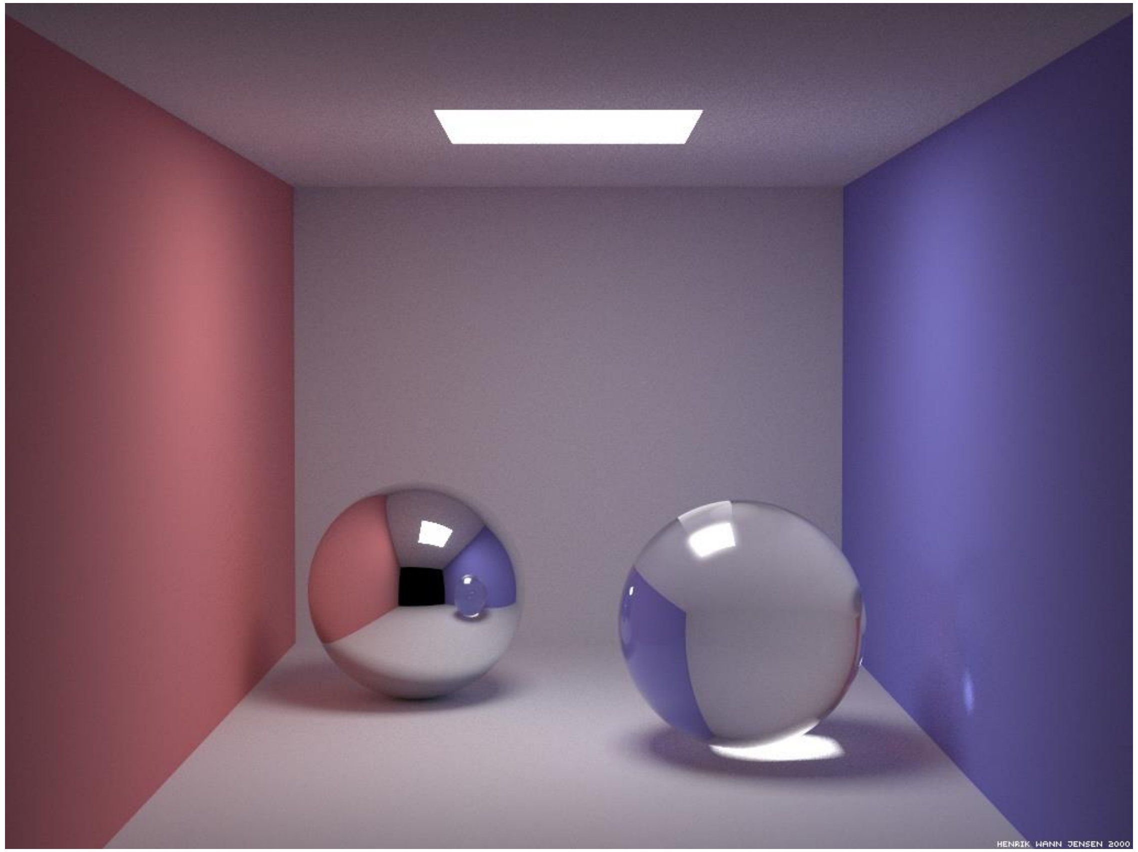
CPSC 427
Video Game Programming

Rendering Pipeline and OpenGL



Helge Rhodin

Recap: Rendering – Rasterization

Approximate objects with triangles

1. Project each corner/vertex

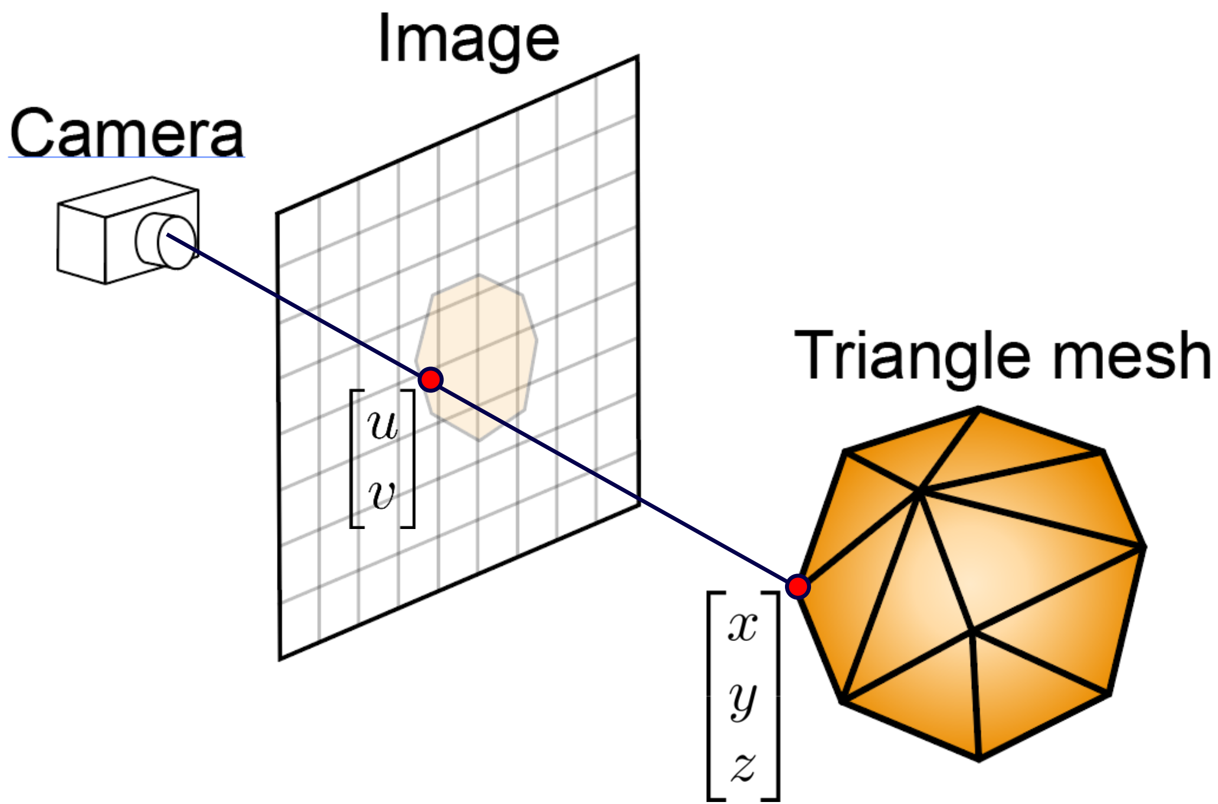
- projection of triangle stays a triangle

$$\begin{bmatrix} u \\ v \end{bmatrix} = \frac{1}{z} \begin{bmatrix} x \\ y \end{bmatrix}$$

- O(n) for n vertices

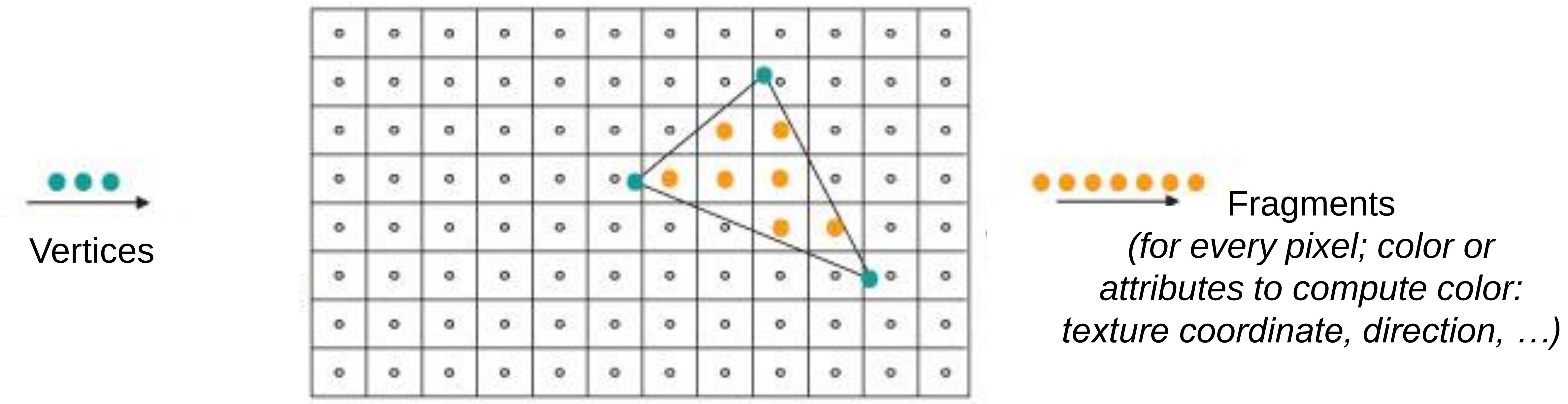
2. Fill pixels enclosed by triangle

- e.g., scan-line algorithm



Recap: Rasterizing a Triangle

- ***Determine pixels enclosed by the triangle***
- ***Interpolate vertex properties linearly***

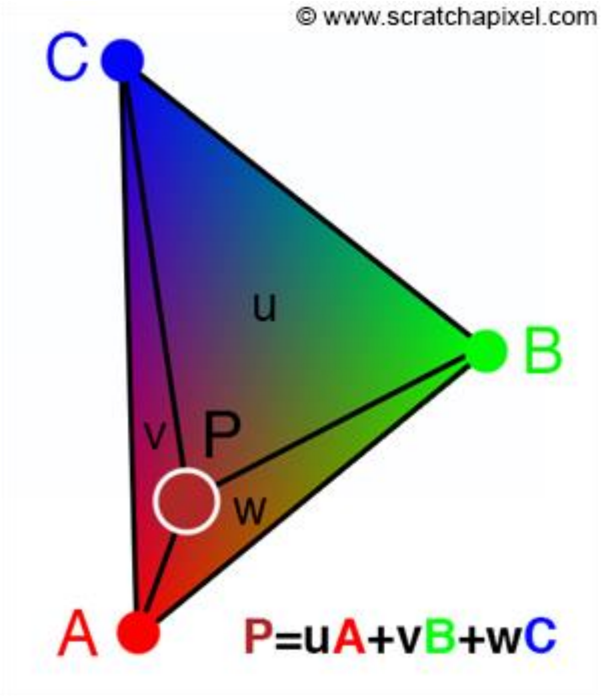


Self study:

Interpolation with barycentric coordinates

- *linear combination of vertex properties*
  - *e.g., color, texture coordinate, surface normal/direction*

- *weights are proportional to the areas spanned by the sides to query point P*



Graphics processing unit (GPU)

Specialized hardware designed for rendering

- highly parallel architecture
- dedicated instructions
- hardware pipeline (parts are not programmable)

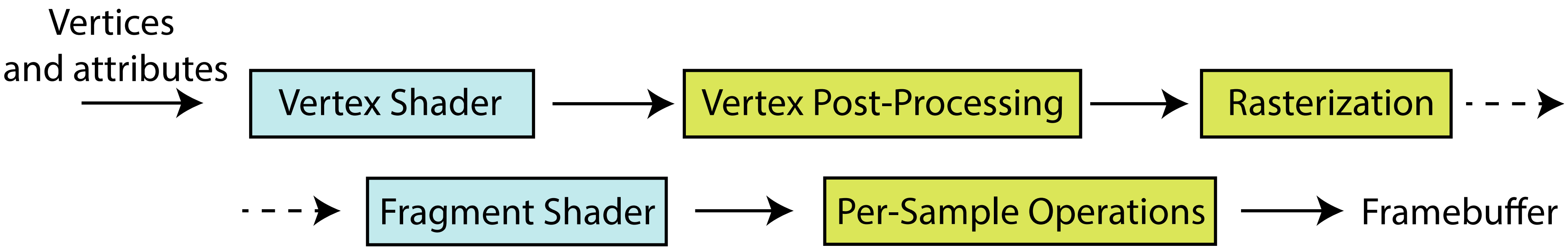
Proved useful for high-performance computing

- machine learning
- bitcoin mining
- …

OpenGL Rendering Pipeline

Input:

- *3D vertex position*
- *Optional vertex attributes: color, texture coordinates,…*



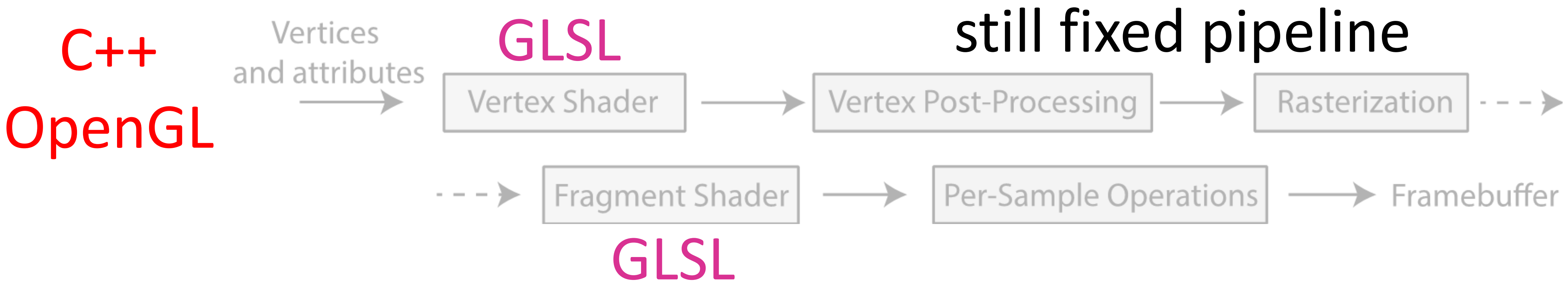
Output:

- ***Frame Buffer :*** *GPU video memory, holds image for display*
- *RGBA pixel color (Red, Green, Blue, Alpha / opacity)*

Programming languages

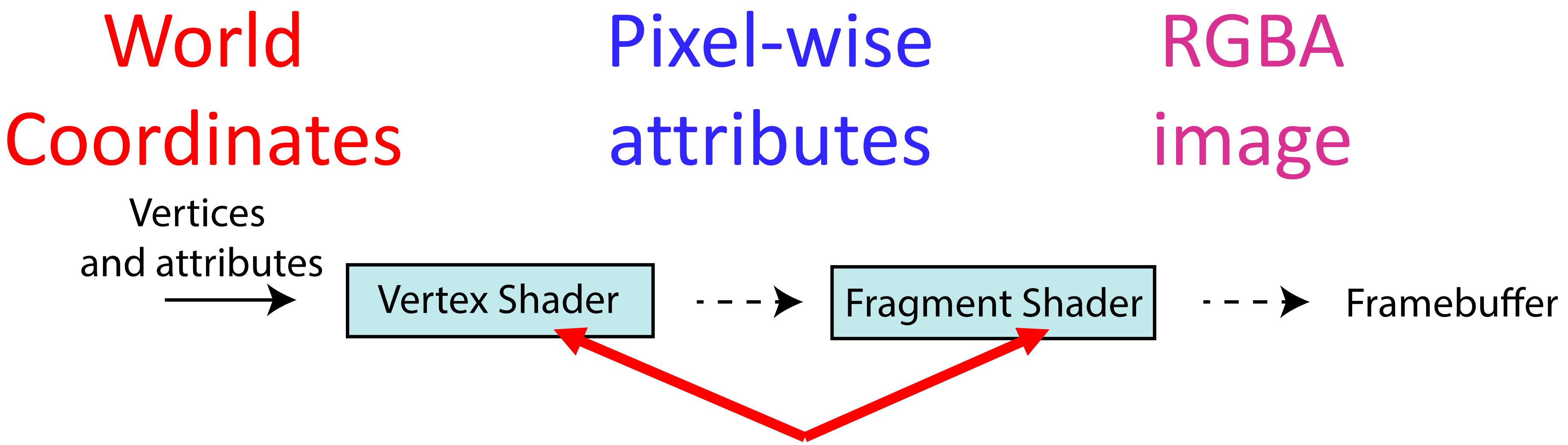
Traditionally, the entire pipeline was fixed (until ~2004)

- *vertex and fragment shaders now programmable with GLSL*



OpenGL Rendering Pipeline (simplified)

1. *Vertex shader: geometric transformations*
2. *Fragment shader: pixel-wise color computation*



Shader: Programmable functions
to define object appearance locally
(vertex wise or fragment wise)

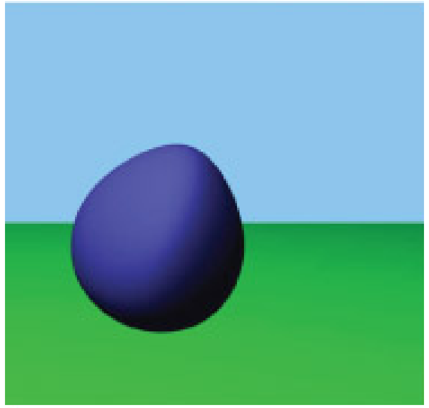
Vertex shader examples

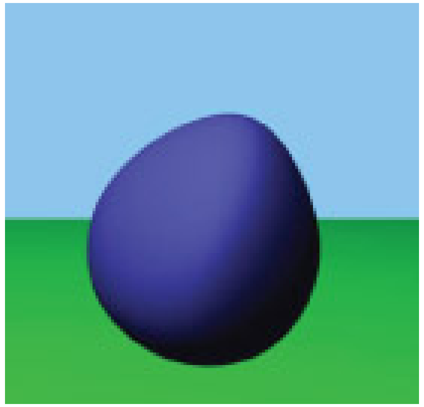
Object motion & transformation

- translation
- rotation
- scaling

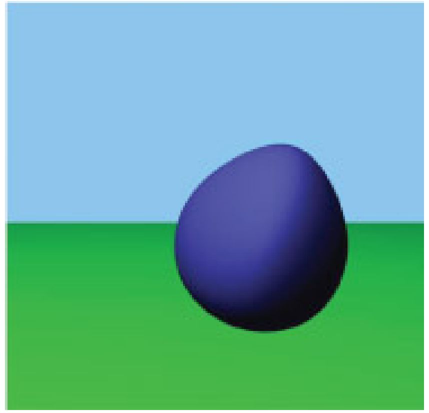
Projection

- Orthographic
  - *simple, without perspective effects*
- Perspective
  - *pinhole projection model*





Scaling



Translation

GLSL Vertex shader

The OpenGL Shading Language (GLSL)

- Syntax similar to the C programming language
- Build-in vector operations
  - functionality as the GLM library our assignment template uses

```
void main()
{
    // Transforming The Vertex
    vec3 out_pos = projection * transform * vec3(in_pos.xy, 1.0);
    gl_Position = vec4(out_pos.xy, in_pos.z, 1.0);
}
```

x and y coordinates of a vec2, vec3 or vec4

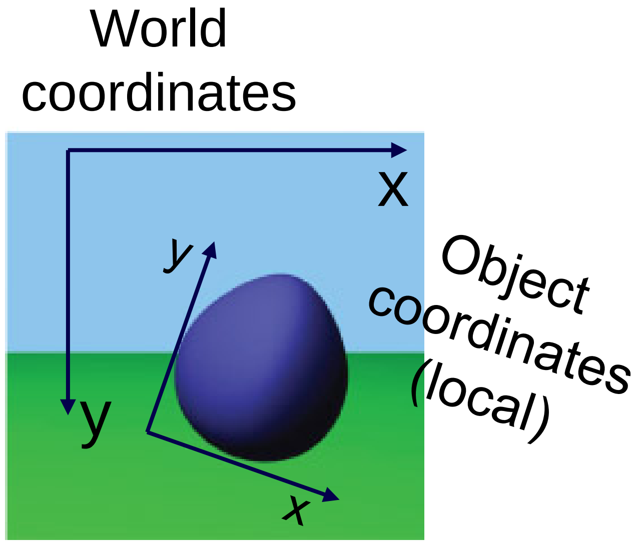
world -> camera

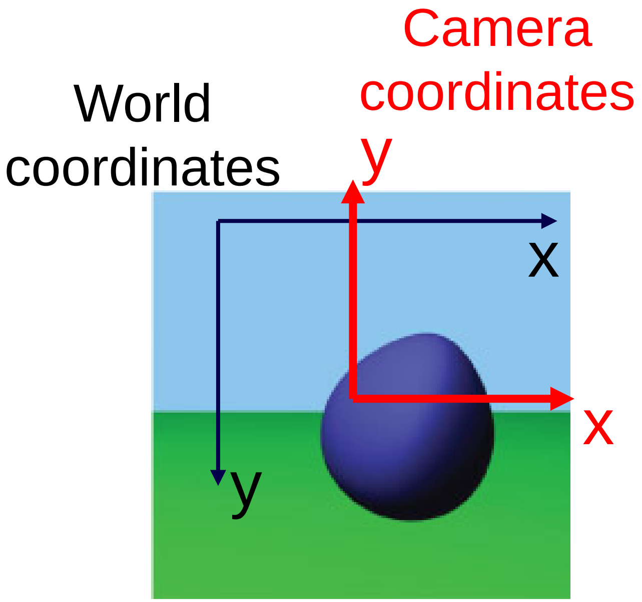
object -> world

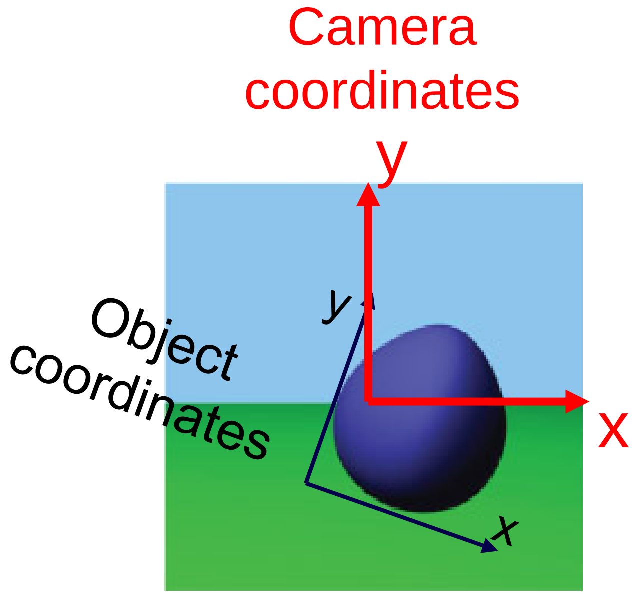
vector of 3 (vec3) and 4 (vec4) floats

float (32 bit)

From local object to camera coordinates





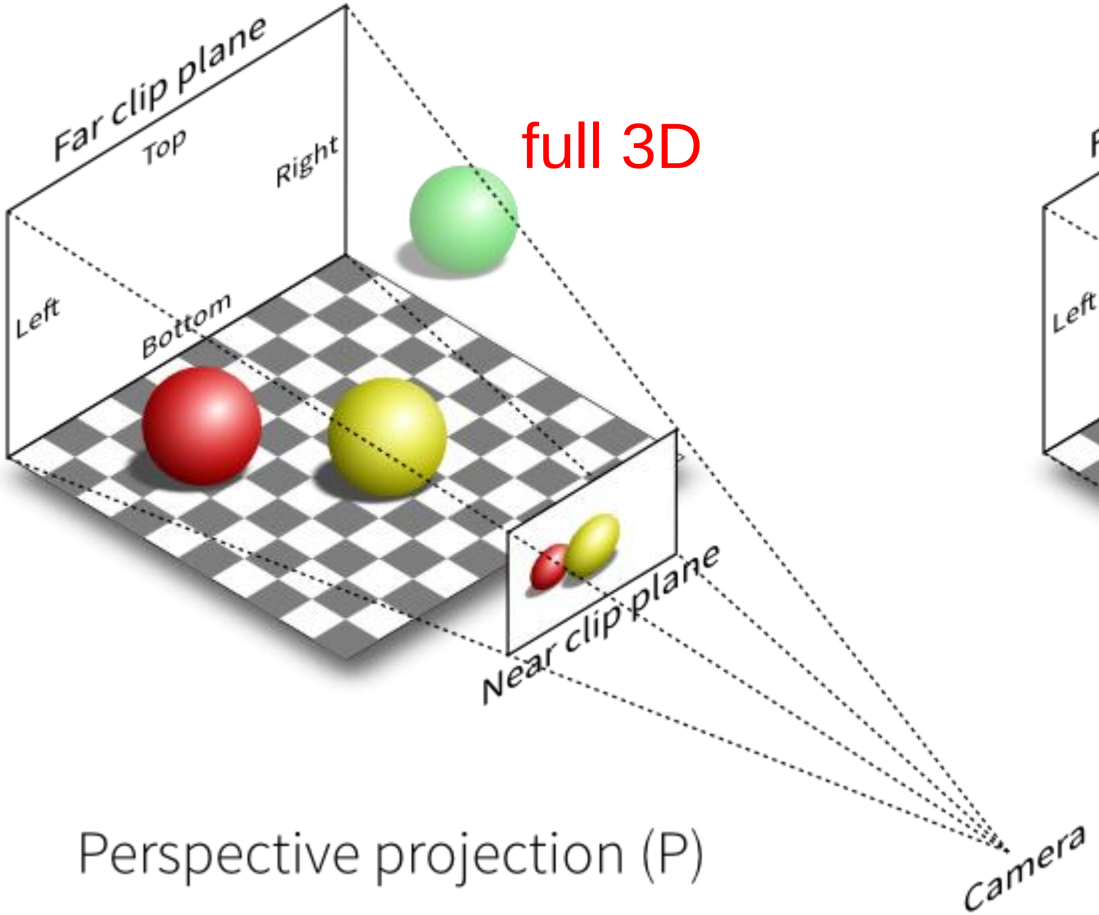


object -> world **world -> camera** **object -> camera**

`transform` `projection` `projection * transform`

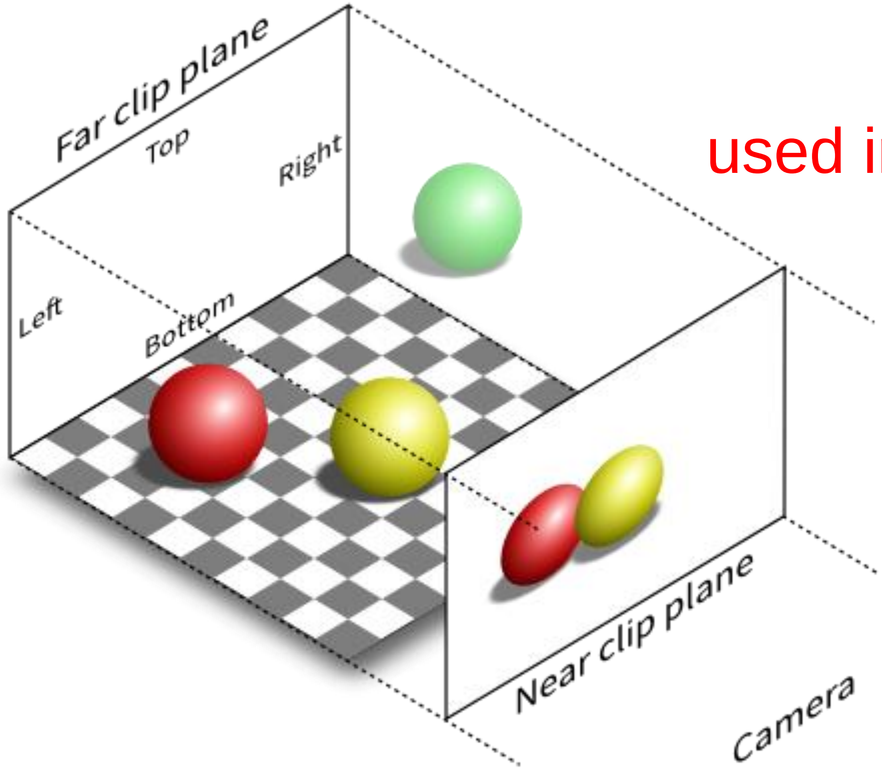
Camera types

full 3D



Perspective projection (P)

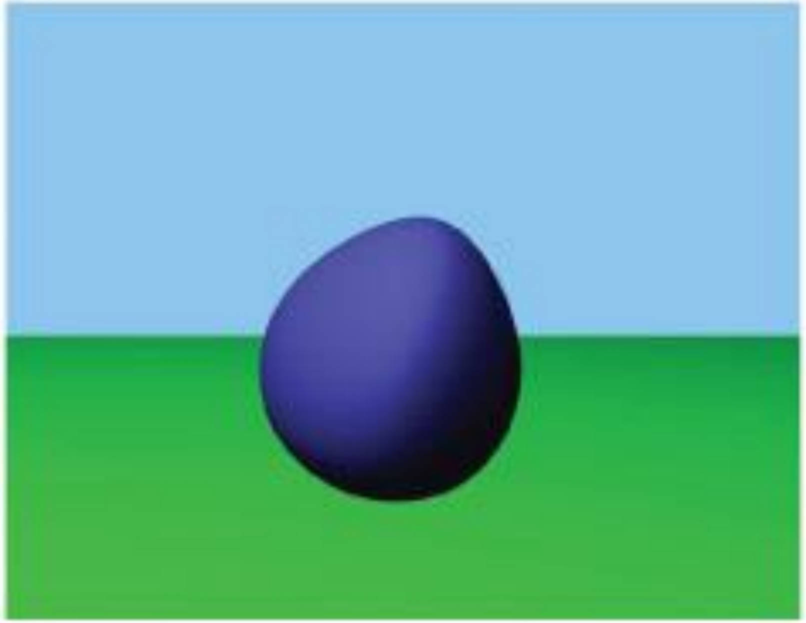
used in our 2D games!



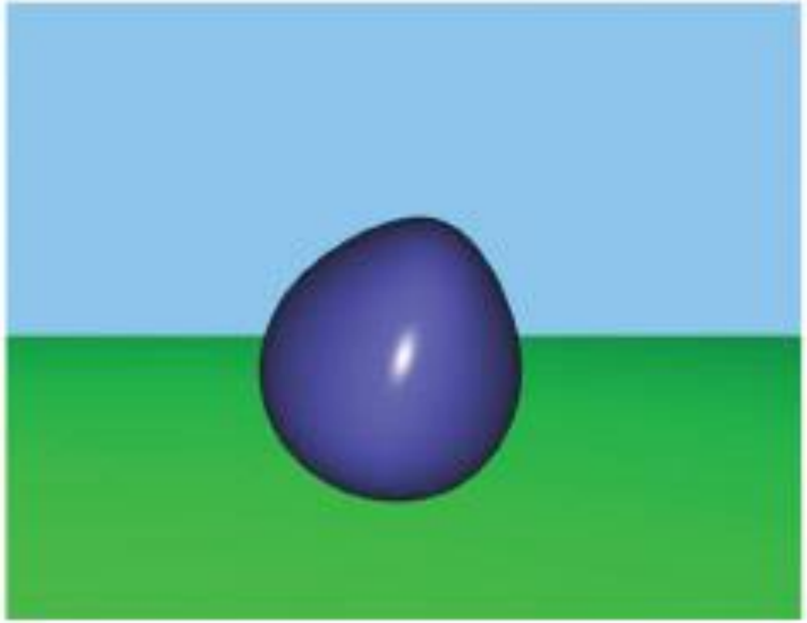
Orthographic projection (O)

Fragment shader examples

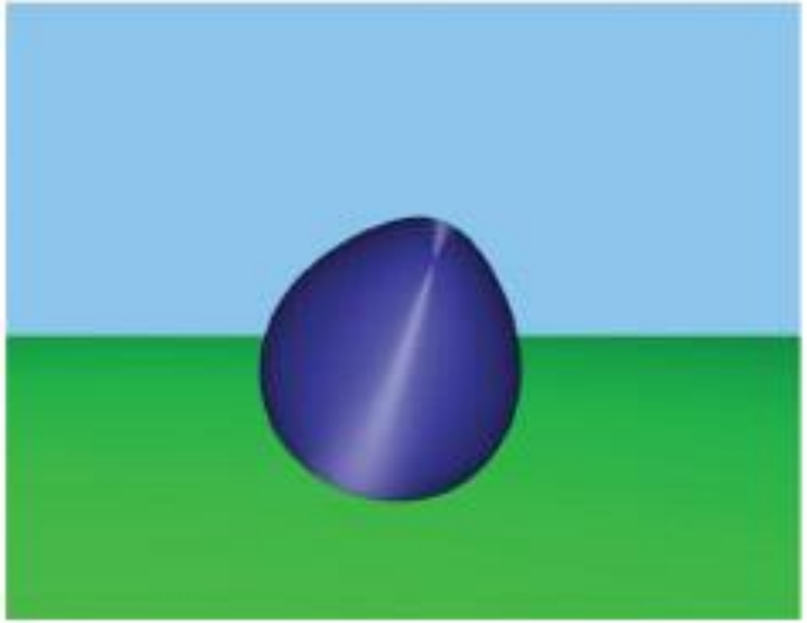
- *simulates materials and lights*
- *can read from textures*



Diffuse



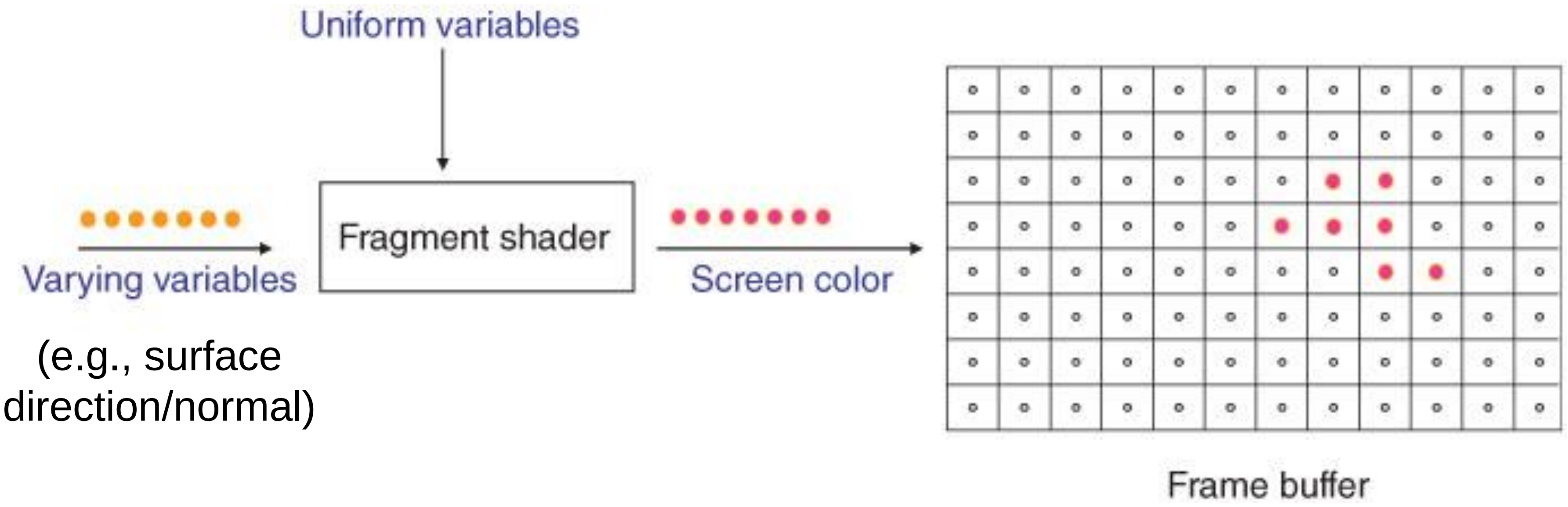
Specular



Directional

Fragment shader overview

(e.g., light direction)



(e.g., surface direction/normal)

GLSL fragment shader examples

Minimal:

```
out vec4 out_color;
void main()
{
    // Setting Each Pixel To ???
    out_color = vec4(1.0, 0.0, 0.0, 1.0);
}
```

Specify color output

Red, Green, Blue, Alpha

Shader demo

- go to https://www.shadertoy.com/view/ttKcWR

- lets play together

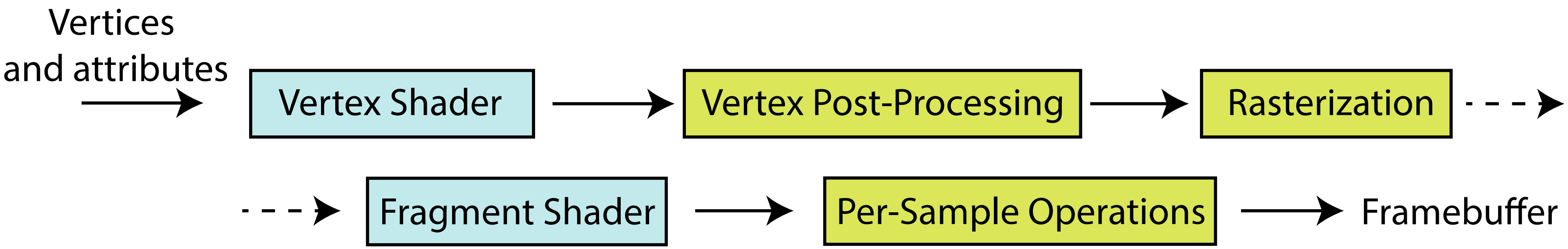
Coordinate transformations

World Coordinates

Camera Coordinates

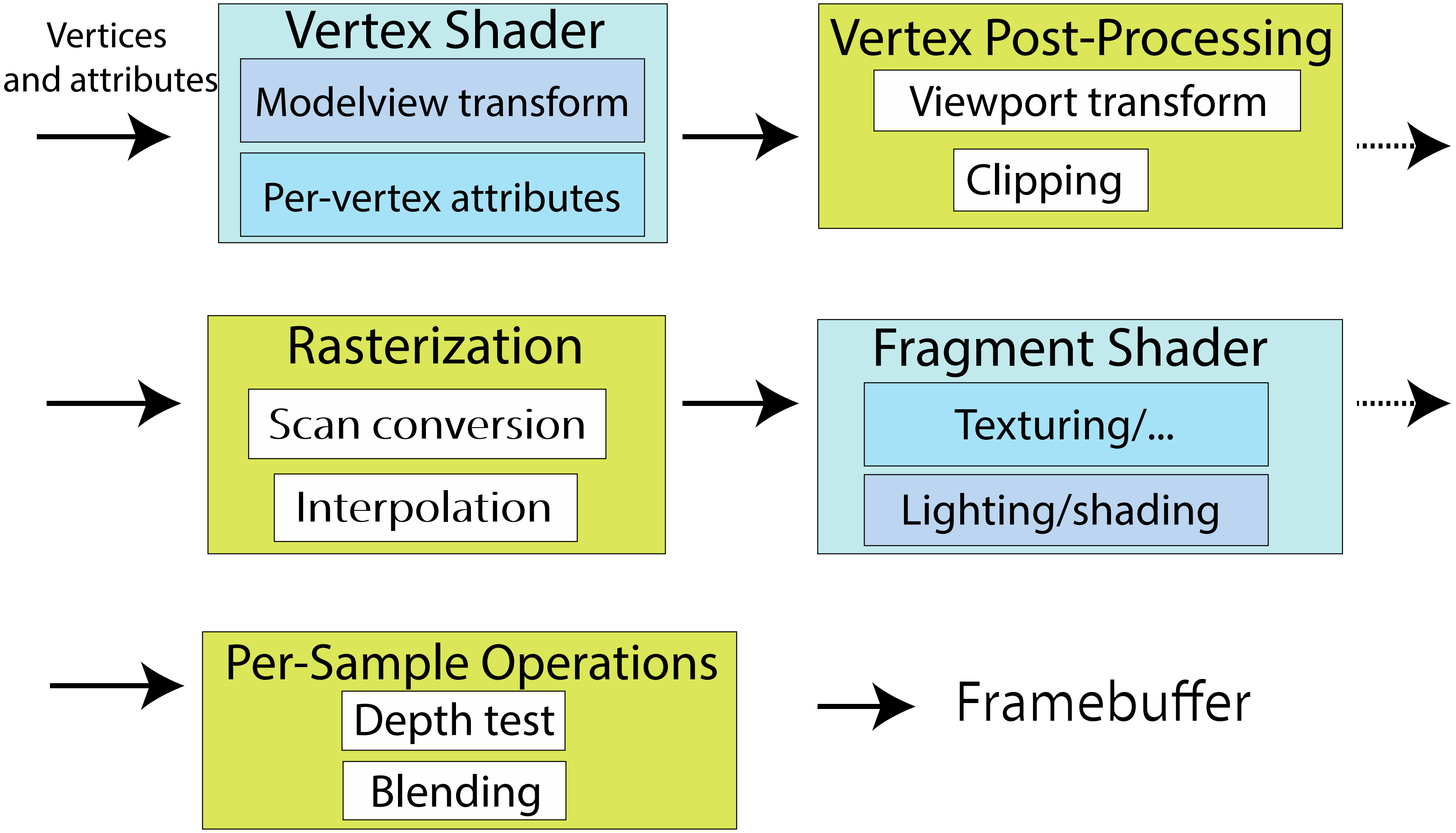
Window Coordinates

Pixel-wise attributes*



*usually multiple fragments for every pixel (fragment != pixel)

OpenGL Rendering Pipeline (detailed)



The OpenGL library

- Low-level graphics API
- C Interface accessed from C++

- ***How to***
- set shaders
- set shader inputs
- start rendering

Loading and compiling shaders

load from data/shaders/salmon.vs.glsl

CREATING SHADER OBJECTS

```
GLuint vertexShader = glCreateShader(GL_VERTEX_SHADER);
glShaderSource(vertexShader, 1, sourceCode, sourceCodeLength);
GLuint fragmentShader = glCreateShader(GL_FRAGMENT_SHADER);
glShaderSource(fragmentShader, 1, sourceCode, sourceCodeLength);
```

load from data/shaders/salmon.fs.glsl

COMPILING

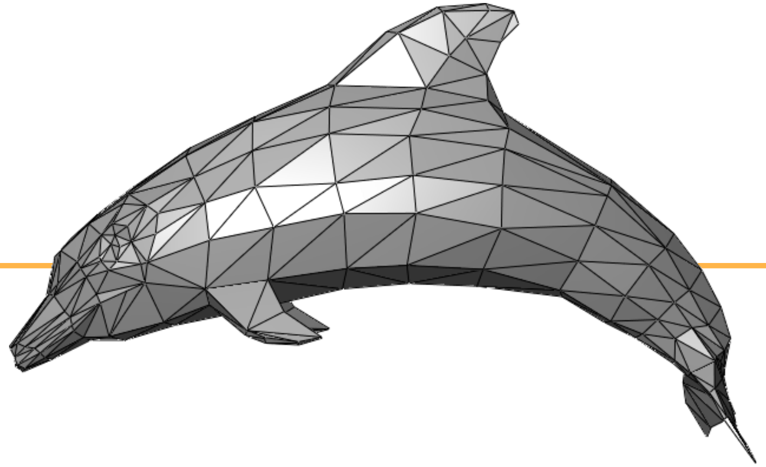
```
glCompileShader(vertexShader);
glCompileShader(fragmentShader);
```

Linking vertex and fragment shaders together

LINKING

```
program = glCreateProgram();
glAttachShader(program, vertexShader);
glAttachShader(program, fragmentShader);
glLinkProgram(program);
```

GEOMETRY



Triangle meshes

- Set of vertices
- Connectivity defined by indices
  - `uint16_t indices[] =` *{vertex_index1, vertex_index2, vertex_index3, …}*

three indices make one triangle

OpenGL resources

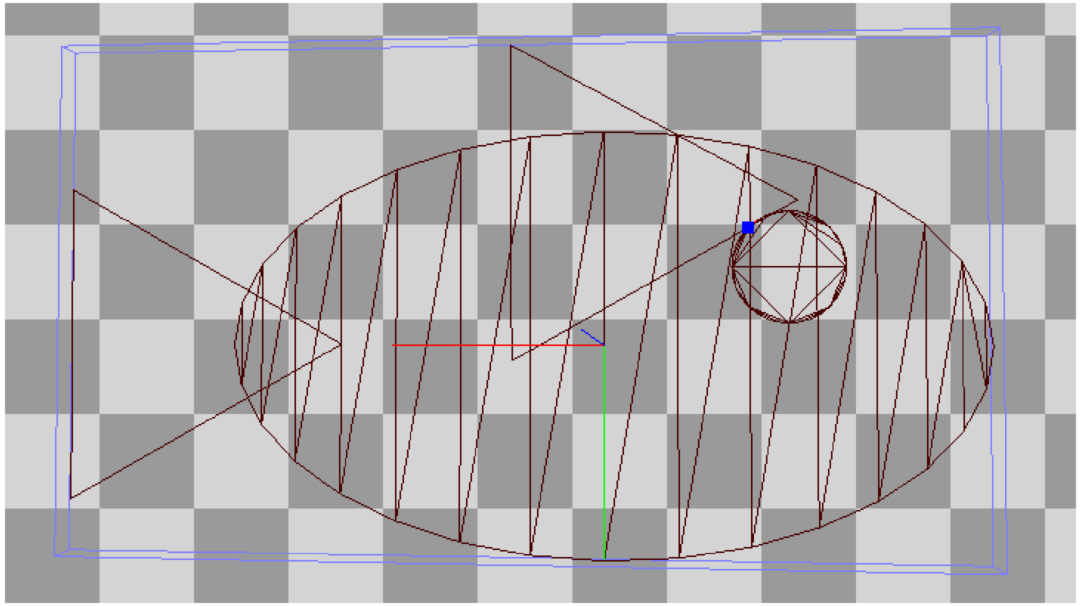
- vertex buffer
- index buffer

Creation

```
Gluint vbo;
glGenBuffers(vbo);

Gluint ibo;
glGenBuffers(ibo);
```

Programmatic geometry definition

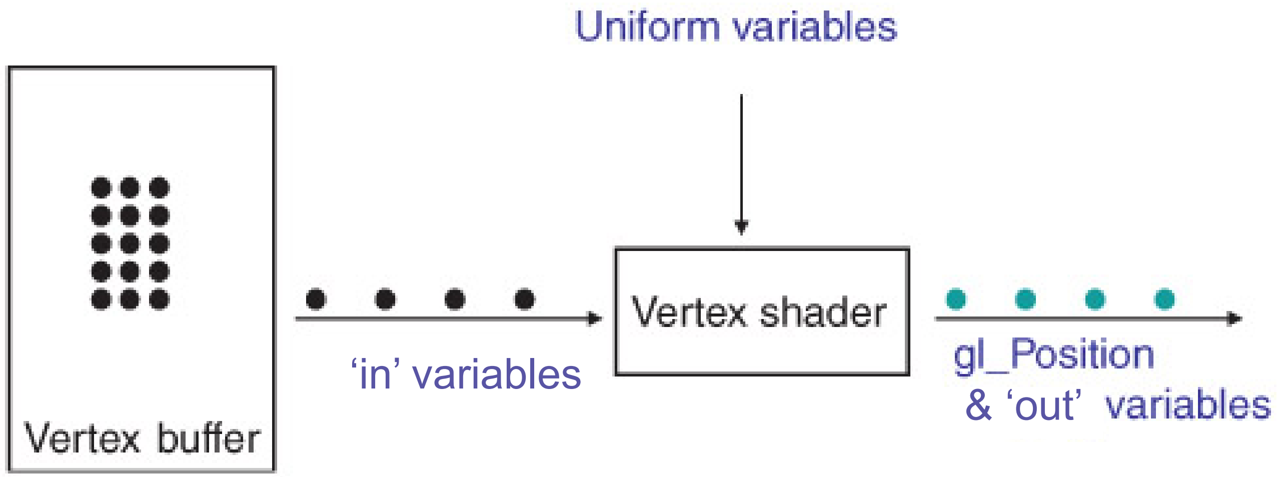
```
vec3 vertices[150];
vertices[0].position = { -0.54, +1.34, -0.01 };
vertices[1].position = { +0.75, +1.21, -0.01 };
…
vertices[150].position = { -1.22, +3.59, -0.01 };

uint16_t indices[] = { 0, 3, 1,.. , 152, 150 };
Gluint vbo;
glGenBuffers(vbo);
glBindBuffer(vbo);
glBufferData(vbo, vertices);
Gluint ibo;
glGenBuffers(ibo);
glBindBuffer(ibo);
glBufferData(ibo, indices);
```



Vertex Shader

- VS is run for each vertex SEPARATELY
  - *doesn't know connectivity (by default)*
- Input:
  - *vertex coordinates in Object Coordinate System*
  - *vertex attributes: color, normal, …*
  - *uniform/global variables*
- It's primary role is to transform

Object coordinates
-> WORLD coordinates
-> VIEW coordinates



Recap: GLSL Vertex shader

The OpenGL Shading Language (GLSL)

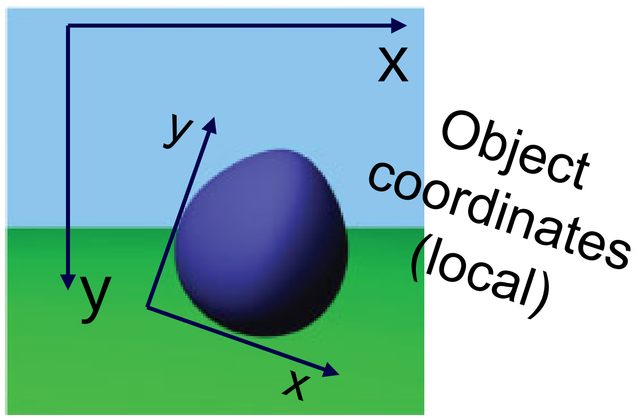
- Syntax similar to the C programming language
- Build-in vector operations
  - functionality as the GLM library our assignment template uses

```
uniform mat3 transform;
uniform mat3 projection;

void main() {
    // Transforming The Vertex
    vec3 out_pos = projection * transform * vec3(in_pos.xy, 1.0);
    gl_Position = vec4(out_pos.xy, in_pos.z, 1.0);
}
```

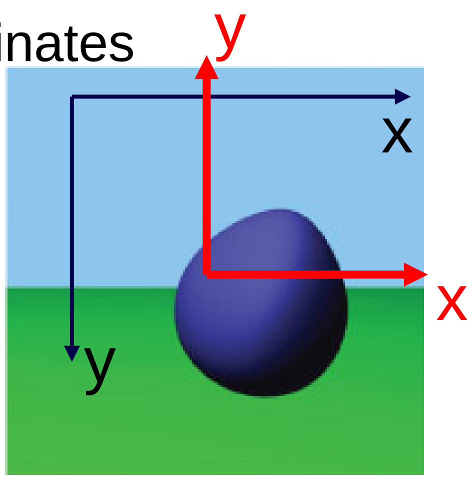
world
-> camera

object
-> world

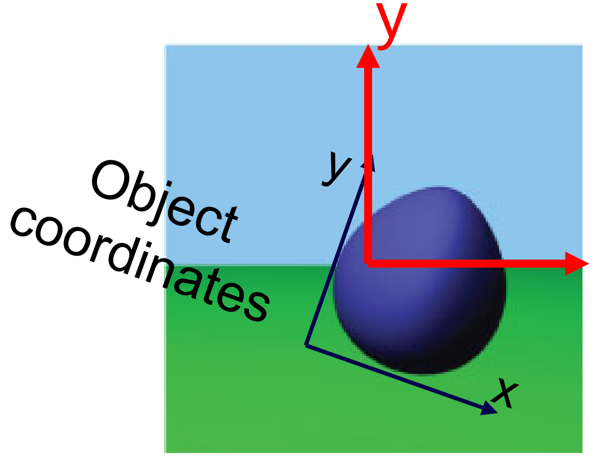
Recap: From local object to camera coordinates



object -> world



world -> camera



object -> camera

`transform` **`projection`** **`projection * transform`**

Setting (Vertex) Shader Variables

Uniform variable

```
mat3 projection_2D{ { sx, 0.f, 0.f },{ 0.f, sy, 0.f },{ tx, ty, 1.f } }; // affine transformation as introduced in the prev. lecture
GLint projection_uloc = glGetUniformLocation(texmesh.effect.program, "projection");
glUniformMatrix3fv(projection_uloc, 1, GL_FALSE, (float*)&projection);
```

In variable (attribute for every vertex)

```
// assuming vbo contains vertex position information already
GLint vpositionLoc = glGetAttribLocation(program, “in_position");
glEnableVertexAttribArray(vpositionLoc);
glVertexAttribPointer(vpositionLoc, 3, GL_FLOAT, GL_FALSE, sizeof(vec3), (void*)0);
```

Variable Types

Uniform

- same for all vertices

Out/In (varying)

- computed per vertex, automatically interpolated for fragments

In (attribute)

- values per vertex
- available only in Vertex Shader

Salmon Vertex shader

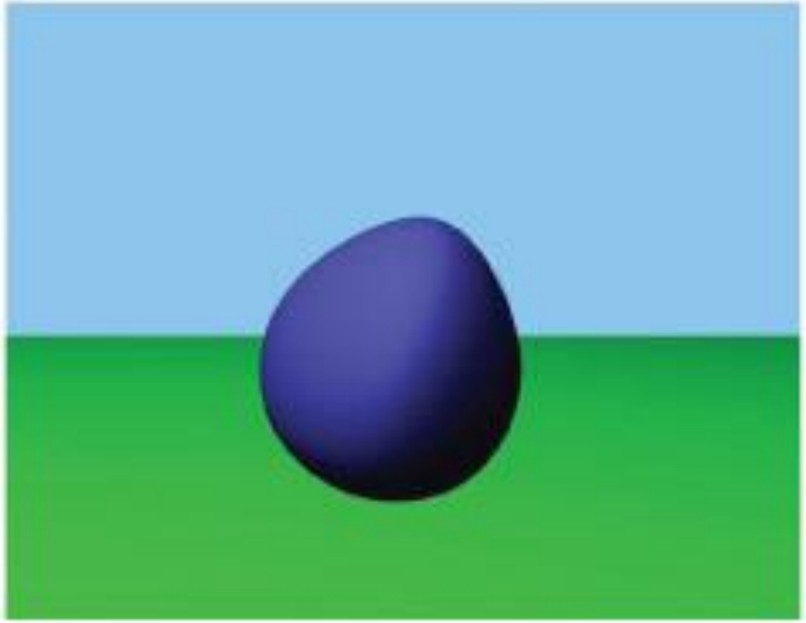
```
#version 330
// Input attributes
in vec3 in_position;
in vec3 in_color;

out vec3 vcolor;
out vec2 vpos;

// Application data
uniform mat3 transform;
uniform mat3 projection;

void main() {
        vpos = in_position.xy; // local coordinated before transform
        vcolor = in_color;
        vec3 pos = projection * transform * vec3(in_position.xy, 1.0);
        gl_Position = vec4(pos.xy, in_position.z, 1.0);
}
```

pass on color and position in object coordinates

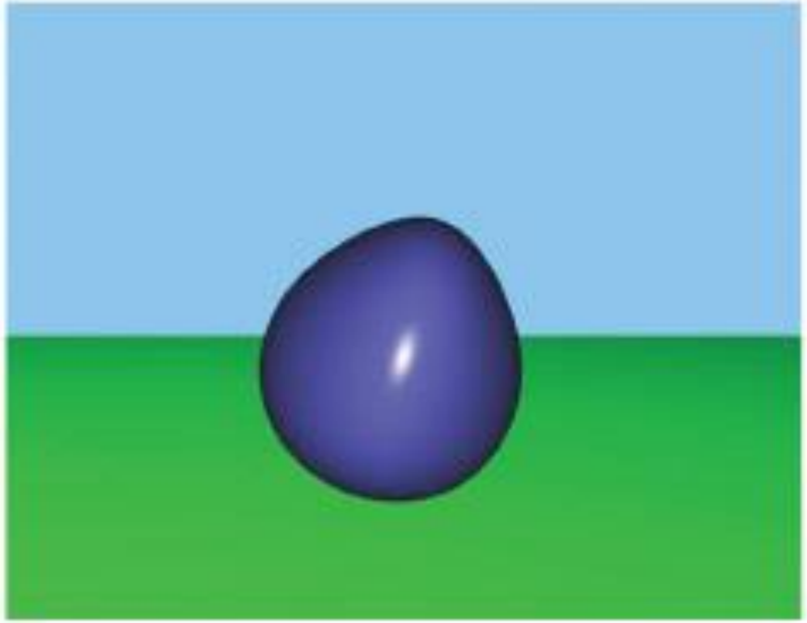
as before

Recap: Fragment shader examples

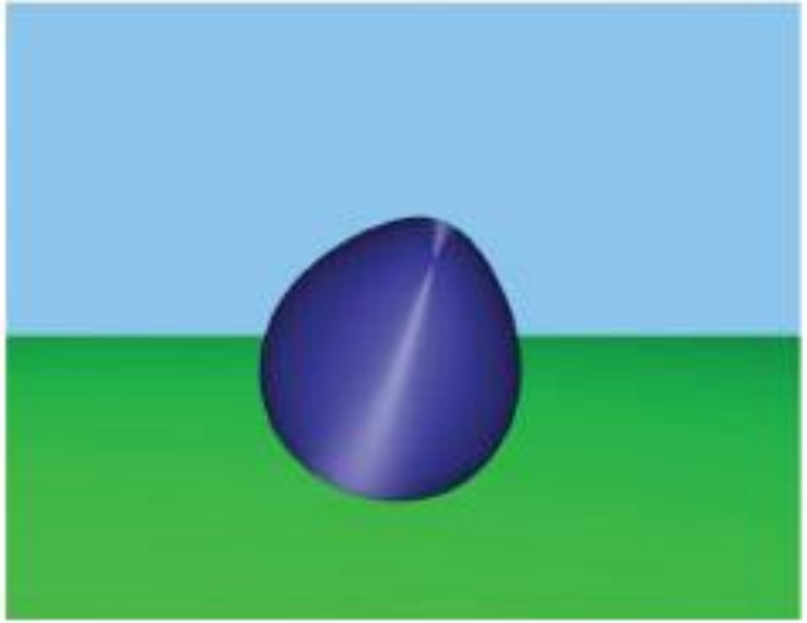
- ***simulates materials and lights***
- ***can read from textures***



Diffuse



Specular



Directional

Salmon Fragment shader

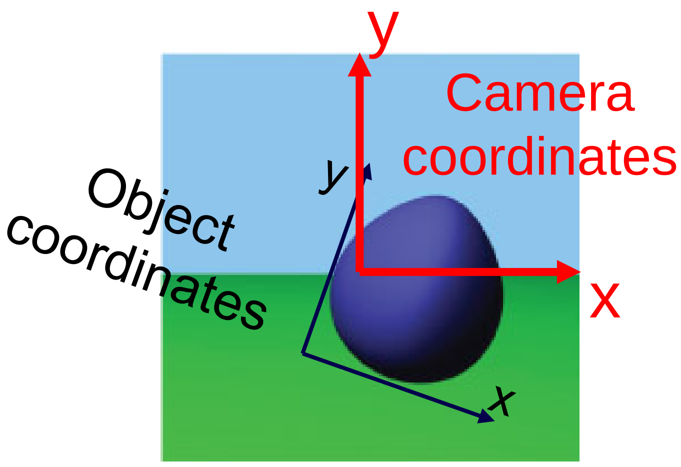
```
#version 330
// From Vertex Shader
in vec3 vcolor;
in vec2 vpos; // Distance from local origin

// Application data
uniform vec3 fcolor;
uniform int light_up;

// Output color
layout(location = 0) out vec4 color;

void main() {
        color = vec4(fcolor * vcolor, 1.0);

        // Salmon mesh is contained in a 1x1 square
        float radius = distance(vec2(0.0), vpos);
        if (light_up == 1 && radius < 0.3) {
                // 0.8 is just to make it not too strong
                color.xyz += (0.3 - radius) * 0.8 * vec3(1.0, 1.0, 0.0);
        }
}
```

interpolated vertex color, times global color

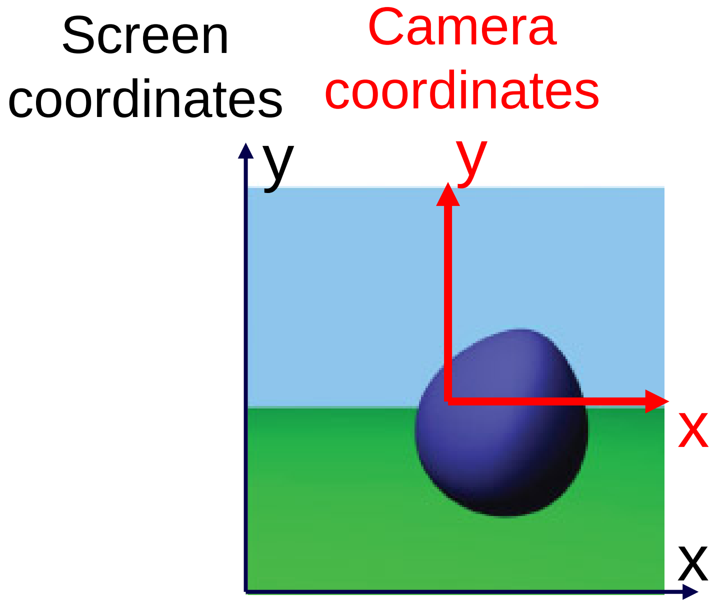
create a spherical highlight around the object center

(Hidden) Vertex Post-Processing

- Viewport transform: camera coordinates to screen/window coordinates
  - set with `glViewport(0, 0, w, h);`



object -> camera

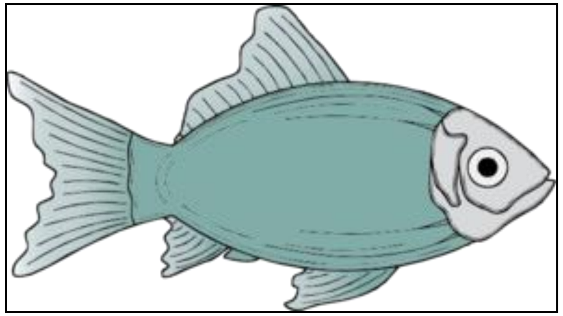


camera -> screen

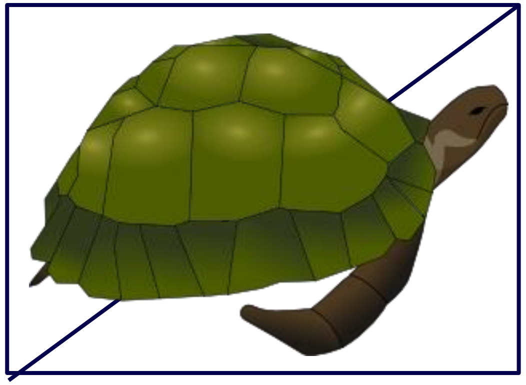
- Clipping: Removing invisible geometry (outside view frame)

SPRITES: Faking 2D Geometry

- Creating geometry is hard
- Creating texture is “easy”
- In 2D it is hard to see the difference

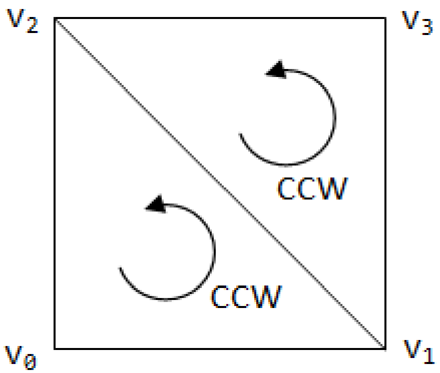


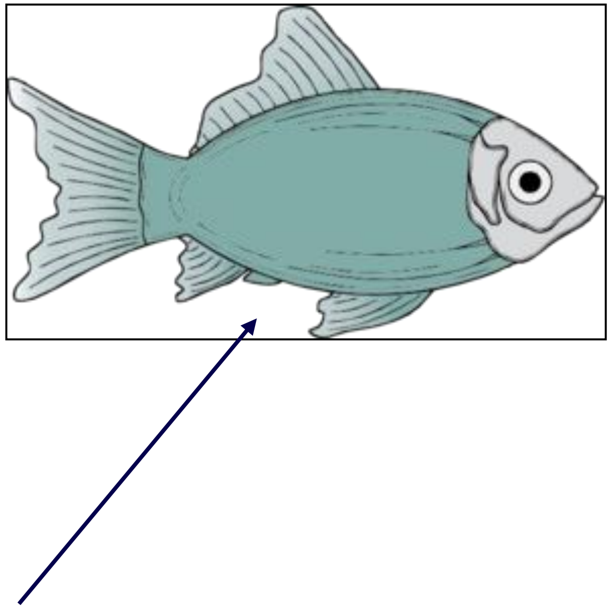
- SPRITE:
  - *Use basic geometry (rectangle = 2 triangles)*
  - *Texture the geometry (transparent background)*
  - *Use blending (more later) for color effects*



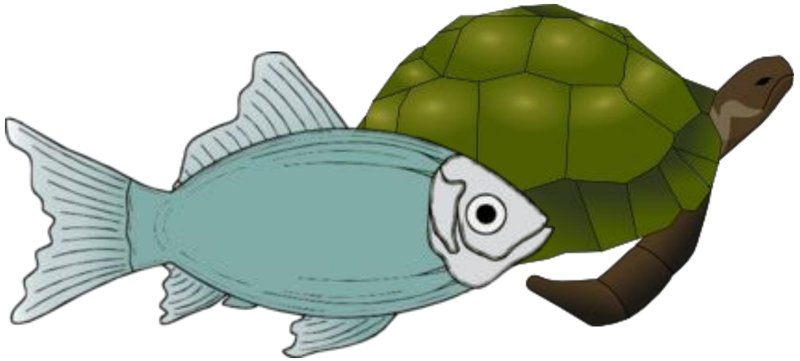
Sprite basics

A textured quad looks like fine-grained 2D geometry





Transparent with alpha = 0
e.g., color_RGBA = {1,1,1,0}



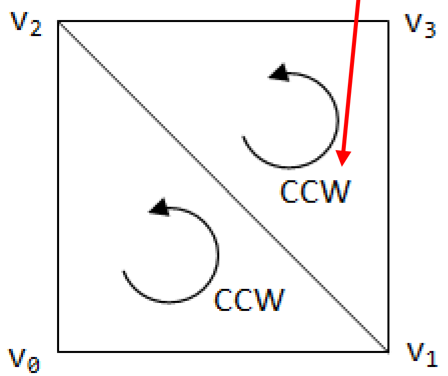
Proper occlusion despite simple geometry

SPRITES: Creation

OpenGL initialization (once):

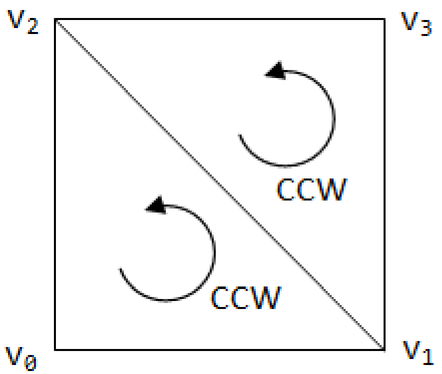
Counter-clockwise winding (CCW)

Create Quad Vertex Buffer




```
vec3 vertices[] = { v0, v1, v2, v3 };

glGenBuffers(1, &vbo);
glBindBuffer(GL_ARRAY_BUFFER, vbo);
glBufferData(GL_ARRAY_BUFFER, vertices_size, vertices,
GL_STATIC_DRAW);
```

SPRITES: Creation

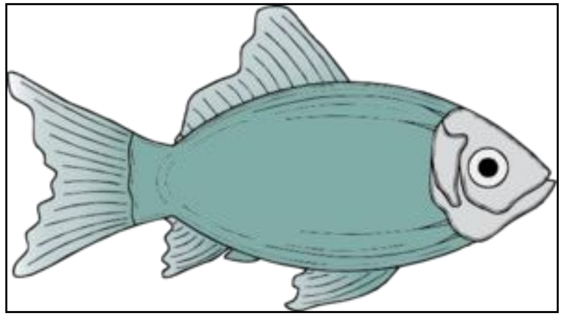


OpenGL initialization (once):

Create Quad Index Buffer

```
uint16_t indices[] = { 0, 1, 2, 1, 3, 2 };
Gluint ibo;
glGenBuffers(1, &ibo);
glBindBuffer(GL_ELEMENT_ARRAY_BUFFER,ibo);
glBufferData(GL_ELEMENT_ARRAY_BUFFER, indices_size, indices,
GL_STATIC_DRAW);
```

Load Texture



```
Gluint tex_id;
glGenTextures(1, &tex_id);
glBindTexture(GL_TEXTURE_2D, tex_id);
glTexImage2D(GL_TEXTURE_2D, GL_RGBA, width, height, .., tex_data);
```

SPRITES: Rendering

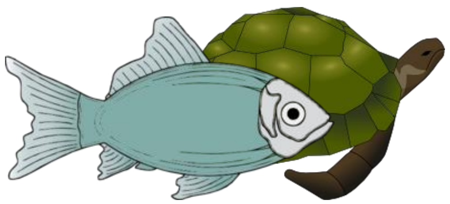
OpenGL rendering (every frame):

Bind Buffers

```
glBindVertexArray(vao);
glBindBuffer(GL_ARRAY_BUFFER, vbo);
glBindBuffer(GL_ELEMENT_ARRAY_BUFFER, ibo);
```

Enable Alpha Blending

```
glEnable(GL_BLEND);
glBlendFunc(GL_SRC_ALPHA, GL_ONE_MINUS_SRC_ALPHA);
// Alpha Channel Interpolation
// RGB_o = RGB_src * ALPHA_src + RGB_dst * (1 - ALPHA_src)
```



SPRITES: Rendering

Bind Texture

```
glActiveTexture(GL_TEXTURE0);
glBindTexture(GL_TEXTURE_2D, texmesh.texture.texture_id);
```

Draw

```
glDrawElements(GL_TRIANGLES, 6, ..); // 6 is the number of indices
```

Color and Texture Mapping

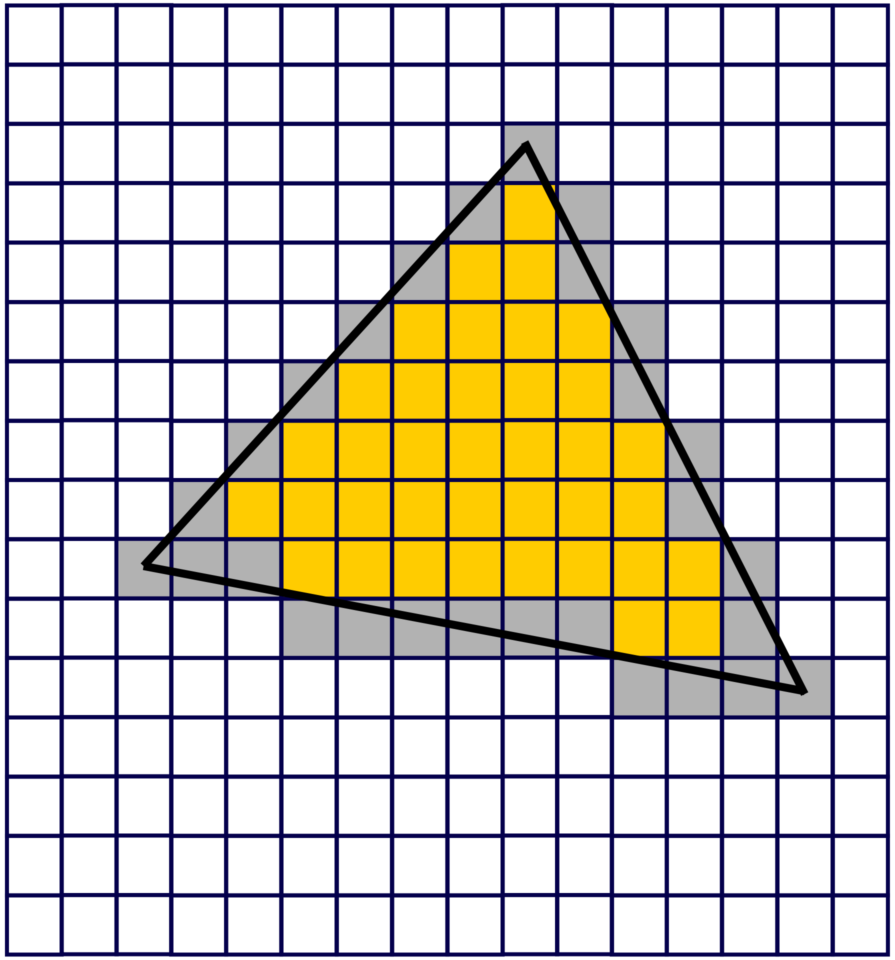
- ***How to map from a 2D texture to a 3D object that is projected onto a 2D scene?***

Scan Conversion/Rasterization

- Convert continuous 2D geometry to discrete
- Raster display – discrete grid of elements
- Terminology

  - ***Screen Space:*** *Discrete 2D Cartesian coordinate system of the screen pixels*

Scan Conversion

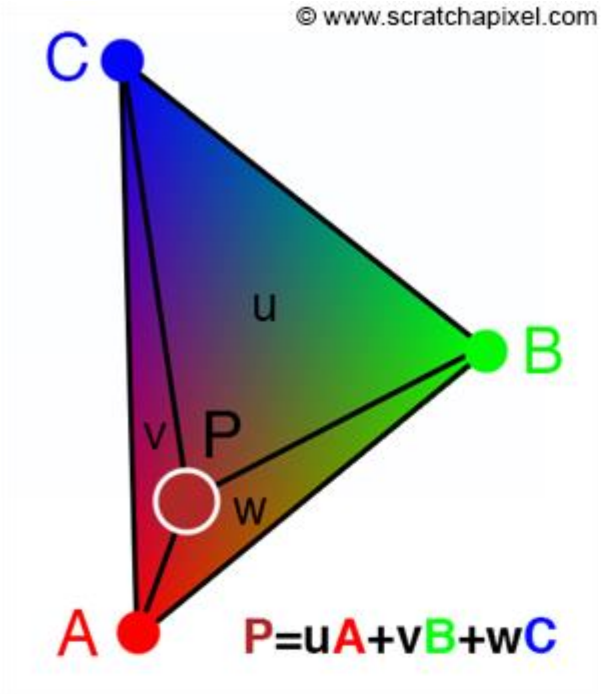


Self study:

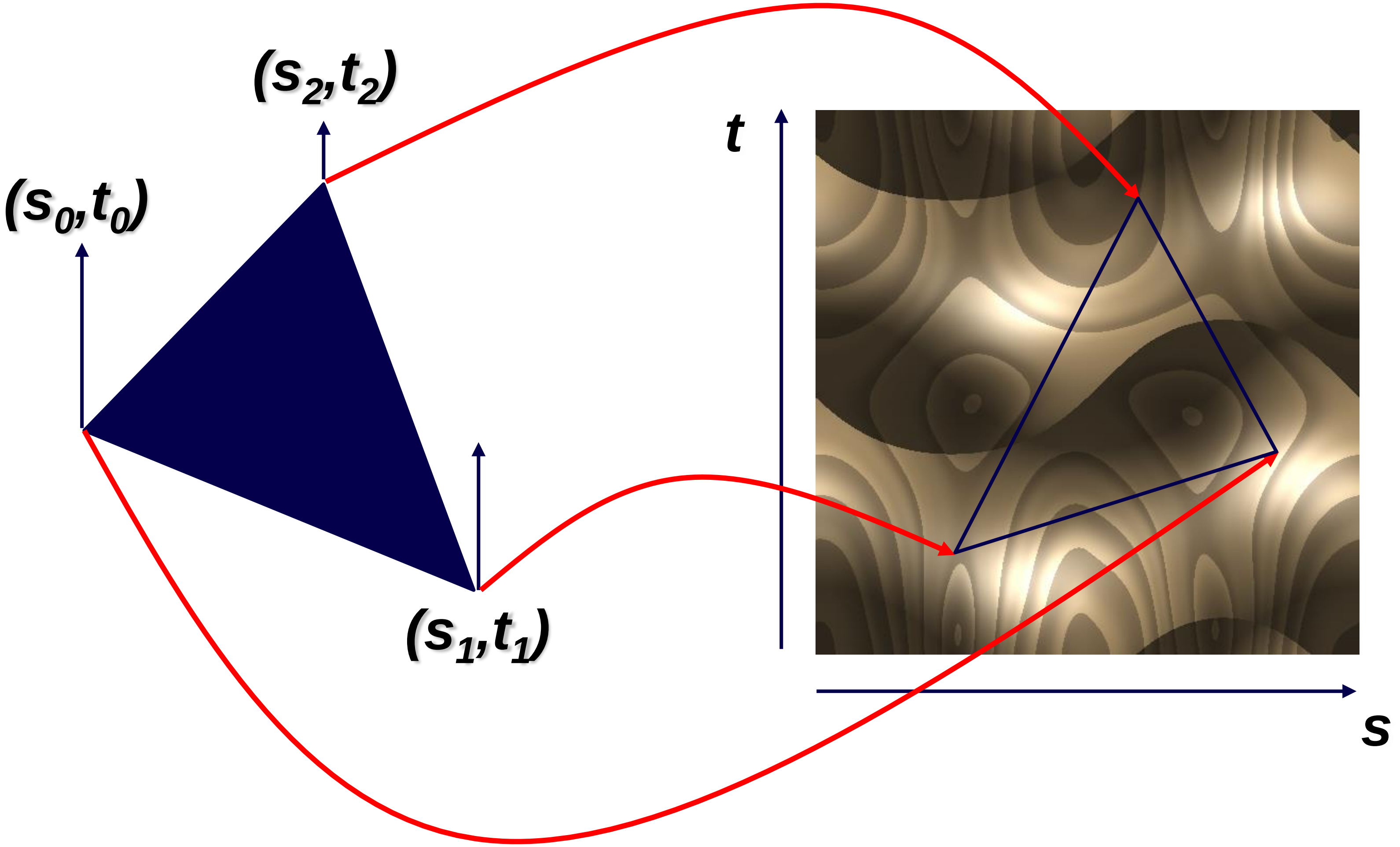
Interpolation with barycentric coordinates

- *linear combination of vertex properties*
  - *e.g., color, texture coordinate, surface normal/direction, …*

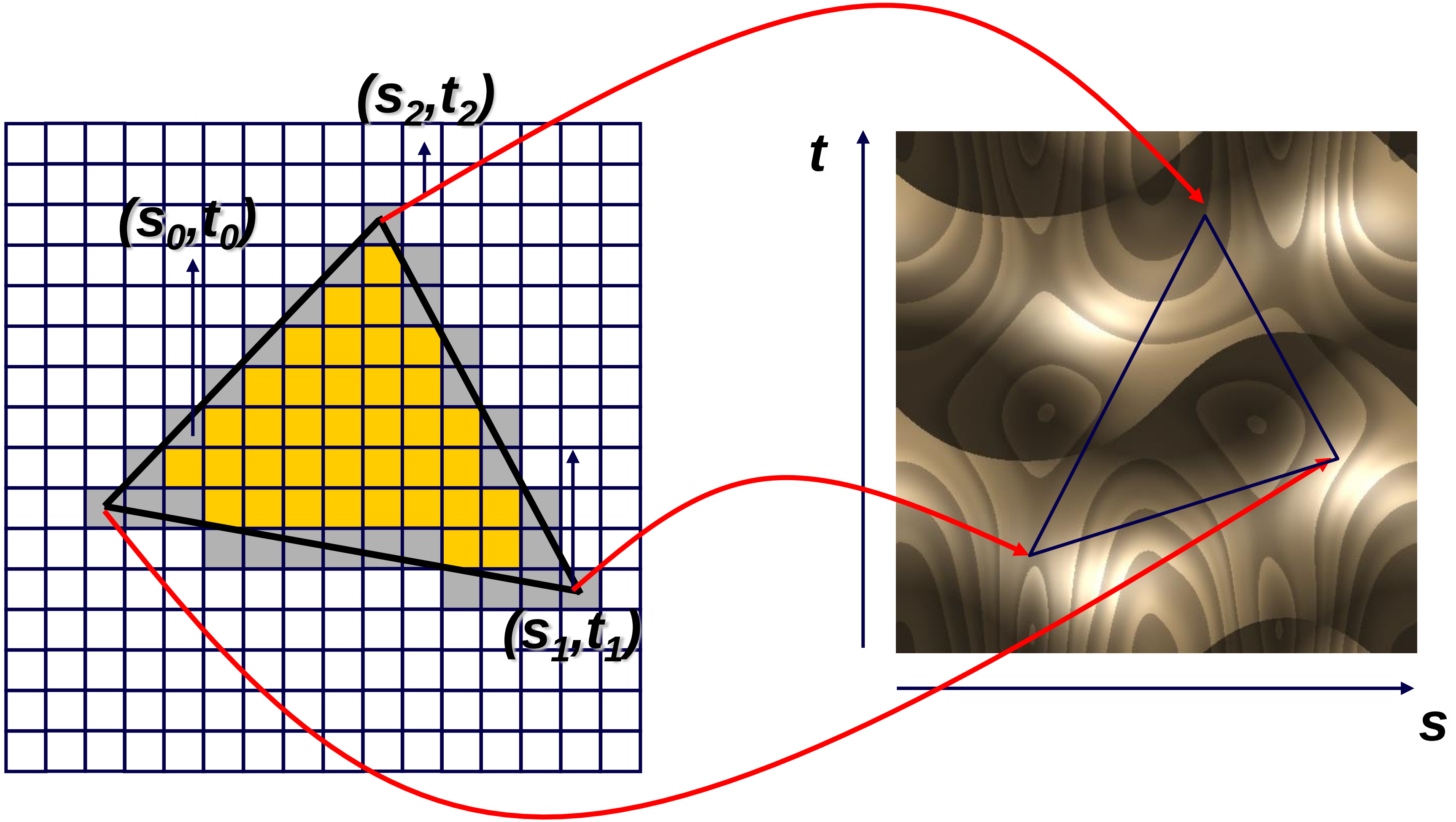
- *weights are proportional to the areas spanned by the sides to query point P*



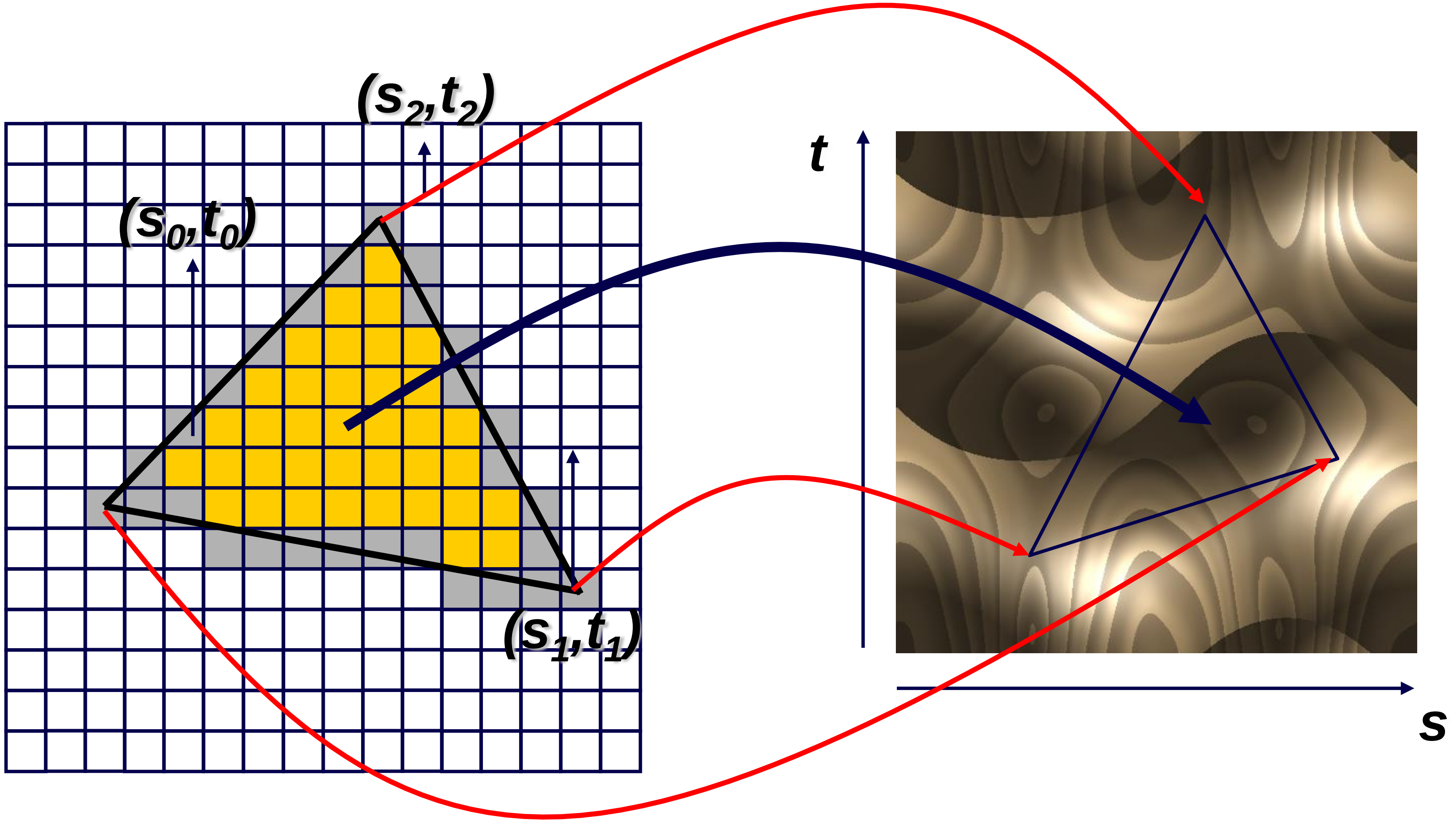
Texture mapping



Texture mapping



Texture mapping



Blending

Blending:

- Fragments -> Pixels
- Draw from farthest to nearest
- No blending – replace previous color
- Blending: combine new & old values with some arithmetic operations
  - *Achieve transparency effects*

Frame Buffer : video memory on graphics board that holds resulting image & used to display it

Depth Test / Hidden Surface Removal

Remove occluded geometry

- Parts that are hidden behind other geometry
- For 2D (view parallel) shapes – use depth order
  - *draw objects back to front*
    - sort objects: furthest object first, closest object last

Self study: Alternative to ordering

Depth buffer with transparent sprites

- ***Fragment shader writes depth to the depth buffer***
  - *discard fragment if depth larger than current depth buffer (occluded)*
  - *alleviates the ordering of objects*
- ***Issue, depth buffer written for fragments with alpha = 0***
- ***Solution:***
  explicitly discard fragments with alpha < 0.5
  - *note, texture sample interpolation leads to non-binary values even if texture is either 0 or 1.*

```
#version 330
in vec2 texCoord;
out vec4 outColor;
uniform sampler2D theTexture;

void main() {
  vec4 texel = texture(theTexture, texCoord);
  if(texel.a < 0.5)
    discard;
  outColor = texel;
}
```