Open GL ES 2.0

An Introduction to the programmable pipeline

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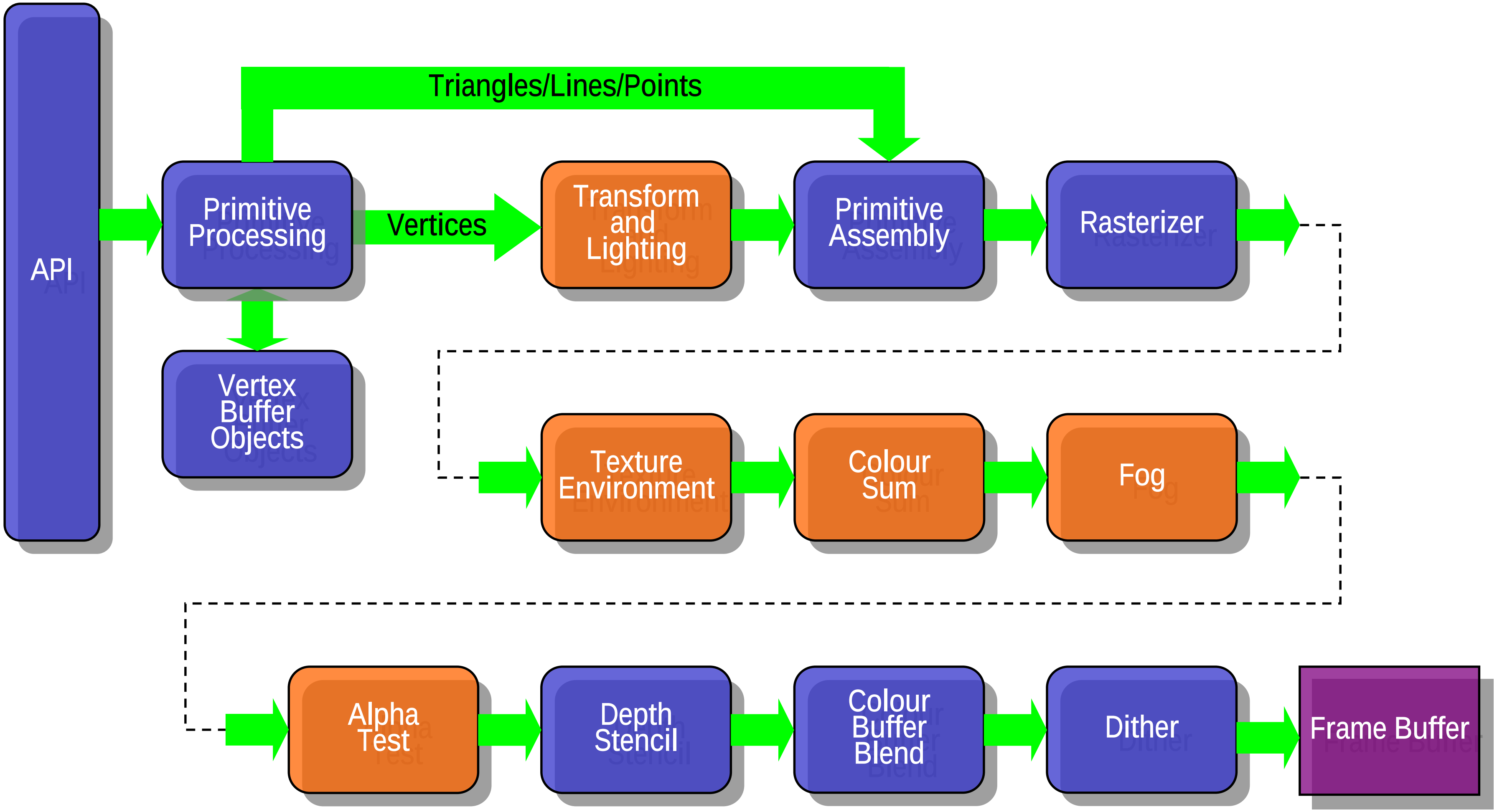
Outline

- OpenGL ES 2.0 Philosophy
- The shader model
- OpenGL ES Shading Language (GLSL ES)
- Example shaders
- Compiling Shaders
- Performance Tips
- Roadmap for shaders

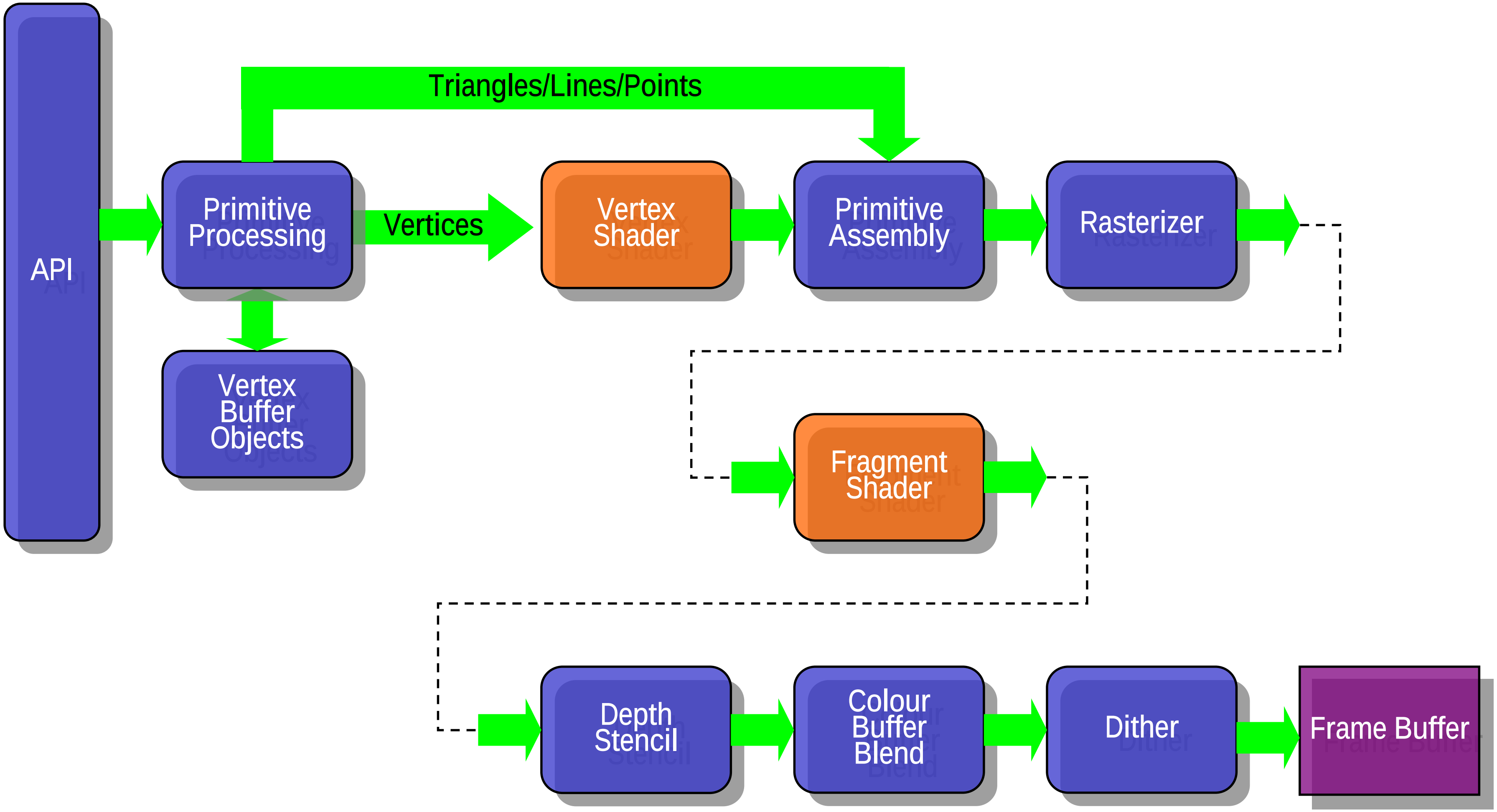
ES 2.0 Philosophy

- Based on GLSL as used in OpenGL 2.0
  - Open standard
  - Proven on desktop
- Pure programmable model
  - Most fixed functionality removed.
- Not 100% backward compatible with ES1.x
  - Embedded systems do not have the legacy requirements of the desktop
- No Software Fallback
  - Implementations (usually) hardware or nothing
  - Running graphics routines in software doesn't make sense on embedded platforms
- Optimized for use in Embedded devices
  - Aim is to reduce silicon cost
  - Reduced shader program sizes
  - Reduced register usage
  - Reduced numeric precision

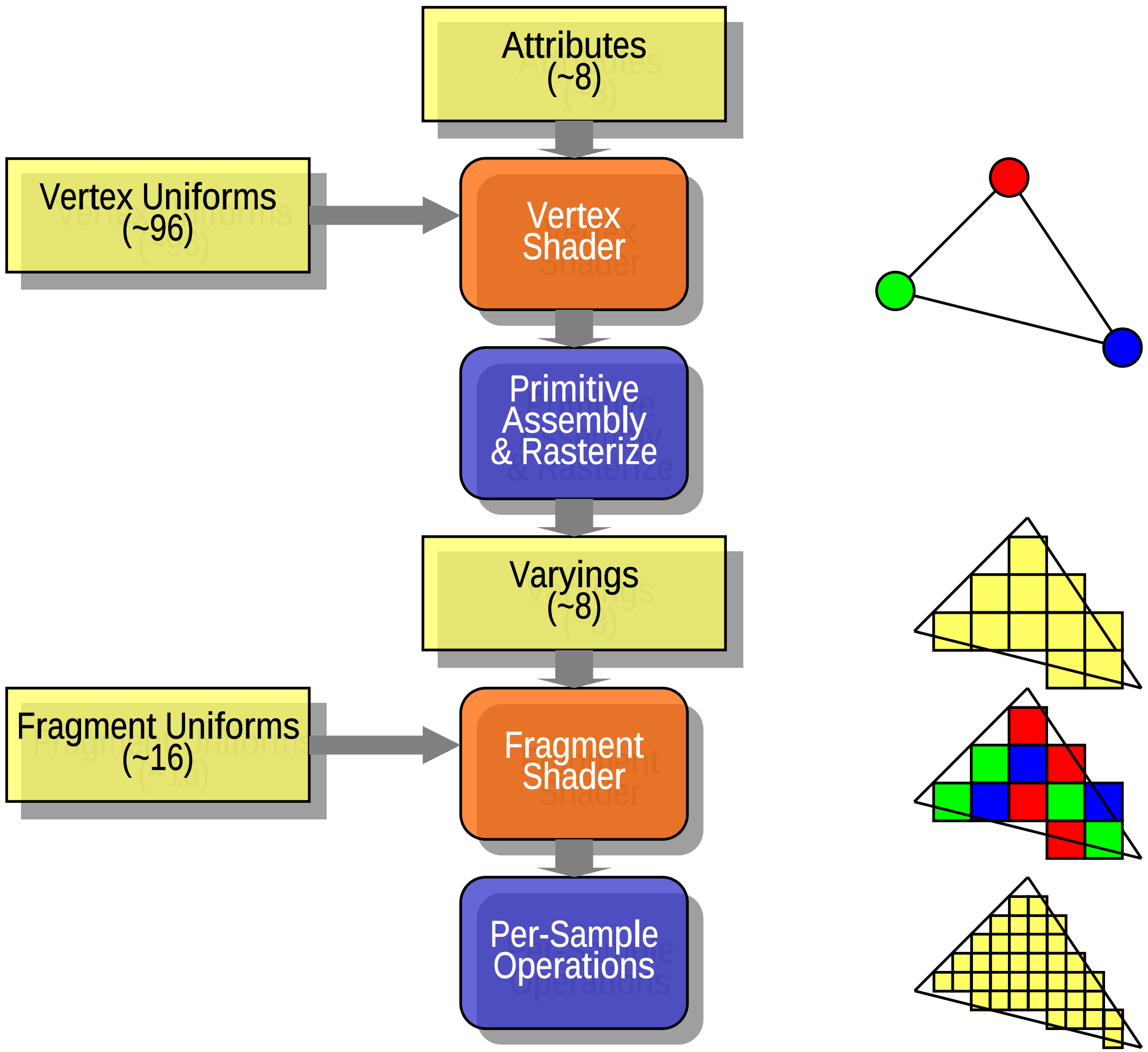
Existing Fixed Function Pipeline



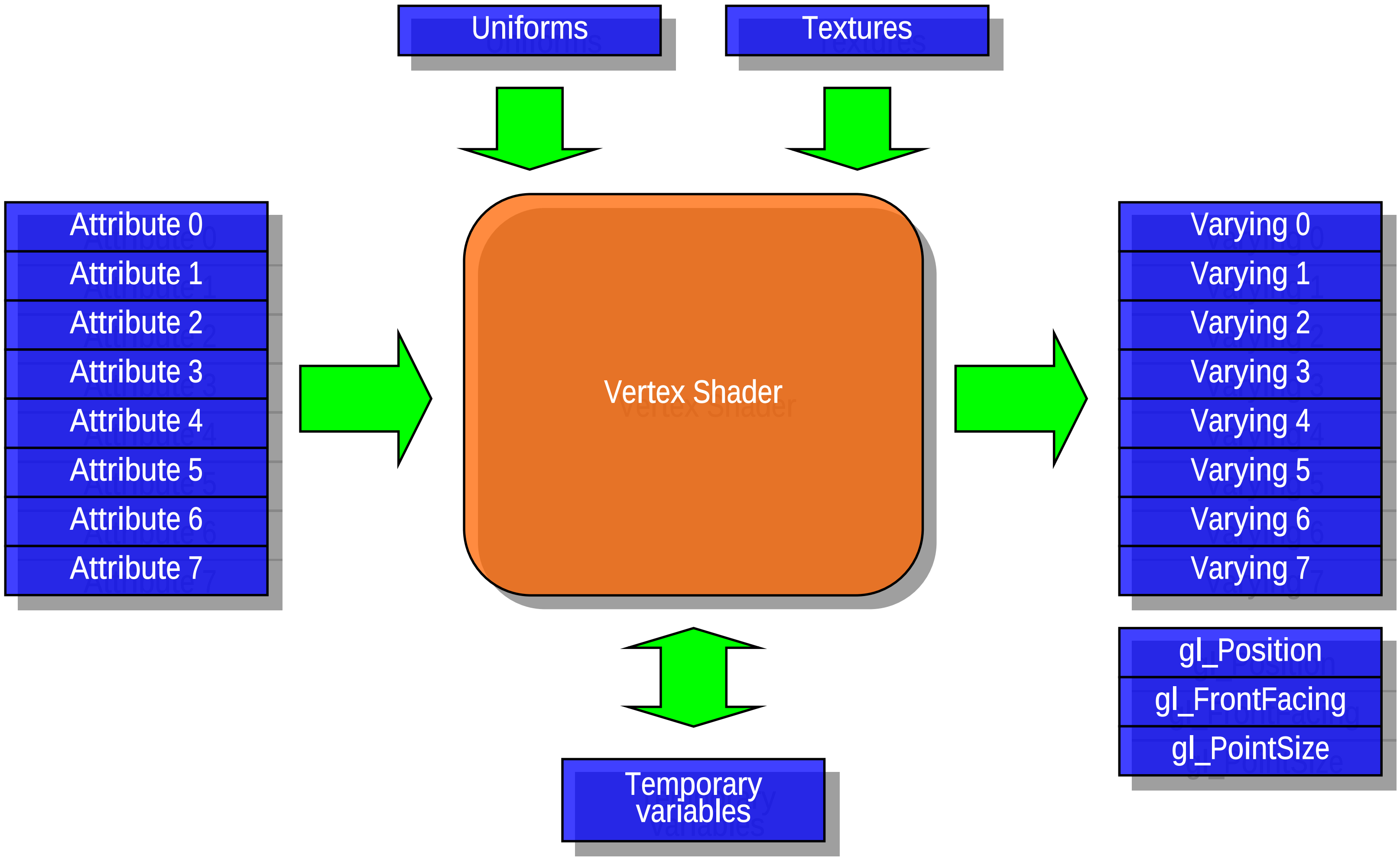
ES2.0 Programmable Pipeline



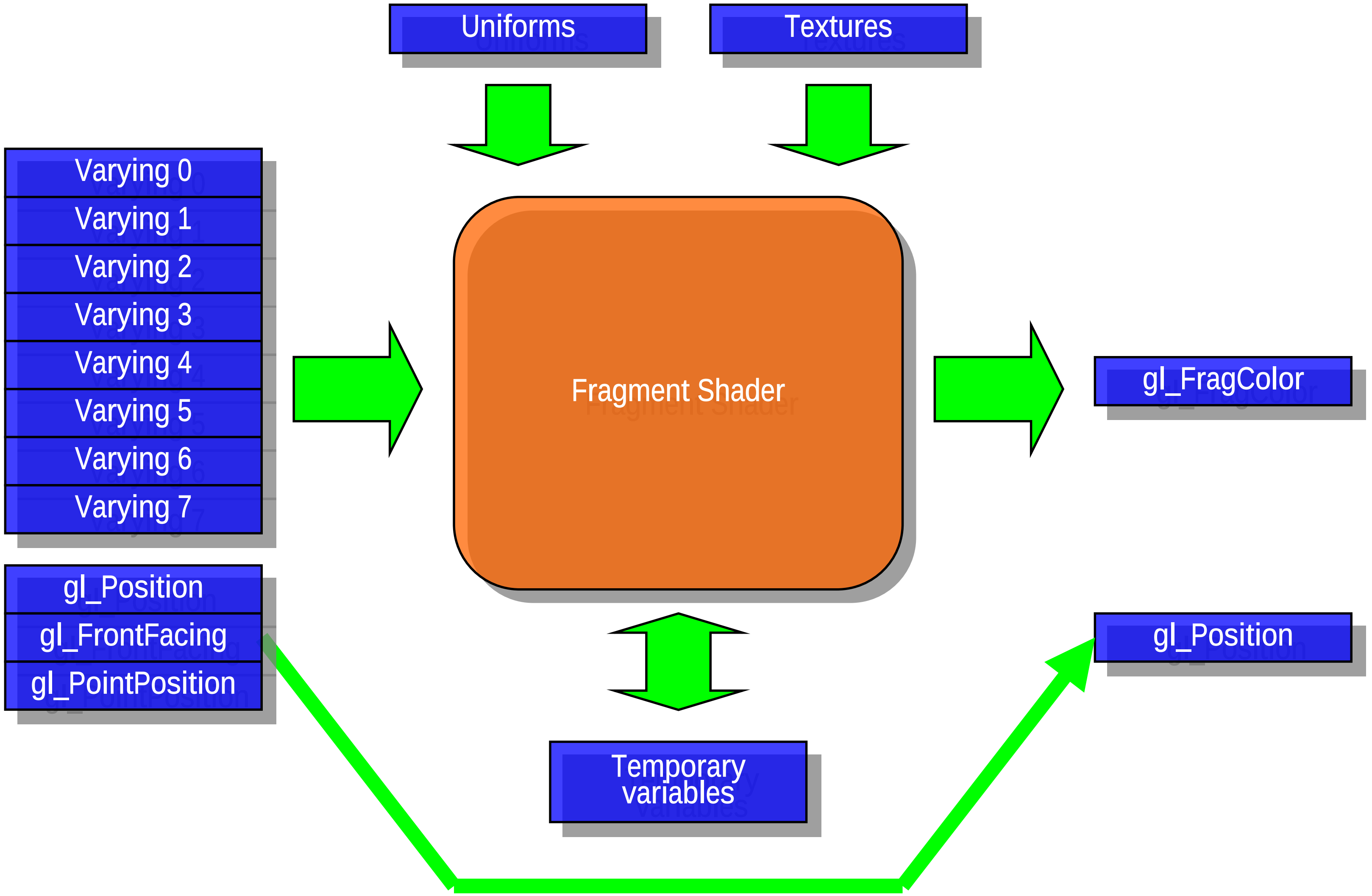
Programmer's model



Vertex Shader



Fragment Shader



GLSL ES Overview

- 'C' – like language
- Many simplifications
  - No pointers
  - No implicit type conversion
  - Simplified preprocessor
- Some graphics-specific additions
  - Built-in vector and matrix types
  - Built-in functions
- Similar to desktop GLSL
  - Removal of most OpenGL fixed function state
  - Restrictions on shader complexity
  - Fewer sampler modes
  - No access to frag depth
  - Support for mixed precisions
  - More general invariance mechanism.

GLSL ES Preprocessor

- Comments
  //
  /*   */

- Macros
  #
  #define
  #undef

- Control
  #if
  #ifdef
  #ifndef
  #else
  #elif
  #endif

  #error

- Operators
  defined

- Extensions
  #pragma
  #extension
  #version
  #line

GLSL ES Types

- Scalar
  void
  float int bool
- Vector
  - boolean
    bvec2 bvec3 bvec4
  - integer
    ivec2 ivec3 ivec4
  - floating point
    vec2 vec3 vec4
- Matrix
  mat2 mat3 mat4
- Sampler
  sampler2D
- Container
  struct
  Arrays

GLSL ES Storage Qualifiers

- **`const`**
  - Local constants within a shader.
- **`uniform`**
  - ‘Constant shader parameters’ (light position/direction, texture units, …)
  - Do not change per vertex.
- **`attribute`**
  - Per-vertex values (position, normal,…)
- **`varying`**
  - Generated by vertex shader
  - Interpolated by the rasterizer to generate per pixel values
  - Used as inputs to Fragment Shader
  - e.g. texture coordinates

GLSL ES Function Parameter Qualifiers

- Functions parameters can be used to pass values in or out or both
- Call by value ‘copy in, copy out’ semantics.
- Qualifiers:

  `in` (default)

  `out`

  `inout`

- Can use ‘const’ with ‘in’.
- Functions can still return a value
  - But use a parameter if returning an array
- e.g.

```
bool f(const in vec2 v, out int a[2]) {...}
```

GLSL ES Precision Qualifiers

- Rationale
  - ALU and register resources are scarce.
  - Many operations require only limited precision

- Available float precisions
  - **`lowp float`**
  - **`mediump float`**
  - **`highp float`**

- Available int precisions
  - **`lowp int`**
  - **`mediump int`**
  - **`highp int`**

GLSL ES Precision Qualifiers

- **`lowp float`**
  - Typically implemented by fixed point sign + 1.8 fixed point.
  - Range is $-2.0 < x < 2.0$
  - Resolution 1/256
  - Use for simple colour blending
- **`mediump float`**
  - Typically implemented by sign + 5.10 floating point
  - $-16384 < x < 16384$
  - Resolution 1 part in 1024
  - Use for HDR blending, some texture coordinate calculations
- **`highp float`**
  - Typically implemented by 24 bit float (16 bits of mantissa)
  - range $\pm 2^{62}$
  - Resolution 1 part in 2^{16}
  - Use of texture coordinate calculation e.g. environment mapping
- single precision
  - Not explicit in GLSL but usually available in the vertex shader

GLSL ES Precision Qualifiers

- Can specify per variable or set a default.
- Per Variable:

```
mediump float x;
```

- Set default:

```
precision mediump float;
```

- Can change the default:

```
{
    precision mediump float;
    float x; // x is a medium precision float
    precision lowp float;
    float y; // y is a low precision float
}
```

GLSL ES Precision

- Precision of a sub-expression depends entirely on the operands
- Evaluated at the highest precision of

```
lowp float x;
mediump float y;
highp float z = x * y;      // ‘*’ evaluated at
                            // medium precision
```

- Literals do not have any defined precision

```
lowp float x;
highp float z = x * 2.0 + 1.2; // evaluated at
                               // low precision
```

- Some special cases
  - If no operands have a precision, use outer-level sub-expression:

```
lowp float x = 1.0 / 3.0;   // evaluated at
                            // low precision
```

  - Use default precision if required

```
bool b = (1.0/3.0 > 0.33); // Must have default
                           // precision defined.
```

GLSL ES Constructors

- Replaces type casting
- All named types have constructors available
  - Includes built-in types, structs
  - Excludes arrays
- No implicit conversion: must use constructors
- Int to Float:

```
int n = 1;
float x,y;
x = float(n);
y = float(2);
```

- Concatenation:

```
float x = 1.0,y = 2.0;
vec2 v = vec2(x,y);
```

- Struct initialization

```
struct S {int a; float b;};
S s = S(2, 3.5);
```

GLSL ES Swizzle operators

- Use to select a set of components from a vector
- Can be used in L-values

```
vec2 u,v;
v.x = 2.0;          // Assignment to single component
float a = v.x;      // Component selection
v.xy = u.yx;        // swap components
v = v.xx;           // replicate components

v.xx = u;           // Error
```

- Component sets

  Use one of:

  xyzw
  rgba
  stpq

- Indexing operator

```
vec4 u,v;
float x = u[0]; // equivalent to u.x
```

- Must use indexing operator for matrices

GLSL ES Features cont.

- Operators
  - ++ -- + - ! () []
  - * / + -
  - < <= > >=
  - == !=
  - && ^^ ||
  - ?:
  - = *= /= += -=
- Flow control
  - <expression> ? <expression_1> : <expression_2>
  - **`if else`**
  - **`for while do`**
  - **`return break continue`**
  - **`discard`** (fragment shader only)

GLSL Built-in Variables

- Aim of ES is to reduce the amount of fixed functionality
  - Ideal would be a totally pure programmable model
  - But still need some

- Vertex shader
  - `vec4 gl_Position;` // Write-only (required)
  - `float gl_PointSize;` // Write-only
- Fragment shader
  - `vec4 gl_FragCoord;` // Read-only
  - `bool gl_FrontFacing;` // Read-only
  - `vec2 gl_PointCoord;` // Read-only
  - `float gl_FragColor;` // Write only (required)

GLSL ES Built-in Functions

- General
  - **pow, exp2, log2, sqrt, inversesqrt**
  - **abs, sign, floor, ceil, fract, mod, min, max, clamp**
- Trig functions
  - **radians, degrees, sin, cos, tan, asin, acos, atan**
- Geometric
  - **length, distance, cross, dot, normalize, faceForward, reflect, refract**
- Interpolations
  - **mix(x,y,alpha)**
    x*(1.0-alpha) + y*alpha)
  - **step(edge,x)**
    x <= edge ? 0.0 : 1.0
  - **smoothstep(edge0,edge1,x)**
    t = (x-edge0)/(edge1-edge0);
    t = clamp(t, 0.0, 1.0);
    return t*t*(3.0-2.0*t);
- Texture
  - **texture1D, texture2D, texture3D, textureCube**
  - **texture1DProj, texture2DProj, textureCubeProj**

GLSL ES Built-in Functions

- Vector comparison (**vec**n, **ivec**n)
  - **bvec**n **lessThan(vec**n, **vec**n**)**
  - **bvec**n **lessThanEqual(vec**n, **vec**n**)**
  - **bvec**n **greaterThan(vec**n, **vec**n**)**
  - **bvec**n **greaterThanEqual(vec**n, **vec**n**)**
- Vector comparison (**vec**n, **ivec**n, **bvec**n)
  - **bvec**n **equal(vec**n, **vec**n**)**
  - **bvec**n **notEqual(vec**n, **vec**n**)**
- Vector (**bvec**n)
  - **bvec**n **any(bvec**n**)**
  - **bvec**n **all(bvec**n**)**
  - **bvec**n **not(bvec**n**)**
- Matrix
  - **matrixCompMult (mat**n, **mat**n**)**

GLSL ES: Invariance – the problem

- Consider a simple transform in the vertex shader:

$$\begin{pmatrix} x' \\ y' \\ z' \\ w' \end{pmatrix} = \begin{pmatrix} a & b & c & d \\ e & f & g & h \\ i & j & k & l \\ m & n & o & p \end{pmatrix} \begin{pmatrix} x \\ y \\ z \\ w \end{pmatrix}$$

$x' = ax + by + cz + dw$

But how is this calculated in practice?

- There may be several possible code sequences

GLSL ES: Invariance

e.g.

```
MUL R1, a, x
MUL R2, b, y
MUL R3, c, z
MUL R4, d, w
ADD R1, R1, R2
ADD R3, R3, R4
ADD R1, R1, R3
```

or

```
MUL R1, a, x
MADD R1, b, y
MADD R1, c, z
MADD R1, d, w
```

GLSL ES: Invariance

- Three reasons the result may differ:
  - Use of different instructions
  - Instructions executed in a different order
  - Different precisions used for intermediate results (only minimum precisions are defined)
- But it gets worse...
- Modern compilers may rearrange your code
  - Values may lose precision when written to a register
  - Sometimes it is cheaper to recalculate a value rather than store it in a register.
    But will it be calculated the same way?

e.g.

```
uniform sampler2D tex1, tex2;
...
const vec2 pos = ...;
vec4 col1 = texture2D(tex1, pos);
...
vec4 col2 = texture2D(tex2, pos);// is this the same value?
gl_FragColor = col1 – col2;
```

GLSL ES: Invariance – The solution

- Solution is in three parts:
- invariant keyword to specify specific variables are invariant

```
invariant varying vec3 LightPosition;
```

  - Currently can only be used on outputs

- Global switch to make all variable invariant

```
#pragma STDGL invariant(all)
```

- General invariance rule within shaders.
  - Values of variables do not change between assignments
- Usage
  - Turn on invariance to make programs ‘safe’ and easier to debug
  - Turn off invariance to get the maximum optimization from the compiler.

GLSL ES Examples: ‘Null Shader’

- Vertex

```
attribute vec4 VertexPositionIn; // Input to Vertex Shader
attribute vec4 VertexColourIn;   // Input to Vertex Shader
varying vec4 VertexColorOut;     // Output from Vertex shader

void main()
{
 VertexColorOut = VertexColorIn
 gl_Position = VertexPositionIn;
}
```

- Fragment

```
varying vec4 FragmentColorIn;    // Input to Fragment Shader

void main()
{
 gl_FragColor = FragmentColorIn;
}
```

Vertex Shader functions

- The vertex shader can do:
  - Transformation of position using model-view and projection matrices
  - Transformation of normals, including renormalization
  - Texture coordinate generation and transformation
  - Per-vertex lighting
  - Calculation of values for lighting per pixel
- The vertex shader cannot do:
  - Anything that requires information from more than one vertex
  - Anything that depends on connectivity.
  - Any triangle operations (e.g. clipping, culling)
  - Access colour buffer

Example Vertex Shader

- Diffuse lighting

```
uniform mat4 ModelViewProjectionMatrix, NormalMatrix;
uniform vec4 LightSourceDiffuse, LightSourcePosition, MaterialDiffuse;

attribute vec4 InputPosition, InputNormal, InputTextureCoordinates;

varying vec4 VertexColour;
varying vec4 TextureCoordinates;

void main()
{
  vec3 normal, lightDirection;
  vec4 diffuse;
  float NdotL;

  normal = normalize(NormalMatrix * Normal);
  lightDirection = normalize(vec3(LightSourcePosition));
  NdotL = max(dot(normal, lightDirection), 0.0);
  diffuse = MaterialDiffuse * LightSourceDiffuse;
  VertexColor = NdotL * diffuse;

  TextureCoordinates = InputTextureCoordinates;

  gl_Position = ModelViewProjectionMatrix * position;
}
```

Fragment Shader Functions

- The fragment shader can do:
  - Texture blending
  - Fog
  - Alpha testing
  - Dependent textures
  - Pixel discard
  - Bump and environment mapping

- The fragment shader cannot do:
  - Blending with colour buffer
  - ROP operations
  - Depth or stencil tests
  - Write depth

Example Fragment Shader

- Simple Texture Blend

```
uniform sampler2D TextureHandle;
varying vec2 TextureCoordinates;
varying vec4 VertexColour;
void main()
{
 vec4 texel = texture2D (TextureHandle,
 TextureCoordinates);
 gl_FragColor = texel * VertexColour;
}
```

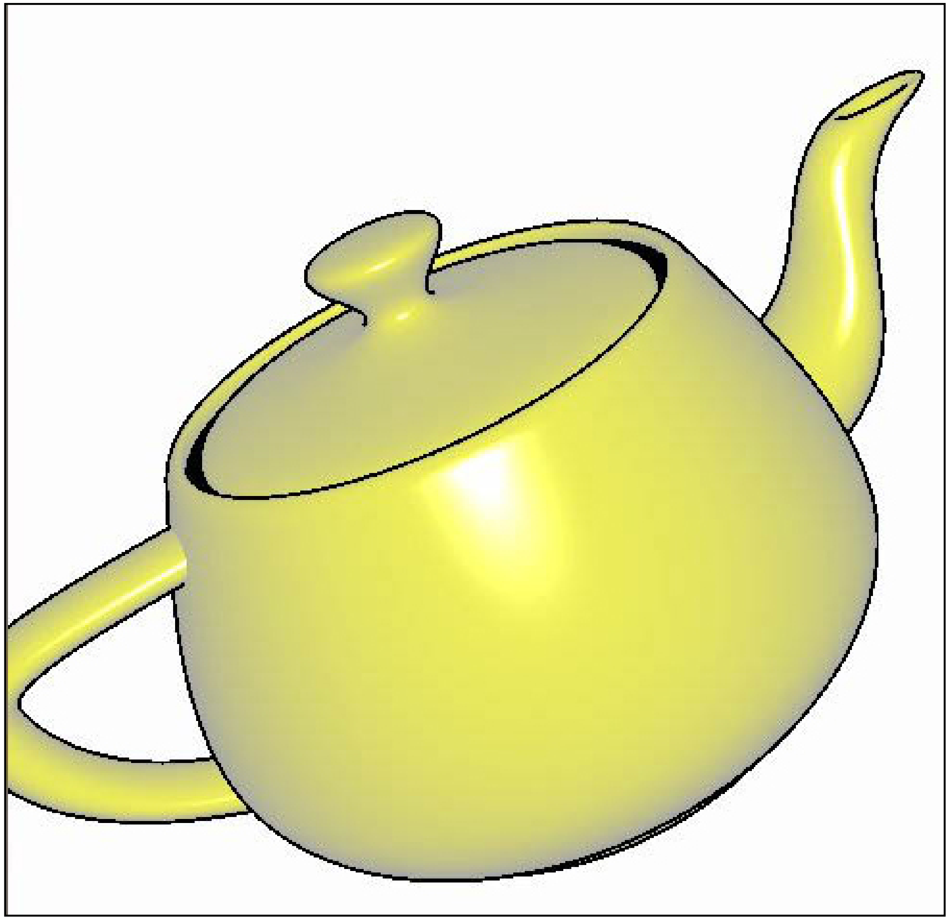
Gooch Shader (Vertex)

```
uniform vec4 lightPos;

varying vec3 normal;
varying vec3 lightVec;
varying vec3 viewVec;

void main()
{
 gl_Position = gl_ModelViewProjectionMatrix *
 gl_Vertex;
 vec4 vert = gl_ModelViewMatrix * gl_Vertex;

 normal   = gl_NormalMatrix * gl_Normal;
 lightVec = vec3(lightPos - vert);
 viewVec  = -vec3(vert);
}
```

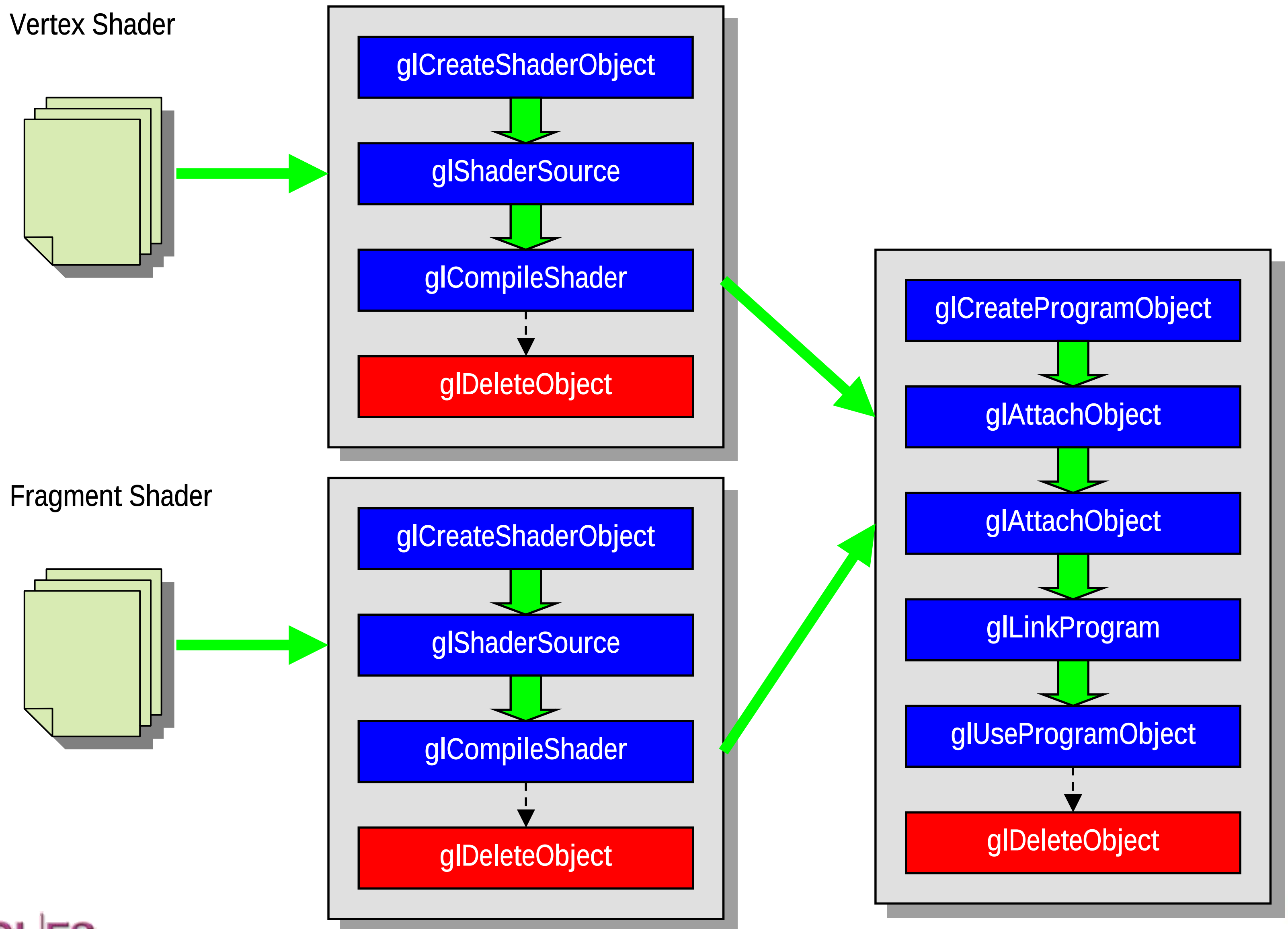
Gooch Shader (Fragment)

```
uniform vec3 ambient;

varying vec3 normal;
varying vec3 lightVec;
varying vec3 viewVec;

void main(){
  const float b = 0.55;
  const float y = 0.3;
  const float Ka = 1.0;
  const float Kd = 0.8;
  const float Ks = 0.9;

  vec3 specularcolor = vec3(1.0, 1.0, 1.0);

  vec3 norm = normalize(normal);
  vec3 L = normalize (lightVec);
  vec3 V = normalize (viewVec);
  vec3 halfAngle = normalize (L + V);
  vec3 orange = vec3(.88,.81,.49);
  vec3 purple = vec3(.58,.10,.76);

  vec3 kCool = purple;
  vec3 kWarm = orange;

  float NdotL = dot(L, norm);
  float NdotH = clamp(dot(halfAngle, norm), 0.0, 1.0);
  float specular = pow(NdotH, 64.0);

  float blendval  = 0.5 * NdotL + 0.5;
  vec3 Cgooch = mix(kWarm, kCool, blendval);

  vec3 result = Ka * ambient + Kd * Cgooch + specularcolor * Ks * specular;

  gl_FragColor = vec4(result, 1.0);
}
```

Gooch Shader



Compiling and using a shader



Compiling and using a shader: The code

```
// Create Shader Objects
GLhandleARB programObject = glCreateProgramObjectARB();
GLhandleARB vertexShaderObject = glCreateShaderObjectARB(GL_VERTEX_SHADER_ARB);
GLhandleARB fragmentShaderObject = glCreateShaderObjectARB(GL_FRAGMENT_SHADER_ARB);

GLcharARB *vertexShaderSource = readShaderFile(vertexShaderFilename);
GLcharARB *fragmentShaderSource = readShaderFile(fragmentShaderFilename);

// Load code into shader objects
glShaderSourceARB(vertexShaderObject, 1, vertexShaderSource, NULL);
glShaderSourceARB(fragmentShaderObject, 1, fragmentShaderSource, NULL);

glCompileShaderARB(vertexShaderObject);
glCompileShaderARB(fragmentShaderObject);

glAttachObjectARB(programObject, vertexShaderObject);
glAttachObjectARB(programObject, fragmentShaderObject);

glLinkProgramARB(programObject);

glUseProgramObjectARB(programObject);
```

Performance Tips

- Keep fragment shaders simple
  - Fragment shader hardware is expensive.
  - Early implementations will not have good performance with complex shaders.
- Try to avoid using textures for function lookups.
  - Calculation is quite cheap, accessing textures is expensive.
  - This is more important with embedded devices.
- Minimize register usage
  - Embedded devices do not support the same number of registers compared with desktop devices. Spilling registers to memory is expensive.
- Minimize the number of shader changes
  - Shaders contain a lot of state
  - May require the pipeline to be flushed
  - Use uniforms to change behaviour in preference to loading a new shader.

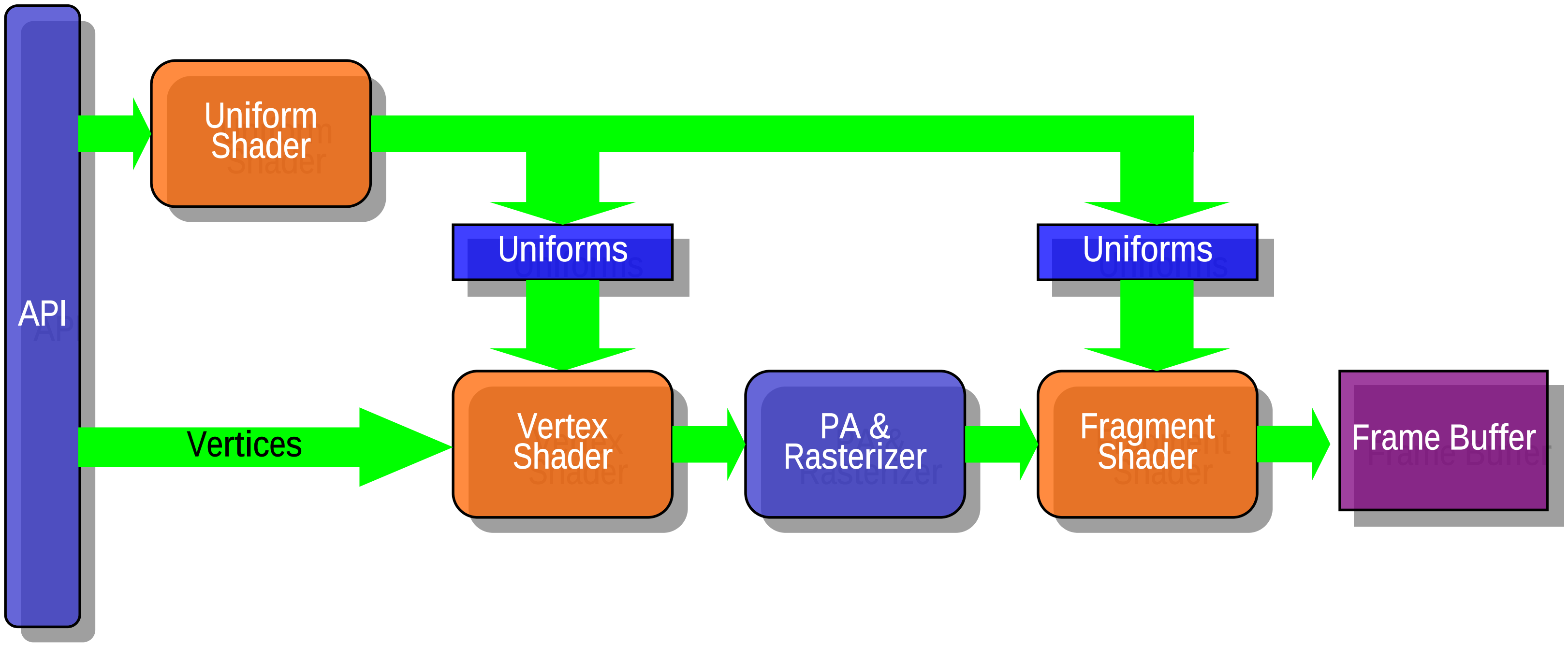
Uniform Shaders

- Problem: How to calculate uniforms?
  - e.g. how to generate inverse matrices

- Issues:
  - Want to remove legacy fixed functions from API
  - Embedded devices may have slow CPU or no floating point

- Possible solutions:
  - Put code in vertex shader and rely on compiler to 'hoist' code and run only once
  - Put fixed functions back
  - Uniform shaders
  - Allow vertex shaders to write results to memory.

Uniform Shaders

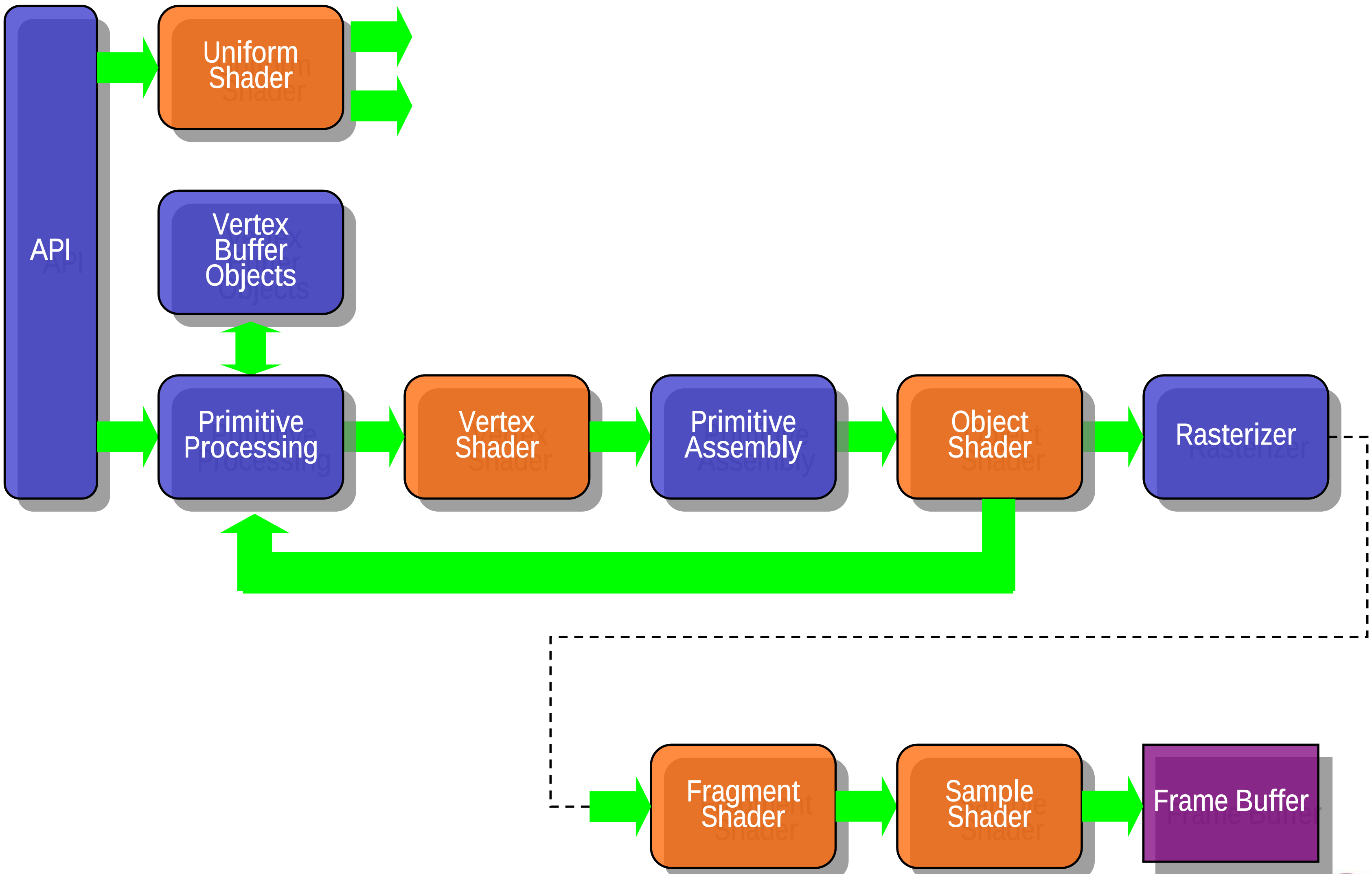


Future Directions

- Sample Shaders
  - Enables alpha testing at per-sample resolution
  - Enables more of the fixed function pipeline to be removed.
  - Allows more programmability when using multi-sampling.
  - e.g. Read and write depth and stencil

- Object (Geometry) Shaders
  - Programmable tessellation
  - Higher order surfaces
  - Procedural geometry
  - Possibility of accelerating many more algorithms e.g. shadows, occlusion culling.

Future ES Pipeline?



Any Questions?