12.2 Programmable Graphics Hardware

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Introduction

- Recent major advance in real time graphics is the programmable pipeline:
  - First introduced by NVIDIA GeForce 3 (in 2001)
  - Supported by all modern high-end commodity cards
    - NVIDIA, ATI
  - Software Support
    - Direct X 8, 9, 10, 11
    - OpenGL 2, 3, 4
- This lecture:
  programmable pipeline and shaders

OpenGL Extensions

- Initial OpenGL version was 1.0 (1992)
- Current OpenGL version is 4.5 (Aug. 2014)
- As graphics hardware improved, new capabilities were added to OpenGL
  - multitexturing
  - multisampling
  - non-power-of-two textures
  - shaders
  -and many more

OpenGL Grows via Extensions

- Phase 1: vendor-specific: GL_NV_multisample
- Phase 2: multi-vendor:
  GL_EXT_multisample
- Phase 3: approved by OpenGL's review board

  GL_ARB_multisample
- Phase 4: incorporated into OpenGL (v1.3)

Deprecation

- New functionality added to OpenGL for ~20 years
- Difficult to maintain/implement drivers
- Many different ways to render same effects:
  - e.g. immediate mode, display lists, vertex buffer objects
- OpenGL 3.2 introduced core/compatibility profiles:
  - Core: deprecated functionality removed
  - Compatibility: backwards compatible w/ earlier versions
- When creating OpenGL context, can request compatibility profile (may not be supported)

Core Profile

- Removes immediate mode (e.g. glVertex*())
- Removes matrix stack (e.g. glTranslate*())
  - Must pass matrices directly to shaders
  - External libs like GLM, Eigen can handle matrix math
- Compatibility profile easier to learn, still widely supported (for now)
- Most of what follows will use OpenGL 2.0 API

OpenGL 2.0 Added Shaders

- Shaders are customized programs that replace a part of the OpenGL pipeline

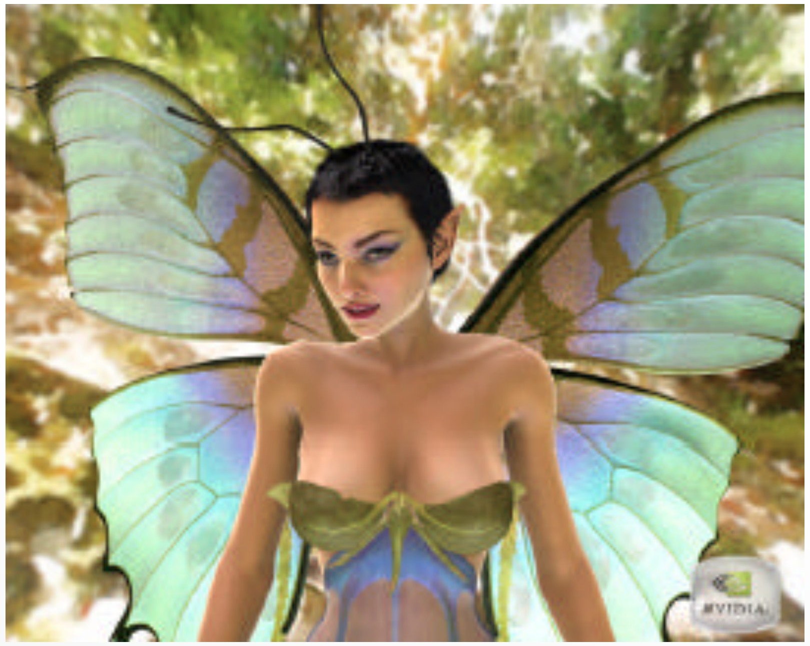
- They enable many effects not possible by the fixed OpenGL pipeline

- Motivated by Pixar's Renderman (offline shader)

Shaders Enable Many New Effects

Complex materials

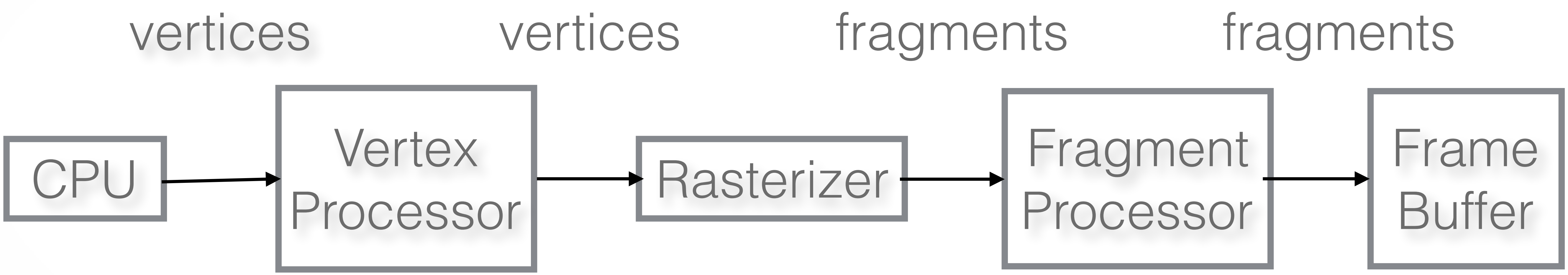
Shadowing



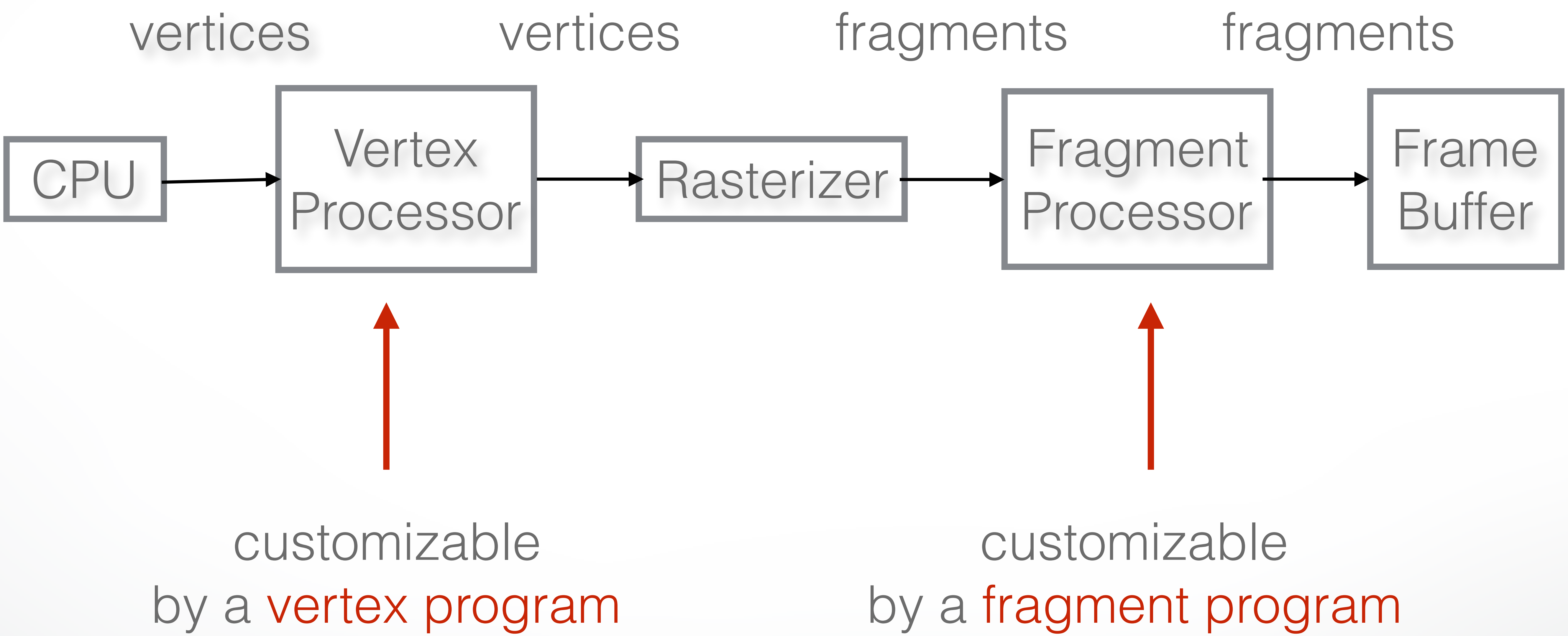
Lighting environments

Advanced mapping

The Rendering Pipeline



Shaders Replace Part of the Pipeline



Shaders

- Vertex shader (= vertex program)
- Fragment shader (= fragment program)
- Geometry shader (recent addition)
- Tessellation shaders (more recent addition)
- Default shaders are provided in OpenGL 2.0
  (fixed-function pipeline)
- Programmer can install her own shaders
  as needed

Shaders Are Written in Shading Languages

- Early shaders: assembly language

- Since ~2004: high-level shading languages
  - OpenGL Shading Language (GLSL)
    - highly integrated with OpenGL
  - Cg (NVIDIA and Microsoft), very similar to GLSL
  - HLSL (Microsoft), almost identical to Cg
  - All of these are simplified versions of C/C++

Vertex Program

- Input: vertices, and per-vertex attributes:
  - color
  - normal
  - texture coordinates
  - many more
- Output:
  - vertex location in clip coordinates
  - vertex color
  - vertex normal
  - many more are possible

Simple Vertex Program in GLSL (OpenGL 2.0)

```
/* pass-through vertex shader */

void main()
{
  gl_Position = gl_ProjectionMatrix
* (gl_ModelViewMatrix * gl_Vertex);
}
```

Simple Vertex Program in GLSL (Core)

```
/* pass-through vertex shader */

uniform mat4 ProjectionMatrix;
uniform mat4 ModelViewMatrix;

in vec3 Vertex;
void main()
{
  gl_Position = ProjectionMatrix
* (ModelViewMatrix * vec4(Vertex, 1.0));
}
```

- In C/C++ code, set values of matrices and vertex position

Fragment Program

- Input: pixels, and per-pixel attributes:
  - color
  - normal
  - texture coordinates
  - many more are possible
- Inputs are outputs from vertex program, interpolated (by the GPU) to the pixel location !
- Output:
  - pixel color
  - depth value

Simple Fragment Program (OpenGL 2.0)

```
/* pass-through fragment shader */

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

Simple Fragment Program #2 (OpenGL 2.0)

```
/* all-red fragment shader */

void main()
{
  gl_FragColor = vec4(1.0, 0.0, 0.0, 1.0);
}
```

Simple Fragment Program #2 (Core)

```
/* all-red fragment shader */
out vec4 FragColor;

void main()
{
  FragColor = vec4(1.0, 0.0, 0.0, 1.0);
}
```

- In C/C++ code, call:

  glBindFragDataLocation(ShaderProgram, 0, "FragColor");

GLSL: Data Types

- Scalar Types
  - float - 32 bit, very nearly IEEE-754 compatible
  - int - at least 16 bit
  - bool - like in C++
- Vector Types
  - vec[2 | 3 | 4] - floating-point vector
  - ivec[2 | 3 | 4] - integer vector
  - bvec[2 | 3 | 4] - boolean vector
- Matrix Types
  - mat[2 | 3 | 4] - for 2x2, 3x3, and 4x4 floating-point matrices
- Sampler Types
  - sampler[1 | 2 | 3]D - to access texture images

GLSL: Operations

- Operators behave like in C++
- Component-wise for vector & matrix
- Multiplication on vectors and matrices
- Examples:
  - vec3 t = u * v;
  - float f = v[2];
  - v.x = u.x + f;

GLSL: Swizzling

- Swizzling is a convenient way to access individual vector components

```
vec4 myVector;
myVector.rgba; // is the same as myVector
myVector.xy; // is a vec2
myVector.b; // is a float
myVector[2]; // is the same as myVector.b
myVector.xb; // illegal
myVector.xxx; // is a vec3
```

GLSL: Global Qualifiers

- Attribute
  - Information specific to each vertex/pixel passed to vertex/fragment shader
  - No integers, bools, structs, or arrays
- Uniform
  - Constant information passed to vertex/fragment shader
  - Cannot be written to in a shader
- Varying
  - Info passed from vertex shader to fragment shader
  - Interpolated from vertices to pixels
  - Write in vertex shader, but only read in fragment shader
- Const
  - To declare non-writable, constant variables

Example:
Vertex Color

Example:
Light Position
Eye Position

Example:
Vertex Color
Texture Coords

Example:
pi, e, 0.480

GLSL: Flow Control

- Loops
  - C++ style if-else
  - C++ style for, while, and do
- Functions
  - Much like C++
  - Entry point into a shader is void main()
  - No support for recursion
  - Call by value-return calling convention
- Parameter Qualifiers
  - in - copy in, but don't copy out
  - out - only copy out
  - inout - copy in and copy out

Example function:

```
void ComputeTangent(
  in vec3 N,
  out vec3 T,
  inout vec3 coord)
{
   if((dot(N, coord)>0)
      T = vec3(1,0,0);
   else
      T = vec3(0,0,0);
    coord = 2 * T;
}
```

GLSL: Built-in Functions

- Wide Assortment
  - Trigonometry (cos, sin, tan, etc.)
  - Exponential (pow, log, sqrt, etc.)
  - Common (abs, floor, min, clamp, etc.)
  - Geometry (length, dot, normalize, reflect, etc.)
  - Relational (less than, equal, etc.)
- Need to watch out for common reserved keywords
- Always use built-in functions, don’t implement your own
- Some functions aren’t implemented on some cards

GLSL: Accessing OpenGL State

- Built-in Variables
  - Always prefaced with gl_
  - Accessible to both vertex and fragment shaders
- Uniform Variables
  - Matrices (ModelViewMatrix, ProjectionMatrix, inverses, transposes)
  - Materials (in MaterialParameters struct, ambient, diffuse, etc.)
  - Lights (in LightSourceParameters struct, specular, position, etc.)
- Varying Variables
  - FrontColor for colors
  - TexCoord[] for texture coordinates

GLSL: Accessing OpenGL State

- Vertex Shader:
  - Have access to several vertex attributes: gl_Color, gl_Normal, gl_Vertex, etc.
  - Also write to special output variables: gl_Position, gl_PointSize, etc.
- Fragment Shader:
  - Have access to special input variables: gl_FragCoord, gl_FrontFacing, etc.
  - Also write to special output variables: gl_FragColor, gl_FragDepth, etc.

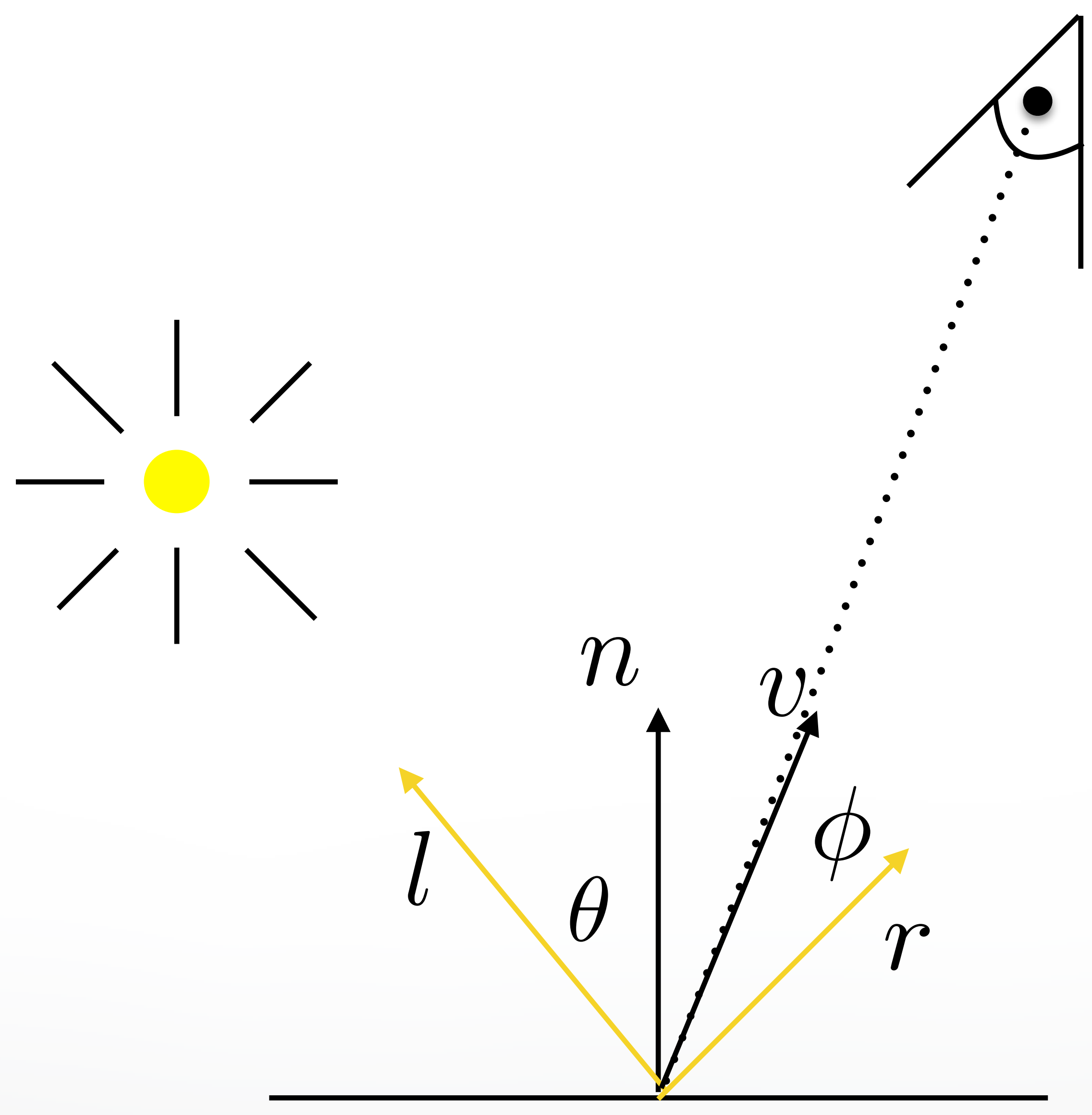
Example: Phong Shader ("per-pixel lighting")

- Questions ?

- Goals:
  - C/C++ Application Setup
  - Vertex Shader
  - Fragment Shader
  - Debugging

Phong Shading Review

$$I = \frac{1}{a + bq + cq^2}\left(k_d L_d (l \cdot n) + k_s L_s (r \cdot v)^{\alpha}\right) + k_a L_a$$



Phong Shader: Setup Steps

- Step 1: Create Shaders
  - Create handles to shaders
- Step 2: Specify Shaders
  - Load strings that contain shader source
- Step 3: Compiling Shaders
  - Actually compile source (check for errors)
- Step 4: Creating Program Objects
  - Program object controls the shaders
- Step 5: Attach Shaders to Programs
  - Attach shaders to program objects via handle
- Step 6: Link Shaders to Programs
  - Another step similar to attach
- Step 7: Enable Shaders
  - Finally, let OpenGL and GPU know that shaders are ready

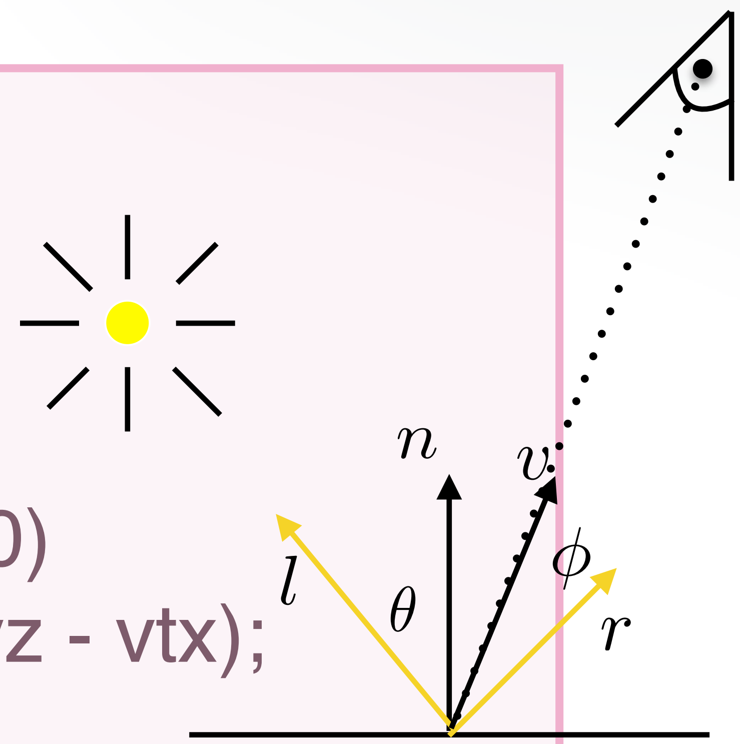
Phong Shader: Vertex Program

```
varying vec3 n;
varying vec3 vtx;
void main(void)
{
  // transform vertex position to eye coordinates:
  vtx = vec3(gl_ModelViewMatrix * gl_Vertex);
  // transform normal:
  n = normalize(gl_NormalMatrix * gl_Normal);
  // transform vertex position to clip coordinates:
  gl_Position = gl_ModelViewProjectionMatrix *
                gl_Vertex;
}
```

these will be
passed to fragment program
(interpolated by hardware)

Phong Shader: Fragment Program

```
varying vec3 n;      } interpolated
varying vec3 vtx;    } from vertex program
void main (void)       outputs
{
  // we are in eye coordinates, so eye pos is (0,0,0)
  vec3 l = normalize(gl_LightSource[0].position.xyz - vtx);
  vec3 v = normalize(-vtx);
  vec3 r = normalize(-reflect(l,n));
  //calculate ambient, diffuse, specular terms:
  vec4 Iamb = gl_FrontLightProduct[0].ambient;
  vec4 Idiff = gl_FrontLightProduct[0].diffuse * max(dot(n,l), 0.0);
  vec4 Ispec = gl_FrontLightProduct[0].specular
    * pow(max(dot(r,v),0.0), gl_FrontMaterial.shininess);
  // write total color:
  gl_FragColor = gl_FrontLightModelProduct.sceneColor +
 Iamb + Idiff + Ispec;
}
```



Debugging Shaders

- More difficult than debugging C programs
- Common show-stoppers:
  - Typos in shader source
  - Assuming implicit type conversion
  - Attempting to pass data to undeclared varying/uniform variables
- Extremely important to check error codes, use status functions like:
  - glGetObjectParameter{I|f}vARB (GLhandleARB shader, GLenum whatToCheck, GLfloat * statusVals)
- Subtle Problems
  - Shader too long
  - Use too many registers

Summary

- OpenGL Extensions
- Shading Languages
- Vertex Programs
- Fragment Programs
- Phong Shading in GLSL

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Thanks!