Image Processing and Computer Graphics

OpenGL

Matthias Teschner

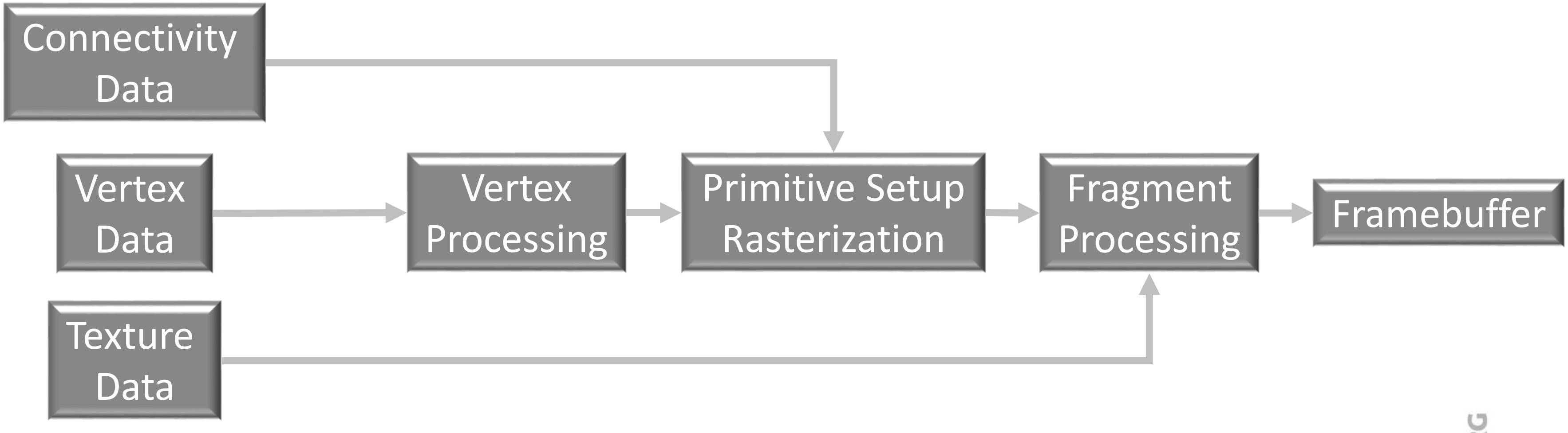
Computer Science Department
University of Freiburg

Introduction

- OpenGL is a graphics rendering API
  - display of geometric representations and attributes
  - independent from operating system and window system
- OpenGL realizes the interaction with GPUs
  - hardware-accelerated rendering

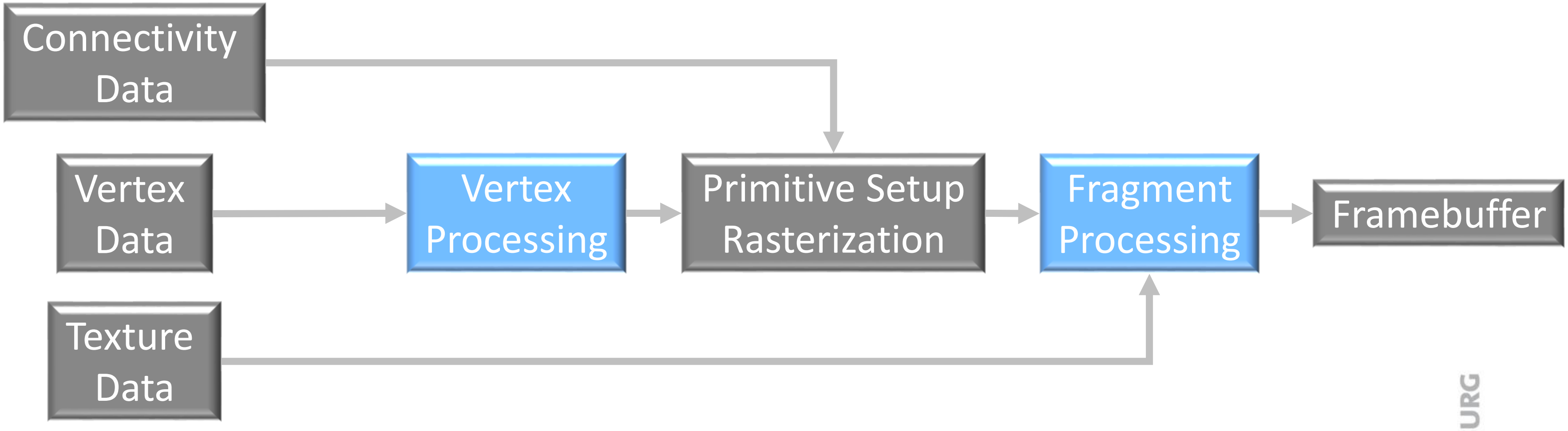
OpenGL 1.0 (1994)

- fixed-function pipeline
- focus on parallelized implementation
- promoted by quasi-standards of all components of a rasterization-based renderer



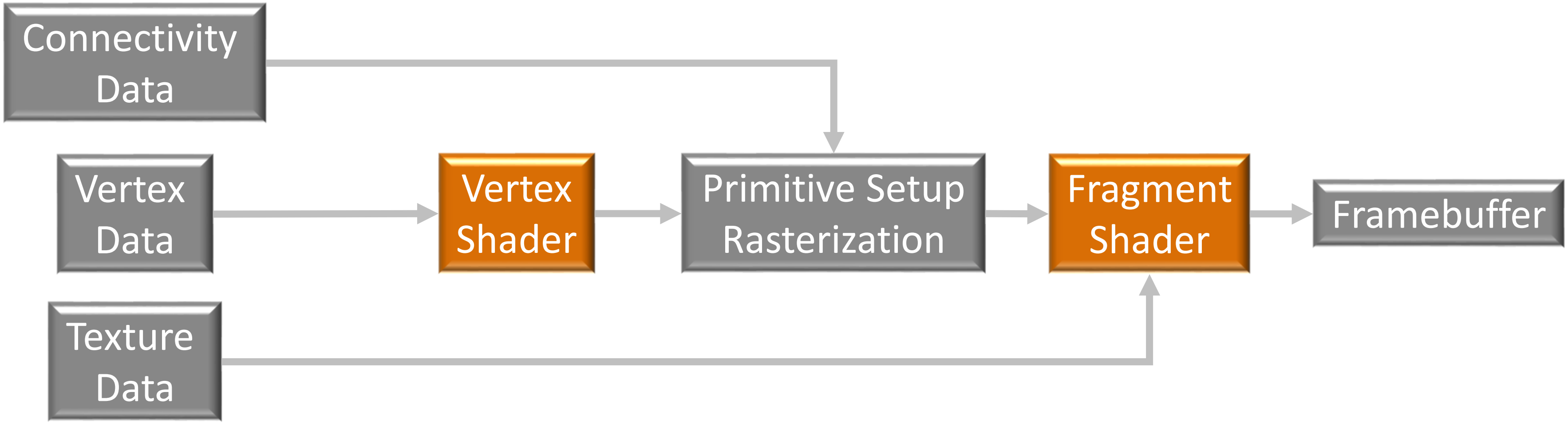
OpenGL 2.0

- fixed-function pipeline with programmable vertex and fragment processing
  - vertex and fragment processing could be replaced by user-defined functionality (shaders)
  - shaders are programs that work on each vertex / fragment



OpenGL 3.0

- programmable vertex and fragment processing
- no fixed-function pipeline
  - vertex and fragment shaders have to be implemented



OpenGL 3.0

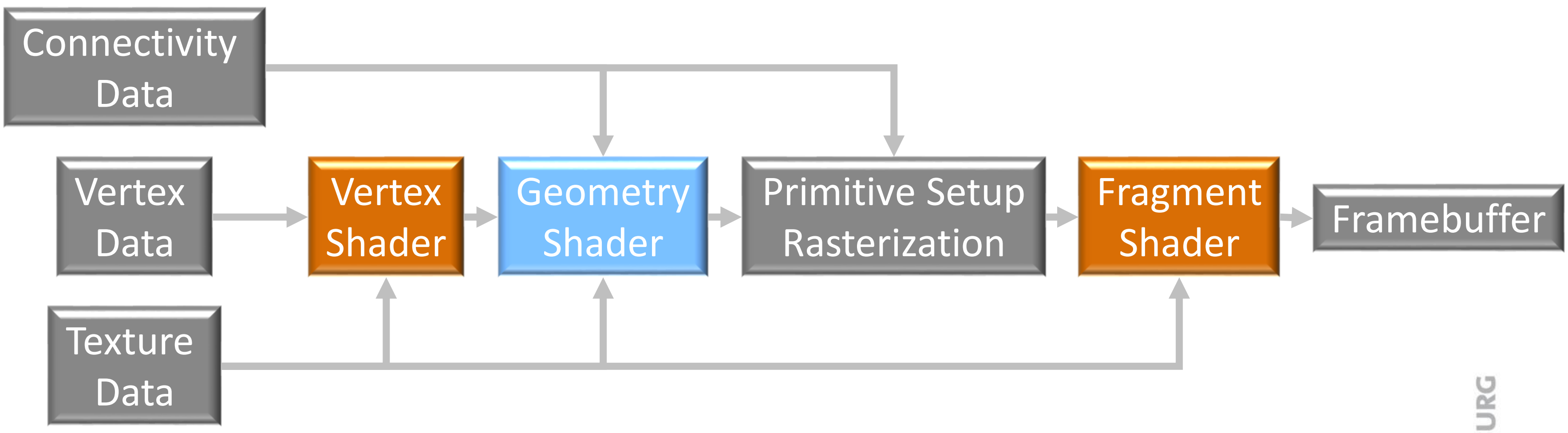
- focus on core functionality
  - removal of OpenGL features
  - deprecation model (full, forward compatible)
- improved handling of large data (buffer objects)
- improved flexibility
  - implementation of non-standard effects not restricted to “misusing” pipeline functionality
- programming
  - not just setting parameters of standard functionality
  - concepts of vertex and fragment processing are not “nice to know”, but required knowledge
    - e.g., transforms, projections

OpenGL 3.0

- deprecated features, e.g., `glRotate`
  - generates a transformation matrix
  - multiplies the matrix with the top element of the current stack
- typically replaced by OpenGL Mathematics glm
  - `glm::Rotate`
  - generates a transformation matrix

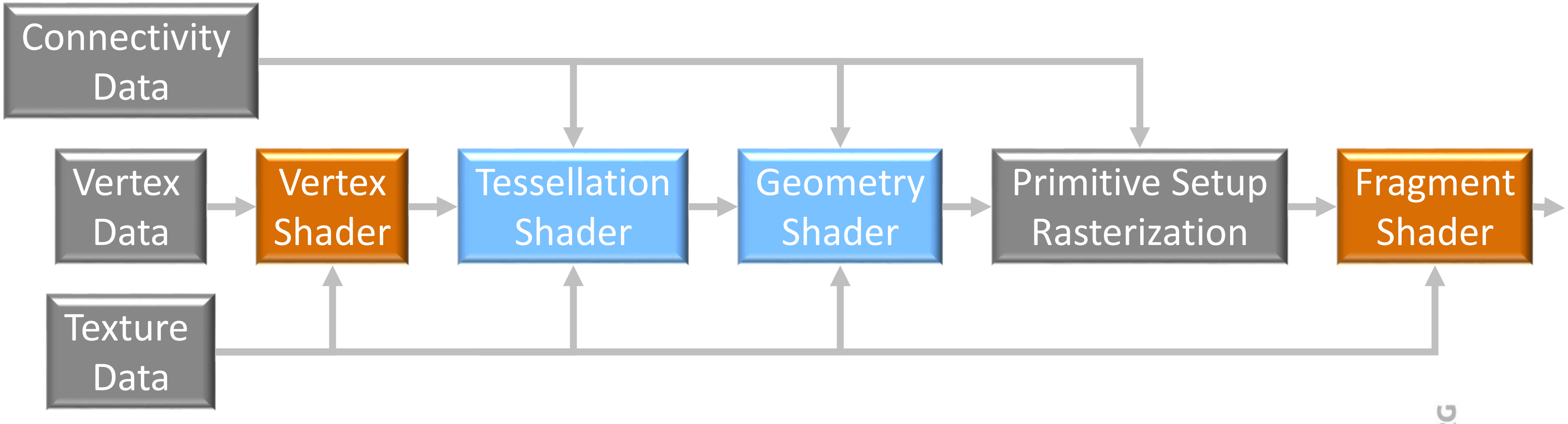
OpenGL 3.2

- geometry shader
  - optional
  - modify geometric primitives
  - generation of geometry no longer restricted to CPU
- flexible use of texture data



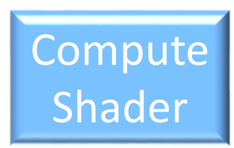
OpenGL 4.1

- tessellation shader
  - optional
  - tessellate patches
  - flexible generation of large and detailed geometries



OpenGL 4.3

- compute shader
    - optional
    - perform arbitrary computations
    - are not part of the rendering pipeline



GPU Data Flow

- data transfer to GPU
  - vertices with attributes and connectivity
- vertex shader
  - a program that is executed for each vertex
  - input and output is a vertex
- rasterizer
- fragment shader
  - a program that is executed for each fragment
  - input and output is a fragment
- framebuffer update

Data Transfer

- Vertex Buffer Object VBO
  - used to copy memory from CPU to GPU
  - contains arbitrary data, typically vertex attributes

```
GLuint gVBO = 0;
glGenBuffers(1, &gVBO);
glBindBuffer(GL_ARRAY_BUFFER, gVBO);

GLfloat vertexData[] = {
    //  X     Y     Z
     0.0f, 0.8f, 0.0f,
    -0.8f,-0.8f, 0.0f,
     0.8f,-0.8f, 0.0f};

glBufferData(GL_ARRAY_BUFFER, sizeof(vertexData),
vertexData, GL_STATIC_DRAW);
```

[Tom Dalling]

Data Transfer

- Vertex Array Object VAO
  - link between VBO and shader programs
  - specifies how to interpret VBO data
  - specifies the mapping to input variables of shaders

```
GLuint gVAO = 0;
glGenVertexArrays(1, &gVAO);
glBindVertexArray(gVAO);

// connect the xyz to the "vert" attribute
// of the vertex shader

glEnableVertexAttribArray(gProgram->attrib("vert"));
glVertexAttribPointer(gProgram->attrib("vert"), 3,
GL_FLOAT, GL_FALSE, 0, NULL);
```

[Tom Dalling]

Shader

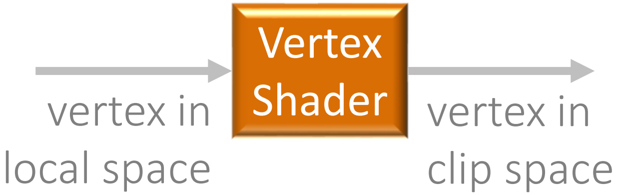
- program
  - written in OpenGL Shading Language GLSL
  - runs on the GPU
  - vertex and fragment shader are mandatory

	Main Program	Shader Program
Language	C++	GLSL
Main function	int main(int, char**);	void main();
Runs on	CPU	GPU
Gets compiled?	yes	yes
Gets linked?	yes	yes

[Tom Dalling]

Vertex Shader

- works on vertices
  - input and output are vertices
- minimum functionality
  - transformation from local to clip space
    (after clipping, rasterizer only works on vertices
    in the canonical view volume [-1..1, -1..1, -1..1])



Simple Vertex Shader Example

- ```
  #version 150

  in vec3 vert;

  void main() {
      // does not alter the vertices at all
      gl_Position = vec4(vert, 1);
  }
  ```
- model, view and projection transform are implicitly set to identity matrices

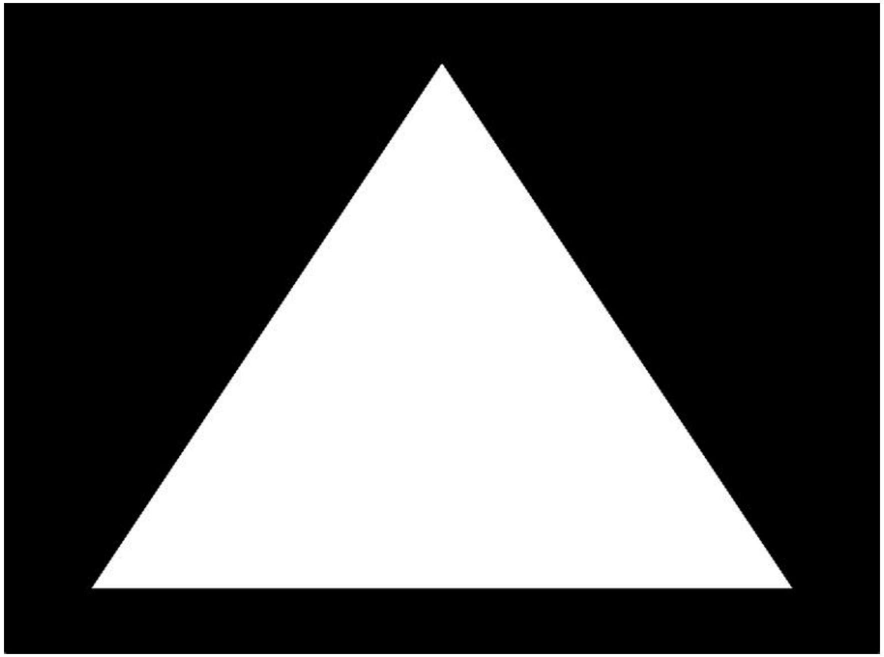
$$\begin{pmatrix} x_{\text{clip}} \\ y_{\text{clip}} \\ z_{\text{clip}} \\ 1 \end{pmatrix} = \mathbf{I} \begin{pmatrix} x_{\text{local}} \\ y_{\text{local}} \\ z_{\text{local}} \\ 1 \end{pmatrix}$$

gl_Position is a built-in output variable of a vertex shader. It is a 4D vector (x,y,z,1) representing the clip-space position of a vertex

[Tom Dalling]
  ```

Simple Vertex Shader Example

- ```
  GLfloat vertexData[] = {
      //  X     Y     Z
       0.0f, 0.8f, 0.0f,
      -0.8f,-0.8f, 0.0f,
       0.8f,-0.8f, 0.0f};
  ```
- results in a visible triangle for the example shader as all input/output vertex positions are within the canonical view volume



[Tom Dalling]
  ```

Typical Vertex Shader Example

- ```
  uniform mat4 projection;
  uniform mat4 camera;
  uniform mat4 model;
  in vec3 vert;

  void main() {
  gl_Position = projection * camera * model * vec4(vert, 1);
  }
  ```
  set in the main program (projection, camera, model); read from VAO (vert)

  projection: internal camera parameters; camera: camera placement; model: object placement

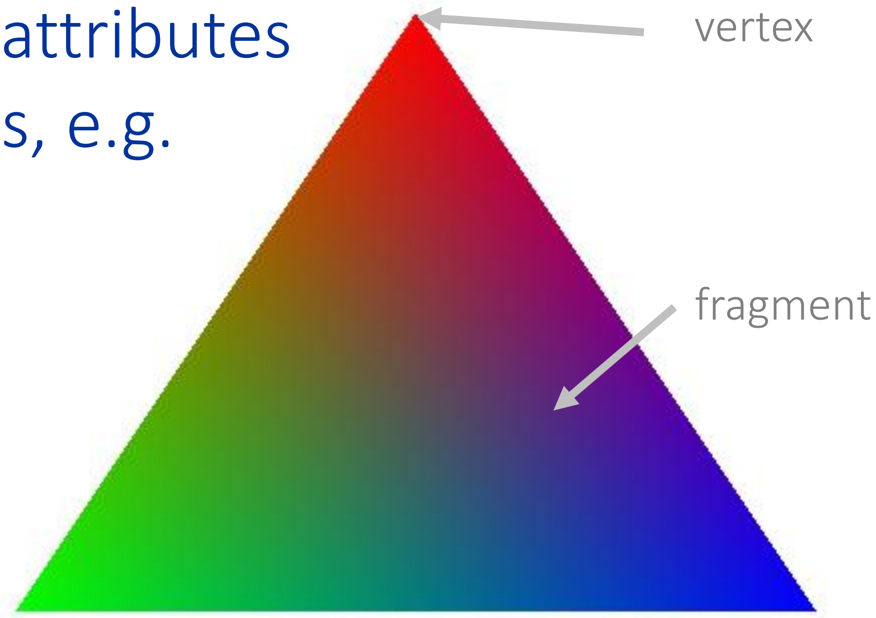
- ```
  glm::mat4 projection = glm::perspective(…);
  gProgram->setUniform("projection", projection);

  glm::mat4 camera = glm::lookAt(glm::vec3(3,3,3),
  glm::vec3(0,0,0), glm::vec3(0,1,0));
  gProgram->setUniform("camera", camera);
  ```

[Tom Dalling]

Vertex Shader

- can compute/set a color at vertices
  - e.g. red, green, blue
- rasterizer can interpolate attributes from vertices to fragments, e.g.



result for an empty fragment shader employing the interpolation functionality of the rasterizer

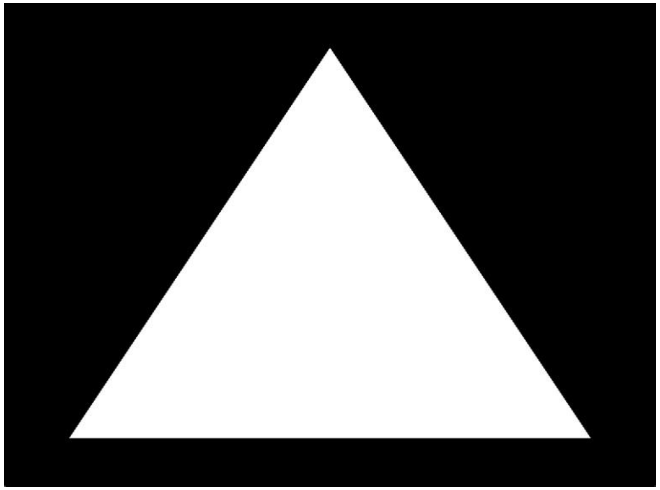
Simple Fragment Shader Example

- ```
  #version 150

  out vec4 finalColor;

  void main() {
      // set every drawn pixel to white
      finalColor = vec4(1.0, 1.0, 1.0, 1.0);
  }
  ```

- if not set-up otherwise, the output is written to the color buffer



[Tom Dalling]
  ```

Typical Fragment Shader Example

```
#version 150

in …
out vec4 finalColor;

void main() {
   //calculate the vector from pixel to light source
   vec3 surfaceToLight = light.position - fragPosition;

   //calculate the cosine of the angle of incidence
   float brightness = dot(normal, surfaceToLight) /
   (length(surfaceToLight) * length(normal));
   brightness = clamp(brightness, 0, 1);

   //calculate final color of the pixel, based on:
   finalColor = vec4(brightness * light.intensities *
   surfaceColor.rgb, surfaceColor.a);
}
```

incomplete shader
for Phong illumination

[Tom Dalling]

GPU Data Flow

- data transfer to GPU
  - VBOs store data, VAOs interpret the data
  - vertices with attributes and connectivity
- vertex shader
  - input is a vertex in local space
  - output is a vertex in clip space
- rasterizer
  - generates fragments
  - interpolates attributes from vertices to fragments
- fragment shader
  - output is a fragment color

OpenGL Setup

- implementations are typically accomplished by additional libraries
  - OpenGL Extension Wrangler GLEW
    - access to OpenGL x.x API functions
  - GLFW
    - windowing, mouse and keyboard handling
  - OpenGL Mathematics GLM
    - processes vectors and matrices
- implementation
  - fragment shader
  - vertex shader