Computer Graphics I

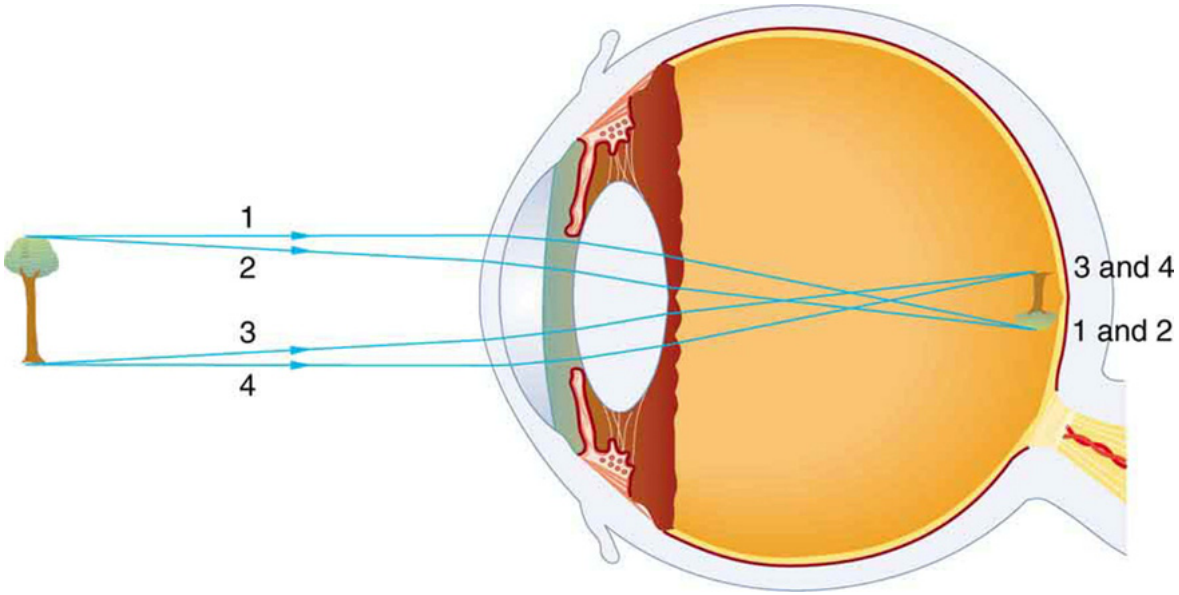
Lecture 2: The first graphics program

Xiaopei LIU

School of Information Science and Technology
ShanghaiTech University

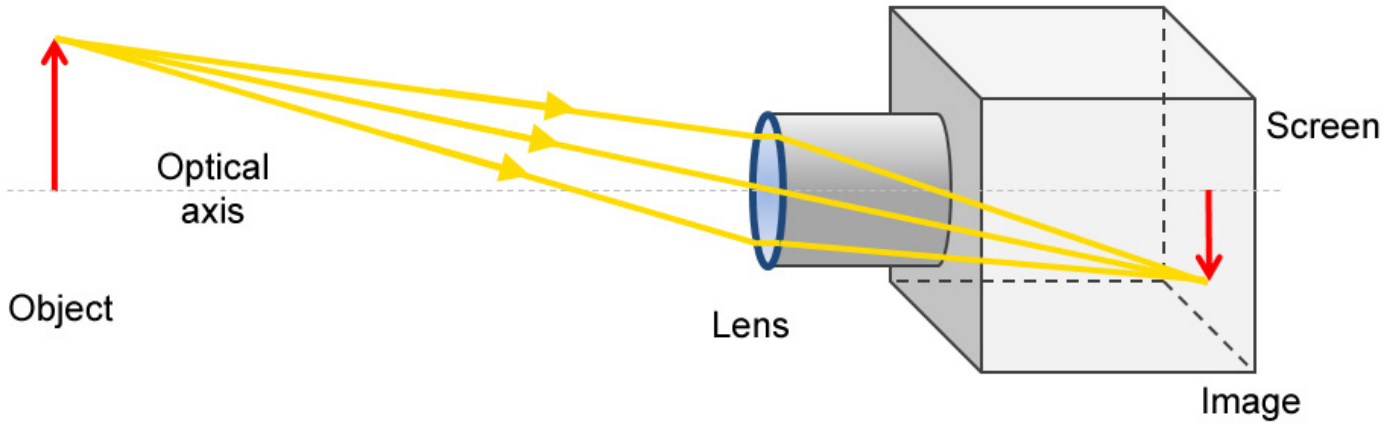
Producing images

- **How can we generate images?**
  - Image formation process in our eye



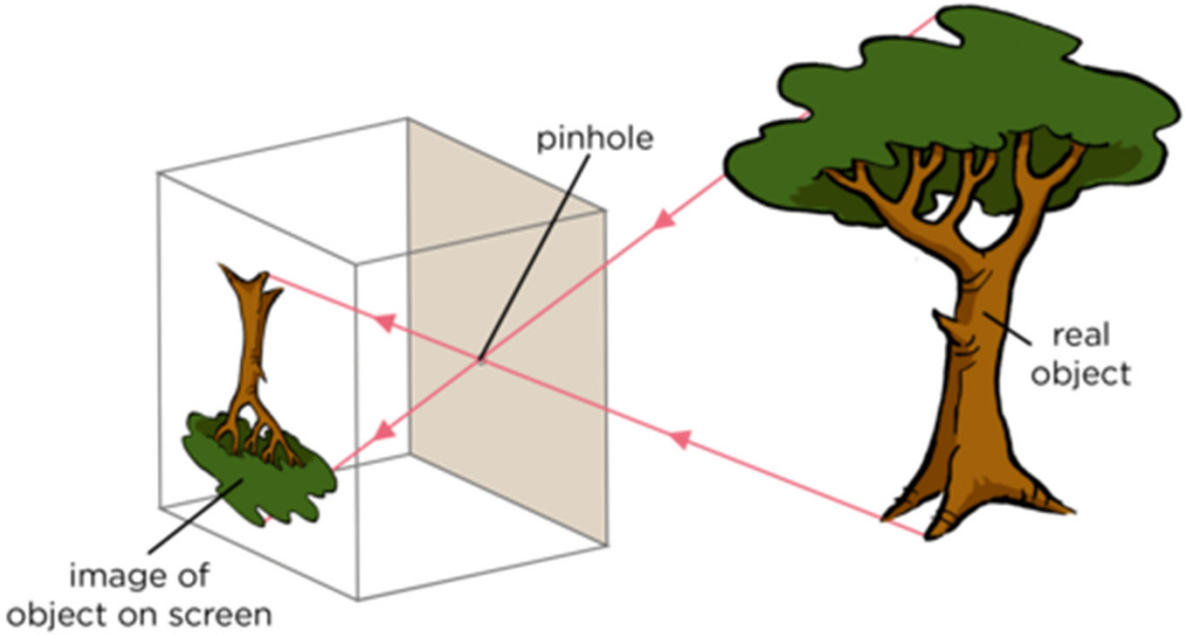
Camera system

- **Imaging in camera system through lens**



Virtual camera model

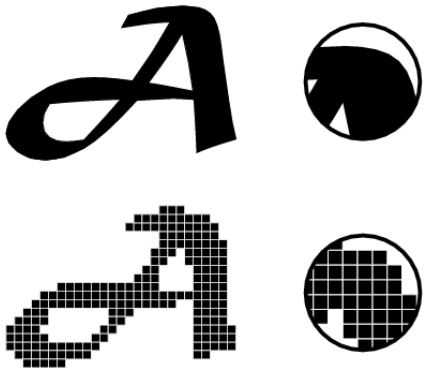
- **Camera model**
  - Pinhole camera



Digital image

- **A two-dimensional rectangle array**
  - Each array element stores bits to represent color (bitmap)
  - Raster image (common) / vector image
  - Pixel/fragment: the element in the 2D array

raster image



vector v.s. raster image

Image resolution

- **Usually refer to spatial resolution**
  - How many samples per array dimension
  - Higher resolution represents more details

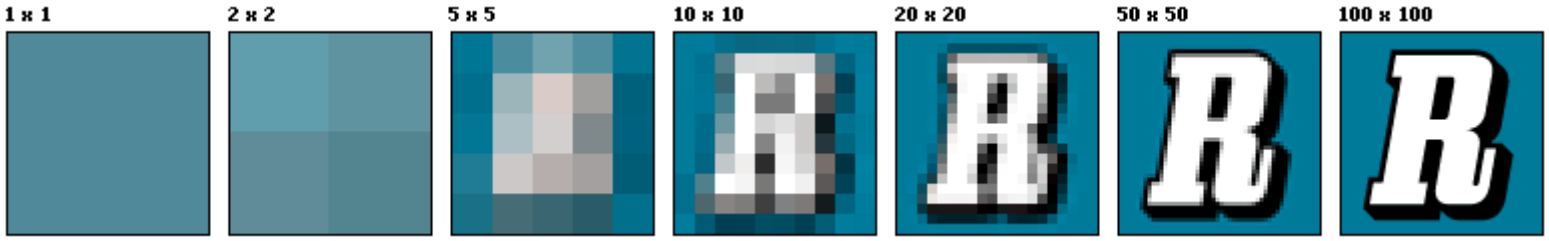
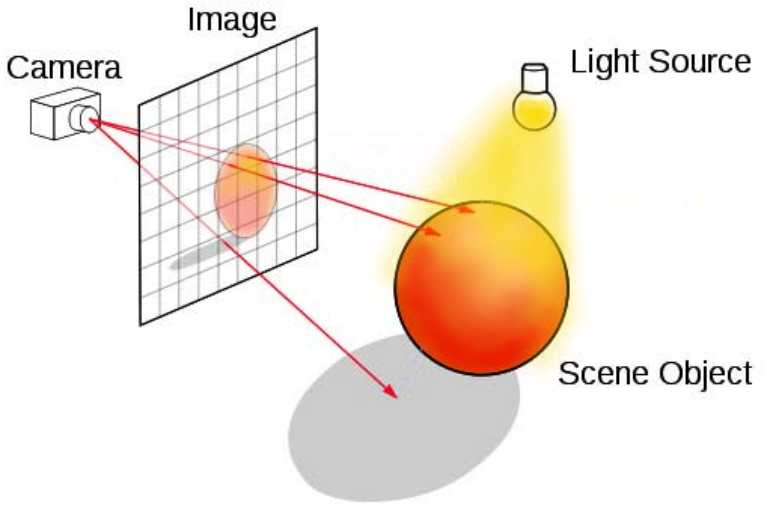
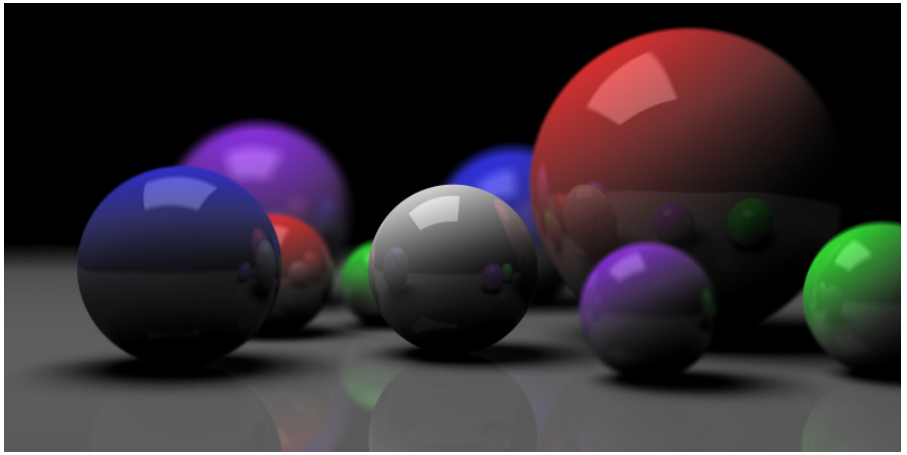


Image formation

- **Imaging with virtual camera**
  - Imaging plane in front of the camera (projection)





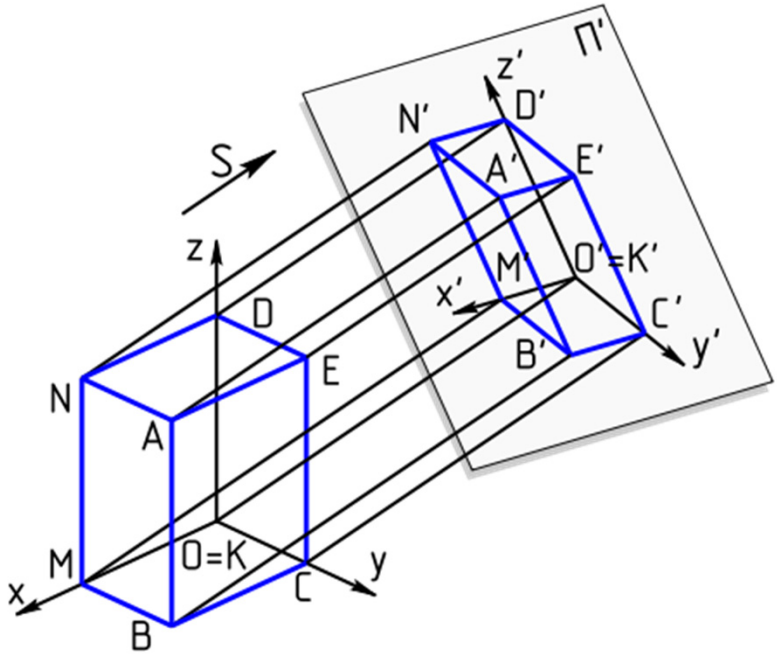
OpenGL

- **A cross-language, cross-platform application programming interface (API)**
  - Rendering 2D and 3D vector graphics
  - Typically used to interact with a graphics processing unit (GPU)
  - Started in 1991 by Silicon Graphics Incorporation (SGI)
  - https://en.wikipedia.org/wiki/OpenGL
  - https://www.opengl.org/
  - Documentation: https://www.khronos.org/registry/OpenGL/index_gl.php

Step 1: Projection

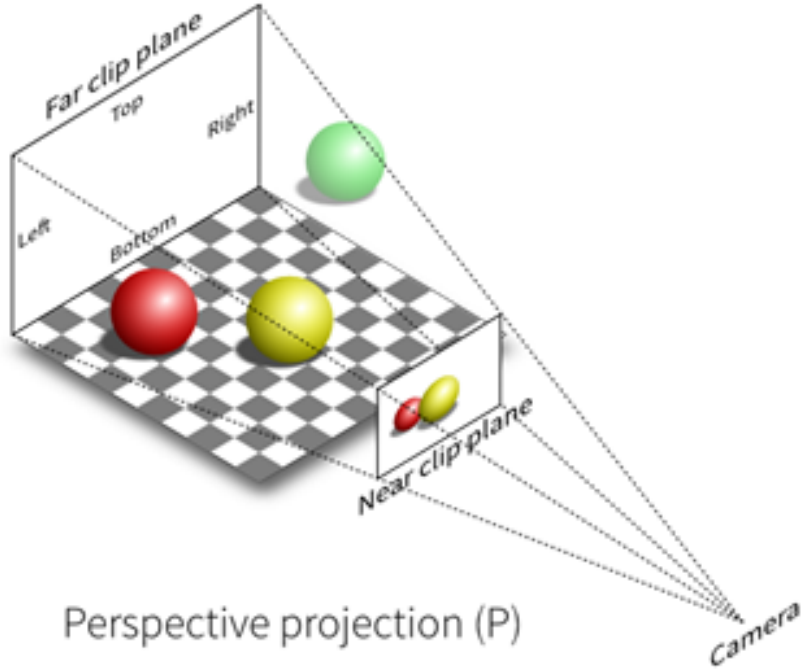
3D projection

- **Any method of mapping three-dimensional points onto a surface**
  - Linear or nonlinear
  - Most commonly, project onto a two-dimensional plane



3D projection

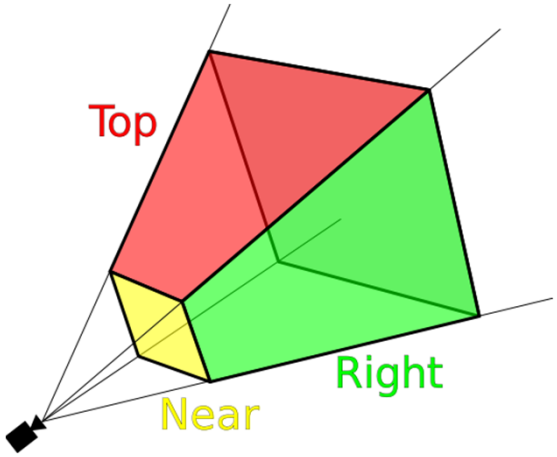
- **Perspective projection**
  - Optical rays converge at a point with finite distance to the projection plane



Perspective projection (P)

3D projection

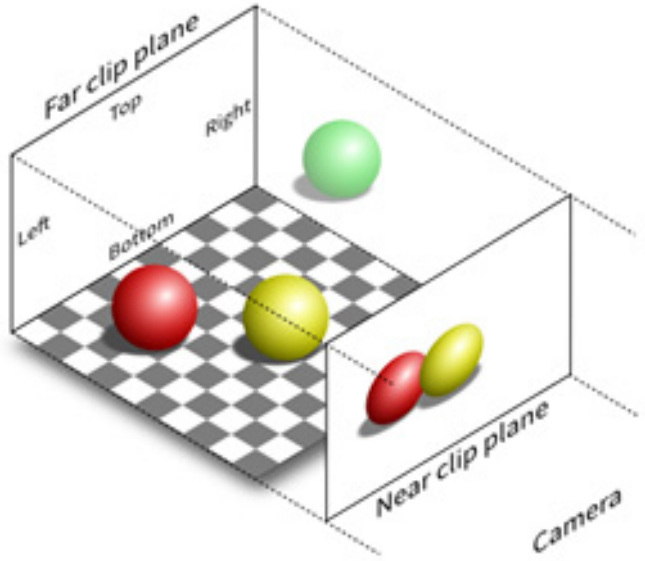
- **View frustum of perspective projection**
  - The region of space in the modeled world that may appear on the screen



- **View frustum culling**
  - The process of removing objects that lie completely outside the viewing frustum

3D projection

- **Orthographic projection**
  - Optical rays converge at a point with infinite distance to the projection plane



Orthographic projection (O)

Setting up 3D projection in OpenGL

- **Orthogonal projection**

```
glMatrixMode(GL_PROJECTION);
glLoadIdentity();

glOrtho(left,right,bottom,top,zNear,zFar);

glMatrixMode(GL_MODELVIEW);
```

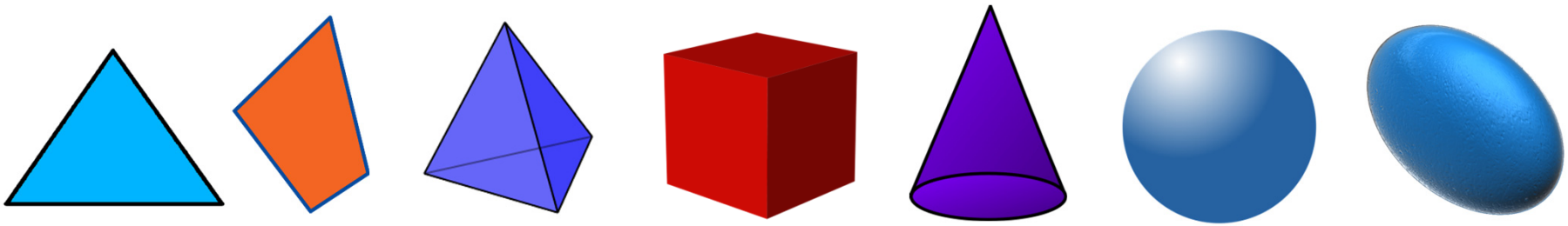
- **Perspective projection**

```
glMatrixMode(GL_PROJECTION);
glLoadIdentity();

gluPerspective(fovy, aspect, zNear, zFar);

glMatrixMode(GL_MODELVIEW);
```

Step 2: Specify geometries

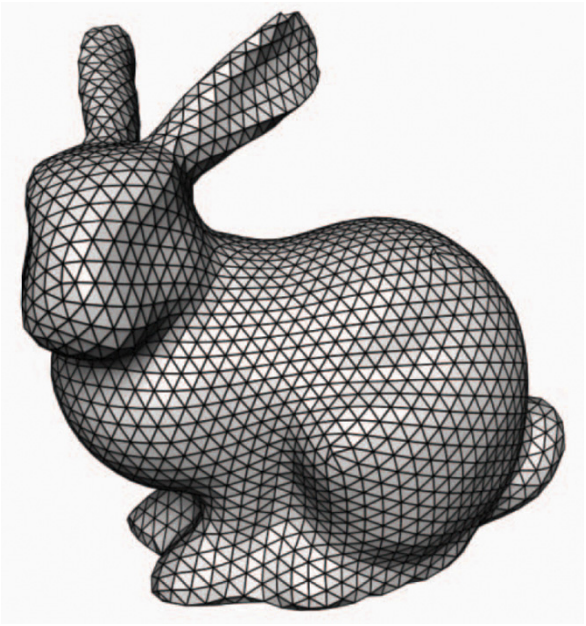
Geometry representation

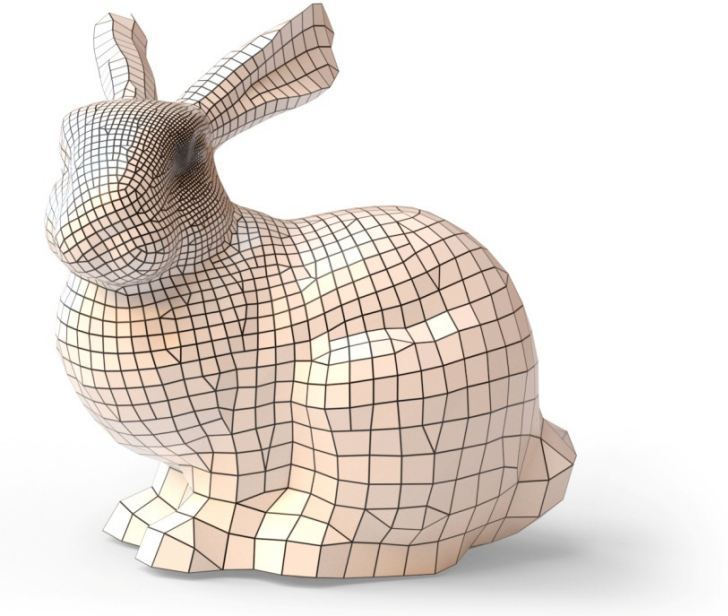
- **How can the shapes of objects be represented?**
  - Simple objects:
    - Triangle, quadrilateral, tetrahedron, cube, cone, sphere, ellipsoid, etc.



Geometry representation

- **Mesh**
  - Representation of shapes with a collection of geometrical primitives
    - Triangles
    - Quadrilaterals





Specify 2D primitives with OpenGL

- **Specify 2D triangles**

```
struct Position2D
{
    float x,y;
};

struct Triangle2D
{
   Position2D
        p1,p2,p3;
};

Triangle2D t1,t2,…;
```

```
glBegin(GL_TRIANGLES);

glVertex2f(t1.p1.x, t1.p1.y);
glVertex2f(t1.p2.x, t1.p2.y);
glVertex2f(t1.p3.x, t1.p3.y);

glVertex2f(t2.p1.x, t2.p1.y);
glVertex2f(t2.p2.x, t2.p2.y);
glVertex2f(t2.p3.x, t2.p3.y);

…

glEnd();
```

Specify 2D primitives with OpenGL

- **Specify 2D quadrilaterals**

```
struct Position2D
{
    float x,y;
};

struct Quad2D
{
   Position2D
        p1,p2,p3,p4;
};

Quad2D q1,q2,…;
```

```
glBegin(GL_QUADS);

glVertex2f(q1.p1.x, q1.p1.y);
glVertex2f(q1.p2.x, q1.p2.y);
glVertex2f(q1.p3.x, q1.p3.y);
glVertex2f(q1.p4.x, q1.p4.y);

glVertex2f(q2.p1.x, q2.p1.y);
glVertex2f(q2.p2.x, q2.p2.y);
glVertex2f(q2.p3.x, q2.p3.y);
glVertex2f(q2.p4.x, q2.p4.y);

…

glEnd();
```

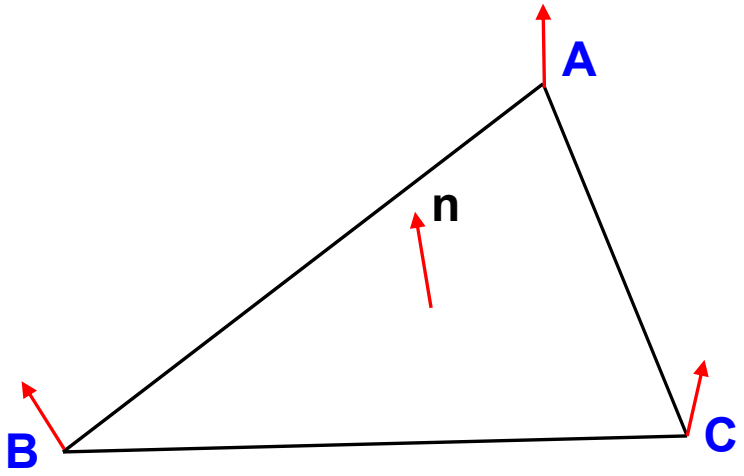
Specify 2D primitives with OpenGL

- **Specify 2D polygon**

```
glBegin(GL_POLYGON);

glVertex2f(x1, y1);
glVertex2f(x2, y2);
glVertex2f(x3, y3);
glVertex2f(x4, y4);
…
glVertex2f(xn, yn);

glEnd();
```

A 3D triangle

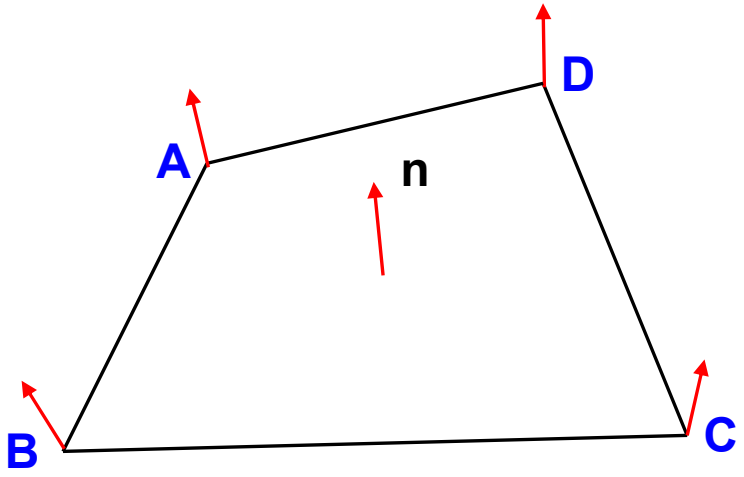
- **What constitute of a 3D triangle?**
  - Three vertices, three edges, one triangular face
  - One face normal, three vertex normals
  - Three vertex colors



n=AB x **AC**

Quadrilaterals

- **What constitute of a 3D quadrilateral?**
  - Four vertices, four edges, one face
    - Do not always ensure co-planar property
  - One face normal, four vertex normals
  - Four vertex colors



n=AC x BD

Specify 3D primitives with OpenGL

- **Specify 3D triangles**

```
struct Position3D
{
    float x,y,z;
};

struct Triangle3D
{
   Position3D
        p1,p2,p3;
};

Triangle2D t1,t2,…;
```

```
glBegin(GL_TRIANGLES);

glVertex3f(t1.p1.x, t1.p1.y, t1.p1.z);
glVertex3f(t1.p2.x, t1.p2.y, t1.p2.z);
glVertex3f(t1.p3.x, t1.p3.y, t1.p3.z);

glVertex3f(t2.p1.x, t2.p1.y, t2.p1.z);
glVertex3f(t2.p2.x, t2.p2.y, t2.p2.z);
glVertex3f(t2.p3.x, t2.p3.y, t2.p3.z);

…

glEnd();
```

Specify 3D primitives with OpenGL

- Specify **3D quadrilaterals**

```
struct Position3D
{
    float x,y,z;
};

struct Quad3D
{
   Position3D
        p1,p2,p3,p4;
};

Quad3D q1,q2,…;
```

```
glBegin(GL_QUADS);

glVertex3f(q1.p1.x, q1.p1.y, q1.p1.z);
glVertex3f(q1.p2.x, q1.p2.y, q1.p2.z);
glVertex3f(q1.p3.x, q1.p3.y, q1.p3.z);
glVertex3f(q1.p4.x, q1.p4.y, q1.p4.z);

glVertex3f(q2.p1.x, q2.p1.y, q2.p1.z);
glVertex3f(q2.p2.x, q2.p2.y, q2.p2.z);
glVertex3f(q2.p3.x, q2.p3.y, q2.p3.z);
glVertex3f(q2.p4.x, q2.p4.y, q2.p4.z);

…

glEnd();
```

Specify 3D primitives with OpenGL

- **Specify 3D triangles with face normal**

```
struct Position3D
{
    float x,y,z;
};

struct Triangle3D
{
   Position3D
        p1,p2,p3;
};

Triangle2D t1,t2,…;
```

```
glBegin(GL_TRIANGLES);

glNormal3f(n1.x,n1.y.n1.z);
glVertex3f(t1.p1.x, t1.p1.y, t1.p1.z);
glVertex3f(t1.p2.x, t1.p2.y, t1.p2.z);
glVertex3f(t1.p3.x, t1.p3.y, t1.p3.z);

glNormal3f(n2.x,n2.y.n2.z);
glVertex3f(t2.p1.x, t2.p1.y, t2.p1.z);
glVertex3f(t2.p2.x, t2.p2.y, t2.p2.z);
glVertex3f(t2.p3.x, t2.p3.y, t2.p3.z);

…

glEnd();
```

Specify 3D primitives with OpenGL

- **Specify 3D triangles with vertex normal**

```
glBegin(GL_TRIANGLES);

glNormal3f(t1.n1.x,t1.n1.y.t1.n1.z); glVertex3f(t1.p1.x, t1.p1.y, t1.p1.z);
glNormal3f(t1.n2.x,t1.n2.y.t1.n2.z); glVertex3f(t1.p2.x, t1.p2.y, t1.p2.z);
glNormal3f(t1.n3.x,t1.n3.y.t1.n3.z); glVertex3f(t1.p3.x, t1.p3.y, t1.p3.z);

glNormal3f(t2.n1.x,t2.n1.y.t2.n1.z); glVertex3f(t2.p1.x, t2.p1.y, t2.p1.z);
glNormal3f(t2.n2.x,t2.n2.y.t2.n2.z); glVertex3f(t2.p2.x, t2.p2.y, t2.p2.z);
glNormal3f(t2.n3.x,t2.n3.y.t2.n3.z); glVertex3f(t2.p3.x, t2.p3.y, t2.p3.z);

…

glEnd();
```

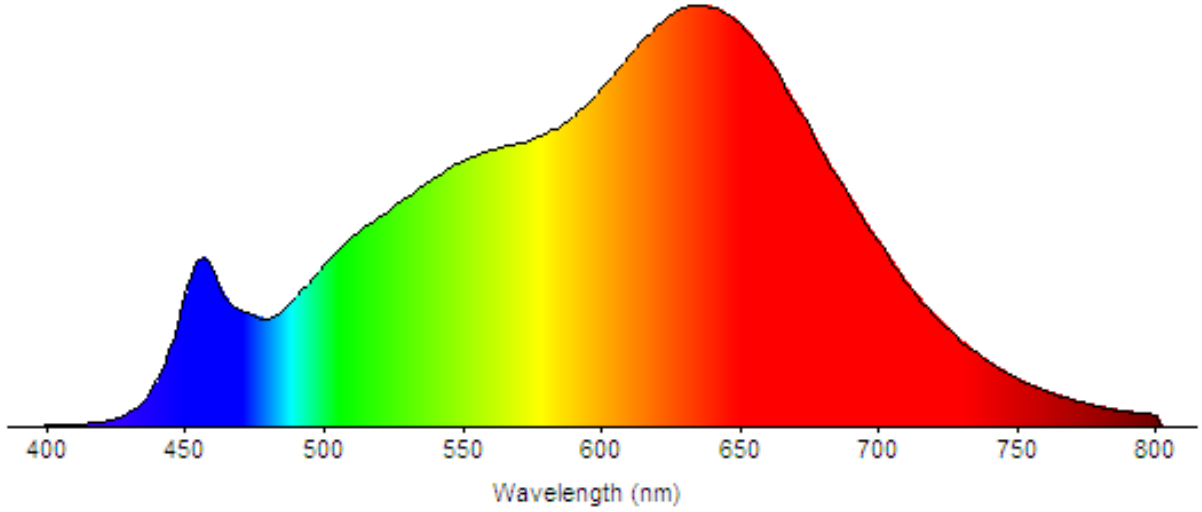
Vertex properties

- **Each vertex contains the coordinate of its location**
  - (x,y) for 2D and (x,y,z) for 3D
- **It can also contain some vertex properties**
  - Vertex color (r,g,b)
  - Vertex normal (used for lighting) (nx,ny,nz)
  - Texture coordinate (for texture mapping)
  - Other user specified quantities

Step 3: Specify color

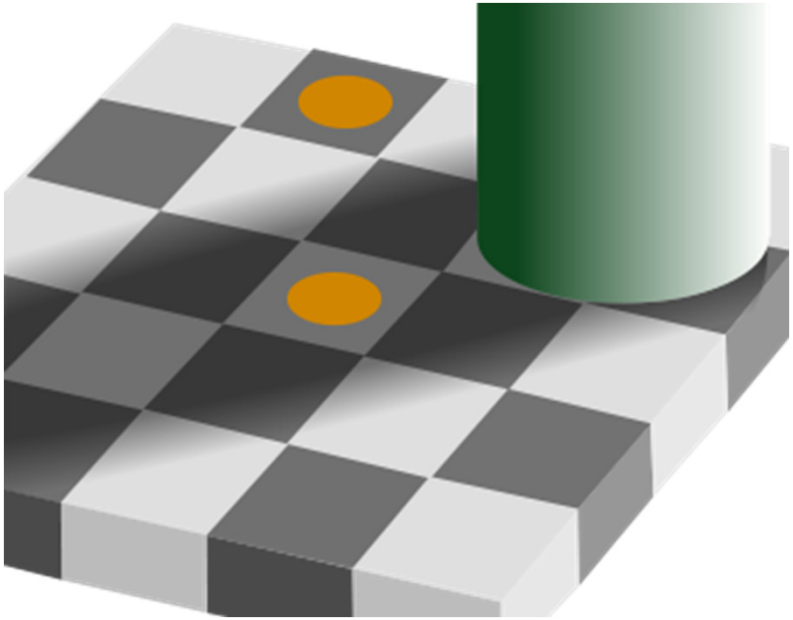
Color representation

- **Spectral power distribution of light**
  - A distribution function of wavelength
  - Describe the amount of light (power) at each (continuous) wavelength



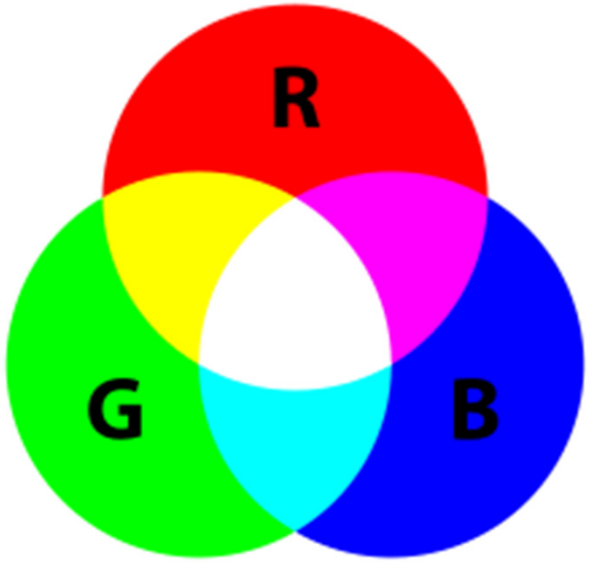
Color representation

- **What is color?**
  - Visual perception property for human eyes (subjective)
  - Is human perception of color consistent to physical representation (objective)?
    - Sometimes NOT!



Color representation

- **RGB color**
  - An additive color model
  - Red, green and blue light are added together in various ways to reproduce a broad array of colors
  - Set R,G,B intensities respectively
  - Unnormalized v.s. normalized
    - Unnormalized: [0,255] – 1 byte
    - Normalized: [0,1] – 1 float



Specify vertex color in OpenGL

- **A color can be associated with each vertex**
  - Specify color for points

```
glBegin(GL_POINTS);

glColor3f(r1,g1,b1); glVertex2f(x1,y1);
glColor3f(r2,g2,b2); glVertex2f(x2,y2);
…
glColor3f(rn,gn,bn); glVertex2f(xn,yn);

glEnd();
```

Specify vertex color in OpenGL

- **A color can be associated with each vertex**
  - Specify color for triangles

```
struct Position2D
{
    float x,y; //position
    float r,g,b; //color
};

struct Triangle2D
{
   Position2D
        p1,p2,p3;
};

Triangle2D t1,t2,…;
```

Specify vertex color in OpenGL

- **A color can be associated with each vertex**
  - Specify color for triangles

```
glBegin(GL_TRIANGLES);

glColor3f(t1.p1.r, t1.p1.g, t1.p1.b); glVertex2f(t1.p1.x, t1.p1.y);
glColor3f(t1.p2.r, t1.p2.g, t1.p2.b); glVertex2f(t1.p2.x, t1.p2.y);
glColor3f(t1.p3.r, t1.p3.g, t1.p3.b); glVertex2f(t1.p3.x, t1.p3.y);

glColor3f(t2.p1.r, t2.p1.g, t2.p1.b); glVertex2f(t2.p1.x, t2.p1.y);
glColor3f(t2.p2.r, t2.p2.g, t2.p2.b); glVertex2f(t2.p2.x, t2.p2.y);
glColor3f(t2.p3.r, t2.p3.g, t2.p3.b); glVertex2f(t2.p3.x, t2.p3.y);

...

glEnd();
```

Specify vertex color in OpenGL

- **A color can be associated with each vertex**
  - Specify color for quadrilaterals

```
struct Position2D
{
    float x,y; //position
    float r,g,b; //color
};

struct Quad2D
{
   Quad2D
        p1,p2,p3,p4;
};

Quad2D t1,t2,…;
```

Specify vertex color in OpenGL

- **A color can be associated with each vertex**
  - Specify color for quadrilaterals

```
glBegin(GL_QUADS);

glColor3f(q2.p1.r, q2.p1.g, q2.p1.b); glVertex2f(q2.p1.x, q2.p1.y);
glColor3f(q2.p2.r, q2.p2.g, q2.p2.b); glVertex2f(q2.p2.x, q2.p2.y);
glColor3f(q2.p3.r, q2.p3.g, q2.p3.b); glVertex2f(q2.p3.x, q2.p3.y);
glColor3f(q2.p4.r, q2.p4.g, q2.p4.b); glVertex2f(q2.p4.x, q2.p4.y);

glColor3f(q2.p1.r, q2.p1.g, q2.p1.b); glVertex2f(q2.p1.x, q2.p1.y);
glColor3f(q2.p2.r, q2.p2.g, q2.p2.b); glVertex2f(q2.p2.x, q2.p2.y);
glColor3f(q2.p3.r, q2.p3.g, q2.p3.b); glVertex2f(q2.p3.x, q2.p3.y);
glColor3f(q2.p4.r, q2.p4.g, q2.p4.b); glVertex2f(q2.p4.x, q2.p4.y);

…

glEnd();
```

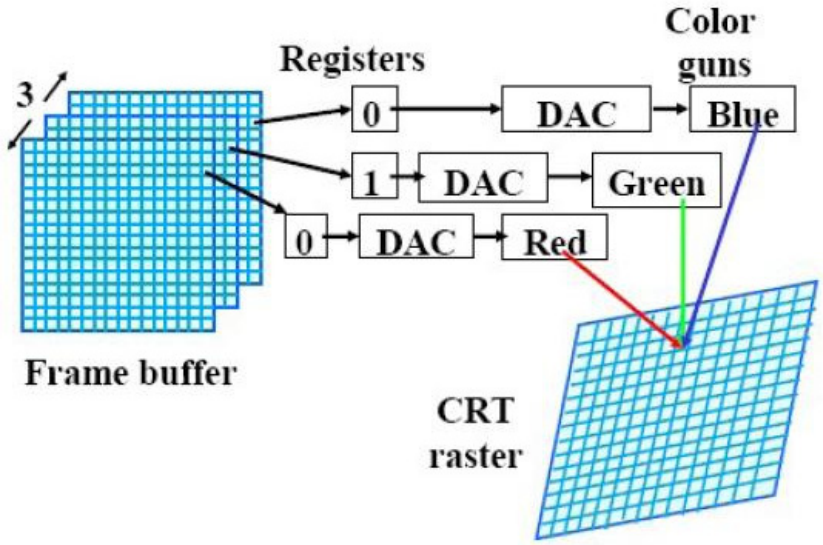
Step 4: Automatic Rasterization

Framebuffer

- **A portion of RAM containing a bitmap that drives a video display**
  - A memory buffer containing a complete frame of data
- **Screen buffer (video buffer)**
  - A part of computer memory used by a computer application
  - For the representation of the content to be shown on the computer display

Framebuffer

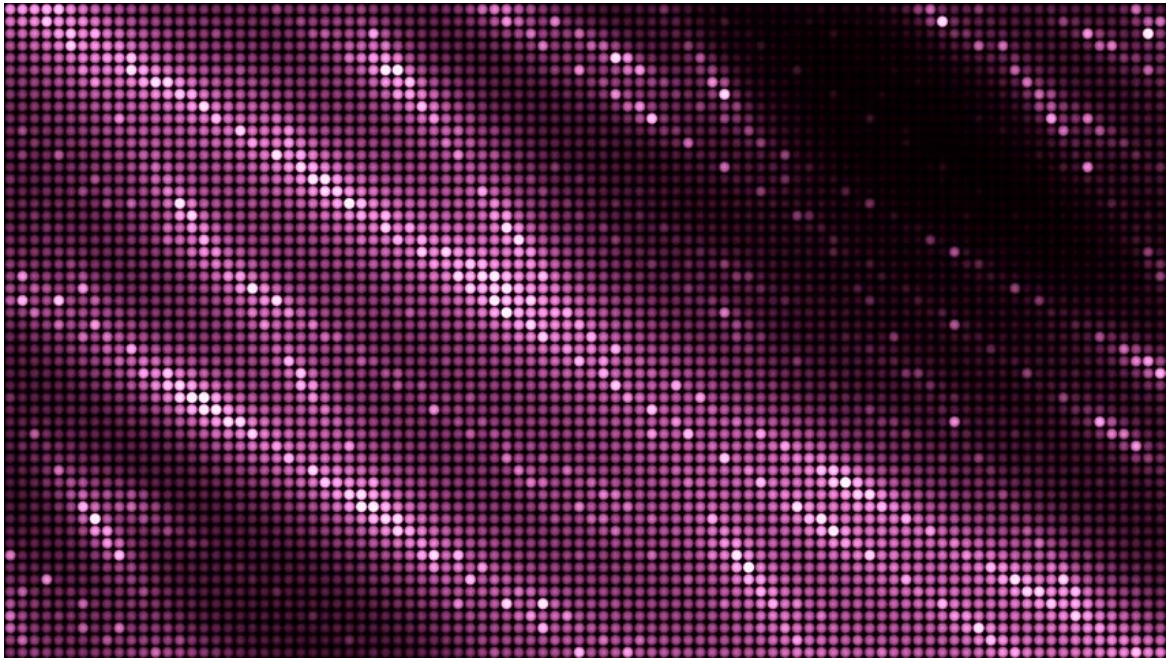
- **A framebuffer storing**
  - 2D array (discretized) containing color, depth, etc.
  - Can have multiple copies
  - Double buffer is commonly adopted



Simple Color buffer

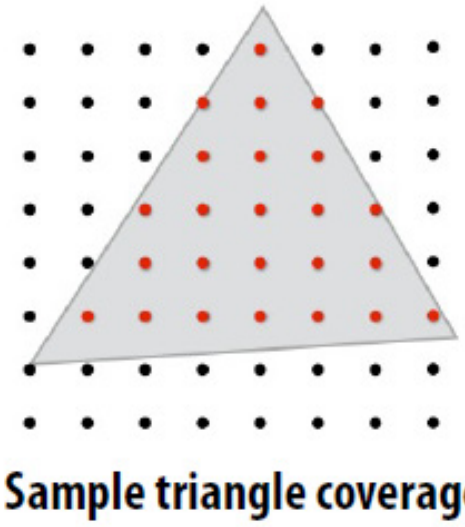
Digital screen

- **A digitized display device**
  - Pixels are physically displayed
  - In terms of 2D arrays, corresponding to an image

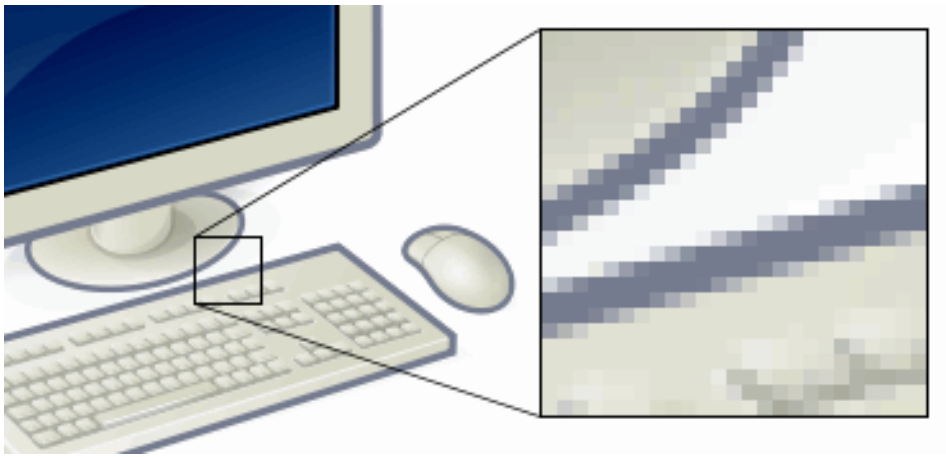


Digital screen

- **Rasterization**
  - The process of converting continuous signals to pixels
  - Filling pixel colors (and other values) in framebuffer



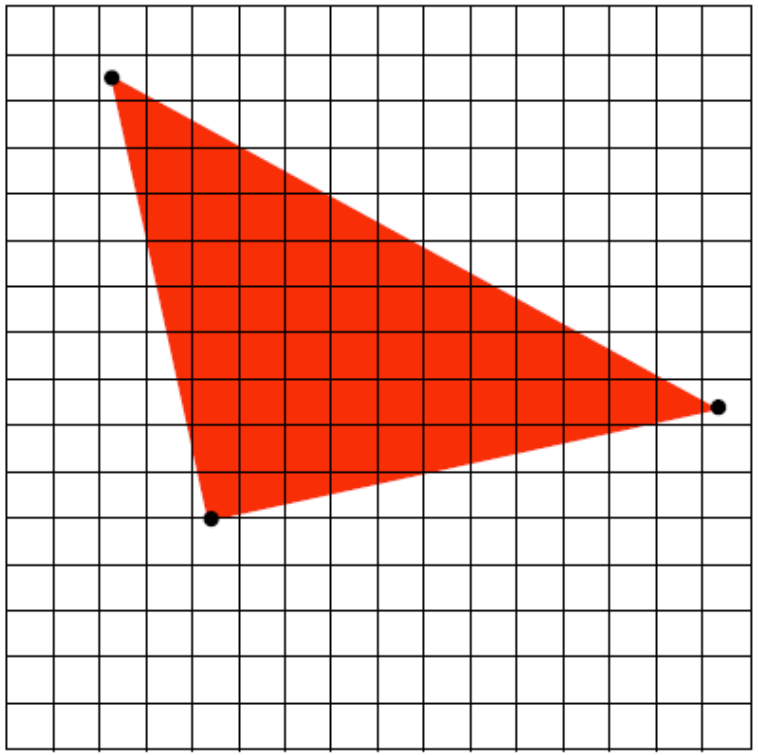
Sample triangle coverage



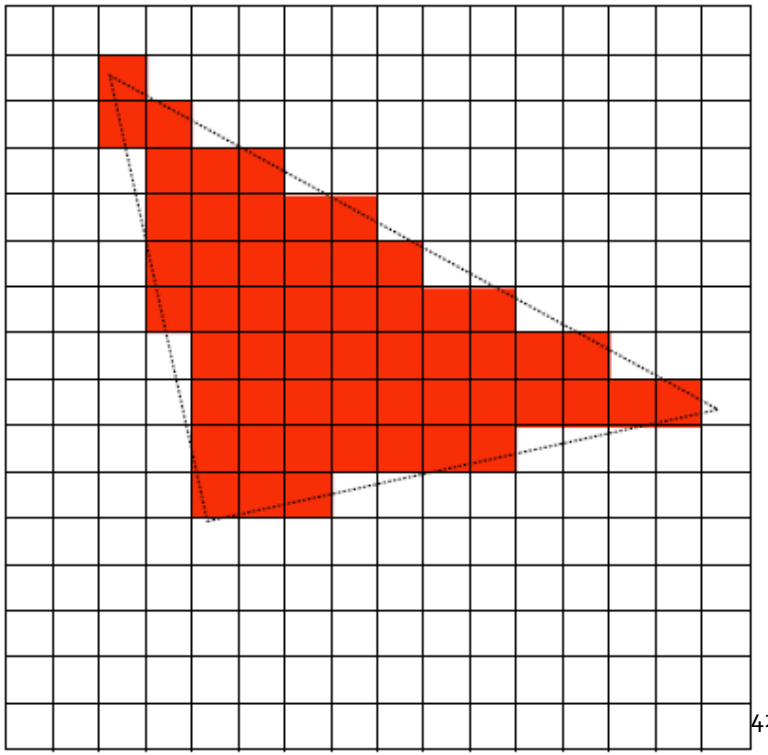
Rasterizing a triangle

- **What pixels do the triangle overlap?**

Input:
projected position of triangle vertices: P_0, P_1, P_2

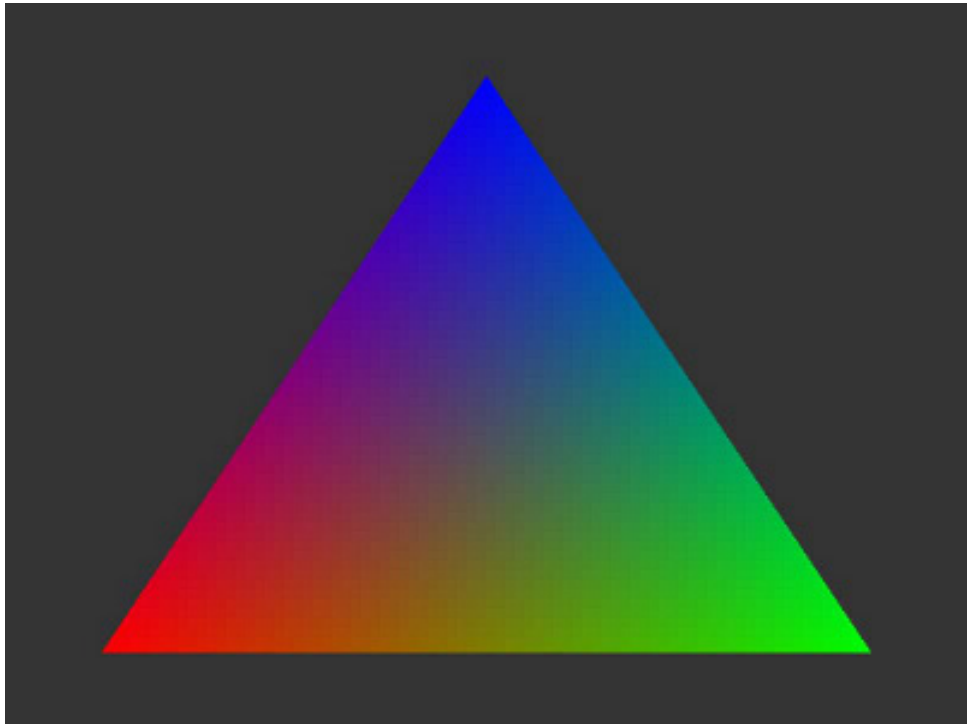


Output:
set of pixels "covered" by the triangle



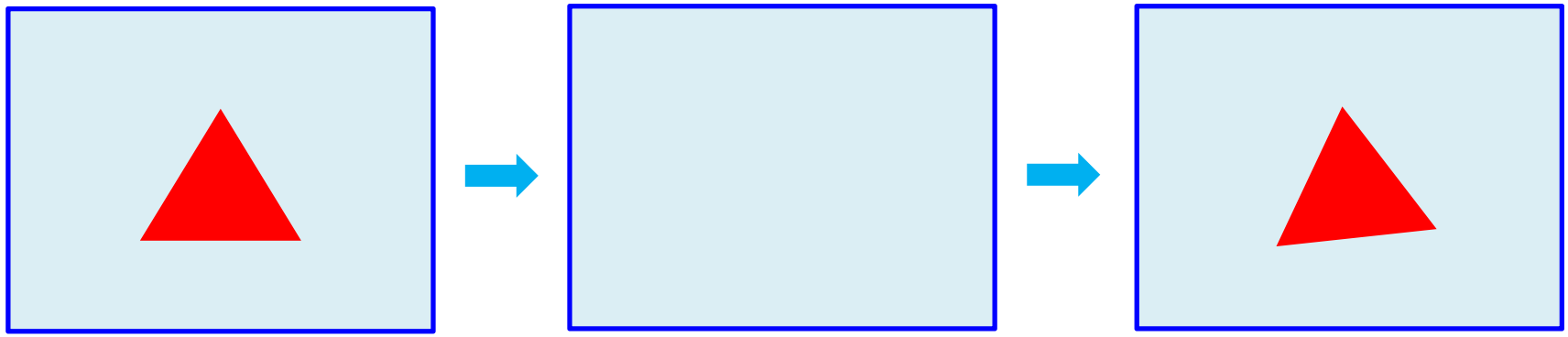
Filling pixel colors

- **Interpolate pixel colors in inner regions**
  - Linear interpolation based on vertex colors automatically



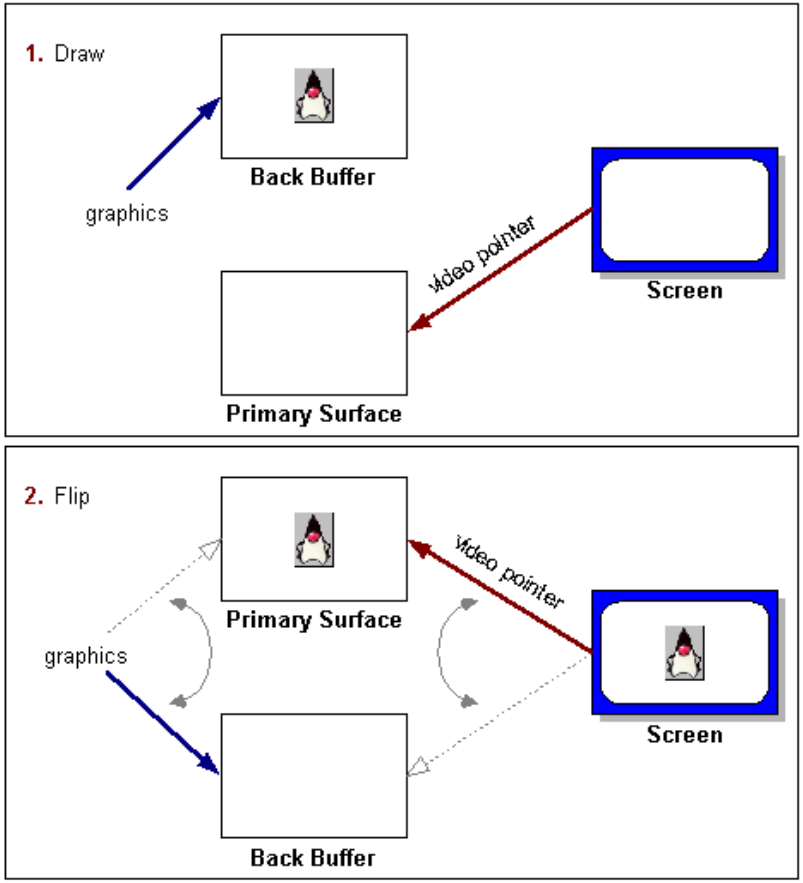
Filling pixel colors

- **Dynamic display**
  - The screen will be erased before displaying the next content
  - The sequential process results in flickering



Double buffering

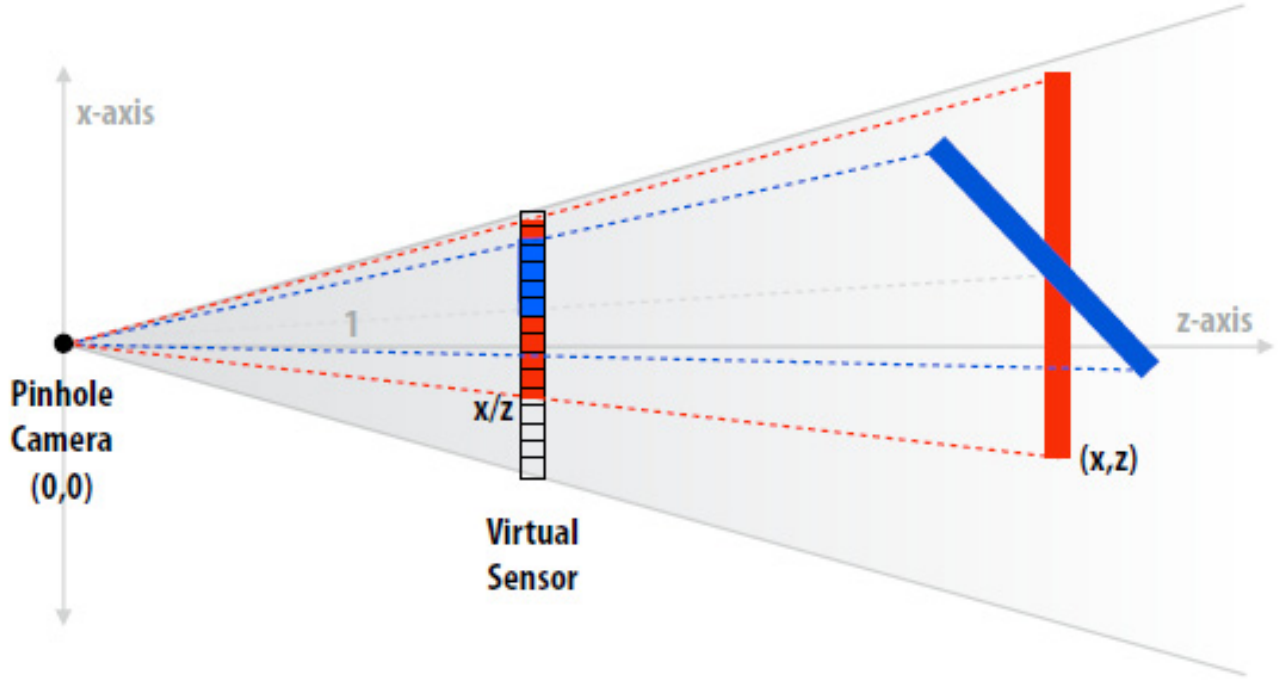
- The way to eliminate flickering



Step 4: Depth-Test

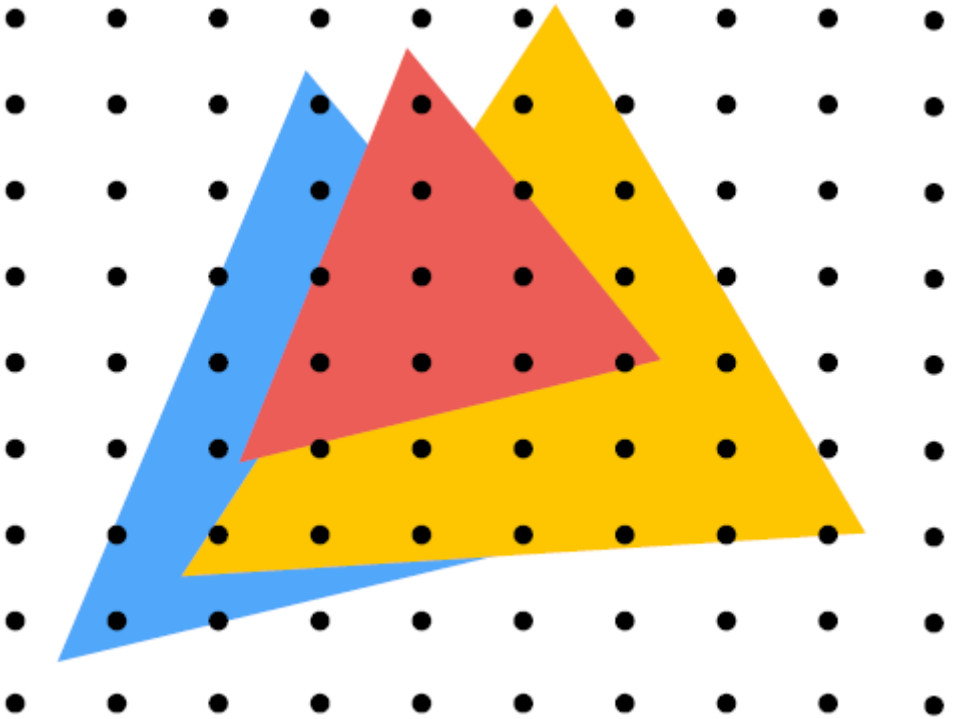
Concept of depth

- The distance of a 3D point to the imaging plane



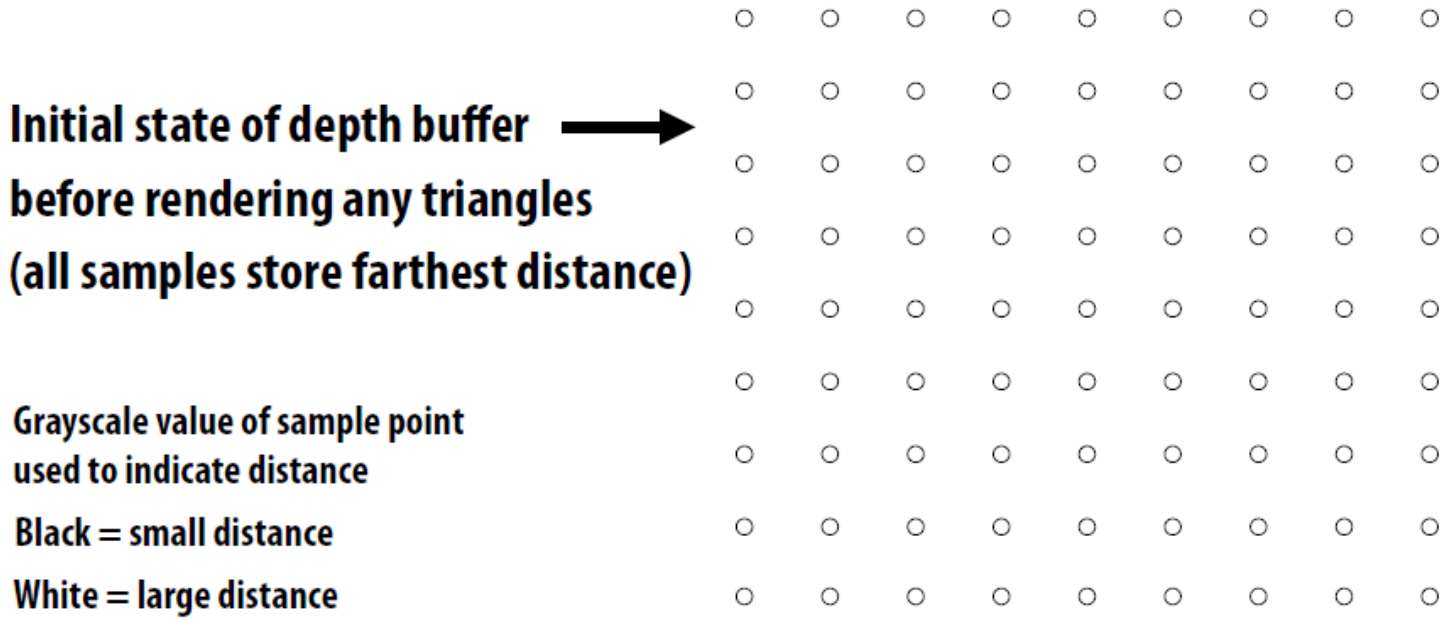
Visibility

- **Visible surface determination**
  - The process used to determine which surfaces and parts of surfaces are not visible from a certain viewpoint



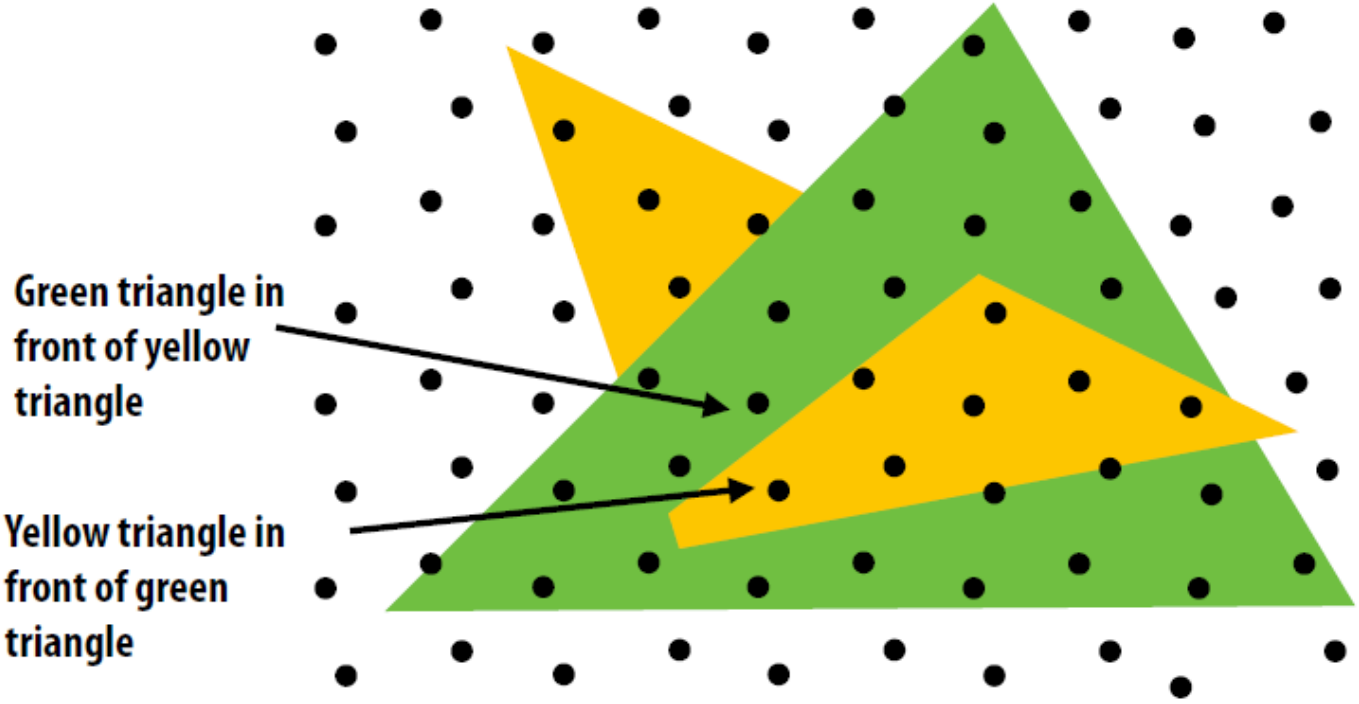
Depth buffer (Z-buffer)

- **For each coverage sample point**
  - Depth-buffer stores depth of closest triangle at this sample point that has been processed by the renderer



Depth buffer (Z-buffer)

- **Does depth-buffer algorithm handle interpenetrating surfaces?**
  - Yes, of course!

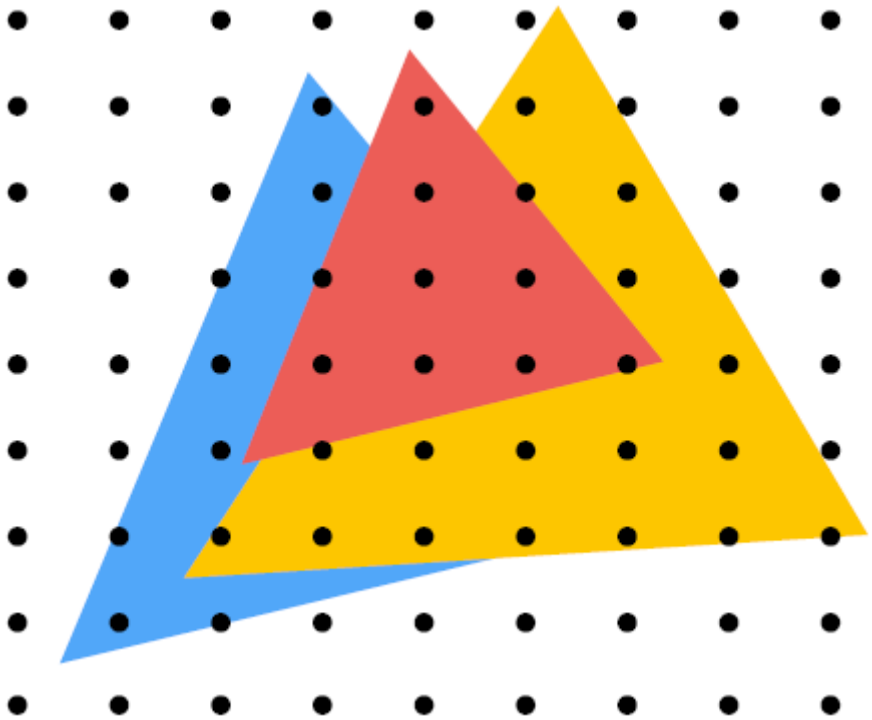


Depth buffer (Z-buffer)

- **An example of depth buffer**

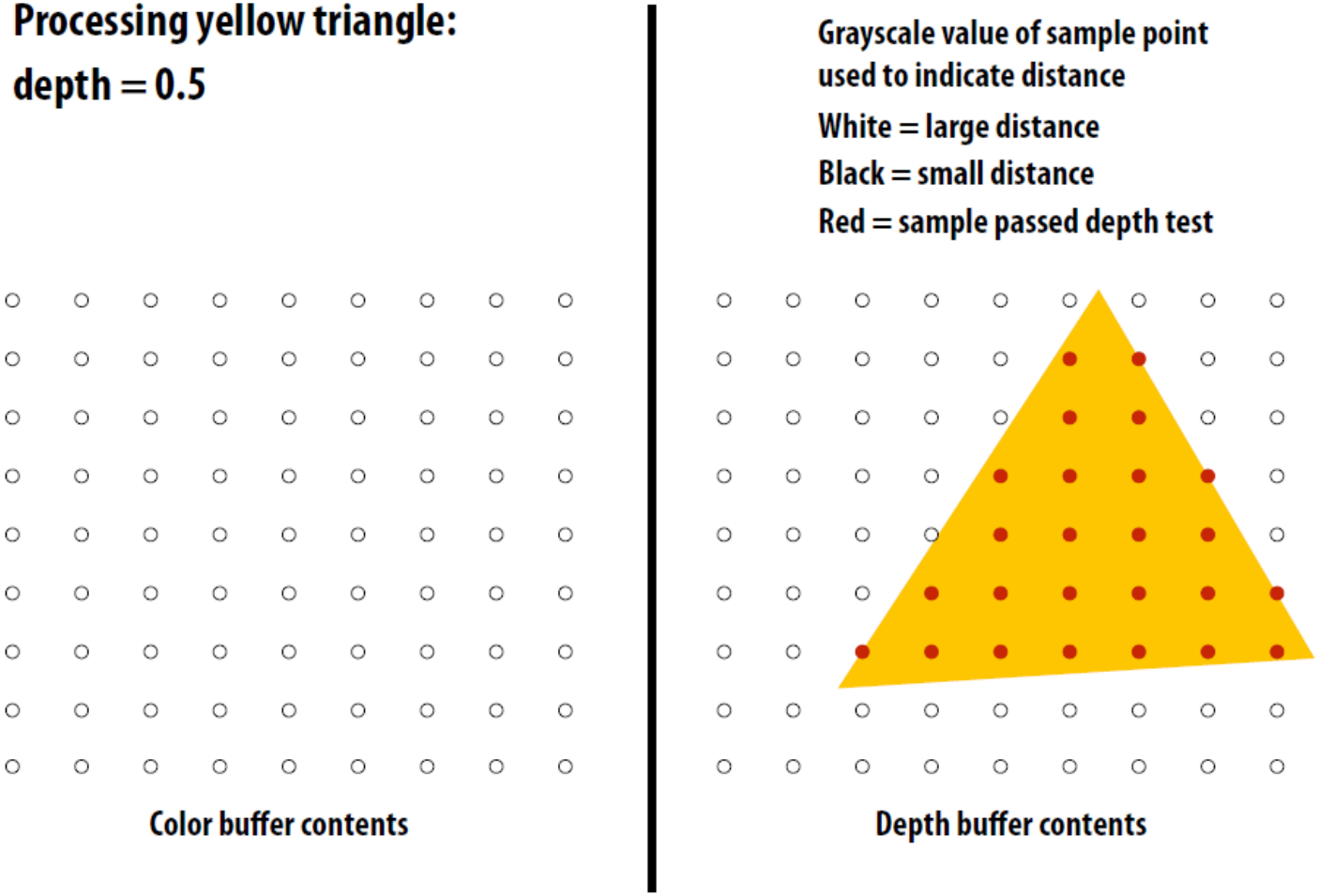
Depth-test in pixel-fill

- **Example: rendering three opaque triangles**



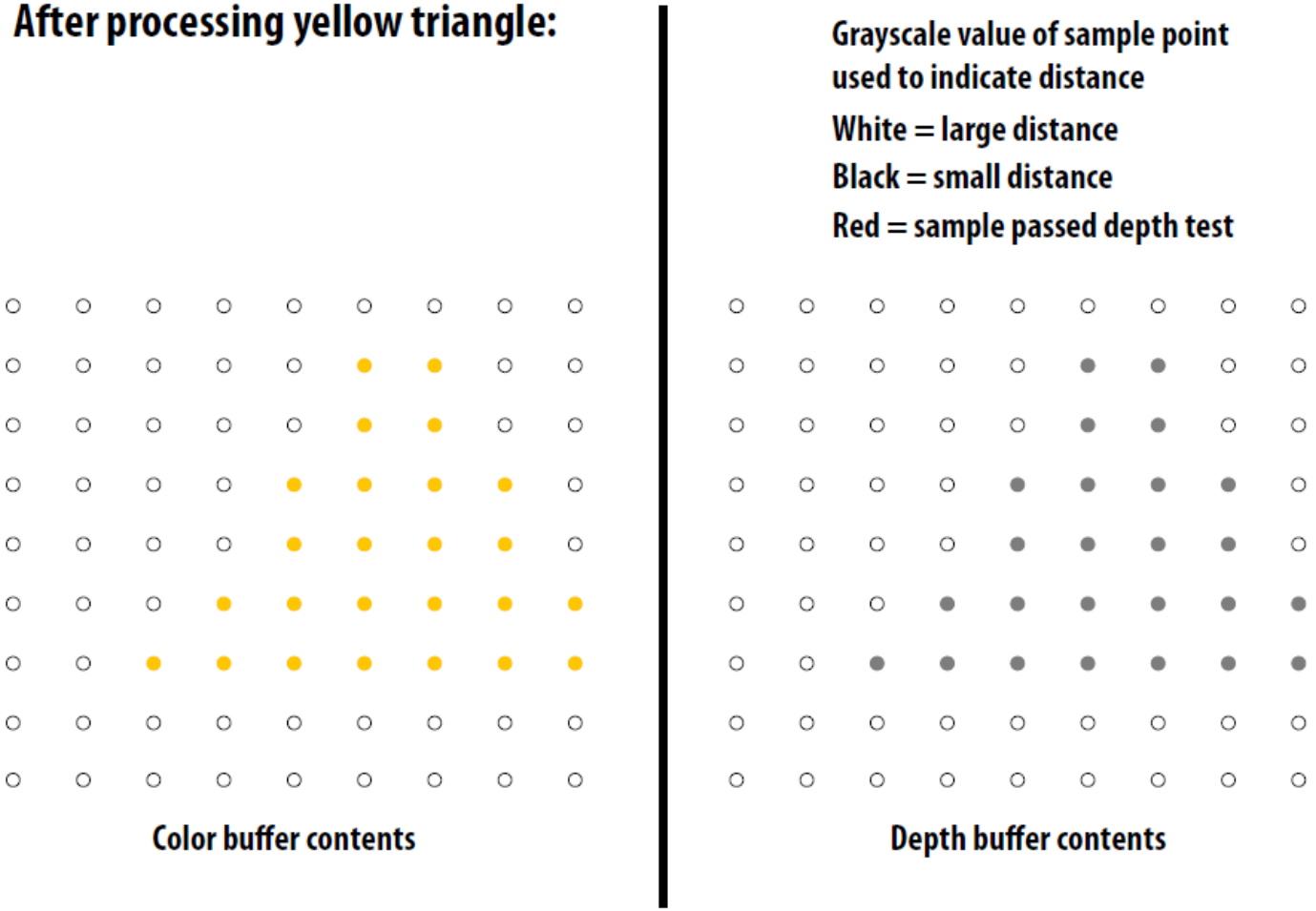
Depth-test in pixel-fill

- Occlusion using the depth-buffer (Z-buffer)



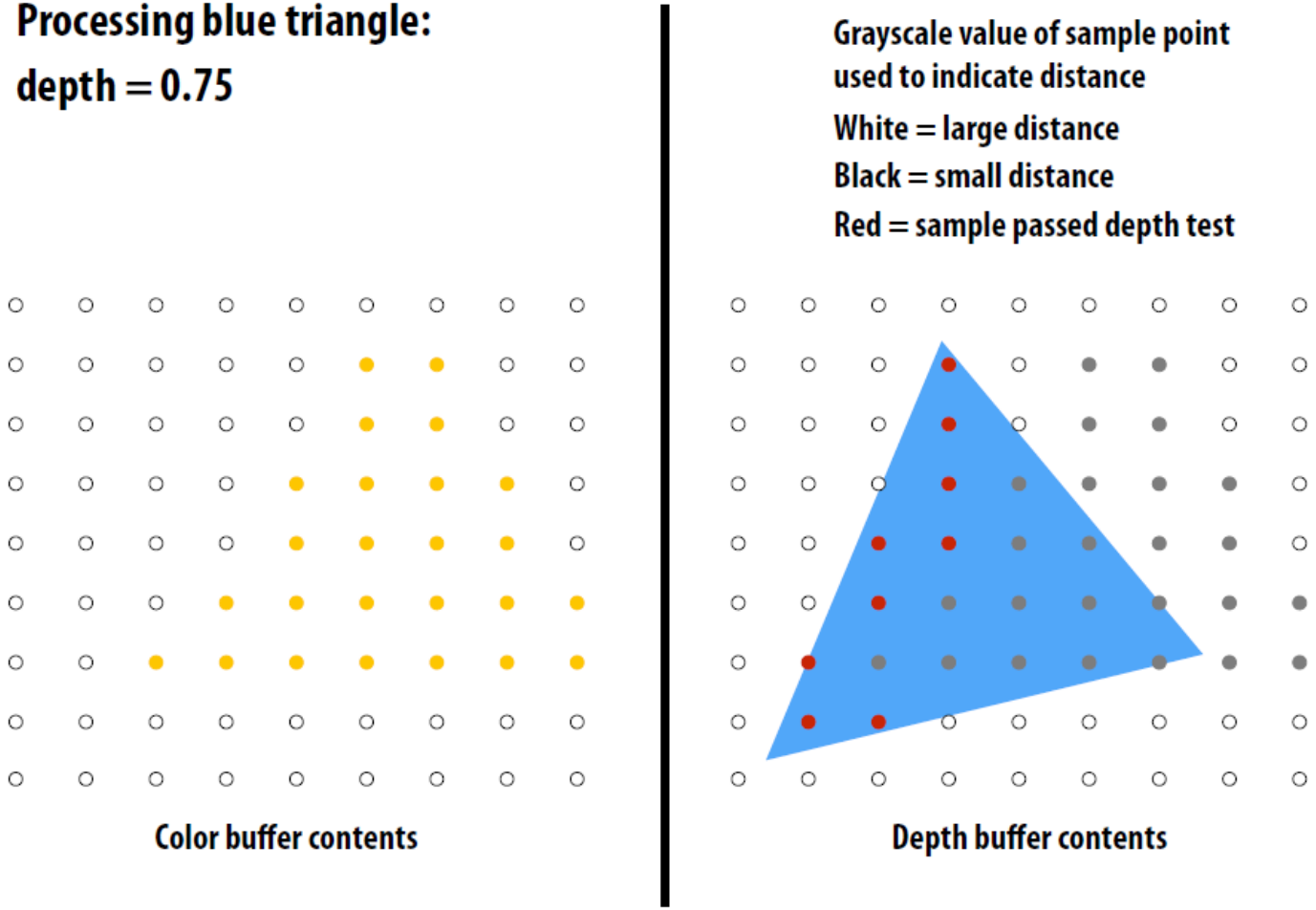
Depth-test in pixel-fill

- Occlusion using the depth-buffer (Z-buffer)



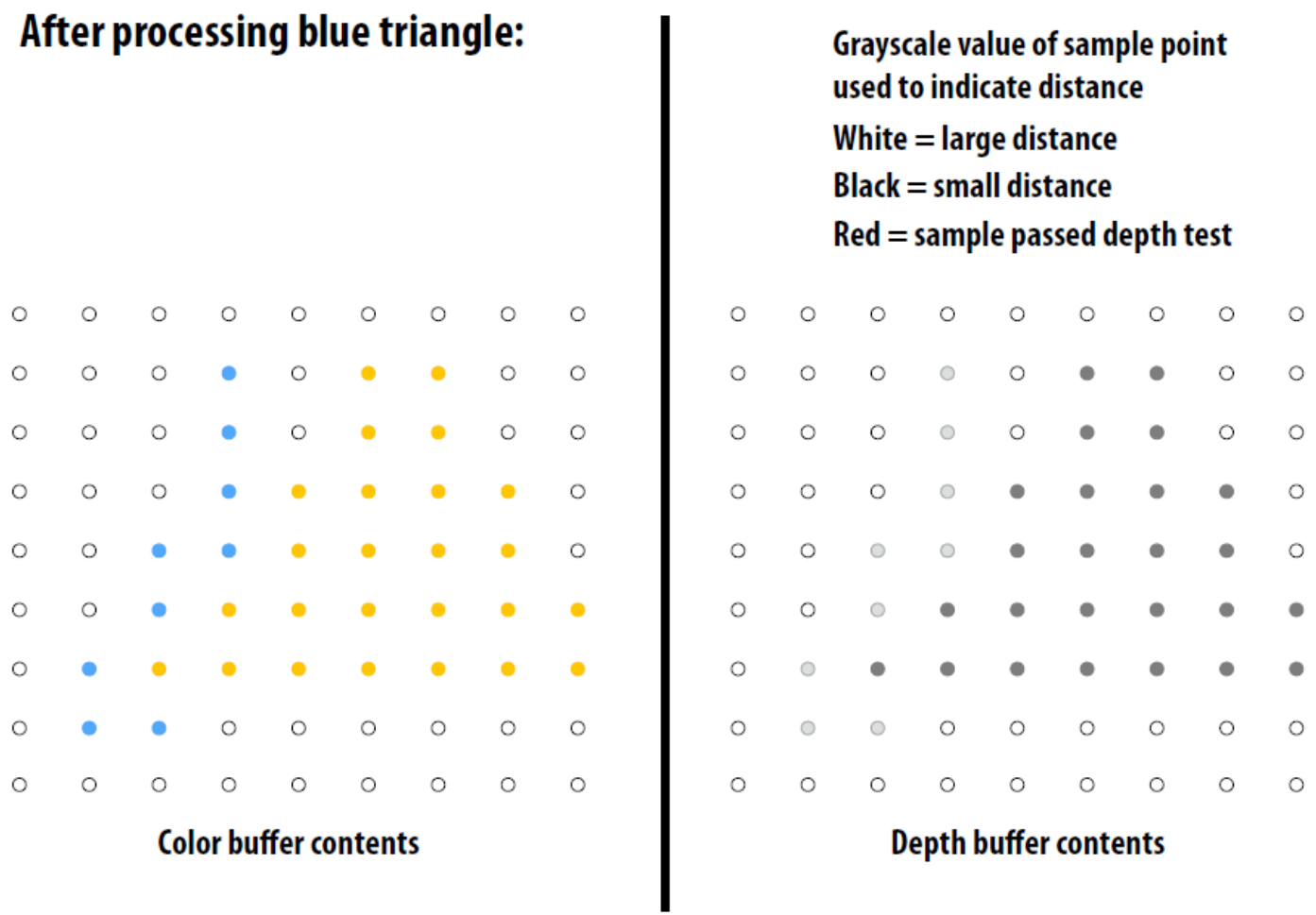
Depth-test in pixel-fill

- Occlusion using the depth-buffer (Z-buffer)



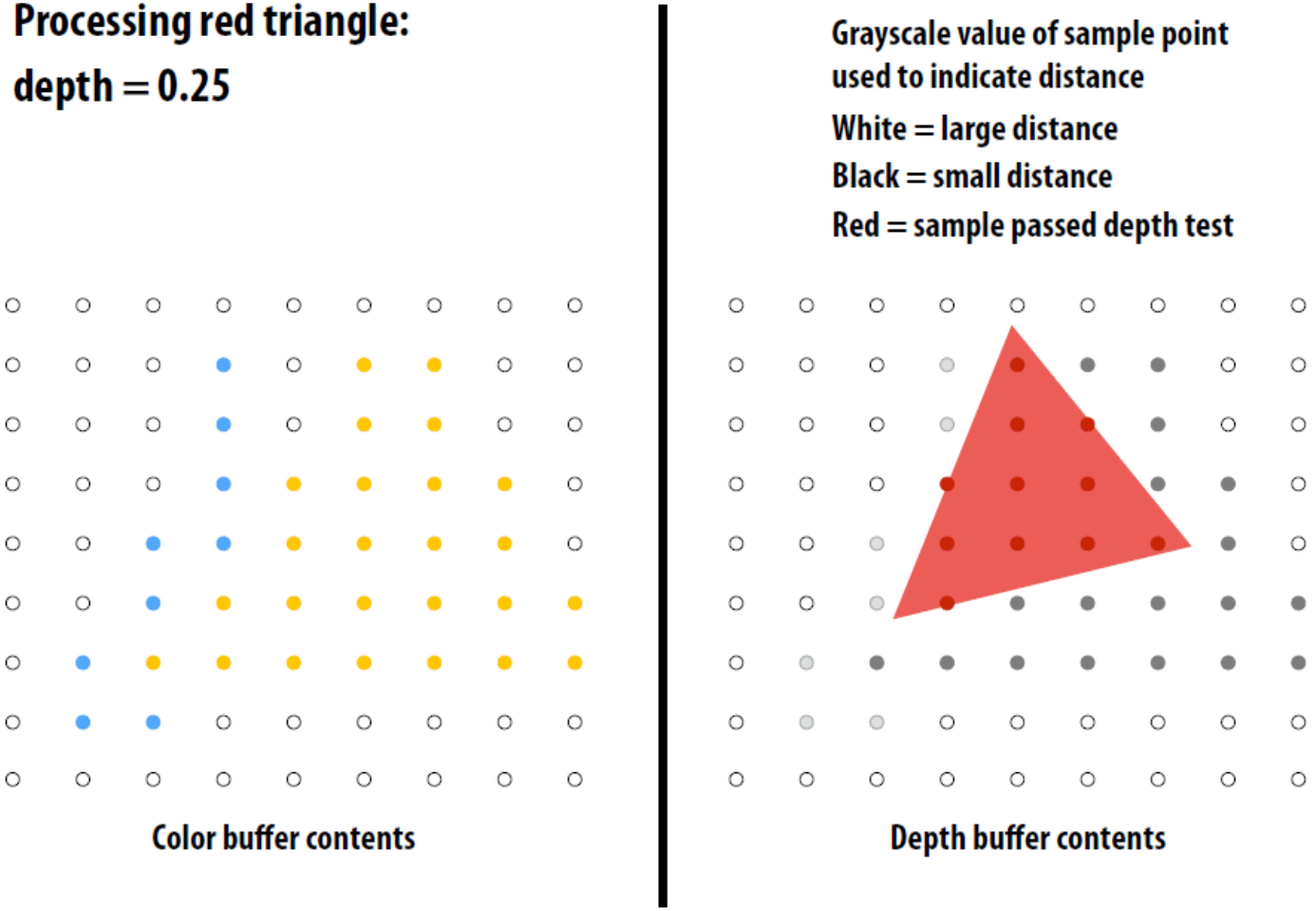
Depth-test in pixel-fill

- Occlusion using the depth-buffer (Z-buffer)



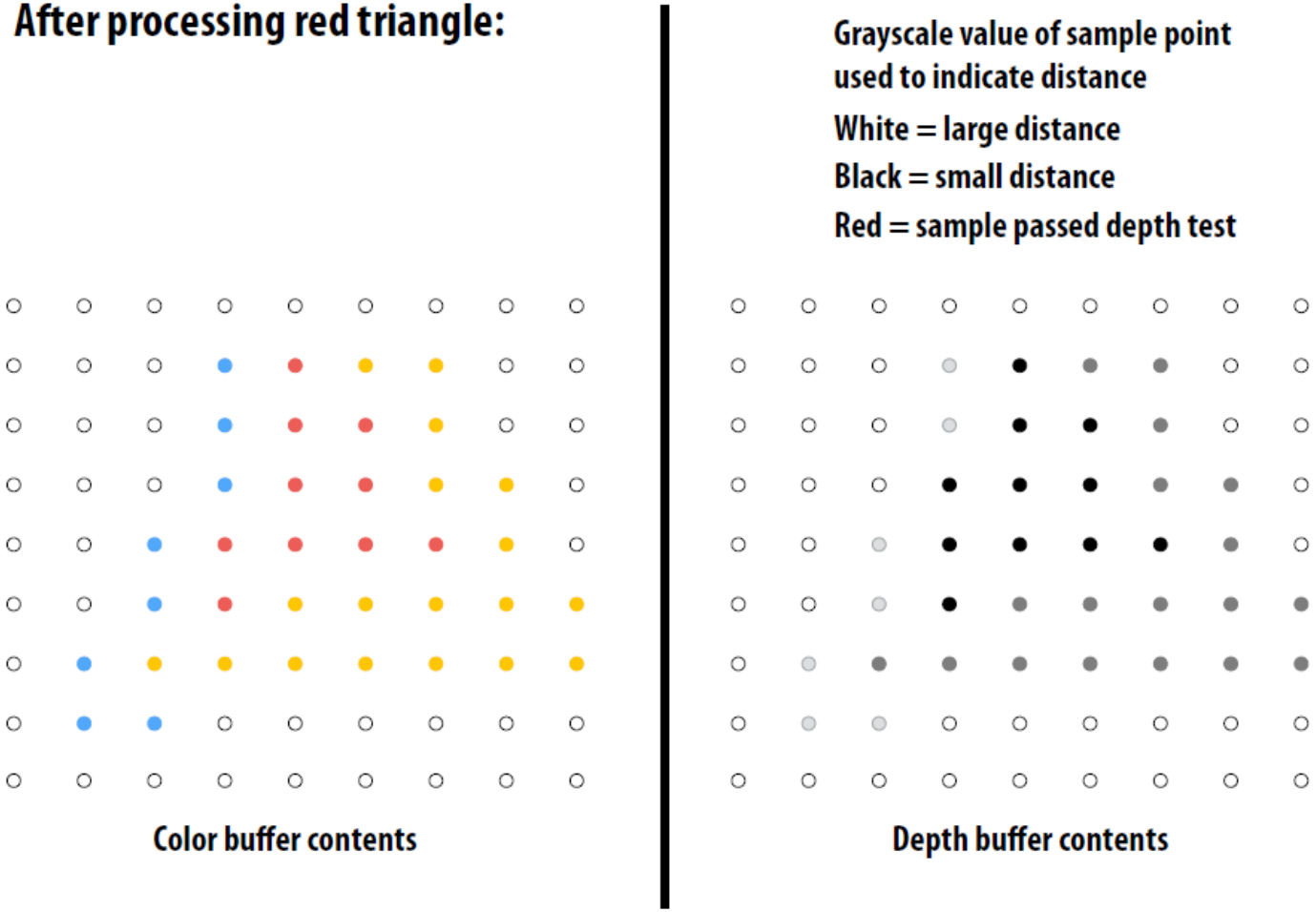
Depth-test in pixel-fill

- Occlusion using the depth-buffer (Z-buffer)



Depth-test in pixel-fill

- Occlusion using the depth-buffer (Z-buffer)



Enable depth-test in OpenGL

- **How to enable and disable depth-test in OpenGL?**

```
/* Make the window's context current */
glfwMakeContextCurrent(window);

glEnable(GL_DEPTH_TEST); //glDisable(GL_DEPTH_TEST);

/* Loop until the user closes the window */
while (!glfwWindowShouldClose(window))
{
    /* Render here */
    glClear(GL_COLOR_BUFFER_BIT);
    /* Swap front and back buffers */

    //add your OpenGL rendering calls here

    glfwSwapBuffers(window);
    …
}
```

The first OpenGL program

The first OpenGL program

- **Using GLFW library** (http://www.glfw.org/)
  - Initialization and window creation, double buffer by default

```
GLFWwindow*  window;

/* Initialize the library */
if (!glfwInit()) return -1;

/* Create a windowed mode window and its OpenGL context */
 window = glfwCreateWindow(640, 480, "Hello World", NULL, NULL);
if (!window) { glfwTerminate(); return -1; }

/* Make the window's context current */
glfwMakeContextCurrent(window);
```

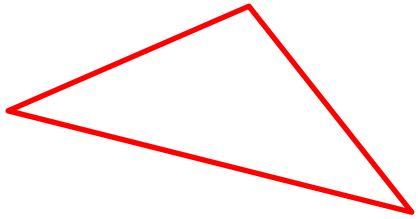
The first OpenGL program

- **Using GLFW library**
  - Render things

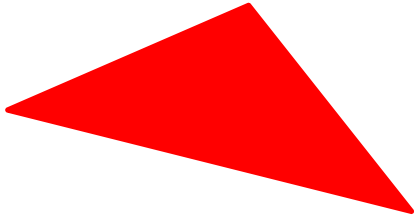
```
/* Loop until the user closes the window */
while (!glfwWindowShouldClose(window))
{
    /* Clear color buffer */
    glClear(GL_COLOR_BUFFER_BIT);

    //add your OpenGL rendering calls here

    /* Swap front and back buffers */
    glfwSwapBuffers(window);
    /* Poll for and process events */
    glfwPollEvents();
}
```

Wired v.s. filled polygons

- **Wired triangle**
  - Only the edges are drawn



- **Filled triangle**
  - Not only the edges are drawn, but also the inner region is filled with color



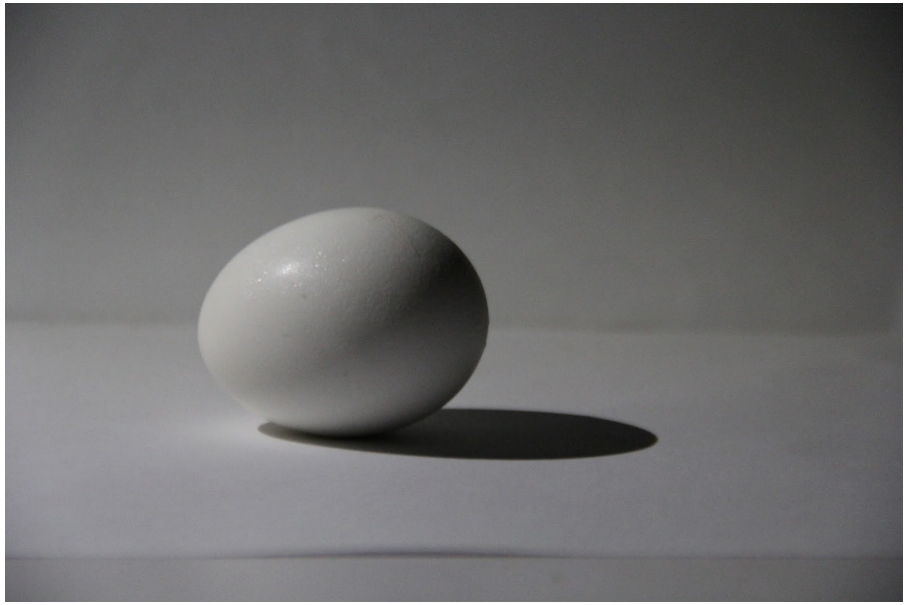
- **Enable/disable polygon filling in OpenGL**

```
glPolygonMode(GL_FRONT_AND_BACK, GL_LINES);
glPolygonMode(GL_FRONT_AND_BACK, GL_FILL);
```

Step 5: Shading

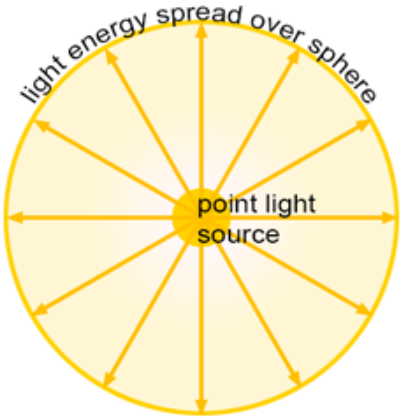
Shading

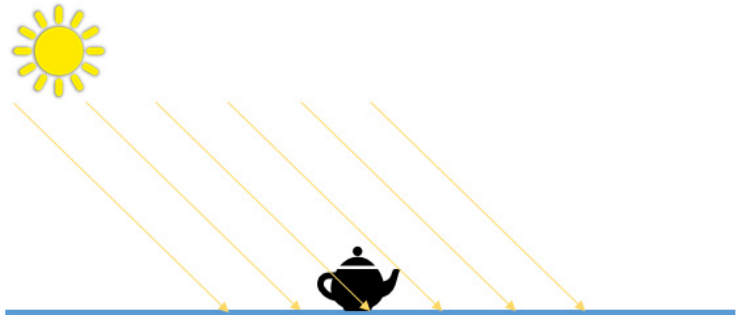
- **What is shading?**
  - Shading refers to the process of altering the color of an object/surface/polygon in the 3D scene
  - Based on the angle to lights and the distance from lights or appearance model to create a photorealistic effect

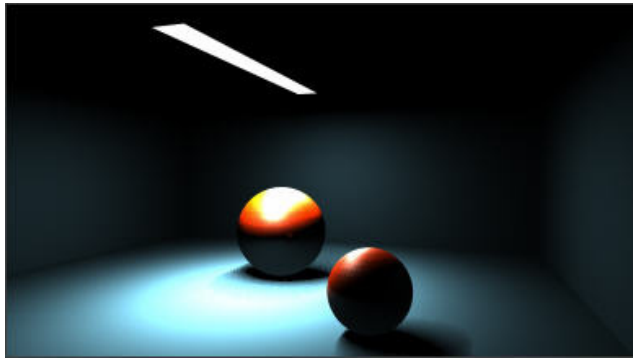


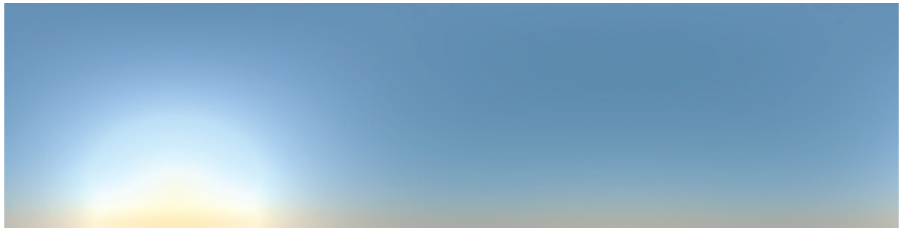
Light sources

- **The sources to illuminate light**
  - Point/parallel/spot light sources
  - Area light sources
  - Environmental light sources





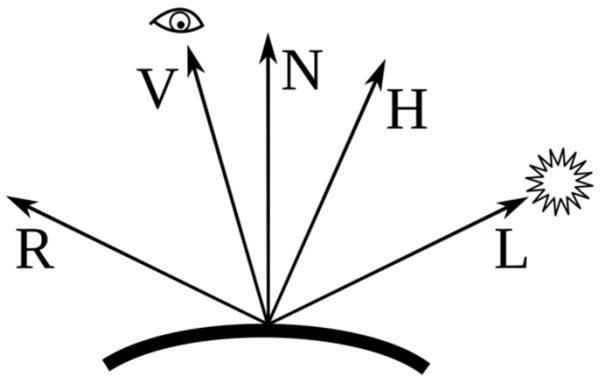


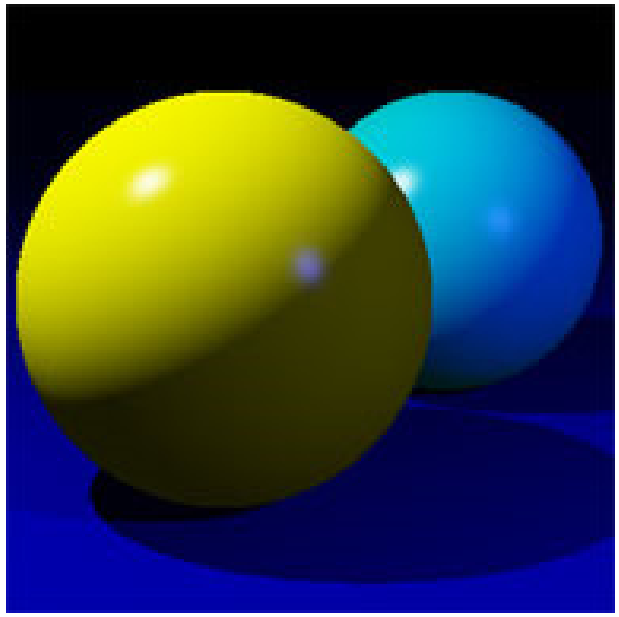


Environment light map

Lighting model

- **Determine how light is reflected**
  - Lambert diffuse reflection model
  - Phong reflection model



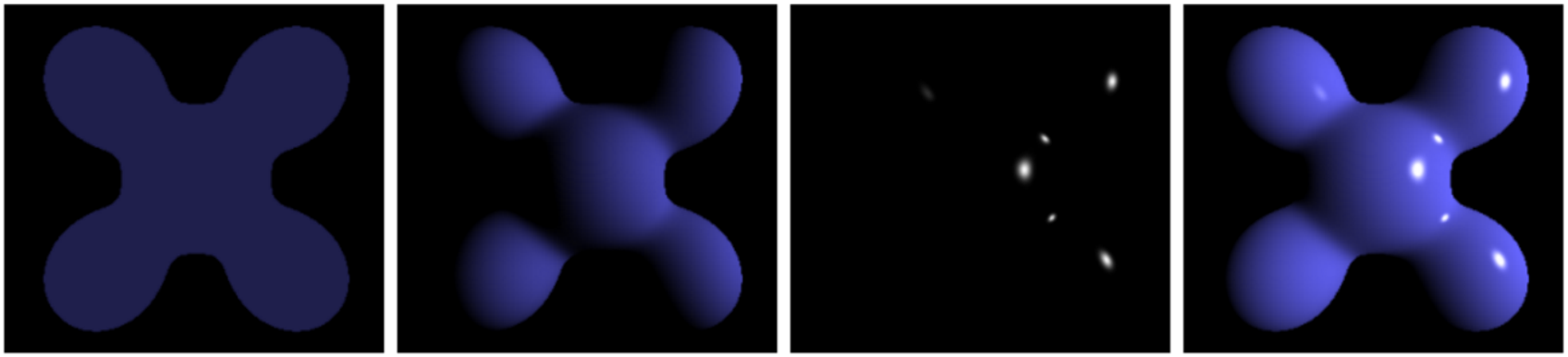


Lighting model

- **Phong reflection model**
  - Light source decomposition
    - Ambient light: constant environment lighting (view independent)
    - Diffuse light: light that is scattered uniformly to each direction (view independent)
    - Specular light: light that is scattered along specific directions (view dependent)
  - Material reflection decomposition
    - Ambient reflection: component that reflects only ambient light
    - Diffuse reflection: component that reflects only diffuse light
    - Specular reflection: component that reflects only specular light

Lighting model

- **Phong reflection model**



$$\hat{R}_m = 2(\hat{L}_m \cdot \hat{N})\hat{N} - \hat{L}_m$$

$$I_\mathrm{p} = k_\mathrm{a} i_\mathrm{a} + \sum_{m \in \text{ lights}} (k_\mathrm{d}(\hat{L}_m \cdot \hat{N}) i_{m,\mathrm{d}} + k_\mathrm{s}(\hat{R}_m \cdot \hat{V})^\alpha i_{m,\mathrm{s}})$$

Lighting in OpenGL

- **Enable lighting and set lighting components**

```
glEnable(GL_LIGHTING);
glEnable(GL_LIGHT0);

// Create light components
GLfloat ambientLight[] = { 0.2f, 0.2f, 0.2f, 1.0f };
GLfloat diffuseLight[] = { 0.8f, 0.8f, 0.8, 1.0f };
GLfloat specularLight[] = { 0.5f, 0.5f, 0.5f, 1.0f };
GLfloat position[] = { -1.5f, 1.0f, -4.0f, 1.0f };

// Assign created components to GL_LIGHT0
glLightfv(GL_LIGHT0, GL_AMBIENT, ambientLight);
glLightfv(GL_LIGHT0, GL_DIFFUSE, diffuseLight);
glLightfv(GL_LIGHT0, GL_SPECULAR, specularLight);
glLightfv(GL_LIGHT0, GL_POSITION, position);
```

Lighting in OpenGL

- **Set material reflection components**

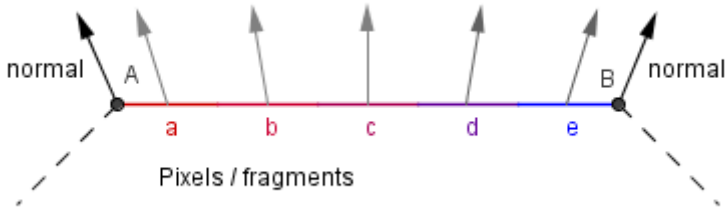
```
GLfloat ambient[] = { 1.0f, 1.0f, 1.0f };
glMaterialfv(GL_FRONT, GL_AMBIENT, ambient);

GLfloat diffuse[] = { 0.0f, 0.0f, 1.0f };
glMaterialfv(GL_FRONT, GL_DIFFUSE, diffuse);

GLfloat specular[] = { 1.0f, 1.0f, 1.0f };
glMaterialfv(GL_FRONT, GL_SPECULAR, specular);
```

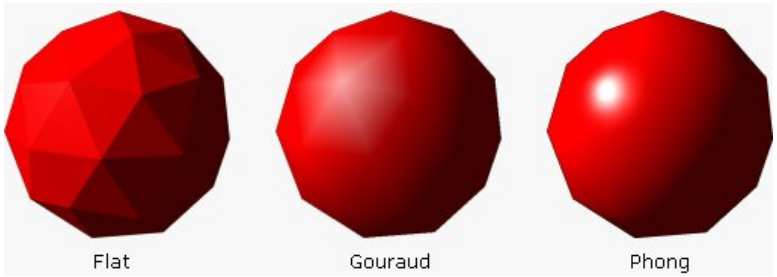
- **Enable smooth shading**

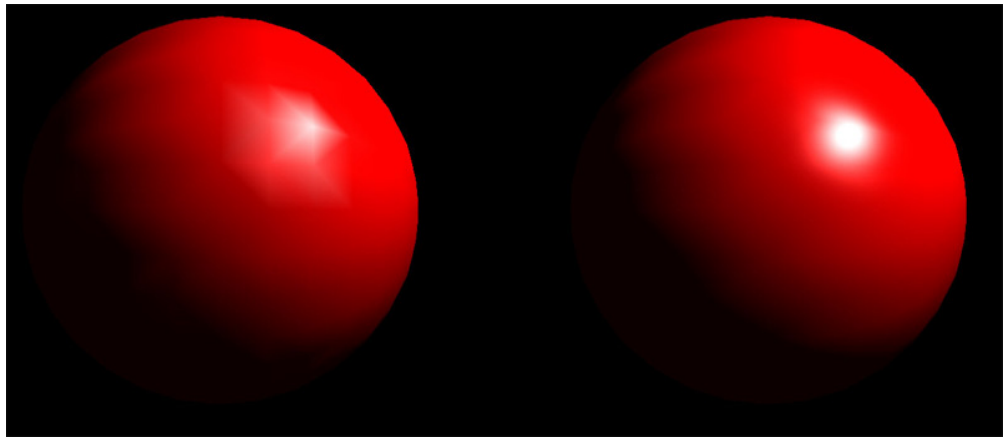
```
glShadeModel(GL_SMOOTH);        //glShadeModel(GL_FLAT);
```

Shading model

- **Gourand v.s. Phong shading**
  - Interpolation by color or by normal

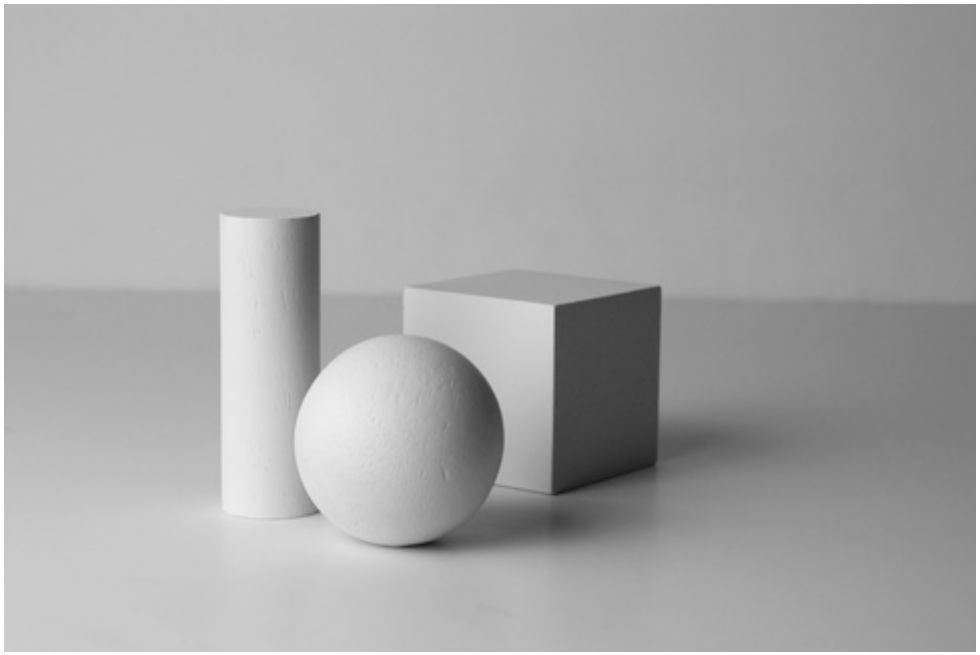






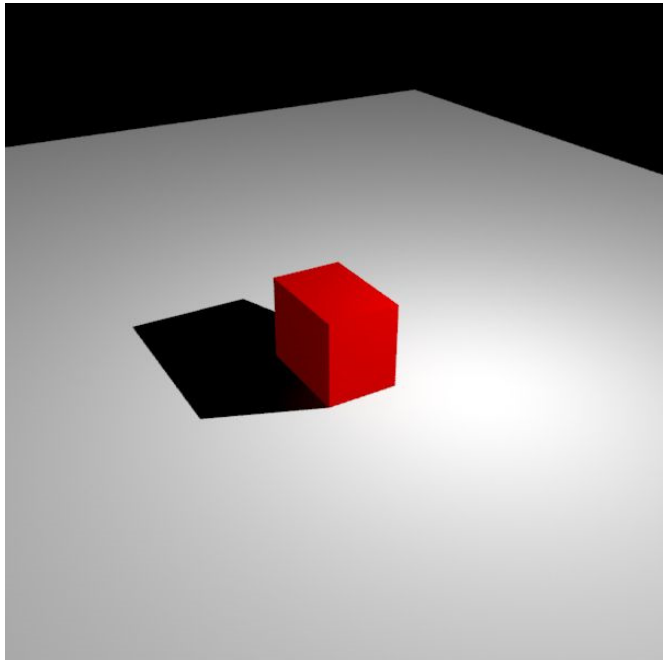
Shadow

- **What is a shadow**
  - A shadow is a dark area where light from a light source is blocked by an opaque object



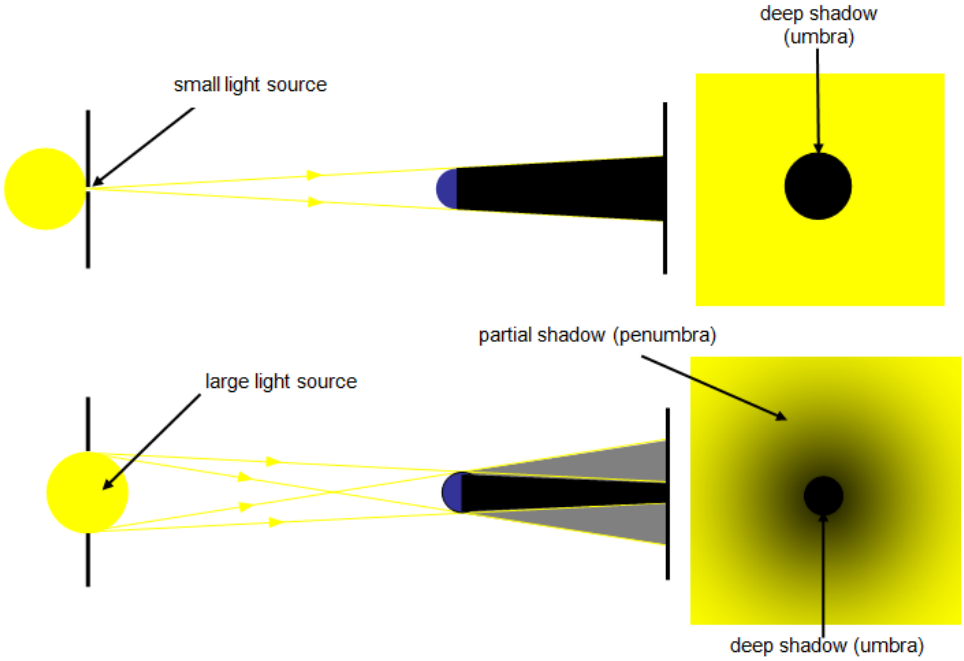
Shadow

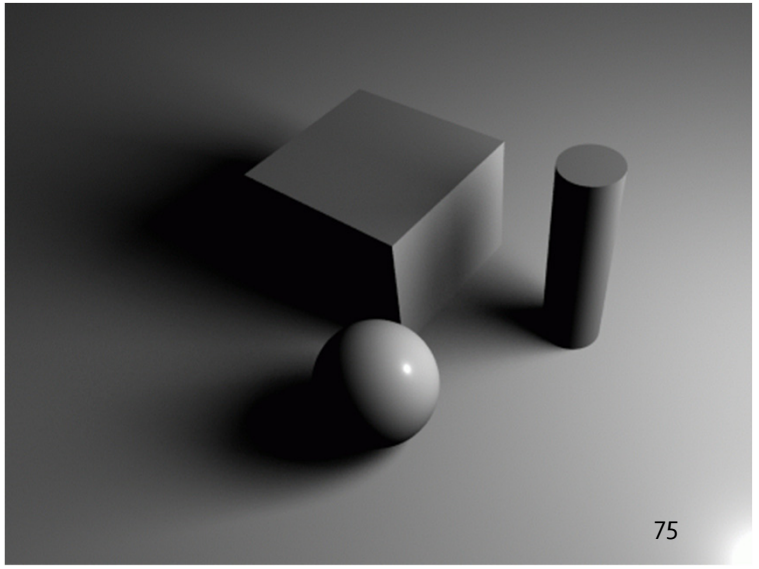
- **Hard shadow**
  - Shadow with sharp boundaries
  - Usually generated from a point/parallel light source
  - Shadow mapping (OpenGL)



Shadow

- **Soft shadow**
  - The boundary is smooth
  - Usually from area or environmental light sources
- **Shadow regions**





Texturing

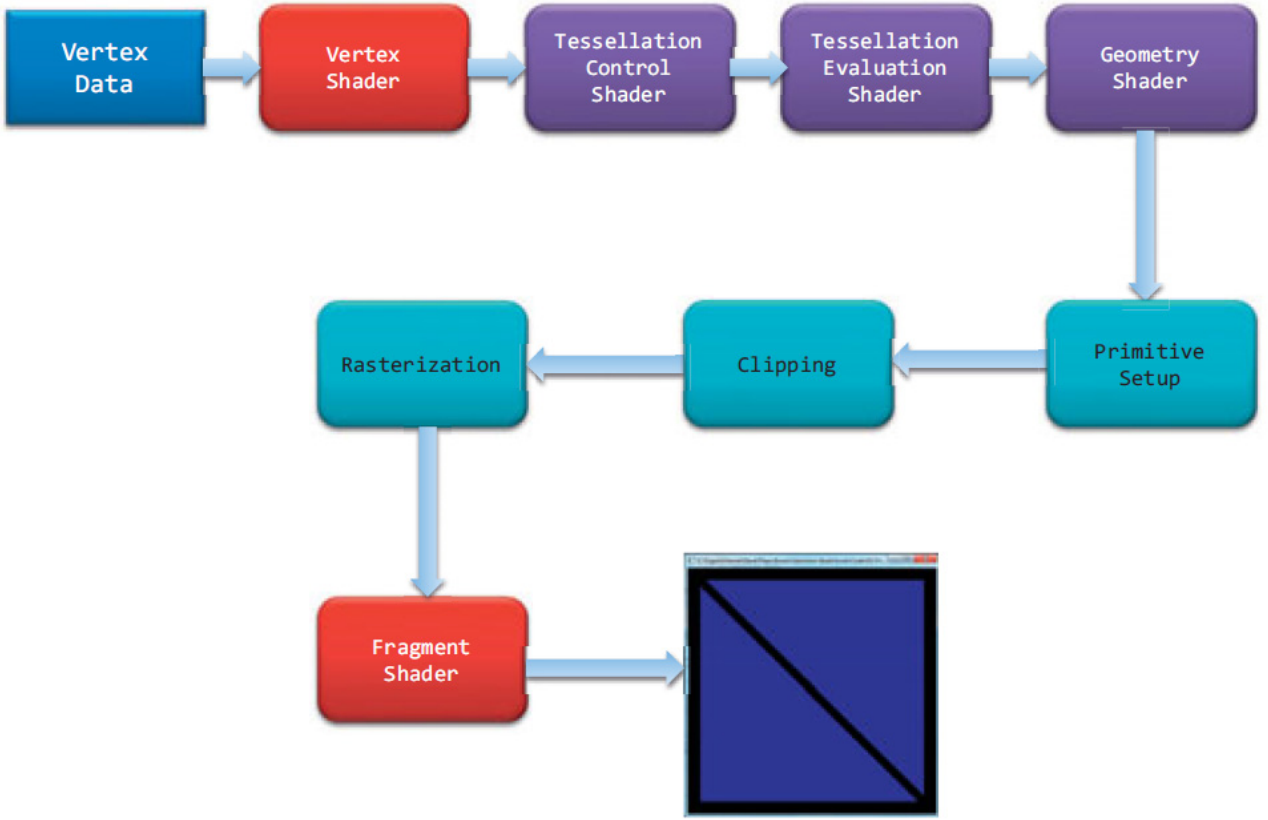
- **Texture map**
  - A texture map is an image applied (mapped) to the surface of a shape (mesh)

- **Texture mapping**
  - A mapping from image space to projection space

OpenGL Shader

OpenGL pipeline

- **OpenGL graphics pipeline**



Shader

- **Without-shader age**
  - Rendering pipeline is fixed
  - Only tune a few parameters
- **With-shader age**
  - Vertex shader
    - Processes each vertex separately
  - Tessellation shader
    - Generates additional geometry
  - Geometry shader
    - Modify entire geometric primitives
  - Fragment shader
    - A fragment's color and depth values are computed

Vertex shader

- **Processing of individual vertices before projection**
  - Receive a single vertex with attributes from the vertex stream
  - Generate a single vertex with modified attributes to the output vertex stream, in parallel

```
void
main()
{
    // set the normal for the fragment shader and
    // the vector from the vertex to the camera
    fragmentNormal = gl_Normal;
    cameraVector = cameraPosition - gl_Vertex.xyz;

    // set the vectors from the vertex to each light
    for(int i = 0; i < NUM_LIGHTS; ++i)
        lightVector[i] = lightPosition[i] - gl_Vertex.xyz;

    // output the transformed vertex
    gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
}
```

Fragment (pixel) shader

- **Processing a fragment generated by rasterization**
  - After the rasterization process, with vertex attributes automatically interpolated
  - Take a single fragment as input and produce a single fragment as output, in parallel

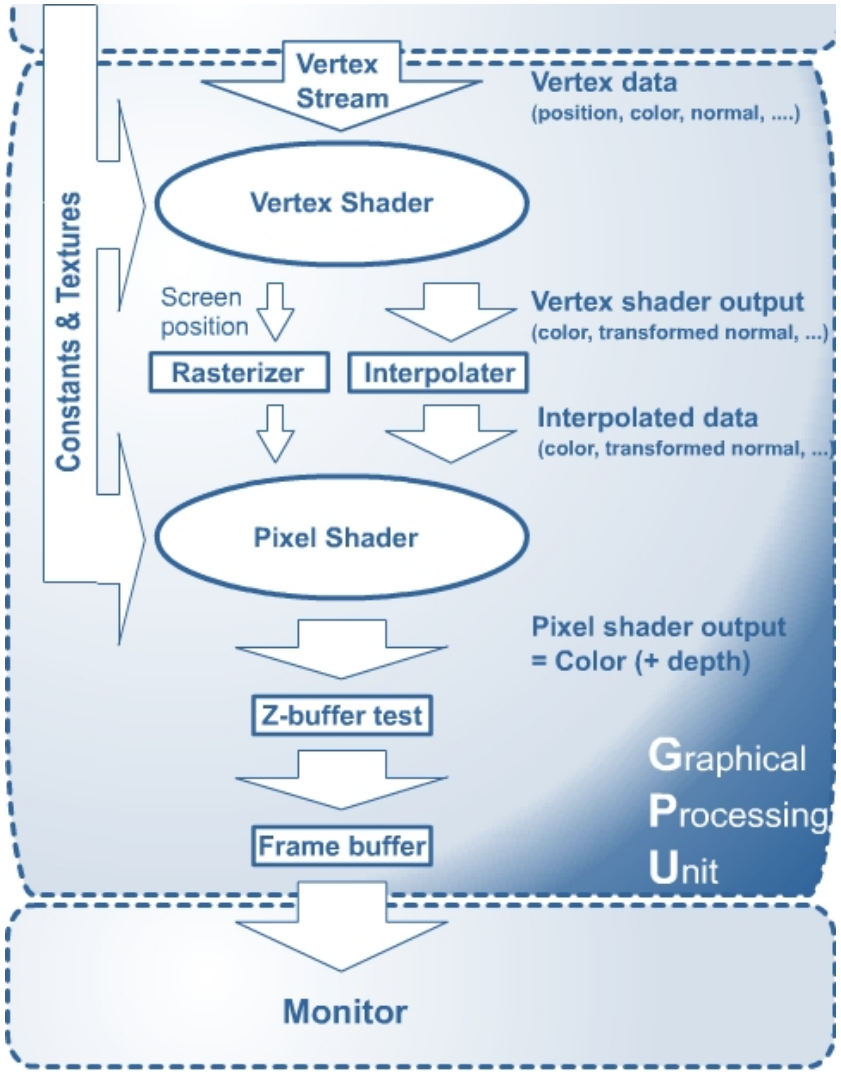
```
void
main()
{
    // initialize diffuse/specular lighting
    vec3 diffuse = vec3(0.0, 0.0, 0.0);
    vec3 specular = vec3(0.0, 0.0, 0.0);

    // normalize the fragment normal and camera direction
    vec3 normal = normalize(fragmentNormal);
    vec3 cameraDir = normalize(cameraVector);


   // loop through each light
   for(int i = 0; i < NUM_LIGHTS; ++i) {
       // calculate distance between 0.0 and 1.0
       float dist = min(dot(lightVector[i], lightVector[i]), MAX_DIST_SQUARED) / MAX_DIST_SQUARED;
       float distFactor = 1.0 - dist;

       // diffuse
       vec3 lightDir = normalize(lightVector[i]);
       float diffuseDot = dot(normal, lightDir);
       diffuse += lightColor[i] * clamp(diffuseDot, 0.0, 1.0) * distFactor;

       ...

  ...
```

Shader compilation

- **Compile at run-time (dynamic compilation)**
  - Reading a file or shader source strings and compile

```
static GLuint
shaderCompileFromFile(GLenum type, const char *filePath)
{
    char *source;
    GLuint shader;
    GLint length, result;

    /* get shader source */
    source = shaderLoadSource(filePath);
    if(!source)
        return 0;

    /* create shader object, set the source, and compile */
    shader = glCreateShader(type);
    length = strlen(source);
    glShaderSource(shader, 1, (const char **)&source, &length);
    glCompileShader(shader);
    free(source);

    /* make sure the compilation was successful */
    glGetShaderiv(shader, GL_COMPILE_STATUS, &result);
    if(result == GL_FALSE) {
        char *log;

        /* get the shader info log */
        glGetShaderiv(shader, GL_INFO_LOG_LENGTH, &length);
        log = malloc(length);
        glGetShaderInfoLog(shader, length, &result, log);

        /* print an error message and the info log */
        fprintf(stderr, "shaderCompileFromFile(): Unable to compile %s: %s\n", filePath, log);
        free(log);

        glDeleteShader(shader);
        return 0;
    }

    return shader;
}
```

Relation between vertex & fragment shader



Next Lecture :

Coordinate spaces, projection & rasterization