GPU Graphics Pipeline (Part II)

Computer Graphics

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Outline

- GPU graphics pipeline
- OpenGL graphics pipeline 1.x

(Part I)

- OpenGL graphics pipeline 2.0
- OpenGL and shader implementation

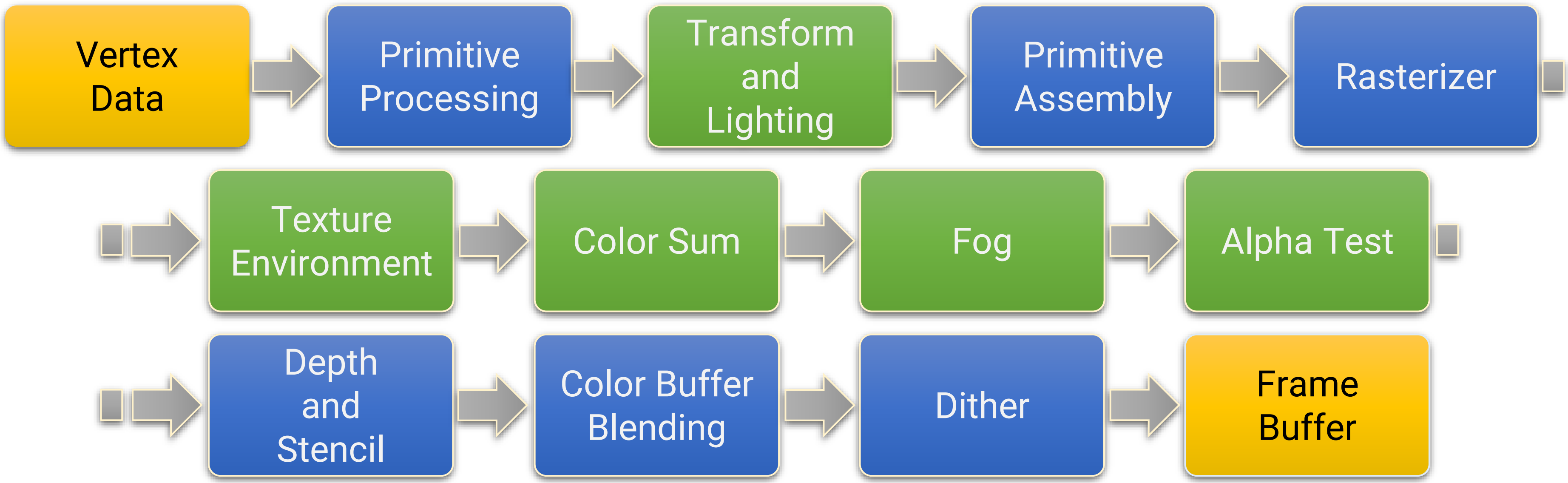
(Part II)

Outline

- GPU graphics pipeline
- OpenGL graphics pipeline 1.x
- **OpenGL graphics pipeline 2.0**
- OpenGL and shader implementation

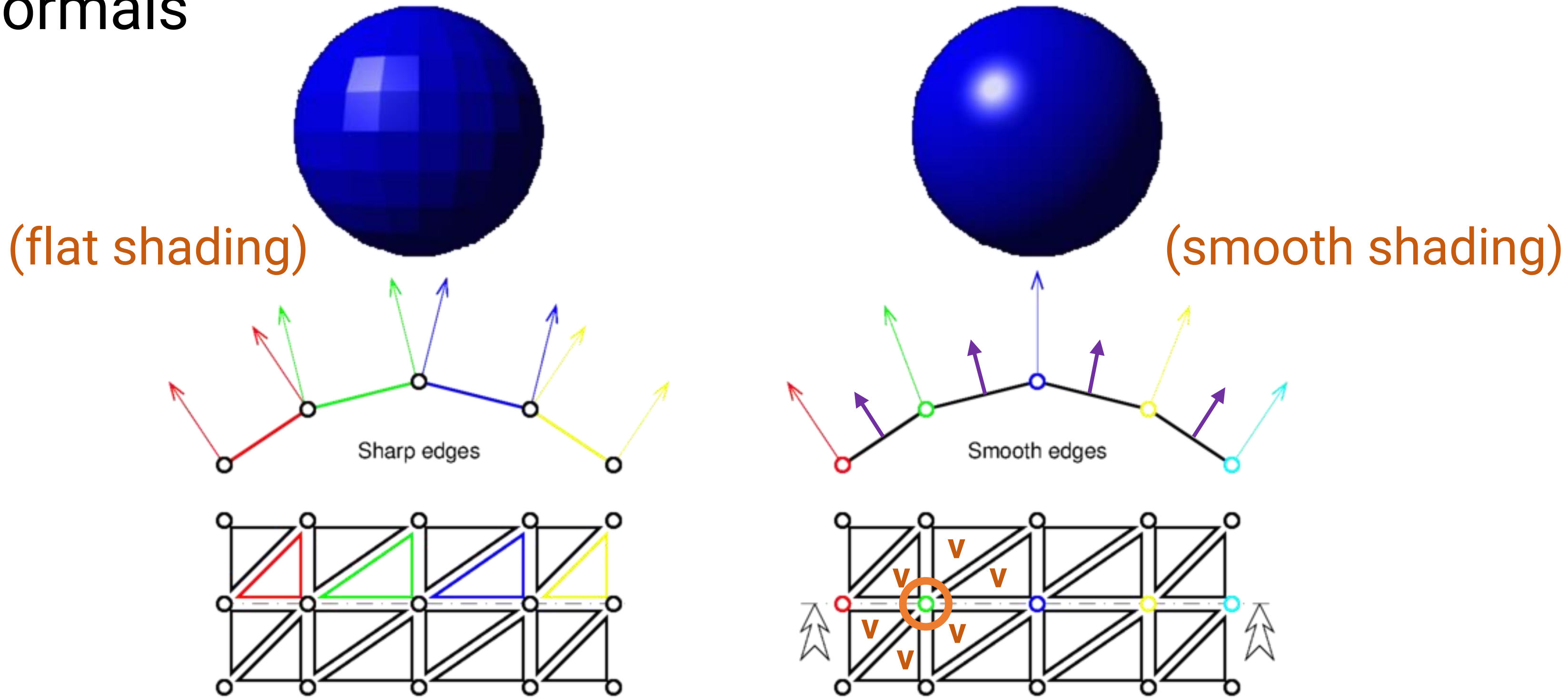
Recap: OpenGL (1.x) Fixed Function Pipeline

- All the functions performed by OpenGL are **fixed** and **could not** be modified except through the manipulation of the **rendering states**
- The stages shown in green have been replaced by **shaders**



Recap: Vertex Normal

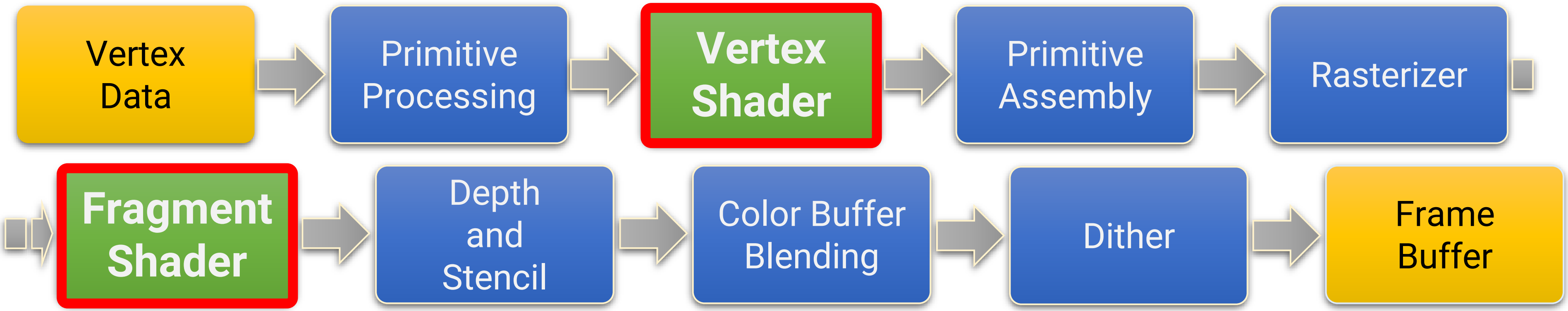
- Compute by **averaging** the surface normals of the faces that contain that vertex
- Can achieve much **smooth** shading than using triangle normals



Recap: Fog In Games

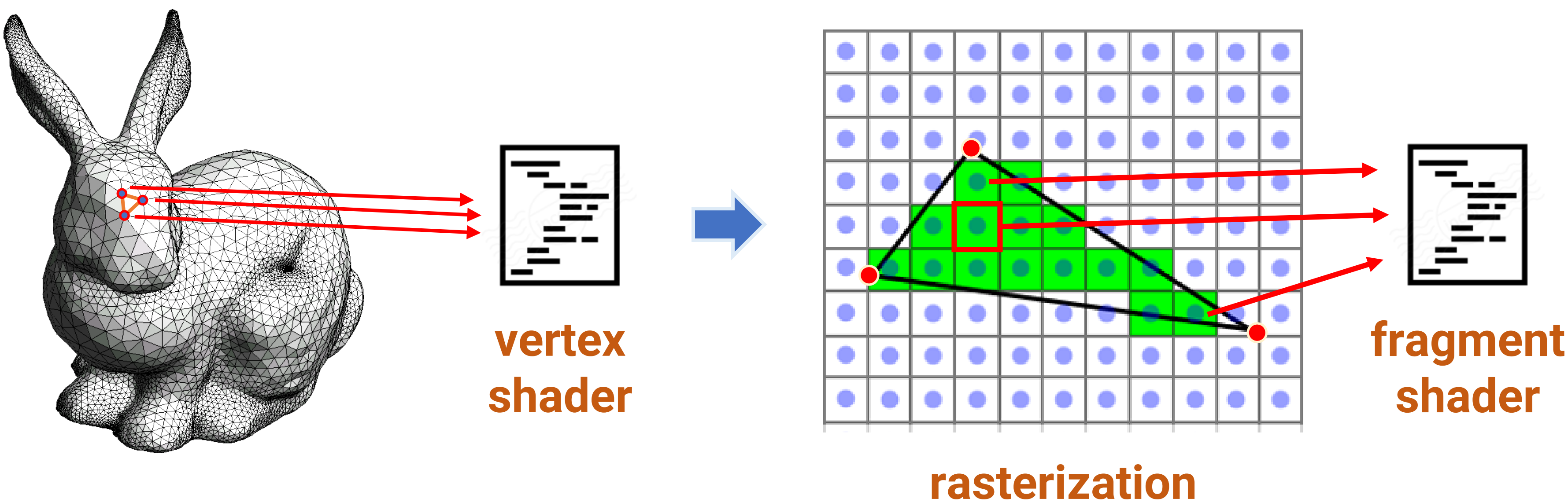
OpenGL (2.0) Graphics Pipeline

- Released in 2004
- Provide the ability to **programmatically** define the vertex transformation and lighting and the fragment operations (with small GPU programs called **shaders**)



Vertex Shader and Fragment Shader

- **Important concepts**
  - The vertex shader runs **per vertex**
  - The fragment shader runs **per (rasterized) fragment**



Vertex Shader (Run per Vertex)

- Provide the programmers more **flexibility** regarding
  - **How the vertices are transformed**
    - We can also choose not to transform the vertices at all
  - **How the lighting is computed**
    - We can also choose to compute lighting in the fragment shader (per-fragment lighting)
- However, ***with great power, comes great responsibility***
  - Programmers have to implement the functions provided by the fixed pipeline on their own
  - The primary responsibility of the vertex shader program is to **transform the vertex position into Clip Space**
    - Commonly, this is done by multiplying the vertex with the **model-view-projection** matrix

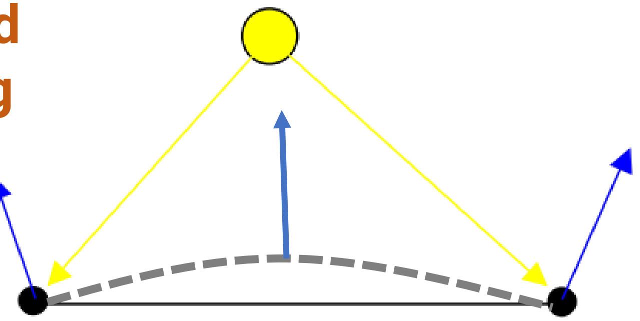
Fragment Shader (Run per Fragment)

- Replace the **texture blending**, **color sum**, **fog**, and **alpha test** operations from the fixed function pipeline
- Graphics programmers have to write a **fragment program** to perform these operations (of course, you can omit them if you do not care!)
- The primary responsibility of the fragment program is to **determine the final color of the fragment**
- Allow for different lighting and fog models, as well as an arbitrary combination of lighting and texture
- Allow for techniques such as per-pixel lighting, bump, normal mapping, etc.

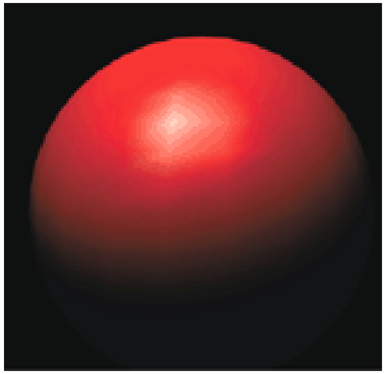
Per-Fragment Shading

- Problem with Gouraud shading
- Phong shading (instead of Gouraud shading)

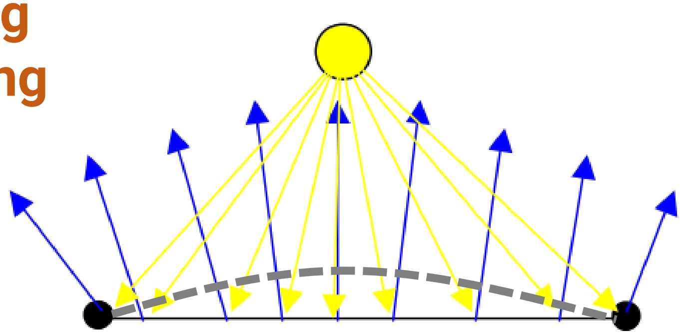
Gouraud shading



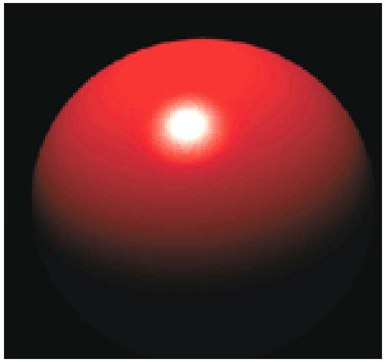
lighting color is interpolated



Phong shading

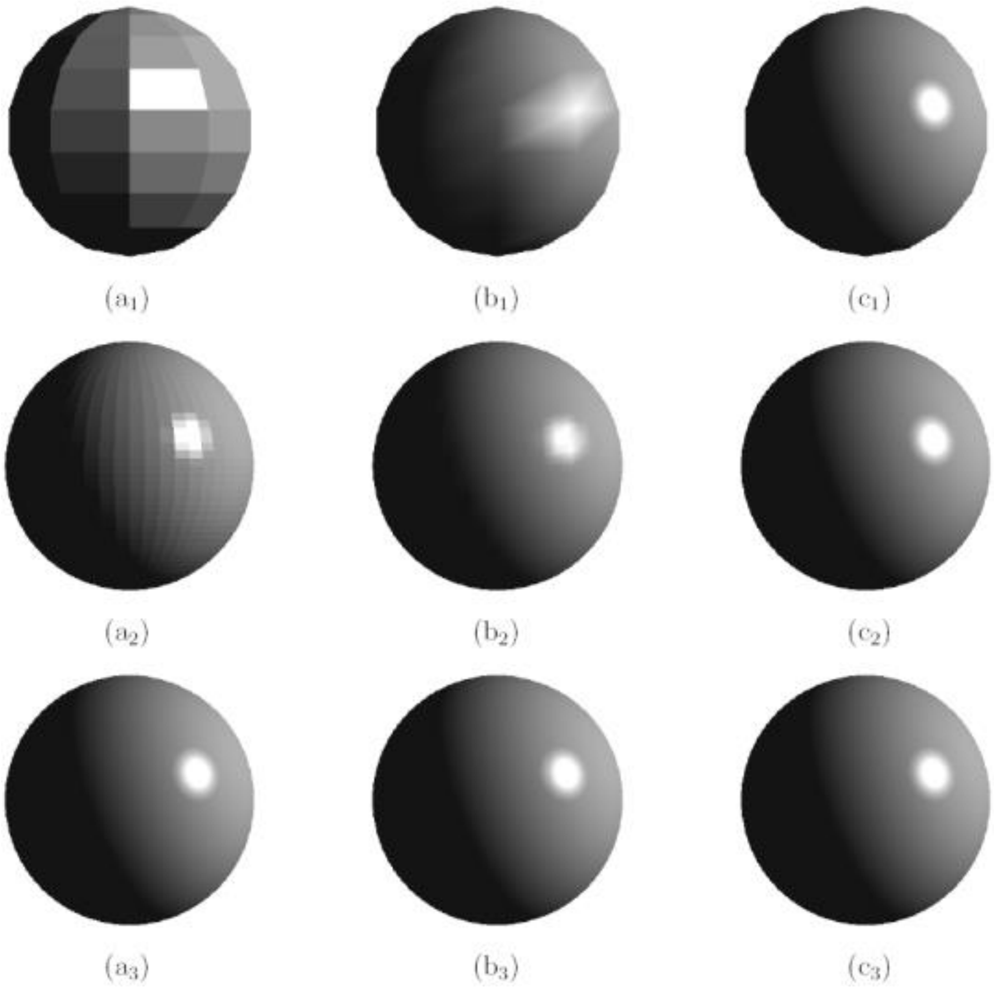


surface normal is interpolated (how? Rasterization!)



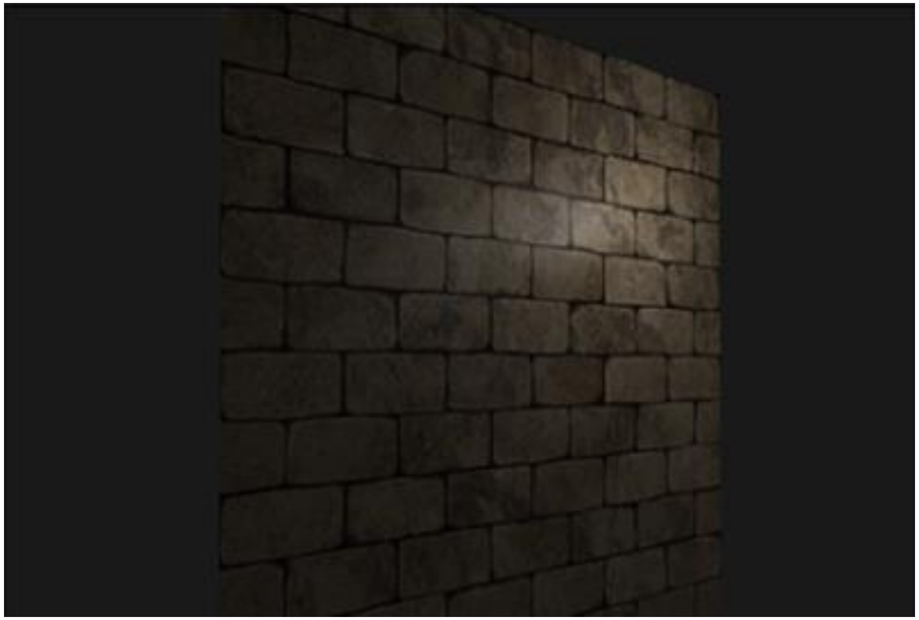
Per-Fragment Shading (cont.)

flat shading Gouraud shading Phong shading

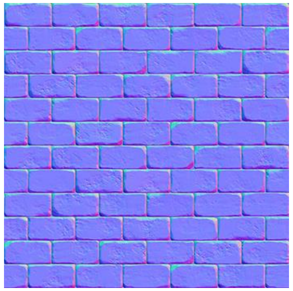


Per-Fragment Shading (cont.)

- Normal mapping



We will talk about this when introducing Textures



Modern Graphics Pipeline

- Modern graphics pipeline comprised more programmable (shader) stages, such as
  - **Geometry shader** in OpenGL 3.2
  - **Tessellation control shader** and **tessellation evaluation shader** in OpenGL 4.0
  - **Compute shader** in OpenGL 4.3
  - **Mesh shader** in OpenGL ?

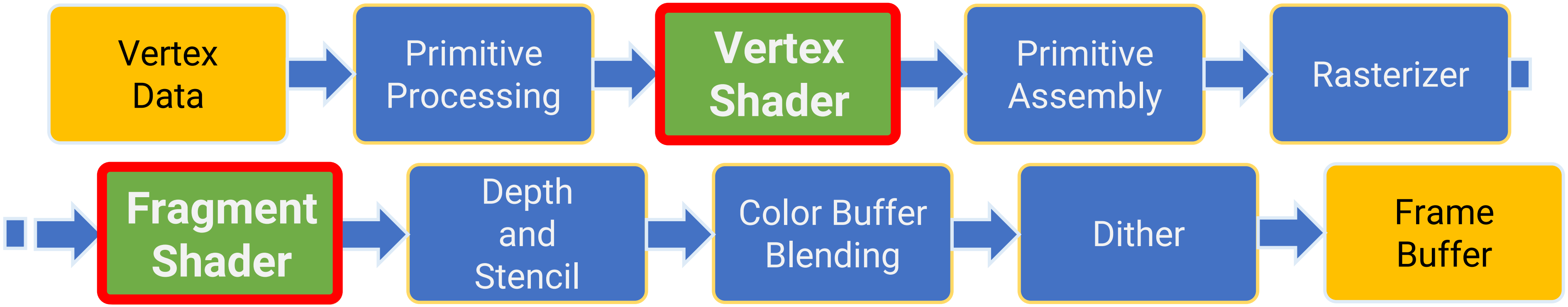
- Hopefully, we could have time to introduce these shaders later in this semester

Outline

- GPU graphics pipeline
- OpenGL graphics pipeline 1.x
- OpenGL graphics pipeline 2.0
- **OpenGL and shader implementation**

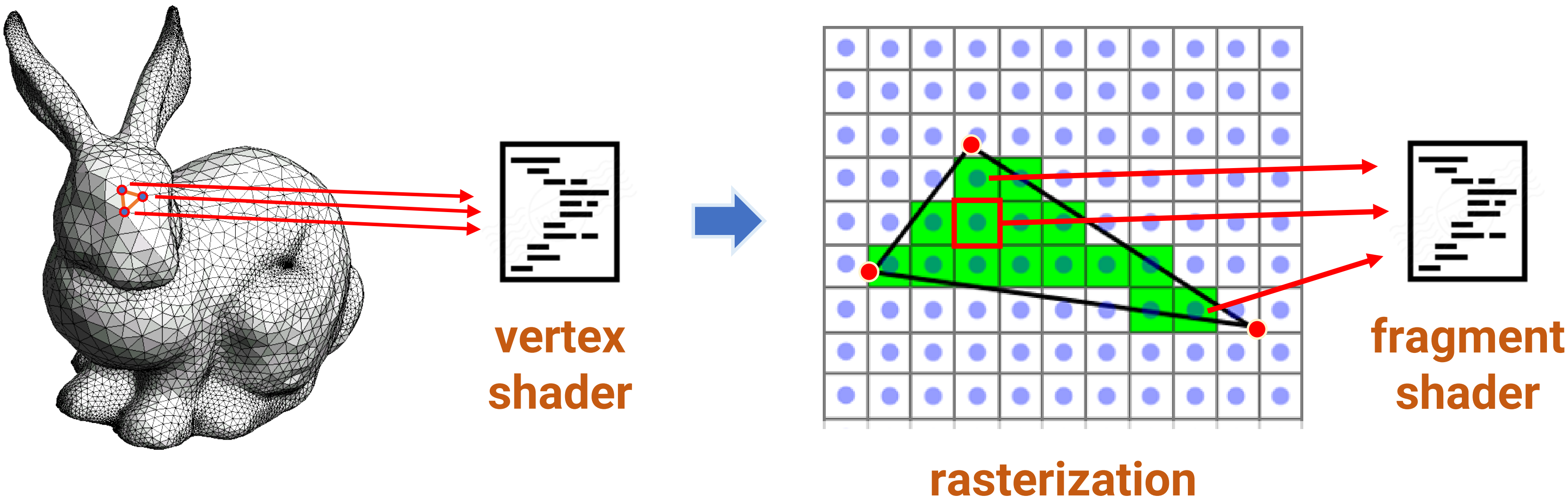
Recap: OpenGL 2.0 Graphics Pipeline

- Programmers need to provide the two shader programs
- Other stages maintain the same (set OpenGL states)



Recap: Vertex Shader and Fragment Shader

- **Important concepts**
  - The vertex shader runs **per vertex**
  - The fragment shader runs **per (rasterized) fragment**



Sample Project

- You can find the sample code in the project, **Shader**

Prepare Shaders

- Shaders are just text files written in a special shader language, such as
  - OpenGL Shading Language (GLSL)
  - High-Level Shading Language (HLSL) for DirectX
  - Nvidia Cg (used by Unity)

the file extension does not matter!

Load and Create an OpenGL Shader

```
// Shader.
GLuint shaderProgId;
GLint locM, locV, locP, locMVP;
GLint locFillColor;

void CreateShader(const std::string vsFilePath, const std::string fsFilePath)
{
    // Create OpenGL shader program.
    shaderProgId = glCreateProgram();
    if (shaderProgId == 0) {
        std::cerr << "[ERROR] Failed to create shader program" << std::endl;
        exit(1);
    }

    // Load the vertex shader from a source file and attach it to the shader program.
    std::string vs, fs;
    if (!LoadShaderTextFromFile(vsFilePath, vs)) {
        std::cerr << "[ERROR] Failed to load vertex shader source: " << vsFilePath << std::endl;
        exit(1);
    }
    GLuint vsId = AddShader(shaderProgId, vs, GL_VERTEX_SHADER);

    // Load the fragment shader from a source file and attach it to the shader program.
    if (!LoadShaderTextFromFile(fsFilePath, fs)) {
        std::cerr << "[ERROR] Failed to load vertex shader source: " << fsFilePath << std::endl;
        exit(1);
    };
    GLuint fsId = AddShader(shaderProgId, fs, GL_FRAGMENT_SHADER);
```

Create OpenGL shader program (ID)

in our case, a shader program consists of a vertex shader and a fragment shader

Load vertex shader source

Create, compile the vertex shader and attach it to the shader program

Load fragment shader source

Create, compile the fragment shader and attach it to the shader program

Load and Create an OpenGL Shader (cont.)

```
// Link and compile shader programs.
GLint success = 0;
GLchar errorLog[MAX_BUFFER_SIZE] = { 0 };
glLinkProgram(shaderProgId);
glGetProgramiv(shaderProgId, GL_LINK_STATUS, &success);
if (success == 0) {
    glGetProgramInfoLog(shaderProgId, sizeof(errorLog), NULL, errorLog);
    std::cerr << "[ERROR] Failed to link shader program: " <<  errorLog << std::endl;
    exit(1);
}

// Now the program already has all stage information, we can delete the shaders now.
glDeleteShader(vsId);
glDeleteShader(fsId);

// Validate program.
glValidateProgram(shaderProgId);
glGetProgramiv(shaderProgId, GL_VALIDATE_STATUS, &success);
if (!success) {
    glGetProgramInfoLog(shaderProgId, sizeof(errorLog), NULL, errorLog);
    std::cerr << "[ERROR] Invalid shader program: " << errorLog << std::endl;
    exit(1);
}

// Get the location of uniform variables.
// Discuss later
```

Link all **attached** shaders to the program

Delete (free memory) vertex/fragment shader object

Validate your shader program

Vertex Shader

Vertex attribute
- **glEnableVertexAttribArray(0)**

```
#version 330 core
layout (location = 0) in vec3 Position;
uniform mat4 modelMatrix;
uniform mat4 viewMatrix;
uniform mat4 projMatrix;
```

uniform variables communicated with the CPU
- Get location by **glGetUniformLocation**
- Set value by **glUniformXXX**

the main program **executed per vertex**

```
void main() {
    gl_Position = projMatrix * viewMatrix *
                  modelMatrix * vec4(Position, 1.0);
}
```

a built-in variable for the Clip Space coordinate (gl_Position)

Vertex Shader

```
#version 330 core
layout (location = 0) in vec3 Position;
uniform mat4 MVP;

void main() {
    gl_Position = MVP * vec4(Position, 1.0);
}
```

Input: vertex attribute

- **glEnableVertexAttribArray(0)**

uniform variables communicated with the CPU

- Get location by **glGetUniformLocation**
- Set value by **glUniformXXX**

the main program **executed per vertex**

gl_Position: **a built-in variable for the Clip Space coordinate**

Fragment Shader

```
#version 330 core
uniform vec3 fillColor;

out vec4 FragColor;

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

uniform variables communicated with the CPU

- Get location by **glGetUniformLocation**
- Set value by **glUniformXXX**

Output: fragment data

the main program **executed per fragment**

Connect the Program with Shaders

- Get the location of uniform variables in the shader

```
// Get the location of uniform variables.
locM = glGetUniformLocation(shaderProgId, "modelMatrix");
locV = glGetUniformLocation(shaderProgId, "viewMatrix");
locP = glGetUniformLocation(shaderProgId, "projMatrix");
locMVP = glGetUniformLocation(shaderProgId, "MVP");
locFillColor = glGetUniformLocation(shaderProgId, "fillColor");
```

- Assign values to the uniform variables in shaders

```
// Bind shader and set parameters.
glUseProgram(shaderProgId);
glUniformMatrix4fv(locM, 1, GL_FALSE, glm::value_ptr(M));
glUniformMatrix4fv(locV, 1, GL_FALSE, glm::value_ptr(camera->GetViewMatrix()));
glUniformMatrix4fv(locP, 1, GL_FALSE, glm::value_ptr(camera->GetProjMatrix()));
// glUniformMatrix4fv(locMVP, 1, GL_FALSE, glm::value_ptr(MVP));
glUniform3fv(locFillColor, 1, glm::value_ptr(fillColor));

// Render the mesh.
if (mesh ≠ nullptr)
    mesh->Draw();

// Unbind shader.
glUseProgram(0);
```

bind (there might be several shaders in your program)

unbind

Connect the Program with Shaders (cont.)

- Bind and unbind to a shader program

the shader program you created

void glUseProgram(GLuint program);

```
glUseProgram(shaderProgId);
// set parameters
// render something
glUseProgram(0);
```

Connect the Program with Shaders (cont.)

- Get the location of uniform variables in the shader

GLint glGetUniformLocation(

GLuint **program** , the shader program you created

const GLchar ***name**

);

the uniform variable in the shader

```
// Get the location of uniform variables.
locM = glGetUniformLocation(shaderProgId, "modelMatrix");
locV = glGetUniformLocation(shaderProgId, "viewMatrix");
locP = glGetUniformLocation(shaderProgId, "projMatrix");
locMVP = glGetUniformLocation(shaderProgId, "MVP");
locFillColor = glGetUniformLocation(shaderProgId, "fillColor");
```

Connect the Program with Shaders (cont.)

- Assign values to the uniform variables
- Lots of variants depending on the variable type, please refer to https://registry.khronos.org/OpenGL-Refpages/gl4/html/glUniform.xhtml

```
void glUniform3fv(
        GLint location ,
        GLsizei count ,
        const GLfloat *value
);
```

- location: the variable location get by glGetUniformLocation
- count: the number of the vectors (1 if not an array)
- *value: the values of the parameters

```
glm::vec3 fillColor = glm::vec3(1.0f, 1.0f, 0.0f);
glUniform3fv(locFillColor, 1, glm::value_ptr(fillColor));
```

Connect the Program with Shaders (cont.)

- Assign values to the uniform variables

```
void glUniformMatrix4fv(
        GLint location ,
        GLsizei count ,
        GLboolean transpose ,
        const GLfloat *value
);
```

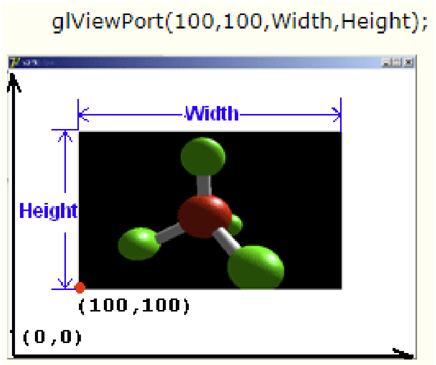
should the matrix be accessed in a transpose way **(since both OpenGL and GLM use column-major, we set it to FALSE)**

```
glUniformMatrix4fv(locM, 1, GL_FALSE, glm::value_ptr(M));
glUniformMatrix4fv(locV, 1, GL_FALSE, glm::value_ptr(camera->GetViewMatrix()));
glUniformMatrix4fv(locP, 1, GL_FALSE, glm::value_ptr(camera->GetProjMatrix()));
```

Resize Window

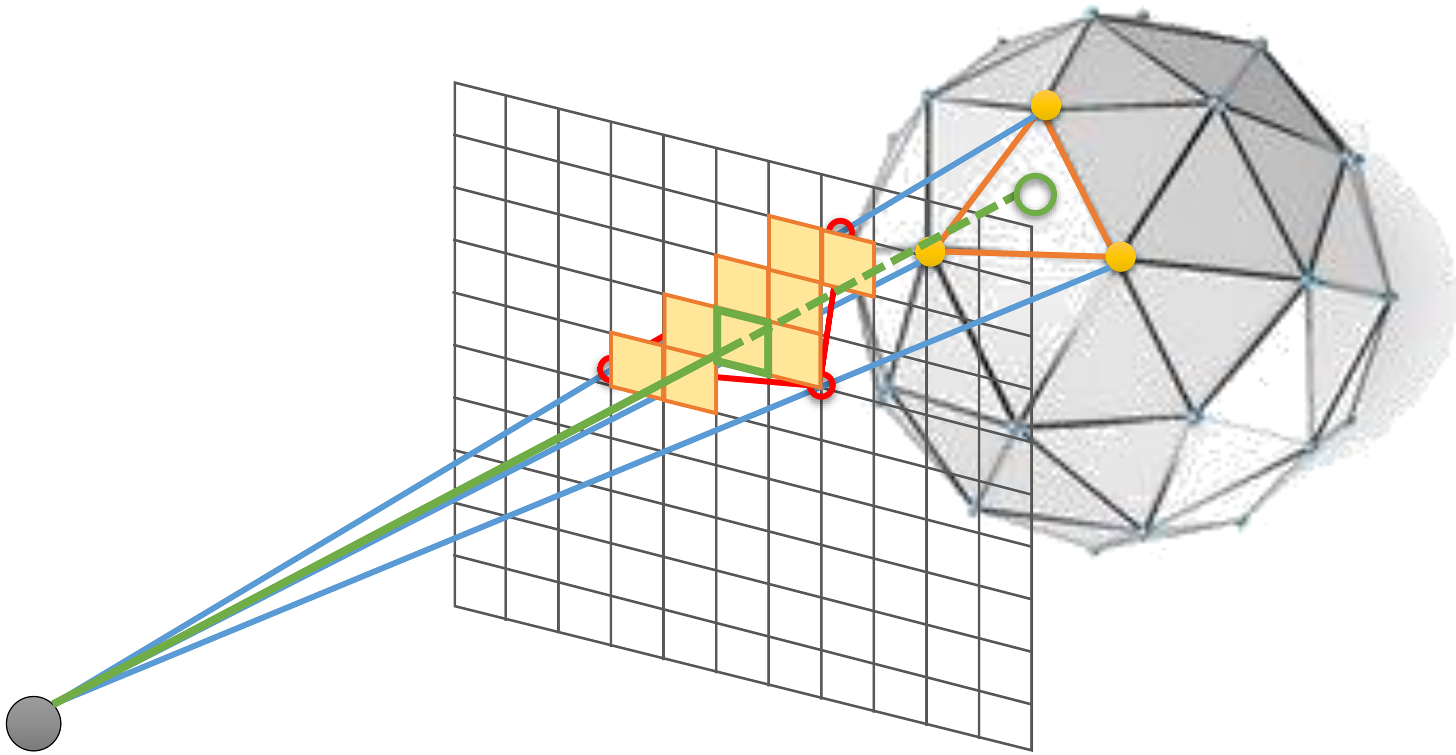
```
glutReshapeFunc(ReshapeCB);

void ReshapeCB(int w, int h)
{
    // Update viewport.
    screenWidth = w;
    screenHeight = h;
    glViewport(0, 0, screenWidth, screenHeight);
    // Adjust camera and projection.
    float aspectRatio = (float)screenWidth / (float)screenHeight;
    camera->UpdateProjection(fovy, aspectRatio, zNear, zFar);
    MVP = camera->GetProjMatrix() * camera->GetViewMatrix() * M;
}
```

remember to reset the range of rendering in an OpenGL window



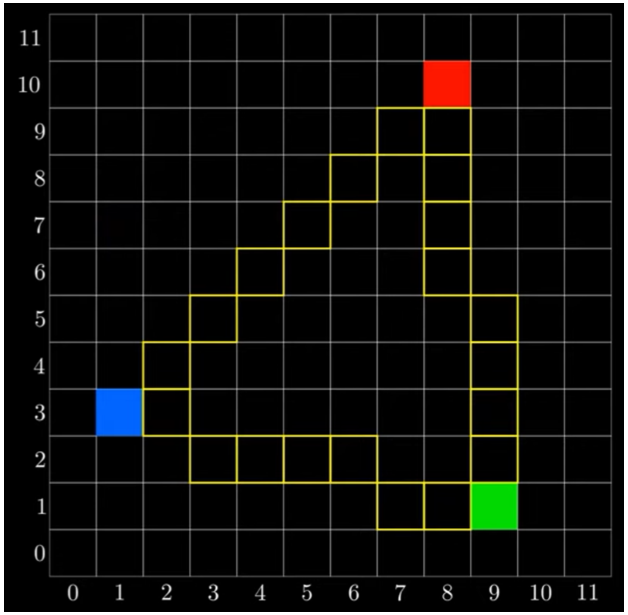
Revisit Rasterization

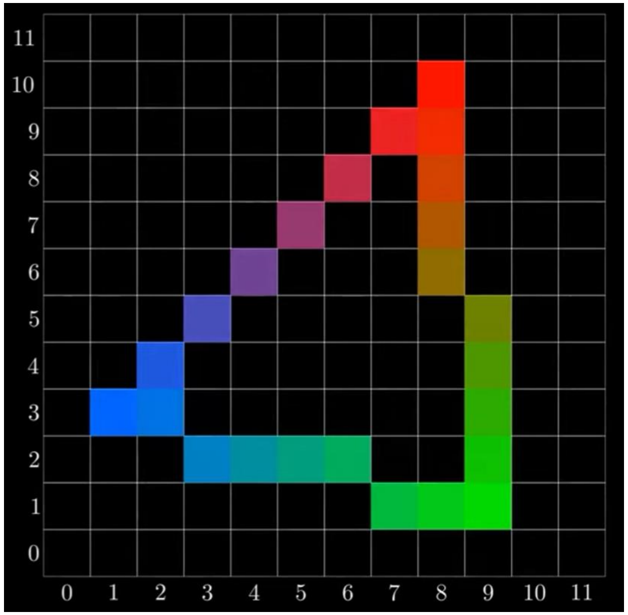
- Generate **fragments** for each triangle
- Interpolate vertex attributes at each fragment



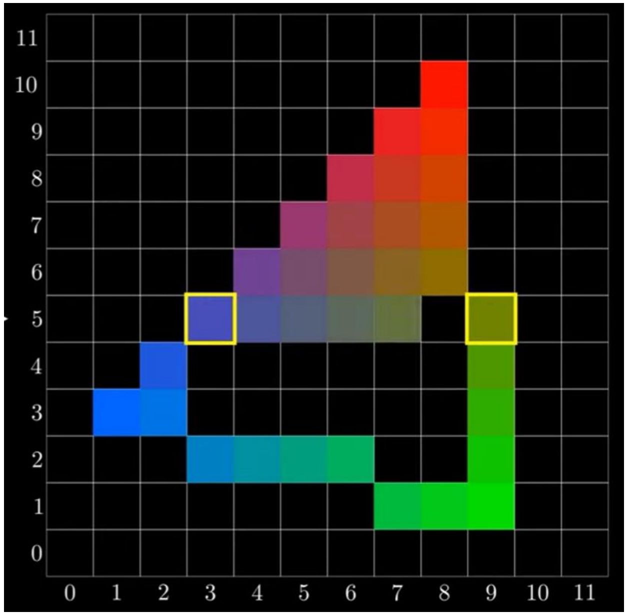
Vertex Attribute Interpolation

- **Interpolate vertex color**





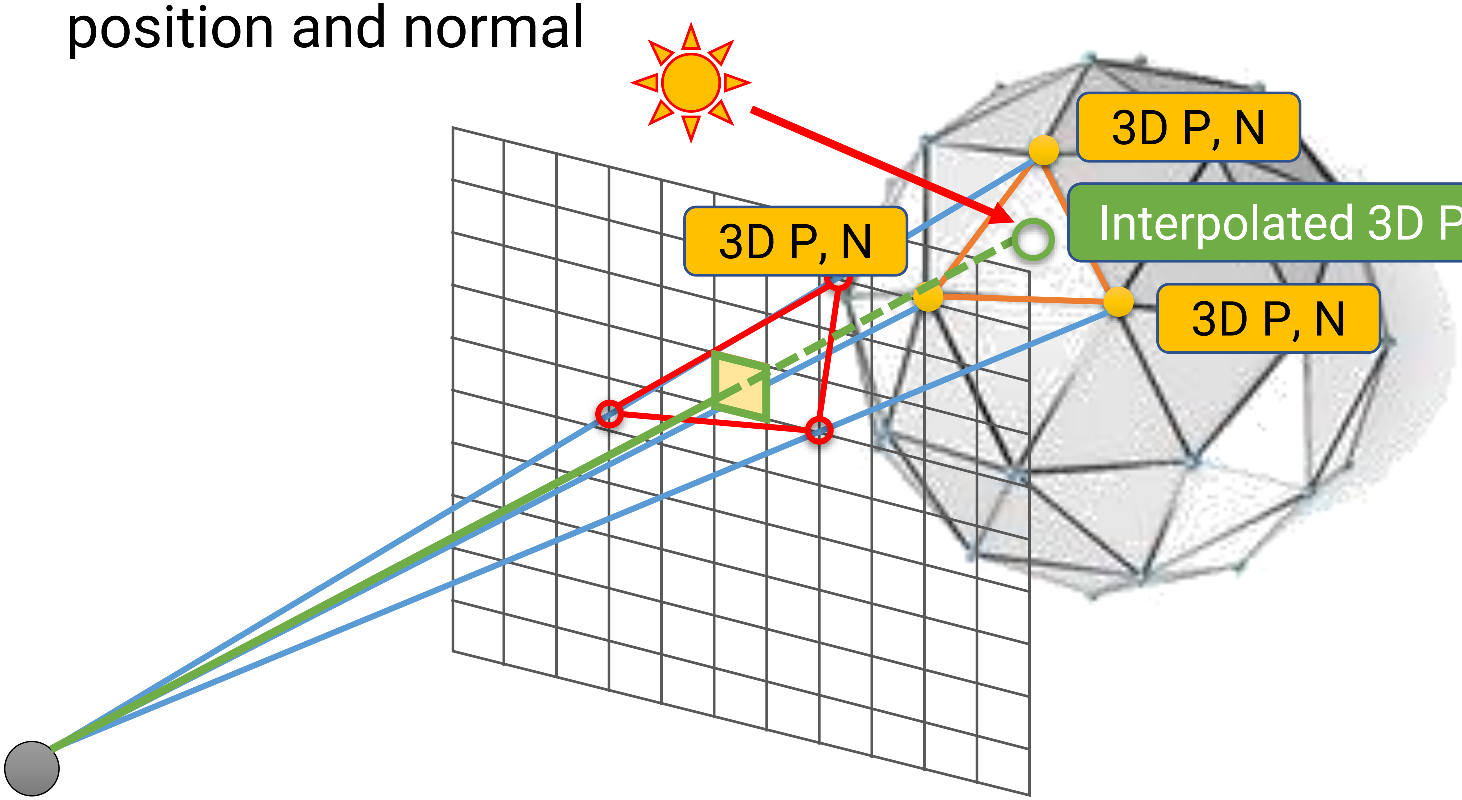
Attributes interpolation of edge pixels using vertices



Attributes interpolation of inner pixels using edge points

Vertex Attribute Interpolation (cont.)

- **Interpolate geometry attributes**
  - Compute lighting at each fragment (in the fragment shader) requires per-fragment geometry attributes such as 3D position and normal



Vertex Attribute Interpolation (cont.)

- Example: interpolate **world-space vertex position** and **world-space vertex normal**

Vertex Shader

```
#version 330 core

layout (location = 0) in vec3 Position;
layout (location = 1) in vec3 Normal;

// Transformation matrix.
uniform mat4 worldMatrix;
uniform mat4 normalMatrix;
uniform mat4 MVP;

// Data pass to fragment shader.
out vec3 iPosWorld;
out vec3 iNormalWorld;

void main()
{
    gl_Position = MVP * vec4(Position, 1.0);

    // Pass vertex attributes.
    vec4 positionTmp = worldMatrix * vec4(Position, 1.0);
    iPosWorld = positionTmp.xyz / positionTmp.w;

    iNormalWorld = (normalMatrix * vec4(Normal, 0.0)).xyz;
}
```

Tell OpenGL you want to interpolate these attributes

Fragment Shader

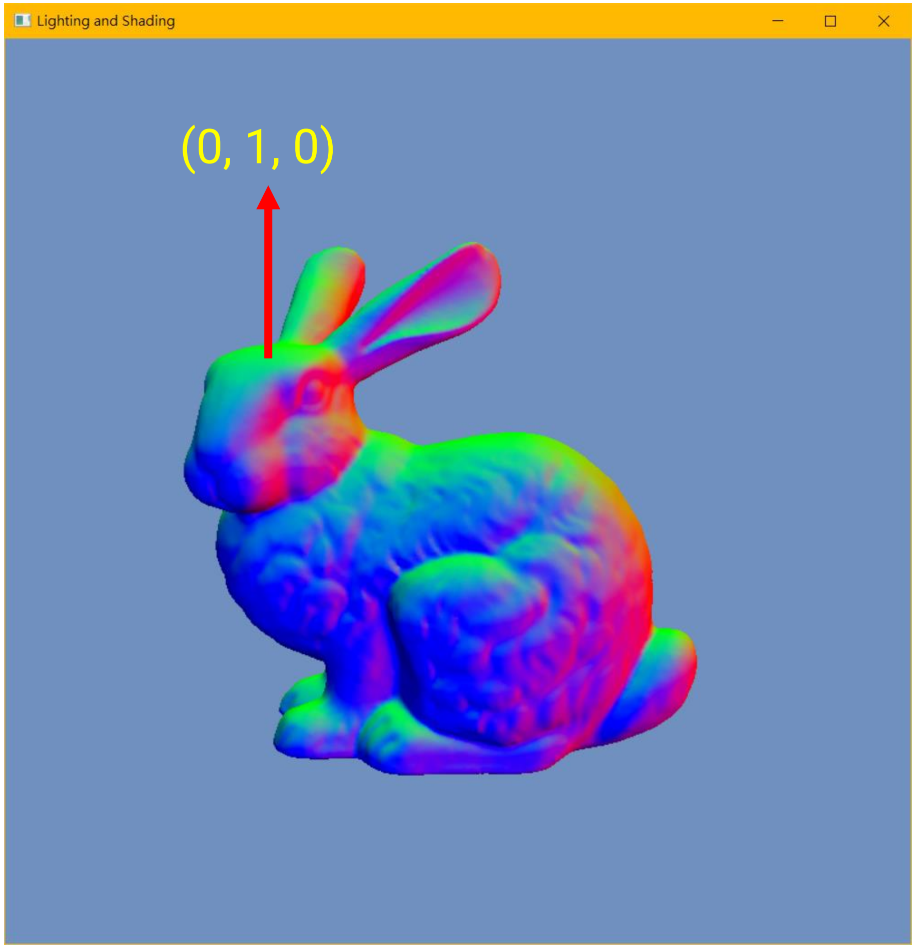
```
#version 330 core

// Data from vertex shader.
in vec3 iPosWorld;
in vec3 iNormalWorld;

out vec4 FragColor;


void main()
{
    vec3 N = normalize(iNormalWorld);
    FragColor = vec4(N, 1.0);
}
```

Ensure the interpolated normal has a unit length

world matrix for transforming normal (intro. in next lecture)

Vertex Attribute Interpolation (cont.)

visualize world-space position as color



visualize world-space normal as color

Vertex Attribute Interpolation (cont.)

- Remember the homogeneous coordinate for a 3D point *(x, y, z)* is *(x, y ,z, **1**)*
  - Why? To enable the combination of a **translation** matrix with other transformation matrices

$$\begin{bmatrix} x' \\ y' \\ z' \\ w \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & t_x \\ 0 & 1 & 0 & t_y \\ 0 & 0 & 1 & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

$$x' = x + t_x$$
$$y' = y + t_y$$
$$z' = z + t_z$$

- When transforming a vector, we represent a 3D direction *(dx, dy, dz)* by *(dx, dy, dz, **0**)* because we do not want a translation for "direction"
  - Otherwise, the direction (0.578, 0.578, 0.578) will become (3.578, 4.578, 5.578) after a translation of (3, 4, 5)

CPU v.s. GPU

- **CPU (what we do in HW1)**

prepare vertex data → apply vertex transform → create vertex buffer and upload vertex data to GPU → **GPU**

loop through all vertices

NDC

```
void ApplyTransformCPU(std::vector<glm::vec3>& vertexPositions, const glm::mat4x4& mvpMatrix)
{
    for (unsigned int i = 0 ; i < vertexPositions.size(); ++i) {
        glm::vec4 p = mvpMatrix * glm::vec4(vertexPositions[i], 1.0f);
        if (p.w != 0.0f) {
            float inv = 1.0f / p.w;
            vertexPositions[i].x = p.x * inv;
            vertexPositions[i].y = p.y * inv;
            vertexPositions[i].z = p.z * inv;
        }
    }
}
```

CPU v.s. GPU (cont.)

- **GPU (what we do with shader)**

prepare vertex data → **create vertex buffer and upload vertex data to GPU** → **GPU** → apply vertex transform

Object Space

parallel processing

```
locMVP = glGetUniformLocation(shaderProgId, "MVP");
glUniformMatrix4fv(locMVP, 1, GL_FALSE, glm::value_ptr(MVP));
```

CPU

1

Vertex Shader

GPU

2

```
#version 330 core
layout (location = 0) in vec3 Position;
uniform mat4 MVP;
void main() {
    gl_Position = MVP * vec4(Position, 1.0);
}
```

gl_Position: a built-in variable for the Clip Space coordinate

No loop because the vertex shader is executed for each vertex **in parallel** by nature

CPU v.s. GPU (cont.)

- In the **CPU** application, we
  - **Load the scene data (from files)**
    - Create vertex and index buffers
    - Provide material properties
    - Setup lights
  - **Load and create shaders**
  - **Setup the rendering state (via OpenGL APIs)**
    - Background color, polygon mode … etc.
  - **Set variable values to the GPU shaders**
    - Transformation matrices, material data, light data … etc.
  - **Call "Draw" functions to render objects (via OpenGL APIs)**
    - Vertex buffer format, primitive type, # of indices

set once unless they are changed at run time

CPU v.s. GPU (cont.)

- On the **GPU**, we
  - Execute the **Vertex Shader** for each vertex that belongs to a triangle
    - Vertex transformation
    - Vertex lighting (optional)
    - Prepare for interpolated vertex attributes (pass to fragment shader)

OpenGL performs **rasterization** by **hardware**

  - Execute the **Fragment Shader** for each fragment generated by the rasterization for each triangle
    - Fragment shading (lighting, texturing … etc.)


END OF PRESENTATION
ANY QUESTIONS?

Supp: Load and Create an OpenGL Shader

```
GLuint AddShader(GLuint& progId, const std::string& sourceText, GLenum shaderType)
{
    GLuint shaderObj = glCreateShader(shaderType);
    if (shaderObj == 0) {
        std::cerr << "[ERROR] Failed to create shader with type " << shaderType << std::endl;
        exit(0);
    }

    const GLchar* p[1];
    p[0] = sourceText.c_str();
    GLint lengths[1];
    lengths[0] = (GLint)(sourceText.length());
    glShaderSource(shaderObj, 1, p, lengths);
    glCompileShader(shaderObj);

    GLint success;
    glGetShaderiv(shaderObj, GL_COMPILE_STATUS, &success);
    if (!success) {
        GLchar infoLog[MAX_BUFFER_SIZE];
        glGetShaderInfoLog(shaderObj, MAX_BUFFER_SIZE, NULL, infoLog);
        std::cerr << "[ERROR] Failed to compile shader with type: " << shaderType << ". Info: " << infoLog << std::endl;
        exit(1);
    }

    glAttachShader(progId, shaderObj);

    return shaderObj;
}
```

Types:
GL_VERTEX_SHADER /
GL_FRAGMENT_SHADER
GL_GEOMETRY_SHADER
GL_TESS_CONTROL_SHADER,
GL_TESS_EVALUATION_SHADER,
GL_COMPUTE_SHADER