The Graphics Pipeline and OpenGL III:
OpenGL Shading Language (GLSL 1.10)

Gordon Wetzstein

Stanford University

EE 267 Virtual Reality

Lecture 4

stanford.edu/class/ee267/

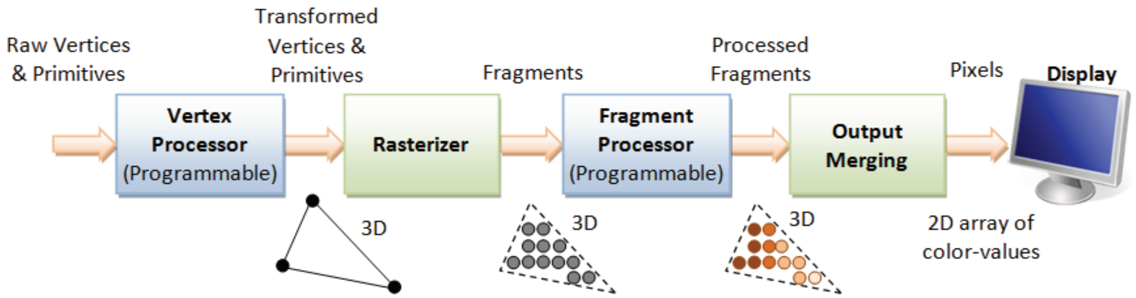
Updates

- for 24h lab access: please email Steven Clark (with some arguments that convince him that you read the lab instructions, e.g. screenshot of last slide)
- lab computers can also be used remotely! (instructions on piazza & website to follow)
- waitlist: looks like everyone who is still on the waitlist will get in
- HW1 due Thursday at midnight!

Lecture Overview

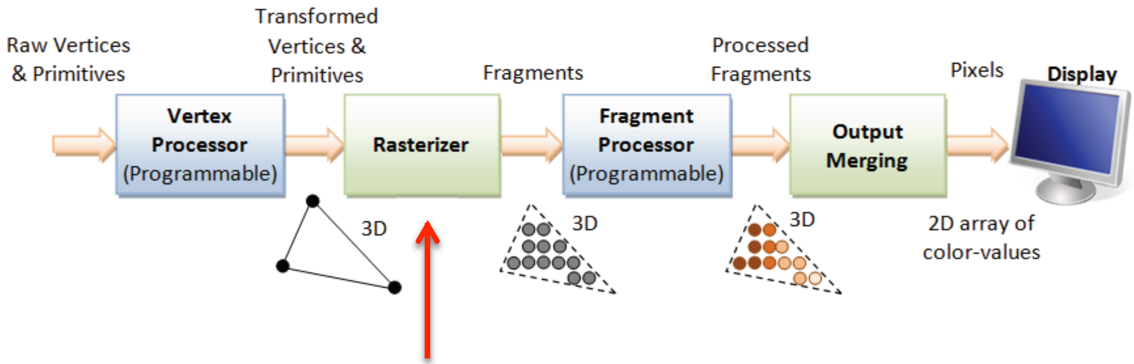
- Review of graphics pipeline
- vertex and fragment shaders
- OpenGL Shading Language (GLSL 1.10)
- Implementing lighting & shading with GLSL vertex and fragment shaders

Reminder: The Graphics Pipeline



https://www.ntu.edu.sg/home/ehchua/programming/opengl/CG_BasicsTheory.html

Reminder: The Graphics Pipeline



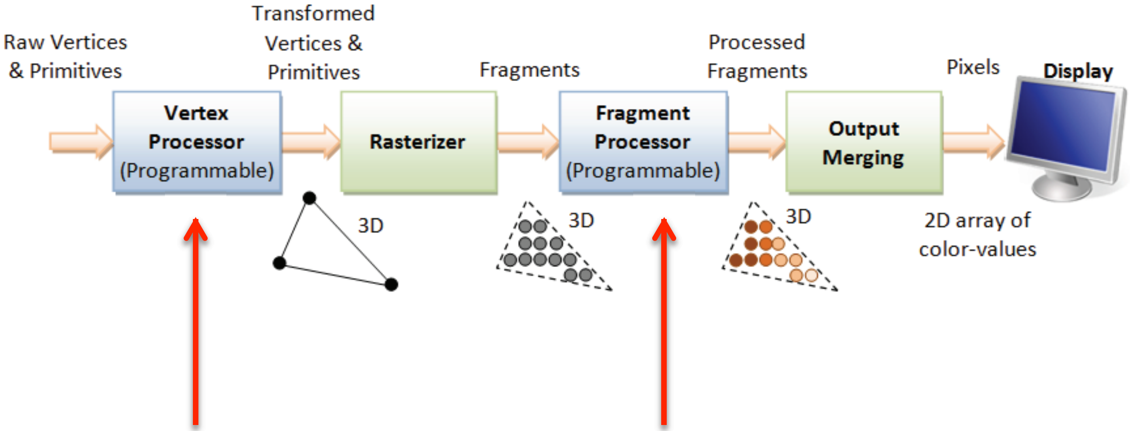
The Rasterizer

two goals:

1. determine which fragments are inside the primitives (triangles) and which ones aren't
2. interpolate per-vertex attributes (color, texture coordinates, normals, …) to each fragment in the primitive

https://www.ntu.edu.sg/home/ehchua/programming/opengl/CG_BasicsTheory.html

Reminder: The Graphics Pipeline



<u>vertex shader</u>

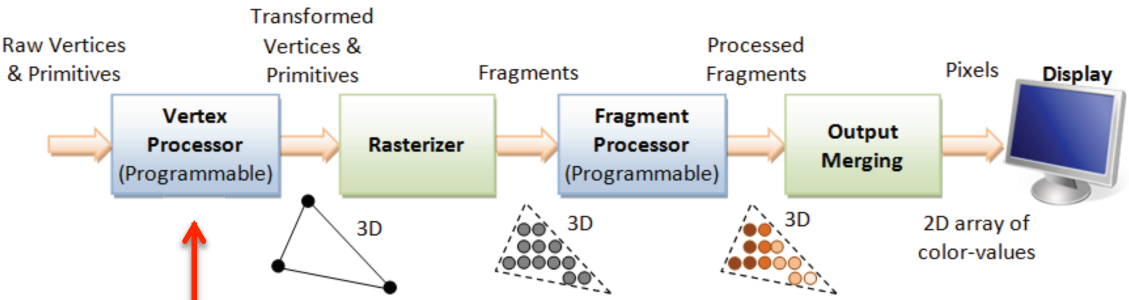
- transforms
- (per-vertex) lighting
- …

<u>fragment shader</u>

- texturing
- (per-fragment) lighting
- …

https://www.ntu.edu.sg/home/ehchua/programming/opengl/CG_BasicsTheory.html

Vertex Shaders



vertex shader (executed for each vertex)

input

- vertex position, normal, color, material, texture coordinates
- modelview matrix, projection matrix, normal matrix
- …

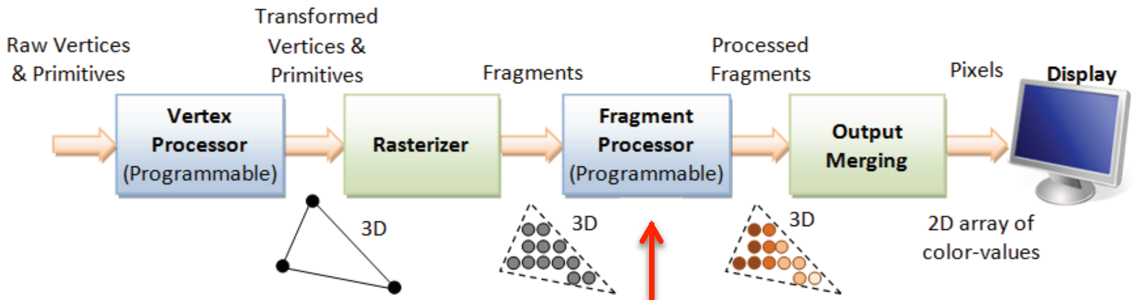
```
void main ()
{
  // do something here
  …

}
```

output

- transformed vertex position (in clip coords), texture coordinates
- …

https://www.ntu.edu.sg/home/ehchua/programming/opengl/CG_BasicsTheory.html

Fragment Shaders



<u>input</u>

- vertex position in window coords, texture coordinates
- …

<u>fragment shader</u> (executed for each fragment)

```
void main ()
{
  // do something here
  …

}
```

<u>output</u>

- fragment color
- fragment depth
- …

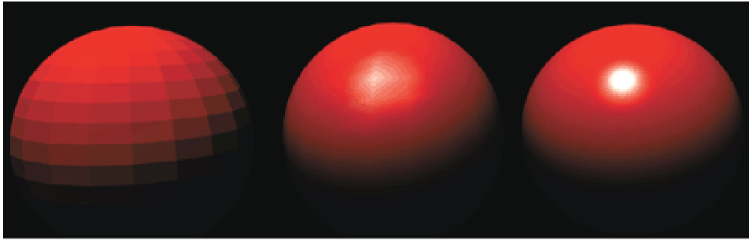
https://www.ntu.edu.sg/home/ehchua/programming/opengl/CG_BasicsTheory.html

Why Do We Need Shaders?

- massively parallel computing
- single instruction multiple data (SIMD) paradigm → GPUs are designed to be parallel processors
- vertex shaders are independently executed for each vertex on GPU (in parallel)
- fragment shaders are independently executed for each fragment on GPU (in parallel)

Why Do We Need Shaders?

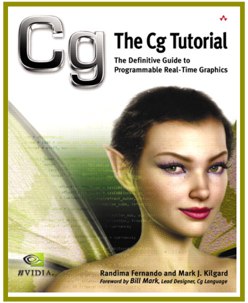
- most important: vertex transforms and lighting & shading calculations
- shading: how to compute color of each fragment (e.g. interpolate colors)
  1. Flat shading
  2. Gouraud shading (per-vertex shading)
  3. Phong shading (per-fragment shading)
- other: render motion blur, depth of field, physical simulation, …



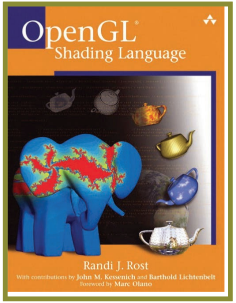
Flat Gouraud Phong

courtesy: Intergraph Computer Systems

Shading Languages

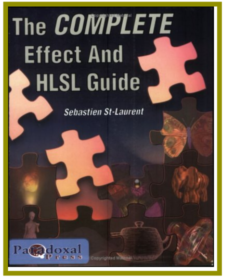


- Cg (C for Graphics – NVIDIA, deprecated)
- GLSL (GL Shading Language – OpenGL)



EE 267

- HLSL (High Level Shading Language - MS Direct3D)



Demo – Simple Vertex Shader

```
// variable passed in from application
uniform float deformation = 1.0;

void main () // vertex shader
{
  // deform vertex position
  vec3 pos = gl_Vertex.xyz + deformation * gl_Normal;

  // convert to clip space
  gl_Position = gl_ModelViewProjectionMatrix *
vec4(pos,1.0);


  // do lighting calculations here (in world space)
  …

}
```

Demo – Simple Fragment Shader

```
// variables passed in from application
uniform sampler2D texture;
uniform float gamma = 1.0;

void main () // fragment shader
{

  // texture lookup
  vec3 textureColor = texture2D(texture,
gl_TexCoord[0].xy).rgb;

  // set output color by applying gamma
  gl_FragColor.rgb = pow(textureColor,gamma);

}
```

Demo – Vertex & Fragment Shader

```
// variable to be passed from vertex to fragment shader
varying vec4 myColor;

void main () // vertex shader – Gouraud shading
{
  // transform position to clip space
  gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;

  // transform position to world space
  vec4 positionWorld = gl_ModelViewMatrix * gl_Vertex;

  // transform normal into world space
  vec3 normalWorld = gl_NormalMatrix * gl_Normal;

  // do lighting calculations here (in world space)
  …
  myColor = …
}
```

```
// variable to be passed from vertex to fragment shader
varying vec4 myColor;

void main () // fragment shader - Gouraud shading
{
  gl_FragColor = myColor;
}
```

Demo – Vertex & Fragment Shader

```
// variable to be passed from vertex to fragment shader
varying vec4 myPos;
varying vec3 myNormal;

void main () // vertex shader — Phong shading
{
  // transform position to clip space
  gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;

  // transform position to world space
  vec4 myPos = gl_ModelViewMatrix * gl_Vertex;

  // transform normal into world space
  vec3 myNormal = gl_NormalMatrix * gl_Normal;

}
```

```
// variable to be passed from vertex to fragment shader
varying vec4 myPos;
varying vec3 myNormal;

void main () // fragment shader - Phong shading
{
  // do lighting calculations here
  …
  gl_FragColor = …;
}
```

Demo – General Purpose Computation Shader

```
// variables passed in from application
uniform sampler2D tex;
uniform float timestep = 1.0;

void main () // fragment shader
{

  vec2 texcoord = gl_TexCoord[0].xy;

  // texture lookups
  float u = texture2D(tex,texcoord).r;

  float u_xp1 = texture2D(tex,
float2(texcoord.x+1,texcoord.y)).r;
  float u_xm1 = texture2D(tex,
float2(texcoord.x-1,texcoord.y)).r;
  float u_yp1 = texture2D(tex,
float2(texcoord.x,texcoord.y+1)).r;
  float u_ym1 = texture2D(tex,
float2(texcoord.x,texcoord.y-1)).r;

  glFragColor.r = u +
timestep*(u_xp1+u_xm1+u_yp1+u_ym1-4*u);

}
```

heat equation: $\frac{\partial u}{\partial t} = \alpha \nabla^2 u \Rightarrow u^{(t+1)} = \Delta_t \alpha \nabla^2 u + u^{(t)}$

OpenGL Shading Language (GLSL)

- high-level programming language for shaders
- syntax similar to C (i.e. has `main` function and many other similarities)
- usually very short programs that are executed in parallel on GPU
- good introduction / tutorial:

https://www.opengl.org/sdk/docs/tutorials/TyphoonLabs/

OpenGL Shading Language (GLSL)

- versions of OpenGL, WebGL, GLSL can get confusing

- here's what we use:
    - WebGL 1.0 - based on OpenGL ES 2.0
    - GLSL 1.10 - shader preprocessor: `#version 110`

- reason: three.js doesn't support WebGL 2.0 yet

GLSL – Simplest (pass-through) Vertex Shader

```
void main () // vertex shader
{
  // transform position to clip space
  // this is similar to gl_Position = ftransform();
  gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;

}
```

GLSL – Simplest Fragment Shader

```
void main () // fragment shader
{
  // set same color for each fragment
  gl_FragColor = vec4(1.0,0.0,0.0,1.0);

}
```

GLSL Data Types

`bool`	– boolean (true or false)
`int`	– signed integer
`float`	– 32 bit floating point
`ivec2, ivec3, ivec4`	– integer vector with 2, 3, or 4 elements
`vec2, vec3, vec4`	– floating point vector with 2, 3, or 4 elements
`mat2, mat3, mat4`	– floating point matrix with 2x2, 3x3, or 4x4 elements
`sampler2D`	– handle to a 2D texture

GLSL Data Types

`uniform type` – read-only values passed in from CPU application,

e.g. **`uniform float`** or **`uniform sampler2D`**

<u>vertex shader</u>

```
void main ()
{

  gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;

}
```

<u>fragment shader</u>

```
uniform sampler2D texture;

void main ()
{
  gl_FragColor = texture2D(texture, gl_TexCoords[0].xy);

}
```

GLSL Data Types

`varying type` – variables that are passed from vertex to fragment shader (i.e. write-only in vertex shader, read-only in fragment shader)

<u>vertex shader</u>

```
varying float myValue;

void main ()
{

  gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;

  myValue = 3.14159 / 10.0;

}
```

<u>fragment shader</u>

```
varying float myValue;

void main ()
{

  gl_FragColor = vec4(myValue, myValue, myValue, 1.0);

}
```

GLSL – Standard Attributes in Vertex Shader

built-in attributes	`vec4 gl_Vertex`	vertex position
	`vec3 gl_Normal`	vertex normal
	`vec4 gl_Color`	vertex color
	`vec4 gl_MultiTexCoordX`	vertex texture coords of texture unit X
built-in uniforms	`mat4 gl_ModelViewMatrix`	modelview matrix
	`mat4 gl_ModelViewProjectionMatrix`	modelview projection matrix
	`mat3 gl_NormalMatrix`	normal matrix (i.e. inverse transpose of modelview matrix)
built-in varying	`vec4 gl_Position`	vertex position in clip coords
	`vec4 gl_FrontColor`	color
	`vec4 gl_TexCoord[X]`	texture coords of texture unit X

Disclaimer

- modelview and projection matrices can be used via either the built-in uniforms OR as regular, user-defined built-in variables

- in the lab & homework, we will not use the built-in variables but pass in the matrices manually

GLSL – Standard Attributes in Fragment Shader

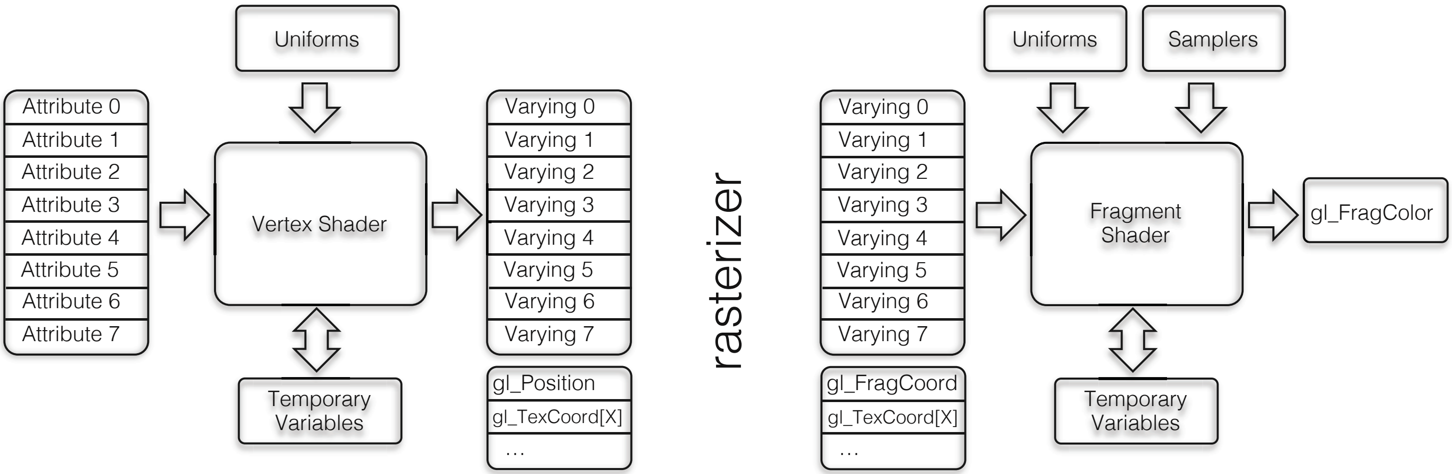
built-in (varying) input

`vec4 gl_FragCoord`	$(x,y,z,1/w_{clip})$ in window space
`vec4 gl_TexCoord[X]`	interpolated texture coordinates
`vec4 gl_Color`	interpolated color from `gl_FrontColor`

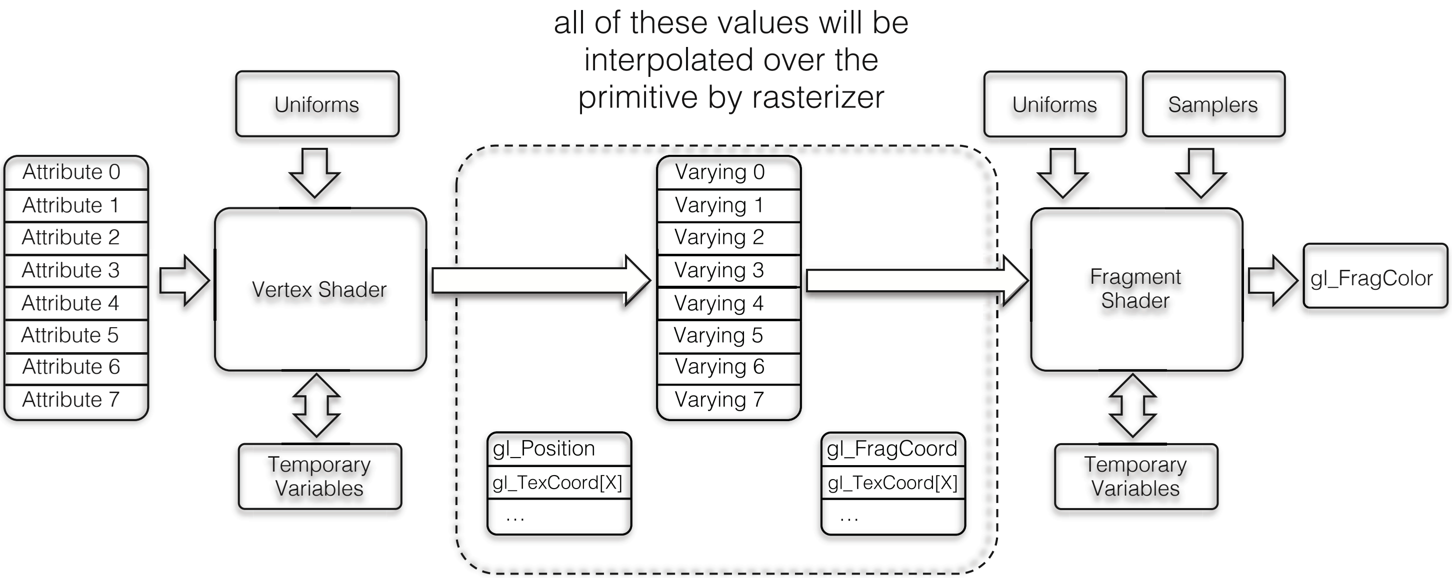
built-in output

`vec4 gl_FragColor`	fragment color
`float gl_FragDepth`	value written to depth buffer, if not specified: gl_FragCoord.z

GLSL Shader


Uniforms
Attribute 0
Attribute 1
Attribute 2
Attribute 3
Attribute 4
Attribute 5
Attribute 6
Attribute 7
Vertex Shader
Temporary Variables
Varying 0
Varying 1
Varying 2
Varying 3
Varying 4
Varying 5
Varying 6
Varying 7
gl_Position
gl_TexCoord[X]
...
rasterizer
Varying 0
Varying 1
Varying 2
Varying 3
Varying 4
Varying 5
Varying 6
Varying 7
gl_FragCoord
gl_TexCoord[X]
...
Uniforms
Samplers
Fragment Shader
Temporary Variables
gl_FragColor

GLSL Shader


all of these values will be interpolated over the primitive by rasterizer
Uniforms
Attribute 0
Attribute 1
Attribute 2
Attribute 3
Attribute 4
Attribute 5
Attribute 6
Attribute 7
Vertex Shader
Temporary Variables
Varying 0
Varying 1
Varying 2
Varying 3
Varying 4
Varying 5
Varying 6
Varying 7
gl_Position
gl_TexCoord[X]
...
gl_FragCoord
gl_TexCoord[X]
...
Uniforms
Samplers
Fragment Shader
Temporary Variables
gl_FragColor

GLSL – built-in functions

`dot`	dot product between two vectors
`cross`	cross product between two vectors
`texture2D`	texture lookup (get color value of texture at some tex coords)
`normalize`	normalize a vector
`clamp`	clamp a scalar to some range (e.g., 0 to 1)

`radiants, degrees, sin, cos, tan, asin, acos, atan, pow, exp, log,`
`exp2, log2, sqrt, abs, sign, floor, ceil, mod, min, max, length, …`

good summary of OpenGL ES (WebGL) shader functions:

http://www.shaderific.com/glsl-functions/

Gouraud Shading with GLSL (only diffuse part)

```
uniform vec3 lightPositionWorld;
uniform vec3 lightColor;
uniform vec3 diffuseMaterial;

void main () // vertex shader
{
  // transform position to clip space
  gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;

  // transform vertex position, normal, and light position to view space
  vec3 P = …
  vec3 L = …
  vec3 N = …

  // compute the diffuse term here
  float diffuseFactor = …

  // set output color
  gl_FrontColor.rgb = diffuseFactor * diffuseMaterial * lightColor;
}
```

Gouraud Shading with GLSL (only diffuse part)

```
void main () // fragment shader
{
  // set output color
  gl_FragColor = gl_Color;
}
```

Phong Shading with GLSL (only diffuse part)

```
varying vec3 vPosition;
varying vec3 vNormal;

void main () // vertex shader
{
  // transform position to clip space
  gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;

  // transform vertex position, normal, and light position to view space
  vec3 P = …
  vec3 N = …

  // set output texture coordinate to vertex position in world coords
  vPosition = P;

  // set output color to vertex normal direction
  vNormal = N;
}
```

Phong Shading with GLSL (only diffuse part)

```
uniform vec3 lightColor;
uniform vec3 diffuseMaterial;
uniform vec3 lightPositionWorld;

varying vec3 vPosition;
varying vec3 vNormal;

void main () // fragment shader
{
  // incoming color is interpolated by rasterizer over primitives!
  vec3 N = vNormal;

  // vector pointing to light source
  vec3 L = …

  // compute the diffuse term
  float diffuseFactor …

  // set output color
  gl_FragColor.rgb = diffuseFactor * diffuseMaterial * lightColor;
}
```

GLSL - Misc

- swizzling:

```
vec4 myVector1;
vec4 myVector2;
vec3 myVector1.xxy + myVector2.zxy;
```

- matrices are column-major ordering
- initialize vectors in any of the following ways:

```
vec4 myVector  = vec4(1.0, 2.0, 3.0, 4.0);
vec4 myVector2 = vec4(vec2(1.0, 2.0), 3.0, 4.0);
vec4 myVector3 = vec4(vec3(1.0, 2.0, 3.0), 4.0);
```

- sometimes OpenGL quantizes `gl_FrontColor` (vertex shader) to `gl_Color` (fragment shader) to 8 bits per channel, despite being a float → may need to use `gl_TexCoord[X]` instead to preserve precision
- these are equivalent: `myVector.xyzw = myVector.rgba = myVector.uvst`
- we omitted a lot of details…

JavaScript & GLSL

goals:

- loading, compiling, and linking GLSL shaders (from a file) using JavaScript
- activating and deactivate GLSL shaders in JavaScript
- accessing uniforms from JavaScript

our approach (for labs and homeworks):

- use three.js to handle all of the above
- can do manually, but more work – we will shield this from you

Summary

- GLSL is your language for writing vertex and fragment shaders
- each shader is independently executed for each vertex/fragment on the GPU
- usually require both vertex and fragment shader, but can “pass-through” data

Further Reading

- GLSL tutorial: https://www.opengl.org/sdk/docs/tutorials/TyphoonLabs/
- summary of built-in GLSL functions: http://www.shaderific.com/glsl-functions/
- GLSL and WebGL: https://webglfundamentals.org/webgl/lessons/webgl-shaders-and-glsl.html