CSE 167: Introduction to Computer Graphics Lecture #8: GLSL

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Announcements

- Homework project #4 due Friday, November 2nd
  - Introduction: Oct 29 at 2:30pm
- This Friday:
  - Late grading for project #3
  - Early grading for project #4
- Midterm exam: Thursday, Oct 25, 2-3:20pm in classroom
- Midterm compatible index cards provided today and in instructor's office
- Reminder: Ted forums exist to discuss homework assignments and midterms

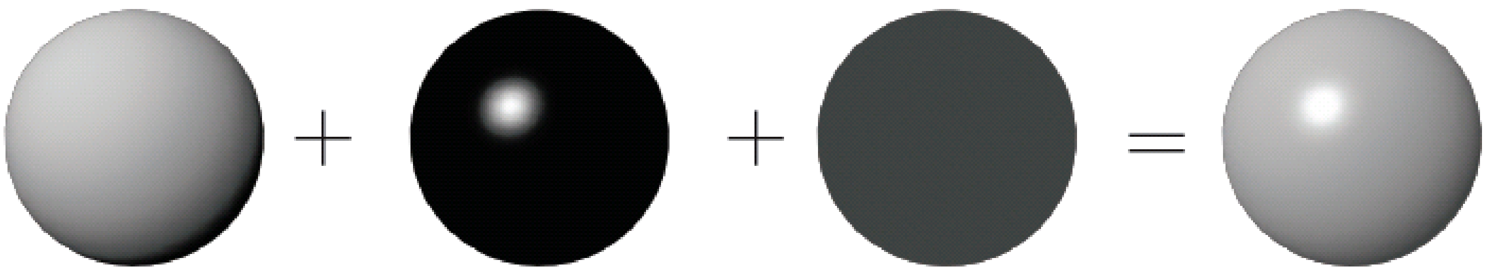
Review

- OpenGL's Shading Model

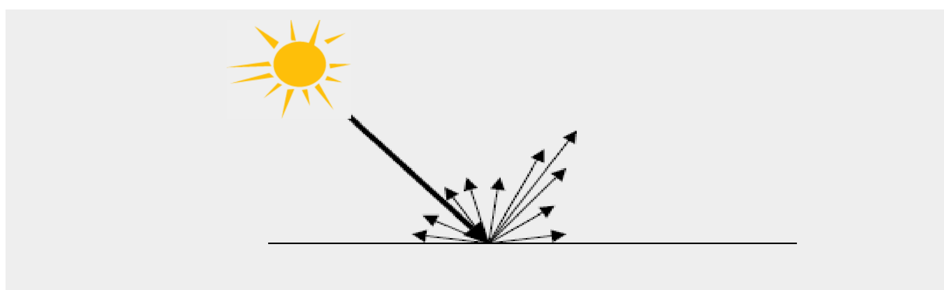
Complete Blinn-Phong Shading Model

- Blinn-Phong model with several light sources I
- All colors and reflection coefficients are vectors with 3 components for red, green, blue

$$c = \sum_i c_{l_i} \left(k_d \left(\mathbf{L}_i \cdot \mathbf{n}\right) + k_s \left(\mathbf{h}_i \cdot \mathbf{n}\right)^s\right) + k_a c_a$$



diffuse specular ambient



BRDFs

- Diffuse, Phong, Blinn models are instances of *bidirectional reflectance distribution functions* (BRDFs)
- For each pair of light directions $\mathbf{L}$ and viewing direction $\mathbf{e}$, the BRDF returns the fraction of reflected light
- Shading with general BRDF f

$$c = \sum_i c_{l\,i} f(\mathbf{L}_i, \mathbf{e})$$

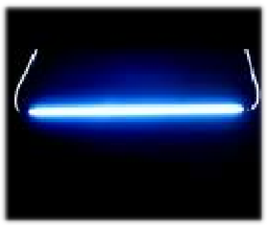
- Many other forms of BRDFs exist in graphics, often named after inventors: Cook-Torrance, Ward, etc.

Lecture Overview

- OpenGL Light Sources
- Types of Geometry Shading
- Shading in OpenGL
  - Fixed-Function Shading
  - Programmable Shaders
    - Vertex Programs
    - Fragment Programs
    - GLSL

Light Sources

- Real light sources can have complex properties
  - Geometric area over which light is produced
  - Anisotropy (directionally dependent)
  - Reflective surfaces act as light sources (indirect light)



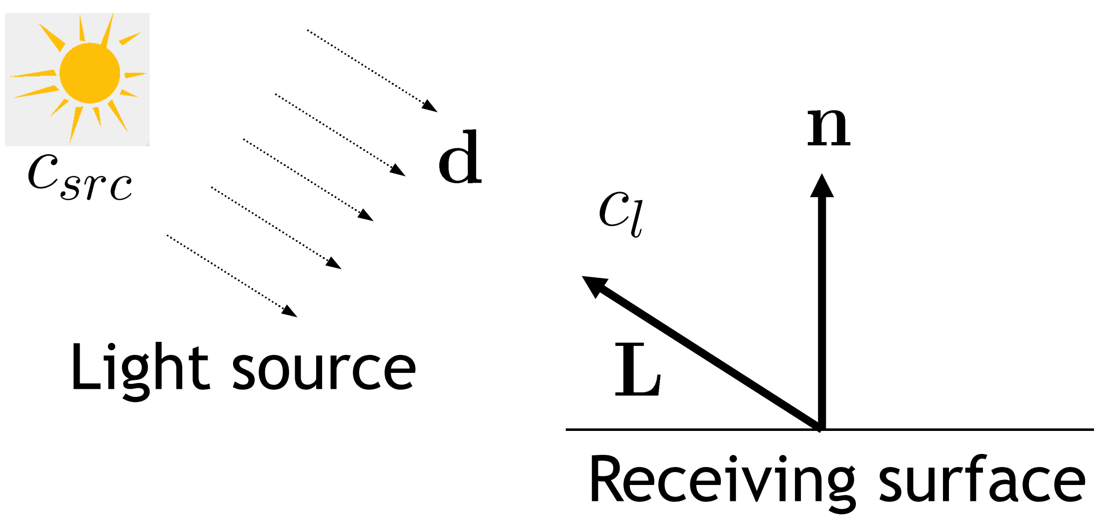

- OpenGL uses a drastically simplified model to allow real-time rendering

OpenGL Light Sources

- At each point on surfaces we need to know
  - Direction of incoming light (the $\mathbf{L}$ vector)
  - Intensity of incoming light (the c_l values)
- Standard light sources in OpenGL
  - Directional: from a specific direction
  - Point light source: from a specific point
  - Spotlight: from a specific point with intensity that depends on direction

Directional Light

- Light from a distant source
  - Light rays are parallel
  - Direction and intensity are the same everywhere
  - As if the source were infinitely far away
  - Good approximation of sunlight
- Specified by a unit length direction vector, and a color



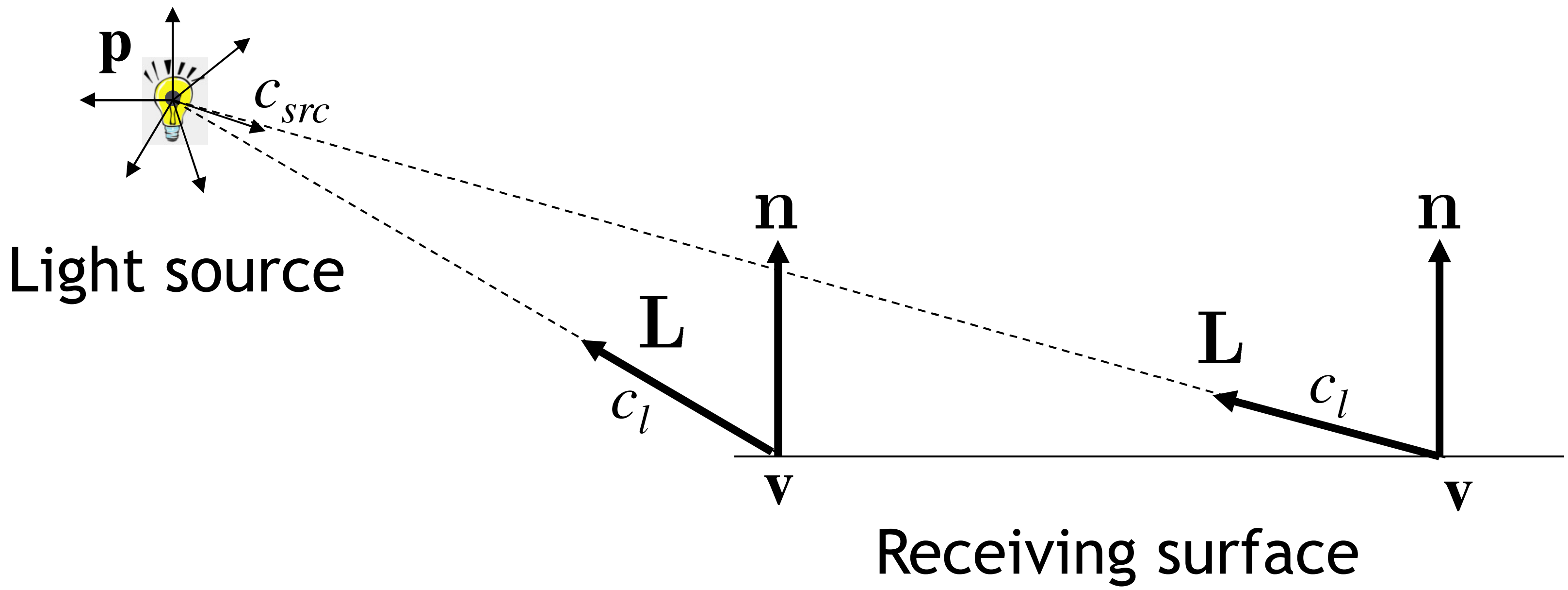
$$\mathbf{L} = -\mathbf{d}$$

$$c_l = c_{src}$$

Point Lights

- Similar to light bulbs
- Infinitely small point radiates light equally in all directions
  - Light vector varies across receiving surface
  - What is light intensity over distance proportional to?
  - Intensity drops off proportionally to the inverse square of the distance from the light
    - Reason for inverse square falloff: Surface area A of sphere: $A = 4 \pi r^2$

Point Lights in Theory



At any point v on the surface:

$$\mathbf{L} = \frac{\mathbf{p} - \mathbf{v}}{\|\mathbf{p} - \mathbf{v}\|}$$

$$c_l = \frac{c_{src}}{\|\mathbf{p} - \mathbf{v}\|^2}$$

Point Lights in OpenGL

- OpenGL model for distance attenuation:

$$c_l = \frac{c_{src}}{k_c + k_l |\mathbf{p} - \mathbf{v}| + k_q |\mathbf{p} - \mathbf{v}|^2}$$

- Attenuation parameters:
  - k_c = constant attenuation, default: 1
  - k_l = linear attenuation, default: 0
  - k_q = quadratic attenuation, default: 0
- Default: no attenuation: $c_l = c_{src}$
- Change attenuation parameters with:
  - GL_CONSTANT_ATTENUATION
  - GL_LINEAR_ATTENUATION
  - GL_QUADRATIC_ATTENUATION

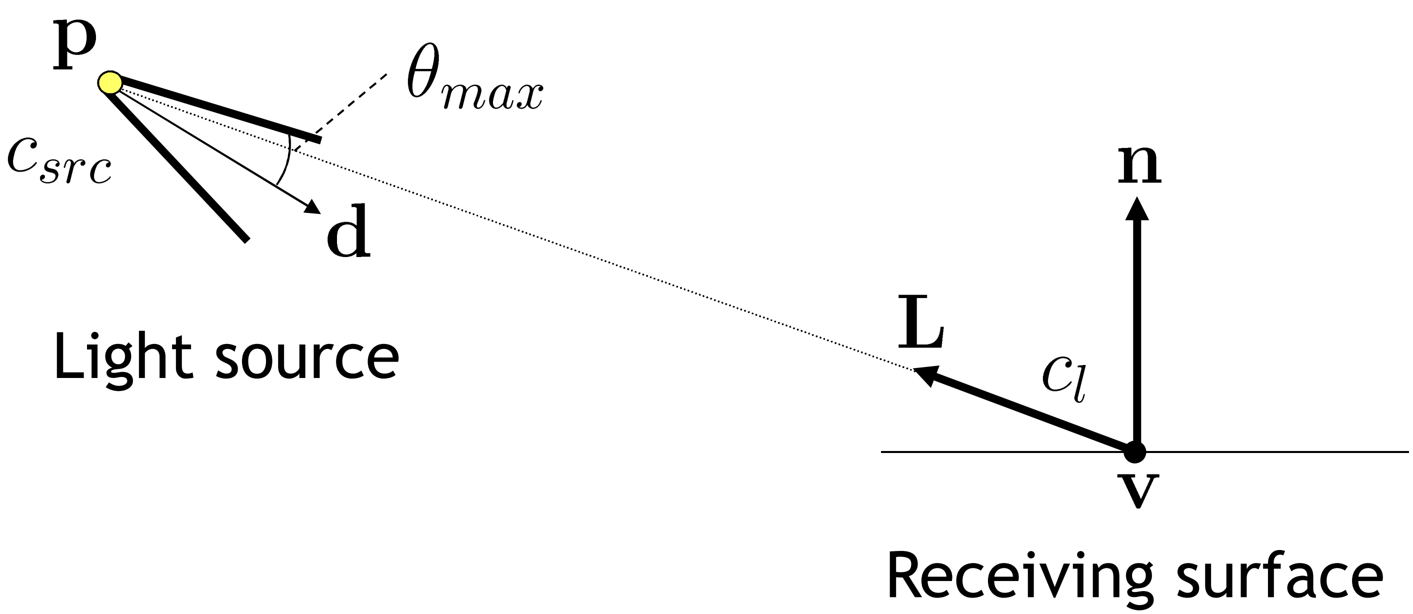
Spotlights

- Like point source, but intensity depends on direction

Parameters

- Position: location of the light source
- Spot direction: center axis of the light source
- Falloff parameters:
  - Beam width (cone angle)
  - The way the light tapers off at the edges of the beam (cosine exponent)

Spotlights

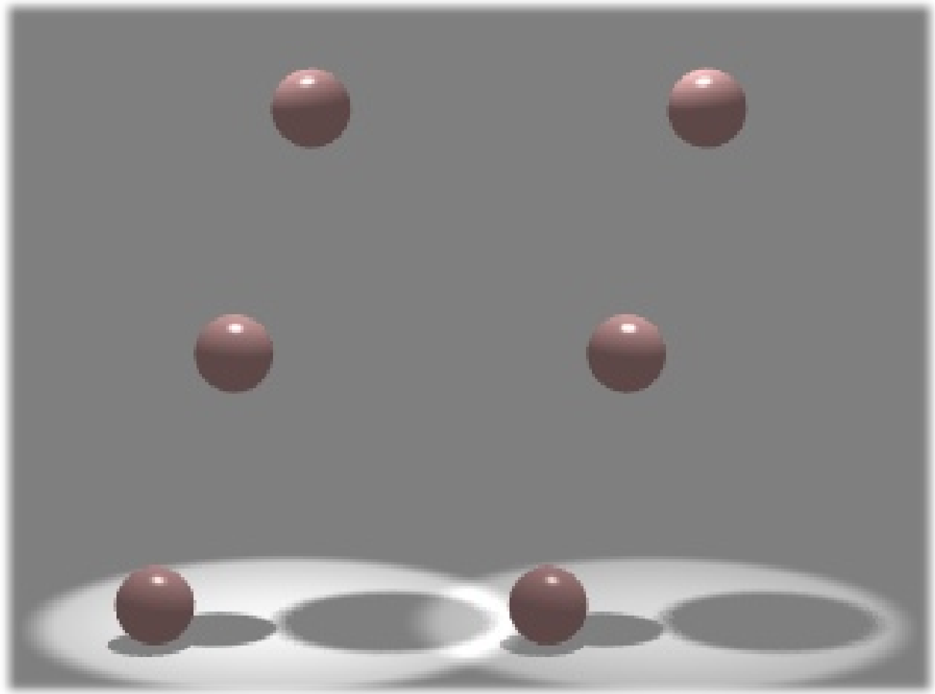


$$\mathbf{L} = \frac{\mathbf{p} - \mathbf{v}}{\|\mathbf{p} - \mathbf{v}\|}$$

$$c_l = \begin{cases} 0 & \text{if} \quad -\mathbf{L} \cdot \mathbf{d} \leq \cos(\theta_{max}) \\ c_{src}\,(-\mathbf{L} \cdot \mathbf{d})^f & \text{otherwise} \end{cases}$$

Spotlights

Photograph of real spotlight



Spotlights in OpenGL

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  - Programmable Shaders
    - Vertex Programs
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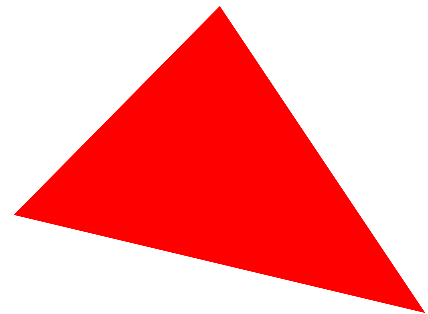
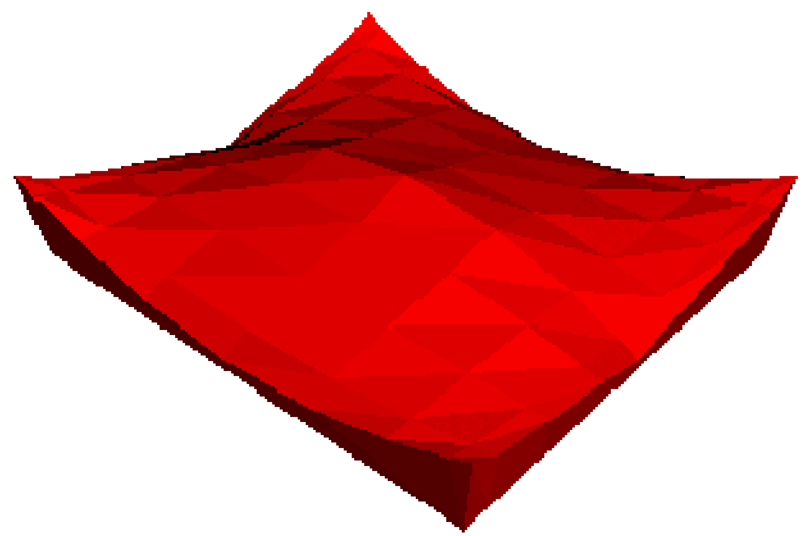
Types of Geometry Shading

- Per-triangle
- Per-vertex
- Per-pixel

Per-Triangle Shading

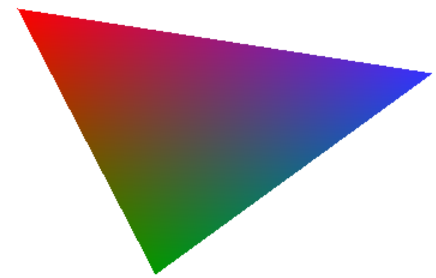
- Known as *flat shading*
- Evaluate shading once per triangle
- Advantage
  - Fast
- Disadvantage
  - Faceted appearance

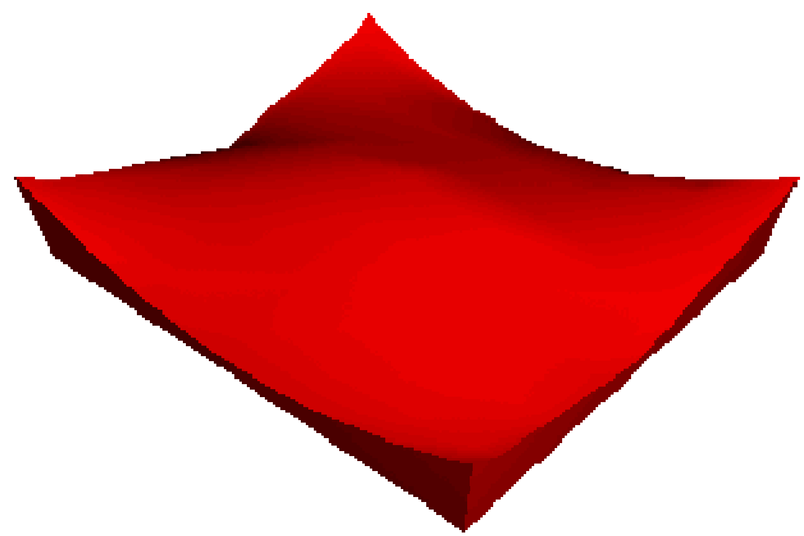




Per-Vertex Shading

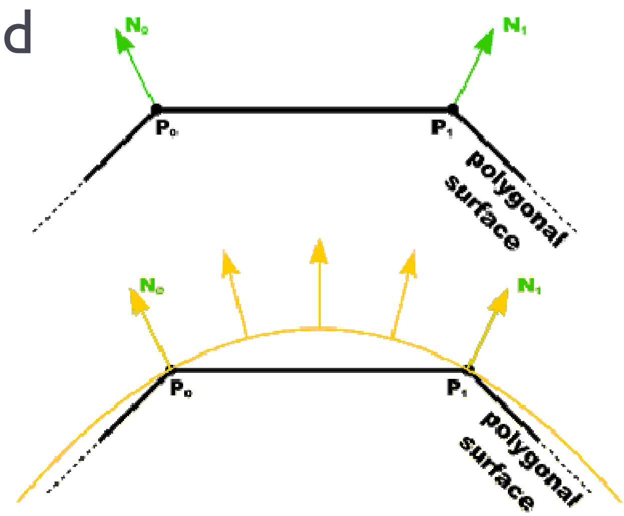
- Known as *Gouraud shading* (Henri Gouraud, 1971)
- Interpolates vertex colors across triangles with Barycentric Interpolation
- Advantages
  - Fast
  - Smoother surface appearance than with flat shading
- Disadvantage
  - Problems with small highlights





Per-Pixel Shading

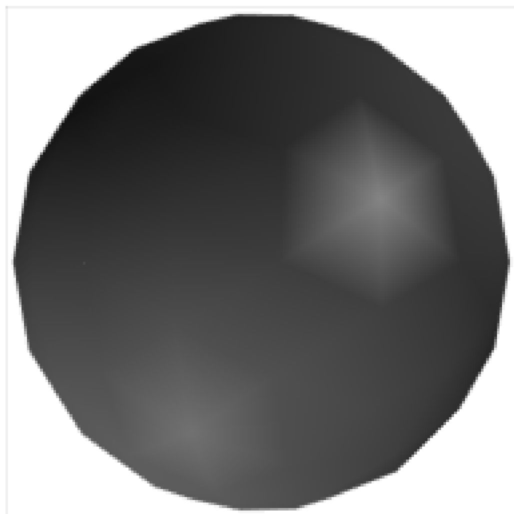
- Also known as *Phong Interpolation* (not to be confused with *Phong Illumination Model*)
  - Rasterizer interpolates normals (instead of colors) across triangles
  - Illumination model is evaluated at each pixel
  - Simulates shading with normals of a curved surface
- Advantage
  - Higher quality than Gouraud shading
- Disadvantage
  - Slow

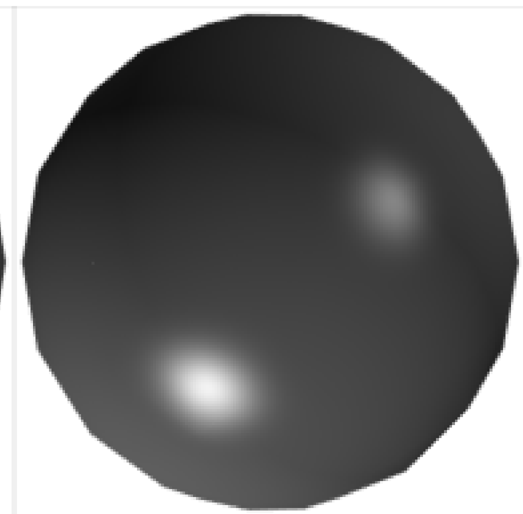


Source: Penny Rheingans, UMBC

Gouraud vs. Per-Pixel Shading

- Gouraud has problems with highlights
- More triangles would improve result, but reduce frame rate





Gouraud Per-Pixel

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Shading with Fixed-Function Pipeline

- Fixed-function pipeline only allows Gouraud (per-vertex) shading
- We need to provide a normal vector for each vertex
- Shading is performed in camera space
  - Position and direction of light sources are transformed by GL_MODELVIEW matrix
- If light sources should be in object space:
  - Set GL_MODELVIEW to desired object-to-camera transformation
  - Use object space coordinates for light positions
- More information:
  - http://glprogramming.com/red/chapter05.html
  - http://www.falloutsoftware.com/tutorials/gl/gl8.htm

Tips for Transforming Normals

- If you need to (manually) transform geometry by a transformation matrix **M,** which includes shearing or scaling:
  - Transforming the normals with **M** will not work: transformed normals are no longer perpendicular to surfaces
- Solution: transform the normals differently:
  - Either transform the end points of the normal vectors separately
  - Or transform normals with ${\mathrm{M}^{-1}}^T$
- Find derivation on-line at:
  - http://www.oocities.com/vmelkon/transformingnormals.html
- OpenGL does this automatically if the following command is used:
  - glEnable(GL_NORMALIZE)

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Programmable Shaders in OpenGL

- Initially, OpenGL only had a fixed-function pipeline for shading
- Programmers wanted more flexibility, similar to programmable shaders in raytracing software (term "shader" first introduced by Pixar in 1988)
- First shading languages came out in 2002:
  - **Cg** (C for Graphics, created by Nvidia)
  - **HLSL** (High Level Shader Language, created by Microsoft)
- **They supported:**
  - **Fragment shaders**: allowed per-pixel shading
  - **Vertex shaders**: allowed modification of geometry
- OpenGL 2.0 supported the OpenGL Shading Language (GLSL) in 2003
- **Geometry shaders** were added in OpenGL 3.2
- **Tessellation shaders** were added in OpenGL 4.0
- Programmable shaders allow real-time:
  Shadows, environment mapping, per-pixel lighting, bump mapping, parallax bump mapping, HDR, etc., etc.

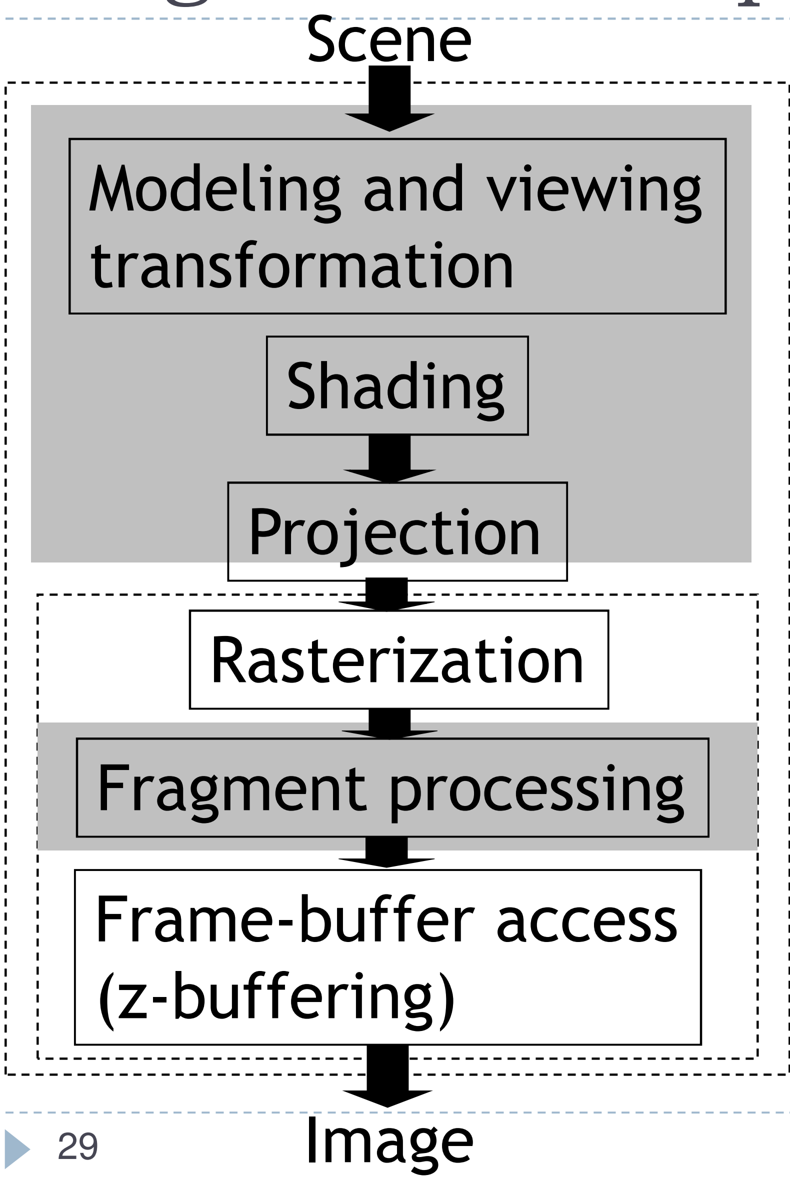
Demo

- NVIDIA Froggy
  - http://www.nvidia.com/coolstuff/demos#!/froggy
- Features
  - Bump mapping shader for Froggy’s skin
  - Physically-based lighting model simulating sub-surface scattering
  - Supersampling for scene anti-aliasing
  - Raytracing shader for irises to simulate refraction for wet and shiny eyes
  - Dynamically-generated lights and shadows

Shader Programs

- Programmable shaders consist of shader programs
- Written in a shading language
  - Syntax similar to C language
- Each shader is a separate piece of code in a separate ASCII text file
- Shader types:
  - Vertex shader
  - Tessellation shader
  - Geometry shader
  - Fragment shader (a.k.a. pixel shader)
- The programmer can provide any number of shader types to work together to achieve a certain effect
- If a shader type is not provided, OpenGL's fixed-function pipeline is used

Programmable Pipeline



- Executed once per vertex:
  - Vertex Shader
  - Tessellation Shader
  - Geometry Shader
- Executed once per fragment:
  - Fragment Shader

Vertex Shader

- Executed once per vertex
- Cannot create or remove vertices
- Does not know the primitive it belongs to
- Replaces functionality for
  - Model-view, projection transformation
  - Per-vertex shading
- If you use a vertex program, you need to implement behavior for the above functionality in the program!
- Typically used for:
  - Character animation
  - Particle systems

Tessellation Shader

- Executed once per primitive
- Generates new primitives by subdividing each line, triangle or quad primitive
- Typically used for:
  - Adapting visual quality to the required level of detail
    - For instance, for automatic tessellation of Bezier curves and surfaces
  - Geometry compression: 3D models stored at coarser level of resolution, expanded at runtime
  - Allows detailed displacement maps for less detailed geometry

Geometry Shader

- Executed once per primitive (triangle, quad, etc.)
- Can create new graphics primitives from output of tessellation shader (e.g., points, lines, triangles)
  - Or can remove the primitive
- Typically used for:
  - Per-face normal computation
  - Easy wireframe rendering
  - Point sprite generation
  - Shadow volume extrusion
  - Single pass rendering to a cube map
  - Automatic mesh complexity modification (depending on resolution requirements)

Fragment Shader

- A.k.a. Pixel Shader
- Executed once per fragment
- Cannot access other pixels or vertices
  - Makes execution highly parallelizable
- Computes color, opacity, z-value, texture coordinates
- Typically used for:
  - Per-pixel shading (e.g., Phong shading)
  - Advanced texturing
  - Bump mapping
  - Shadows

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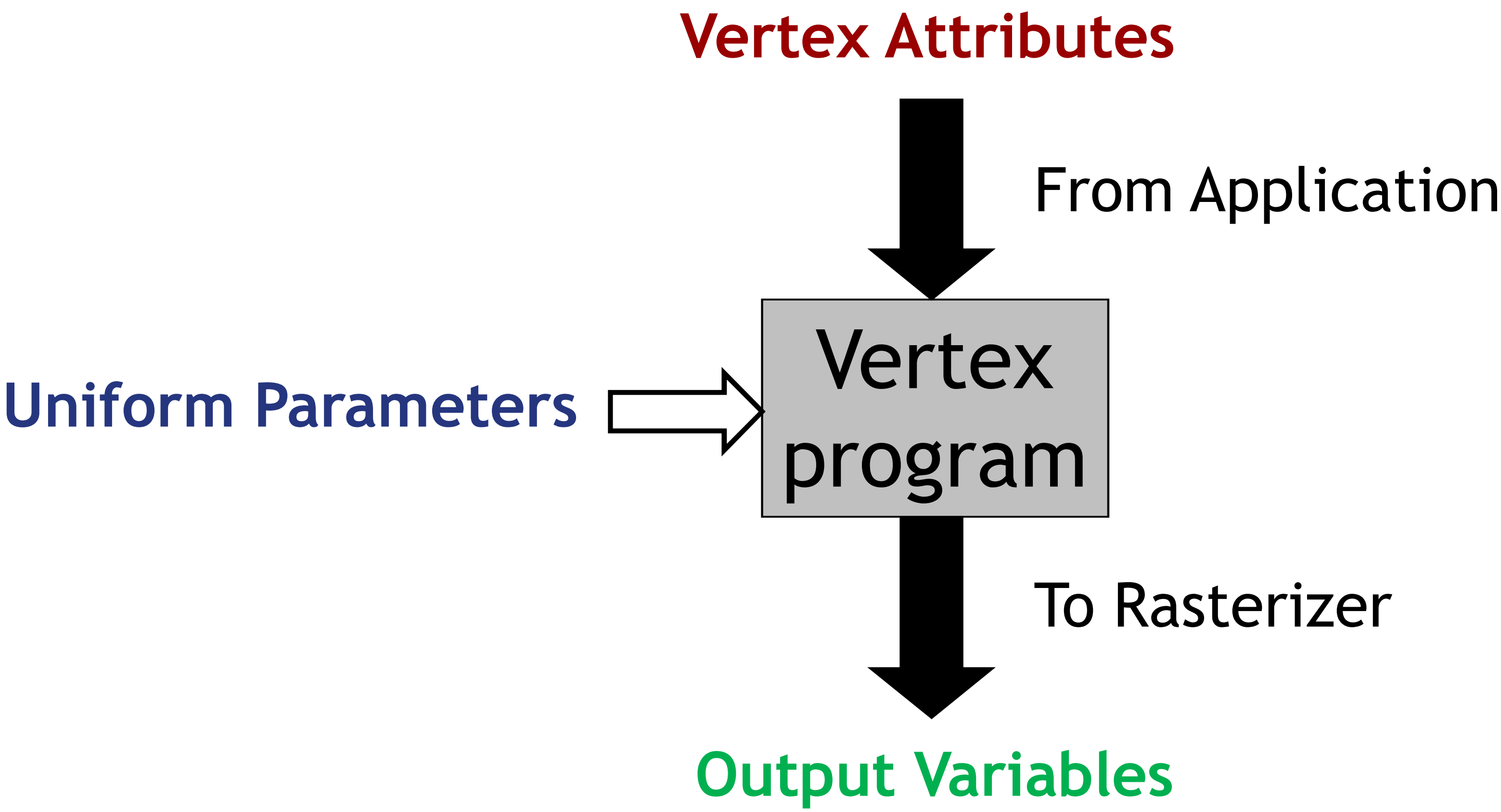
Vertex Programs



Vertex Attributes

- Declared using the `attribute` storage classifier
- Different for each execution of the vertex program
- Can be modified by the vertex program
- Two types:
  - Pre-defined OpenGL attributes. Examples:
    ```
    attribute vec4 gl_Vertex;
    attribute vec3 gl_Normal;
    attribute vec4 gl_Color;
    ```
  - User-defined attributes. Example:
    ```
    attribute float myAttrib;
    ```

Uniform Parameters

- Declared by `uniform` storage classifier
- Normally the same for all vertices
- Read-only
- Two types:
  - Pre-defined OpenGL state variables
  - User-defined parameters

Uniform Parameters: Pre-Defined

- Provide access to the OpenGL state
- Examples for pre-defined variables:

```
uniform mat4 gl_ModelViewMatrix;
uniform mat4 gl_ModelViewProjectionMatrix;
uniform mat4 gl_ProjectionMatrix;
uniform gl_LightSourceParameters
        gl_LightSource[gl_MaxLights];
```

Uniform Parameters: User-Defined

- Parameters that are set by the application
- Should not be changed frequently
  - Especially not on a per-vertex basis!
- To access, use `glGetUniformLocation, glUniform*` in application
- Example:
  - In shader declare

    ```
    uniform float a;
    ```
  - Set value of `a` in application:

    ```
    GLuint p;
    int I = glGetUniformLocation(p,"a");
    glUniform1f(i, 1.0f);
    ```

Vertex Programs: Output Variables

- Required output: homogeneous vertex coordinates
  `vec4 gl_Position`
- **`varying`** output variables
  - Mechanism to send data to the fragment shader
  - Will be interpolated during rasterization
  - Fragment shader gets interpolated data
- Pre-defined `varying` output variables, for example:

  ```
  varying vec4 gl_FrontColor;
  varying vec4 gl_TexCoord[];
  ```

  Any pre-defined output variable that you do not overwrite will have the value of the OpenGL state.
- User-defined `varying` output variables, e.g.:

  ```
  varying vec4 vertex_color;
  ```

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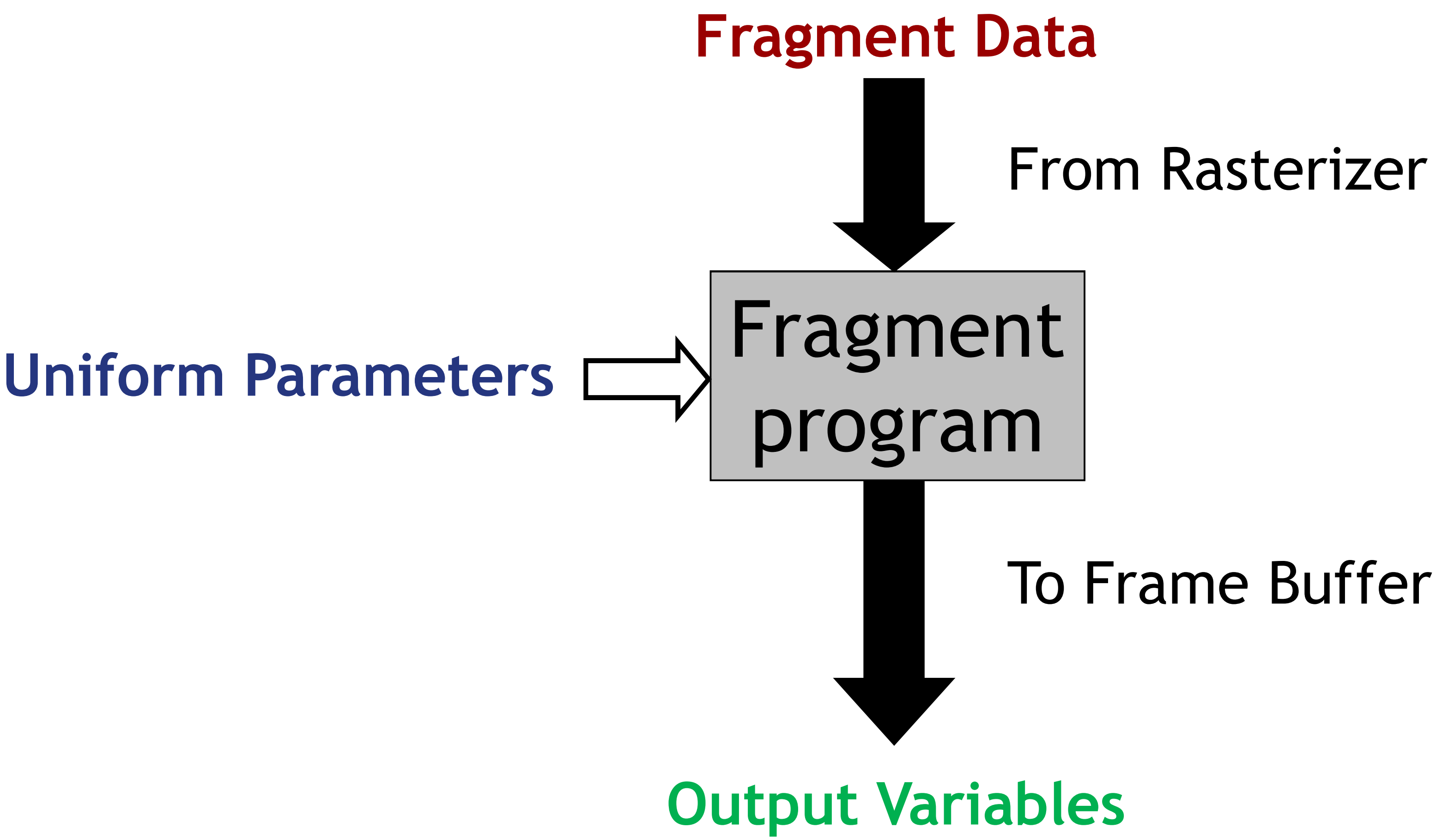
Fragment Programs



Fragment Data

- Changes for each execution of the fragment program
- Fragment data includes:
  - Interpolated standard OpenGL variables for fragment shader, as generated by vertex shader, for example:
    ```
    varying vec4 gl_Color;
    varying vec4 gl_TexCoord[];
    ```
  - Interpolated `varying` variables from vertex shader
    - Allows data to be passed from vertex to fragment shader

Uniform Parameters

- Same as in vertex programs

Output Variables

- Pre-defined output variables:
  - `gl_FragColor`
  - `gl_FragDepth`
- OpenGL writes these to the frame buffer
- Result is undefined if you do not set these variables!

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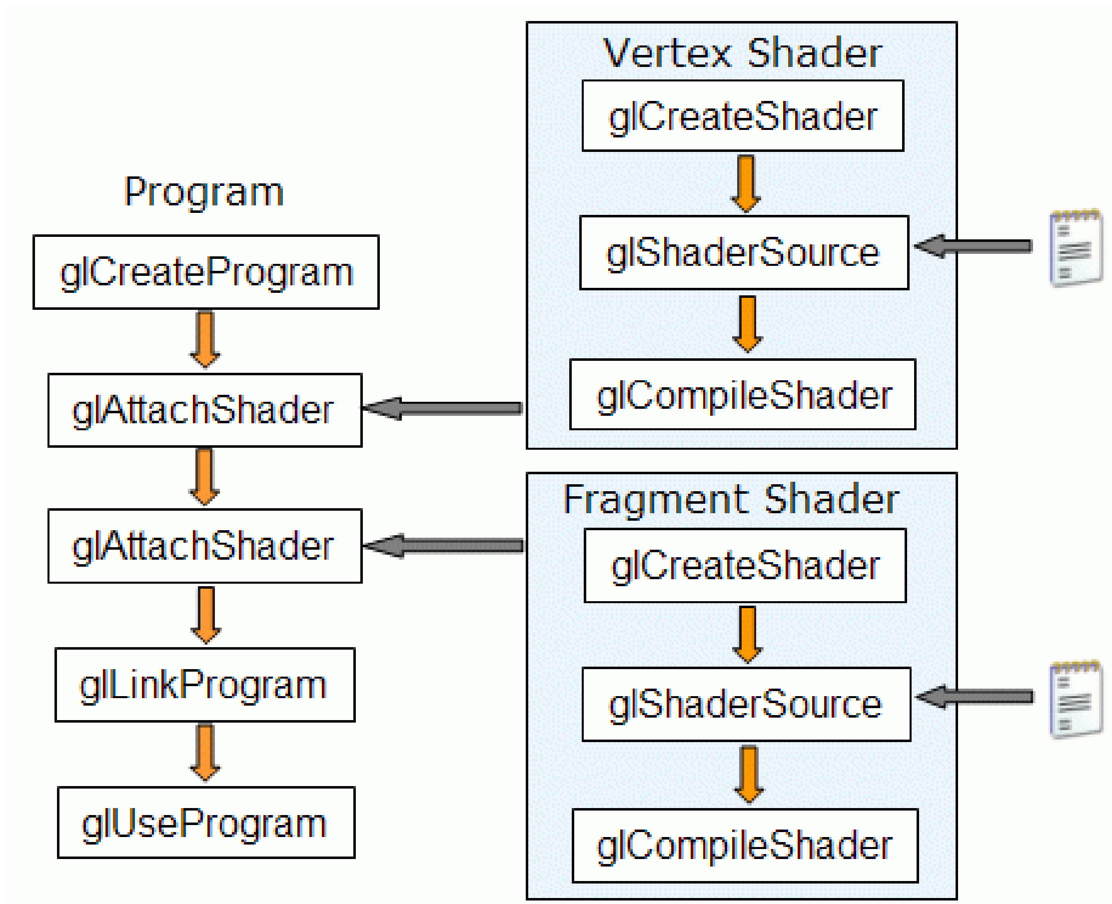
GLSL Main Features

- Similar to C language
- `attribute`, `uniform`, `varying` storage classifiers
- Set of predefined variables
  - Access to per-vertex, per-fragment data
  - Access OpenGL state
- Built-in vector data types, vector operations
- No pointers
- No direct access to data or variables in your C++ code

Example: Treat normals as colors

```
// Vertex Shader
varying vec4 color;

void main()
{
  // Treat the normal (x, y, z) values as (r, g, b) color
components.
  color = vec4(clamp(abs((gl_Normal + 1.0) * 0.5), 0.0, 1.0),
1.0);

  gl_Position = ftransform();
}

// Fragment Shader
varying vec4 color;

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

Creating Shaders in OpenGL



Source: Gabriel Zachmann, Clausthal University

Tutorials and Documentation

- OpenGL and GLSL specifications
  - http://www.opengl.org/documentation/specs/
- GLSL tutorials
  - http://www.lighthouse3d.com/opengl/glsl/
  - http://www.clockworkcoders.com/oglsl/tutorials.html
- OpenGL Programming Guide (Red Book)
- OpenGL Shading Language (Orange Book)
- OpenGL API Reference Card
  - http://www.khronos.org/files/opengl43-quick-reference-card.pdf