifier.
 4: Data type.
 5: Variable name.



 // Interface Block
        A group of variables that share a storage qualifier and
        other attributes.

     in Data { int hidx; vec3 normal_o; vec4 color;} In;
 11 2222   3333333333333333333333333333333333   44;

 1: Storage Qualifier
 2: Interface Block Name.
 3: Variable declarations.
 4: Instance name.


\sNewPage

\medskip
% TeXize cc
\beginlit

 Sample code:
 float len = length(In.normal_o);
 vec4 lcolor = generic_lighting(mvp * In.normal_o);
```

/// Shader Code Delcaration of Uniform Variables

```
lighted_color = ub.color_front * light_here;

1: The "layout" keyword.
2: Binding information.
3: The "uniform" keyword.
4: Interface block name. This name is used by the host, not shader code.
5: Members of the uniform block.
6: (Optional): Instance name. This is seen by shader code.
```

/// Shader Code Declaration of Storage Buffers (Arrays)

```
layout ( binding = 3 ) buffer Colors { vec4 colors[]; };
  11    22222222222   333333 444444   55555555555555
```

/// Quick Examples

Single Declarations

```
  out vec2 my_tex_coor;
 111 2222 33333333333

 1: The storage qualifier.
      In this case, indicating a shader output variable.
 2: Data Type.
 3: Variable names, or name in this case.

 Sample code writing to variable:
   my_tex_coor.x = a + b;


   in vec2 my_tex_coor;

 Sample code:
   ypos = my_tex_coor.y;


layout ( location = 3 ) uniform float wire_radius;
 111    222222222222   3333333 44444 55555555555

 1: The layout keyword.
 2: Layout information.
```

```
     In general, info about where data is and how data arranged.
     In example above, indicates CPU can find data in location 3.
3: Storage Qualifier. uniform in this case.
4: Data type.
5: Variable names. (Just one name in example.)
```

// :Def: **Interface Block**

```
       A group of variables that share a storage qualifier and
       other attributes.

  in Data { int hidx; vec3 normal_o; vec4 color;} In;
11 2222   3333333333333333333333333333333333   44;

1: Storage Qualifier
2: Interface Block Name.
3: Variable declarations.
4: Instance name.

Sample code:
float len = length(In.normal_o);
vec4 lcolor = generic_lighting(mvp * In.normal_o);
```

```
layout ( binding = 7 ) buffer Helix_Coord  { vec4  helix_coord[];  };
 111   22222222222   333333 44444444444  5555555555555555555555555

 1: The layout keyword.
 2: Layout information. In this case, an identifier used by CPU.
 3: Storage Qualifier.
 4: Interface block name.
```

/// Shader Inputs (in)

```
 :ogsl45: Section 4.3.4

   A shader input is a variable that can be read by the shader
     for which it's defined.

   Each shader stage has its own set of inputs.

   Except for the vertex shader ..
   .. shader inputs for one stage ..
   .. must match the shader outputs of the prior stage.

   There is a different set of values for each shader invocation.
```

```
  It is an error to write a shader input.

  There are pre-defined and user-defined shader inputs.

  Vertex shader inputs get values from host commands ..
  .. like glColor3f for pre-defined inputs ..
  .. and glVertexAttrib for user-defined inputs.

  Other stages' input values are produced by outputs of the prior stage.
```

/// Shader Outputs (out)

```
:ogsl45: Section 4.3.6

  A shader output is a variable that can be written by the shader
    for which it's defined.

  Each shader stage has its own set of outputs.

  Except for the fragment shader ..
  .. shader outputs for one stage ..
  .. must match the shader inputs of the next stage.

  It is okay to read a shader output ..
```

.. but value is undefined if shader has not yet written it.

There are pre-defined and user-defined shader outputs.

Programmable Shaders

Programmable Shaders’ Role

Written by OpenGL Programmers (that would be us).

The shaders implement the functionality of a RP stage.

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 **storage buffer** (Vulkan) or a **buffer object** (OpenGL). Can be read and written.

Predefined Shader Inputs and Outputs

Each stage has predefined inputs and outputs.

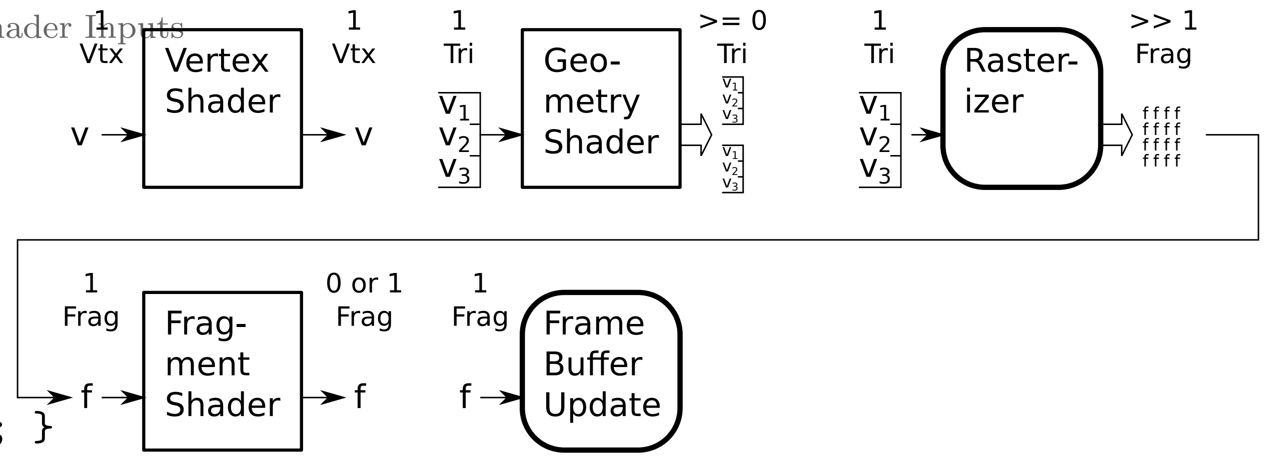
Used to communicate with fixed-function hardware.

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.

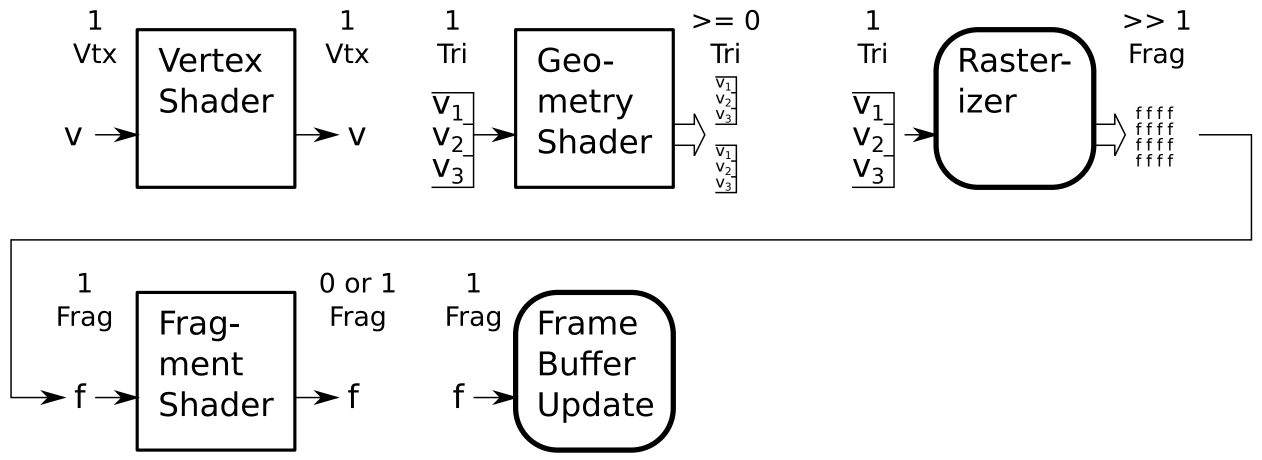
In the diagram a vertex, including all its attributes, shown as `v`, `v1`, etc.

Major Rendering Pipeline Stages

The major stages summarized in the next few slides.

Some are programmable, some are fixed function.

The Vertex Shader



Input: One vertex.

Output: One vertex.

Historical Role:

Compute lighted color of vertex.

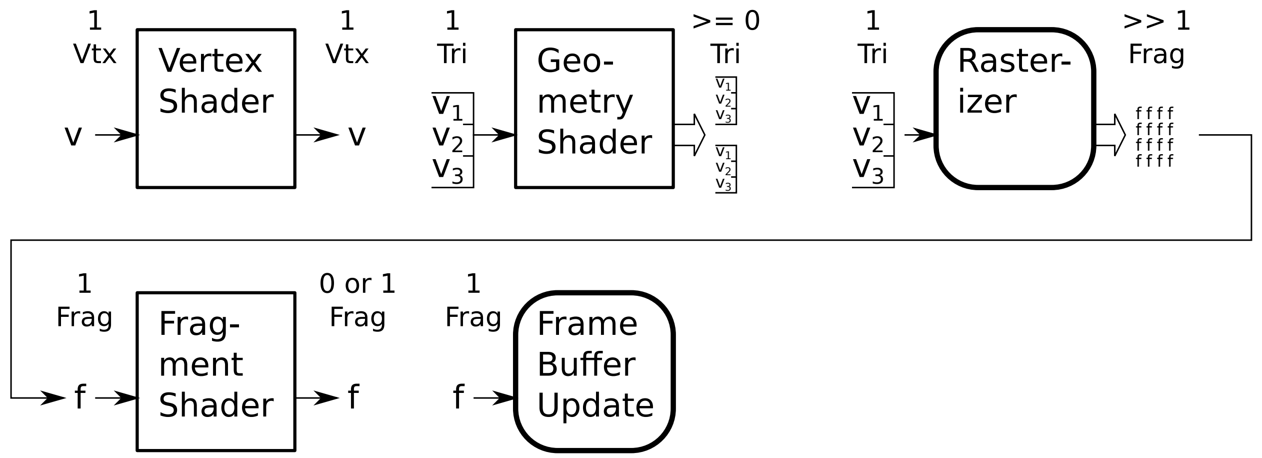
Convert object-space coordinates to clip space.

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.

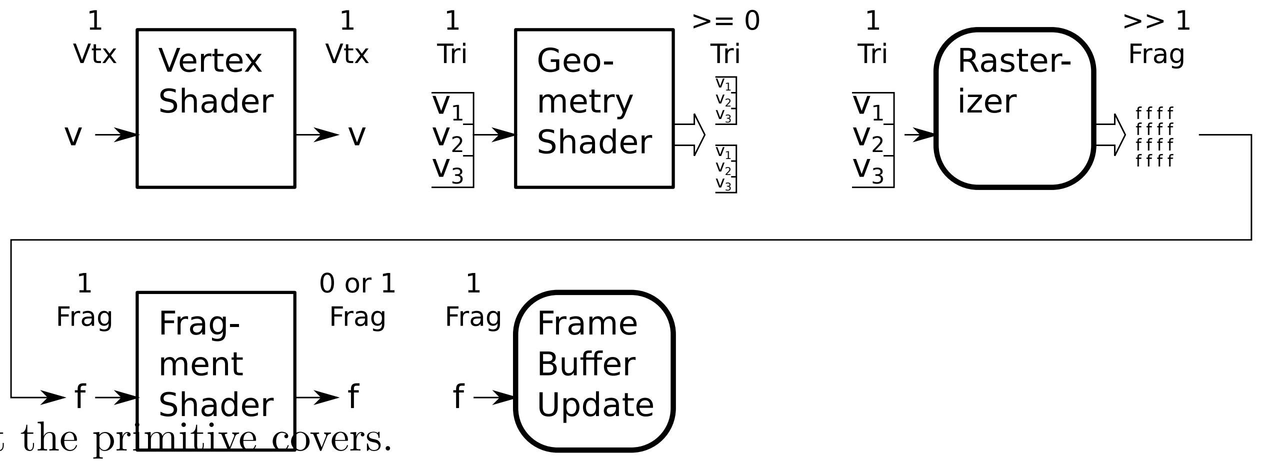
Output primitive type can be freely chosen.

Current Role:

Must write clip-space coordinates to `gl_Position`.

Also writes whatever other data fragment shader needs.

Rasterizer



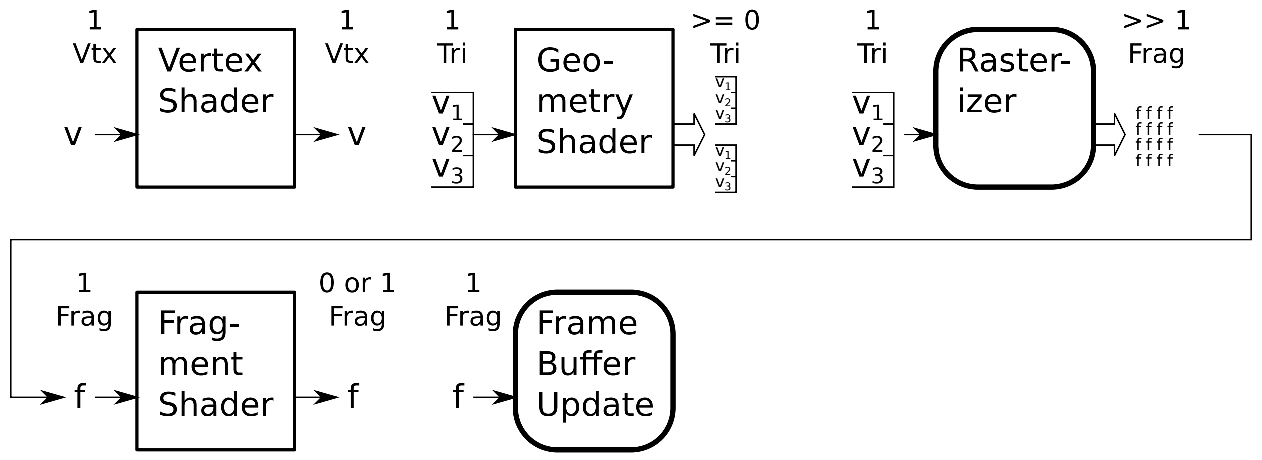
Input: One primitive . . .
. . . (type determined by geometry shader).

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



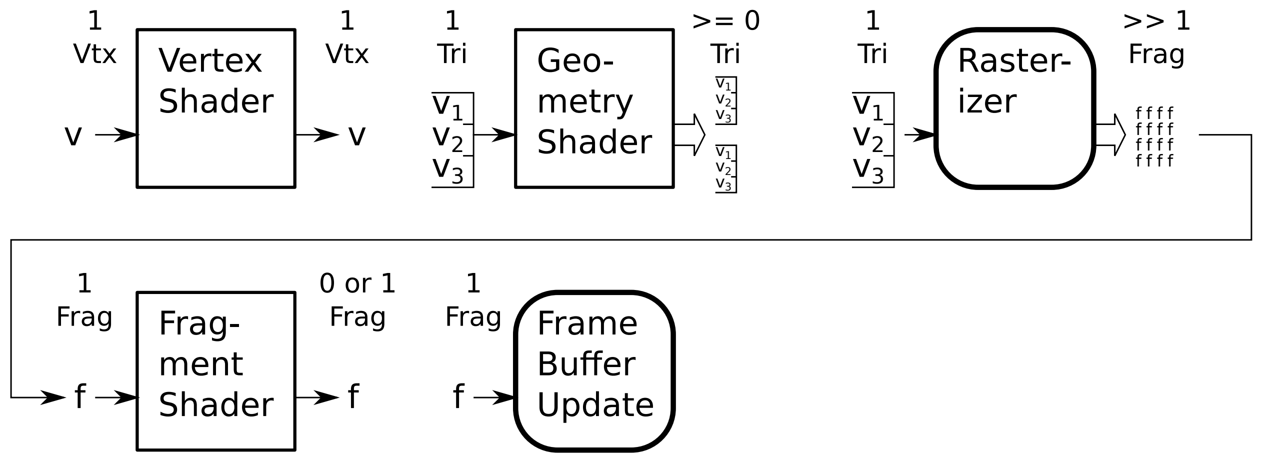
Input: One fragment.

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.

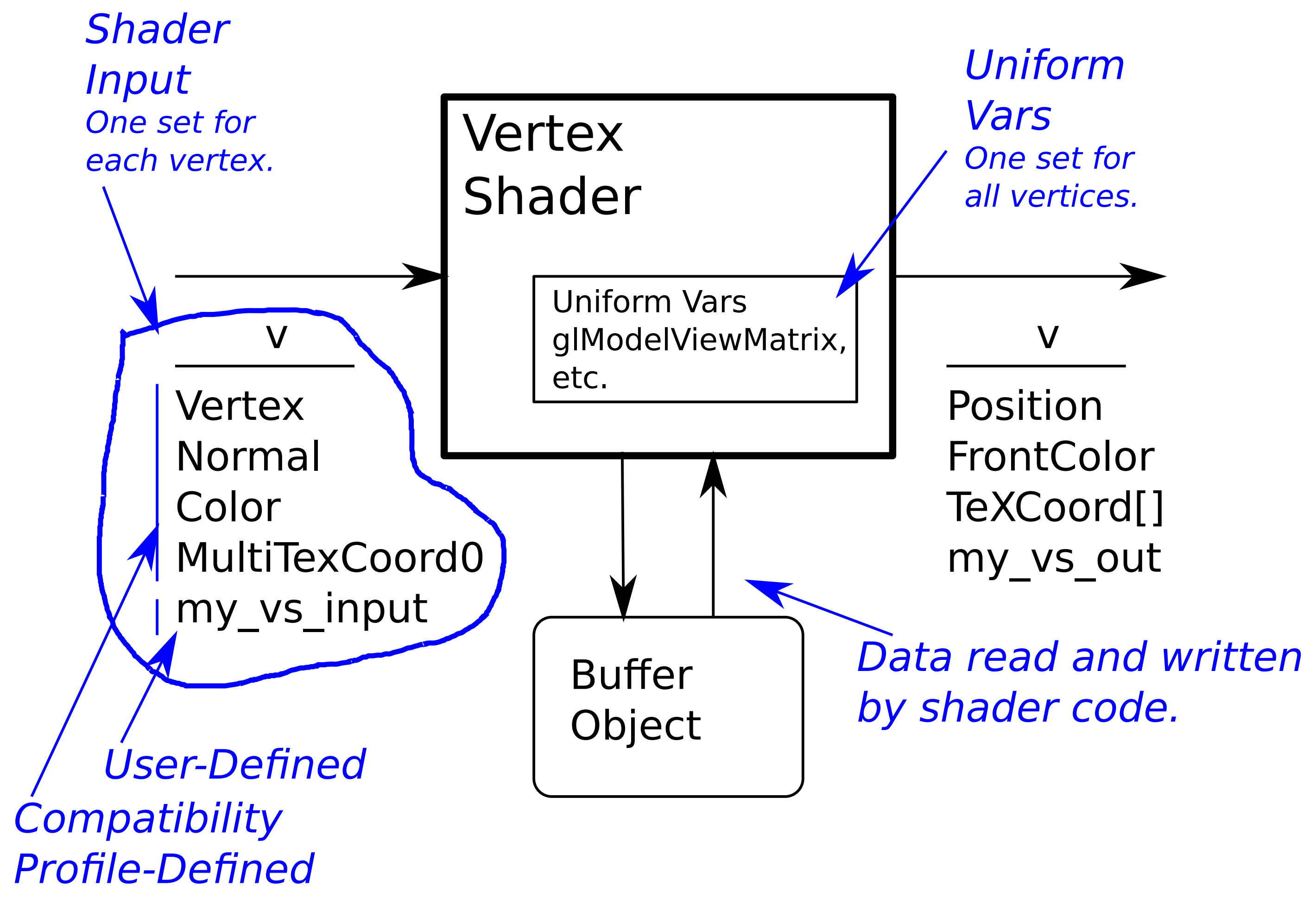
Data Access by Shaders

Categories

Shader inputs and outputs.

Uniform variables.

Buffer objects.



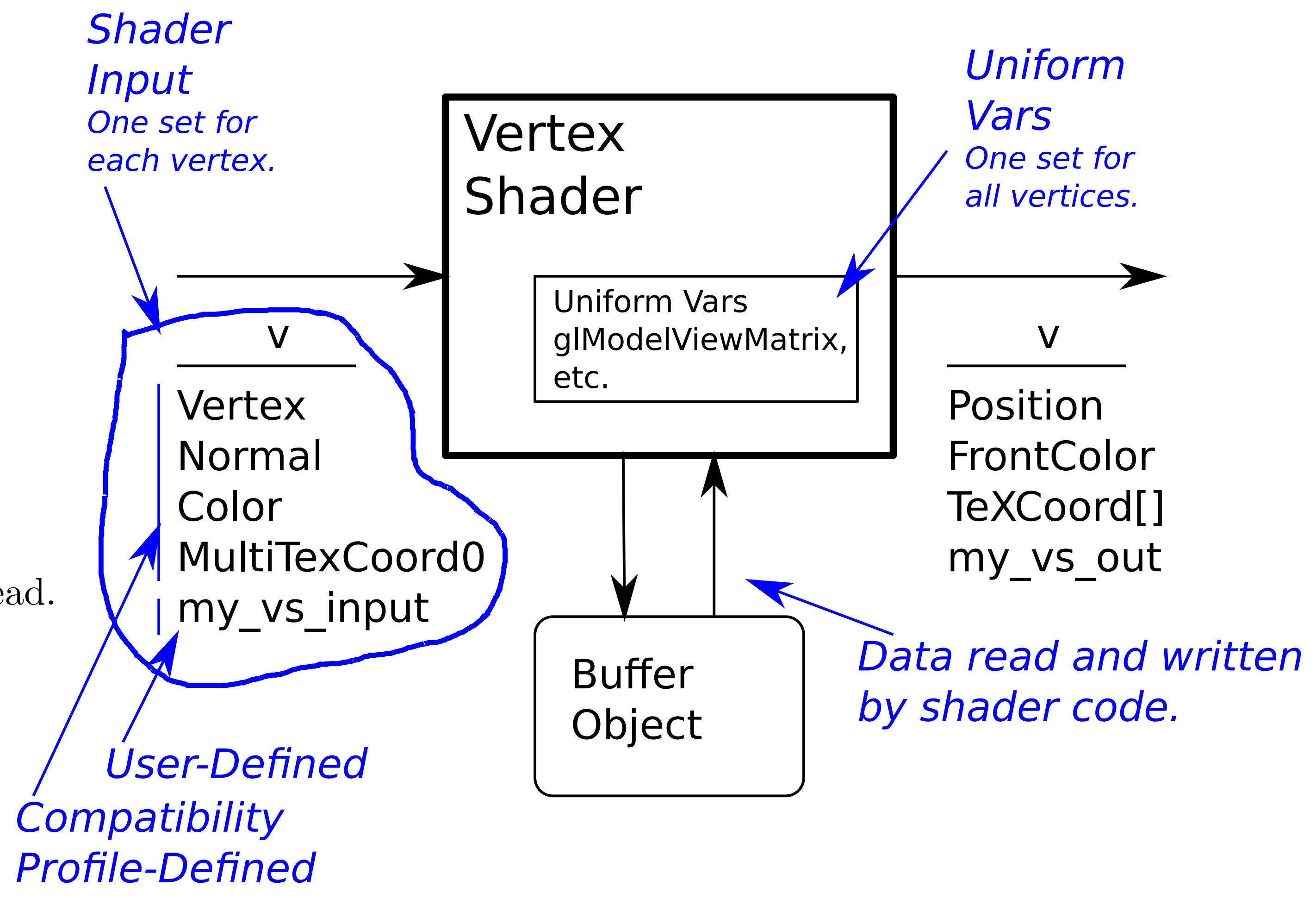
Shader Inputs and Outputs

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.



Uniform Variables

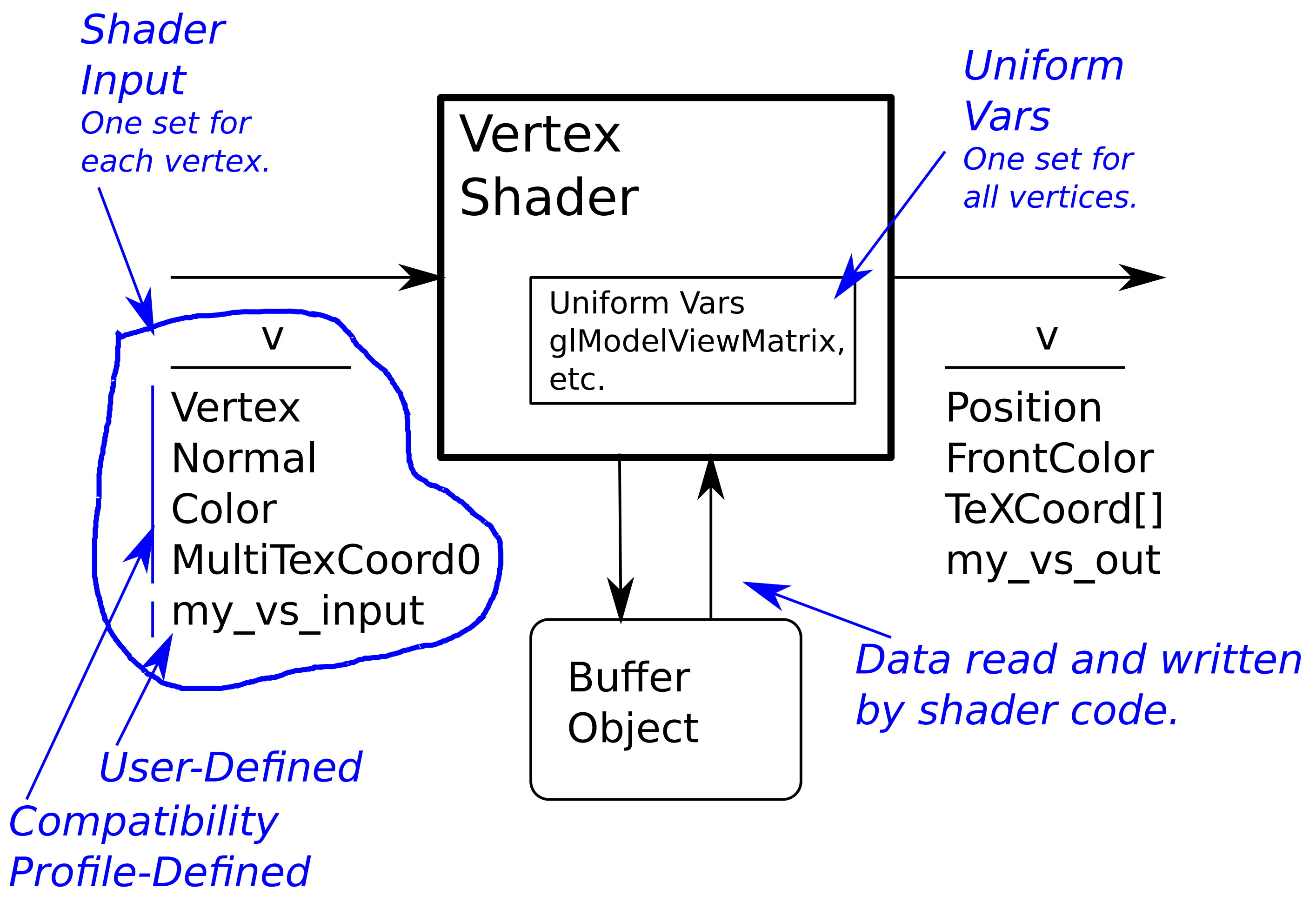
One set of data shared by all.

In Vulkan, created with usage set to…
… `vk::BufferUsageFlagBits::eUniformBuffer`.

Read only.

Size is limited, typically 64 kiB.

Usually cached (especially if < 8 kiB accessed).



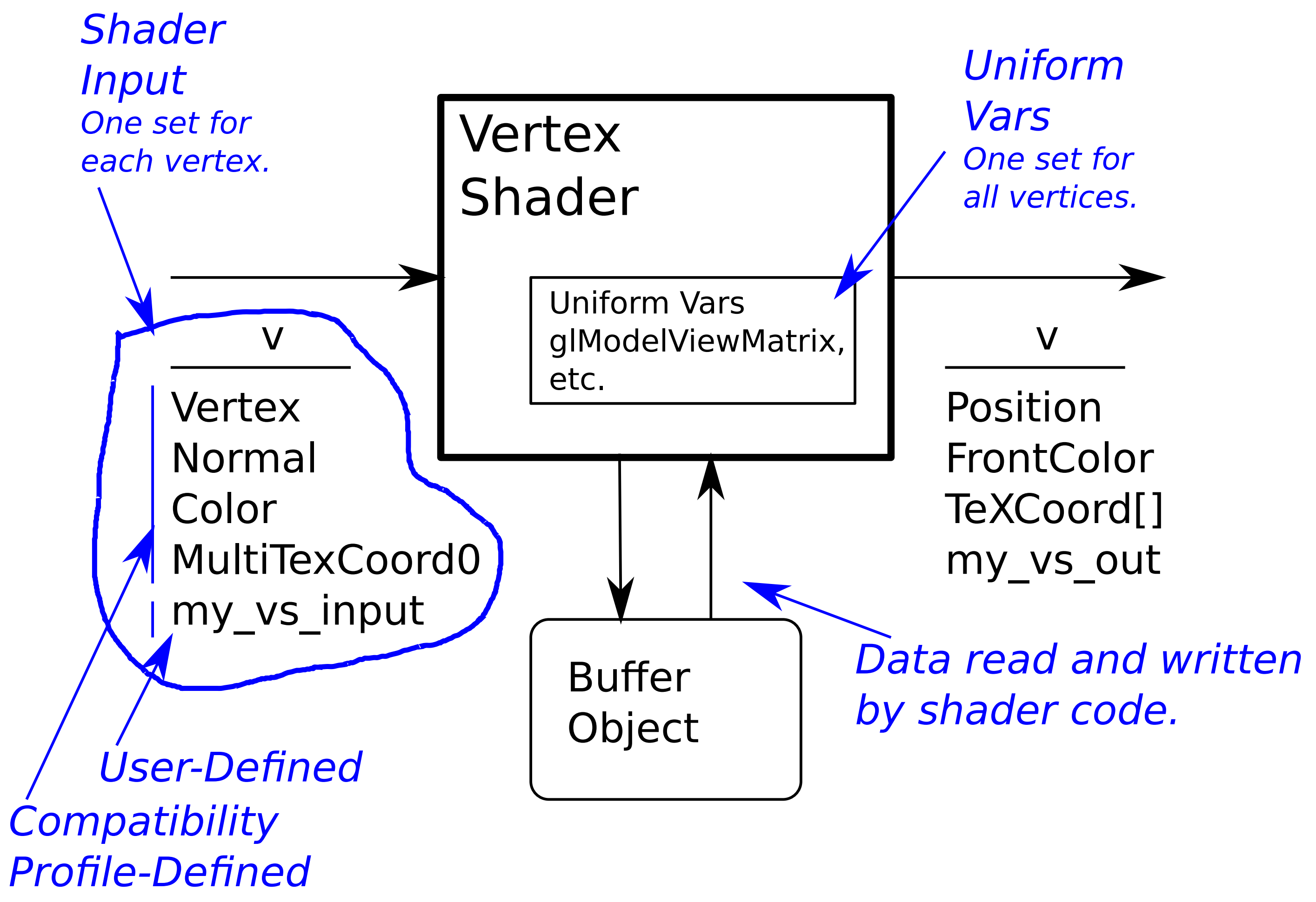
Storage Buffers

In OpenGl, called **Buffer Objects**

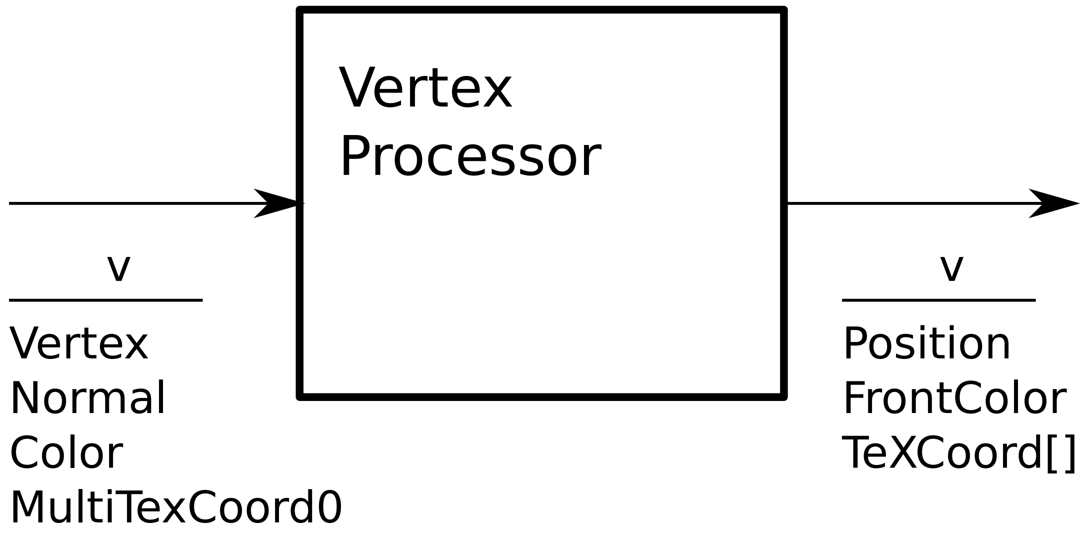
In Vulkan, created with usage set to...
... `vk::BufferUsageFlagBits::eStorageBuffer`.

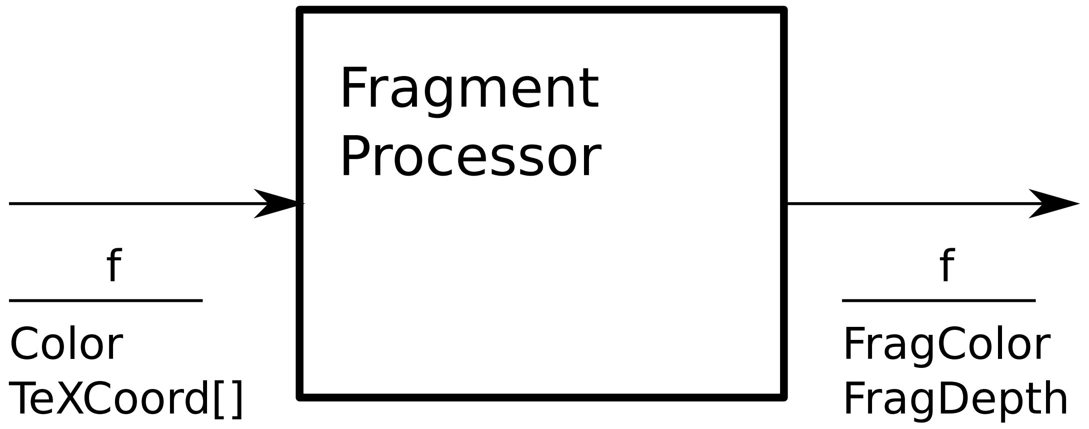
Can be read and written,...
... typically as an array.

Size is large.



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 (GLSL)

OpenGL Shader Language Important Features

C-like

CPP-like preprocessor directives.

Library of useful geometry functions.

Includes vector and matrix types and operators.

GLSL 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;
```

GLSL 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:
Linear interpolation in object space. (Perspective-correct interpolation).

noperspective:
Linear interpolation in clip space. (Faster, but an approximation.)

Deprecated Storage Qualifiers.

These were used in earlier versions of GLSL.

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;
```

GLSL 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 4.6 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);
```

GLSL 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.