Computer Graphics

13 - Rasterization & Visibility

Yoonsang Lee
Spring 2021

기말고사 모의테스트 1 분석 결과

- 다음과 같은 부정행위로 간주될 수 있는 사례들이 있었음.

- 시험 도중 손이나 머리가 카메라에 잘 보이지 않음 - 3명+
- 카메라 혹은 모니터 각도로 인해 화면이 잘 보이지 않음 - 6명+
- 빛이나 모니터 밝기에 의해 화면이 잘 보이지 않음 - 9명+
- 녹화된 영상이 90도 회전해 있음 - 2명+
- 주변에 다른 디바이스 스크린이 존재 - 6명+
- 시험 종료 시간 전에 PC로 다른 작업을 함 - 5명+
- 카메라가 준비되지 않음 - 10명+

- 내일 있을 모의테스트 2에 모두 성실히 임해주기 바랍니다.
  – 미응시하는 경우 실습 결석으로 체크할 예정

Topics Covered

- Two Approaches for Rendering
  - Object-oriented (Rasterization)
  - Image-oriented (Raytracing)

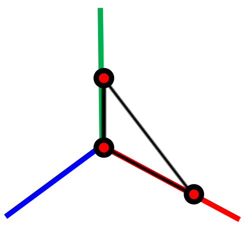
- Rasterization (in a narrow sense)
  - Line / Polygon Drawing

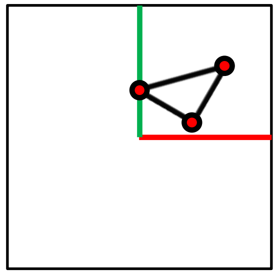
- Visibility Problem
  - Clipping (Viewing frustum culling)
  - Back-face culling
  - Hidden surface removal

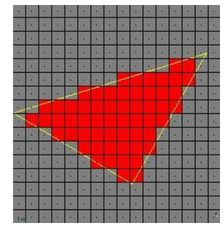
- Rendering (Graphics) Pipeline Again

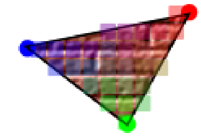
- Course Wrap-up

Recall: Rendering (Graphics) Pipeline









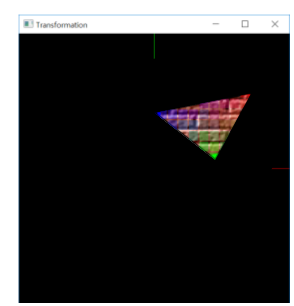
vertex processing → **rasterization** → **fragment processing** → output merging

vertex processing: performs a sequence of vertex transformations

rasterization: assembles polygons & converts each polygon into a set of fragments (pixels)

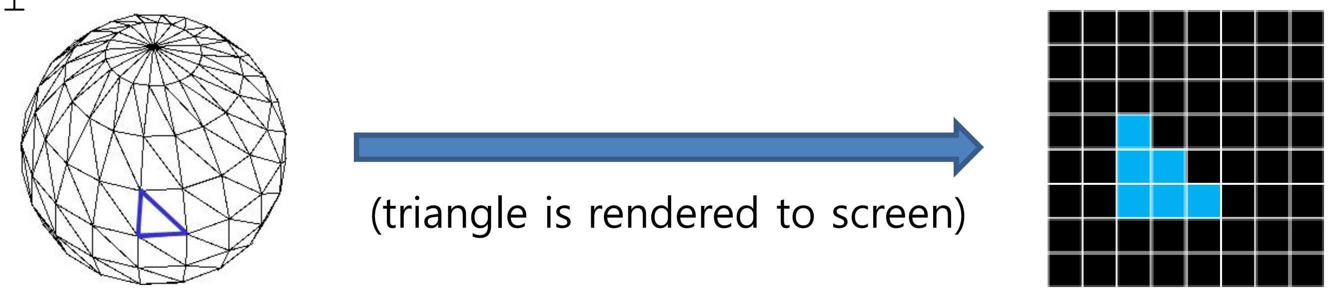
fragment processing: determines color of each fragment with light & texture

output merging



Two Approaches for Rendering - 1

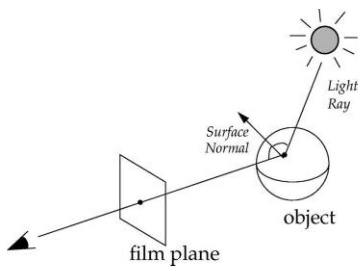
```
for each object in scene
    transform the object to viewport   # vertex processing
    find pixels for the object   # rasterization (in a narrow sense)
    set color of the pixels based on texture and lighting
model                                    # fragment processing
```



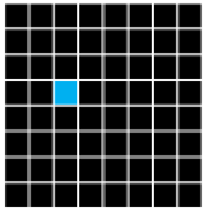
- This is called **rendering (graphics) pipeline**
- or **rasterization** (in a broad sense)
- or **object-oriented rendering**.

Two Approaches for Rendering - 2

```
for each pixel in image(film plane)
    determine which object should be shown at the pixel
    set color of the pixel based on texture and lighting model
```



(ray intersection is rendered to screen)



- This is called **ray tracing**
- or **image-oriented rendering.**

- We'll skip ray tracing part, see *13 - reference-RayTracing.pdf* for more information about it.

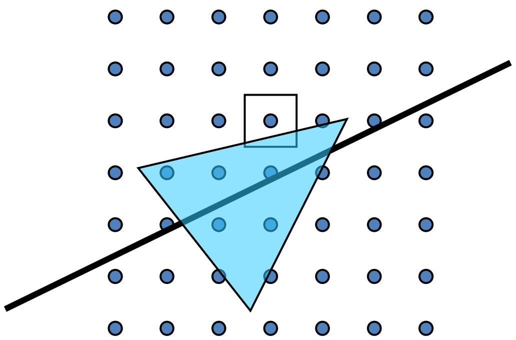
Rasterization (in a broad sense) & Ray Tracing in this Course

- Most topics we've covered are *fundamental concepts* of computer graphics, regardless of these two rendering approaches.
  - Transformations, Hierarchical Modeling, Orientation & Rotation, Kinematics & Animation
  - Mesh, Lighting & Shading, Curves, Texture Mapping

- Except some topics:
  - Rendering Pipeline, Viewing / Projection / Viewport transformations
  - Rasterization & Visibility (today's topic)
- are specific to **rasterization** (in a broad sense).

Rasterization (in a narrow sense)

- Rasterization converts vertex representation to pixel representation (fragments)



- First job: Compute which pixels belong to a primitive
  - to enumerate the pixels covered by the primitive
- Second job: Interpolate values across the primitive
  - e.g. colors computed at vertices
  - e.g. normals at vertices

Rasterization (in a narrow sense)

- A primitive can be a point, line, or polygon

- Line drawing algorithms
  - Digital differential analyzer (DDA)
  - Bresenham's (a.k.a. Midpoint)
  - Xiaolin Wu's

- Polygon drawing algorithms
  - Scanline
  - Boundary fill
  - Flood fill

Rasterization (in a narrow sense)

- But, we'll just skip details of these algorithms.

- Actually, line drawing and polygon drawing are not so easy as one might think.
  - Computational efficiency, anti-aliasing, ...

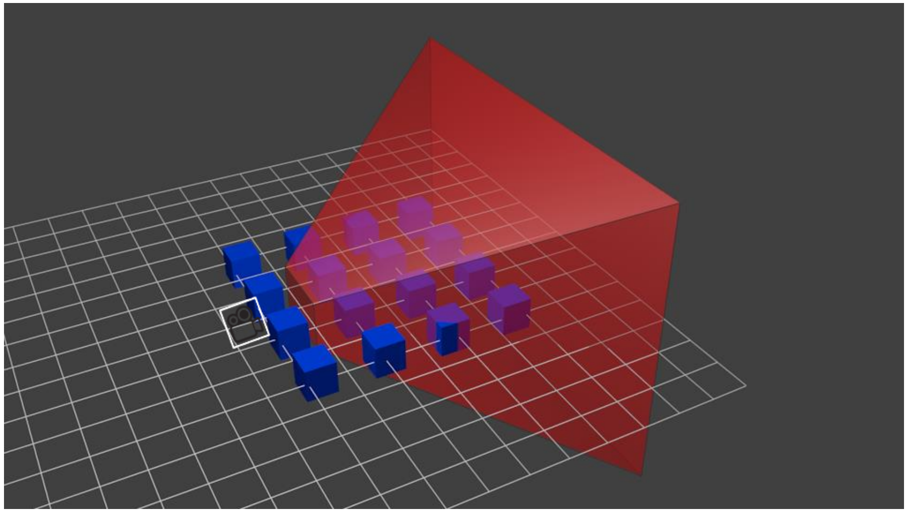
- But most graphics APIs (including OpenGL) basically support these operations.
  - These algorithms were intensively studied in early days of computer graphics, so quite mature now.
  - Now basic algorithms are implemented in graphics hardware (GPU) and you can use them by calling such graphics APIs.

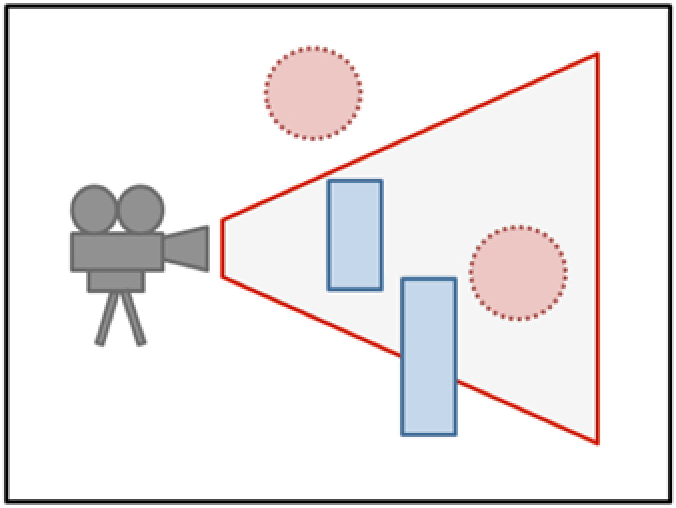
- So nowadays you can think lines and polygons as “primitives” that are basically rendered.

Visibility Problem

- What is VISIBLE?

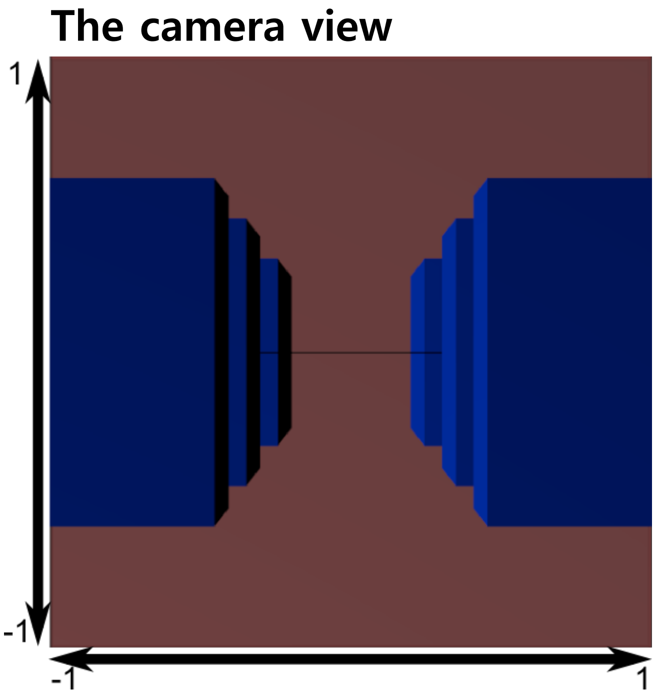
Red: viewing frustum, Blue: objects

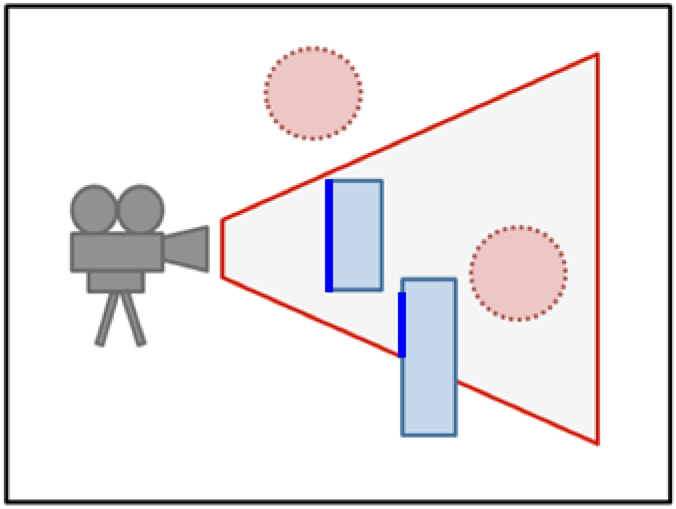




Visibility Problem

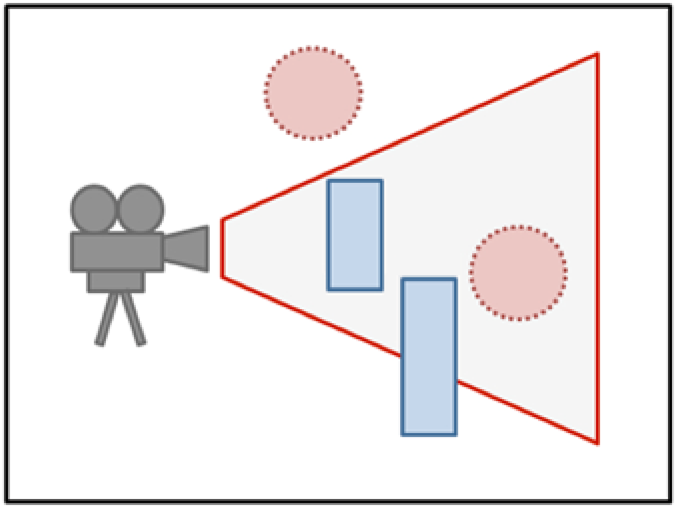
- The answer is:





Visibility Problem

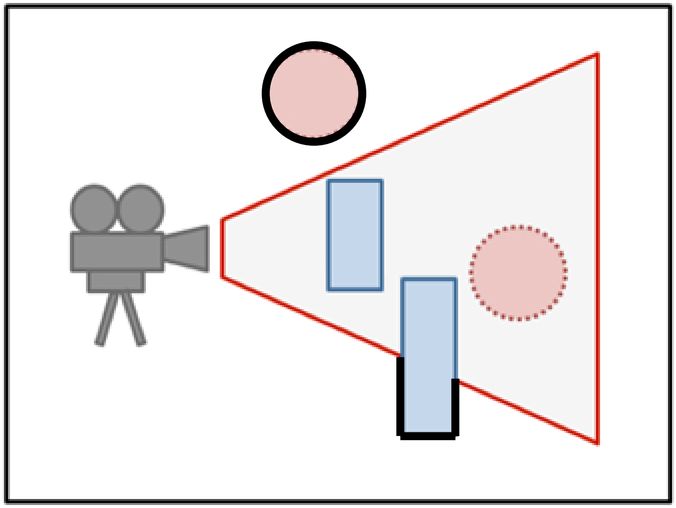
- What is NOT VISIBLE?



Visibility Problem

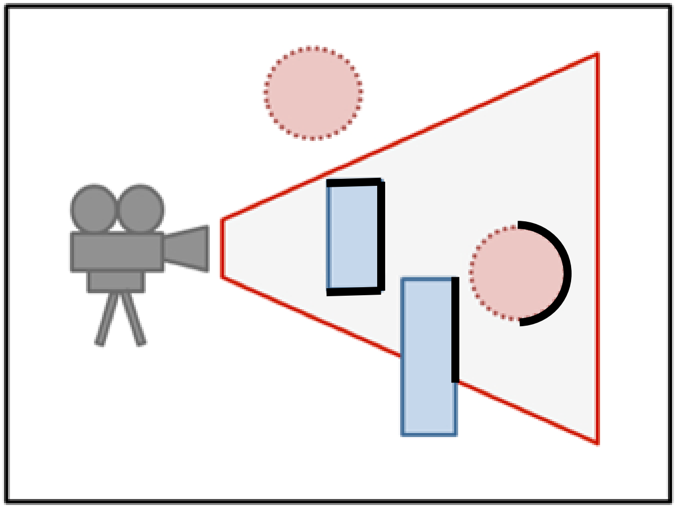
- What is NOT VISIBLE?

- **Primitives outside of the viewing frustum**



Visibility Problem

- What is NOT VISIBLE?
- Primitives outside of the viewing frustum
- **Back-facing primitives**



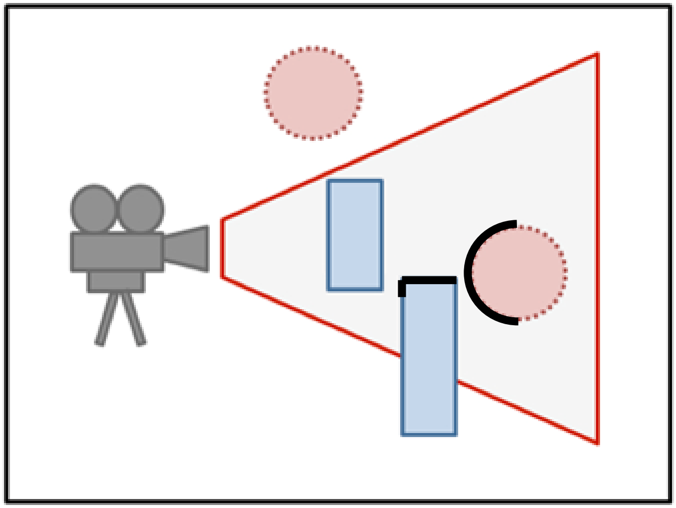
Visibility Problem

- What is NOT VISIBLE?

- Primitives outside of the viewing frustum

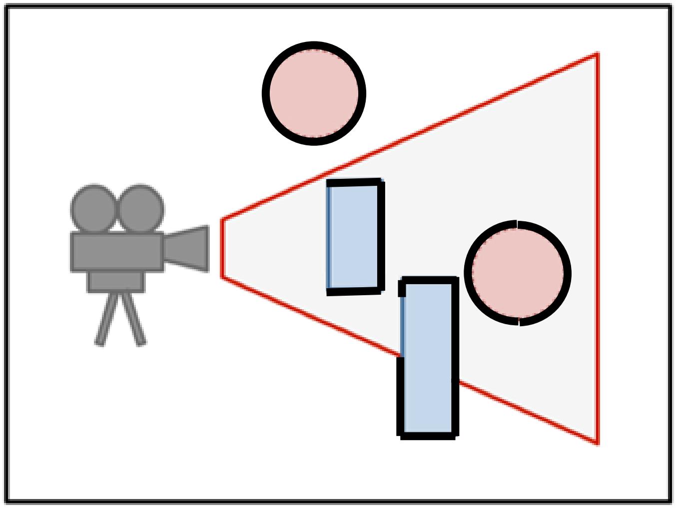
- Back-facing primitives

- **Primitives occluded by other objects closer to the camera**



Visibility Problem

- These **invisible primitives should be removed** because…
- No need to spend time to process invisible vertices and polygons.
- A close object must hide a farther one.
- So, removing these primitives is required for efficient and correct rendering.



Visibility Problem

- Removing...

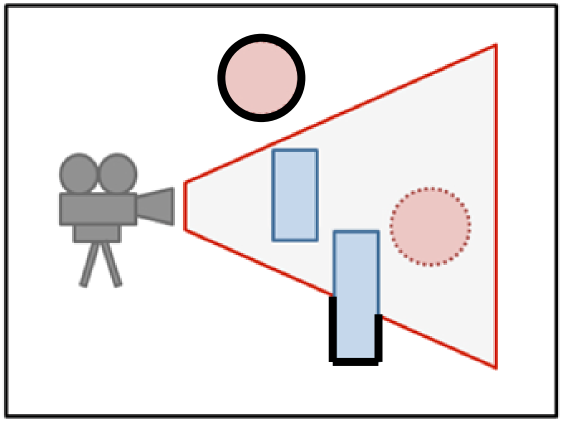
- Primitives outside of the viewing frustum
- → **Clipping (Viewing frustum culling)**

- Back-facing primitives
- → **Back-face culling**

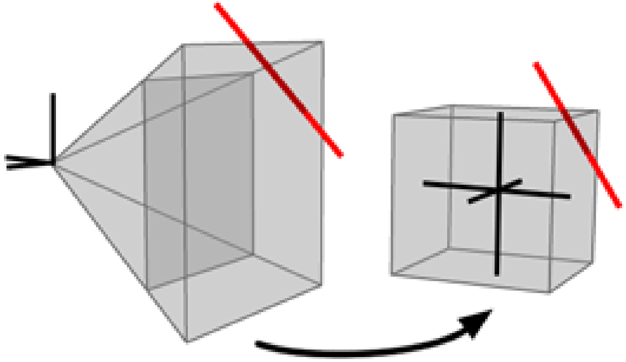
- Primitives occluded by other objects closer to the camera
- → **Hidden surface removal**

Clipping (Viewing Frustum Culling)

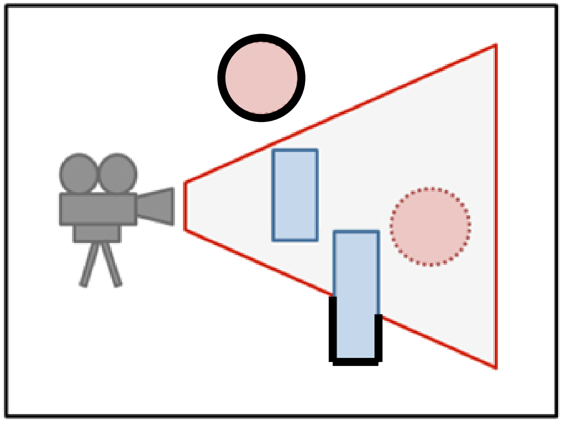
- Removing primitives outside of the viewing frustum



- Clipping is much easier with canonical view volume.
  - actually done in *clip space*



Clipping (Viewing Frustum Culling)



- Line clipping algorithms
  - Cohen–Sutherland
  - Liang–Barsky
  - Cyrus–Beck
- Polygon clipping algorithms
  - Sutherland–Hodgman
  - Weiler–Atherton

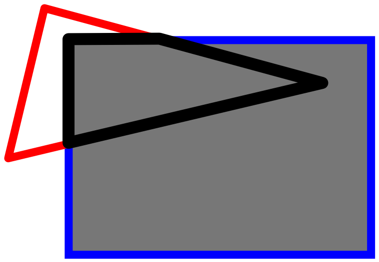
Clipping (Viewing Frustum Culling)

- Polygon clipping algorithms are more complicated.
  - Vertices may be added to or deleted from the triangle.

- Again, let's just skip details of these algorithms.

- Most graphics APIs (including OpenGL) performs clipping by default.
  - You just set the view frustum, then OpenGL will do clipping for you.

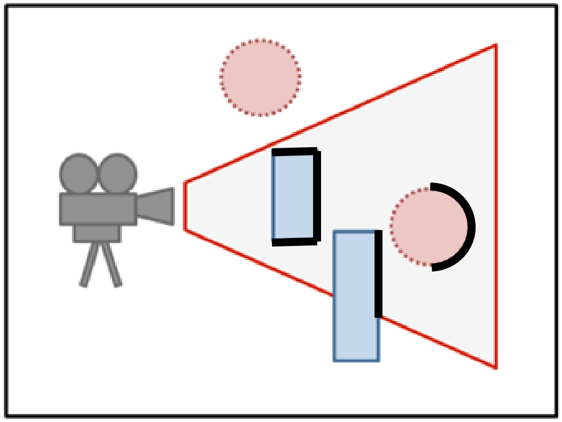
- *13 - reference-rasterization,clipping.pdf* has brief slides about DDA (line drawing) & Cohen-Sutherland algorithms (line clipping). If you're interested, please refer it.



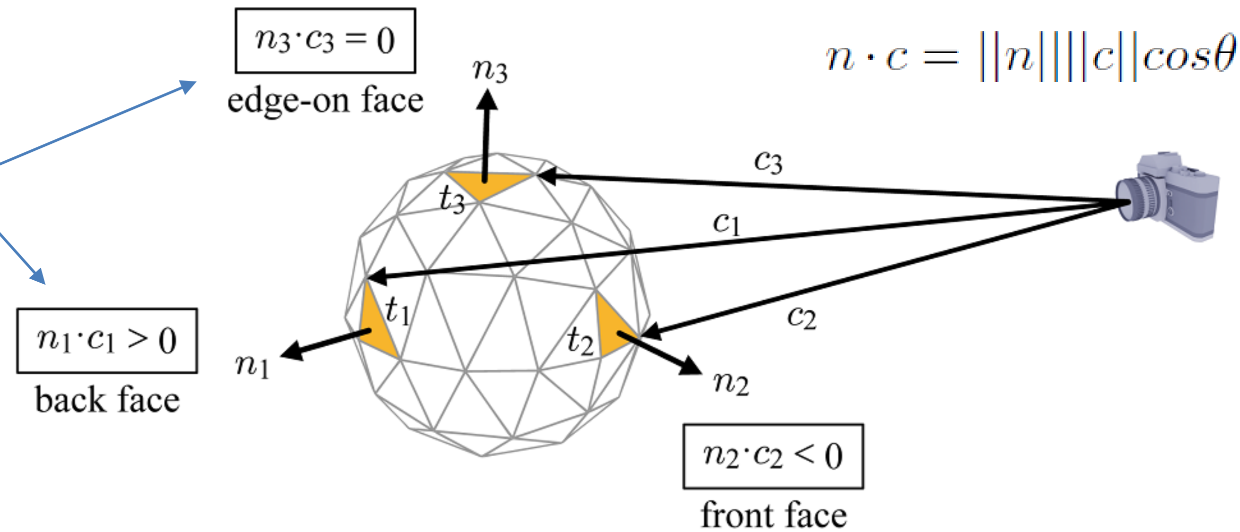
triangle → quad

Back-Face Culling

- Removing back-facing primitives
- Determined by the dot product of normal and view (camera) vectors.

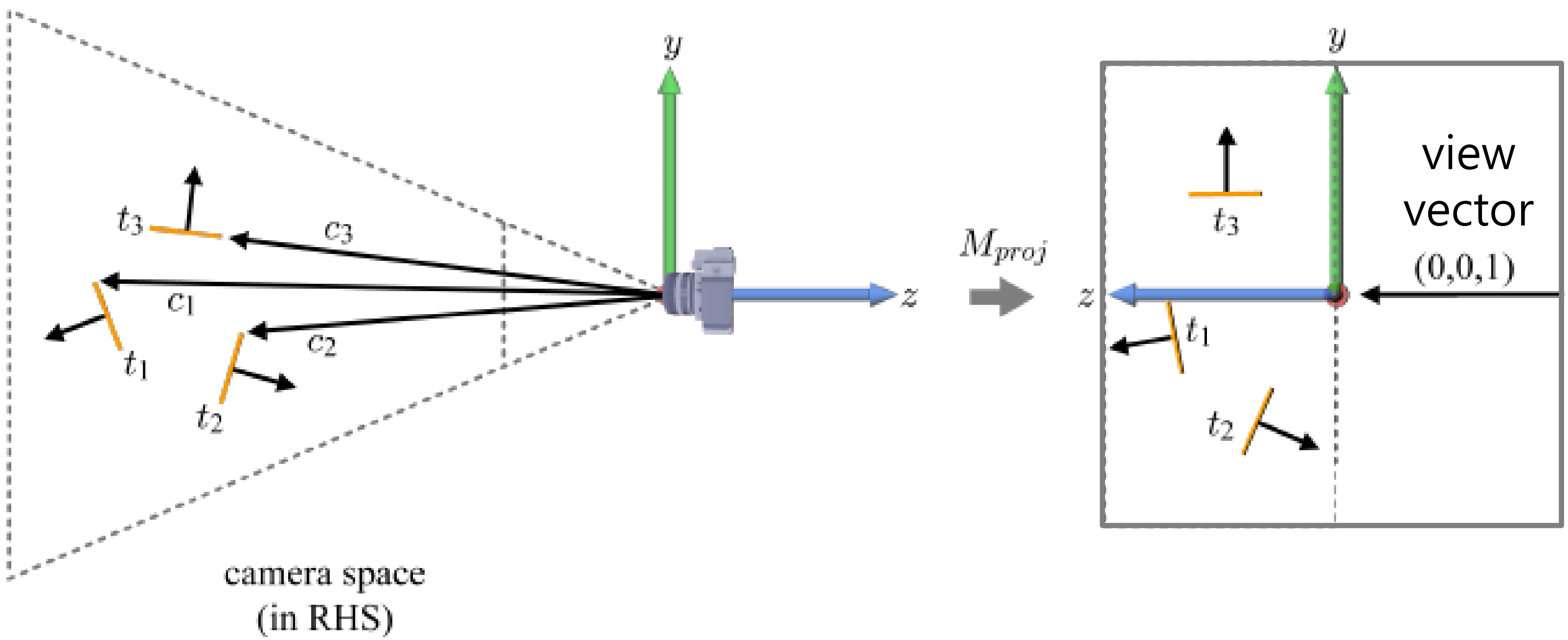


Discard!

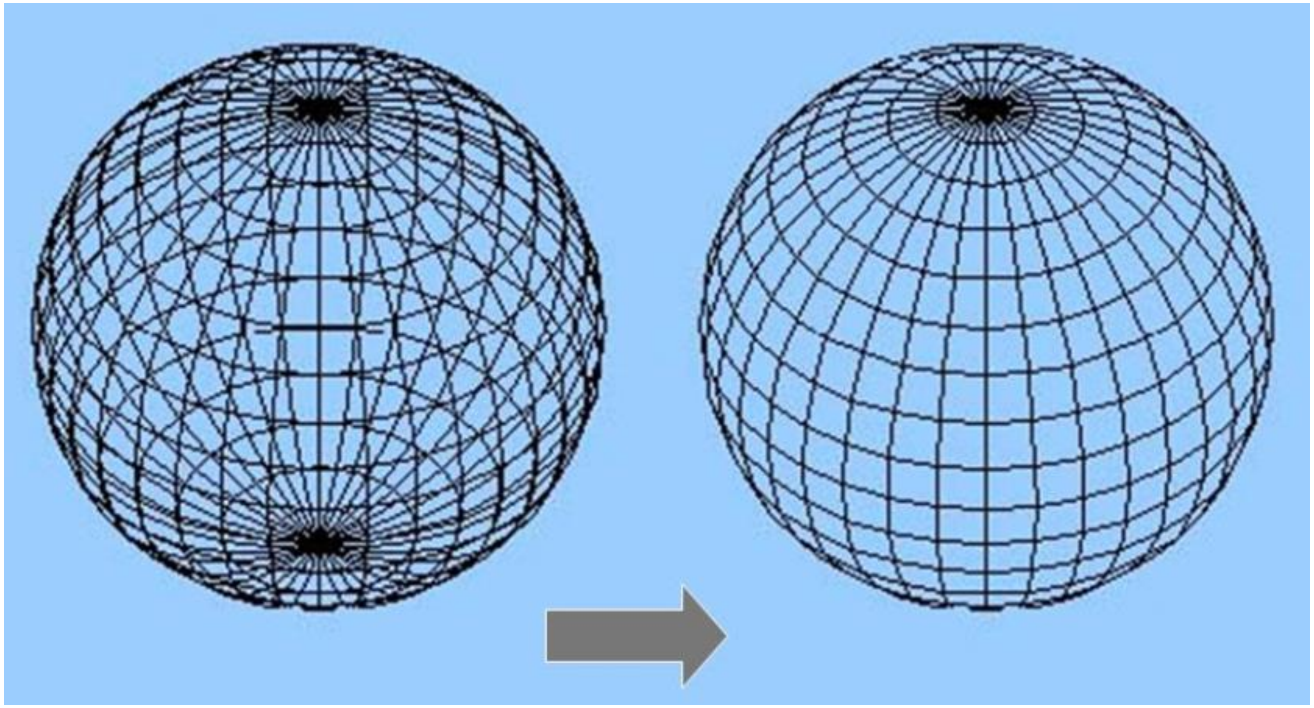


Back-Face Culling

- Back-face culling is much more efficient when performed in canonical view volume.
  – Because in canonical view volume, we can use a single view vector, (0,0,1).



Back-Face Culling



Back-Face Culling in OpenGL

- **Can cull front faces or back faces**
- **Back-face culling can sometimes double performance**

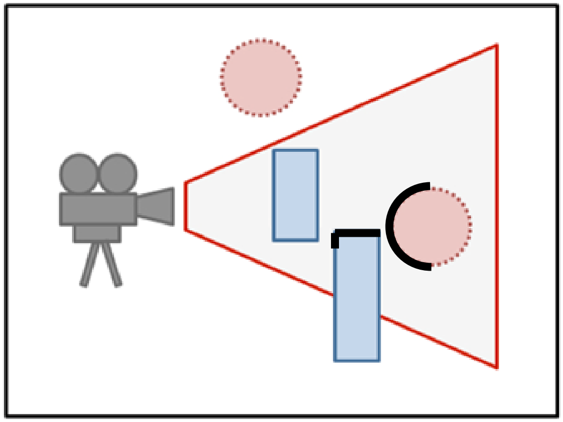
(initial value: GL_CCW)

```
if (cull):
    glFrontFace(GL_CCW)       # define winding order
    glEnable(GL_CULL_FACE)    # enable Culling
    glCullFace(GL_BACK)       # which faces to cull
else:
    glDisable(GL_CULL_FACE)
```

(initially disabled)

You can also do front-face culling!

Hidden Surface Removal



- Removing primitives occluded by other objects closer to the camera

- Also known as
  - Hidden Surface Elimination
  - Hidden Surface Determination
  - Visible Surface Determination
  - Occlusion Culling

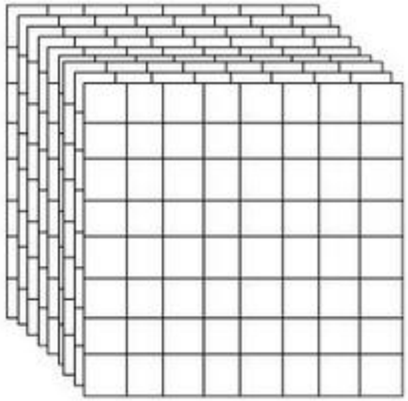
Hidden Surface Removal

- Many algorithms
  - Z-buffer (Depth buffer)
  - Painter’s algorithm
  - BSP tree
  - ...
- Z-buffer is the standard method.
- Let’s see the ideas of Painter’s algorithm & Z-buffer.

Frame Buffer (background knowledge for understanding HSR algorithms)

- Frame buffer is the portion of memory to hold the bitmapped image that is sent to the (raster) display device.

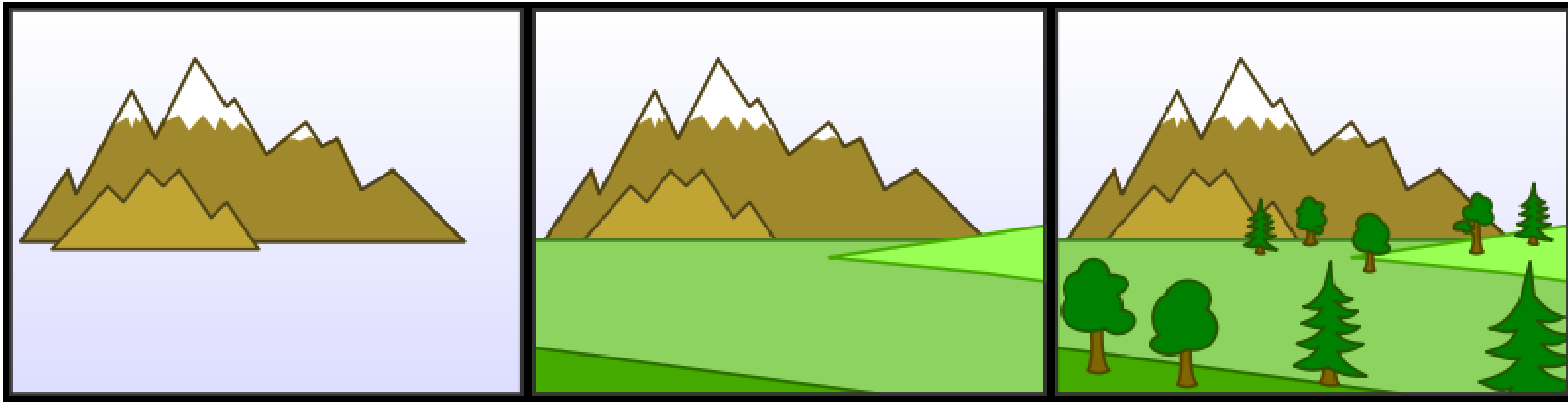
- A frame buffer is characterized by its width, height, and depth.
  - E.g. The frame buffer size for 4K UHD resolution with 32bit color depth = 3840 x 2160 x 32 bits



- Typically stored on the graphic card's memory.
  - But integrated graphics (e.g. Intel HD Graphics) use the main memory to store the frame buffer.

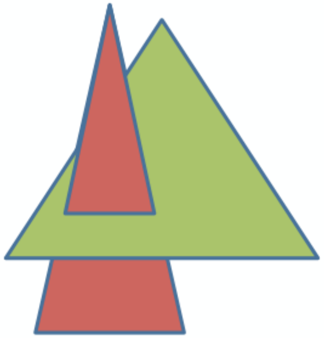
Painter's algorithm

- Simplest way to do hidden surfaces
- Draw from back to front, use overwriting in framebuffer
- Requires sorting all polygons by their depth

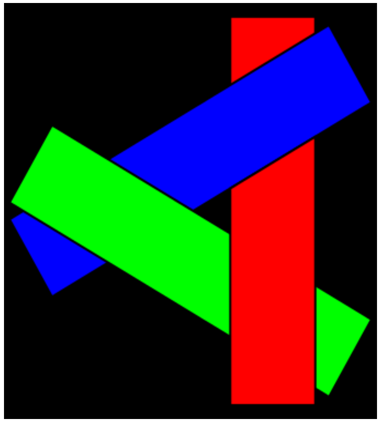


Weakness of Painter's Algorithm

- What if there are cycles in the sorted graph?
  - The only solution is dividing these polygons into small pieces.



- Need to update the sorted graph whenever camera or object location is changed.



- → Time-consuming!

The *z* buffer

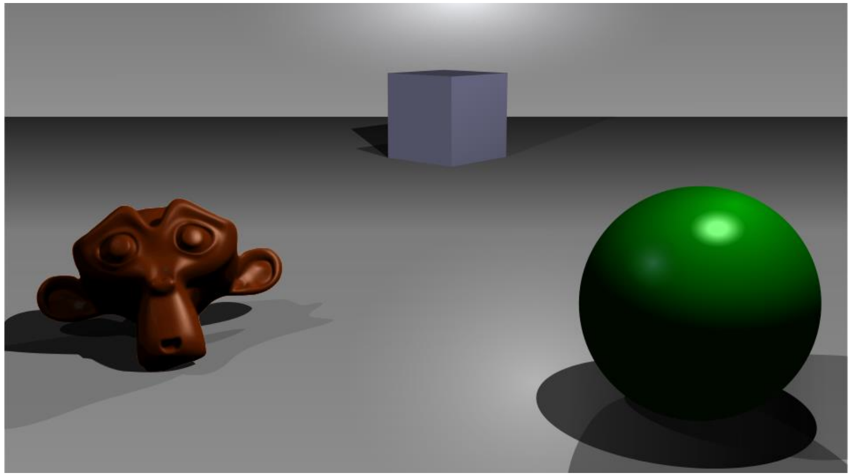
- In many (most) applications maintaining a *z* sort is too expensive
  - changes all the time when the view changes
  - many data structures exist, but complex
- Solution: draw in any order, keep track of closest
  - Z-buffer keeps track of closest depth so far
  - when drawing, compare object's depth to current closest depth and discard if greater

Z-Buffering: Algorithm

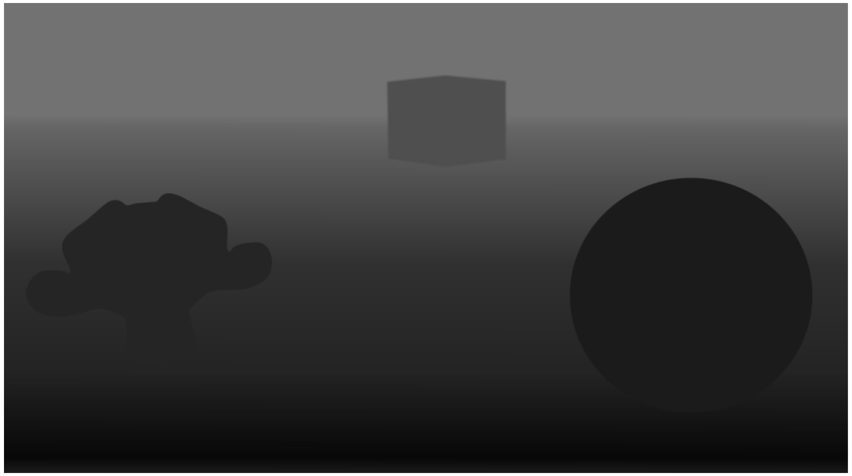
```
allocate depth_buffer;          // Allocate depth buffer → Same size as viewport.

for each pixel (x,y)            // For each pixel in viewport.
  write_frame_buffer(x,y,backgrnd_color);    // Initialize color.
  write_depth_buffer(x,y,farPlane_depth);    // Initialize depth (z) buffer.

for each polygon                // Draw each polygon (in any order).
  for each pixel (x,y) in polygon    // Rasterize polygon.
    color = polygon's color at (x,y);
    pz = polygon's z-value at (x,y);// Interpolate z-value at (x, y).
    if (pz < read_depth_buffer(x,y))        // If new depth is closer:
      write_frame_buffer(x,y,color);      //  Write new (polygon) color.
      write_depth_buffer(x,y,pz);         //  Write new depth.
```

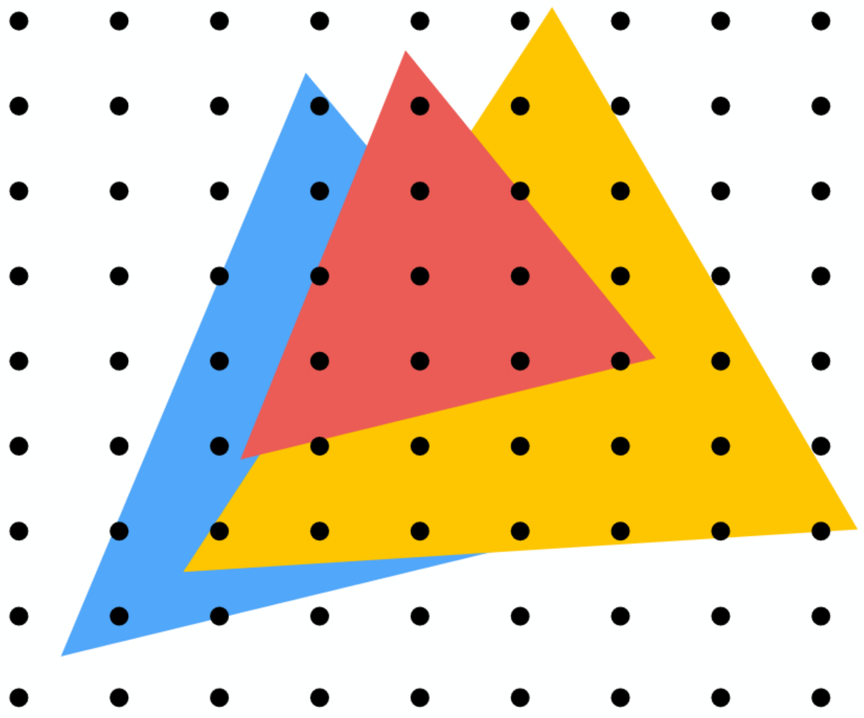


Frame buffer



Z-buffer (Depth buffer)

Example: rendering three opaque triangles



Occlusion using the depth-buffer (Z-buffer)

Processing yellow triangle:

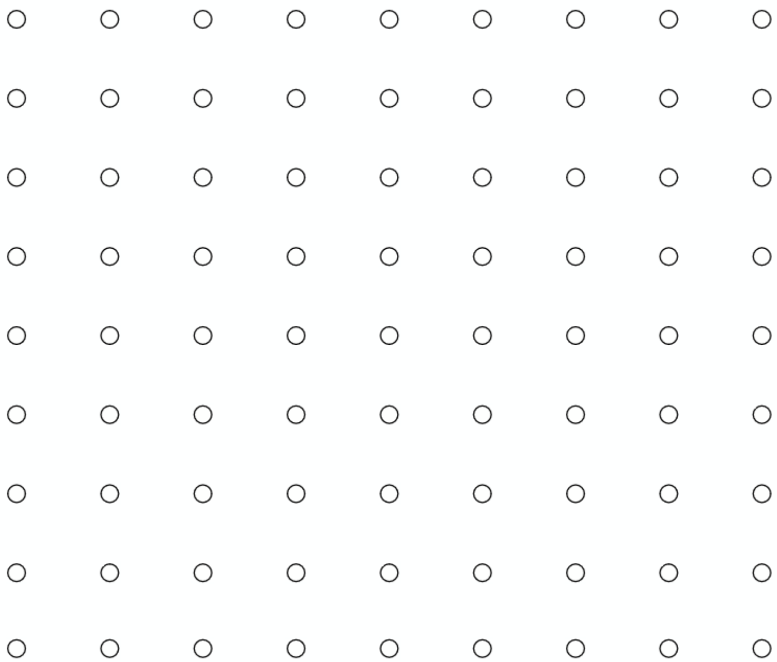
depth = 0.5

Grayscale value of sample point used to indicate distance

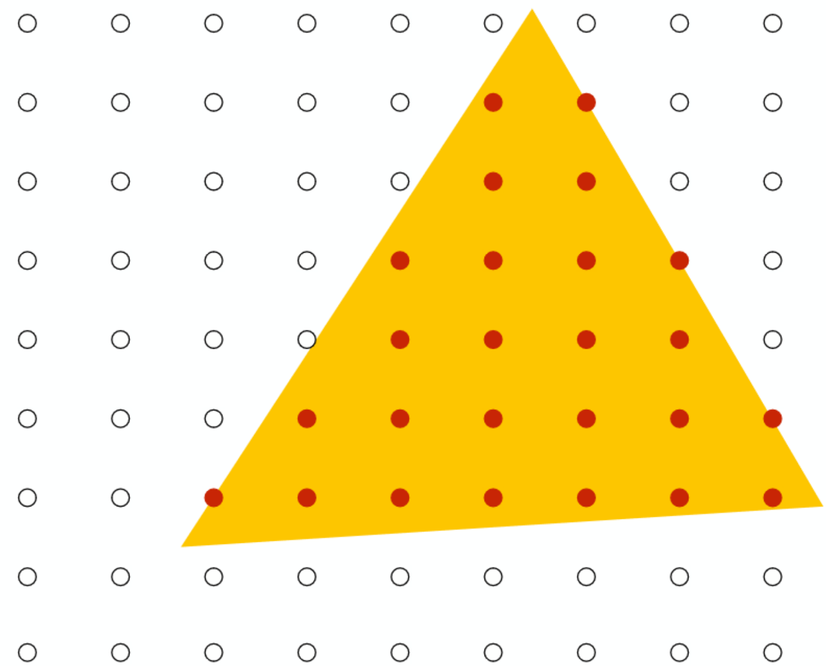
White = large distance

Black = small distance

Red = sample passed depth test



Color buffer contents



Depth buffer contents

Occlusion using the depth-buffer (Z-buffer)

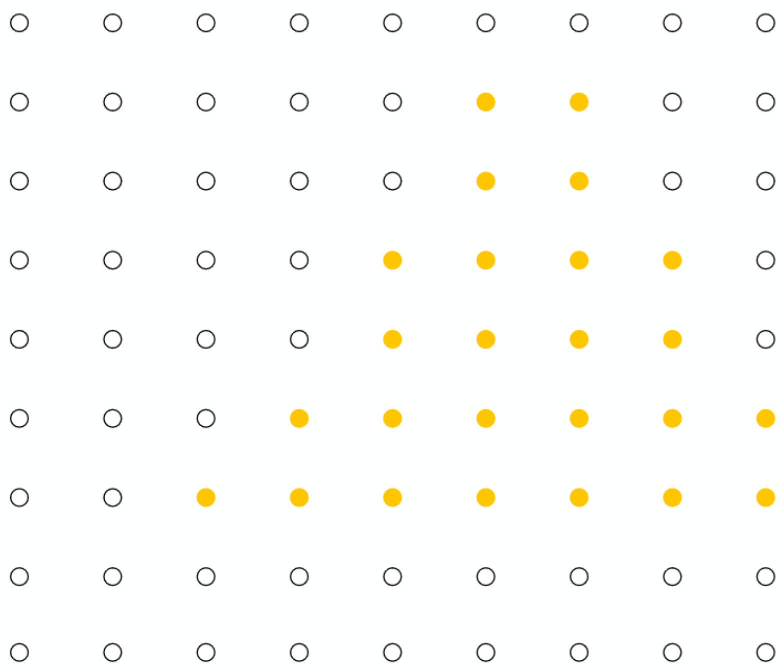
After processing yellow triangle:

Grayscale value of sample point used to indicate distance

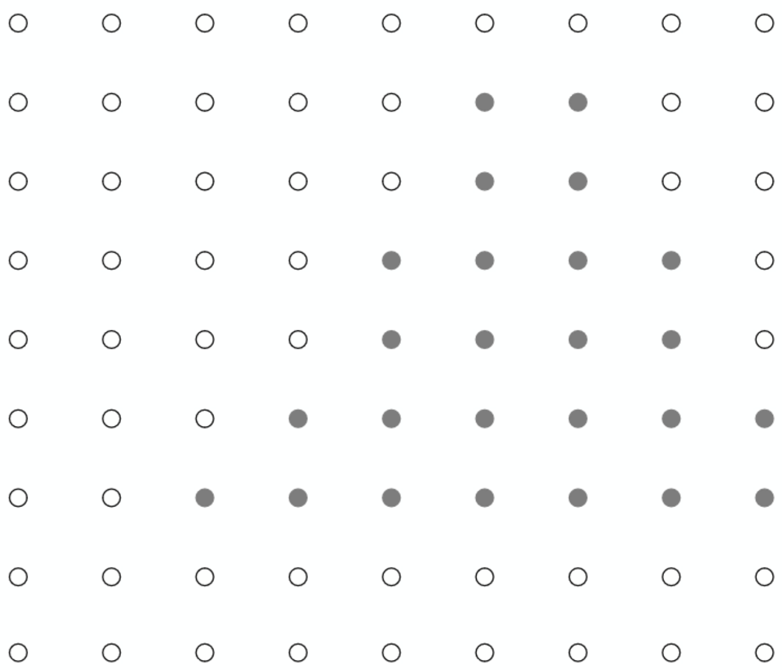
White = large distance

Black = small distance

Red = sample passed depth test



Color buffer contents



Depth buffer contents

Occlusion using the depth-buffer (Z-buffer)

Processing blue triangle:

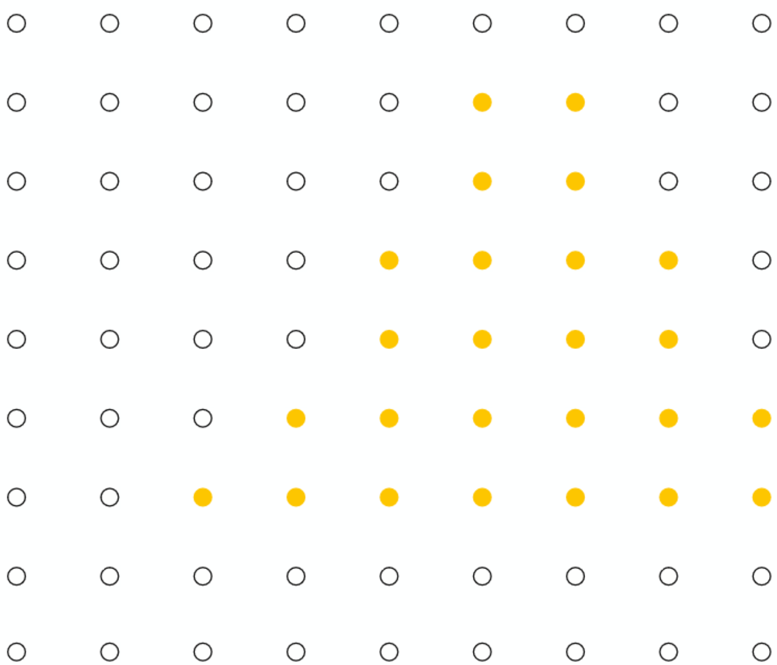
depth = 0.75

Grayscale value of sample point used to indicate distance

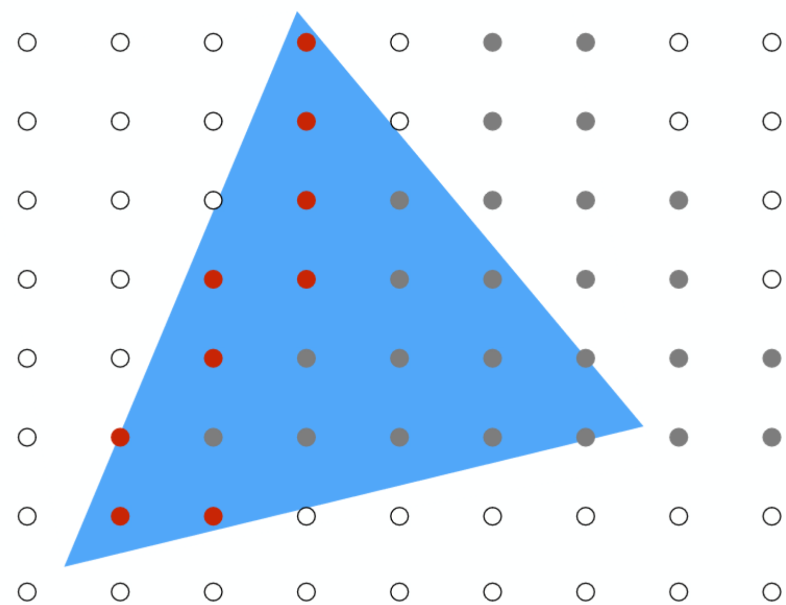
White = large distance

Black = small distance

Red = sample passed depth test



Color buffer contents



Depth buffer contents

Occlusion using the depth-buffer (Z-buffer)

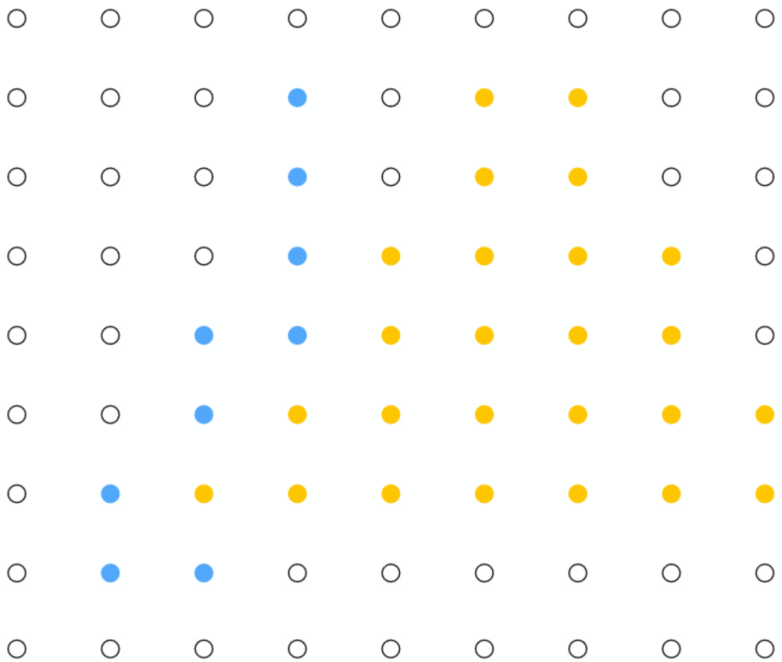
After processing blue triangle:

Grayscale value of sample point used to indicate distance

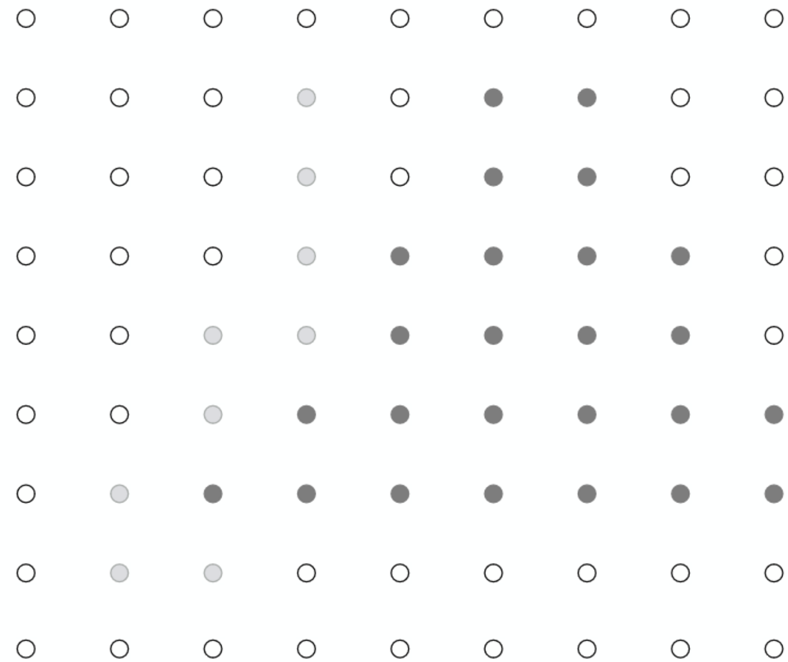
White = large distance

Black = small distance

Red = sample passed depth test



Color buffer contents



Depth buffer contents

Occlusion using the depth-buffer (Z-buffer)

Processing red triangle:

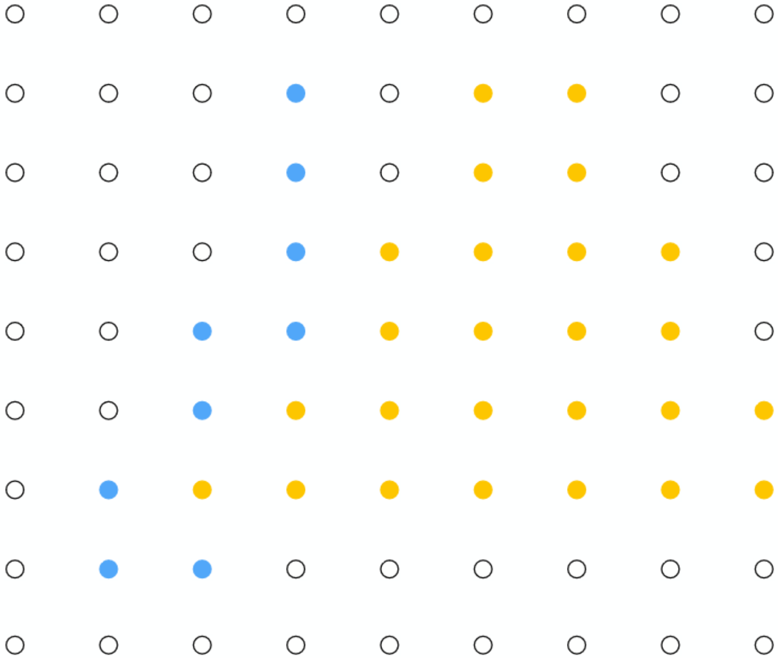
depth = 0.25

Grayscale value of sample point used to indicate distance

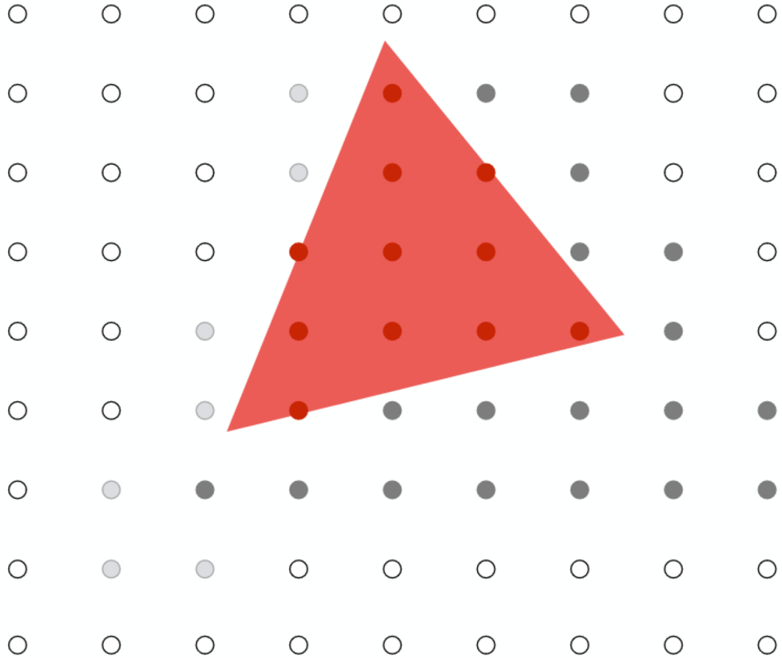
White = large distance

Black = small distance

Red = sample passed depth test



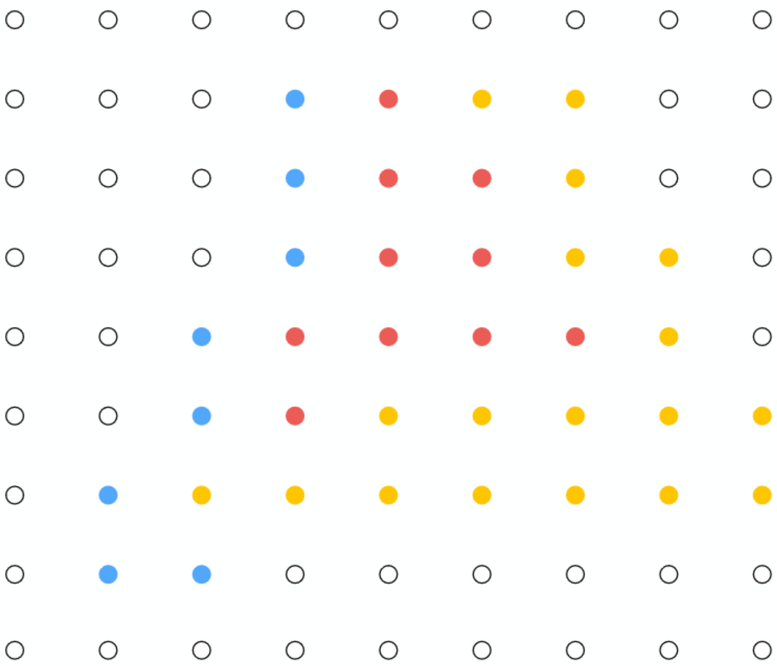
Color buffer contents



Depth buffer contents

Occlusion using the depth-buffer (Z-buffer)

After processing red triangle:



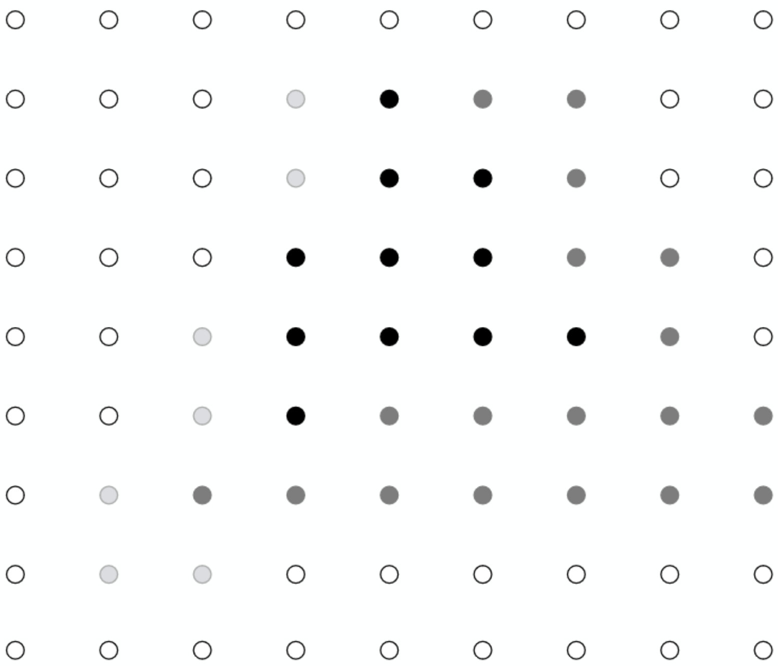
Color buffer contents

Grayscale value of sample point used to indicate distance

White = large distance

Black = small distance

Red = sample passed depth test

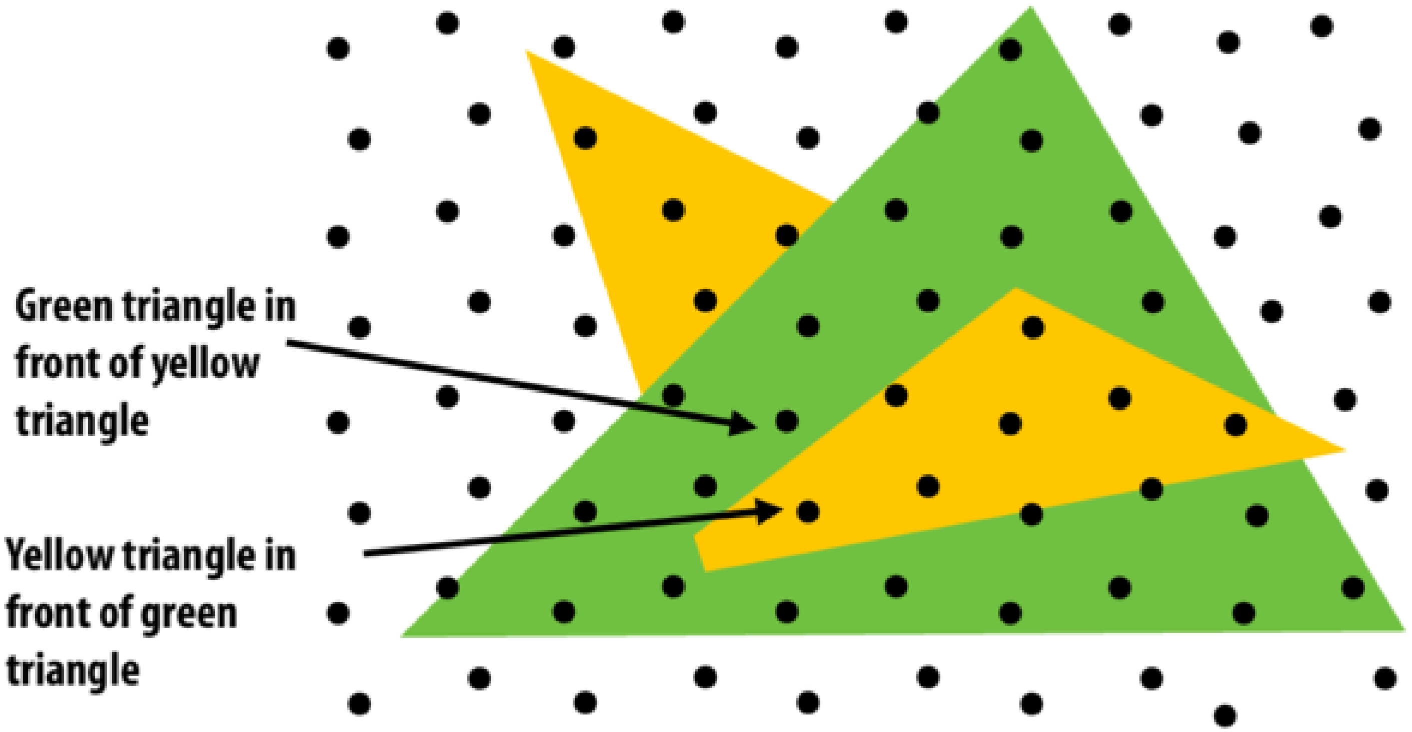


Depth buffer contents

Does depth-buffer algorithm handle interpenetrating surfaces?

Of course!

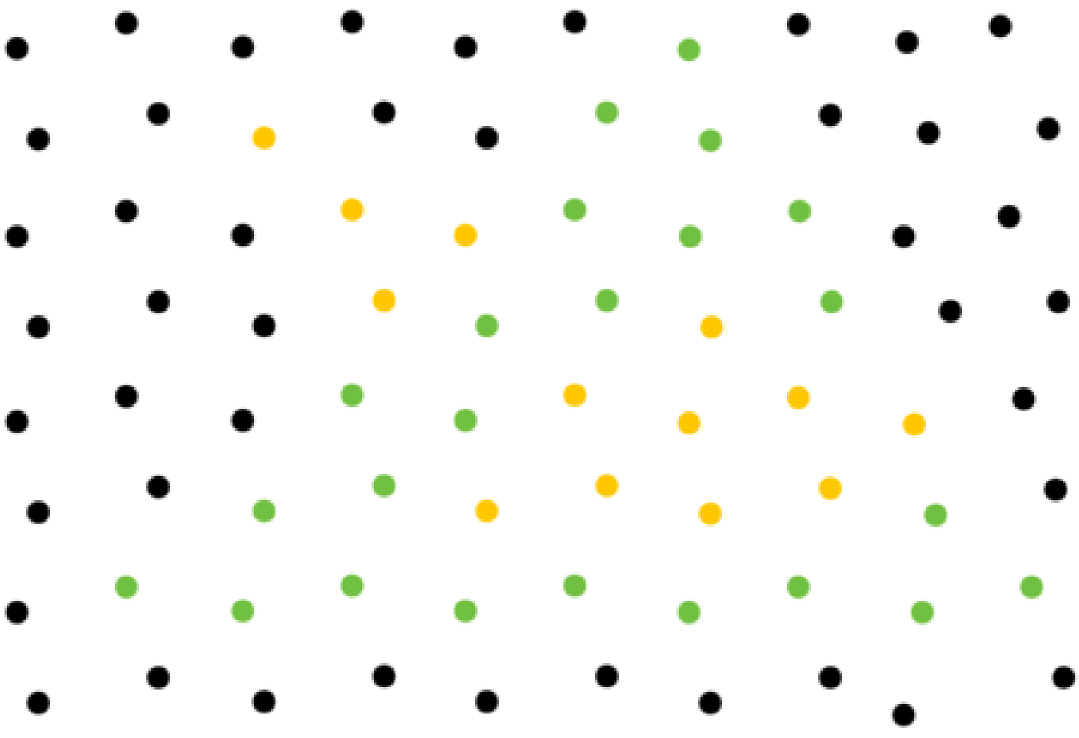
Occlusion test is based on depth of triangles at a given sample point. The relative depth of triangles may be different at different sample points.



Does depth-buffer algorithm handle interpenetrating surfaces?

Of course!

Occlusion test is based on depth of triangles at a given sample point. The relative depth of triangles may be different at different sample points.

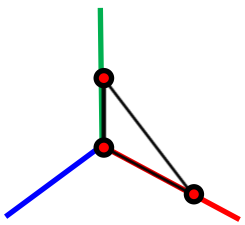


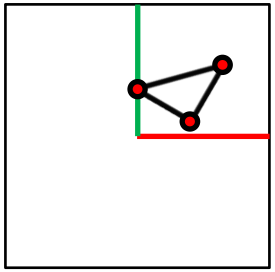
Z-Buffering : Summary

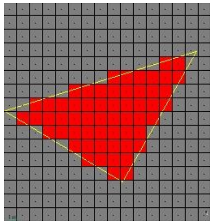
- Current standard algorithm that is implemented on all graphics hardwares

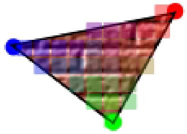
- Advantages / Disadvantages:
  - Easy to implement
  - Fast with hardware support → Fast depth buffer memory
  - Polygons can be drawn in any order
  - Extra memory required for z-buffer
    - not a problem anymore

Rendering (Graphics) Pipeline Again









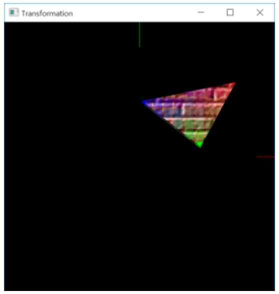
vertex processing → **rasterization** → **fragment processing** → output merging

vertex processing
: performs a sequence of vertex transformations

rasterization
: assembles polygons converts each polygon into a set of fragments (pixels)

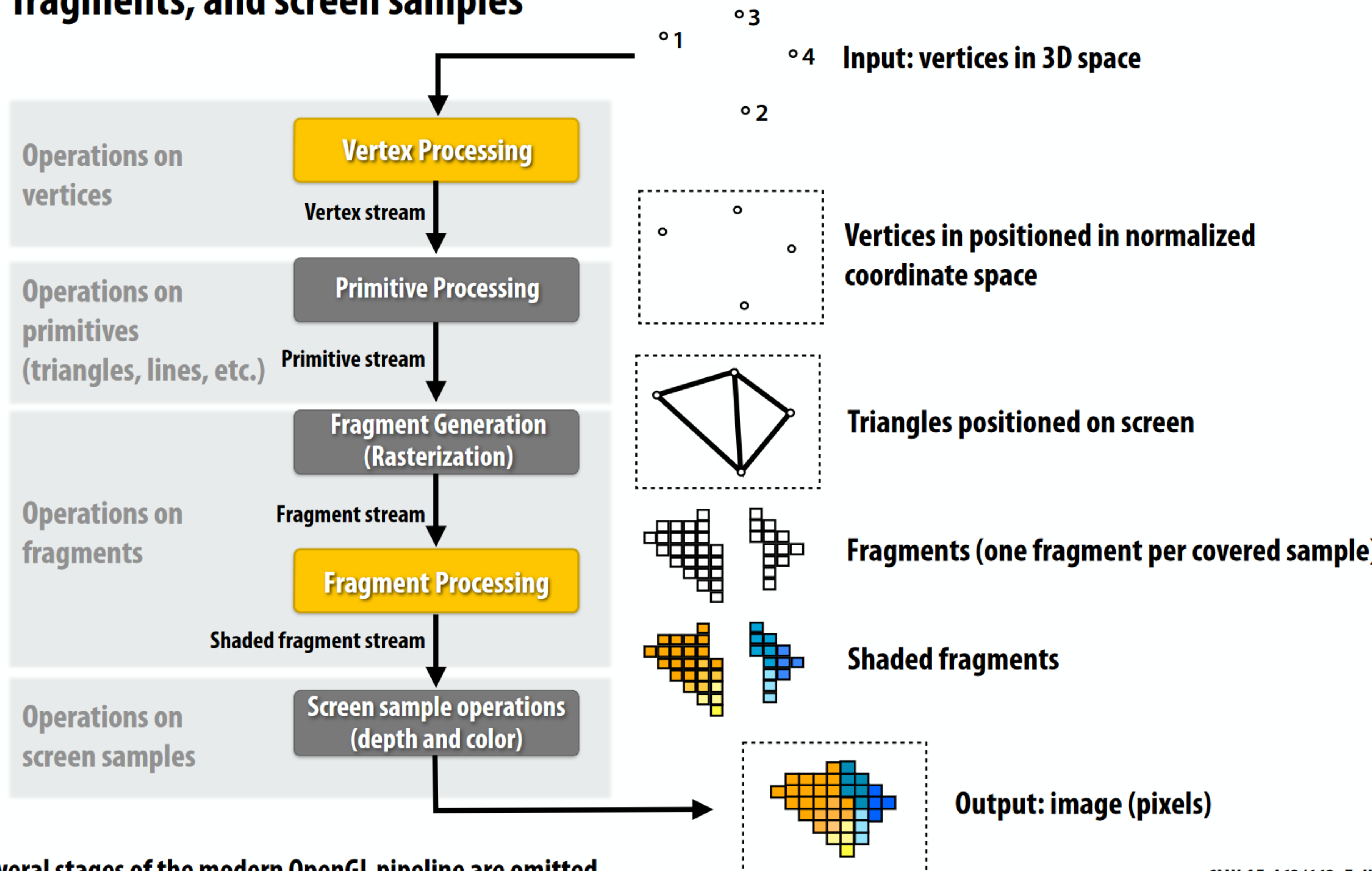
fragment processing
: determines color of each fragment with light & texture

output merging



OpenGL/Direct3D graphics pipeline *

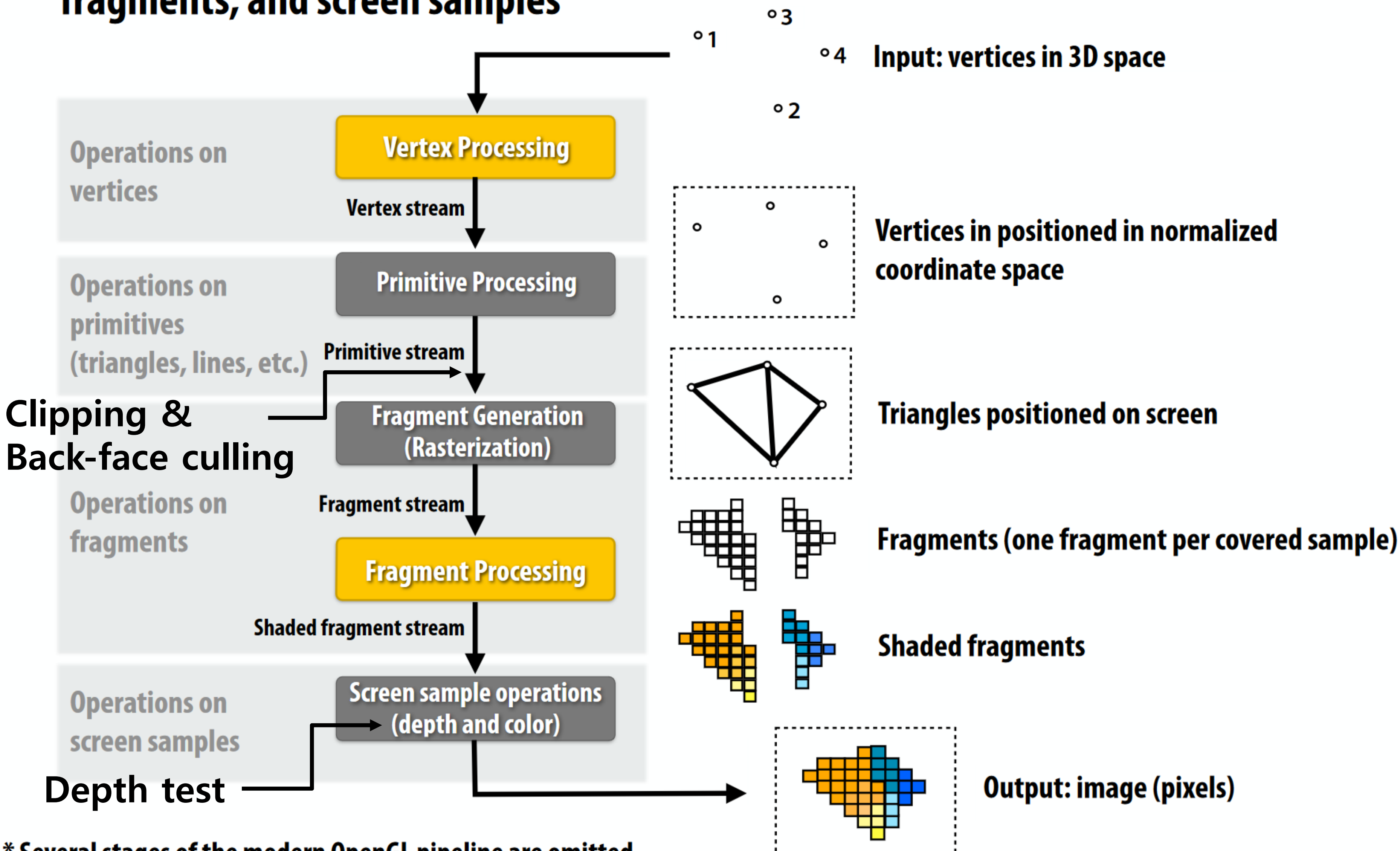
Structures rendering computation as a series of operations on vertices, primitives, fragments, and screen samples



* Several stages of the modern OpenGL pipeline are omitted

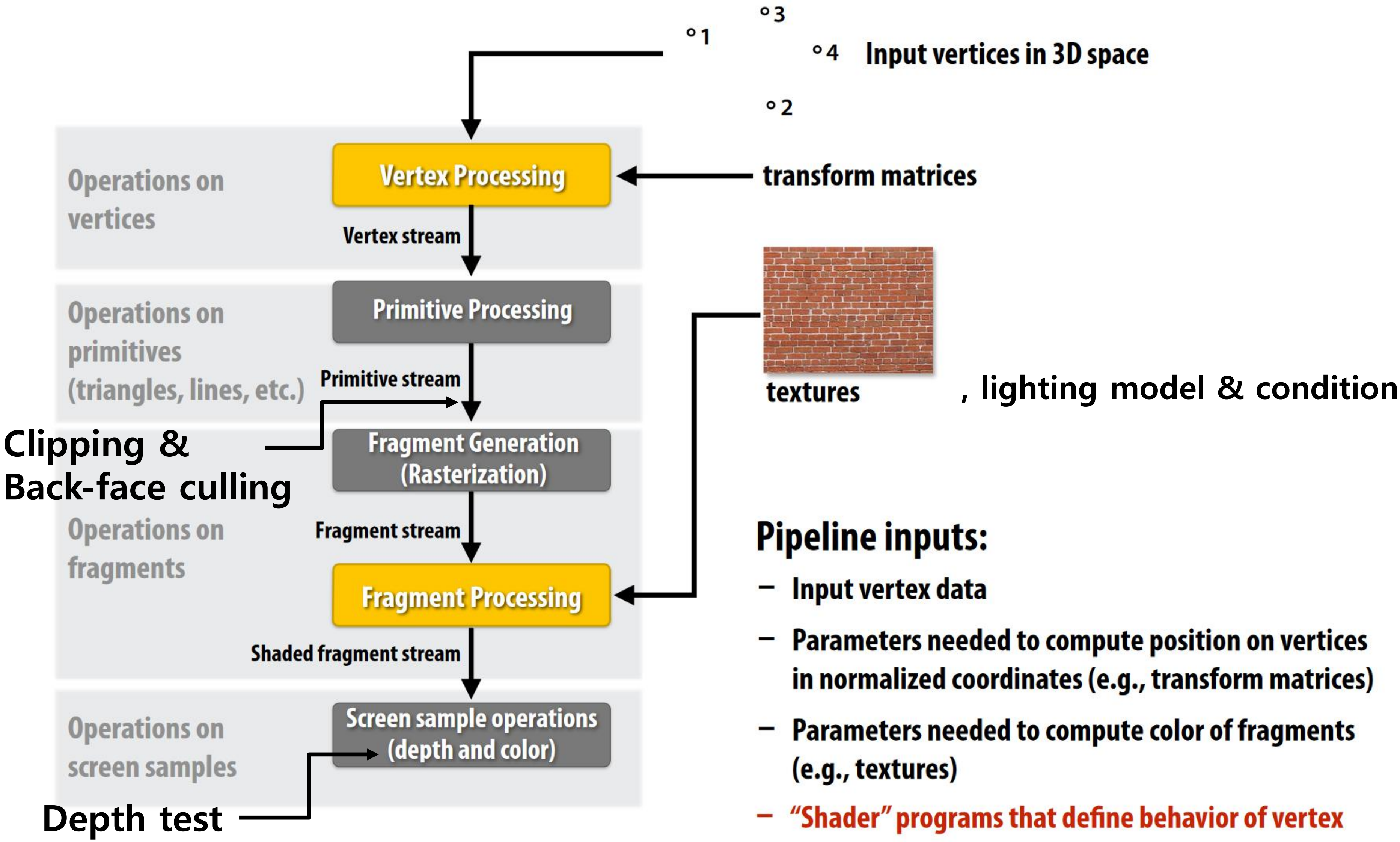
OpenGL/Direct3D graphics pipeline *

Structures rendering computation as a series of operations on vertices, primitives, fragments, and screen samples



* Several stages of the modern OpenGL pipeline are omitted

OpenGL/Direct3D graphics pipeline *

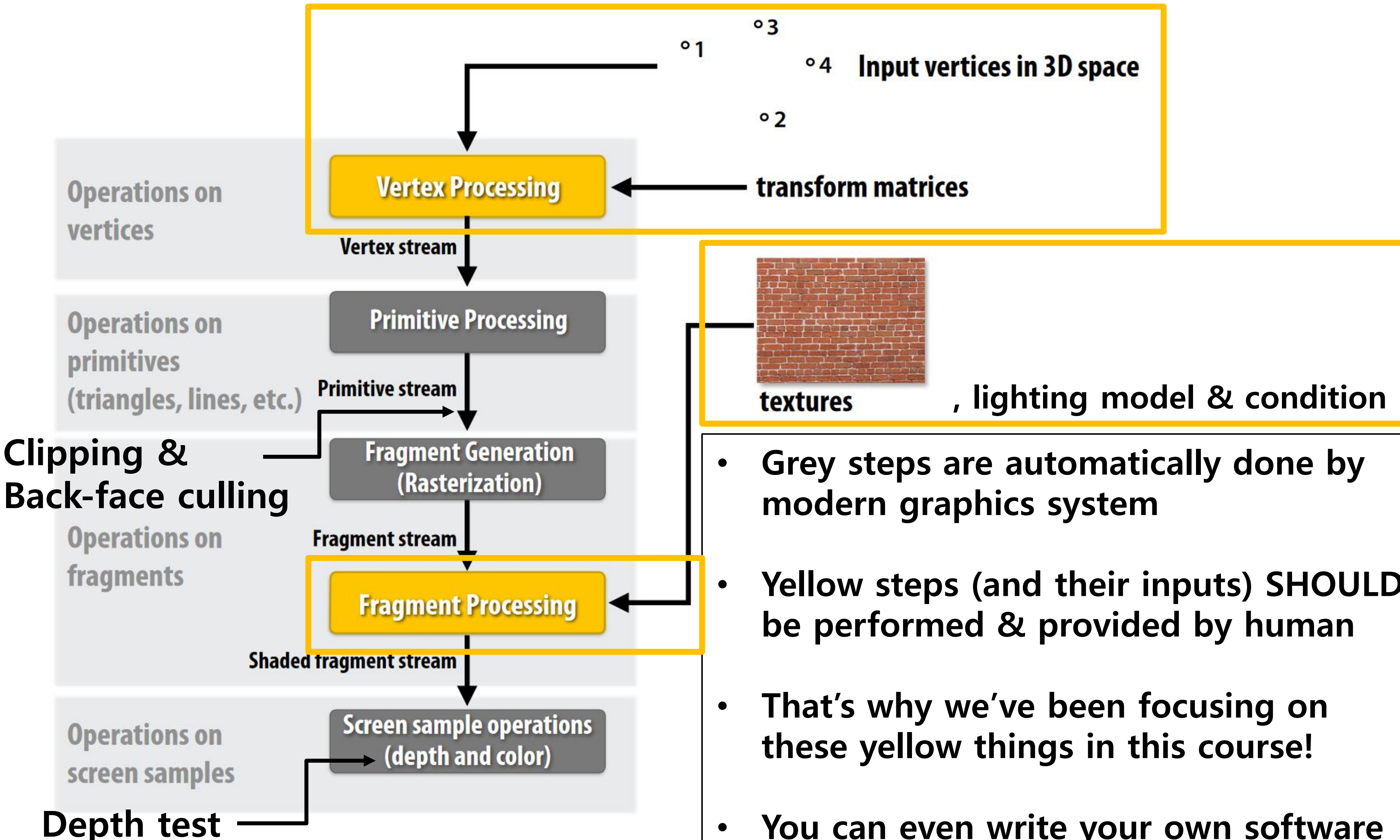


Pipeline inputs:

- Input vertex data
- Parameters needed to compute position on vertices in normalized coordinates (e.g., transform matrices)
- Parameters needed to compute color of fragments (e.g., textures)
- "Shader" programs that define behavior of vertex and fragment stages

* several stages of the modern OpenGL pipeline are omitted

OpenGL/Direct3D graphics pipeline *



- Grey steps are automatically done by modern graphics system
- Yellow steps (and their inputs) SHOULD be performed & provided by human
- That's why we've been focusing on these yellow things in this course!
- You can even write your own software renderer that covers whole process!

* several stages of the modern OpenGL pipeline are omitted

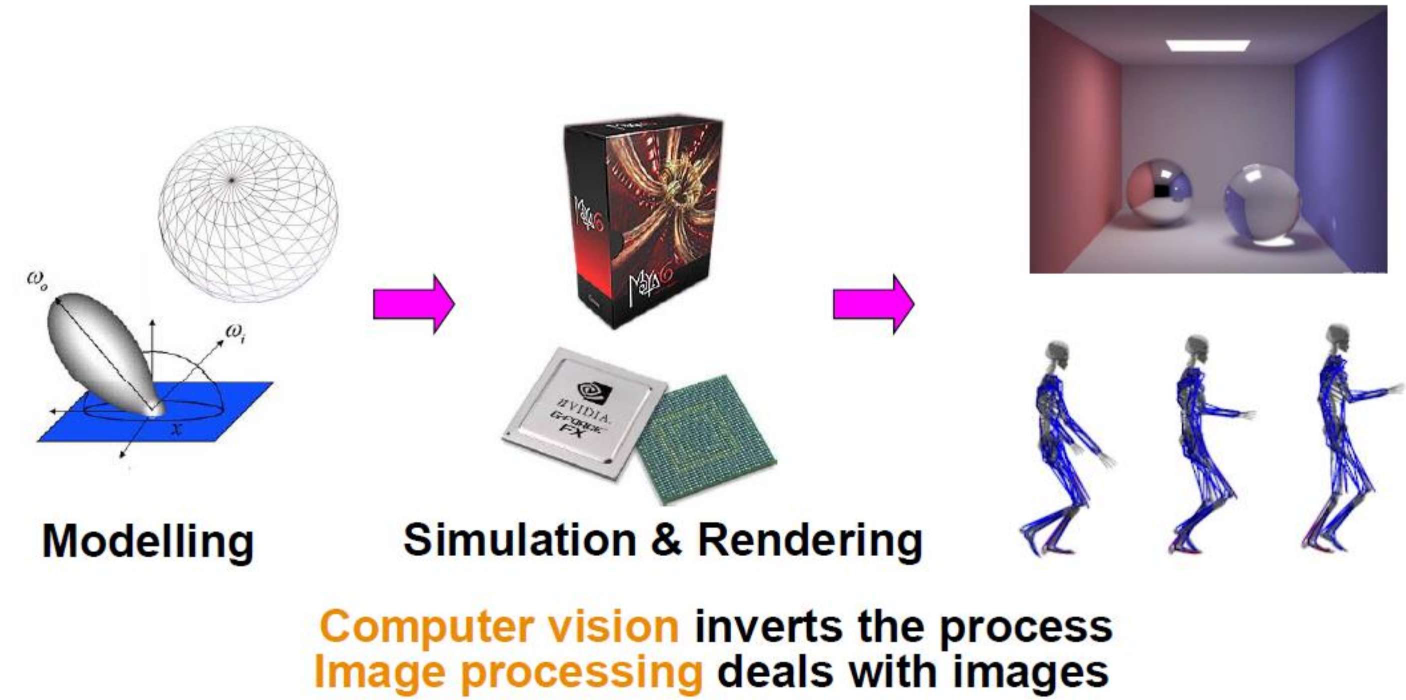
Acknowledgement

- Acknowledgement: Some materials come from the lecture slides of
  - Prof. Sung-eui Yoon, KAIST, https://sglab.kaist.ac.kr/~sungeui/CG/
  - Prof. JungHyun Han, Korea Univ., http://media.korea.ac.kr/book/
  - Prof. Taesoo Kwon, Hanyang Univ., http://calab.hanyang.ac.kr/cgi-bin/cg.cgi
  - Prof. Steve Marschner, Cornell Univ., http://www.cs.cornell.edu/courses/cs4620/2014fa/index.shtml
  - Prof. Kayvon Fatahalian and Prof. Keenan Crane, CMU, http://15462.courses.cs.cmu.edu/fall2015/

Course Wrap-up

Do you remember?

- Computer graphics: The study of creating, manipulating, and using visual images in the computer.



Image

Animation (a series of images)

Questions about Computer Graphics

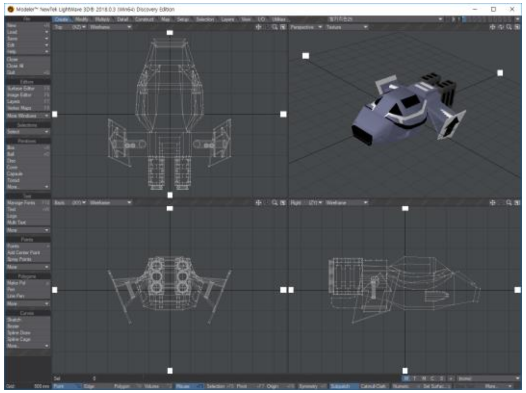
- To do this, we should be able to answer:
- How to express movement, placement, shape, and appearance of objects
- How to map 3D objects into 2D screen
- How the whole rendering process is performed

Movement & placement	3 - Transformation 1 4 - Transformation 2 5 - Rendering Pipeline, Viewing & Projection 1 8 - Hierarchical Modeling 9 - Orientation & Rotation 10 - Kinematics & Animation 11 - Curves
Mapping to 2D screen	5 - Rendering Pipeline, Viewing & Projection 1 6 - Viewing & Projection 2, Mesh
Shape	6 - Viewing & Projection 2, Mesh 11 - Curves
Appearance	7 - Lighting & Shading 12 - More Lighting, Texture
Rendering Pipeline	5 - Rendering Pipeline, Viewing & Projection 1 13 - Rasterization & Visibility

How do you feel?

- If you've **had more fun** in this course than other courses, you already have **the potential** to do interesting research in computer graphics!

- I think, **passion** is the most important thing in computer graphics.
  - That was the starting point for me on this path.



If you think "that's me!" and "I want to study more!",

- 캐릭터 애니메이션 관련 프로젝트를 해보고 싶다:
  - (4학년이 되면) 졸업프로젝트를 함께 해봅시다.

- 캐릭터 애니메이션을 더 공부하고 실컷 프로그래밍해보고 싶다 :
  - (4학년 1학기) "COMPUTER SCIENCE Capstone PBL (Character Motion Synthesis and Character Control)" 수강을 추천
    - Software Design Principles
    - Understanding Motion Data, Software Design for Motion Viewer
    - Forward Kinematics, Inverse Kinematics
    - Motion Warping, Stitching, Blending
    - Particle Dynamics
    - Rigid Body Dynamics, Character Simulation & Control

- 4학년이 되기 전부터 뭔가 해보고 싶다!:
  - 저한테 이메일을 보내주세요: yoonsanglee@hanyang.ac.kr

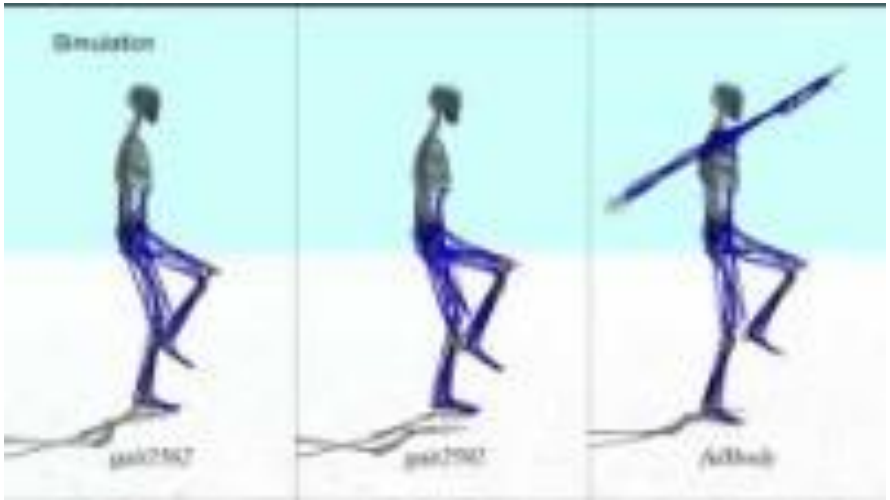
Computer Graphics 연구의 특성

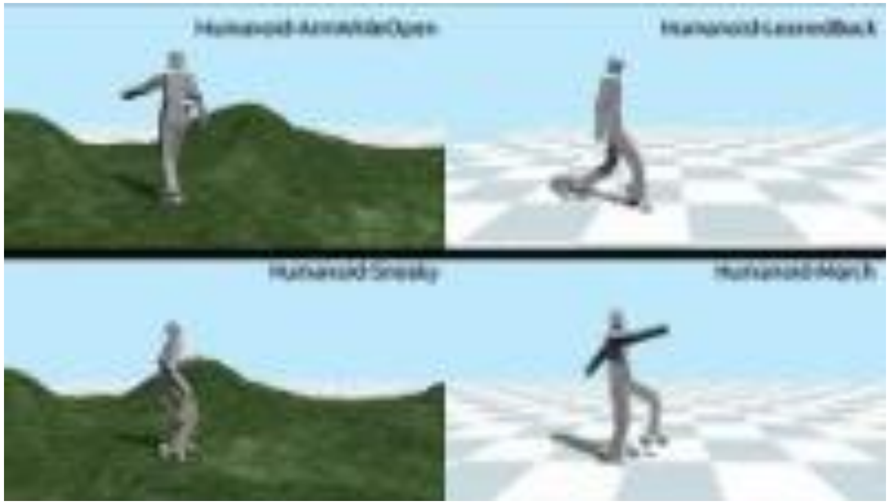
- **구현**을 많이 한다 (프로그래밍을 좋아하고, 자신이 있으면 잘 할 가능성이 크다).

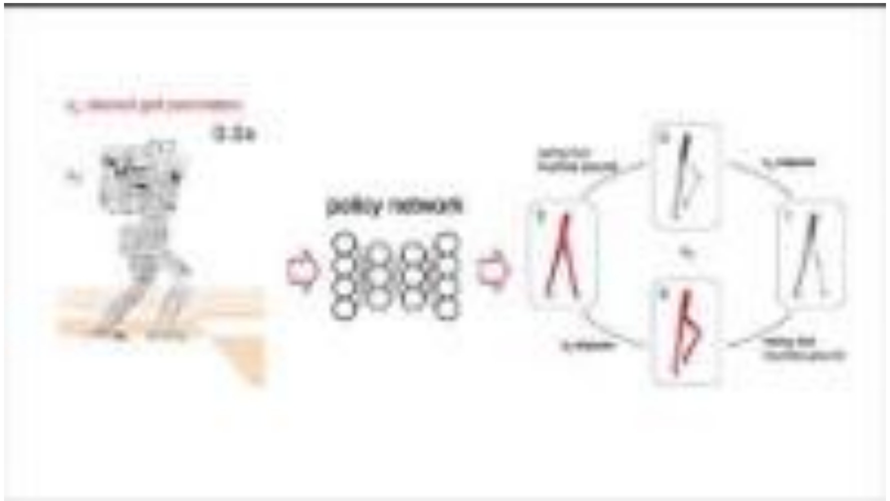
- 모든 연구 결과는 눈으로 확인할 수 있는 형태로 나오기 때문에, **재미있다**.
  - Computer graphics 분야에서는 논문을 submit 할 때 비디오를 첨부하는 것이 기본

Computer Graphics and Robotics Lab.

- https://cgrhyu.github.io/







Thanks for being a great class!