CPSC 314
SHADERS, OPENGL, &JS
RENDERING PIPELINE

UGRAD.CS.UBC.CA/~CS314

slide credits:

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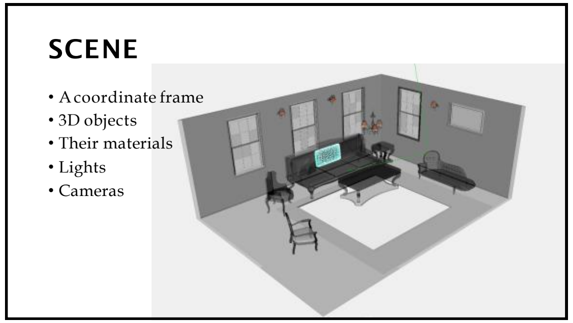
WHAT IS RENDERING?

Generating image from a 3D scene

WHAT IS RENDERING?

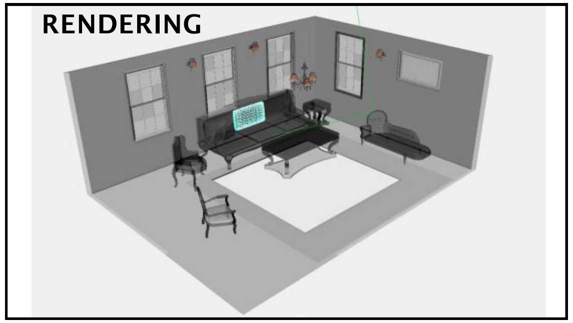
Generating image from a 3D scene

Let's think HOW.

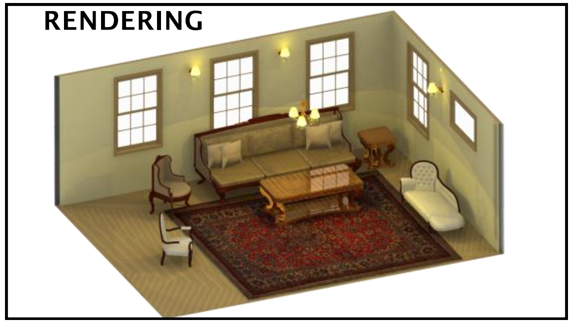


SCENE

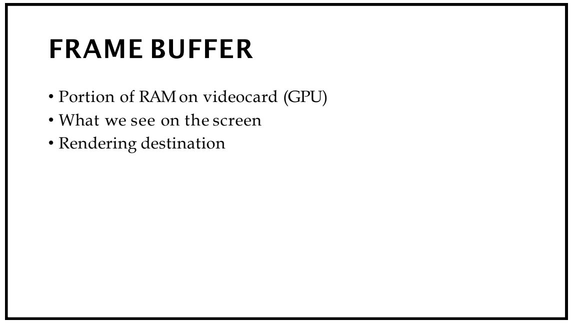
- A coordinate frame
- 3D objects
- Their materials
- Lights
- Cameras



RENDERING

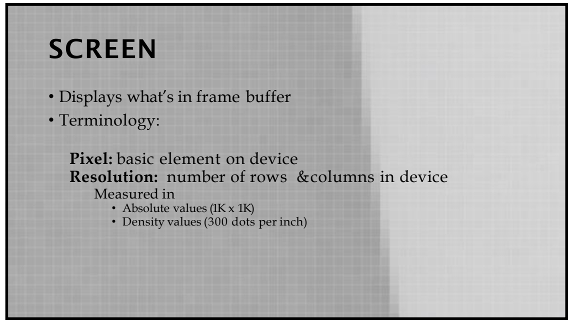


RENDERING



FRAME BUFFER

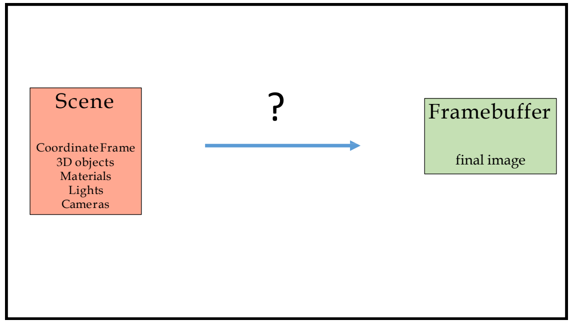
- Portion of RAM on videocard (GPU)
- What we see on the screen
- Rendering destination



SCREEN

- Displays what's in frame buffer
- Terminology:

Pixel: basic element on device
Resolution: number of rows &columns in device
Measured in
- Absolute values (1K x 1K)
- Density values (300 dots per inch)



Scene

Coordinate Frame
3D objects
Materials
Lights
Cameras

?

Framebuffer

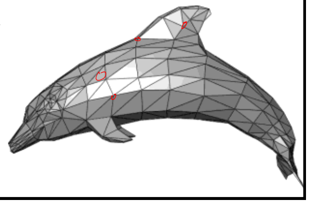
final image

SINGLE OBJECT

- How to describe a single piece of geometry?
- So far geometry has been constructed for you.

SHAPES: TRIANGLE MESHES

- Triangle = 3 vertices
- Mesh = {vertices, triangles}
- Example

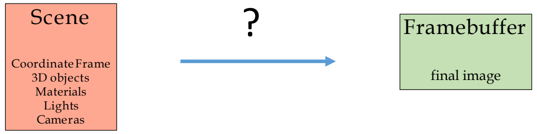


SCENE

- How to describe a scene?

SCENE

- How to describe a scene?
- Local Transformations



Scene

Coordinate Frame
3D objects
Materials
Lights
Cameras

?

Framebuffer

final image

SKETCH OF A RENDERING PIPELINE

- Scene
  - Coordinate frame
  - 3D models
    - Coordinates
    - Local transforms
    - properties (color, material)
  - Lights
  - Camera

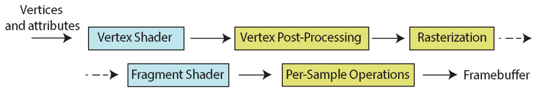
SKETCH OF A RENDERING PIPELINE

- **Scene**
  - Coordinate frame
  - 3D models
    - Coordinates
    - properties (color, material)
  - Lights
  - Camera
- **Camera View**
  - 2D positions of shapes
  - Depth of shapes
  - Normals
- **Image**
  - Shape pixels
  - Their color
  - Which pixel is visible

OPENGL/WEBGL

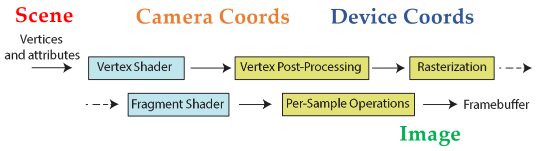
- Open Graphics Library
- One of the most popular libraries for 2D/3D rendering
- Asoftware interface to communicate with graphics hardware
- Cross-language API

OPENGL RENDERING PIPELINE



Vertices and attributes → Vertex Shader → Vertex Post-Processing → Rasterization → Fragment Shader → Per-Sample Operations → Framebuffer

OPENGL RENDERING PIPELINE



Scene

Camera Coords

Device Coords

Vertices and attributes → Vertex Shader → Vertex Post-Processing → Rasterization - - →

- - → Fragment Shader → Per-Sample Operations → Framebuffer

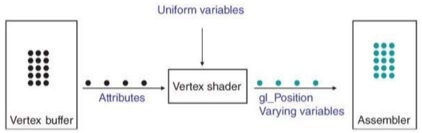
Image

VERTEX SHADER

Vertices and attributes → Vertex Shader →

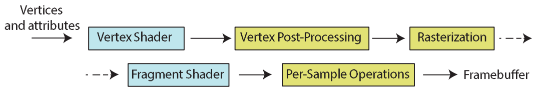
VERTEX SHADER

Vertices and attributes → Vertex Shader →



- Vertices are stored in vertex buffer
- Each one is processed by vertex shader
- Outputs 2D position
- May compute per-vertex variables (normal, etc.)

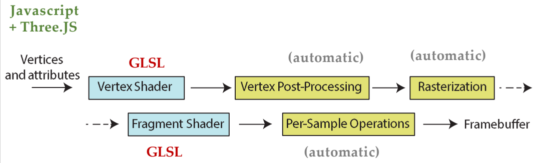
OPENGL RENDERING PIPELINE



Vertices and attributes → Vertex Shader → Vertex Post-Processing → Rasterization - - →

- - → Fragment Shader → Per-Sample Operations → Framebuffer

OPENGL RENDERING PIPELINE



Javascript + Three.JS

Vertices and attributes → Vertex Shader (GLSL) → Vertex Post-Processing (automatic) → Rasterization (automatic) - - →

- - → Fragment Shader (GLSL) → Per-Sample Operations (automatic) → Framebuffer

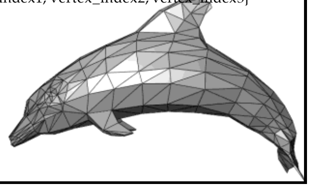
THREE.JS

- High-level library for Javascript
- Uses WebGL for rendering

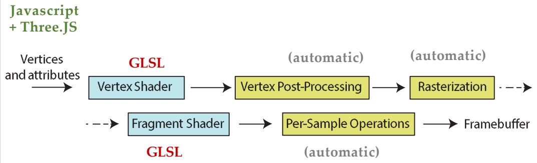
- Has **Scene**, **Mesh, Camera** objects
- **Scene** is hierarchical
- **Mesh** has geometry and material properties
- **Camera** is used for rendering

GEOMETRY

- Triangle meshes
  - Set of vertices
  - Triangle defines as {vertex_index1, vertex_index2, vertex_index3}



OPENGL RENDERING PIPELINE



Javascript + Three.JS

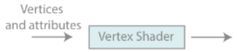
Vertices and attributes → Vertex Shader (GLSL) → Vertex Post-Processing (automatic) → Rasterization (automatic) - - →

- - → Fragment Shader (GLSL) → Per-Sample Operations (automatic) → Framebuffer

GLSL

- OpenGL shading language
- Used for Fragment and Vertex shaders
- Lots of useful stuff:
  - vec3, vec4, dvec4, mat4, sampler2D
  - mat*vec, mat*mat
  - Reflect, refract
  - vec3 v(a.xy, 1)

VERTEX SHADER



- VS is run for each vertex SEPARATELY
- By default doesn't know connectivity

- Input: vertex coordinates in Object Coordinate System
- Its main goal is to set **gl_Position**

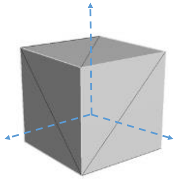
Object coordinates -> WORLD coordinates -> VIEW coordinates

VERTEX SHADER

- Except simple conversion to world coordinates
- You can do anything with vertices (or anything that's passed)
  - e.g. deform vertices
  - e.g. skinning!

[courtesy NVIDIA]

```
var verticesOfCube = [
    -1,-1,-1,    1,-1,-1,    1, 1,-1,    -1, 1,-1,
    -1,-1, 1,    1,-1, 1,    1, 1, 1,    -1, 1, 1,
];
var indicesOfFaces = [
    2,1,0,    0,3,2,
    0,4,7,    7,3,0,
    0,1,5,    5,4,0,
    1,2,6,    6,5,1,
    2,3,7,    7,6,2,
    4,5,6,    6,7,4
];
var geometry = new THREE.PolyhedronGeometry(
verticesOfCube, indicesOfFaces, 6, 2 );
```



GEOMETRY (JAVASCRIPT/THRE.JS)

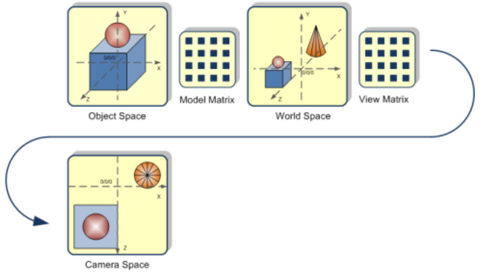
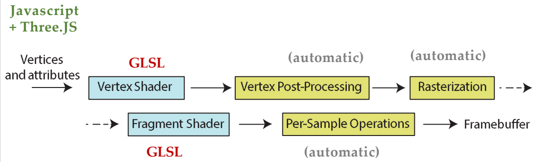
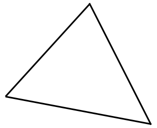


Image © Egon Rath

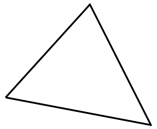
OPENGL RENDERING PIPELINE



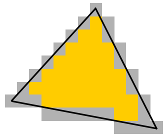
CAMERA VIEW



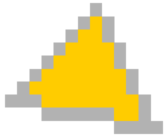
RASTERIZATION



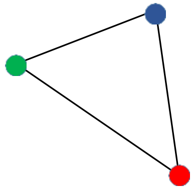
RASTERIZATION



RASTERIZATION



RASTERIZATION - INTERPOLATION



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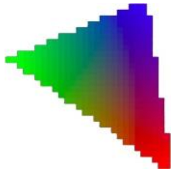
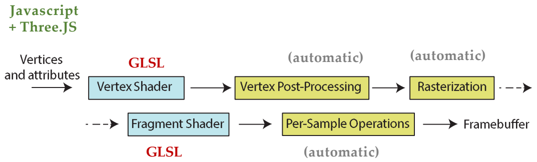
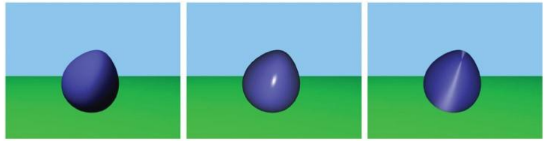


OPENGL RENDERING PIPELINE



FRAGMENT SHADER

- Fragment = data for drawing a pixel
- Has gl_FragCoord – 2D window coords
- May set color!



FRAGMENT SHADER

- Common Tasks:
  - texture mapping
  - per-pixel lighting and shading
- Synonymous with Pixel Shader

MINIMAL VERTEX SHADER

```
void main()
{
    // Transforming The Vertex
    gl_Position = modelViewMatrix * position;
}
```

MINIMAL FRAGMENT SHADER

```
void main()
{
    // Setting Each Pixel To Red  gl_FragColor =
    vec4(1.0, 0.0, 0.0, 1.0);
}
```

MINIMAL VERTEX SHADER

```
void main()
{
    // Transforming The Vertex
    gl_Position = modelViewMatrix * position;
}
```

defined by Three.JS

MINIMAL FRAGMENT SHADER

```
void main()
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MINIMAL VERTEX SHADER

```
void main()
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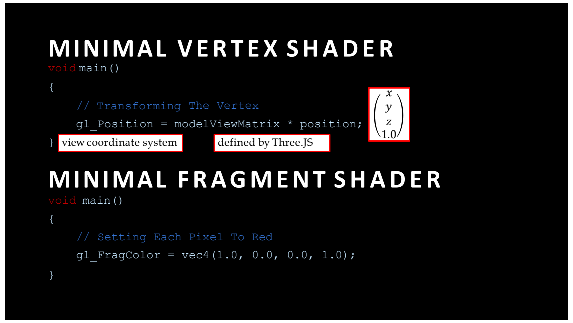
}
```

defined by Three.JS

$$\begin{pmatrix} x \\ y \\ z \\ 1.0 \end{pmatrix}$$

MINIMAL FRAGMENT SHADER

```
void main()
{
    // Setting Each Pixel To Red
    gl_FragColor = vec4(1.0, 0.0, 0.0, 1.0);
}
```



MINIMAL VERTEX SHADER

```
void main()
{
    // Transforming The Vertex
    gl_Position = modelViewMatrix * position;
}
```

view coordinate system

defined by Three.JS

$$\begin{pmatrix}x\\y\\z\\1.0\end{pmatrix}$$

MINIMAL FRAGMENT SHADER

```
void main()
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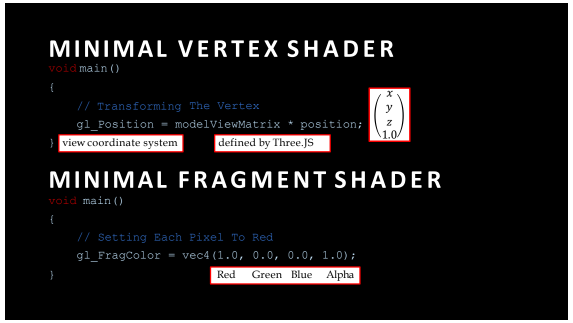
```



MINIMAL VERTEX SHADER

```
void main()
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    gl_Position = modelViewMatrix * position;
}
```

view coordinate system

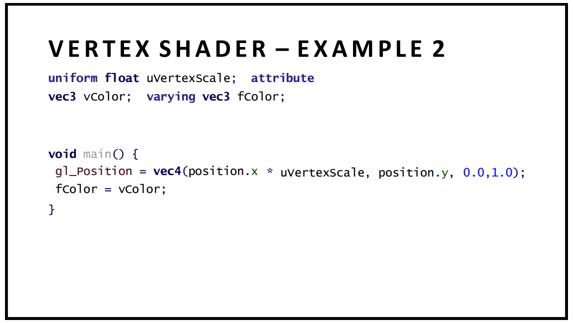
defined by Three.JS

$$\begin{pmatrix}x\\y\\z\\1.0\end{pmatrix}$$

MINIMAL FRAGMENT SHADER

```
void main()
{
    // Setting Each Pixel To Red
    gl_FragColor = vec4(1.0, 0.0, 0.0, 1.0);
}
```

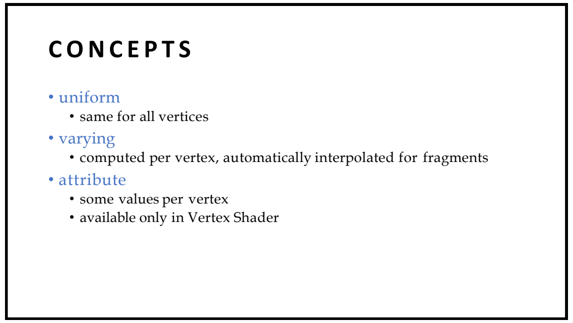
Red Green Blue Alpha



VERTEX SHADER – EXAMPLE 2

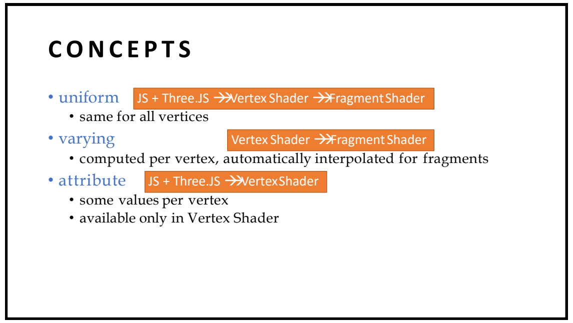
```
uniform float uVertexScale;  attribute
vec3 vColor;  varying vec3 fColor;


void main() {
 gl_Position = vec4(position.x * uVertexScale, position.y, 0.0,1.0);
 fColor = vColor;
}
```



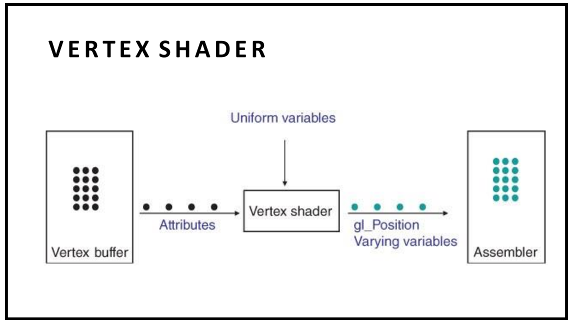
CONCEPTS

- uniform
  - same for all vertices
- varying
  - computed per vertex, automatically interpolated for fragments
- attribute
  - some values per vertex
  - available only in Vertex Shader

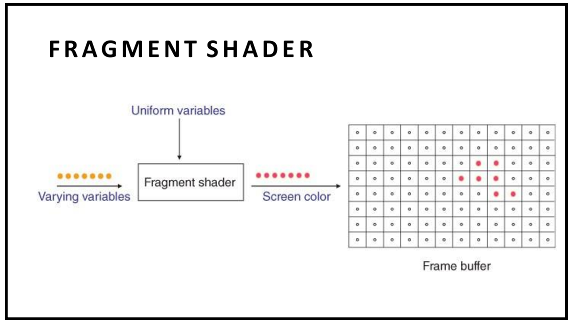


CONCEPTS

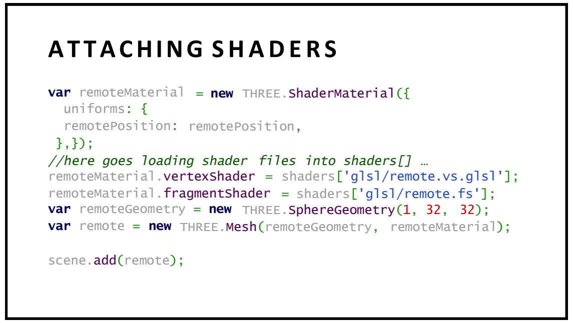
- uniform JS + Three.JS → Vertex Shader → Fragment Shader
  - same for all vertices
- varying Vertex Shader → Fragment Shader
  - computed per vertex, automatically interpolated for fragments
- attribute JS + Three.JS → Vertex Shader
  - some values per vertex
  - available only in Vertex Shader



VERTEX SHADER



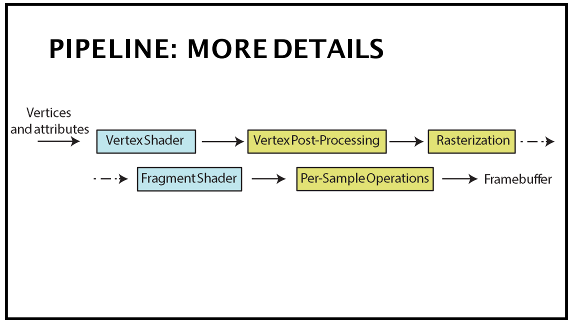
FRAGMENT SHADER



ATTACHING SHADERS

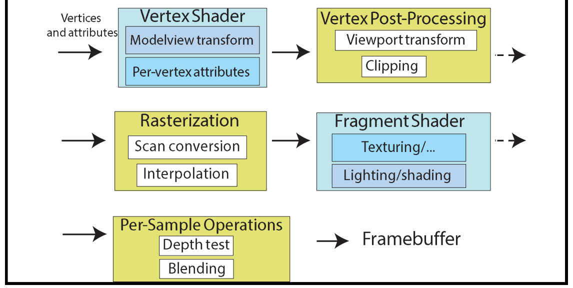
```
var remoteMaterial  = new THREE.ShaderMaterial({
  uniforms: {
  remotePosition: remotePosition,
 },});
//here goes loading shader files into shaders[] …
remoteMaterial.vertexShader = shaders['glsl/remote.vs.glsl'];
remoteMaterial.fragmentShader = shaders['glsl/remote.fs'];
var remoteGeometry = new THREE.SphereGeometry(1, 32, 32);
var remote = new THREE.Mesh(remoteGeometry, remoteMaterial);

scene.add(remote);
```

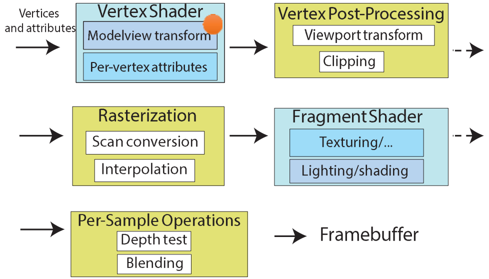


PIPELINE: MORE DETAILS

OPENGL RENDERING PIPELINE



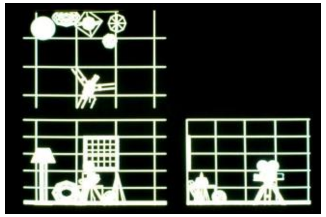
PIPELINE: MORE DETAILS



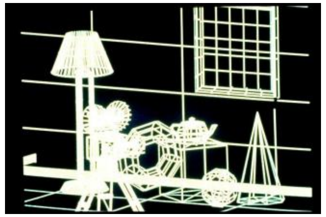
MODELING AND VIEWING TRANSFORMATIONS

- Placing objects - Modeling transformations
  - Map points from object coordinate system to world coordinate system
- Looking from the camera - Viewing transformation
  - Map points from world coordinate system to camera (or eye) coordinate system

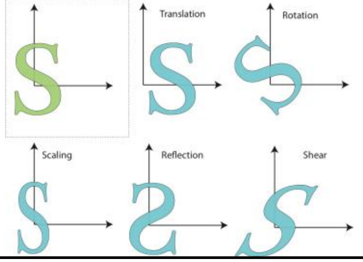
MODELING TRANSFORMATIONS: OBJECT PLACEMENT



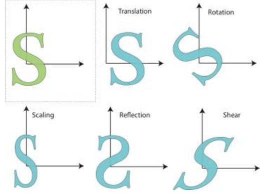
VIEWING TRANSFORMATION: LOOKING FROMA CAMERA



MODELING & VIEWING TRANSFORMATIONS



MODELING & VIEWING TRANSFORMATIONS



- Other transformations (not handled by rendering pipeline):
  - Freeform deformation

MODELING & VIEWING TRANSFORMATION

- Linear transformations
  - Rotations, scaling, shearing
  - Can be expressed as 3x3 matrix
  - E.g. scaling (non uniform):

$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} 2 & 0 & 0 \\ 0 & 3 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$

MODELING & VIEWING TRANSFORMATION

- Affine transformations
  - Linear transformations + translations
  - Can be expressed as 3x3 matrix +3 vector
  - E.g. scale+ translation:

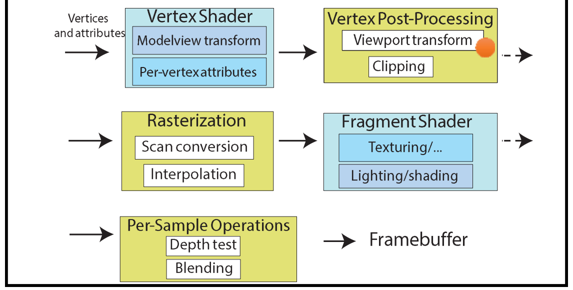
$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} 2 & 0 & 0 \\ 0 & 3 & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} x \\ y \\ z \end{pmatrix} + \begin{pmatrix} t_x \\ t_y \\ t_z \end{pmatrix}$$

  - Another representation: 4x4 homogeneous matrix

MATRICES

- Object coordinates -> World coordinates
  - **Model Matrix**
  - One per object
- World coordinates -> Camera coordinates
  - **View Matrix**
  - One per camera

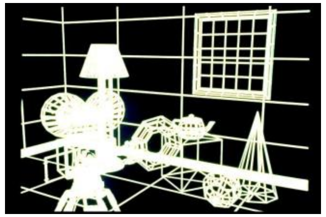
PIPELINE: MORE DETAILS



PERSPECTIVE TRANSFORMATION

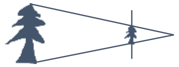
- Purpose:
  - Project 3D geometry to 2D image plane
  - Simulates a camera
- Camera model:
  - Pinhole camera (single view point)
  - More complex camera models exist, but are less common in CG

PERSPECTIVE PROJECTION



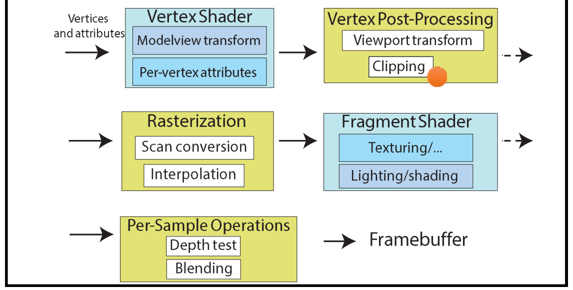
PERSPECTIVE TRANSFORMATION

- In computer graphics:
  - Image plane conceptually in front of center of projection



  - Perspective transformation is **one of** projective transformations
  - Linear & affine transformations also belong to this class
  - All projective transformations can be expressed as 4x4 matrix operations

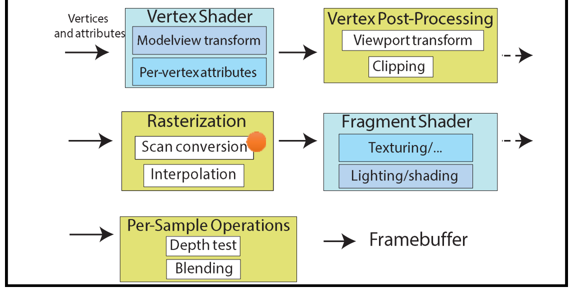
PIPELINE: MORE DETAILS



CLIPPING

- Removing invisible geometry
  - Geometry outside viewing frustum
  - Plus too far or too near one
- Optimization

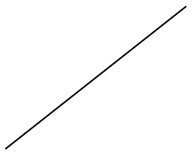
PIPELINE: MORE DETAILS



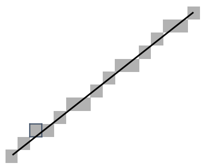
SCAN CONVERSION/RASTERIZATION

- 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



SCAN CONVERSION

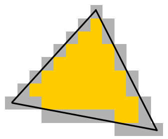


SCAN CONVERSION

- Problem:
  - Line is infinitely thin, but image has finite resolution
  - Results in steps rather than a smooth line
    - Jaggies
    - Aliasing
  - One of the fundamental problems in computer graphics

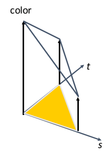
SCAN CONVERSION

-



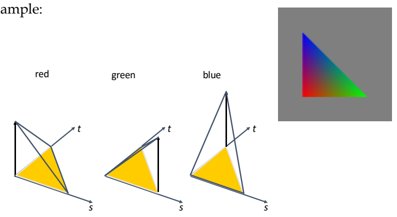
COLOR INTERPOLATION

Linearly interpolate per-pixel color from vertex color values
Treat every channel of RGB color separately

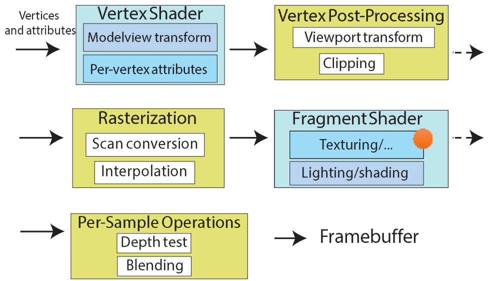


COLOR INTERPOLATION

- Example:



PIPELINE: MORE DETAILS



Vertices and attributes

Vertex Shader
- Modelview transform
- Per-vertex attributes

Vertex Post-Processing
- Viewport transform
- Clipping

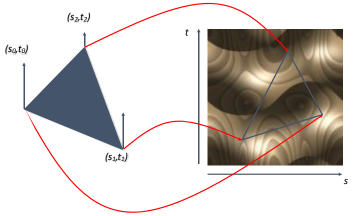
Rasterization
- Scan conversion
- Interpolation

Fragment Shader
- Texturing/...
- Lighting/shading

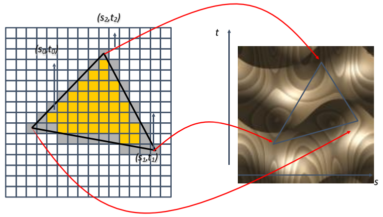
Per-Sample Operations
- Depth test
- Blending

Framebuffer

TEXTURING



TEXTURING



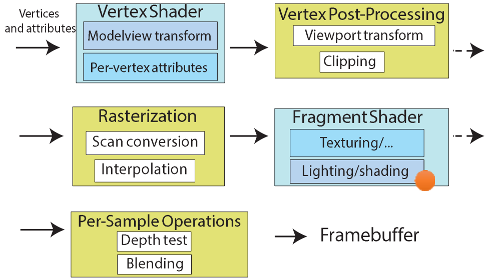
TEXTURE MAPPING

DISPLACEMENT MAPPING

TEXTURING

- Issues:
  - Computing 3D/2D map (low distortion)
  - How to map pixel from texture (texels) to screen pixels
    - Texture can appear widely distorted in rendering
    - Magnification / minification of textures
  - Filtering of textures
  - Preventing aliasing (anti-aliasing)

PIPELINE: MORE DETAILS



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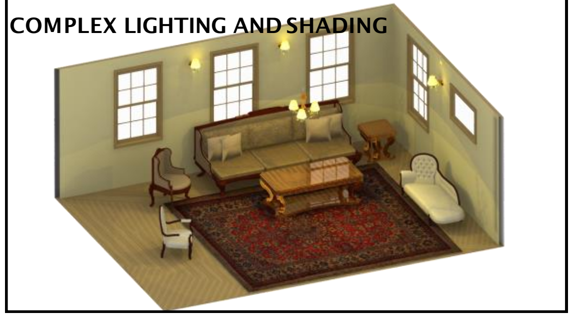
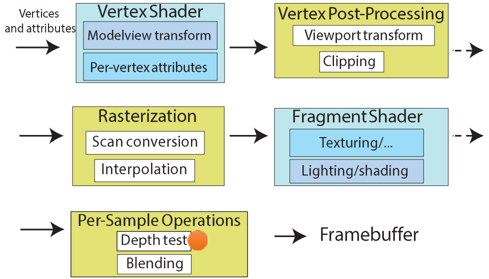
LIGHTING

COMPLEX LIGHTING AND SHADING



PIPELINE: MORE DETAILS



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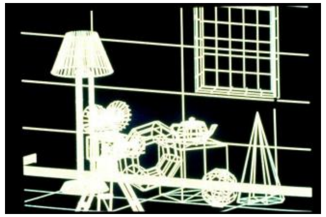
WITHOUT HIDDEN LINE REMOVAL



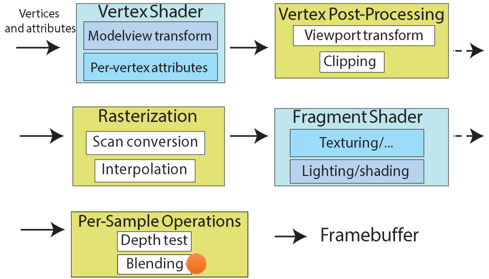
HIDDEN LINE REMOVAL

HIDDEN SURFACE REMOVAL

DEPTH TEST / HIDDEN SURFACE REMOVAL

- Remove invisible geometry
  - Parts that are hidden behind other geometry
- Possible Implementations:
  - Pixel level decision
    - Depth buffer
  - Object space decision
    - E.g. intersection order for ray tracing

PIPELINE: MORE DETAILS



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BLENDING

- Blending:
  - Fragments -> Pixels
  - Draw from farthest to nearest
  - No blending – replace previous color
  - Blending: combine new & old values with some arithmetic operations
- Frame Buffer : video memory on graphics board that holds resulting image & used to display it

REFLECTION/SHADOWS