U.PORTO
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Interactive Graphics Systems
M.EIC

Shaders

Concepts and Practice

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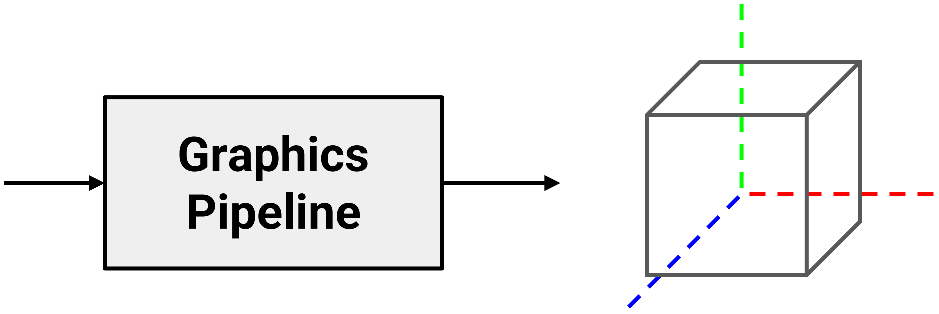
From object definition to rendering

Objects are defined by **vertices**, **indices**, **normals** and **texture coordinates**

Let's see how this data is used to render objects in the scene

```
…
initBuffers(){
  this.vertices = [...]
  this.indices = [...]
  this.normals = [...]
  this.texCoords = [...]
}
```

Object definition using ***CGFobject*** class



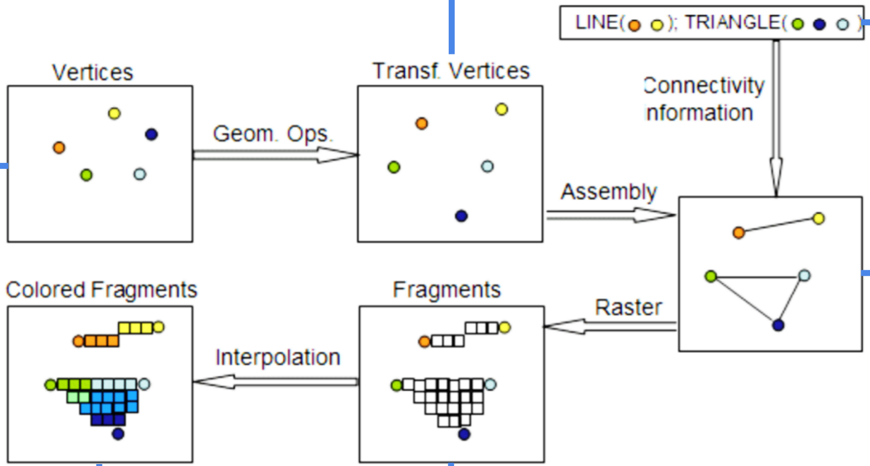
Rendered scene in screen

Graphics Pipeline - Visualization

Vertices positioned in screen space

Type of primitive defined in CGFobject

Vertices defined for CGFobject



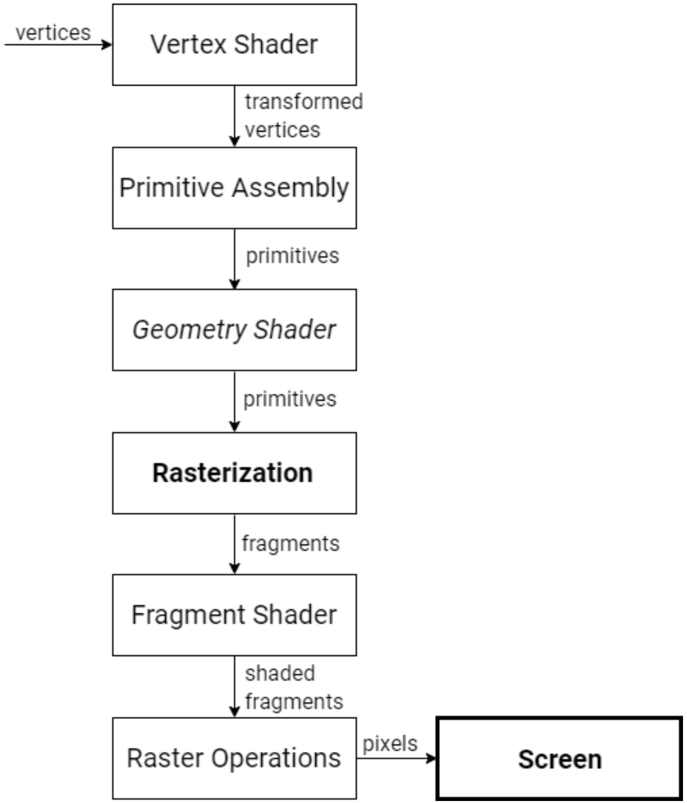
Connecting vertices according to indices from CGFobject

Remaining fragments are defined using interpolation

Fragments contains data for each pixel of the primitive's vertices

Graphics Pipeline

- Inputs
- **Vertex shading**
- Primitive assembly
- Geometry shading
- Projection and rasterization
- **Fragment shading**
- Raster operations
- Output to screen



Shaders

Small programs that receive and manipulate data on the 3D scene:

- **Vertex shaders** - Manipulate and define properties **for each vertex**
- **Fragment shaders** - Manipulate and define properties **for each fragment**

Custom data may be passed to the shaders from the application

Data may be passed **from vertex to fragment shader** (not inversely)

Shaders are commonly **simple programs**; however, they are executed in **parallel** on a **large quantity of data**

Shaders in WebGL/WebCGF

In **WebGL**, shaders may be loaded as strings and compiled in real time

In the **WebCGF** library, the **default shaders** that are used allow for:

- Application of **Gouraud** illumination model
- Multi-light sources (8)
- Application of materials and textures

These can be replaced by **custom shaders** and applied to some or all scene objects

Custom shaders in WebGL/WebCGF

To apply shaders to a scene using **WebCGF**, these are the general steps:

1. **Create** the shader files
2. Load the created files to a ***CGFshader*** class object
3. Set the new *CGFshader* object as the **scene's active shader**
4. **Pass values** from application to shaders (optional)

1 Creating Shaders - Structure

Shader may be defined in `.vert` or `.frag` files, for vertex or fragment shaders
A shader program commonly contains:

- List of **input**/**output** and **uniform** variables
- A ***main()* function**, where input data is processed and output is returned

The *main()* function runs for **each vertex** or for **each fragment**

Note: In our classes we will use *.vert* and *.frag* files, but normally *.glsl* files are used for both shaders.

1 Creating Shaders - Vertex Shader

A vertex shader receives **input** relative to:

- each **vertex** (position, normal, texture coordinate)
- lights, materials, camera (for illumination model and other functionalities)
- **custom data** provided from the application

A vertex shader creates as **output**:

- the **calculated position** for each vertex
- data to be passed to the **fragment shader**

1 Creating Shaders - Vertex Shader Example

```
attribute vec3 aVertexPosition;
attribute vec3 aVertexNormal;
attribute vec2 aTextureCoord;
uniform mat4 uMVMatrix;
uniform mat4 uPMatrix;
uniform mat4 uNMatrix;
...
void main() {
...
    gl_Position = uPMatrix * uMVMatrix * vec4(aVertexPosition, 1.0);
}
```

Input variables

Main function, processes each vertex

Output vertex position

1 Creating Shaders - Variables

```
attribute vec3 aVertexPosition
```

Qualifier

Data Type Qualifiers

- `uniform` - read-only global input, from WebGL or application
- `attribute` - read-only per-vertex input to vertex shader
- `varying` - writable output (vertex shader)
  - read-only input (fragment shader)
- `const` - read-only compile-time constant

1 Creating Shaders - Variables

```
attribute vec3 aVertexPosition
```

$\underbrace{\texttt{vec3}}_{\text{Type}}$

Data Type

- **Scalars** - bool, int, float, …
- **Vectors** - vec2, vec3, vec4, …
- **Matrices** - mat2, mat3, mat4, …
- **Textures** sampler1D, sampler2D, sampler3D, …
- And others

1 Creating Shaders - Variables in Vertex Shader

```
attribute vec3 aVertexPosition;
attribute vec3 aVertexNormal;
attribute vec2 aTextureCoord;
uniform mat4 uMVMatrix;
uniform mat4 uPMatrix;
uniform mat4 uNMatrix;
...
void main() {
...
    gl_Position = uPMatrix * uMVMatrix * vec4(aVertexPosition, 1.0);
}
```

position of **each vertex** (attribute) as **3D vector** (vec3)

global (uniform) model-view **4x4 matrix** (mat4)

1 Creating Shaders - Vertex Shader main() function

```
void main() {
...
    gl_Position = uPMatrix * uMVMatrix * vec4(aVertexPosition, 1.0);
}
```

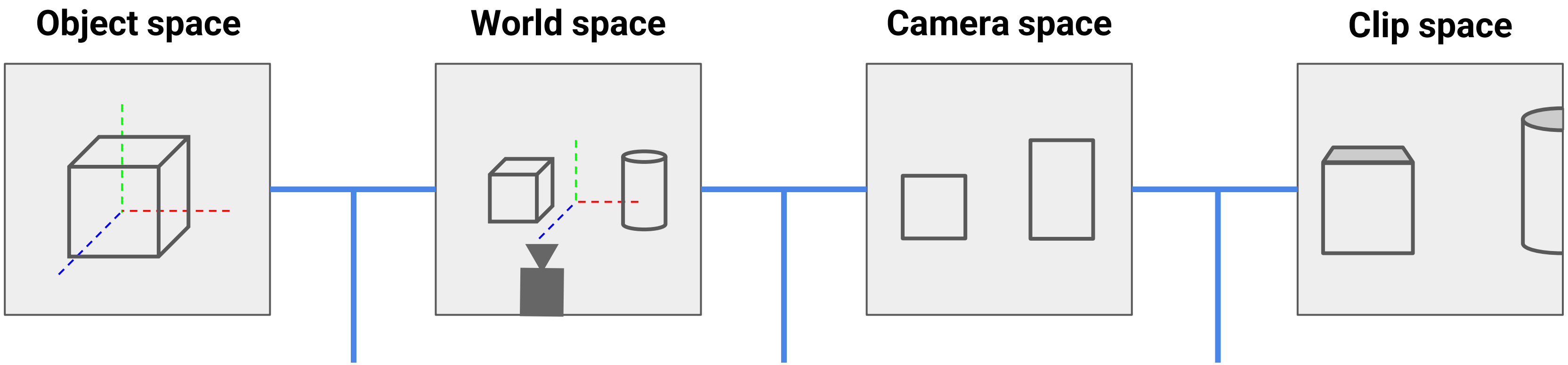
Output vertex position

Projection Matrix
Applies transformations related to camera frustum

Model-View Matrix
Represents transformations applied to scene, and camera position

Input 3D position vector for vertex (as defined in application)

Model-View-Projection Matrix



Model Matrix

Matrix representing every **geometric transformation** applied in the scene

View Matrix

Matrix that transforms objects according to the **active camera.**

It is the inverse of the camera's transformation matrix.

Projection Matrix

Matrix that defines a viewing box (**frustum**) - visible area in the screen.

Coordinates outside the frustum are **clipped**.

1 Creating Shaders - Fragment Shader

A fragment shader receives as **input**:

- Data from previous operations in the graphics pipeline (e.g., vertex shader)
- Custom data from application

A fragment shader creates as **output**:

- the **color for the current fragment**

1 Creating Shaders - Fragment Shader Example

```
struct lightProperties {
    ...
};
```

Local struct for light properties (position, ambient, diffuse,...)

```
#define N_LIGHTS 8
uniform lightProperties uLight[N_LIGHTS];
```

Input array of lightProperties (length 8)

```
void main() {
```

Main function, processes each fragment

```
                  gl_FragColor = uLight[0].diffuse;
}
```

Output fragment color

2 Loading Shaders using WebCGF library

The **WebCGF** library has a class for shaders - **CGFshader**

```
new CGFshader(gl, urlVertexShader, urlFragmentShader)
```

The scene has an **active shader** (initially default shader provided in library)

```
CGFscene.activeShader
```

Created shaders may be set as the scene's active shader

```
CGFscene.setActiveShader(CGFshader)
```

To set back to default, provide
`CGFscene.defaultShader`

3 Applying Shaders - Example

```
CGFscene.init(){
        …
        this.shaderA = new CGFshader(...)
}
…
CGFscene.display(){
        …
        this.setActiveShader(this.shaderA);
        …
        this.object.display();
        …
        this.setActiveShader(this.defaultShader);
}
```

Initializing shaders and other objects

Scene setup (cameras, lights, matrices)

Drawn elements affected by the custom shader

4 Passing Data from Application to Shaders

Data may be passed from the application to the `CGFshader` object

```
CGFshader.setUniformsValues(dictionary)
```

Key-value pair collection, equivalent to a JS object

This data is accessible in the shaders as uniform variables

```
uniform type variableKey;
```

The shaders may use this data to **transform the output**

4 Passing Scalar Data to Shader - Example

CGFscene

```
this.shaderA = new CGFshader(...)
this.shaderA.setUniformsValues(
         { scale: 2.0, key:value, ...});
```

Initializing shaders and passing uniforms' values

Vertex shader

```
uniform float scale;
uniform valueType key;
```

Initializing the uniforms

```
...
void main() {
    gl_Position = uPMatrix * uMVMatrix * vec4(aVertexPosition*scale, 1.0);
}
```

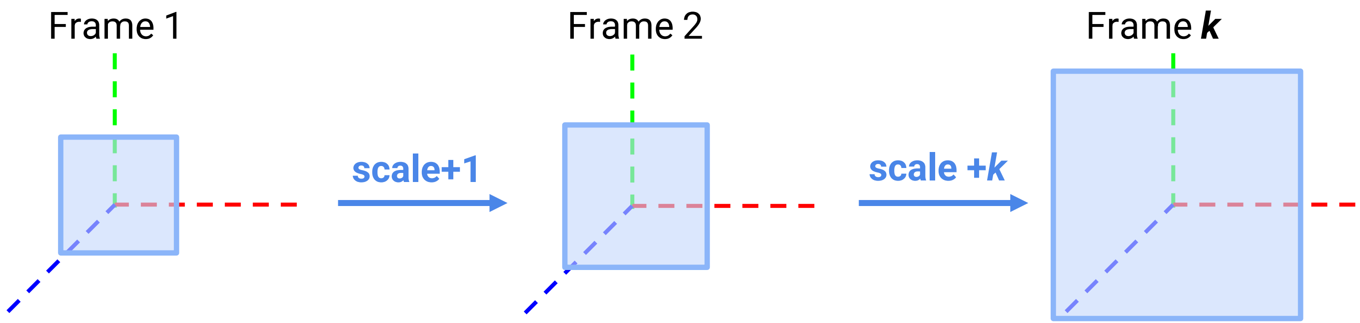
Applying uniform data to transform the output

4 Passing Scalar Data to Shader - Example

What happens if the value provided to the shader is altered periodically?

```
CGFscene.display(){
  this.scale++;
  this.shaderA.setUniformsValues({scale: this.scale});
}
```

Sequence of frames with variation in object - Animation



4 Passing Texture to Shader - Example

CGFscene

```
display(){
  …
  this.setActiveShader(this.shaderA);
  this.texture0.bind();
  this.object.display();
}
```

Bind texture0 to WebGL context

Vertex/Fragment shader

```
uniform sampler2D uSampler;
…
```

Where is `uSampler` defined?

And what if we want more than one texture?

4 Passing Multiple Textures to Shader

WebGL has a global array of references to textures – **texture units**

```
CGFtexture.bind(unit)
```

The ***unit*** parameter is the **texture unit** to which the texture is bound

By default, `CGFscene` passes the texture at `unit = 0` as `uSampler`

pseudo-code

```
activeShader.setUniformsValues({uSampler: 0});
```

4 Passing Multiple Textures - Example

```
CGFscene.init(){
  this.shaderA = new CGFshader(...)
  this.texture1 = new CGFtexture(...);
  this.texture2 = new CGFtexture(...);
  this.shaderA.setUniformsValues({texture2: 1});
}
CGFscene.display(){
  this.setActiveShader(this.shaderA);
  this.texture1.bind();
  this.texture2.bind(1);
  this.object.display();
  …
}
```

Passing as uniforms values the texture unit for the 2nd texture

Binding textures to units 0 and 1

4 Passing Multiple Textures - Example

```
varying vec2 vTextureCoord;

uniform sampler2D uSampler;

uniform sampler2D texture2;

void main() {
  vec4 color = texture2D(uSampler, vTextureCoord);
  …

  gl_FragColor = …
}
```

texture coordinates from vertex shader

Texture passed by CGFscene

Texture passed by our code

Shader function that retrieves a texel from the sampler at specified coordinates

Shaders - Practical examples

Using the example code for shaders (available on Moodle), we are going to explore 2 cases:

- **Color mixing** – Obtain new colors from mixing two colors
- **Sinusoidal functions** – Explore usefulness of these functions

These serve as basis for the shaders of the **Practical Work 2**

Color Mixing

Two or more colors can be added in different quantities to create a new color – **color mixing**

A basic example of mixing two colors in equal parts would be:

```
void main() {
  vec4 color1 = vec4(1.0, 0.0, 0.0, 1.0);
  vec4 color2 = vec4(0.0, 1.0, 0.0, 1.0);
  gl_FragColor = color1 * 0.5 + color2 * 0.5;
}
```

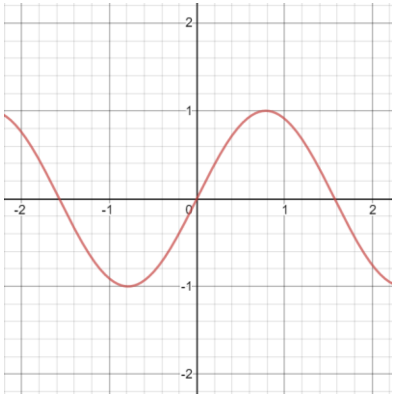
GLSL provides a function `mix(value1, value2, t)` which performs a linear interpolation between the two values, with ***t*** = [0.0 – 1.0] as weight.

Sinusoidal Functions

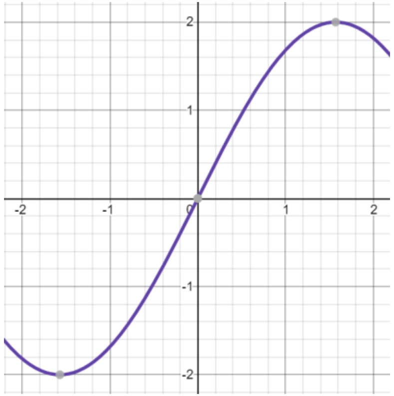
A sinusoidal function may be represented as:

$$y(t) = \boldsymbol{A} * \sin(\boldsymbol{\omega} * t + \boldsymbol{\varphi})$$

- Multiplying the *sin()* function by a constant (***A***) changes the deviation from zero (**amplitude**)
- Multiplying function variable (***t***) by a constant ($\boldsymbol{\omega}$) changes the number of oscillations (**angular frequency**)
- Adding a constant in the *sin()* function ($\boldsymbol{\varphi}$) shifts the position of the wave horizontally (**phase**)



f(x) = sin(2*x)



f(x) = 2*sin(x)

Graphing calculator online at: https://www.desmos.com/calculator

Sinusoidal Functions in Shaders

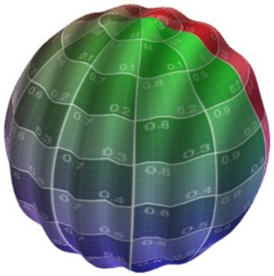
Sinusoidal functions can have many interesting uses within shaders

Vertex shader examples:

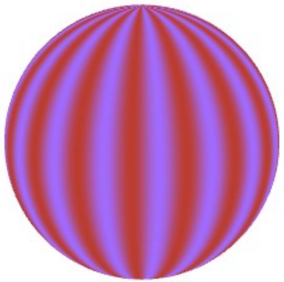
- Geometric transformations with smooth animation
- Deformation of surfaces, e.g., ripple (wavy) effect

Fragment shader examples:

- Color gradients/patterns
- Animated mapping of textures



Ripple effect along surface



Repeating linear gradient

Documentation and guides

Introduction to shaders using GLSL (presentation at Moodle)

GLSL Reference Card (available on Moodle)

WebCGF documentation for CGFshader

https://paginas.fe.up.pt/~ruirodrig/pub/sw/webcgf/docs/class/lib/CGF/CGFshader.js~CGFshader.html

Texture2D function

https://thebookofshaders.com/glossary/?search=texture2D

WebGL Shaders Tutorial

https://webglfundamentals.org/webgl/lessons/webgl-shaders-and-glsl.html

Graphing calculator

https://www.desmos.com/calculator