CPSC 427
Video Game Programming

Rendering and Transformations

Helge Rhodin

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Today

- What is rendering?

- How to represent our game world, graphically!

Outcome:

- Learning about different rendering approaches
- Understanding affine transformations

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Our game loop (A1, main.cpp)

```
// 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;
```


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Video Game Programming

Rendering basics

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What is rendering?

Generating an image from a (3D) scene

Let’s think how!

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Scene

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

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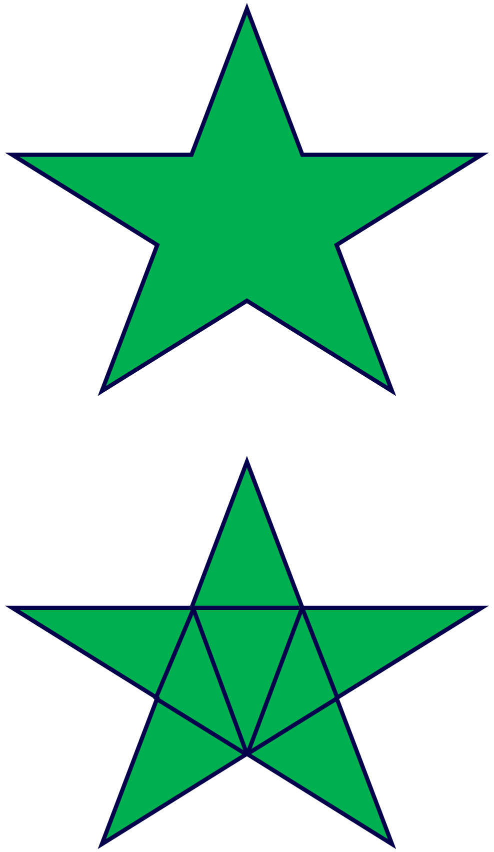
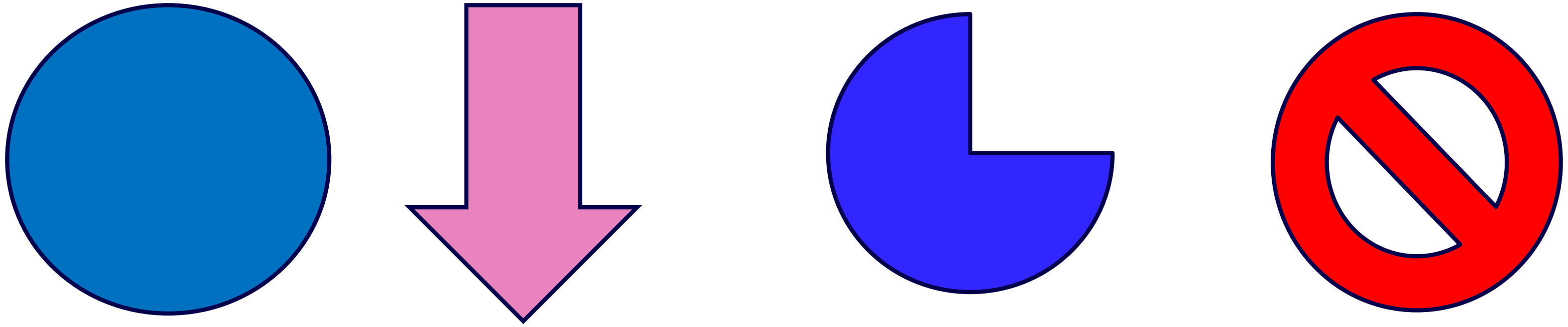
SINGLE OBJECT

How to describe a single piece of geometry?

2D

- Triangulated polygon
- Smooth geometry => **discretized/triangulated at render time**
  - *Closed curve (implicit)*
  - *Boolean combination of simple shapes*





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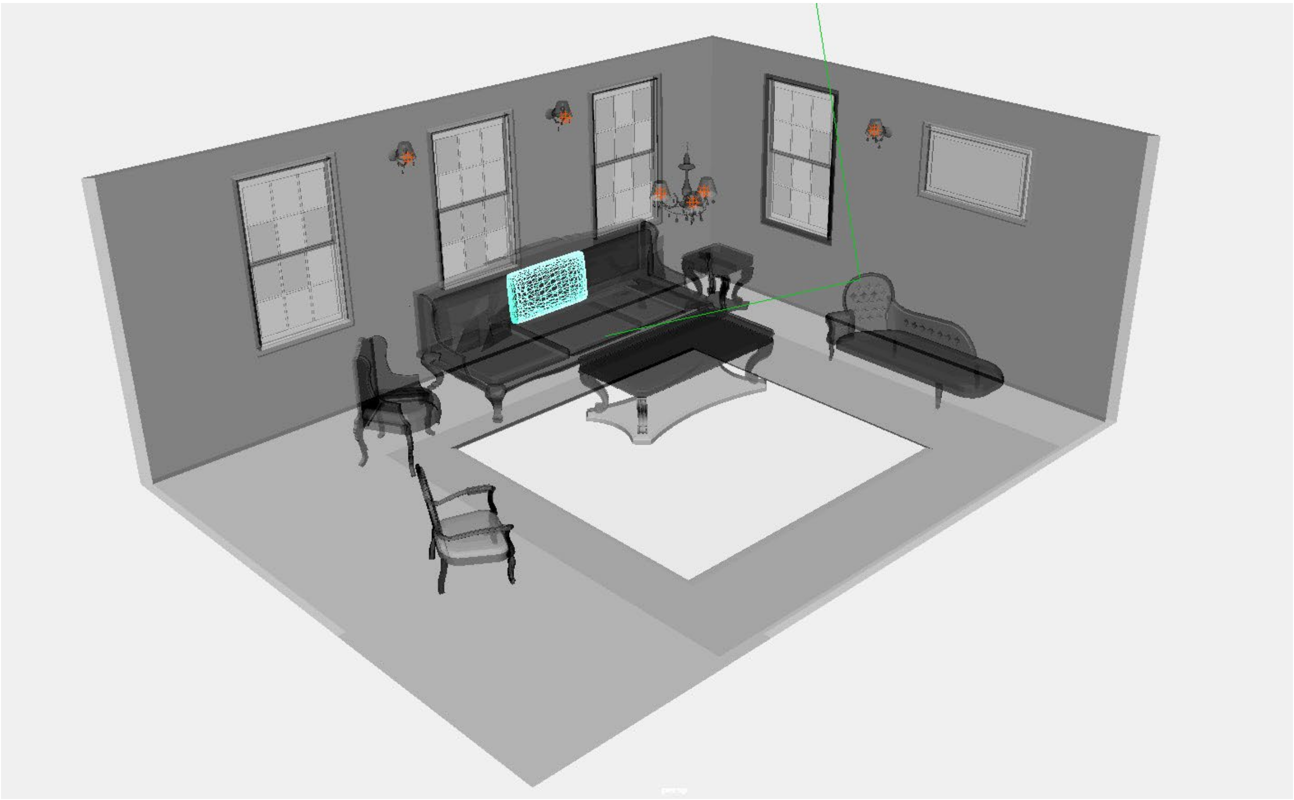
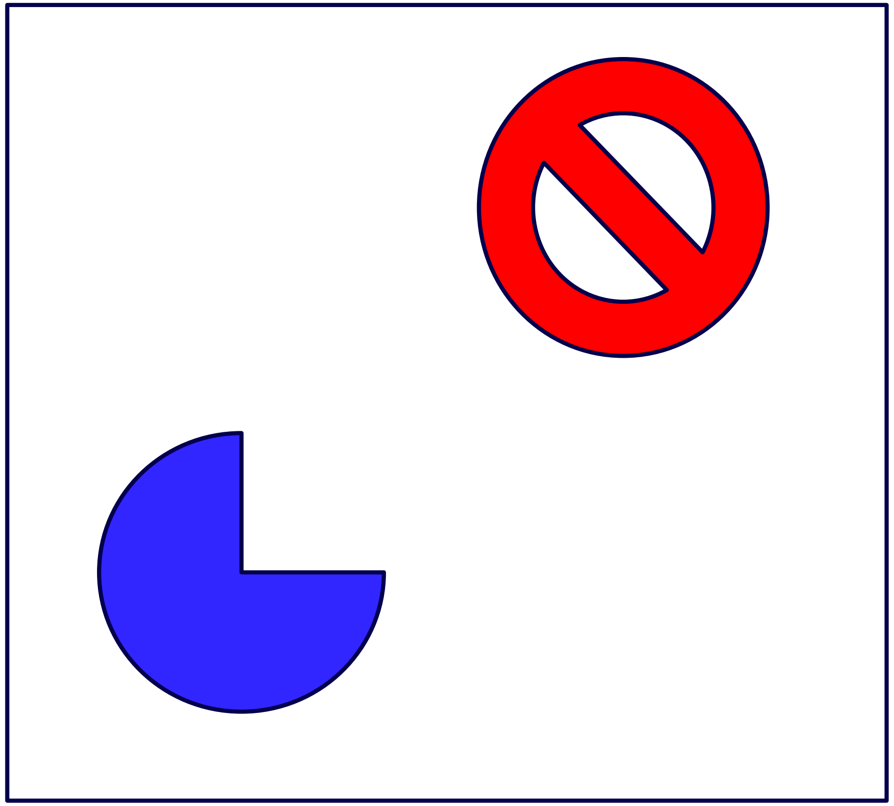
SCENE

How to describe a scene?





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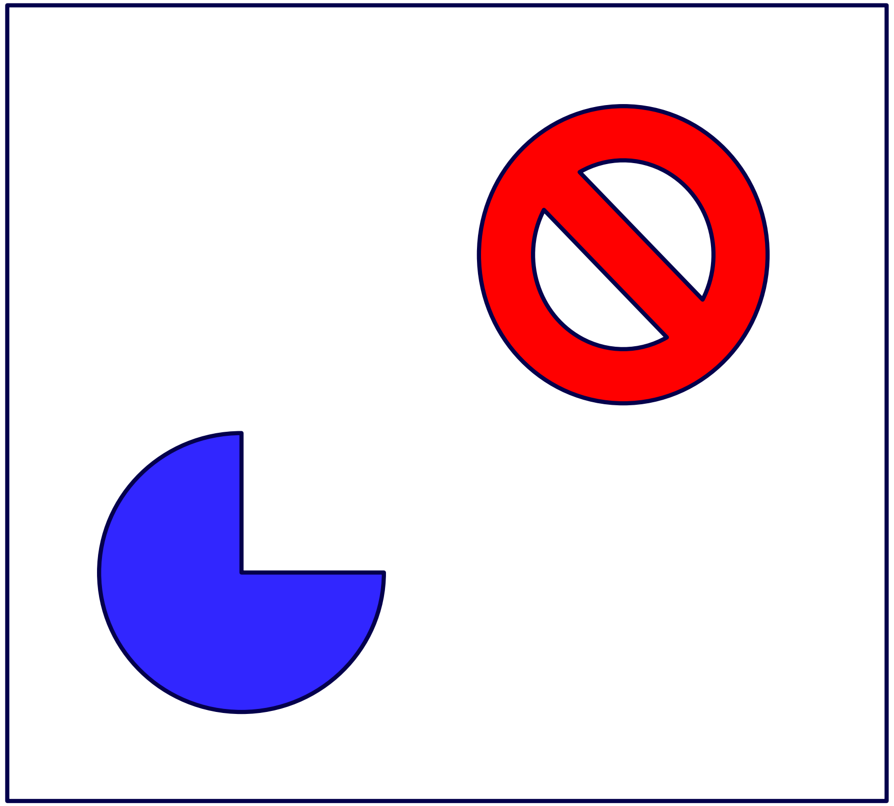
SCENE

How to describe a scene?

Local Coordinate Systems joined via Transformations



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Object

Most common:

- ***surface representation using a (textured) mesh***

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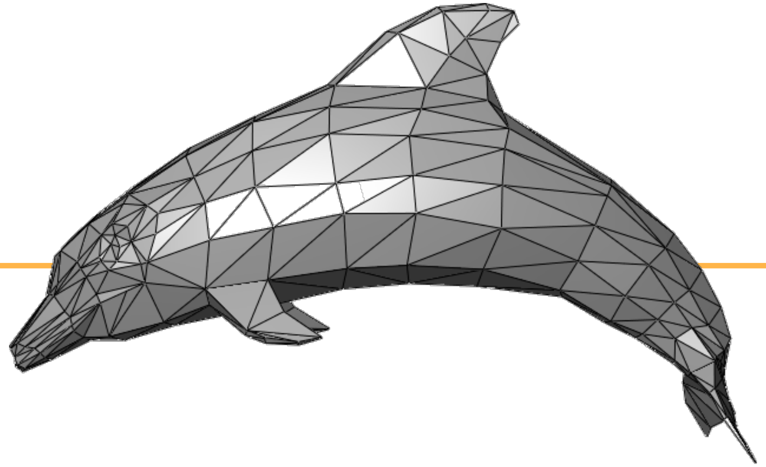
GEOMETRY



Triangle meshes

- List 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);
```

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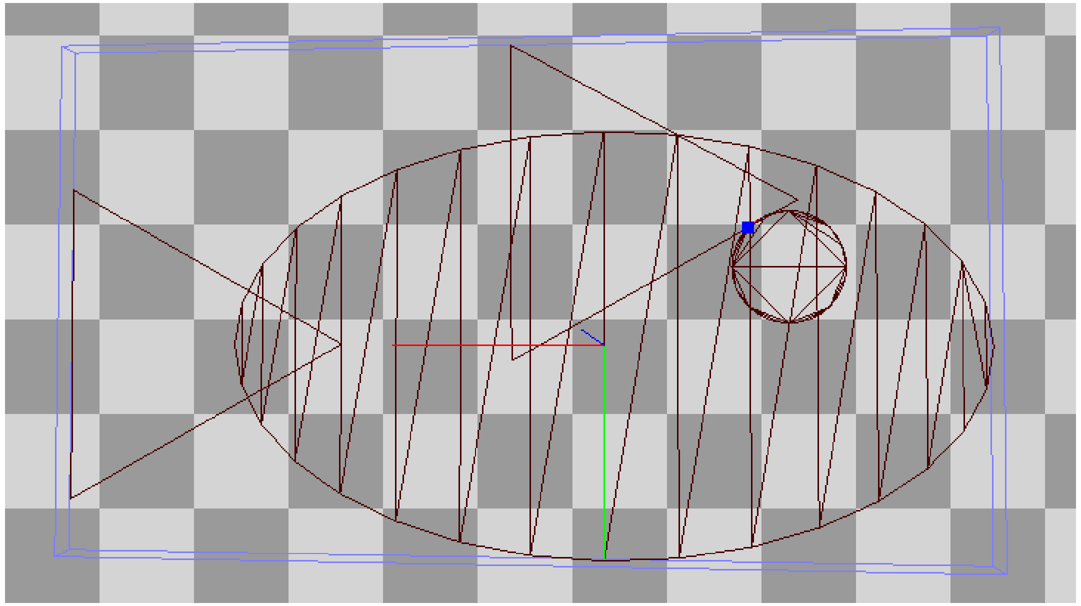
Programmatic geometry definition

```
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

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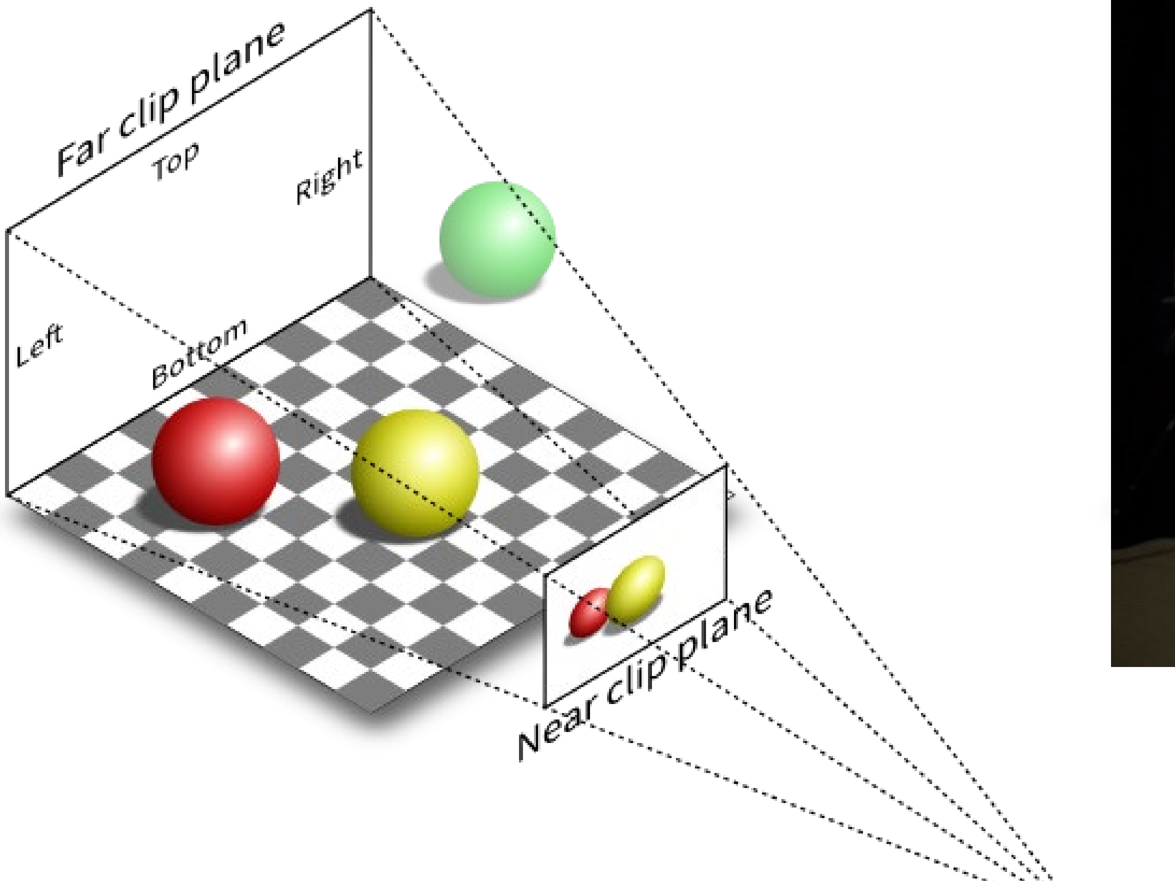
Screen

Displays what's in frame buffer

Terminology:

Pixel: basic element on device
Resolution: number of rows & columns in device

Virtual Camera



Perspective projection (P)

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

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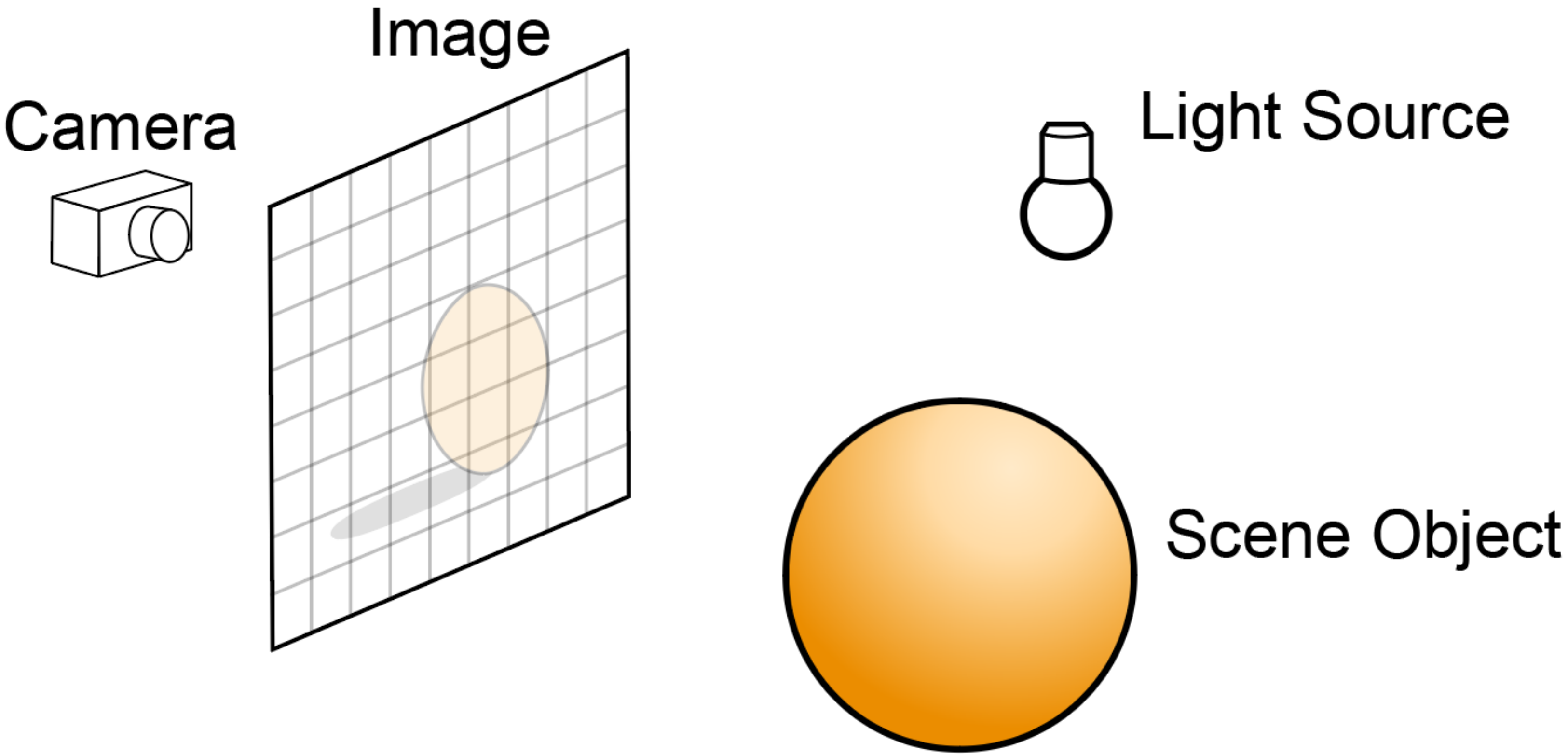
Rendering?

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



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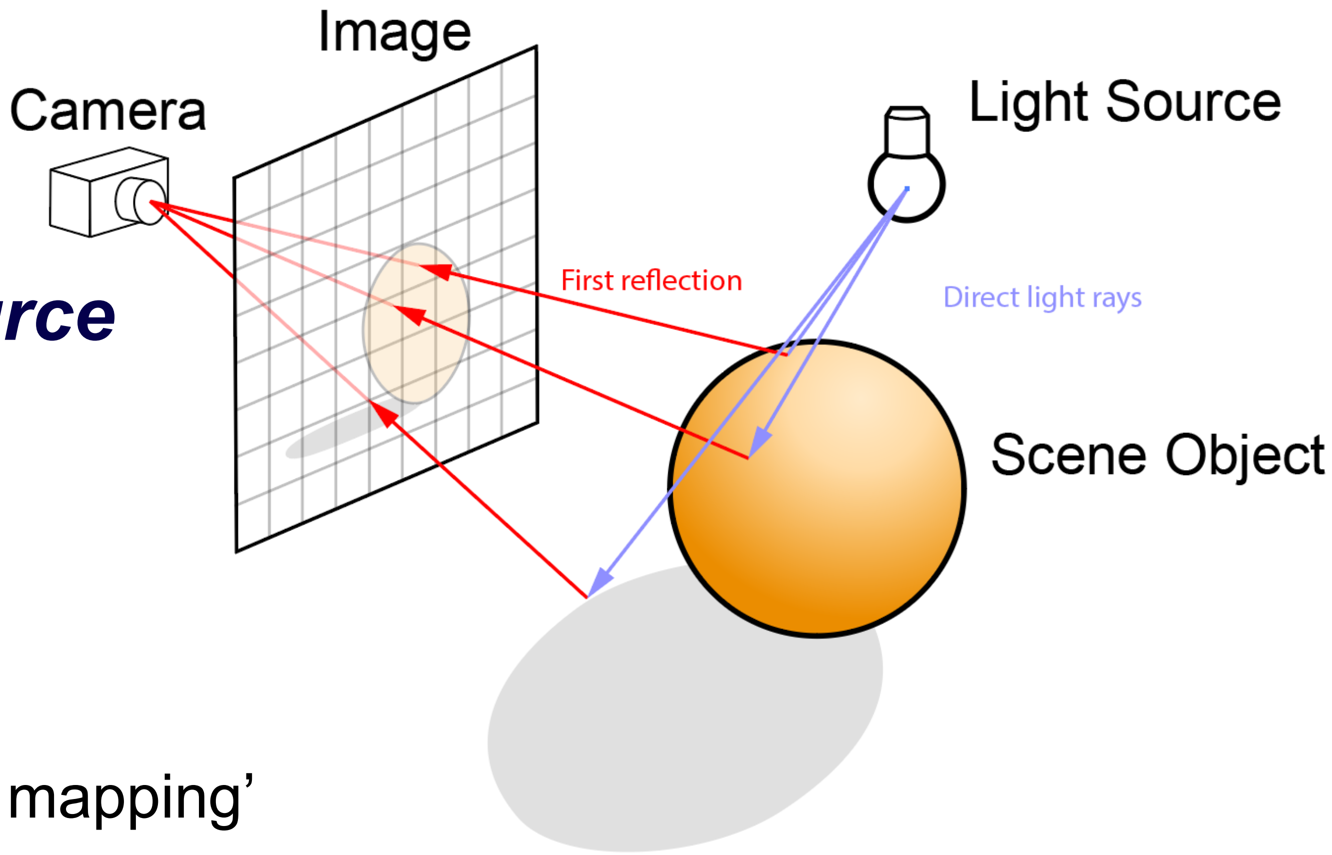
Rendering – Photon Tracing

- ***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'

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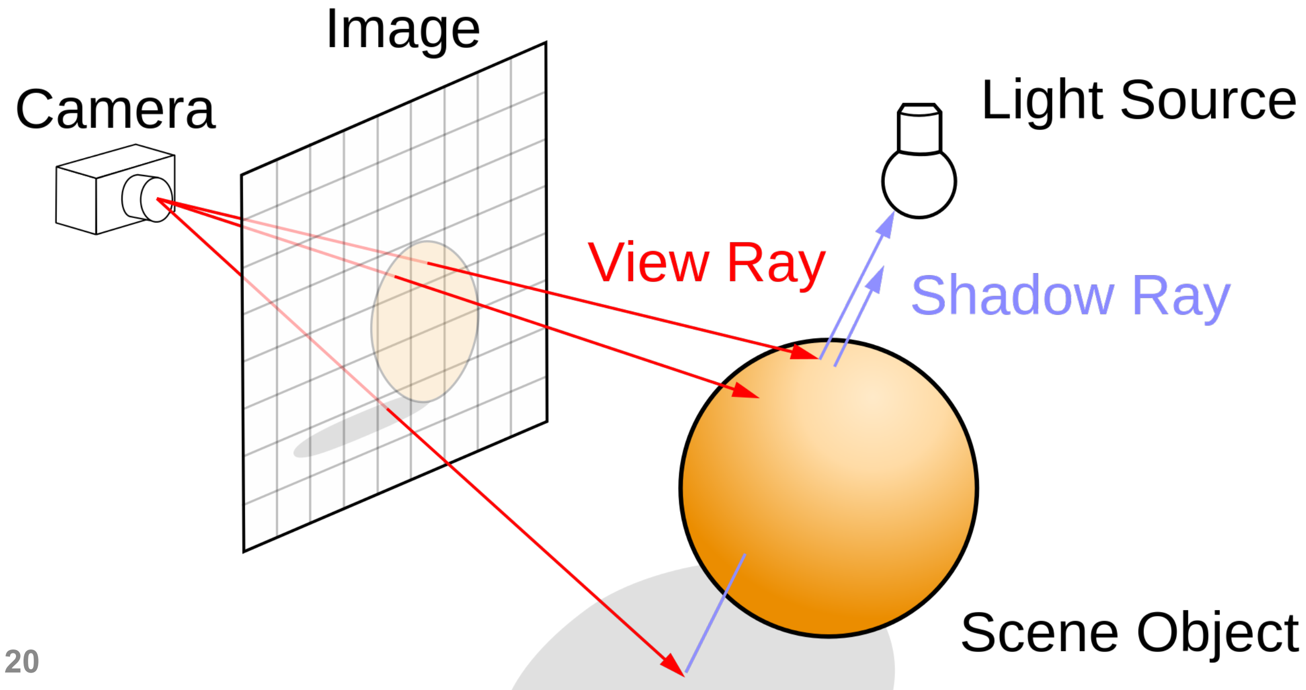
Rendering – Ray Tracing

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

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Problems of ray tracing

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

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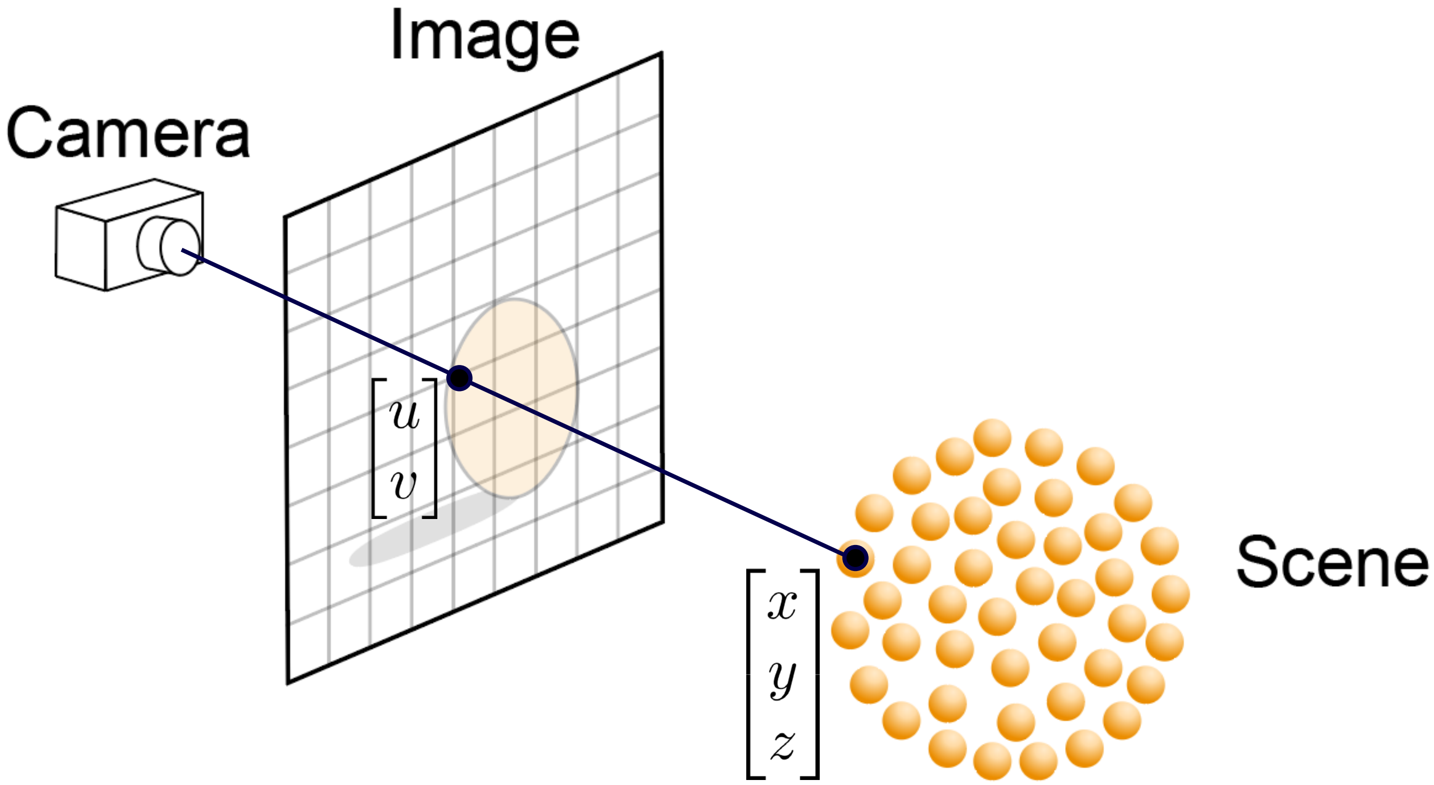
Rendering – Splatting

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?

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Rendering – Rasterization

Approximate objects with triangles

1. *Project each corner/vertex*

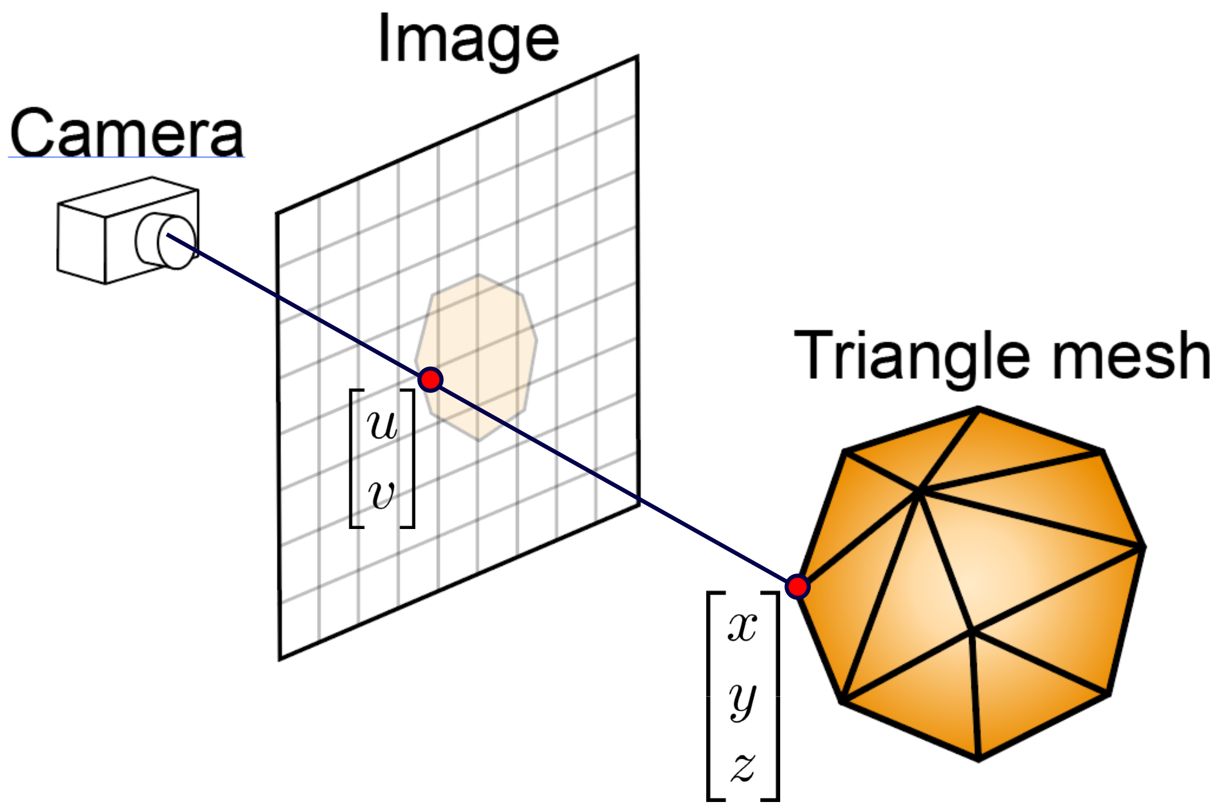
- projection of triangle stays a triangle

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

- O(n) for n vertices

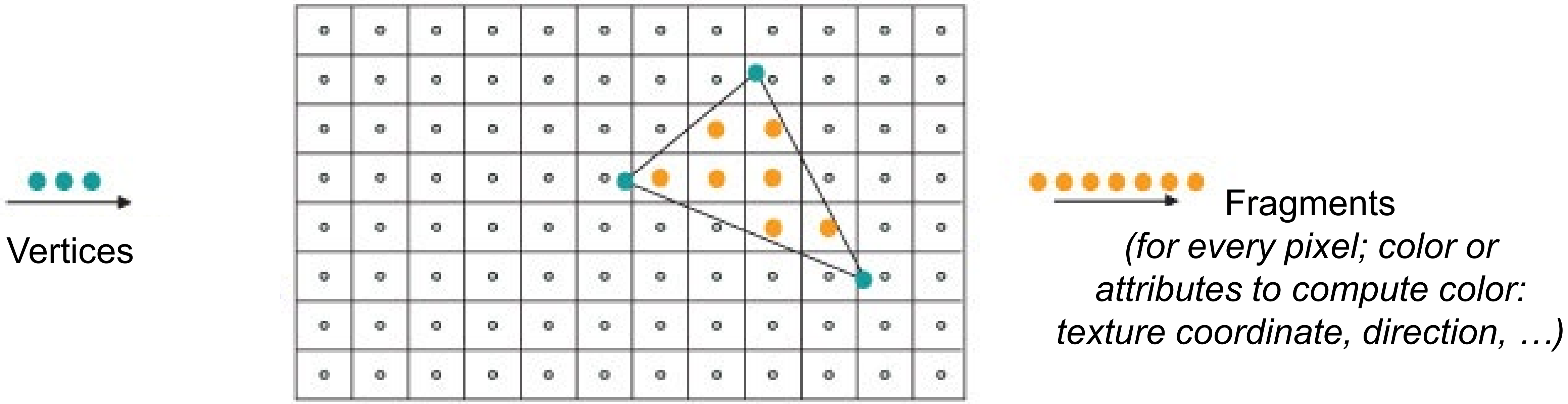
2. *Fill pixels enclosed by triangle*

- e.g., scan-line algorithm



Rasterizing a Triangle

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



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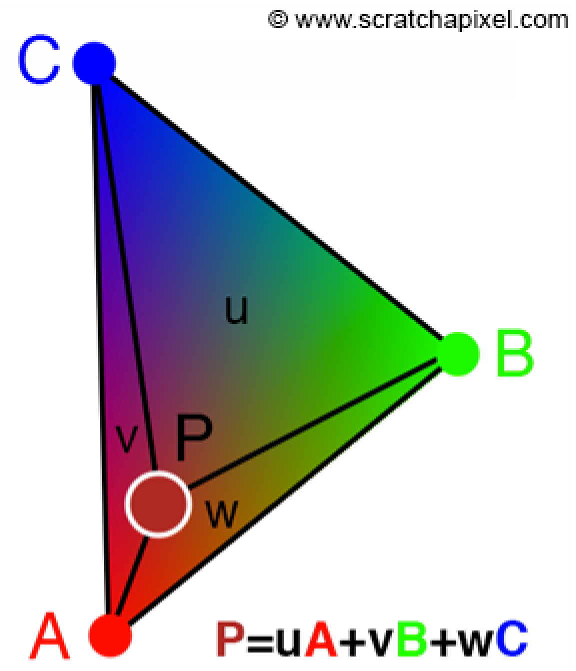
Self study:
Interpolation with barycentric coordinates

- *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*



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Backup

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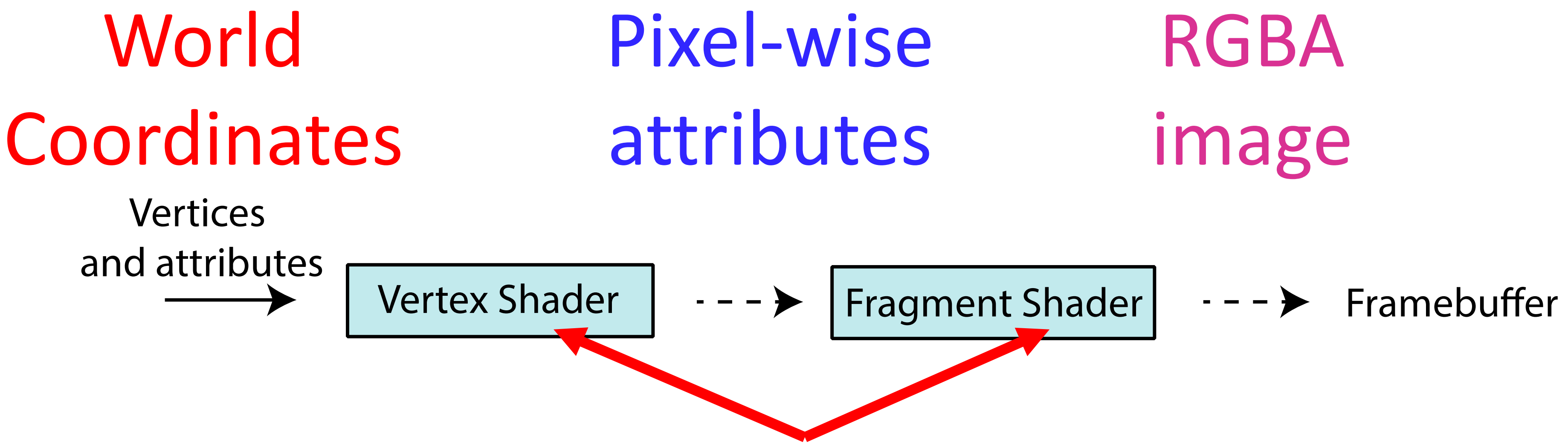
OpenGL Rendering Pipeline (simplified)

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)

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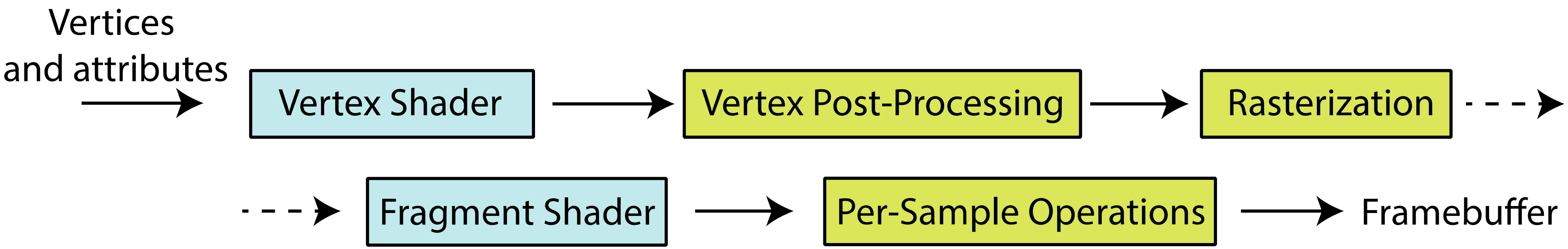
OpenGL Rendering Pipeline

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)*

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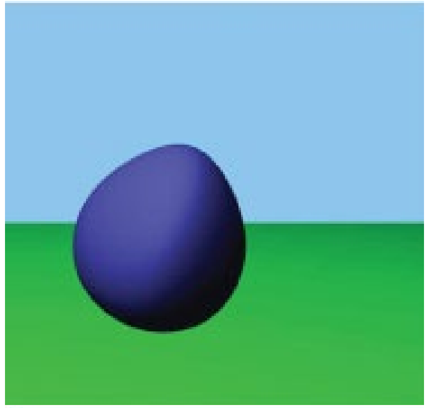
Vertex shader examples

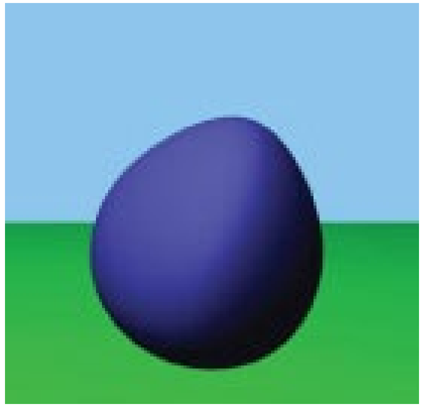
Object motion & transformation

- translation
- rotation
- scaling

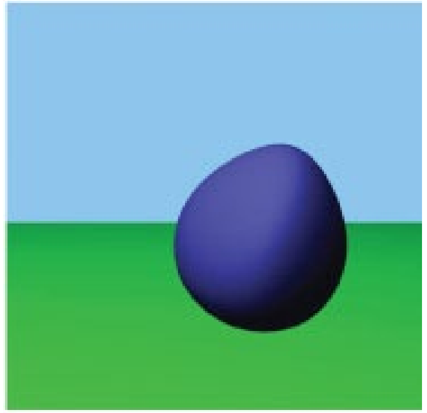
Projection

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





Scaling



Translation

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GLSL Vertex shader

The OpenGL Shading Language (GLSL)

- Syntax similar to the C programming language
- Build-in vector operations
  - functionality as the GLM library (used in the assignment template)

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);
}
```

float (32 bit)

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

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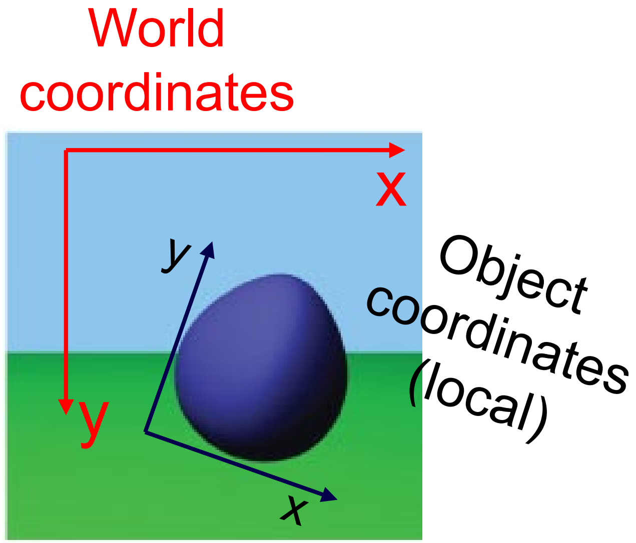
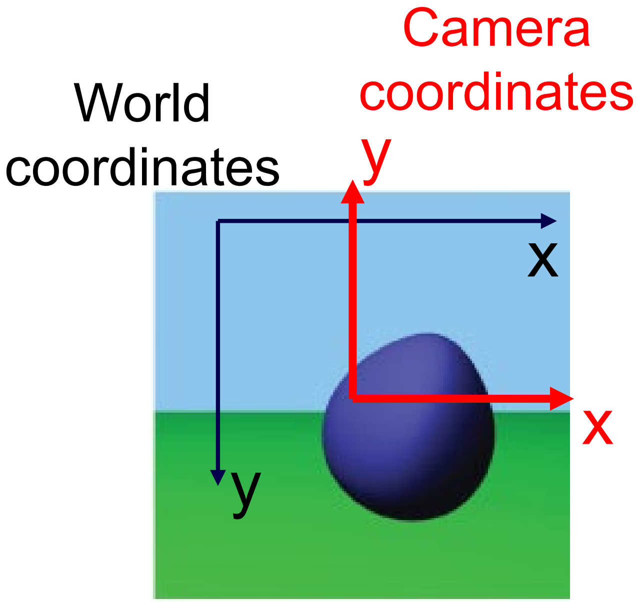
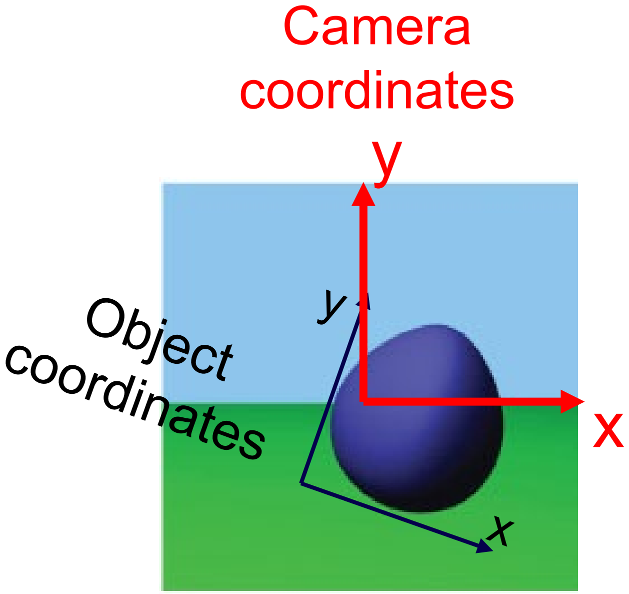
From local object to camera coordinates



object -> world



world -> camera



object -> camera

`transform` `projection` `projection * transform`

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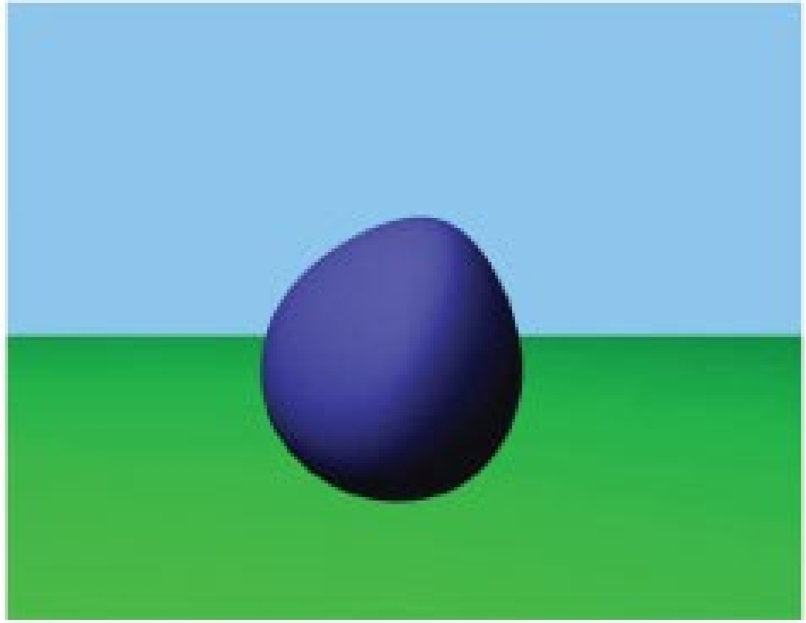
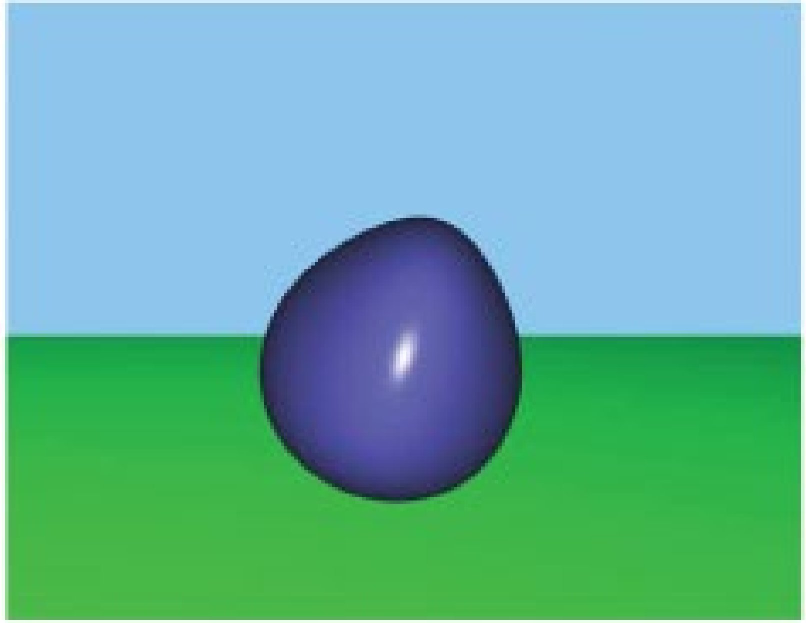
Fragment shader examples

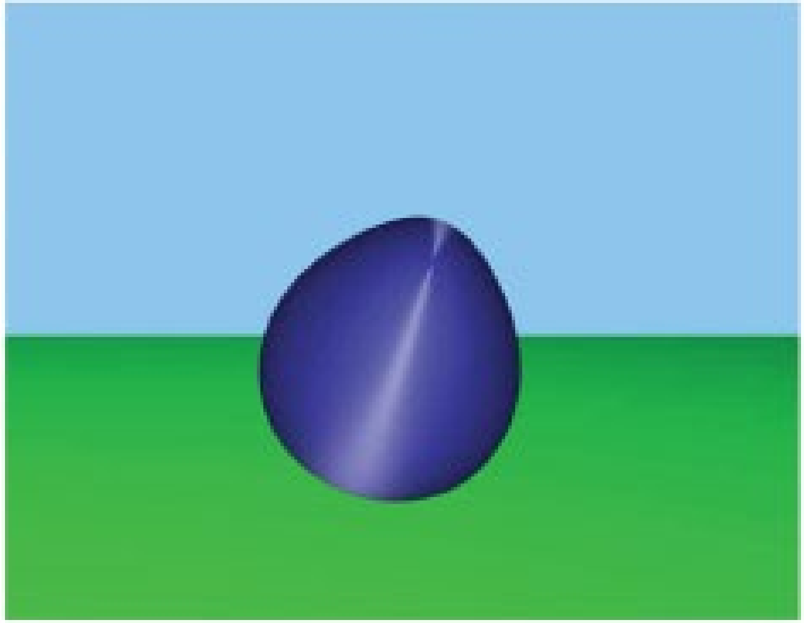
- *simulates materials and lights*
- *can read from textures*



Diffuse



Specular



Directional

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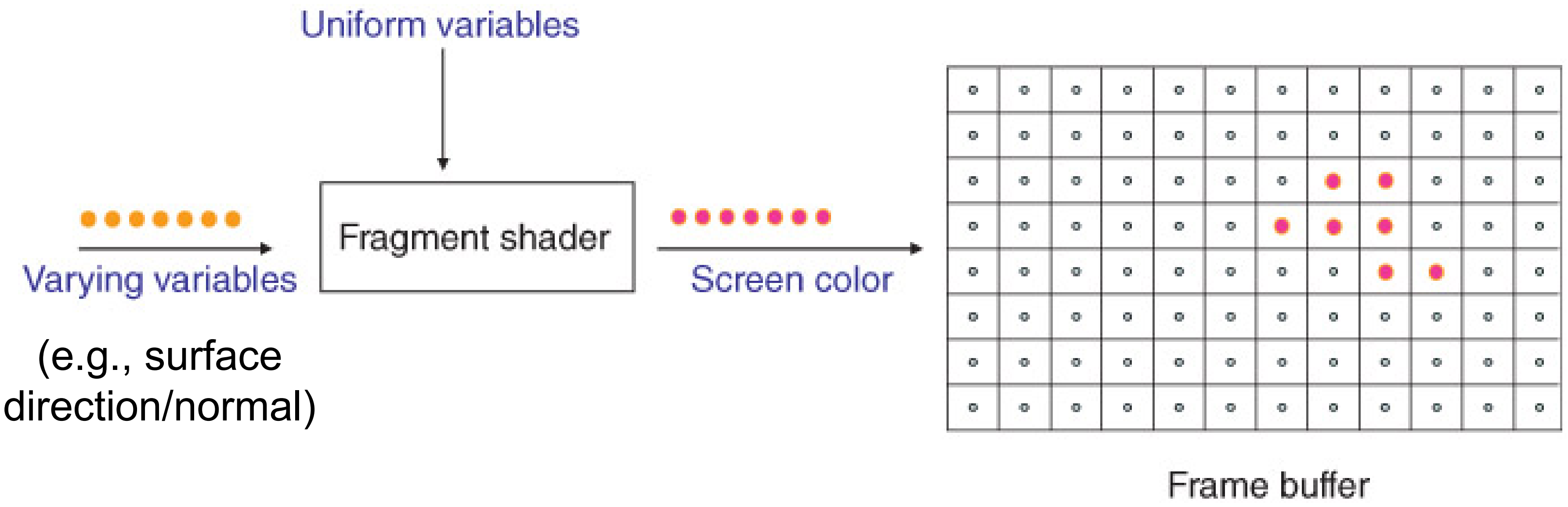
Fragment shader overview

(e.g., light direction)



(e.g., surface direction/normal)

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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

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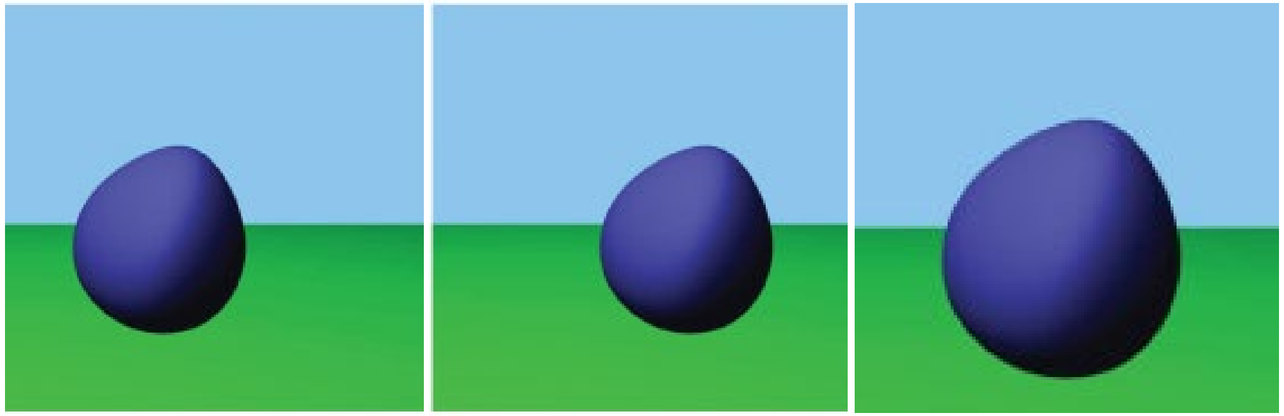
Video Game Programming

Transformations



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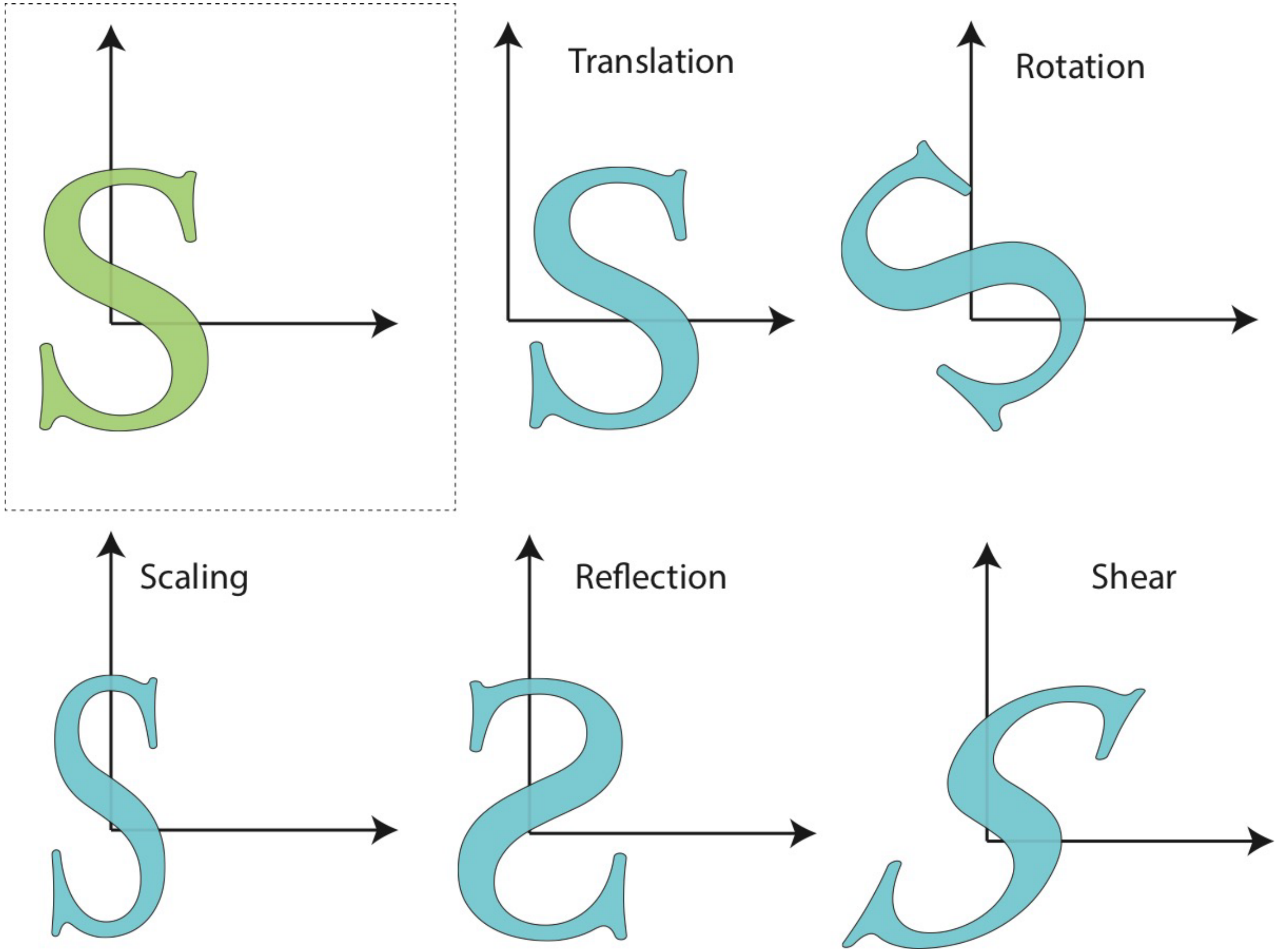
Modeling Transformations



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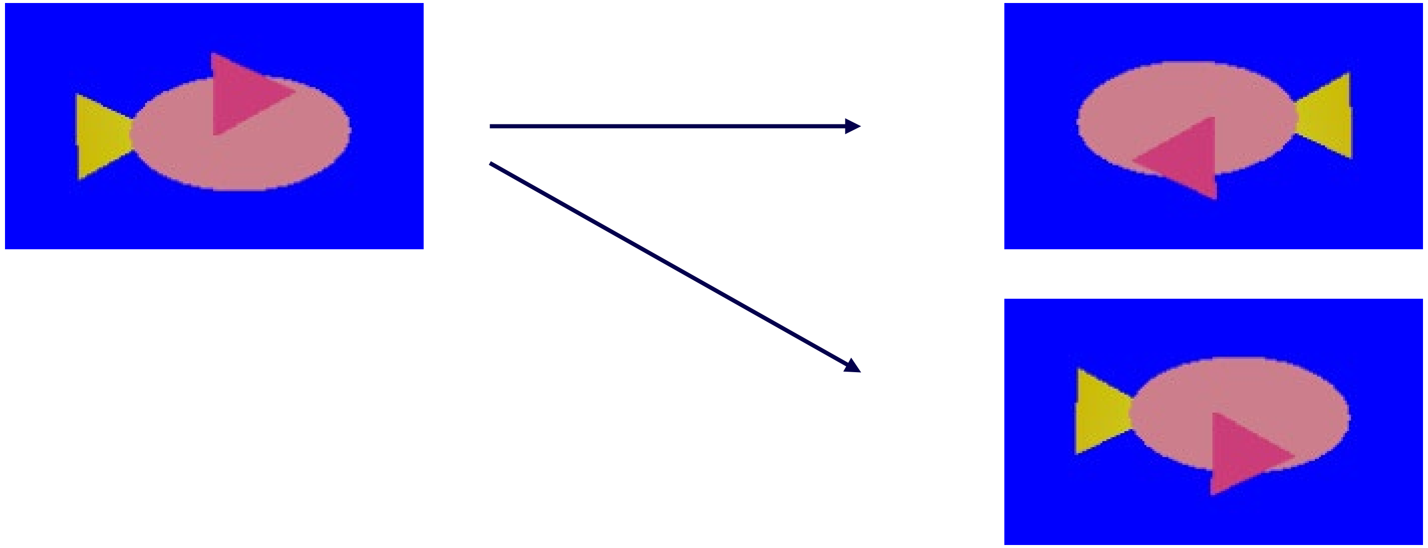
How to turn the fish?



Both versions are fine for Assignment 1 (A1)!

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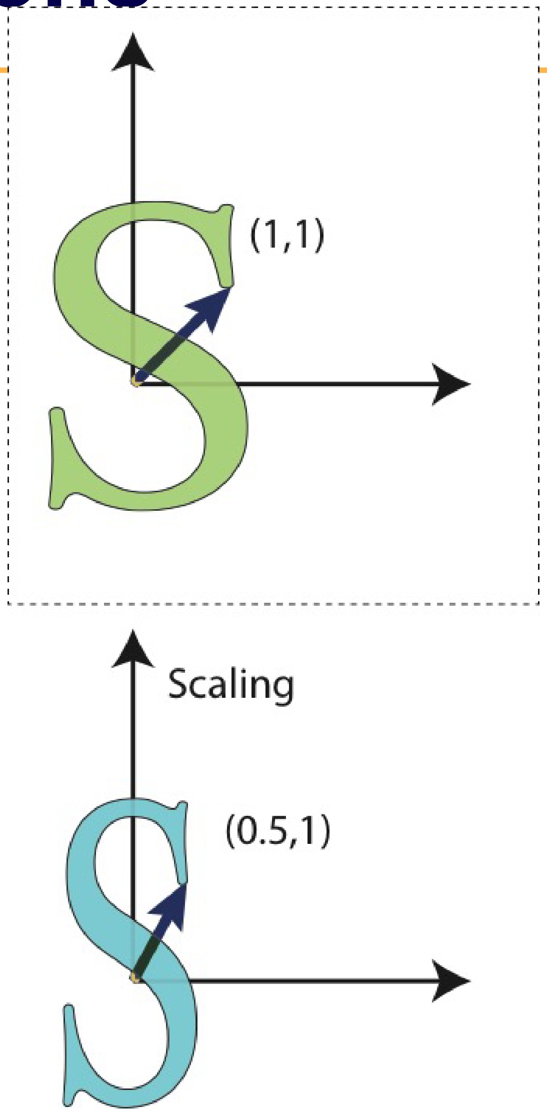
Matrix representations

Scale:



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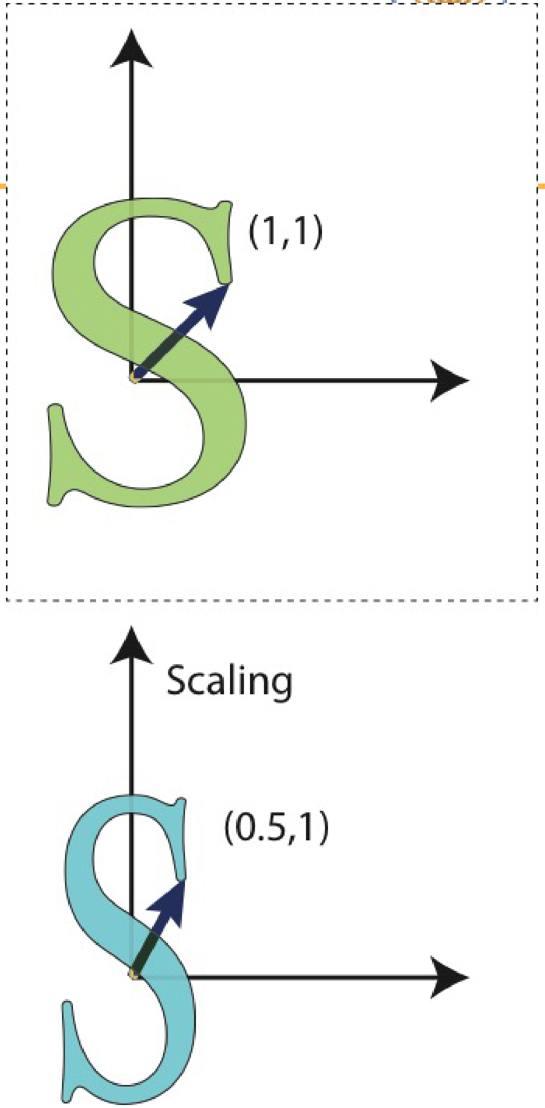
Matrix representations

Scale:

$$M = \begin{bmatrix} \alpha & 0 \\ 0 & \beta \end{bmatrix}$$

Example:

$$\begin{bmatrix} \alpha & 0 \\ 0 & \beta \end{bmatrix} \begin{pmatrix} 1 \\ 2 \end{pmatrix} = \begin{pmatrix} \alpha \\ 2\beta \end{pmatrix}$$



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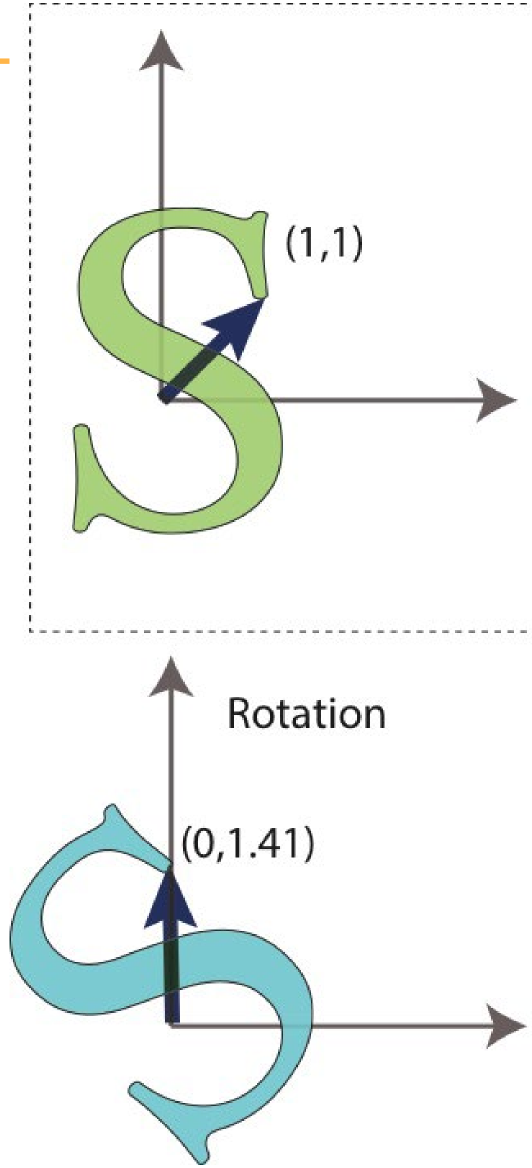
Matrix representations

Rotation



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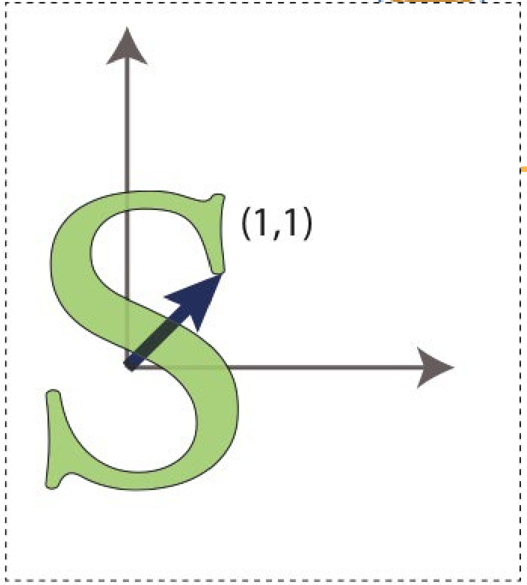
Matrix representations

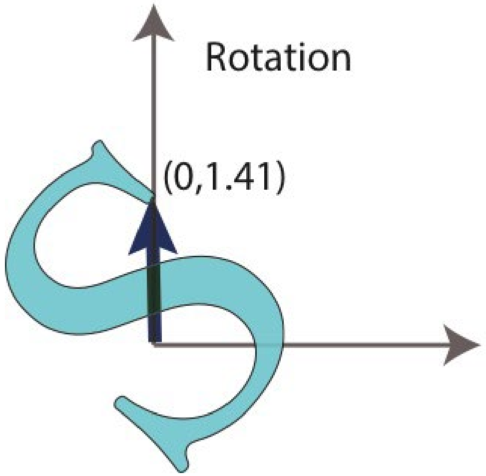
Rotation

$$R(\alpha) = \begin{bmatrix} \cos(\alpha) & -\sin(\alpha) \\ \sin(\alpha) & \cos(\alpha) \end{bmatrix}$$



Example:

$$\begin{bmatrix} \cos(\alpha) & -\sin(\alpha) \\ \sin(\alpha) & \cos(\alpha) \end{bmatrix} \begin{pmatrix} 1 \\ 1 \end{pmatrix} = \begin{pmatrix} \cos(\alpha) - \sin(\alpha) \\ \cos(\alpha) + \sin(\alpha) \end{pmatrix}$$



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What does this 2D transformation do?

$$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

A. Rotates by 90 deg
B. Scales by a factor of 2
C. Rotates by -90 deg
D. Nothing

What does this 2D transformation do?

$$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix},$$

A. Rotates by 90 deg
B. Reflects the object
C. Rotates by -90 deg
D. Scales the object

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TRANSLATION

There's a minor glitch.

- Translation: can't be represented as 2x2 matrix multiplication

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general transformations

We need to represent all the linear transformations + translation.

Ideas?

$$T(v) = Mv + \boldsymbol{b}$$

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AUGMENTED MATRIX

$$M_{2x2} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} x' \\ y' \end{bmatrix}$$

$$\begin{bmatrix} M_{2x2} & & \begin{matrix} 0 \\ 0 \end{matrix} \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix}$$

Haven't changed much, have we?

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AUGMENTED MATRIX

$$\begin{bmatrix} M_{2x2} & & \begin{matrix} b_x \\ b_y \end{matrix} \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} x' + b_x \\ y' + b_y \\ 1 \end{bmatrix} = \begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} + \boldsymbol{b}$$

Translation

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Affine transformations

- Linear (rotation, scaling, shear, reflections) + TRANSLATION

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Affine transformations

- Linear (rotation, scaling, shear, reflections) + TRANSLATION

- How to convert a linear transformation matrix into affine matrix?

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AFFINE Transformations

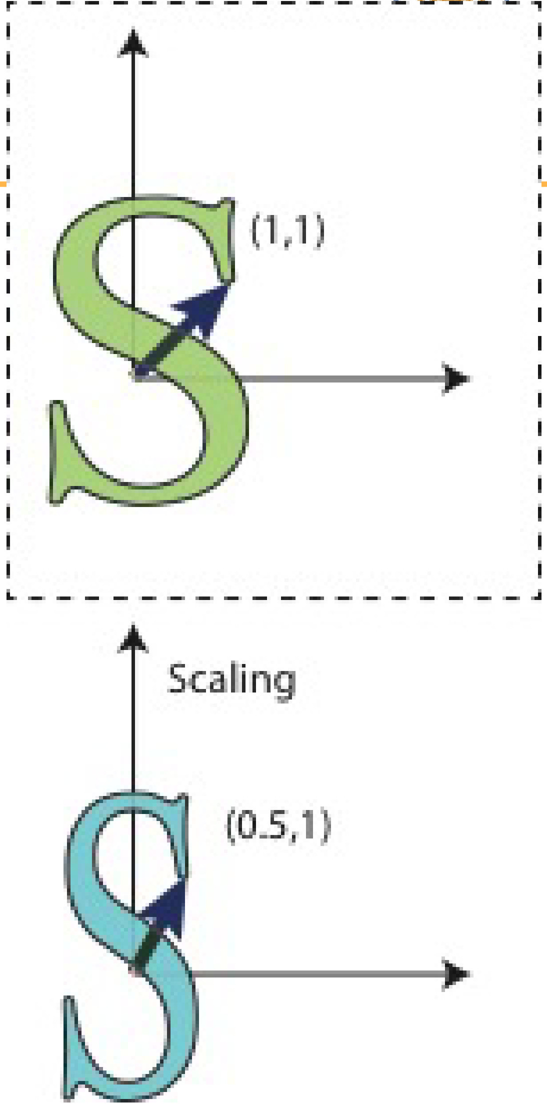
Scale:

$$M = \begin{bmatrix} a & 0 \\ 0 & b \end{bmatrix}$$

$$M = \begin{bmatrix} a & 0 & 0 \\ 0 & b & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Example:

$$\begin{pmatrix} a \cdot 1 \\ b \cdot 2 \\ 1 \end{pmatrix} = \begin{bmatrix} a & 0 & 0 \\ 0 & b & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} 1 \\ 2 \\ 1 \end{pmatrix}$$



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AFFINE Transformations

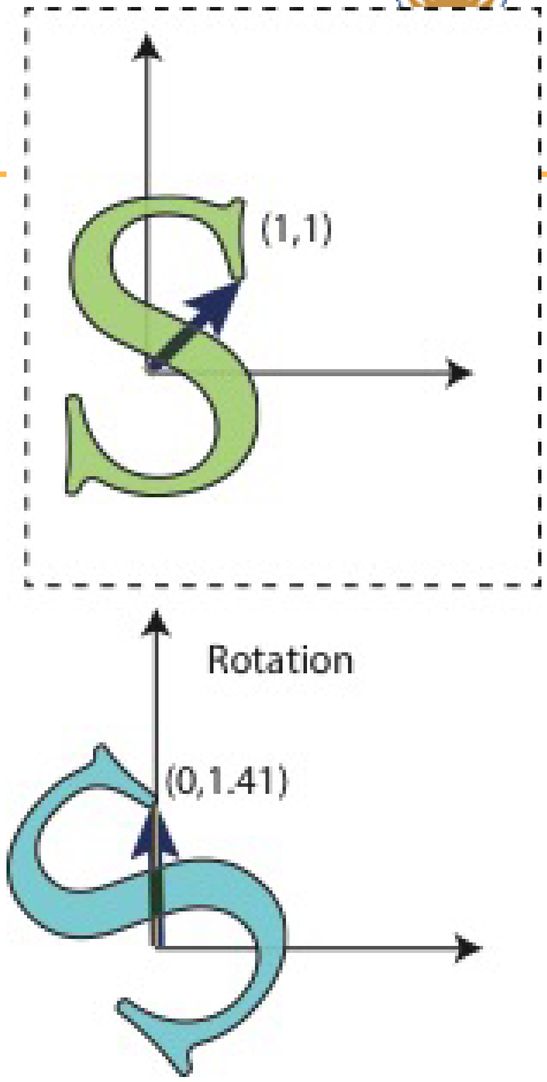
Rotation

$$M = \begin{bmatrix} a & 0 \\ 0 & b \end{bmatrix}$$

$$M = \begin{bmatrix} a & 0 & 0 \\ 0 & b & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Example:

$$\begin{pmatrix} a \cdot 1 \\ b \cdot 2 \\ 1 \end{pmatrix} = \begin{bmatrix} a & 0 & 0 \\ 0 & b & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} 1 \\ 2 \\ 1 \end{pmatrix}$$



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AFFINE Transformations

Translation

$$M = \begin{bmatrix} 1 & 0 & C_x \\ 0 & 1 & C_y \\ 0 & 0 & 1 \end{bmatrix}$$

Example:

$$\begin{bmatrix} 1 & 0 & C_x \\ 0 & 1 & C_y \\ 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = \begin{pmatrix} x + C_x \\ y + C_y \\ 1 \end{pmatrix}$$

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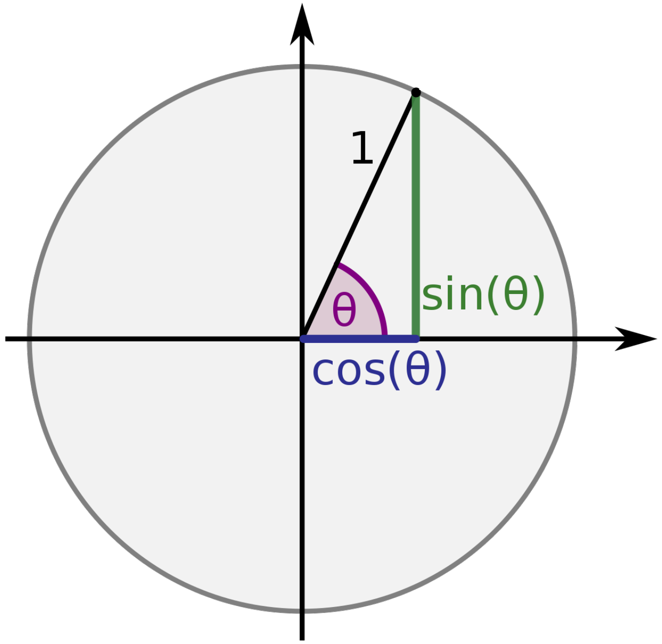
Linear transformations

- 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

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Affine transformations

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

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

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Modeling Transformation

Adding a third coordinate

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

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

Affine transformations are now linear

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

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Combination of Transformations?

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

… into one matrix?

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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

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

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