Course 2: Rendering and Transformations

Today

- *Game loop*
- *2D Transformations*
- *Rendering*

The game loop

Can you imagine a game without?

A game is a simulator

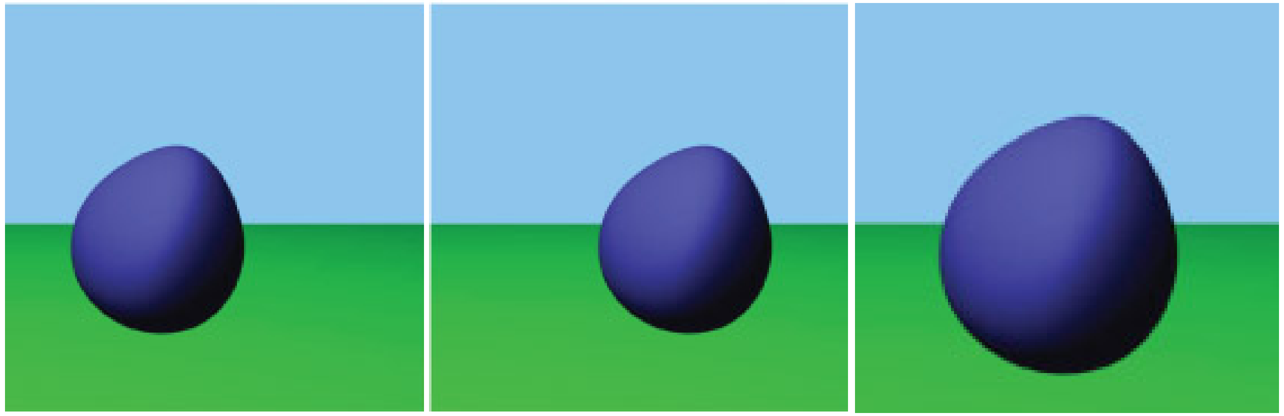
1. ***AI and user input***
2. ***Environment reaction***
3. ***Equations of Motion***
   - sum forces & torques, solve for accelerations: $\vec{\boldsymbol{F}} = \boldsymbol{ma}$
4. ***Numerical integration***
   - update positions, velocities
5. ***Collision detection***
6. ***Collision resolution***

We will have a separate lecture on physics simulation!

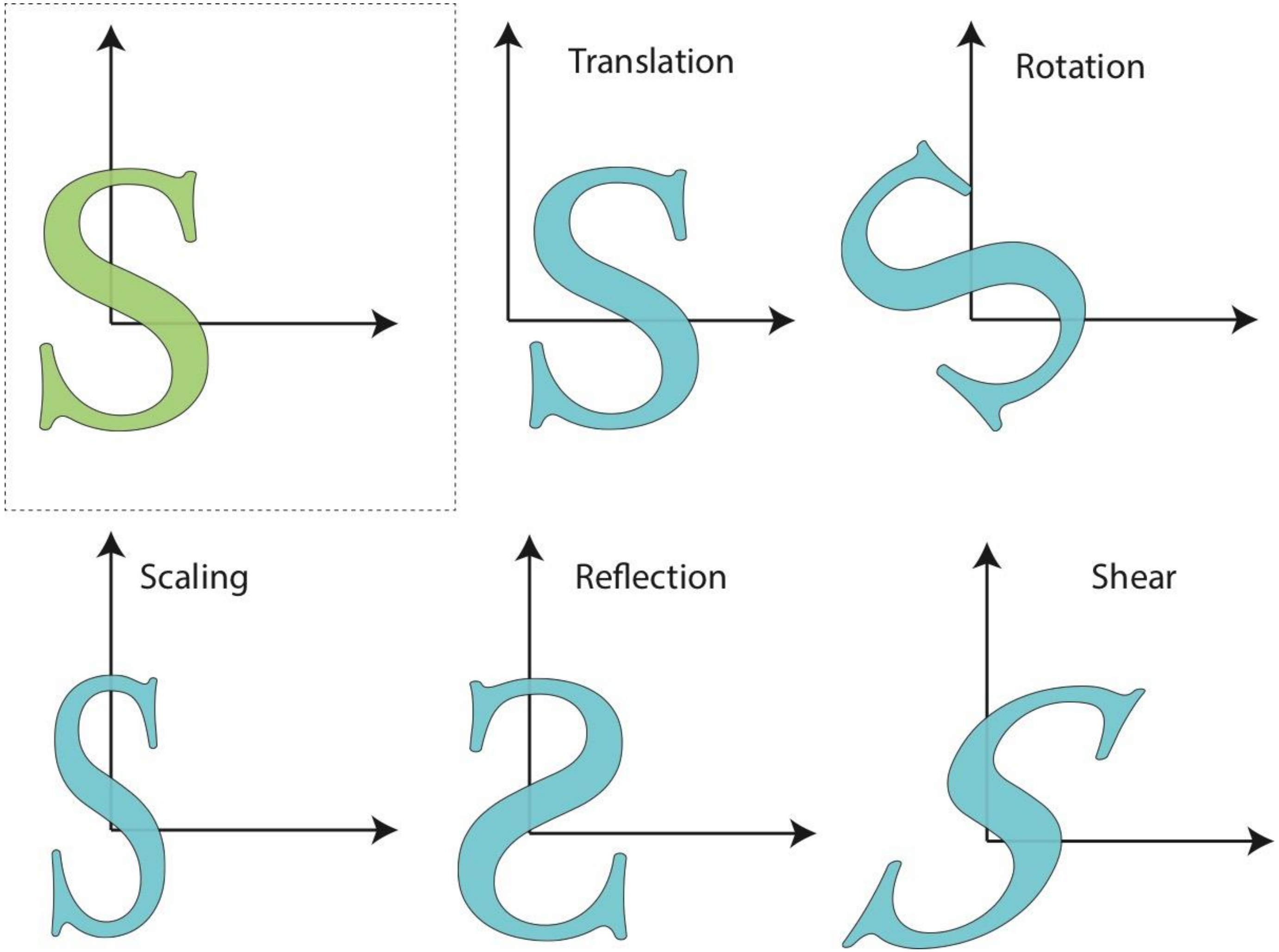
A game loop

```
// Set all states to default
world.restart();
auto t = Clock::now();
// Variable timestep loop
while (!world.is_over())
{
    // Processes system messages, if this wasn't present the window would become unresponsive
    glfwPollEvents();

    // Calculating elapsed times in milliseconds from the previous iteration
    auto now = Clock::now();
    float elapsed_ms = static_cast<float>((std::chrono::duration_cast<std::chrono::microseconds>(now - t)).count()) / 1000.f;
    t = now;

    DebugSystem::clearDebugComponents();
    ai.step(elapsed_ms, window_size_in_game_units);
    world.step(elapsed_ms, window_size_in_game_units);
    physics.step(elapsed_ms, window_size_in_game_units);
    world.handle_collisions();

    renderer.draw(window_size_in_game_units);
}

return EXIT_SUCCESS;
```

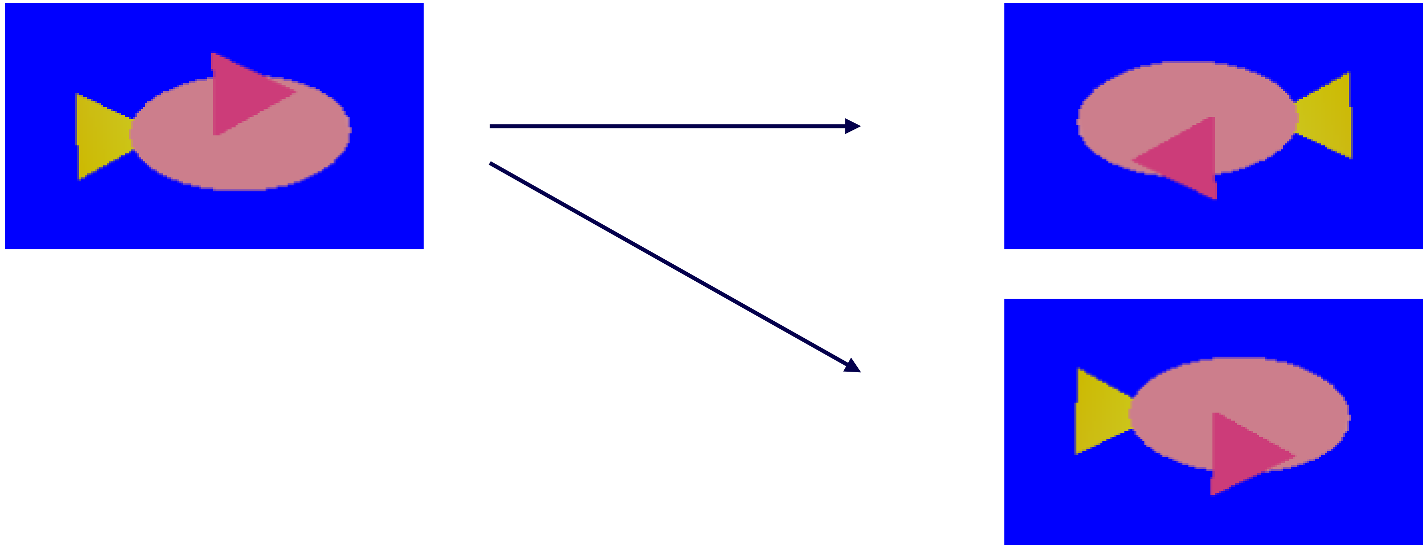
Transformations



Modeling Transformations



How to turn the fish?



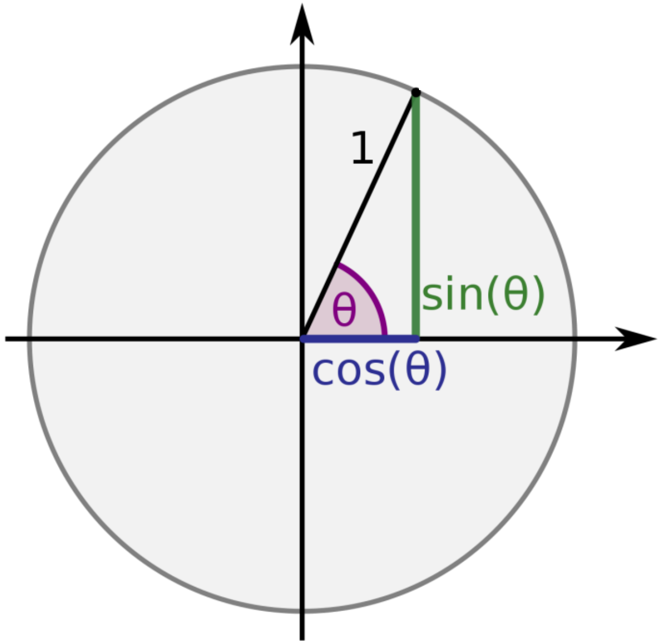
Linear transformations

- Rotations, scaling, shearing
- Can be expressed as 2x2 matrix (for 2D points)
- E.g.

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} 2 & 0 \\ 0 & 2 \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

- or a rotation

$$\begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$



Rotation angle θ, cos, and sin

https://en.wikipedia.org/wiki/Trigonometric_functions

Affine transformations

- Linear transformations + translations
- Can be expressed as 2x2 matrix + 2 vector
- E.g. scale+ translation:

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} 2 & 0 \\ 0 & 2 \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} + \begin{pmatrix} t_x \\ t_y \end{pmatrix}$$

Modeling Transformation

Adding a third coordinate

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} 2 & 0 \\ 0 & 2 \end{pmatrix}\begin{pmatrix} x \\ y \end{pmatrix} + \begin{pmatrix} t_x \\ t_y \end{pmatrix} \quad \Rightarrow \quad \begin{pmatrix} x' \\ y' \\ 1 \end{pmatrix} = \begin{pmatrix} 2 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} x \\ y \\ 1 \end{pmatrix} + \begin{pmatrix} t_x \\ t_y \\ 0 \end{pmatrix}$$

$$= \begin{pmatrix} 2 & 0 & t_x \\ 0 & 2 & t_y \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} x \\ y \\ 1 \end{pmatrix}$$

Affine transformations are now linear

- one 3x3 matrix can express: 2D rotation, scale, shear, and translation

Combination of Transformations?

- ***How can we combine***
  - translation
  - rotation
  - scaling

… into one matrix?

Self study: Homogeneous coordinates

- Homogeneous coordinates are defined as vectors, with equivalence

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} x/z \\ y/z \\ 1 \end{pmatrix} = \begin{pmatrix} x\lambda \\ y\lambda \\ z\lambda \end{pmatrix}$$

- Can also represent projective equations
- homogeneous matrix becomes 4x4

$$\begin{pmatrix} x' \\ y' \\ z' \\ 1 \end{pmatrix} = \begin{pmatrix} 2 & 0 & 0 & t_x \\ 0 & 2 & 0 & t_y \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix}$$

Rendering basics

What is rendering?

Generating an image from a (3D) scene

Let's think how!

Scene

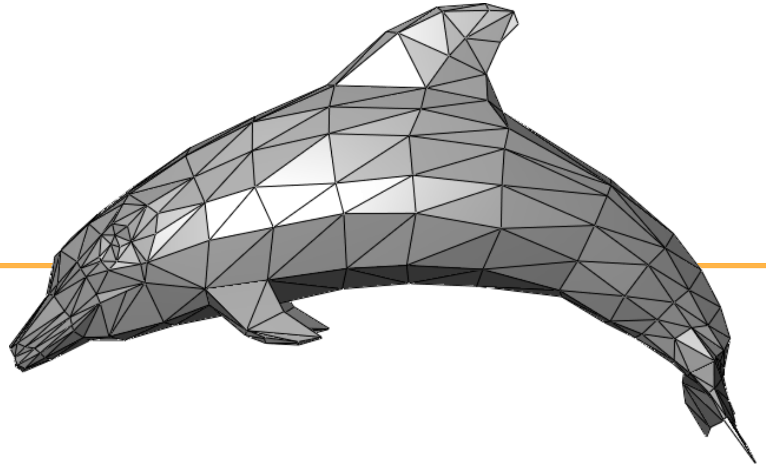
- A coordinate frame
- Objects
- Their materials
- (Lights)
- (Camera)

Object

Most common:

- ***surface representation***

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

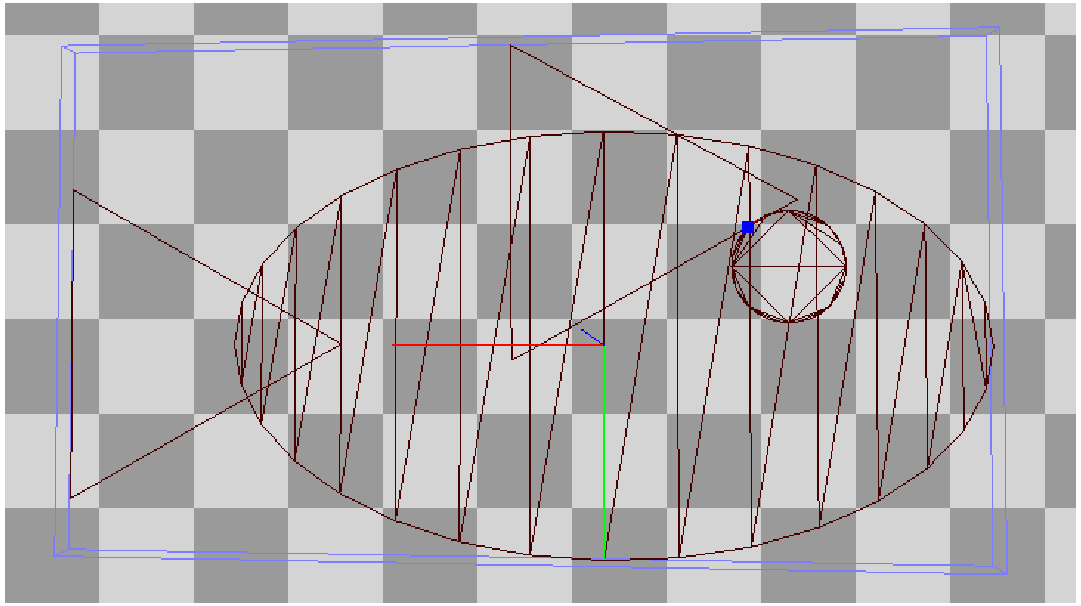
- vertex buffer
- index buffer

Creation

```
Gluint vbo;
glGenBuffers(vbo);

Gluint ibo;
glGenBuffers(ibo);
```

Programmatic geometry definition

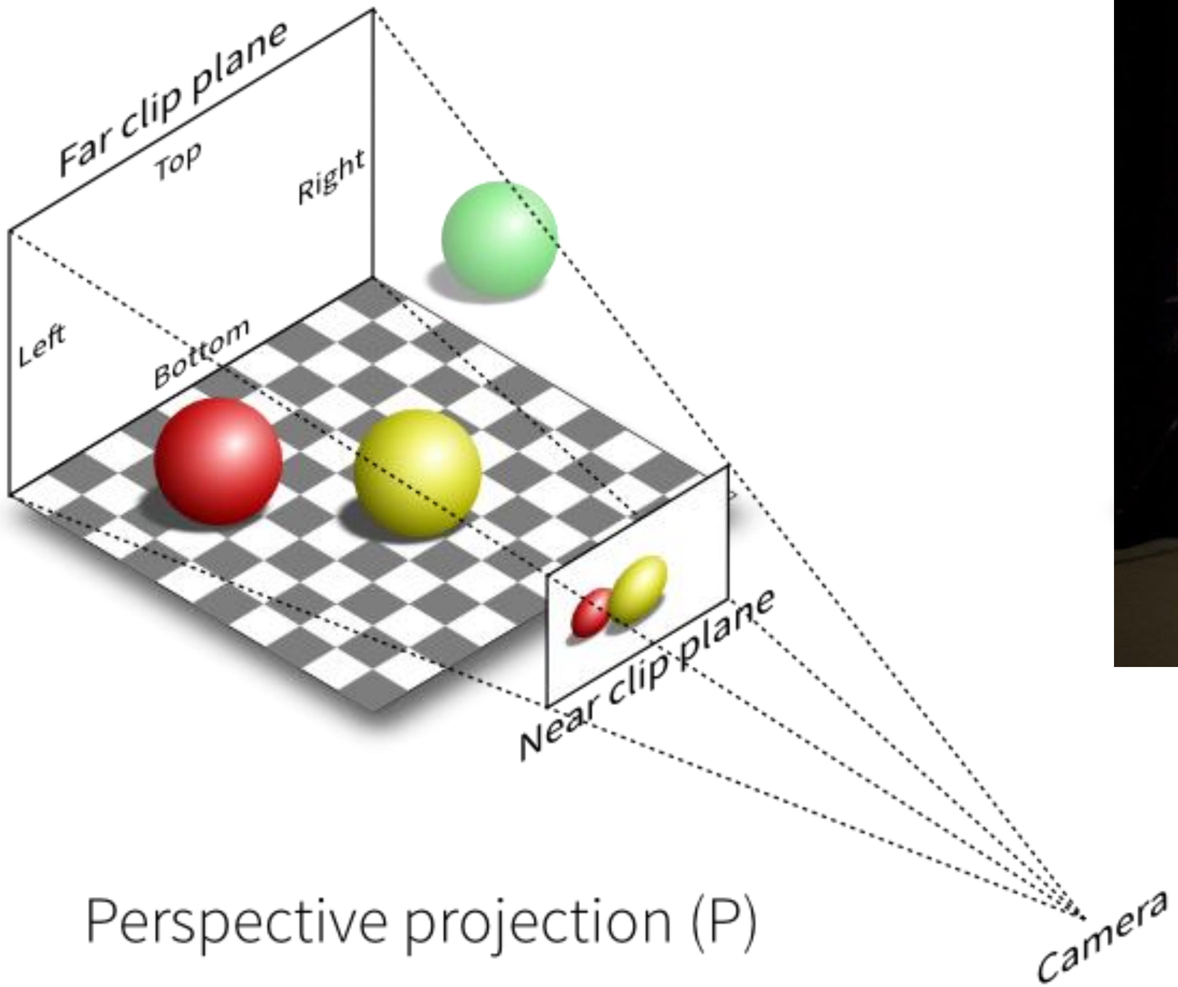
```
vec3 vertices[153];
vertices[0].position = { -0.54, +1.34, -0.01 };
vertices[1].position = { +0.75, +1.21, -0.01 };
…
vertices[152].position = { -1.22, +3.59, -0.01 };

uint16_t indices[] = { 0,3,1, 0,4,1,... , 151,152,150 };
Gluint vbo;
glGenBuffers(vbo);
glBindBuffer(vbo);
glBufferData(vbo, vertices);
Gluint ibo;
glGenBuffers(ibo);
glBindBuffer(ibo);
glBufferData(ibo, indices);
```



Image

A grid of color values

Virtual Camera

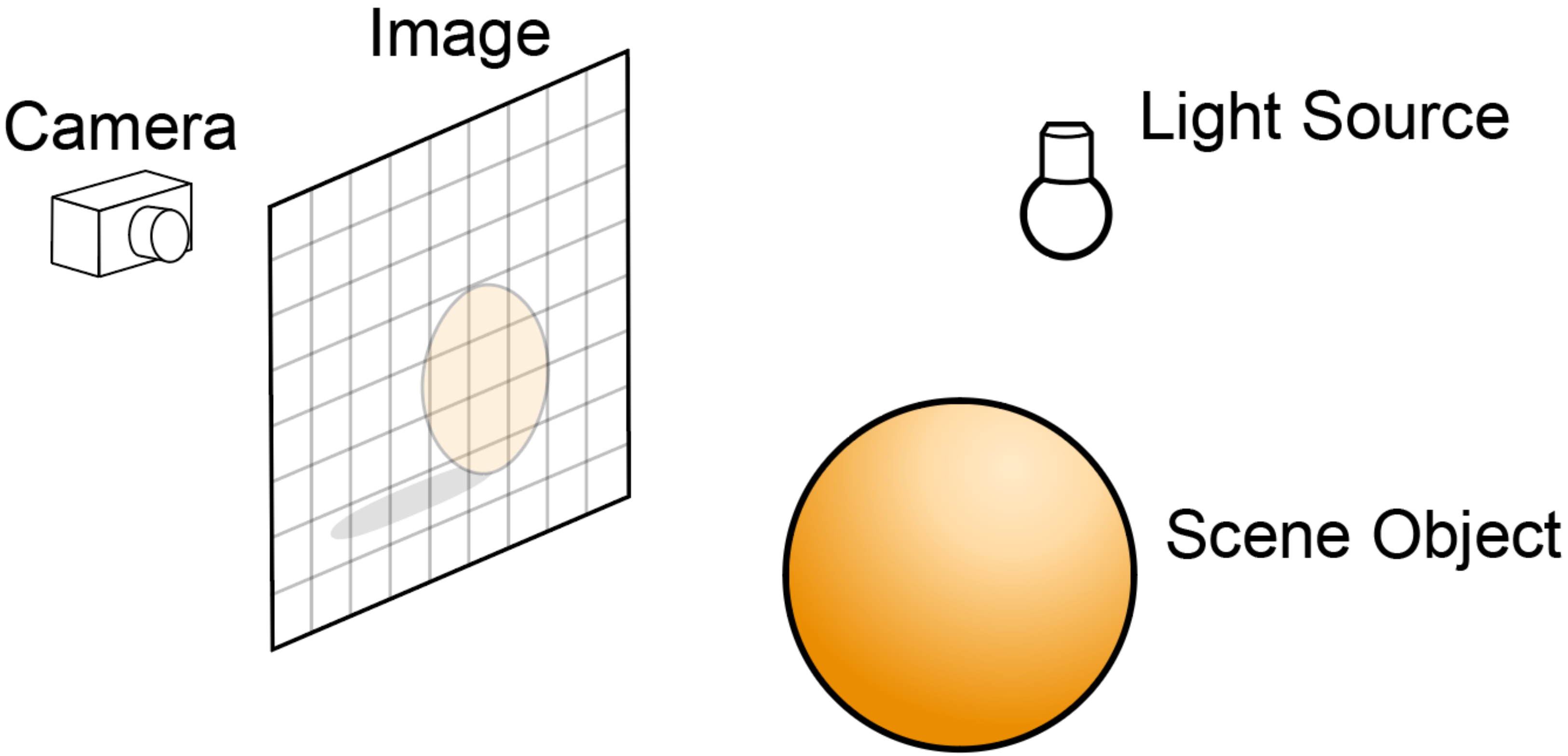


Perspective projection (P)

Virtual camera registered in the real world
(using marker-based motion capture)

Rendering?

- ***Simulating light transport***
  - How to simulate light efficiently?



Rendering – Photon Tracing

- ***simulate physical light transport from a source to the camera***
  - *the paths of photons*

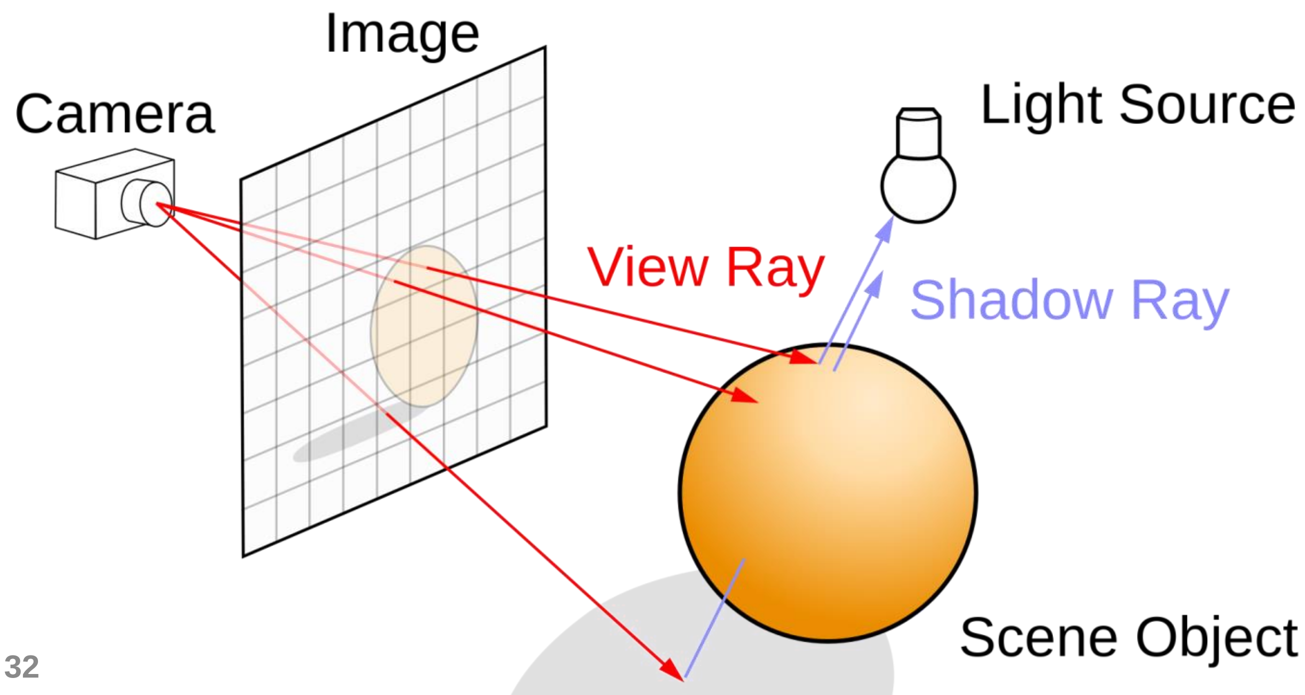
- ***shoot rays from the light source***
  - *random direction*
- ***compute first intersection***
  - *continue towards the camera*

- used for indirect illumination: ‘photon mapping’

Rendering – Ray Tracing

Start rays from the camera (opposes physics, an optimization)

- *View rays: trace from every pixel to the first occlude*
- *Shadow ray: test light visibility*



Nvidia RTX does ray tracing

Problems of ray tracing

- ***the collision detection is costly***
- ray-object intersection
  - *n objects*
  - *k rays*
  - *naïve: O(n*k) complexity*

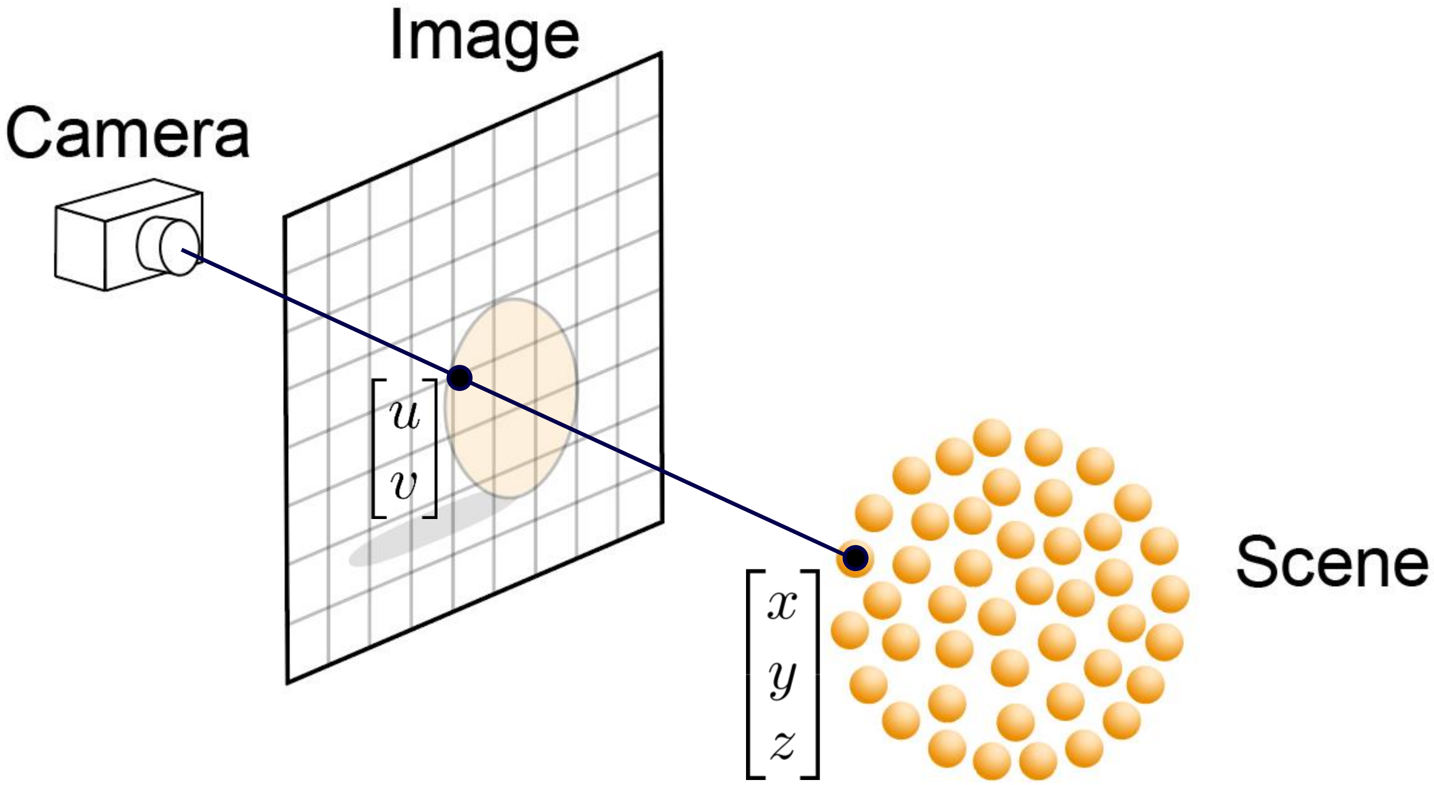
Rendering – Splatting

Approximate scene with spheres

- *sort spheres back-to front*
- *project each sphere*
  - simple equation

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

  - O(n) for n spheres



Many spheres needed!

Shadows?

Rendering – Rasterization

Approximate objects with triangles

1. *Project each corner/vertex*

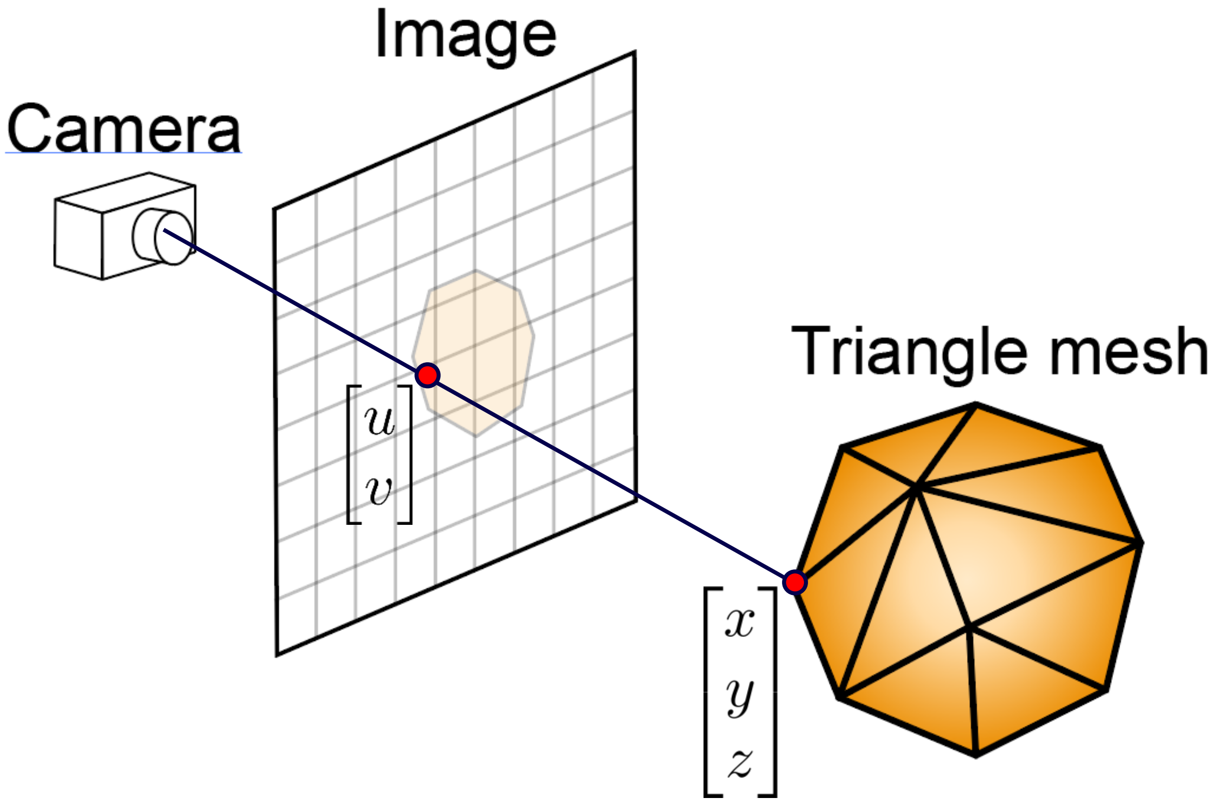
- projection of triangle stays a triangle

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

- O(n) for n vertices

2. *Fill pixels enclosed by triangle*

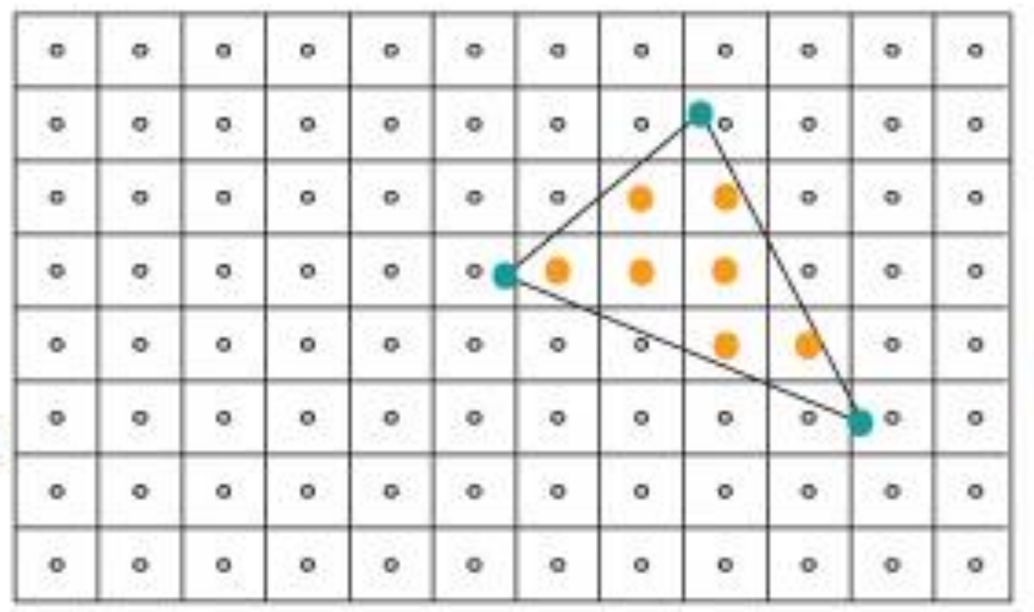
- e.g., scan-line algorithm



Rasterizing a Triangle

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

Vertices



Fragments

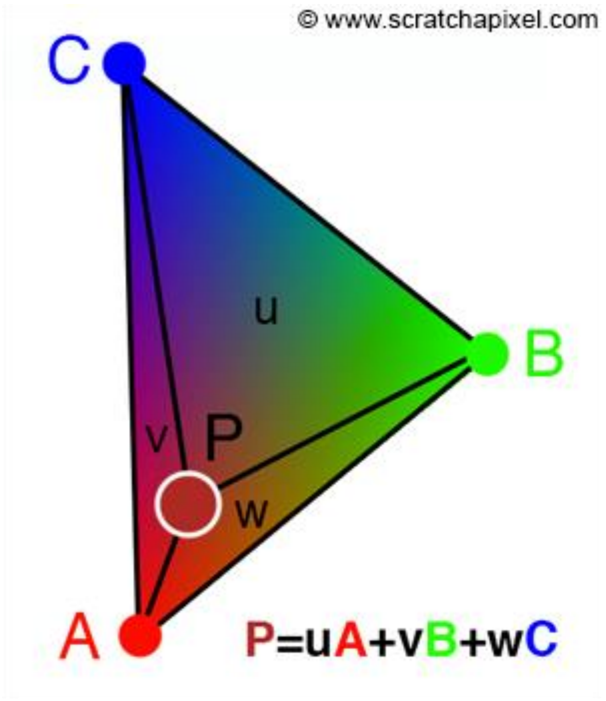
(for every pixel; color or attributes to compute color: texture coordinate, direction, …)

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*



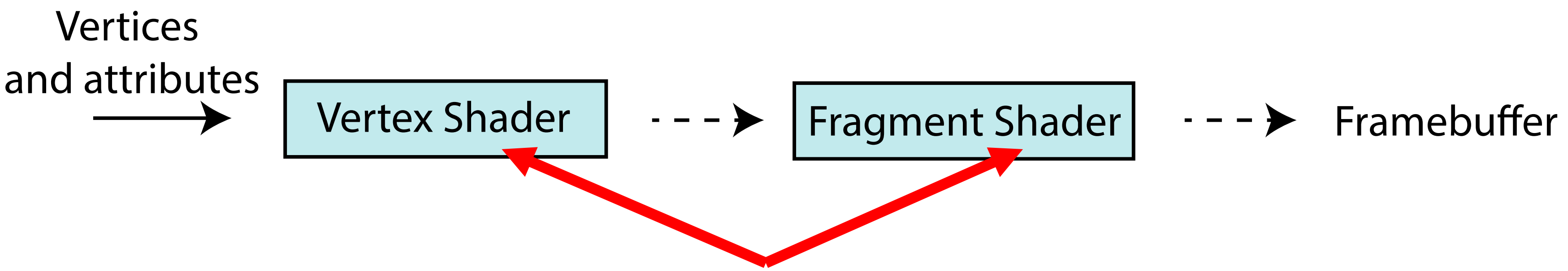
OpenGL Rendering Pipeline (simplified)

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

World Coordinates

Pixel-wise attributes

RGBA image

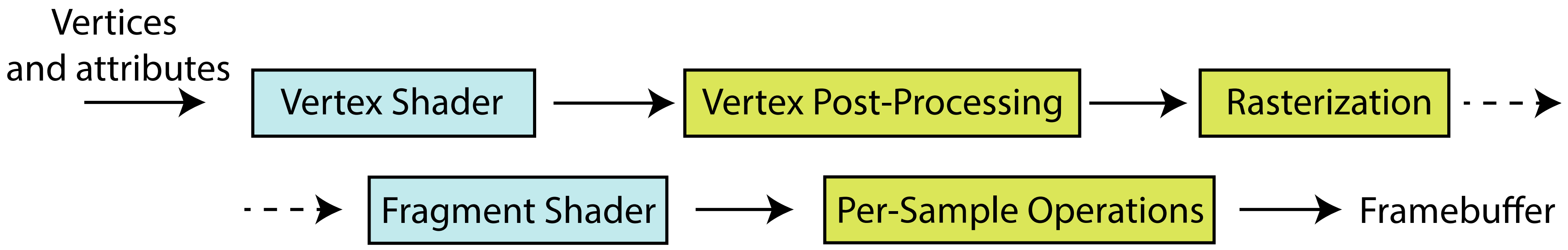


Shader: Programmable functions
to define object appearance locally
(vertex wise or fragment wise)

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)*

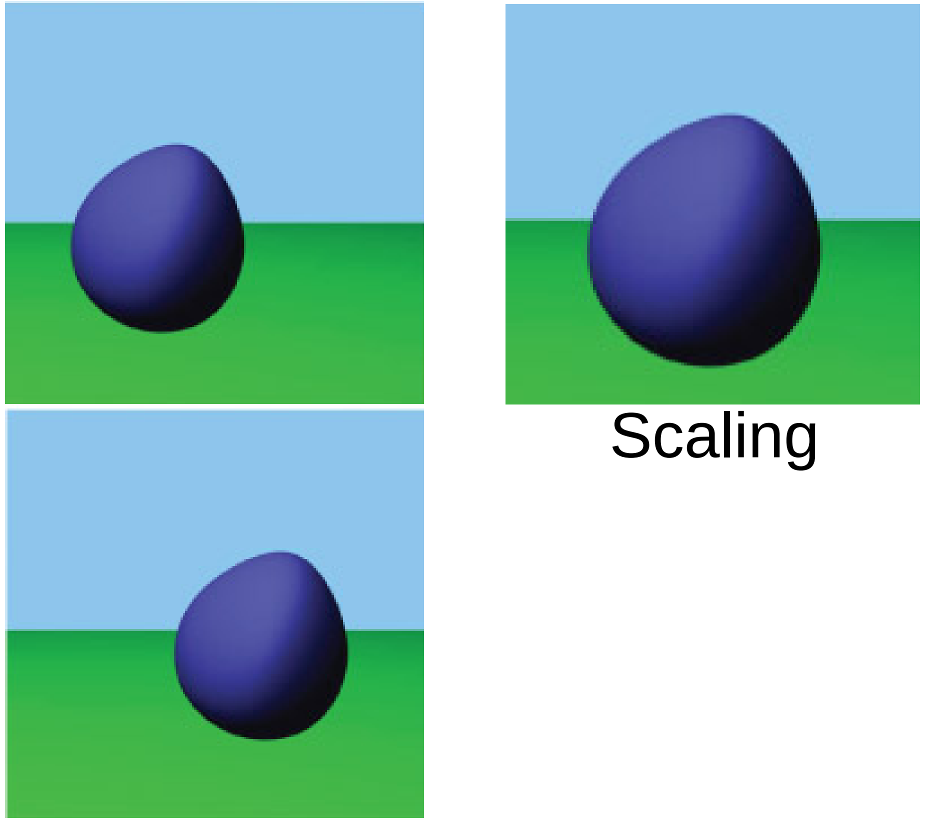
Vertex shader examples

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

x and y coordinates
of a vec2, vec3 or vec4

world
-> camera

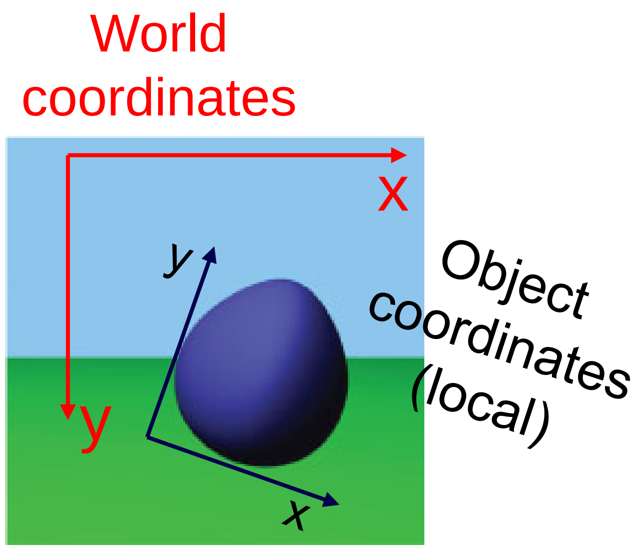
object
-> world

```
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);
}
```

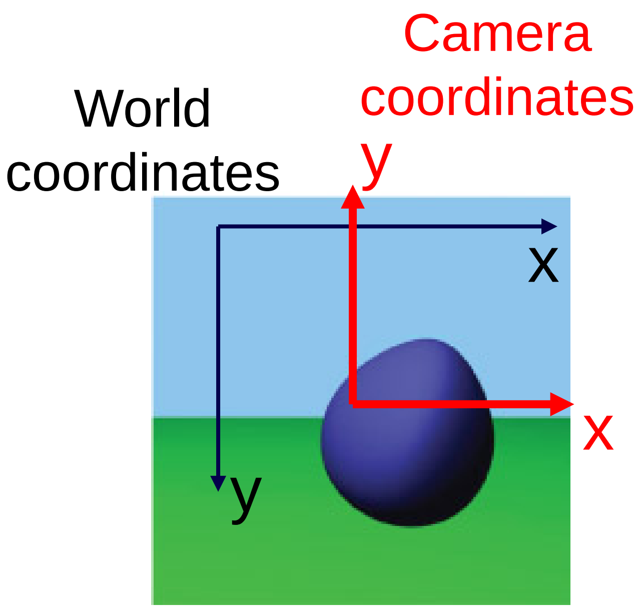
vector of 3 (vec3) and 4 (vec4) floats

float
(32 bit)

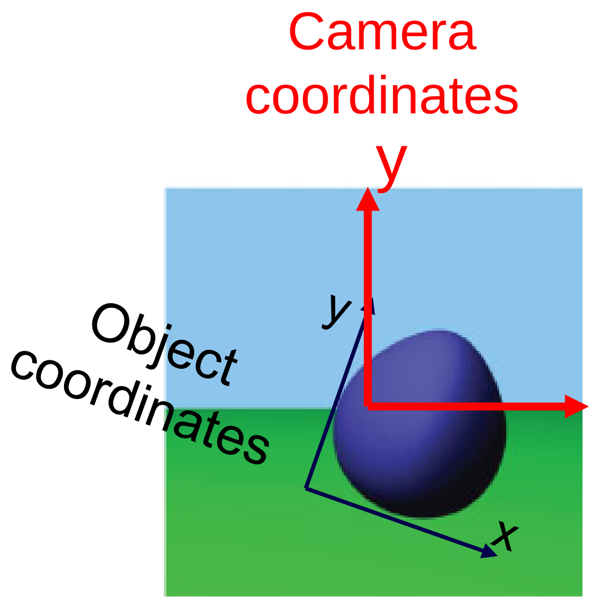
From local object to camera coordinates



object -> world



world -> camera



object -> camera

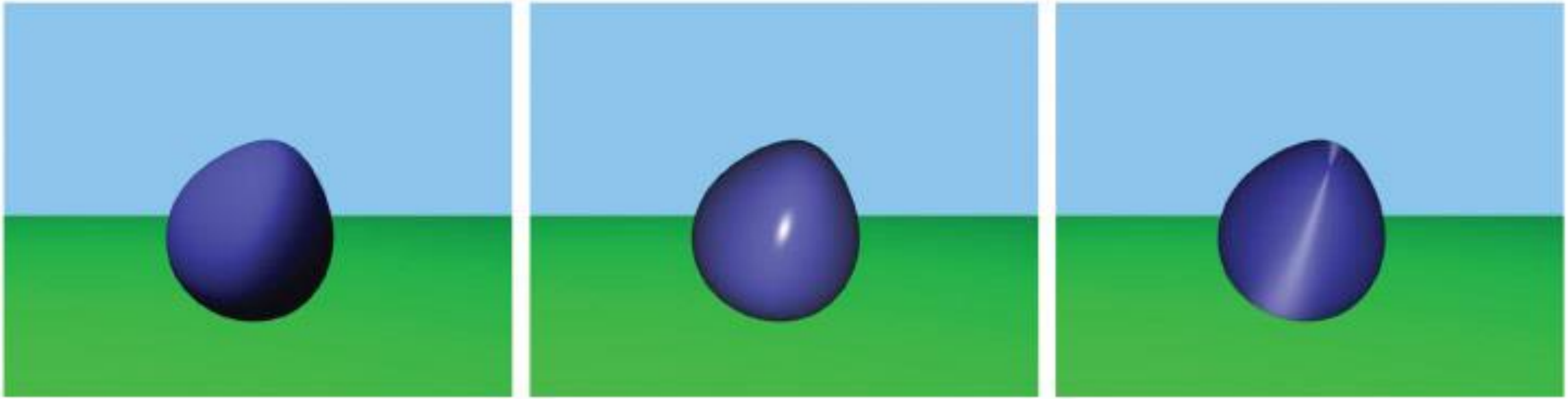
`transform`

`projection`

`projection * transform`

Fragment shader examples

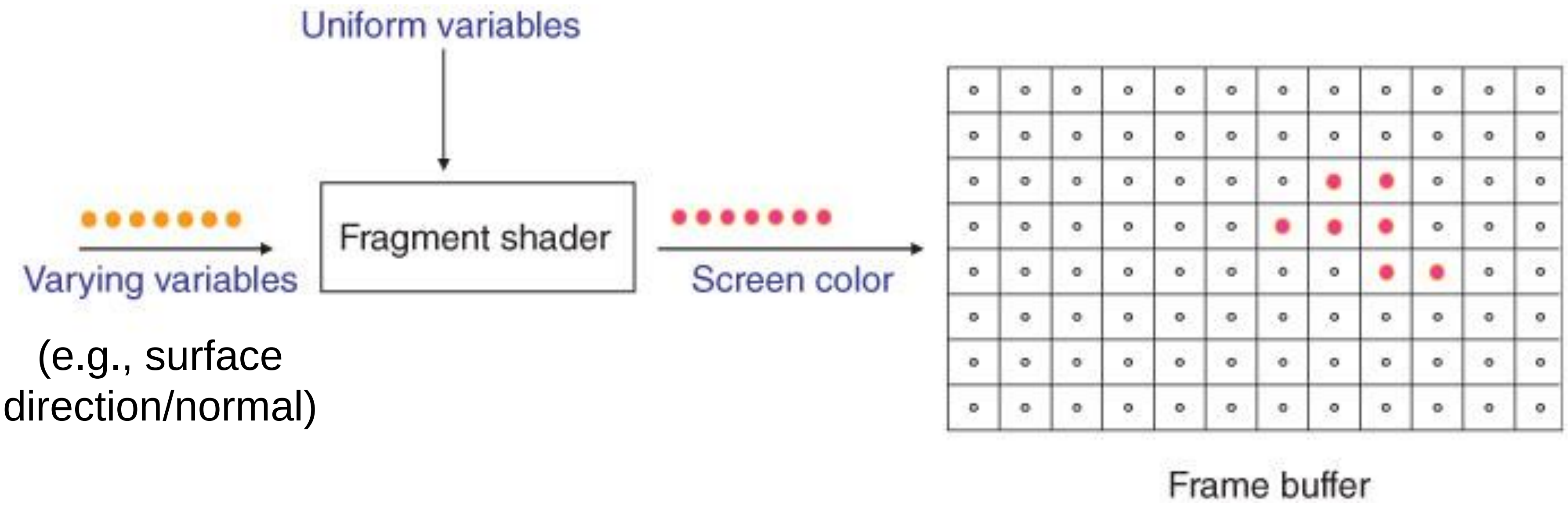
- *simulates materials and lights*
- *can read from textures*



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