Introduction to Computer Graphics (CS360A)

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Graphics API

- Goal of Graphics APIs are to perform graphics rendering and enable developers to use Graphics Processing Units (GPU)
- There are several popular graphics APIs
  - OpenGL
  - DirectX (Microsoft)
  - Vulkan
  - Metal (Apple)
- Web-based graphics APIs
  - WebGL (This course)
  - WebGPU (Relatively new, under development)

Graphics API

- **OpenGL:**
  - Cross-language, cross-platform application programming interface (API)
  - Used for rendering 2D and 3D graphics in a graphics processing unit (GPU), to achieve hardware-acceleration

- **OpenGL ES:**
  - OpenGL for Embedded Systems (OpenGL ES or GLES)
  - A subset of the OpenGL API
  - Used in mobile devices

Wikipedia.org

Graphics API

- **Direct3D (DirectX):**
  - A graphics API for Microsoft Windows
  - Often used to render three-dimensional graphics in applications where performance is important, such as games
  - Direct3D uses hardware acceleration if it is available on the graphics card
  - DirectXBox → Xbox (game console)

Wikipedia.org

Graphics API

- **Vulkan:**
  - A low-overhead, cross-platform API, open standard for 3D graphics and computing
  - Targets high-performance real-time 3D-graphics applications
  - Intended to offer higher performance and more efficient CPU and GPU usage compared to the OpenGL and DirectX

Wikipedia.org

Graphics API

- **Metal:**
  - Metal powers hardware-accelerated graphics on Apple platforms
  - Provides a low-overhead API, rich shading language, tight integration between graphics and compute
  - Offers an unparalleled suite of GPU profiling and debugging tools

https://developer.apple.com/metal/

Web-based Graphics API

- **WebGL:**
  - A JavaScript API for rendering interactive 2D and 3D graphics within any compatible web browser
  - Fully integrated with other web standards, allowing GPU-accelerated usage of physics and image processing and effects as part of the web page canvas.
  - WebGL 1.0 is based on OpenGL ES 2.0
  - WebGL 2.0 is based on OpenGL ES 3.0
  - https://www.khronos.org/webgl/

- **WebGPU:**
  - A potential web standard and JavaScript API for accelerated graphics and compute, aiming to provide "modern 3D graphics and computation capabilities"

Wikipedia.org

WebGL v2.0

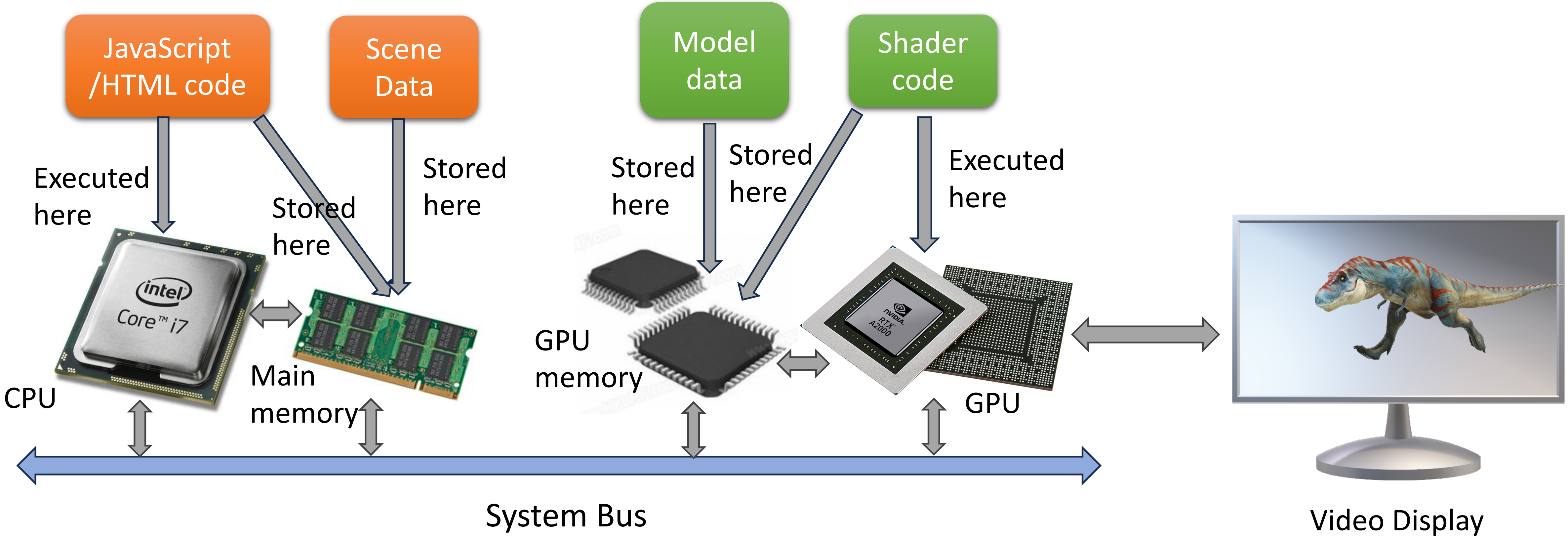
WebGL: Web Graphics Library

- We are going to use WebGL in this course
  - Works seamlessly in modern browsers
  - Easy code building
  - No compilation issues
  - Cross platform development environment

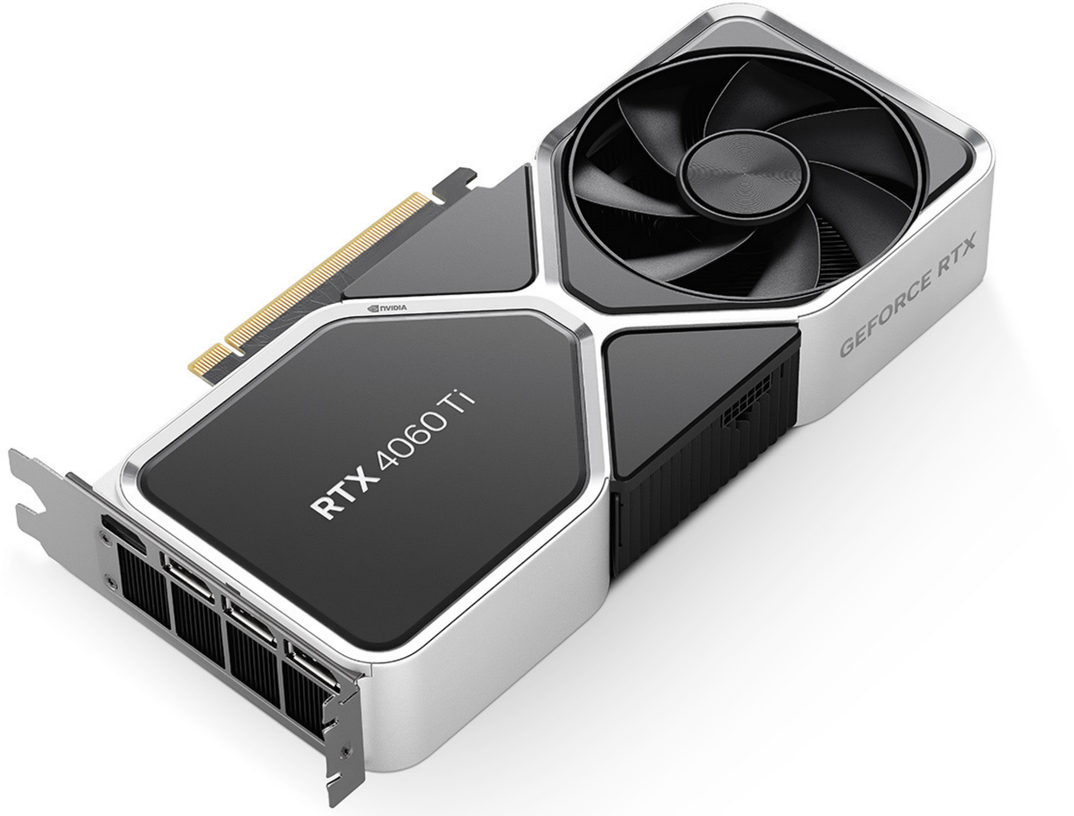
A Typical WebGL Program

- A HTML (Hypertext Markup Language) description of the web page
- A CSS (Cascading Style Sheet) that describes how each element of the HTML description is formatted (Optional)
- A HTML canvas element in the web page that provides a rectangular area in which 3D computer graphics can be rendered
- Graphical data that defines the 3D objects to be rendered
- JavaScript programs that load your graphical data, configure your graphical data, render your graphical data, and code that responds to user events
- OpenGL Shader programs (GLSL) that perform critical parts of the graphical rendering

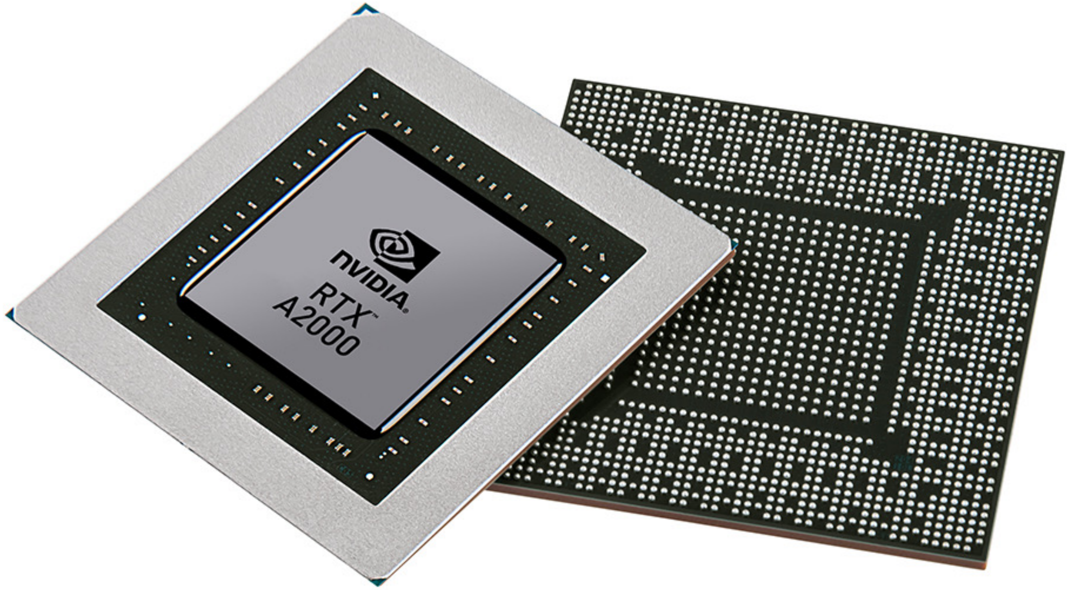
A Typical WebGL Program



GPU Pipeline

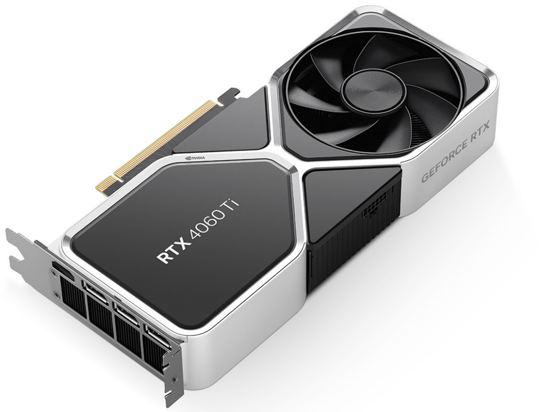


Graphics/Video Card



Graphics Processing Unit (GPU) Chip

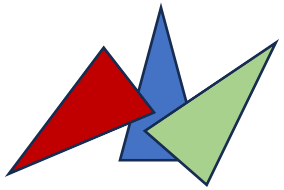
GPU Pipeline



- One of the primary tasks of a GPU is to produce raster images (graphics)
  - Videos, games, visualization, animation, etc.
- GPUs can be used for general purpose computing, known as **GPGPU**
  - Consider taking Parallel Programming (CS433) and Parallel Computing (CS633)
- In this course, we focus on Graphics APIs (WebGL) to perform real-time 2D/3D rendering using GPUs

GPU Pipeline

CPU memory



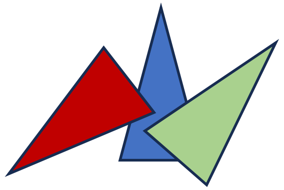
Source: Google

GPU Pipeline

GPU memory

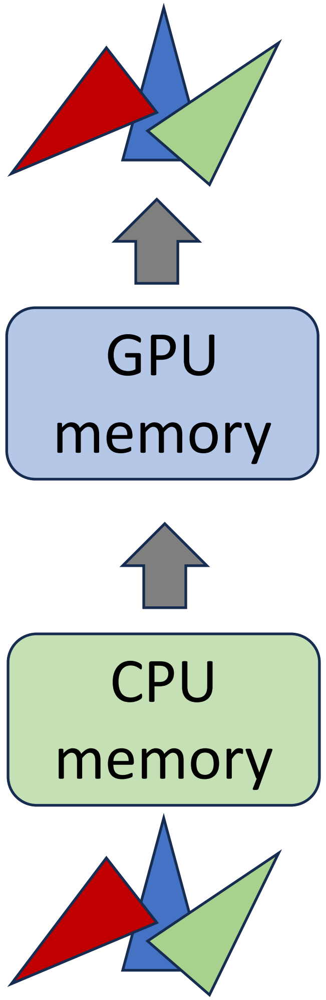
↑

CPU memory



Source: Google

GPU Pipeline



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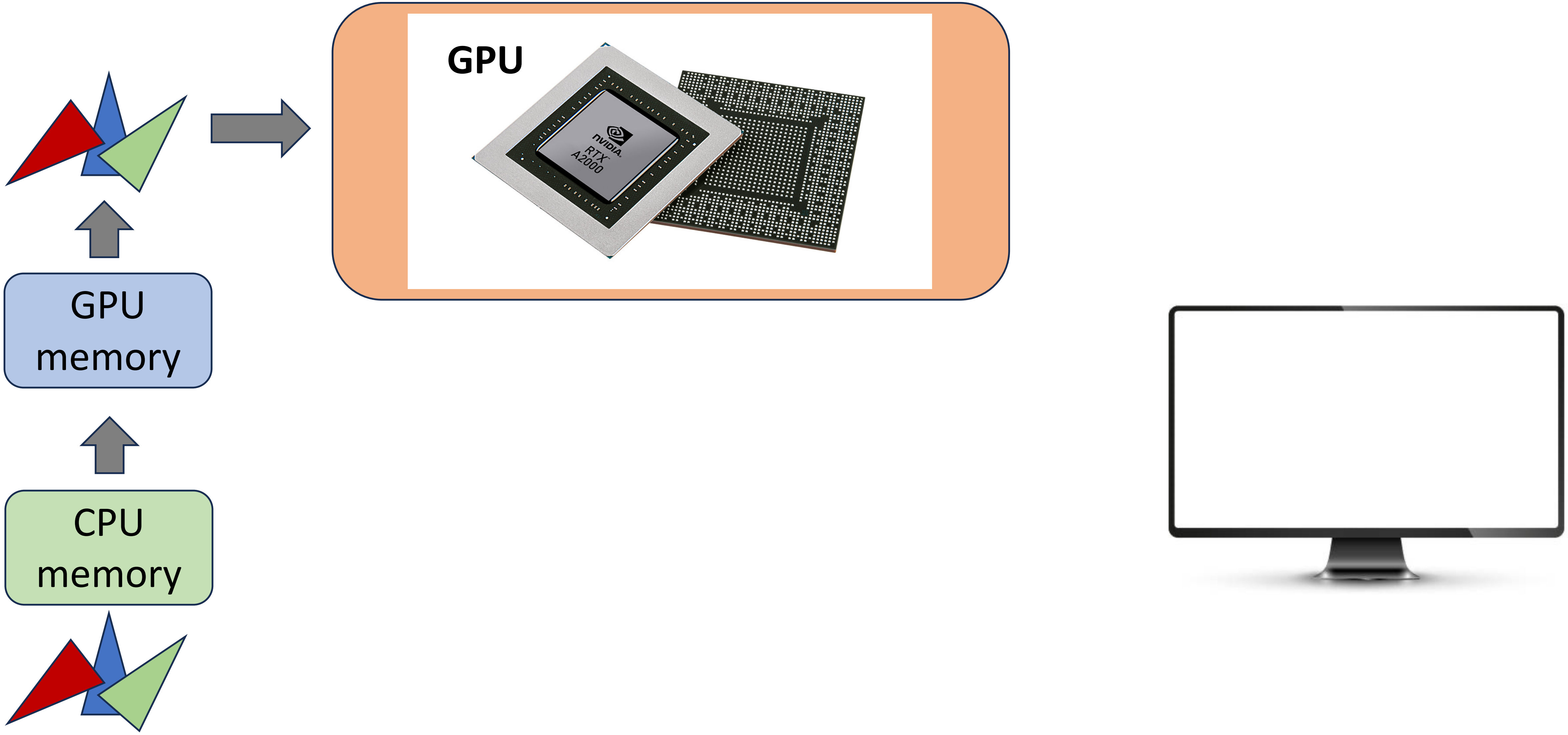
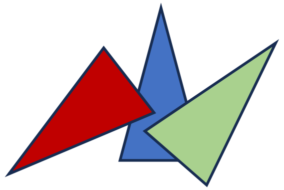
GPU Pipeline

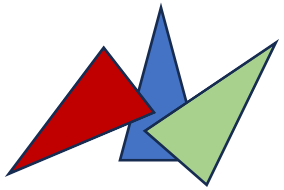


GPU Pipeline

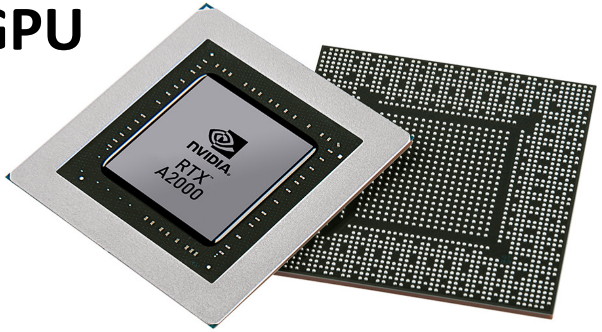


GPU memory

CPU memory

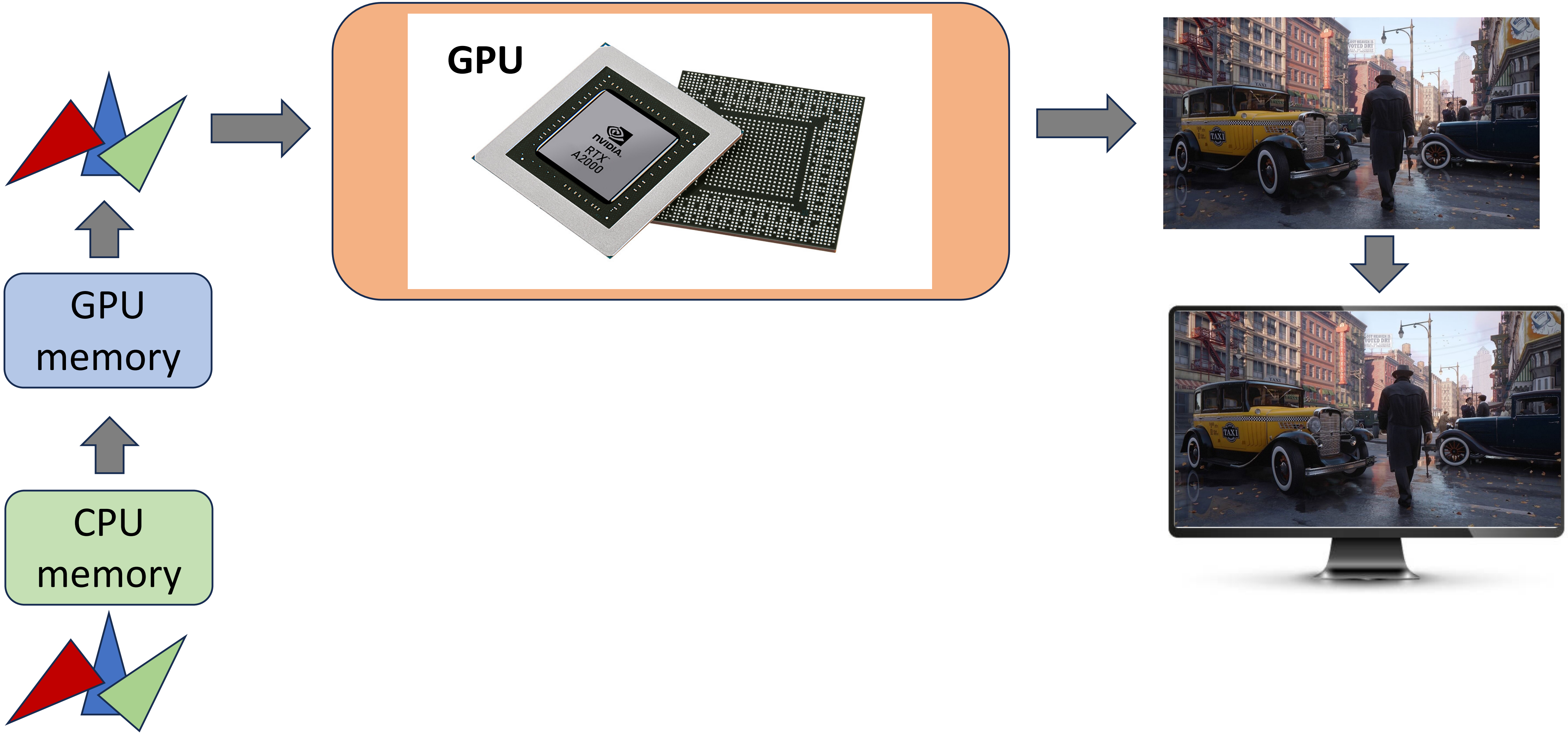


GPU

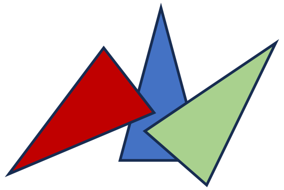


Source: Google

GPU Pipeline

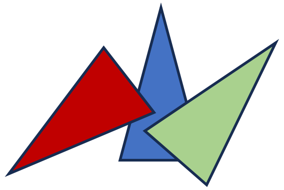


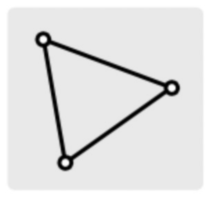
GPU Pipeline



GPU memory

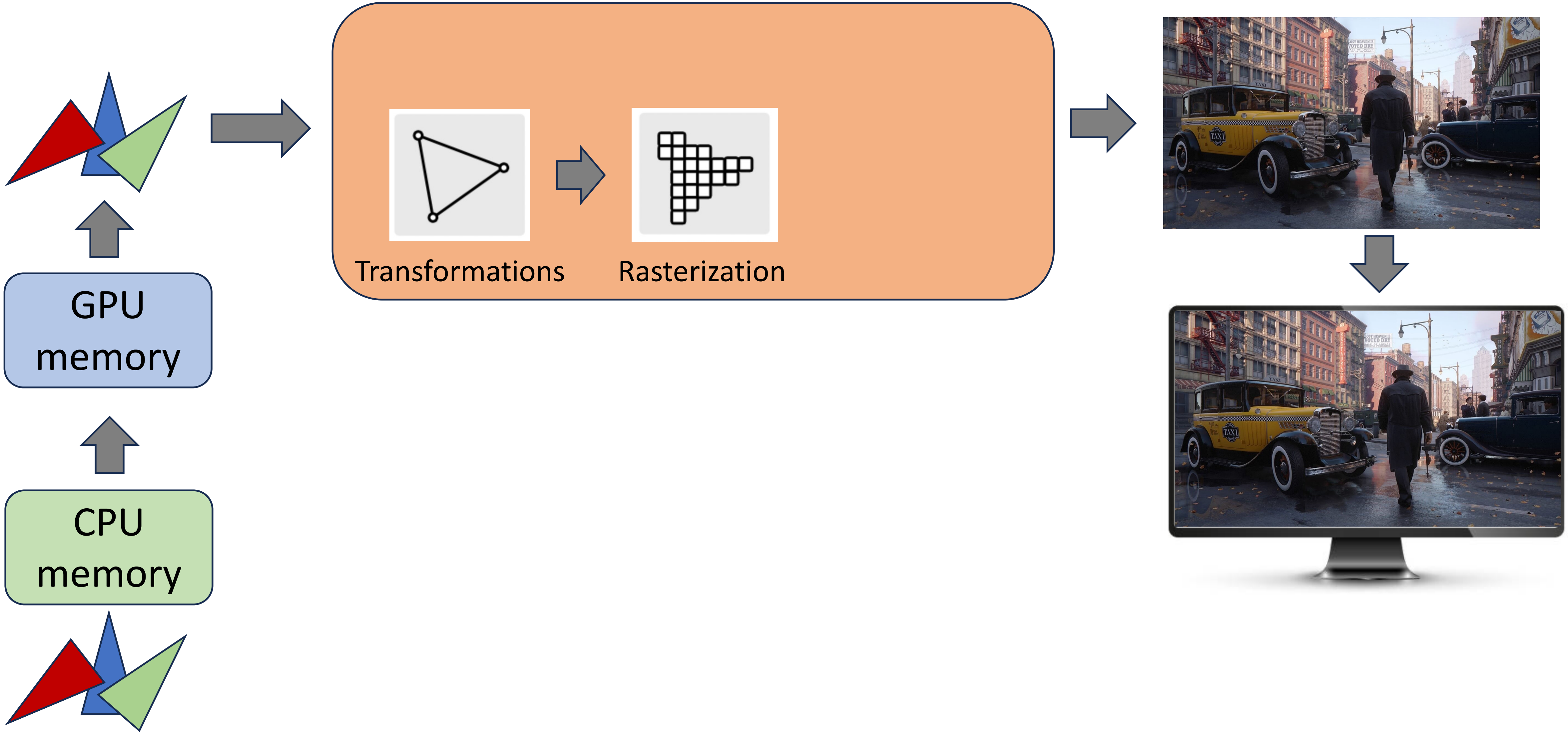
CPU memory



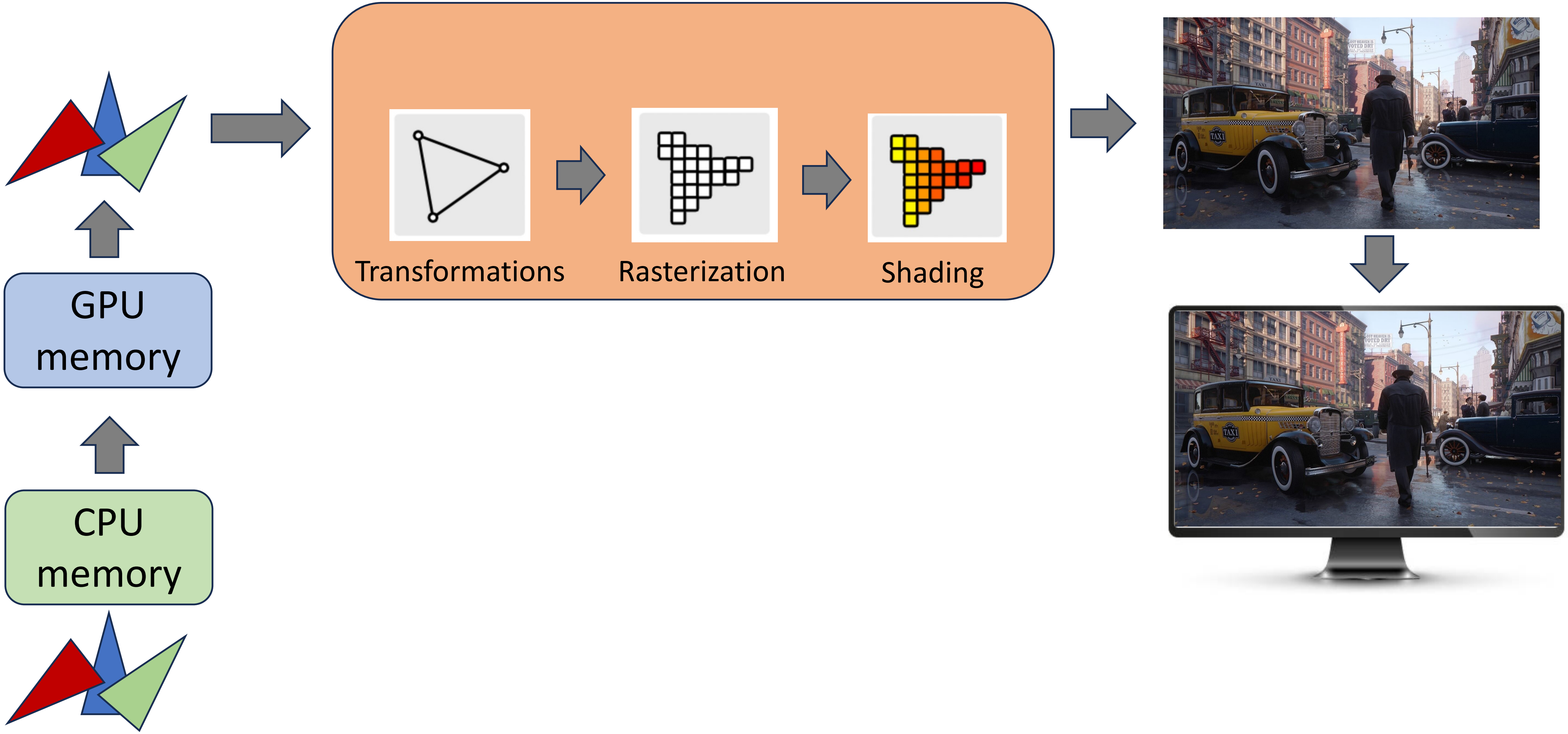


Transformations

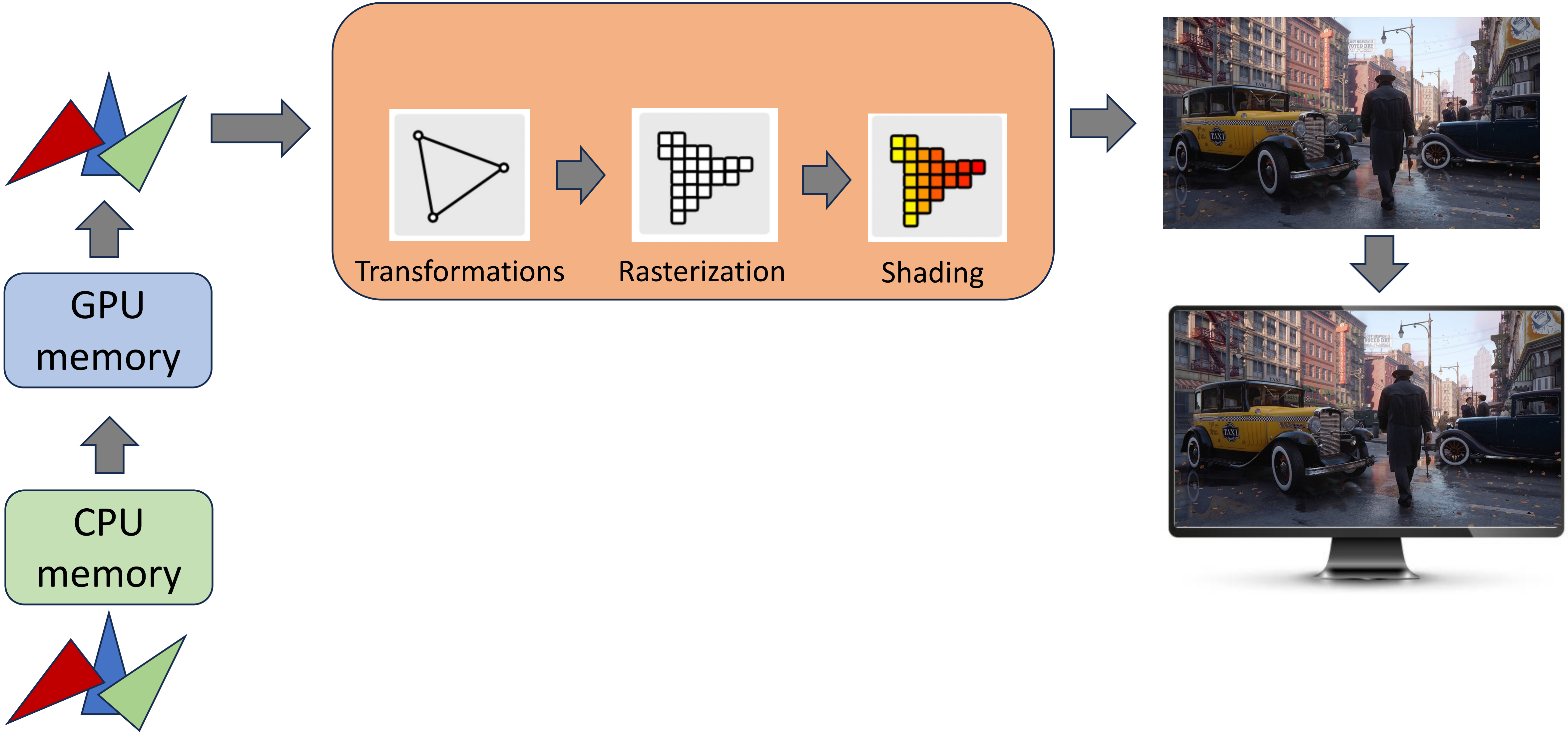
GPU Pipeline



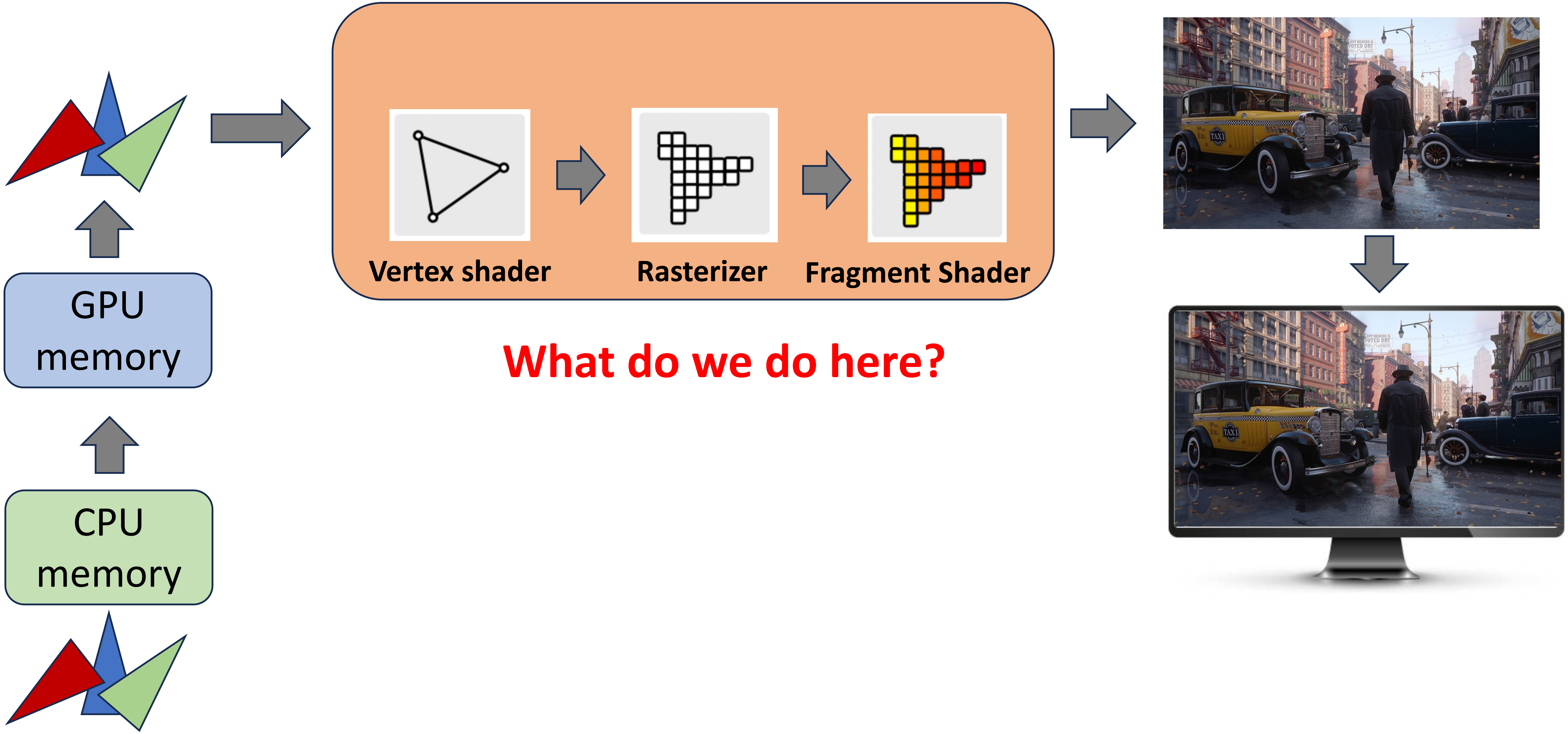
GPU Pipeline



GPU Pipeline



GPU Pipeline



GPU Pipeline

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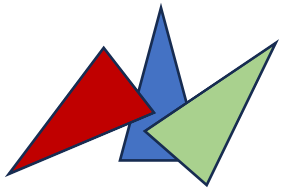
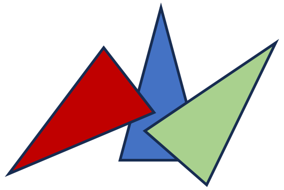


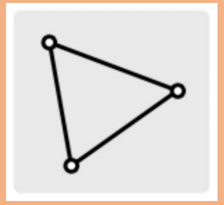
GPU memory

CPU memory



Programmable

Programmable



Vertex shader

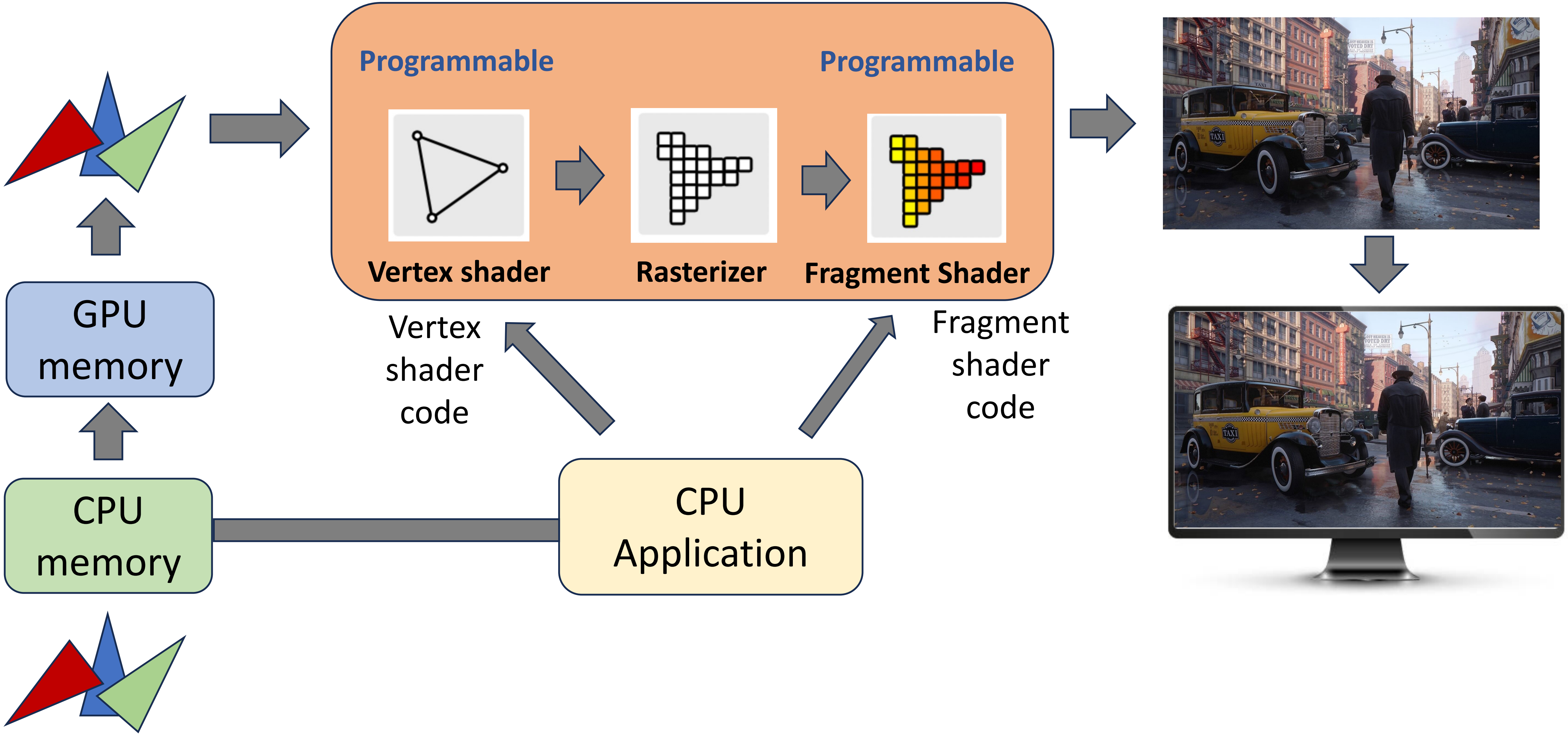
Rasterizer

Fragment Shader

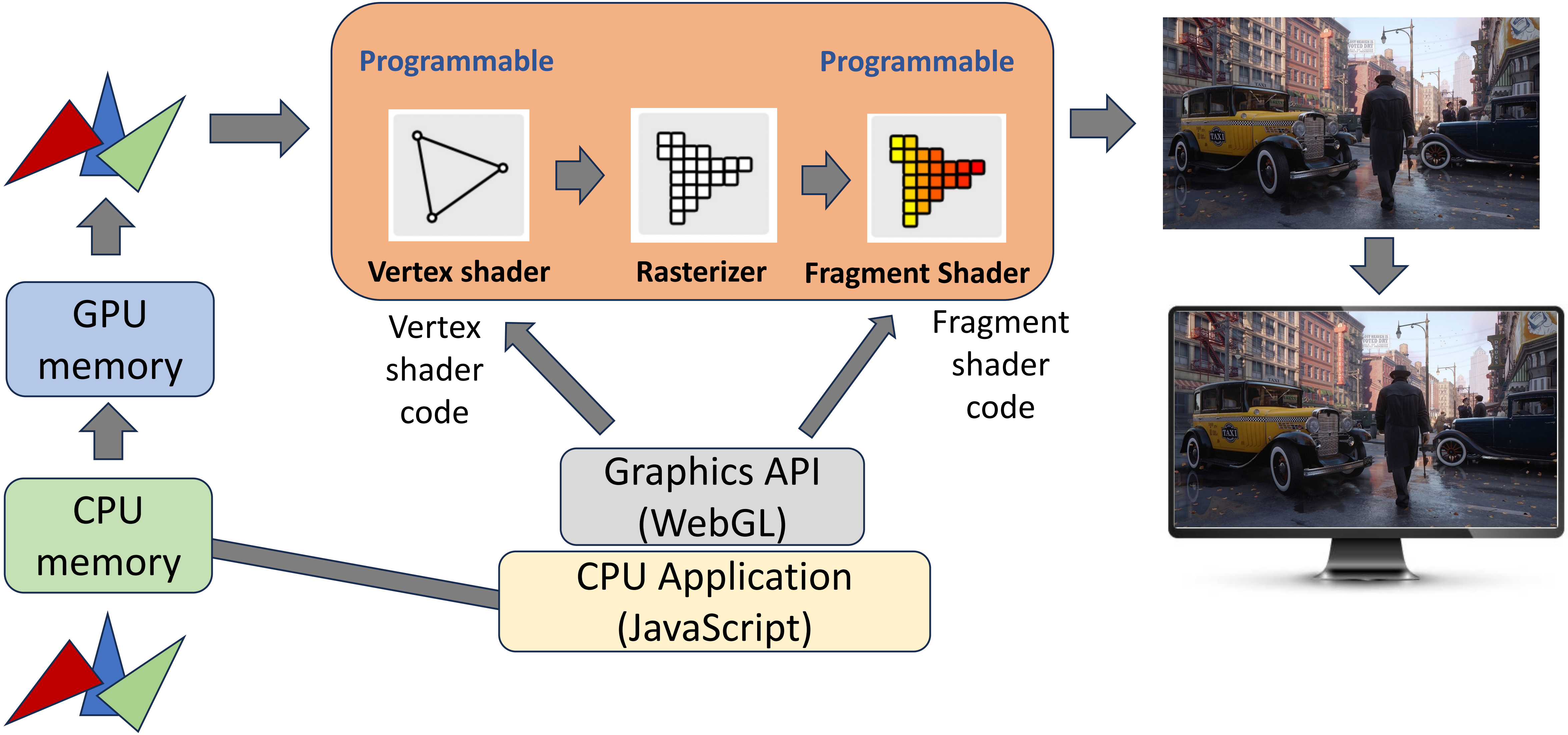
What do we do here?

Source: Google

GPU Pipeline



GPU Pipeline



WebGL

- https://developer.mozilla.org/en-US/docs/Web/API/WebGL_API

WebGL: Simple Canvas (HTML)

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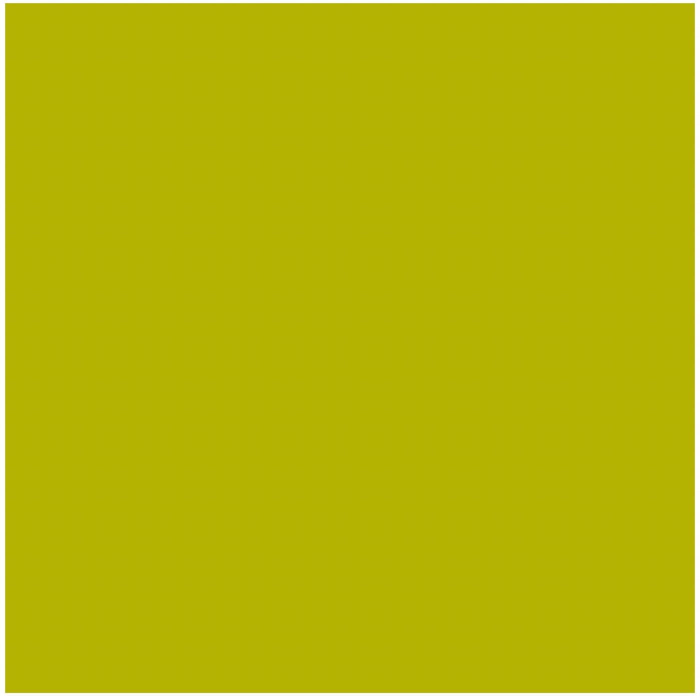
```html
<!DOCTYPE html>
<html>

  <head>
    <title>WebGL SimpleCanvas</title>
    <script type="text/javascript"
            src="simpleCanvas.js"></script>
  </head>

  <body onload="webGLStart();">
    <canvas
      id="simpleCanvas"
      width="500"
      height="500"
    ></canvas>
  </body>

</html>
```

WebGL: Simple Canvas (JavaScript)

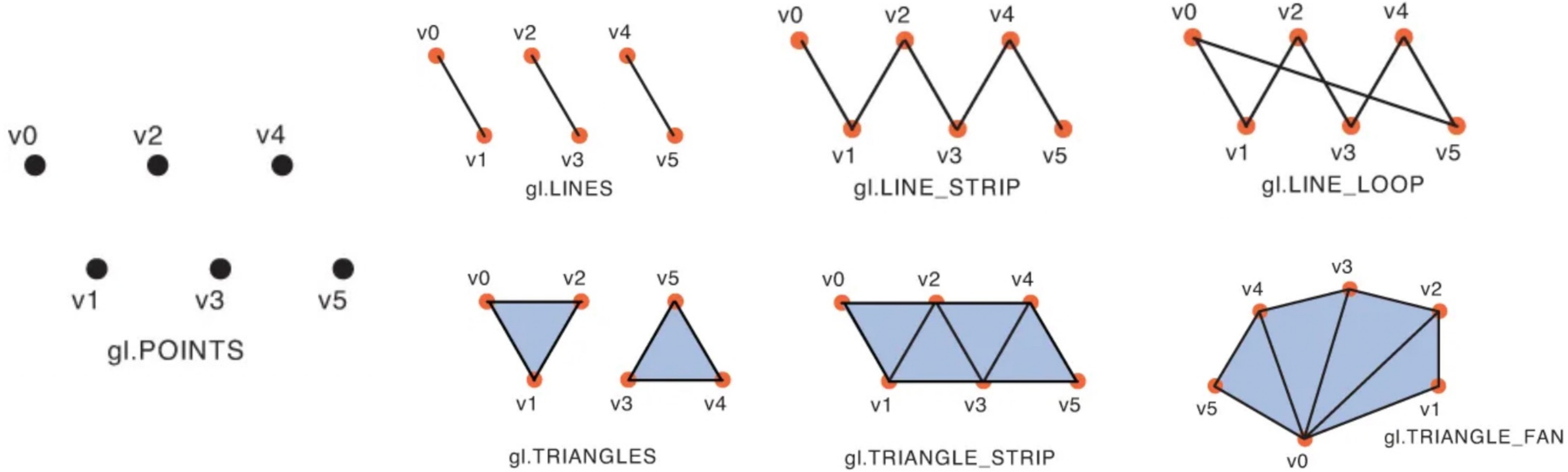
```javascript
var gl;

function initGL(canvas) {
  try {
    gl = canvas.getContext("webgl2"); // the webgl2 graphics context
    gl.viewportWidth = canvas.width; // the width
    gl.viewportHeight = canvas.height; // the height
  } catch (e) {}
  if (!gl) {
    alert("WebGL initialization failed");
  }
}

////////////////////////////////////////////////////////////////////////
// The main drawing routine, but does nothing except clearing the canvas
//
function drawScene() {
  gl.viewport(0, 0, gl.viewportWidth, gl.viewportHeight);
  gl.clearColor(0.7, 0.7, 0.0, 1.0);
  gl.clear(gl.COLOR_BUFFER_BIT | gl.DEPTH_BUFFER_BIT);
}

// This is the entry point from the html
function webGLStart() {
  var canvas = document.getElementById("simpleCanvas");
  initGL(canvas);
  drawScene();
}
```



Output

WebGL: Scene Data

- Scene data will be primarily consisted of vertices (points)
  - Vertices will form primitives (triangles)
  - Primitives will form objects
  - Objects will form a scene
- WebGL Primitives:



WebGL: Draw A Triangle: webGLStart()

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```
// This is the entry point from the html
function webGLStart() {
  var canvas = document.getElementById("triangleRender");
  initGL(canvas);
  shaderProgram = initShaders();

  // Print how many vertex attributes are supported in your device
  console.log(gl.getParameter(gl.MAX_VERTEX_ATTRIBS));

  drawScene();
}
```

WebGL: Draw A Triangle: initGL(canvas)


```
function initGL(canvas) {
  try {
    gl = canvas.getContext("webgl2"); // the graphics webgl2 context
    gl.viewportWidth = canvas.width; // the width of the canvas
    gl.viewportHeight = canvas.height; // the height
  } catch (e) {}
  if (!gl) {
    alert("WebGL initialization failed");
  }
}
```

Vertex Buffer Object (VBO)

- A Vertex Buffer Object (VBO) is a memory buffer in the high-speed memory of graphics card
  - Hold information about vertices and its properties
- We can create just one VBO for a model and then render that model multiple times using the same VBO by instancing it
  - Apply transformations to translate/rotate/scale the model before rendering

Vertex Buffer Object (VBO)

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```
// buffer for the three points and their color
const bufData = new Float32Array([
0.0, 0.5, 1.0, 0.0, 0.0, -0.5, -0.5, 0.0, 1.0, 0.0, 0.5, -0.5,
0.0, 0.0, 1.0,]);

// create VBO
const buf = gl.createBuffer();

// decide where to copy the data in GPU memory by binding
gl.bindBuffer(gl.ARRAY_BUFFER, buf);

// copy data from CPU buffer to GPU memory
gl.bufferData(gl.ARRAY_BUFFER, bufData, gl.STATIC_DRAW);
```

WebGL: Draw A Triangle: drawScene()

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```
function drawScene() {
  gl.viewport(0, 0, gl.viewportWidth, gl.viewportHeight);
  gl.clearColor(0.9, 0.9, 0.9, 1.0);
  gl.clear(gl.COLOR_BUFFER_BIT | gl.DEPTH_BUFFER_BIT);

  //get locations of attributes declared in the vertex shader
  const aPositionLocation = gl.getAttribLocation(shaderProgram, "aPosition");
  const aColorLocation = gl.getAttribLocation(shaderProgram, "aColor");

  // buffer for the three points
  const bufData = new Float32Array([
    0.0, 0.5, 1.0, 0.0, 0.0,
    -0.5, -0.5, 0.0, 1.0, 0.0,
    0.5, -0.5, 0.0, 0.0, 1.0,
  ]);
  const buf = gl.createBuffer();
  // decide where to copy the data in GPU memory by binding to it
  gl.bindBuffer(gl.ARRAY_BUFFER, buf);
  // copy data from CPU buffer to GPU memory
  gl.bufferData(gl.ARRAY_BUFFER, bufData, gl.STATIC_DRAW);
```

```
  gl.vertexAttribPointer(aPositionLocation, 2, gl.FLOAT, false, 5 * 4, 0);
  gl.vertexAttribPointer(aColorLocation, 3, gl.FLOAT, false, 5 * 4, 2 * 4);

  //enable the attribute arrays
  gl.enableVertexAttribArray(aPositionLocation);
  gl.enableVertexAttribArray(aColorLocation);

  // It says how many points are being drawn.
  // try: LINE_LOOP/TRIANGLES
  gl.drawArrays(gl.TRIANGLES, 0, 3); // 3 = 3 points are part of drawing
}
```

WebGL: Draw A Triangle: initShaders()


```
function initShaders() {
  shaderProgram = gl.createProgram();

  var vertexShader = vertexShaderSetup(vertexShaderCode);
  var fragmentShader = fragmentShaderSetup(fragShaderCode);

  // attach the shaders
  gl.attachShader(shaderProgram, vertexShader);
  gl.attachShader(shaderProgram, fragmentShader);
  //link the shader program
  gl.linkProgram(shaderProgram);

  // check for compilation and linking status
  if (!gl.getProgramParameter(shaderProgram, gl.LINK_STATUS)) {
    console.log(gl.getShaderInfoLog(vertexShader));
    console.log(gl.getShaderInfoLog(fragmentShader));
  }

  //finally use the program.
  gl.useProgram(shaderProgram);

  return shaderProgram;
}
```

WebGL: Draw A Triangle: ShaderSetUps


```
function vertexShaderSetup(vertexShaderCode) {
  shader = gl.createShader(gl.VERTEX_SHADER);
  gl.shaderSource(shader, vertexShaderCode);
  gl.compileShader(shader);
  // Error check whether the shader is compiled correctly
  if (!gl.getShaderParameter(shader, gl.COMPILE_STATUS)) {
    alert(gl.getShaderInfoLog(shader));
    return null;
  }
  return shader;
}
```

```
function fragmentShaderSetup(fragShaderCode) {
  shader = gl.createShader(gl.FRAGMENT_SHADER);
  gl.shaderSource(shader, fragShaderCode);
  gl.compileShader(shader);
  // Error check whether the shader is compiled correctly
  if (!gl.getShaderParameter(shader, gl.COMPILE_STATUS)) {
    alert(gl.getShaderInfoLog(shader));
    return null;
  }
  return shader;
}
```

WebGL: Draw A Triangle: Shaders


```
const vertexShaderCode = `#version 300 es
in vec2 aPosition;
in vec3 aColor;
out vec3 fColor;

void main() {
  fColor = aColor;
  gl_Position = vec4(aPosition,0.0,1.0);
}`;
```

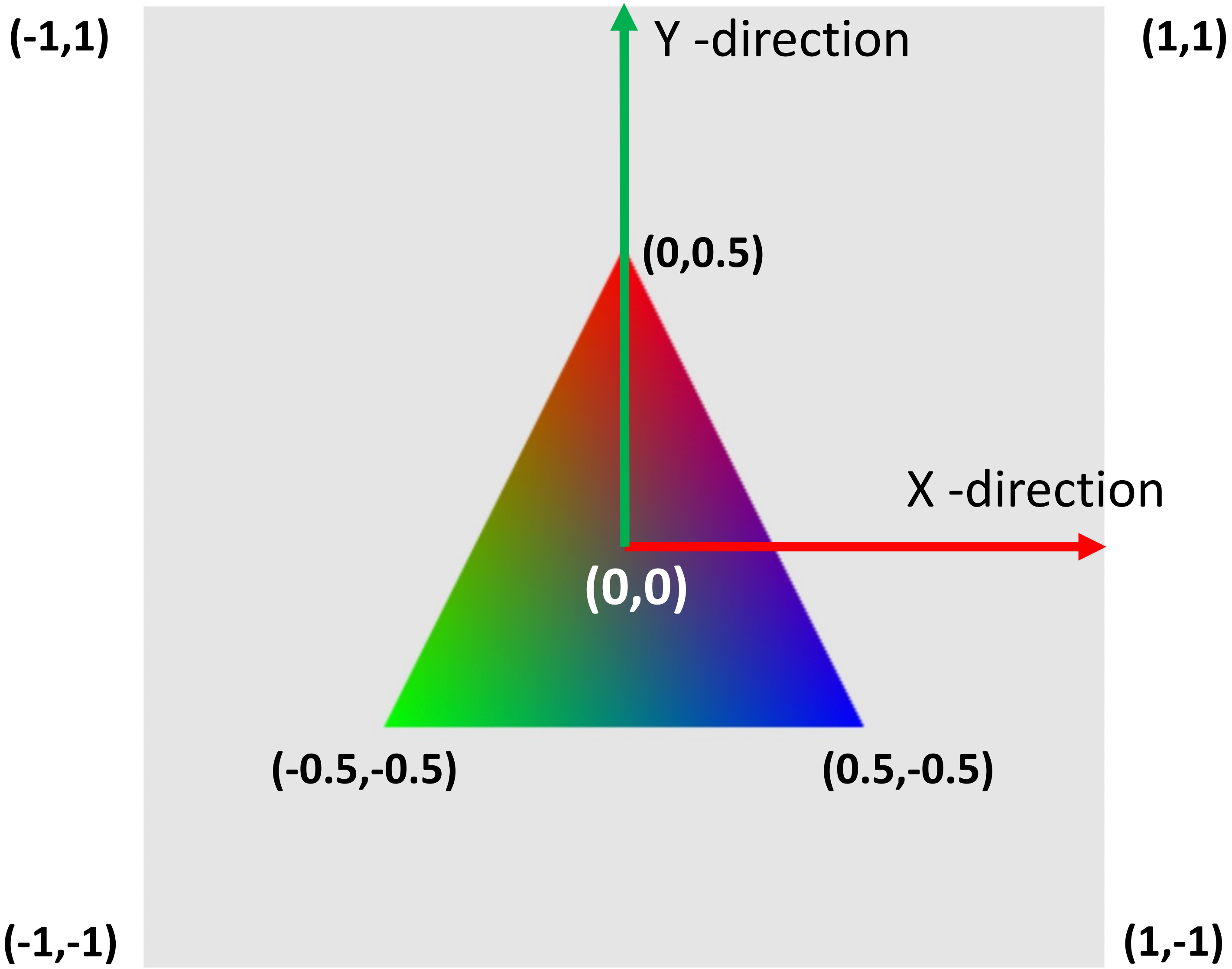
Vertex Shader Code

```
const fragShaderCode = `#version 300 es
precision mediump float;
out vec4 fragColor;
in vec3 fColor;

void main() {
  fragColor = vec4(fColor, 1.0);
}`;
```

Fragment Shader Code

WebGL: Draw A Triangle: Output



OpenGL Shading Language (GLSL)

- A high-level shading language with a syntax based on the C programming language
- Created by the OpenGL ARB (OpenGL Architecture Review Board) to give developers more direct control of the graphics pipeline without having to use ARB assembly language or hardware-specific languages

- WebGL2 supports GLSL ES 3.0 Spec: https://registry.khronos.org/OpenGL/specs/es/3.0/GLSL_ES_Specification_3.00.pdf
- https://www.khronos.org/files/opengl42-quick-reference-card.pdf

Wikipedia

OpenGL Shading Language (GLSL)

- Data Types:
    - bool
    - int
    - float
    - bvec2, bvec3, bvec4: 2, 3, and 4-component Boolean vectors
    - ivec2, ivec3, ivec4: 2, 3, and 4-component integer vectors
    - vec2, vec3, vec4: 2, 3, and 4-component floating point vectors
    - mat2, mat3, mat4: 2x2, 3x3, and 4x4 floating point matrices
- Special Data types
    - sampler2D: a reference to a TEXTURE_2D *texture unit* (which has an attached *texture object*)
    - samplerCube: a reference to a SAMPLER_CUBE *texture unit*

Vector Components

- The individual element of a vector can be accessed using array notation, 0^{th} element of vector a is = a[0]
- 'dot' notation can also be used such as 0^{th} element of vector a is = a.x
  - The names of the vector components are x,y,z,w, or r,g,b,a, or s,t,p,q
  - You can use any of these names on a vector, regardless of the actual data in the vector
    - But, the intent is to use x,y,z,w when you are accessing geometric data
    - r,g,b,a when you are accessing color data
    - s,t,p,q when you are accessing texture data

Vector Components


```
vec3 alpha = vec3(1.0, 2.0, 3.0);
vec4 a;
vec3 b;
vec2 c;
float d;

b = alpha.xyz;  // b is now (1.0, 2.0, 3.0)
d = alpha[2];   // d is now 3.0
a = alpha.xxxx; // a is now (1.0, 1.0, 1.0, 1.0)
c = alpha.zx;   // c is now (3.0, 1.0)
b = alpha.rgb;  // b is now (1.0, 2.0, 3.0)
b = alpha.stp;  // b is now (1.0, 2.0, 3.0)
a = alpha.yy;   // compiler error; the right hand side is a 2-component vector,
                // while "a" is a 4-component vector.
```

Overall Execution of GLSL Program

- A shader program is composed of one or more functions.
- Execution always begins with the main function which receives no parameters and returns no value:

```
void main(void) {
  // statement(s)
}
```

Main function

```
vec3 example(float x, bool beta) {
  // statement(s)
}
```

A different function declaration

Function Parameter Qualifiers

- **const**: for function parameters that cannot be written to
- **in**: for function parameters passed into function
- **out**: for function parameters passed back out of function, but not initialized when passed in
- **inout**: for function parameters passed both into and out of a function

Storage Qualifiers

- **none**: (default) local read/write memory, or input parameter
- **const**: global compile-time constant, or read-only function parameter, or read-only local variable
- **in**: linkage into shader from previous stage
- **out**: linkage out of a shader to next stage

Storage Qualifiers

- How can we pass information from JavaScript to vertex/fragment shader code?
    - Use uniforms
- uniform: linkage between a shader, OpenGL, and the application
    - uniform1i, uniform 1f
    - uniform2fv, uniform3fv, uniform4fv, ….
    - uniformMatrix2fv, uniformMatrix3fv , uniformMatrix4fv, …

Some Useful Built-in Shader Functions

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- abs() = absolute value
- sign() = returns -1.0, 0.0, or 1.0
- min(), max()
- floor(), ceil(), round(), trunc()
- mod() = modulus
- Length() = length of a vector
- distance() = distance between two points
- dot() = dot product between two vectors
- cross() = cross product between two vectors
- normalize() = normalize a vector
- reflect() = compute reflection vector
- refract() = compute refraction vector

- transpose() = matrix transpose
- inverse() = matrix inverse
- determinant() = matrix determinant
- matrixCompMult() = component-wise multiply