Image Processing and Computer Graphics
Rendering Pipeline

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Outline

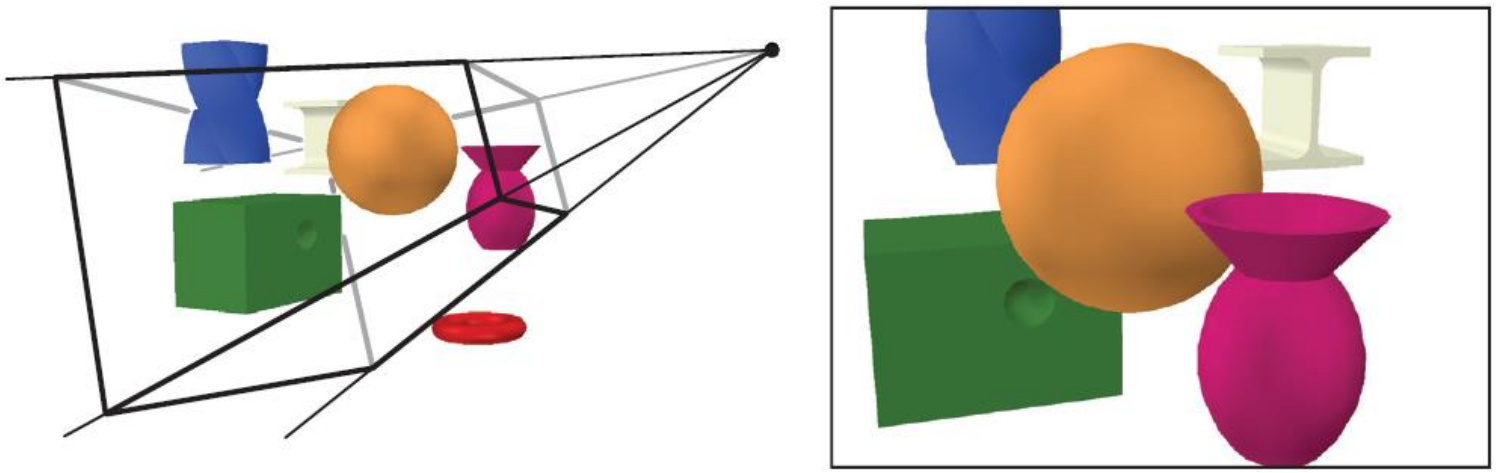
- introduction
- rendering pipeline
- vertex processing
- primitive processing
- fragment processing
- summary

Rendering

- the process of generating an image given
  - a virtual camera
  - objects
  - light sources
- various techniques, e. g.
  - rasterization (topic of this course)
  - raytracing (topic of the course “Advanced Computer Graphics”)
- one of the major research topics in computer graphics
  - rendering
  - animation
  - geometry processing

Rasterization

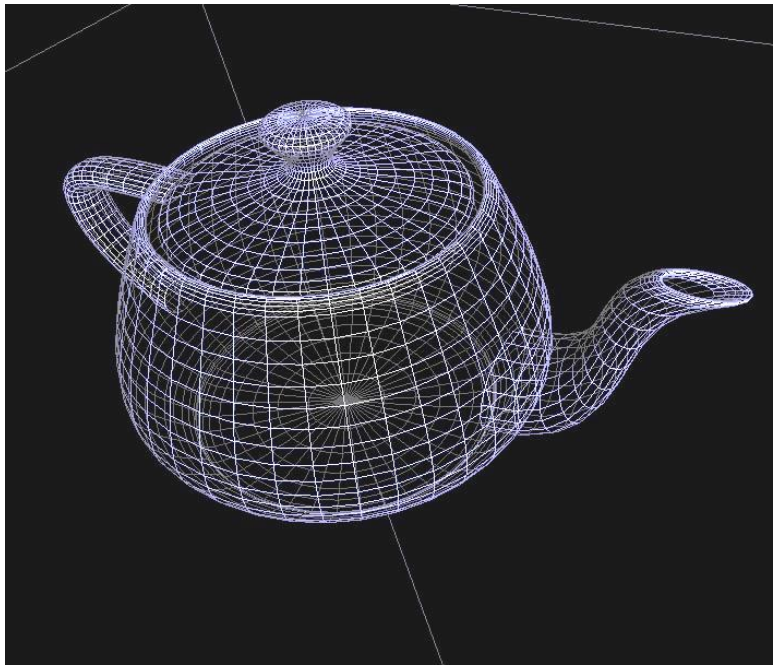
- rendering algorithm for generating 2D images from 3D scenes
- transforming geometric primitives such as lines and polygons into raster image representations, i. e. pixels



[Akenine-Moeller et al.: Real-time Rendering]

Rasterization

- 3D objects are approximately represented by vertices (points), lines, polygons
- these primitives are processed to obtain an 2D image



[Akenine-Moeller]

Rendering Pipeline

- processing stages comprise the rendering pipeline (graphics pipeline)
- supported by commodity graphics hardware
  - GPU - graphics processing unit
  - computes stages of the rasterization-based rendering pipeline
- OpenGL and DirectX are software interfaces to graphics hardware
  - this course focuses on concepts of the rendering pipeline
  - this course assumes OpenGL in implementation-specific details

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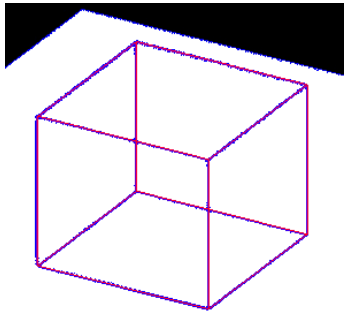
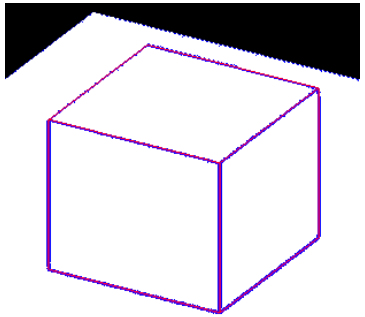
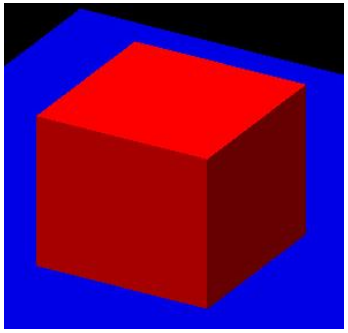
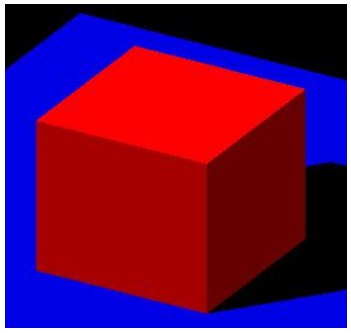
Rendering Pipeline - Task

- 3D input
  - a virtual camera
    - position, orientation, focal length
  - objects
    - points (vertex / vertices), lines, polygons
    - geometry and material properties (position, normal, color, texture coordinates)
  - light sources
    - direction, position, color, intensity
  - textures (images)
- 2D output
  - per-pixel color values in the framebuffer

Rendering Pipeline / Some Functionality

- resolving visibility
- evaluating a lighting model
- computing shadows (not core functionality)
- applying textures


visibility lighting model shadow texture

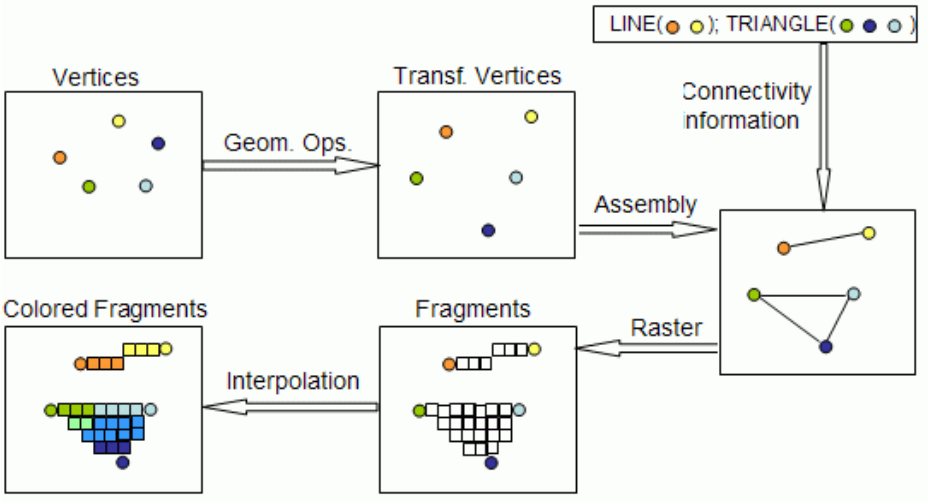
[Wright et al.: OpenGL SuperBible]

Rendering Pipeline
Main Stages

- vertex processing / geometry stage / vertex shader
  - processes all vertices independently in the same way
  - performs transformations per vertex, computes lighting per vertex
- geometry shader
  - generates, modifies, discards primitives
- primitive assembly and rasterization / rasterization stage
  - assembles primitives such as points, lines, triangles
  - converts primitives into a raster image
  - generates fragments / pixel candidates
  - fragment attributes are interpolated from vertices of a primitive
- fragment processing / fragment shader
  - processes all fragments independently in the same way
  - fragments are processed, discarded or stored in the framebuffer

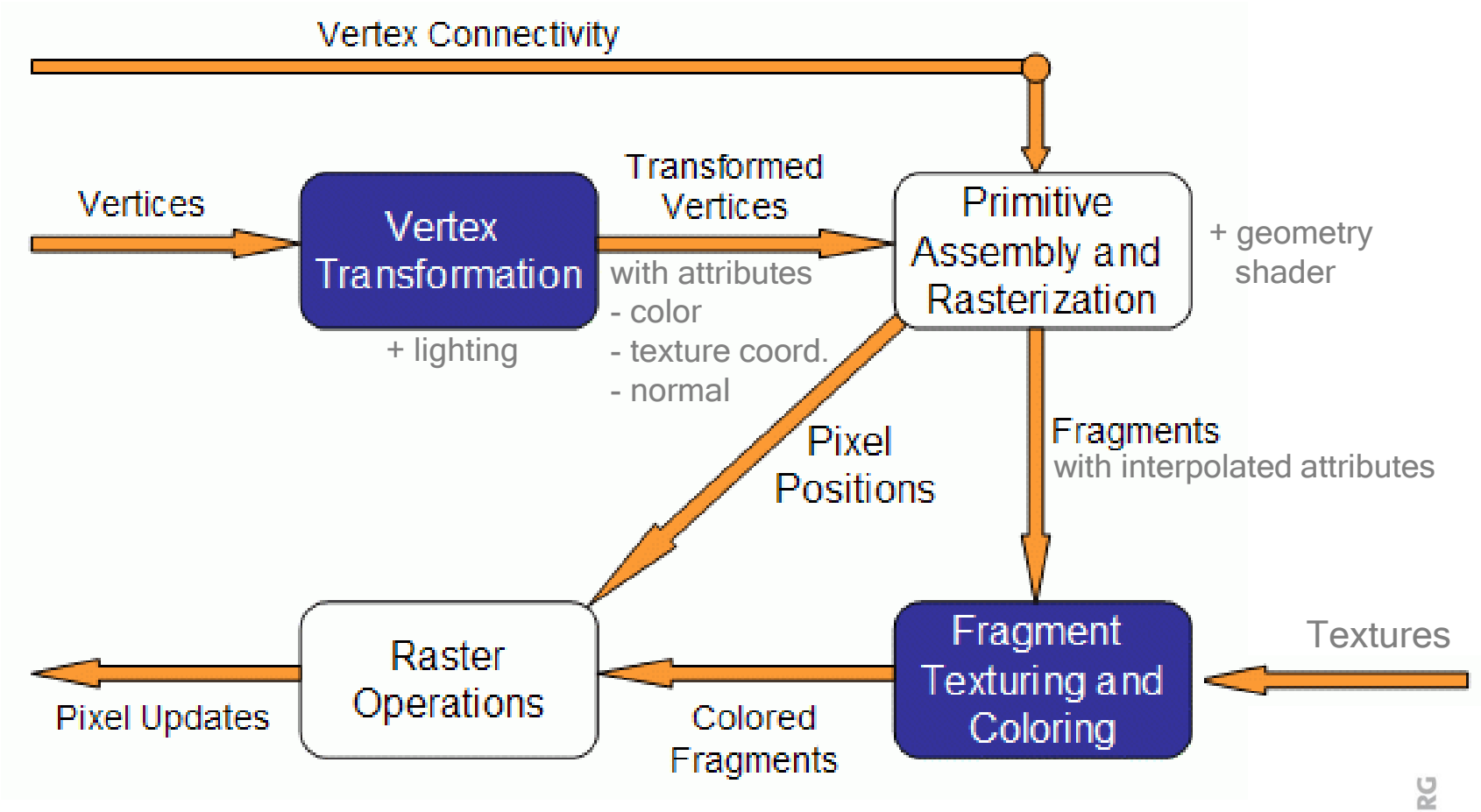
Rendering Pipeline
Main Stages

- vertex position transform
- lighting per vertex
- primitive assembly, combine vertices to lines, polygons
- rasterization, computes pixel positions affected by a primitive
- fragment generation with interpolated attributes, e. g. color
- fragment processing (not illustrated), fragment is discarded or used to update the pixel information in the framebuffer, more than one fragment can be processed per pixel position



[Lighthouse 3D]

Rendering Pipeline
Main Stages



[Lighthouse 3D]

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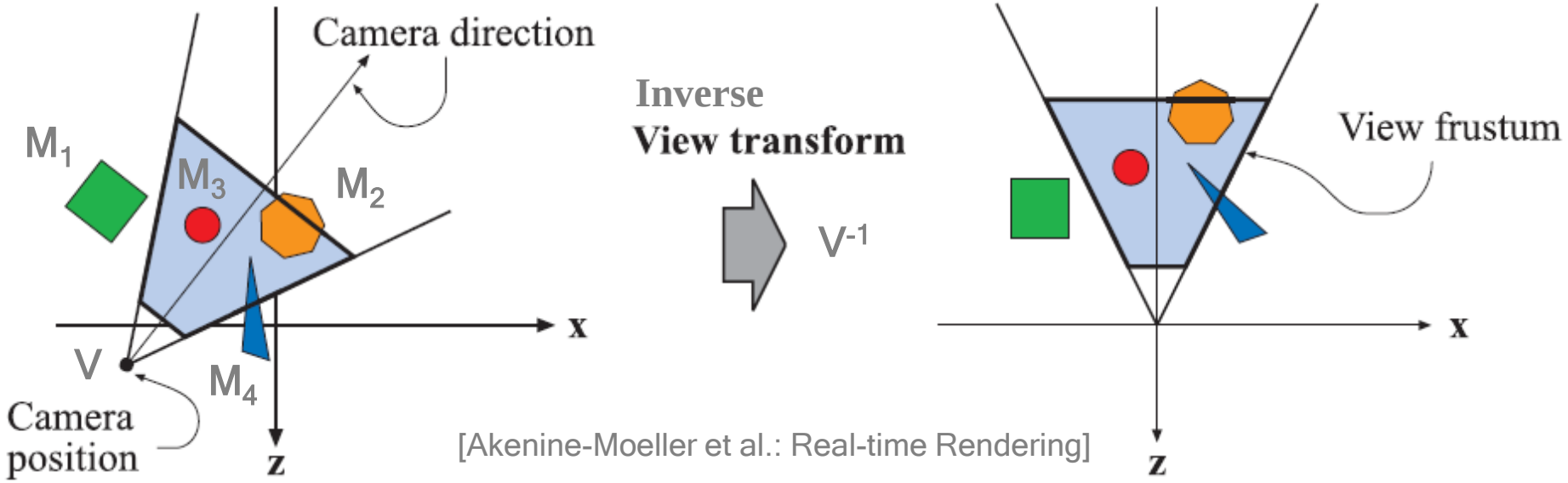
Vertex Processing (Geometry Stage)

- model transform
- view transform
- lighting
- projection transform
- clipping
- viewport transform

Model Transform
View Transform

- each object and the respective vertices are positioned, oriented, scaled in the scene with a model transform
- camera is positioned and oriented, represented by the view transform
- i. e., the inverse view transform is the transform that places the camera at the origin of the coordinate system, facing in the negative z-direction
- entire scene is transformed with the inverse view transform

Model Transform
View Transform



[Akenine-Moeller et al.: Real-time Rendering]

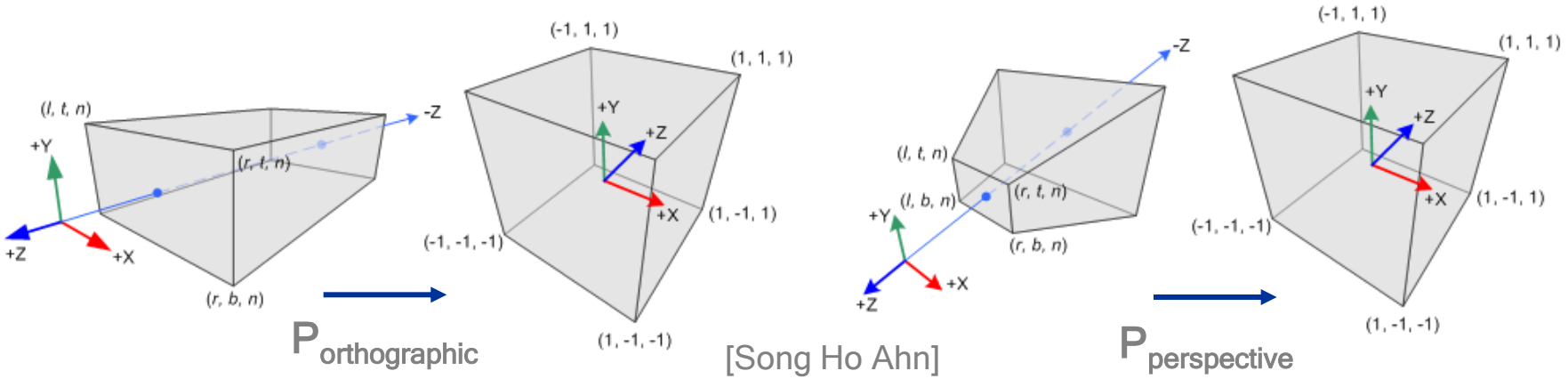
- M_1, M_2, M_3, M_4, V are matrices representing transformations
- M_1, M_2, M_3, M_4 are model transforms to place the objects in the scene
- V places and orientates the camera in space
  - V^{-1} transforms the camera to the origin looking along the negative z-axis
- model and view transforms are combined in the modelview transform
- the modelview transform $V^{-1}M_{1..4}$ is applied to the objects

Lighting

- interaction of light sources and surfaces
  is represented with a lighting / illumination model
- lighting computes color for each vertex
  - based on light source positions and properties
  - based on transformed position, transformed normal,
    and material properties of a vertex

Projection Transform

- **P** transforms the view volume to the canonical view volume
- the view volume depends on the camera properties
  - orthographic projection → cuboid
  - perspective projection → pyramidal frustum



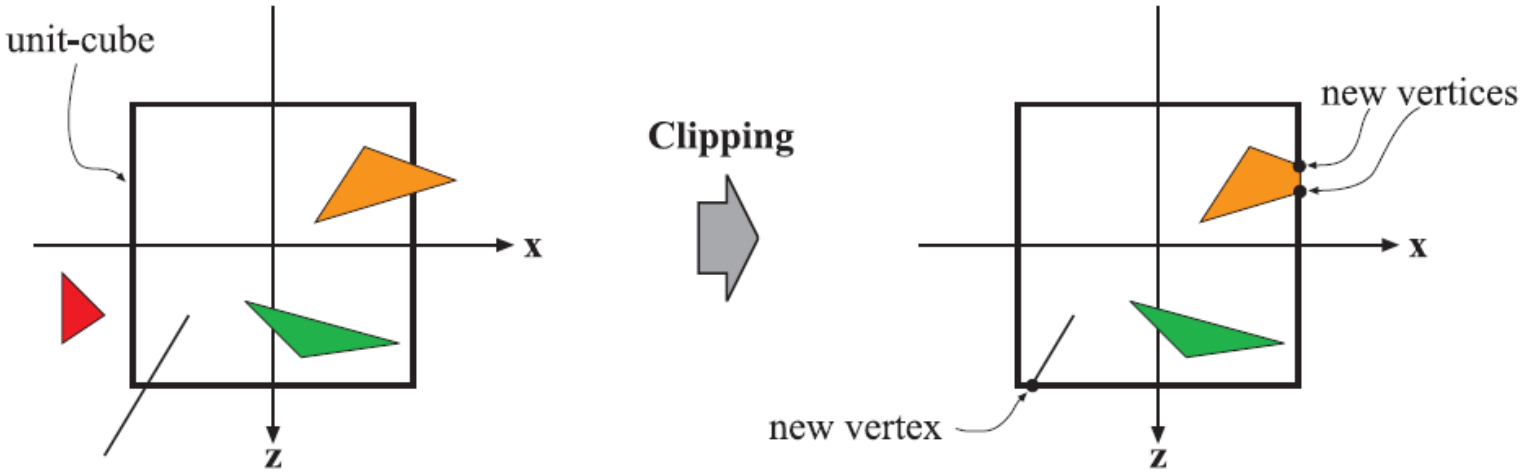
- canonical view volume is a cube from (-1,-1,-1) to (1,1,1)
- view volume is specified by near, far, left, right, bottom, top

Projection Transform

- view volume (cuboid or frustum) is transformed into a cube (canonical view volume)
- objects inside (and outside) the view volume are transformed accordingly
- orthographic
  - combination of translation and scaling
  - all objects are translated and scaled in the same way
- perspective
  - complex transformation
  - scaling factor depends on the distance of an object to the viewer
  - objects farther away from the camera appear smaller

Clipping

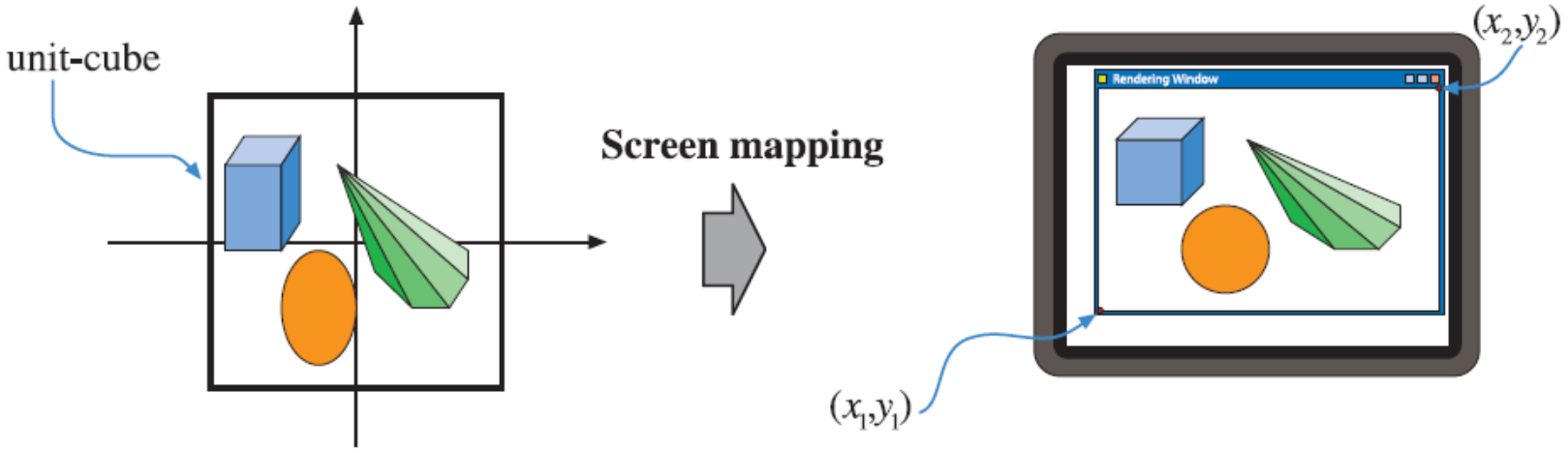
- primitives, that intersect the boundary of the view volume, are clipped
  - primitives, that are inside, are passed to the next processing stage
  - primitives, that are outside, are discarded
- clipping deletes and generates vertices and primitives



[Akenine-Moeller et al.: Real-time Rendering]

Viewport Transform / Screen Mapping

- projected primitive coordinates (x_p, y_p, z_p) are transformed to screen coordinates (x_s, y_s)
- screen coordinates together with depth value are window coordinates (x_s, y_s, z_w)



[Akenine-Moeller et al.: Real-time Rendering]

Viewport Transform / Screen Mapping

- (x_p, y_p) are translated and scaled from the range of (-1, 1) to actual pixel positions (x_s, y_s) on the display
- z_p is generally translated and scaled from the range of (-1, 1) to (0,1) for z_w
- screen coordinates (x_s, y_s) represent the pixel position of a fragment that is generated in a subsequent step
- z_w , the depth value, is an attribute of this fragment used for further processing

Vertex Processing - Summary

object space

⇓ modelview transform

eye space / camera space

⇓ lighting, projection

clip space / normalized device coordinates

⇓ clipping, viewport transform

window space

Vertex Processing - Summary

- input
  - vertices in object / model space
  - 3D positions
  - attributes such as normal, material properties, texture coordinates
- output
  - vertices in window space
  - 2D pixel positions
  - attributes such as normal, material properties, texture coordinates
  - additional or updated attributes such as
    - normalized depth (distance to the viewer)
    - color (result of the evaluation of the lighting model)

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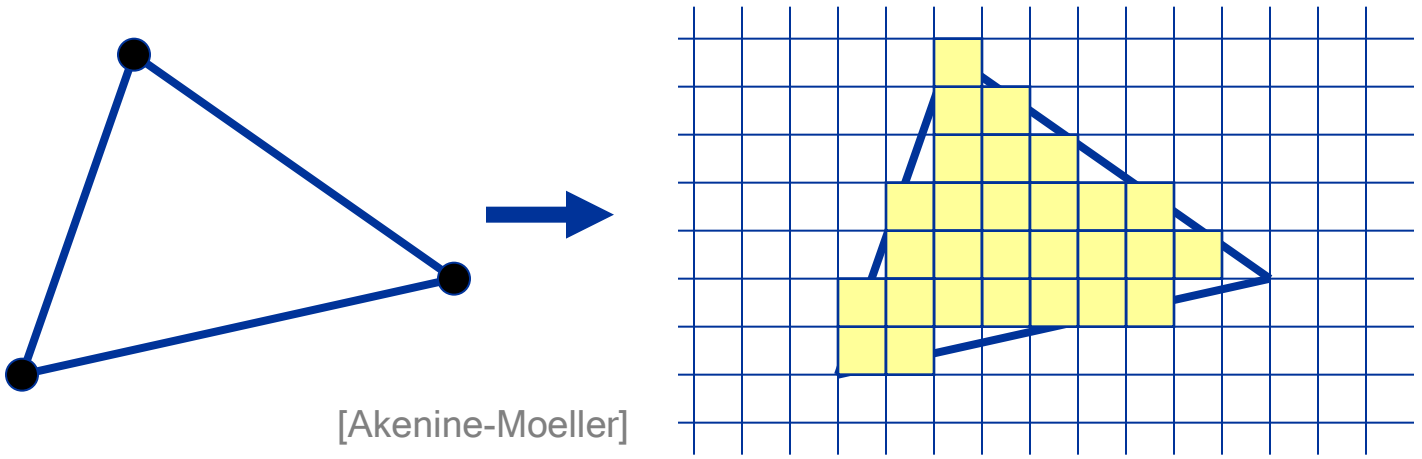
Primitive Assembly / Rasterization

- primitive assembly
  - vertex information and connectivity information are combined for further processing of points, lines and triangles
- geometry shader
  - change, delete, generate primitives
- rasterization
  - converts primitives into fragments
  - computes positions of screen pixels that are affected by a primitive
  - generates a fragment for each affected pixel position
  - interpolates attributes from vertices to fragments

Rasterization

- input
  - vertices with attributes and connectivity information
  - attributes: color, depth, texture coordinates
- output
  - fragments with attributes
    - pixel position
    - interpolated color, depth, texture coordinates



[Akenine-Moeller]

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Fragment Processing

- fragment attributes are processed and tests are performed
  - fragment attributes are processed
  - fragments are discarded or
  - fragments pass a test and finally update the framebuffer
- processing and testing make use of
  - fragment attributes
  - textures
  - additional data that is available for each pixel position
    - depth buffer
    - color buffer
    - stencil buffer
    - accumulation buffer

Attribute Processing

- texture lookup
  - use texture coordinates to look up a texel (pixel of an texture image)
- texturing
  - combination of color and texel
- fog
  - adaptation of color based on fog color and depth value
- antialiasing
  - adaptation of alpha value (and color)
  - color has three components: red, green, blue
  - color is represented as a 4D vector (red, green, blue, alpha)

Tests

- scissor test
  - check if fragment is inside a specified rectangle
  - used for, e. g., masked rendering
- alpha test
  - check if the alpha value fulfills a certain requirement
  - comparison with a specified value
  - used for, e. g., transparency and billboarding
- stencil test
  - check if the stencil value in the framebuffer at the position of the fragment fulfills a certain requirement
  - comparison with a specified value
  - used for various rendering effects, e. g. masking, shadows

Depth Test

- depth test
  - compare depth value of the fragment and depth value of the framebuffer at the position of the fragment
  - used for resolving the visibility
  - if the depth value of the fragment is larger than the framebuffer depth value, the fragment is discarded
  - if the depth value of the fragment is smaller than the framebuffer depth value, the fragment passes and (potentially) overwrites the current color and depth values in the framebuffer

Blending / Merging

- blending
  - combines the fragment color with the framebuffer color at the position of the fragment
  - usually determined by the alpha values
  - resulting color (including alpha value) is used to update the framebuffer
- dithering
  - finite number of colors
  - map color value to one of the nearest renderable colors
- logical operations / masking

Fragment Processing - Summary

- texture lookup
- texturing
- fog
- antialiasing
- scissor test
- alpha test
- stencil test
- depth test
- blending
- dithering
- logical operations

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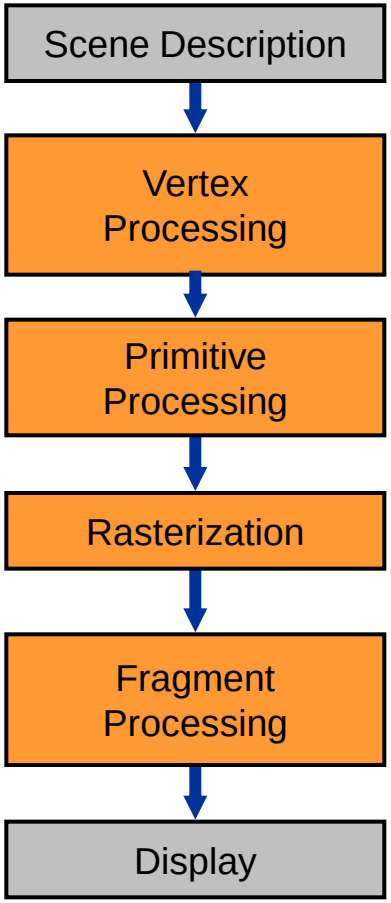
Rendering Pipeline - Summary



Rendering Pipeline - Summary

- primitives consist of vertices
- vertices have attributes (color, depth, texture coordinates)
- vertices are transformed and lit
- primitives are rasterized into fragments / pixel candidates with interpolated attributes
- fragments are processed using
  - their attributes such as color, depth, texture coordinates
  - texture data / image data
  - framebuffer data / data per pixel position (color, depth, stencil, acc.)
- if a fragment passes all tests, it replaces the pixel data in the framebuffer