

Computer Graphics I

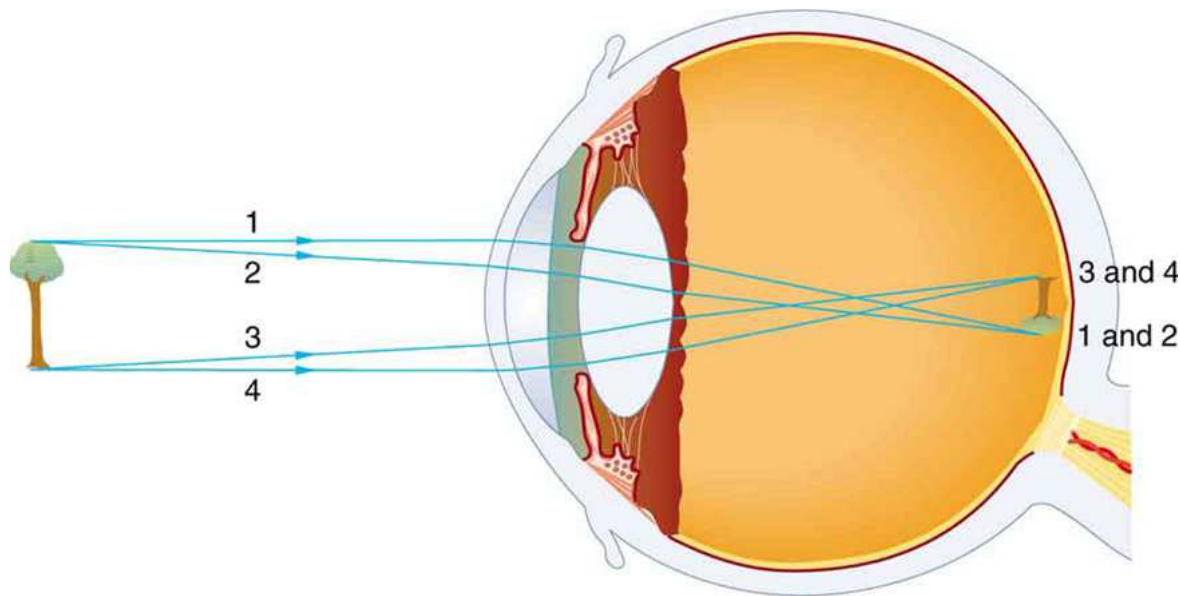
Lecture 2: The first graphics program

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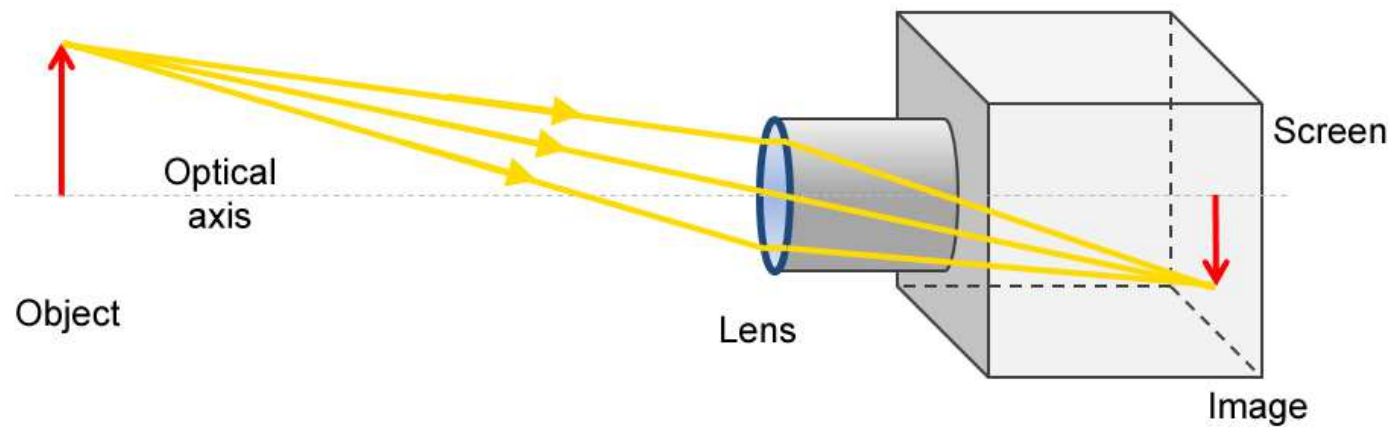
Producing images

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



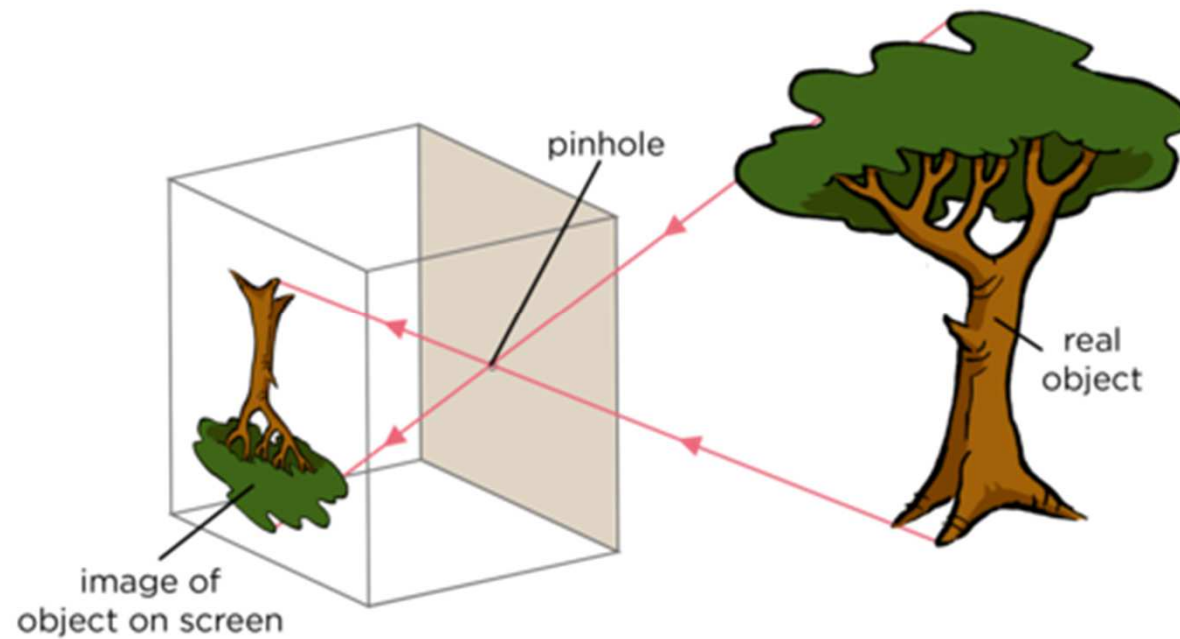
Camera system

- Imaging in camera system through lens



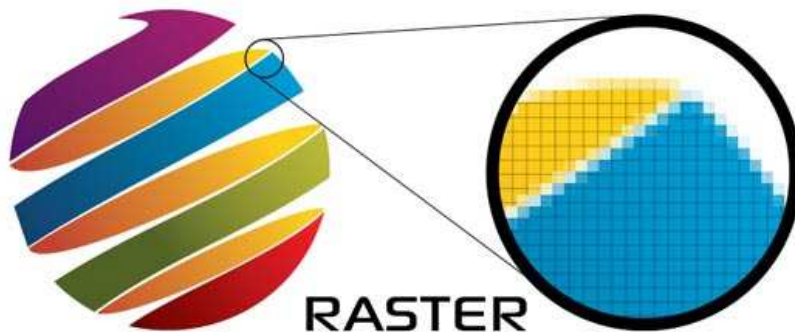
Virtual camera model

- **Camera model**
 - Pinhole camera

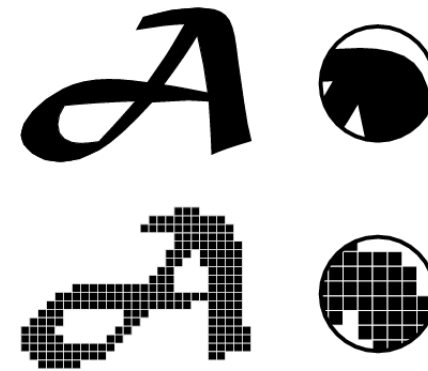


Digital image

- **A two-dimensional rectangle array (2D grid)**
 - Each grid 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 grid resolution
 - How many samples per grid dimension
 - Higher resolution represents more details

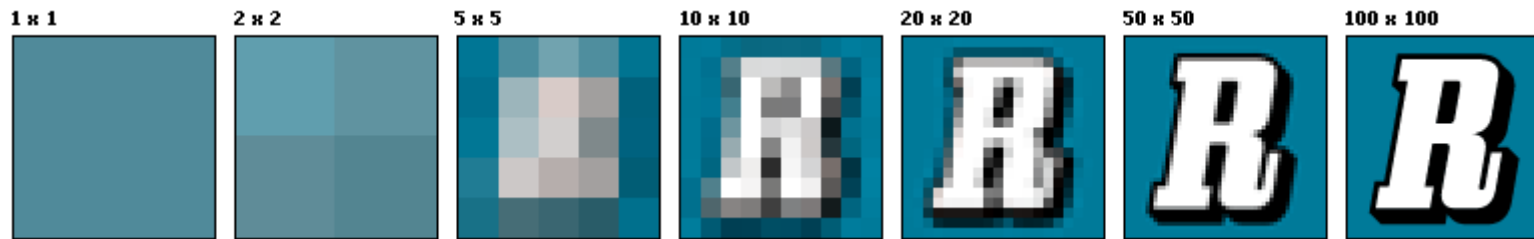
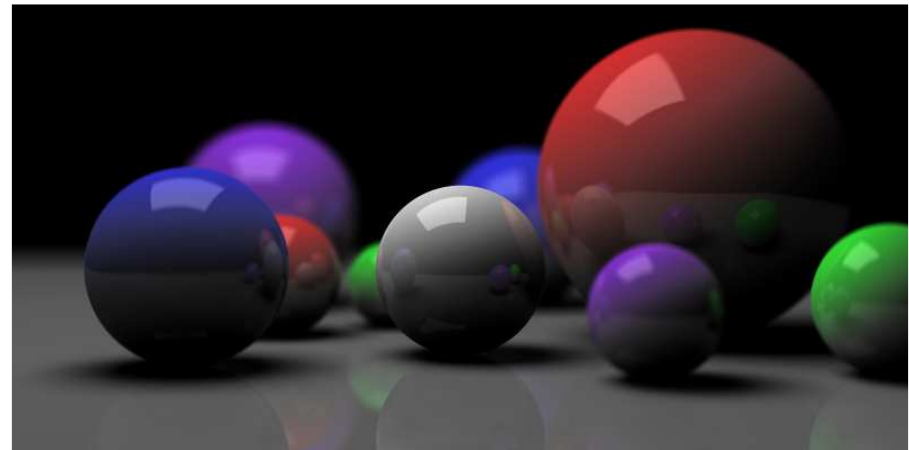
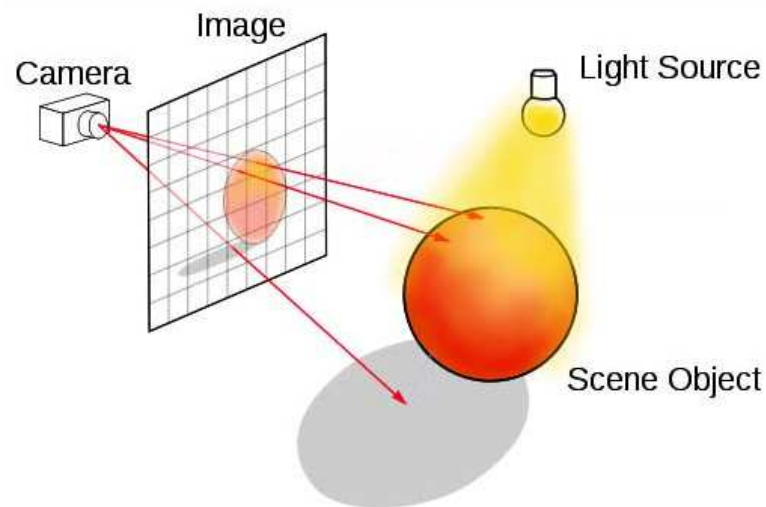


Image formation

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



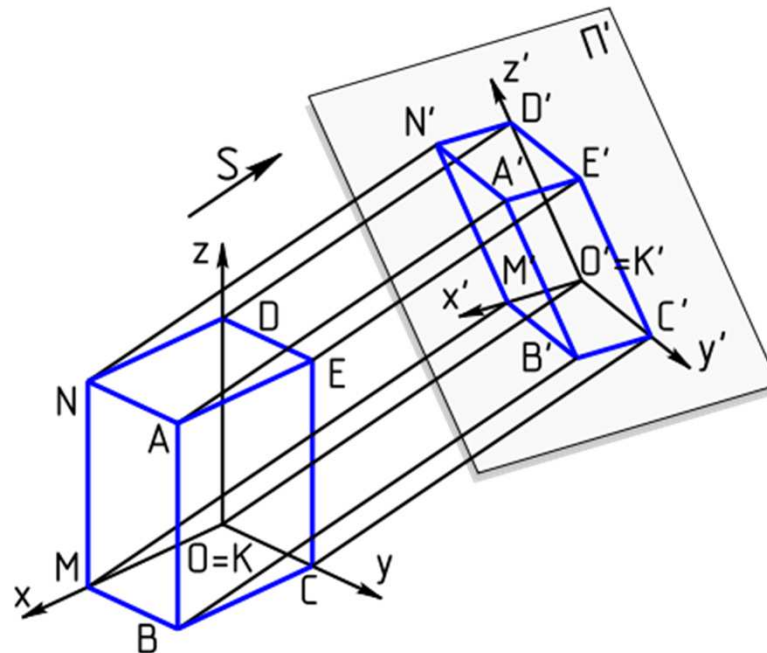
OpenGL

- **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

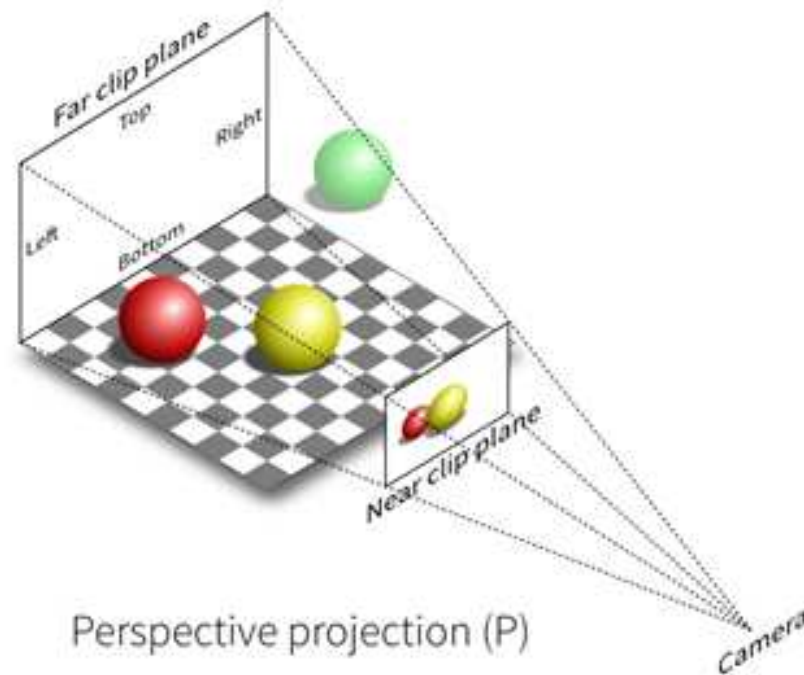
3D projection

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



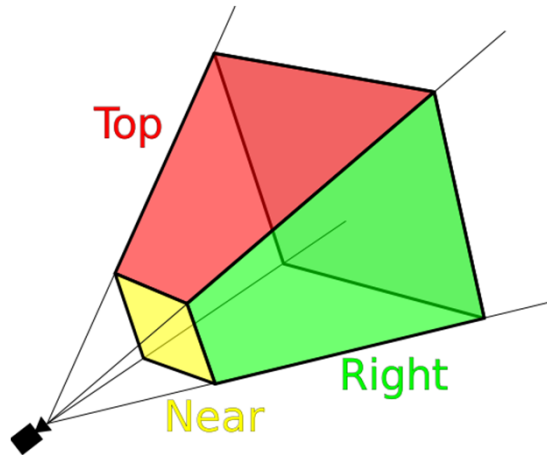
3D projection

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



3D projection

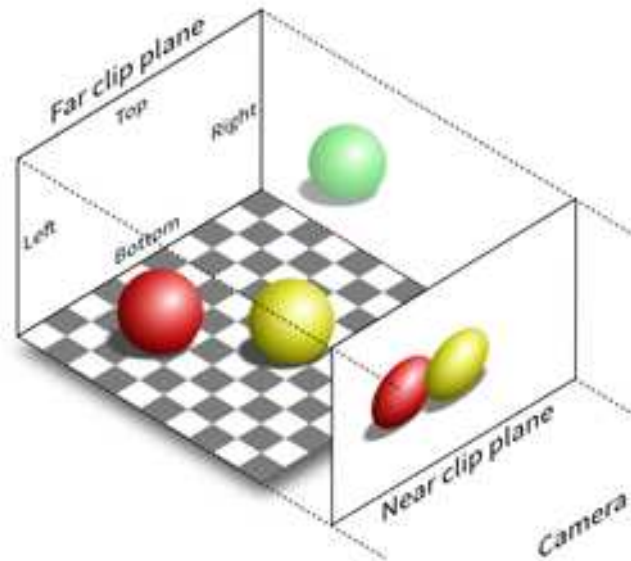
- **View frustum of perspective projection**
 - The region of space in the modeled world that may appear on the screen



- **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();
```

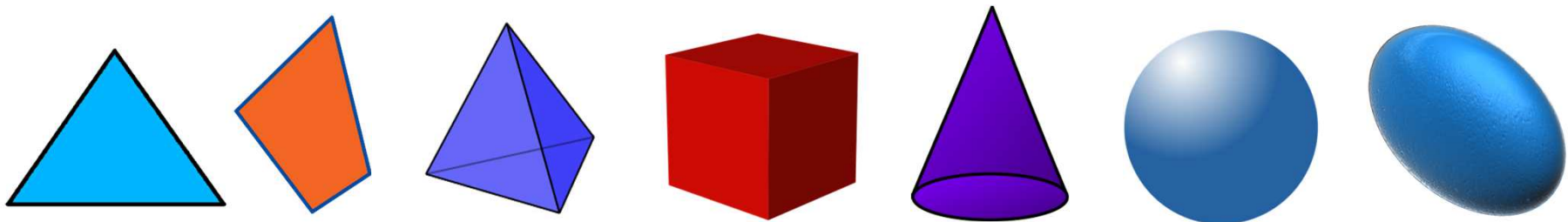
```
gluPerspective(fovy, aspect, zNear, zFar);
```

```
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.

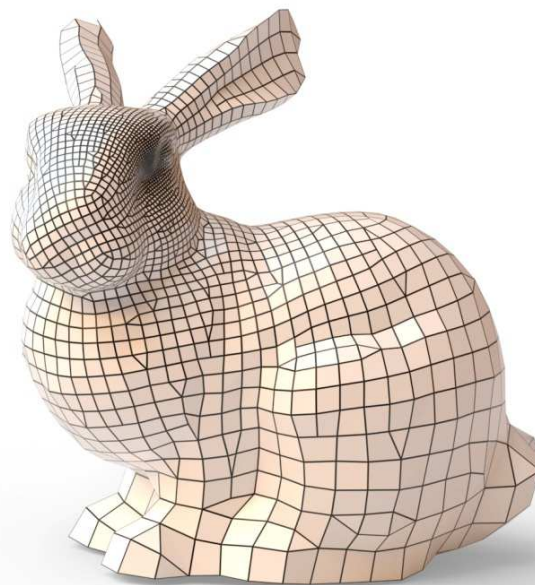
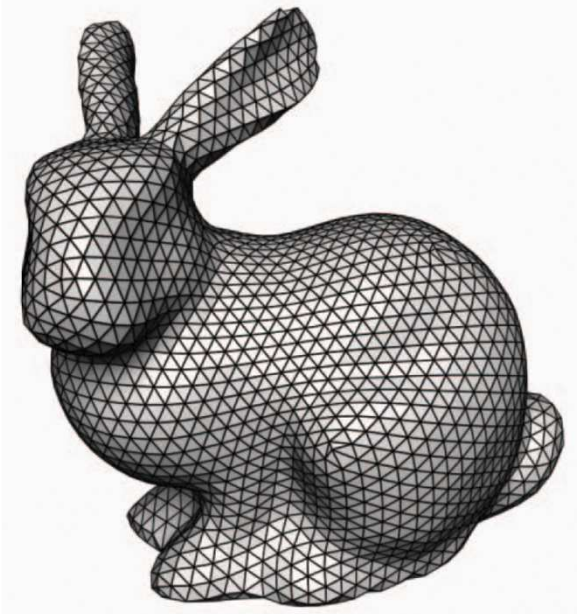


Geometry representation

- **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);
```

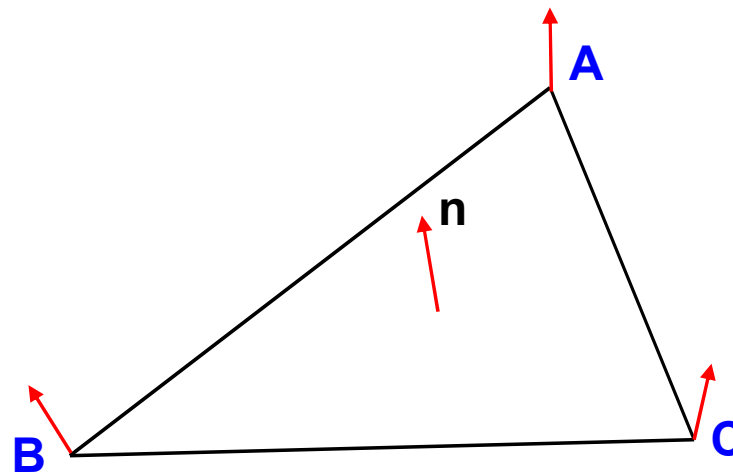
```
...
```

```
glVertex2f(xn, yn);
```

```
glEnd();
```

A 3D triangle

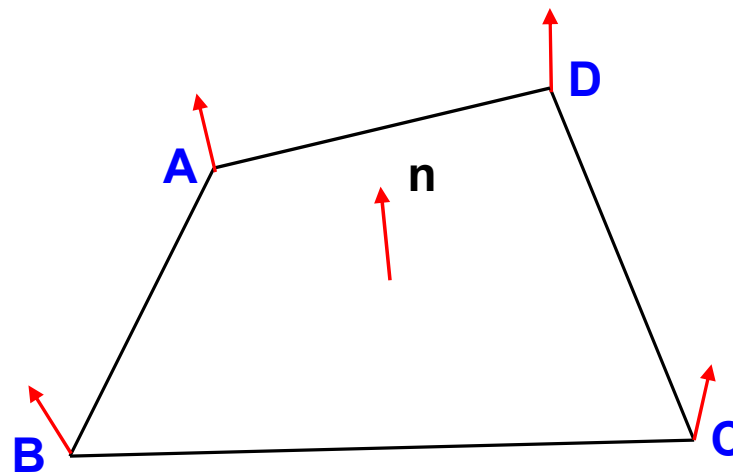
- **What constitute of a 3D triangle?**
 - Three vertices, three edges, one triangular face
 - One face normal, three vertex normals
 - Three vertex colors



$$\mathbf{n} = \mathbf{AB} \times \mathbf{AC}$$

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



$$n = AC \times BD$$

Specify 3D primitives with OpenGL

- Specify 3D triangles

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

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

```
Triangle3D 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;
};
```

```
Triangle3D 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();
```

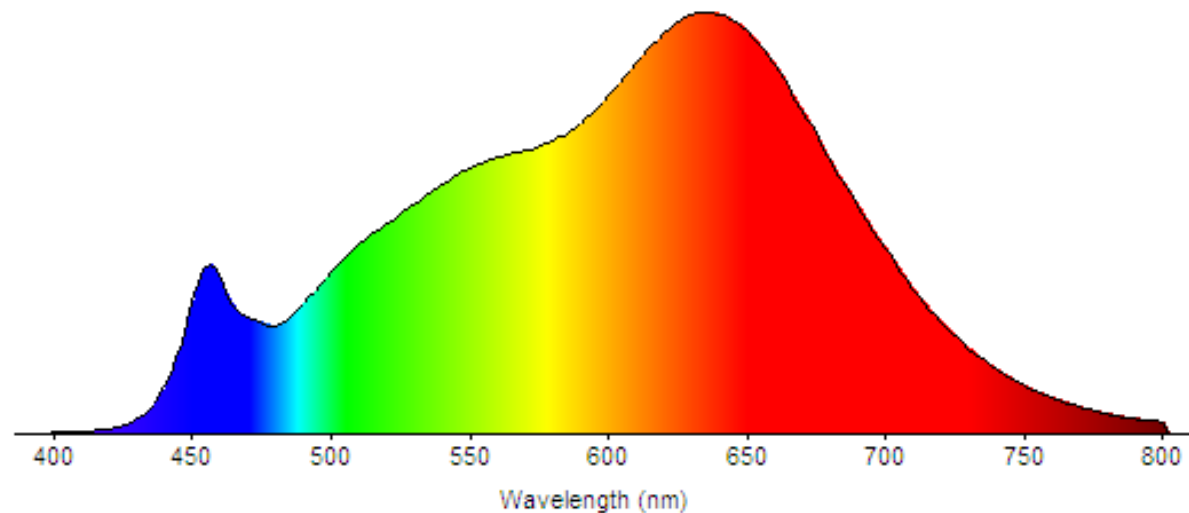
Vertex properties

- **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) (n_x,n_y,n_z)
 - Texture coordinate (for texture mapping)
 - Other user specified quantities

Step 3: Specify color

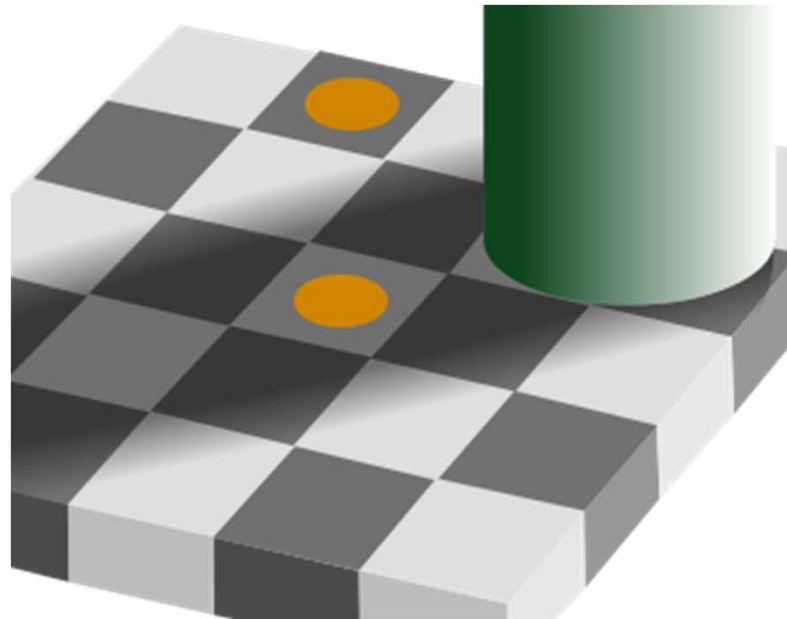
Color representation

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



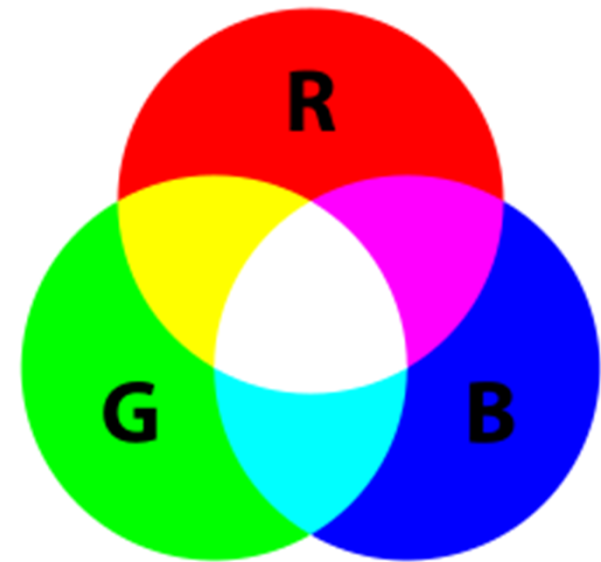
Color representation

- **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();
```

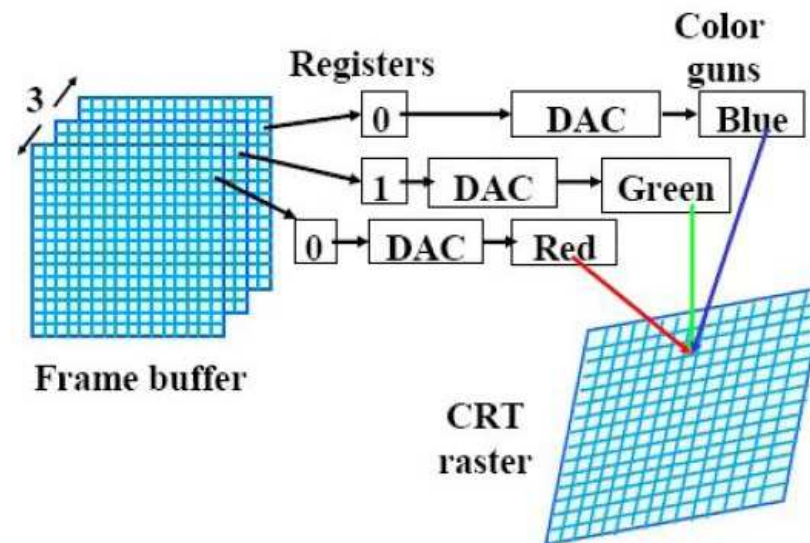
Step 4: Automatic Rasterization

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

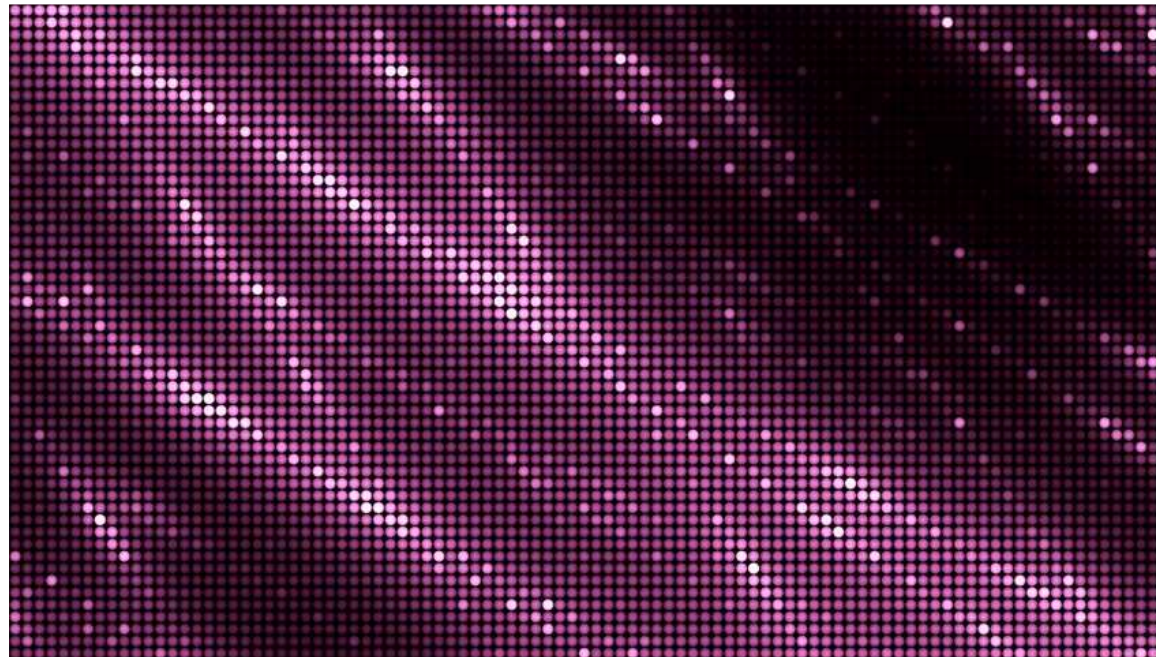
- **A framebuffer storing**
 - 2D array (discretized) containing color, depth, etc.
 - Can have multiple copies
 - Double buffer is commonly adopted



Simple Color buffer

Digital screen

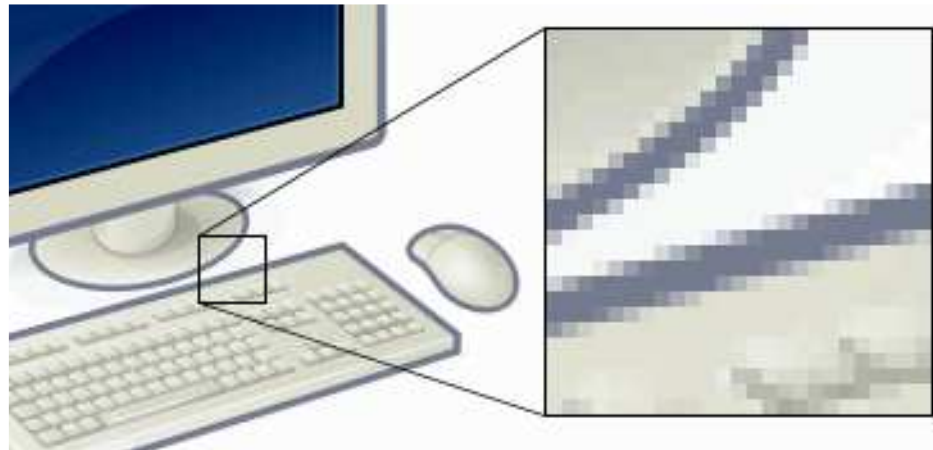
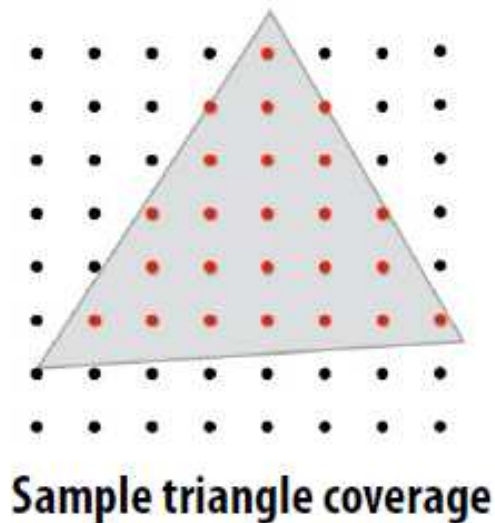
- **A digitized display device**
 - Pixels are physically displayed
 - In terms of 2D arrays, corresponding to an image



Digital screen

- **Rasterization**

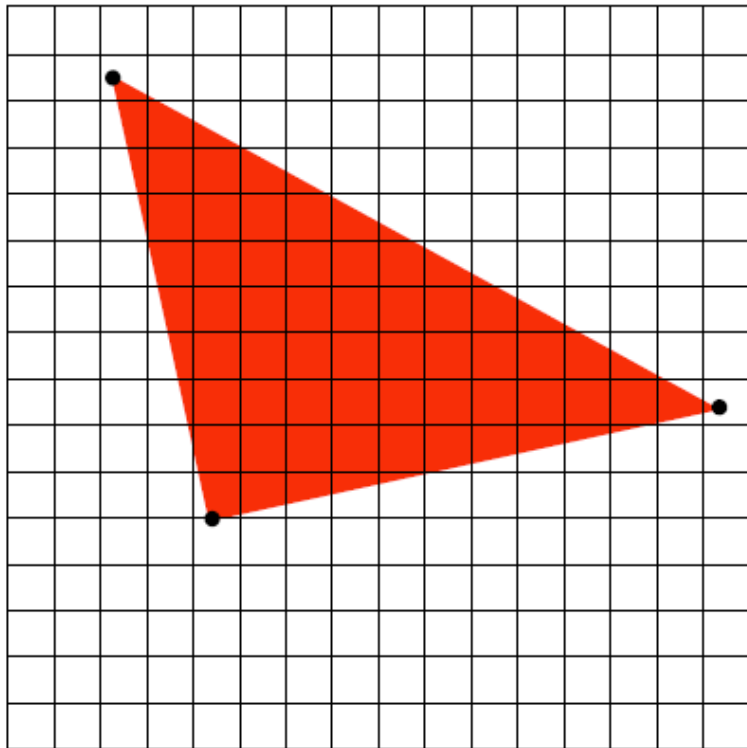
- The process of converting continuous signals to pixels
- Filling pixel colors (and other values) in framebuffer



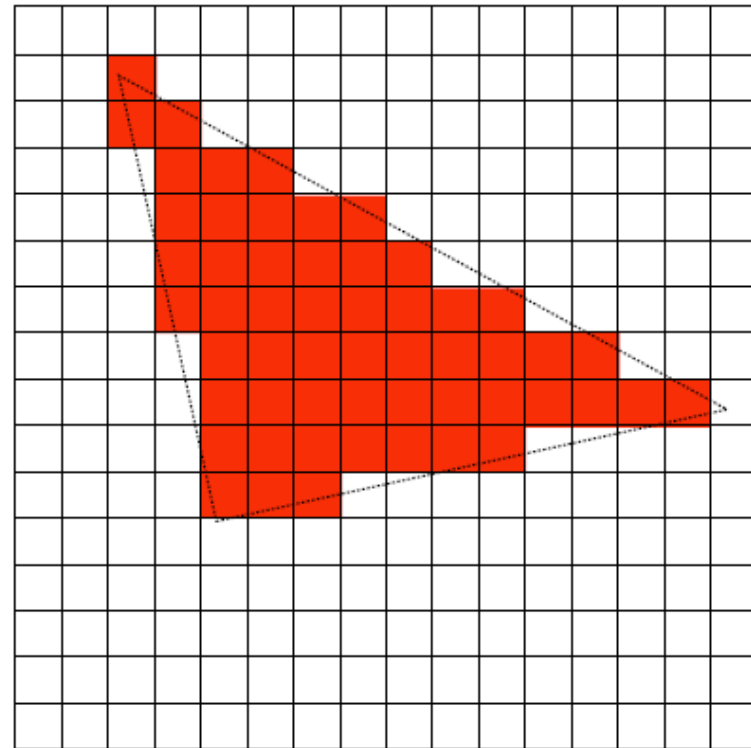
Rasterizing a triangle

- What pixels do the triangle overlap?

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

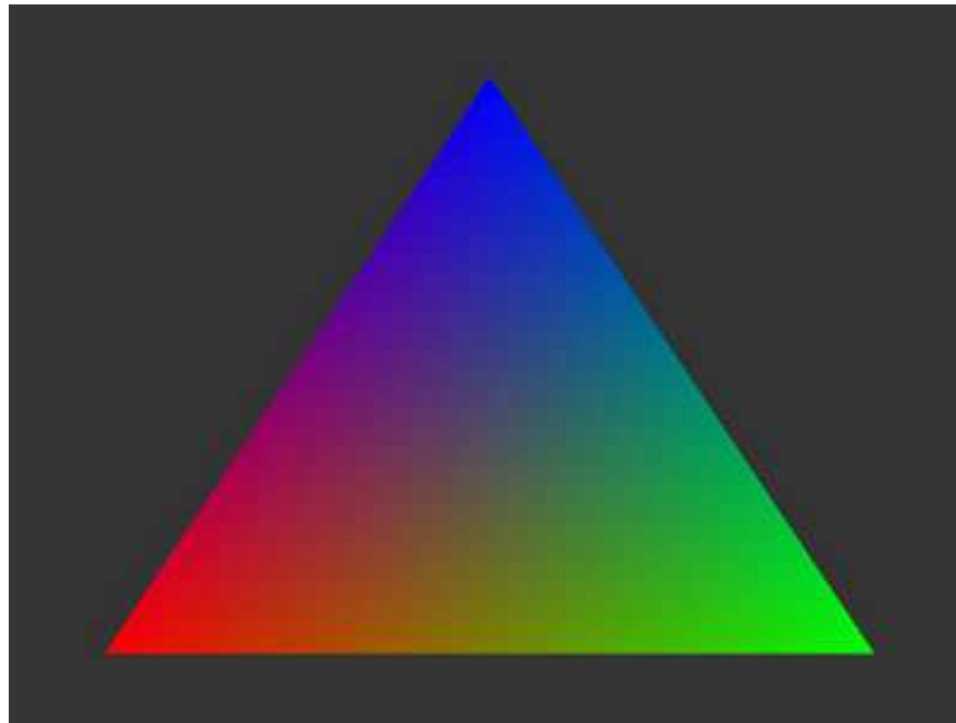


Output:
set of pixels "covered" by the triangle



Filling pixel colors

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



Filling pixel colors

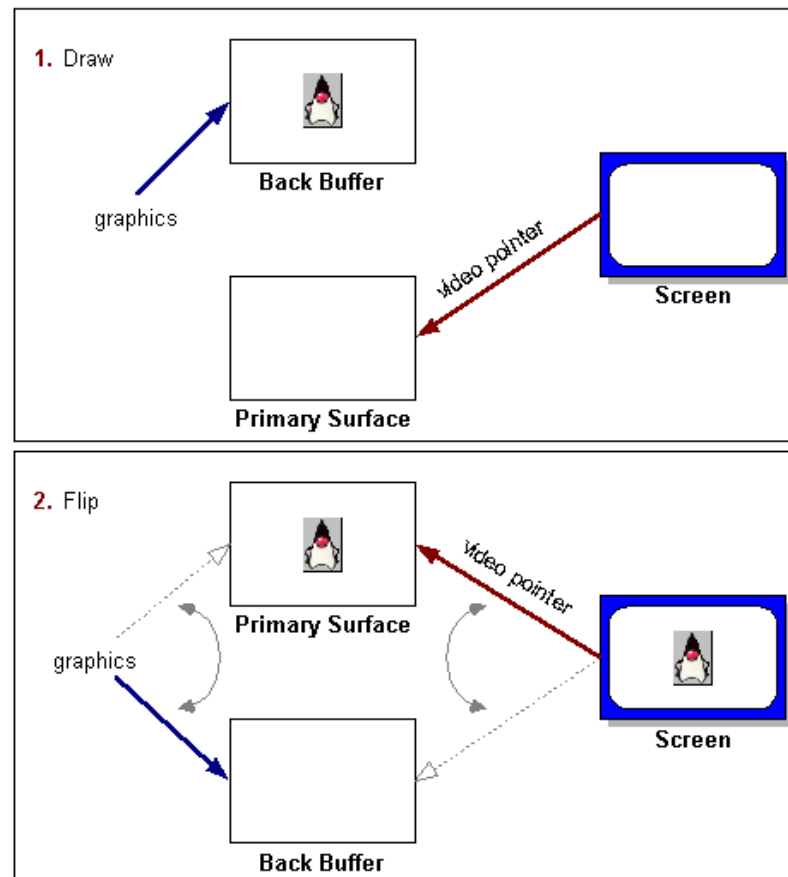
- **Dynamic display**

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



Double buffering

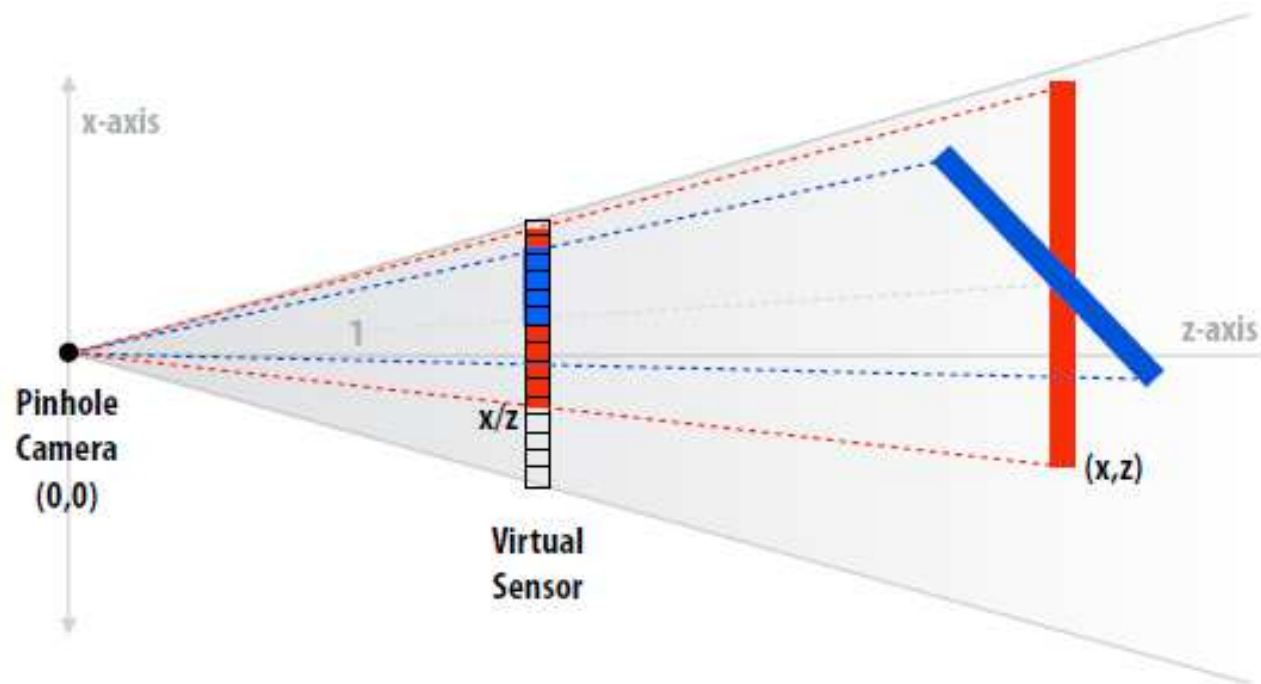
- The way to eliminate flickering



Step 4: Depth-Test

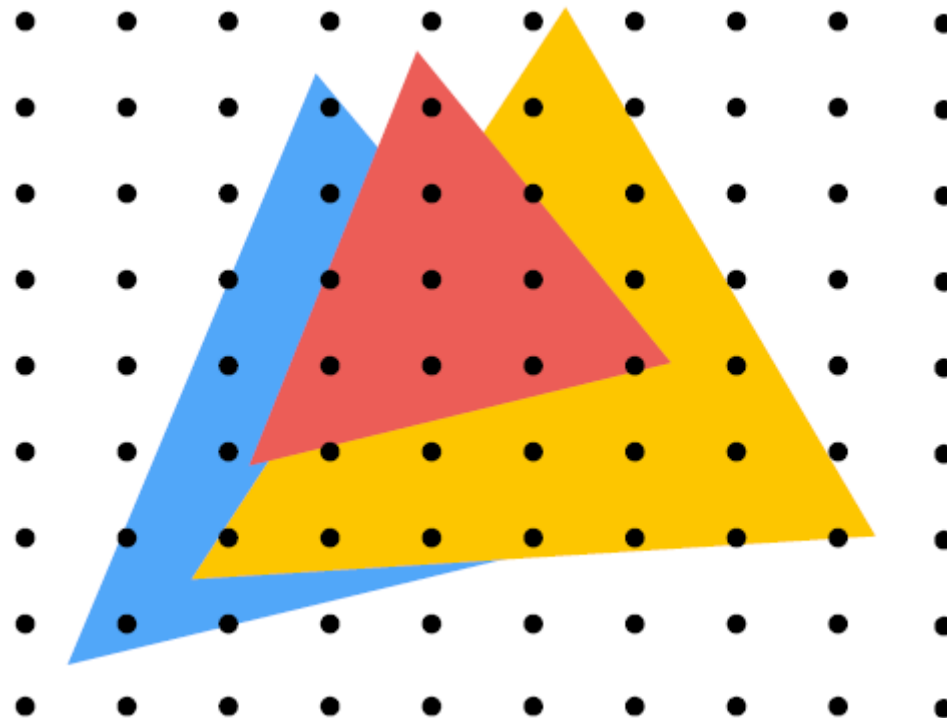
Concept of depth

- 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)

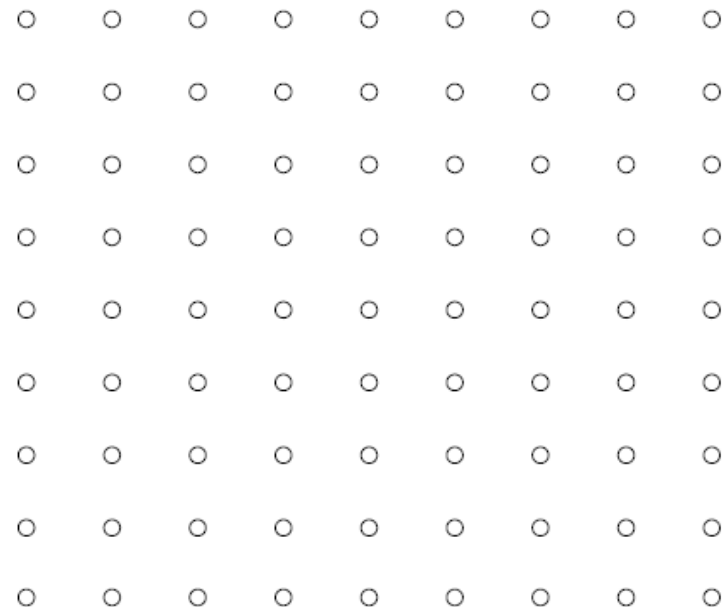
- **For each coverage sample point**
 - Depth-buffer stores depth of closest triangle at this sample point that has been processed by the renderer

Initial state of depth buffer →
before rendering any triangles
(all samples store farthest distance)

Grayscale value of sample point
used to indicate distance

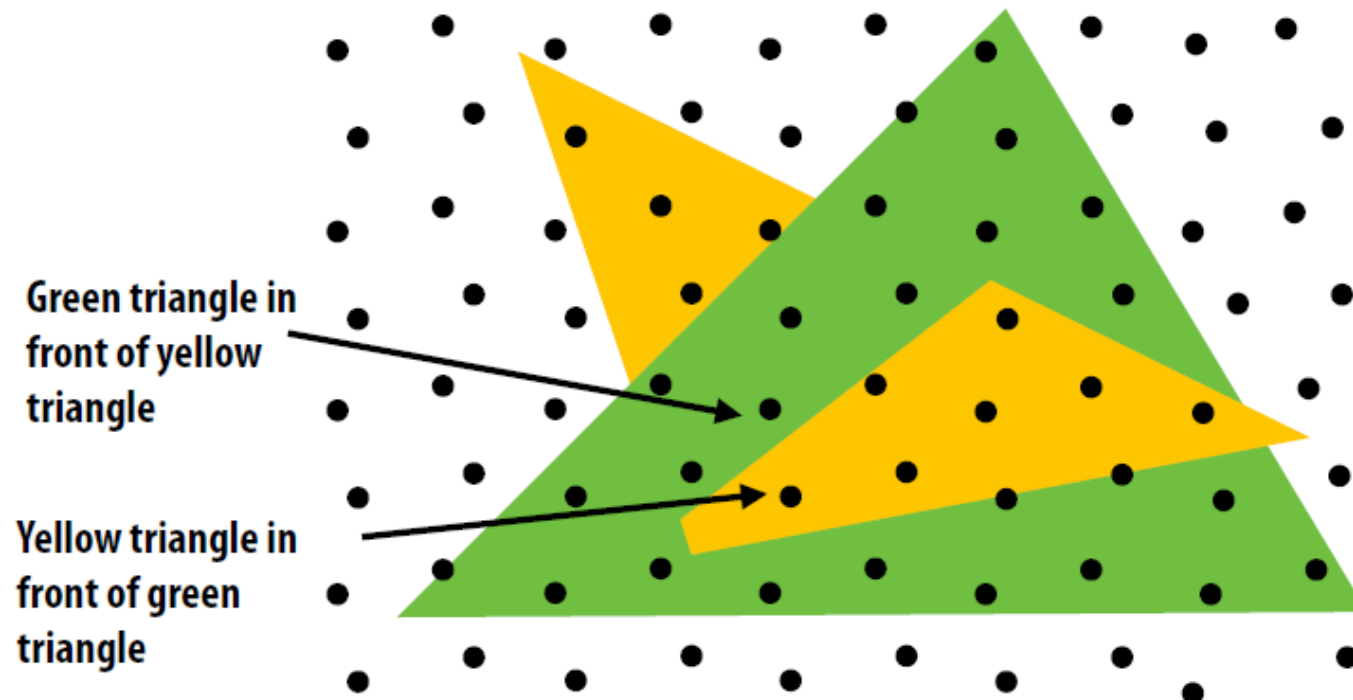
Black = small distance

White = large distance



Depth buffer (Z-buffer)

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



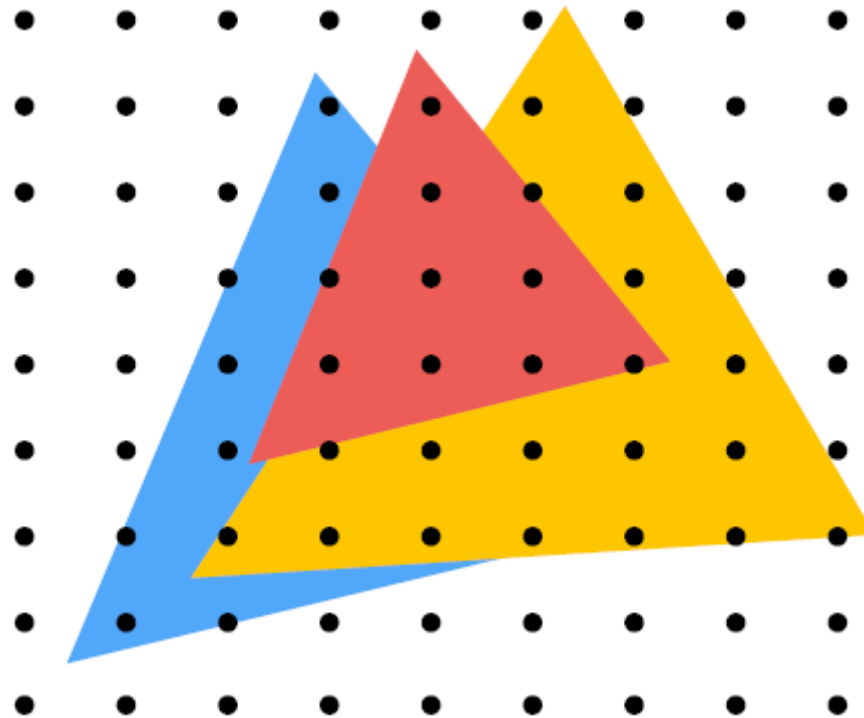
Depth buffer (Z-buffer)

- An example of depth buffer



Depth-test in pixel-fill

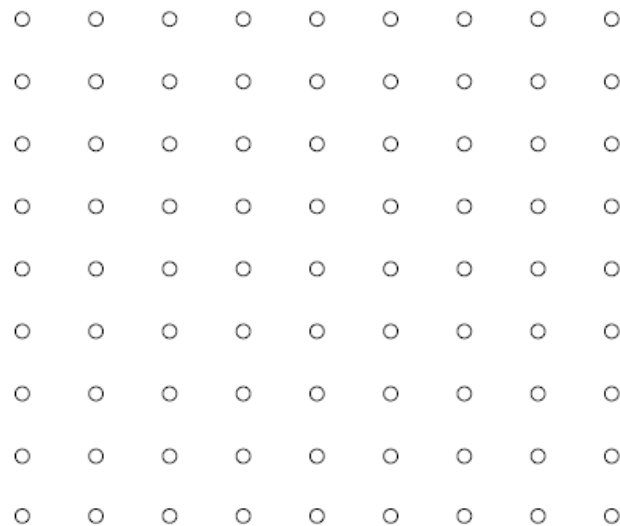
- Example: rendering three opaque triangles



Depth-test in pixel-fill

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

Processing yellow triangle:
depth = 0.5



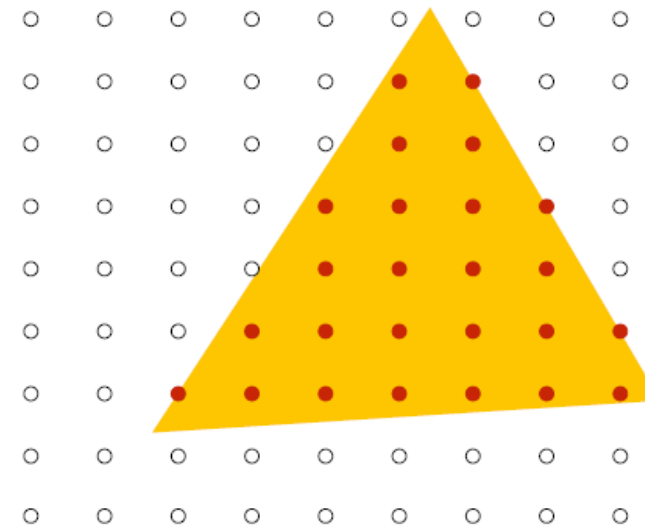
Color buffer contents

Grayscale value of sample point
used to indicate distance

White = large distance

Black = small distance

Red = sample passed depth test

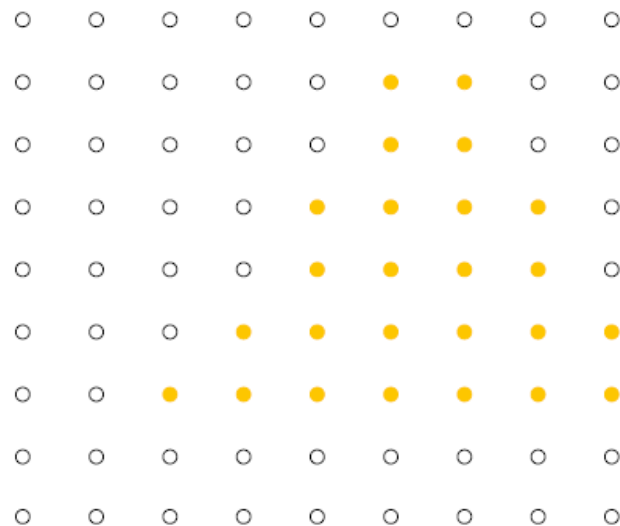


Depth buffer contents

Depth-test in pixel-fill

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

After processing yellow triangle:



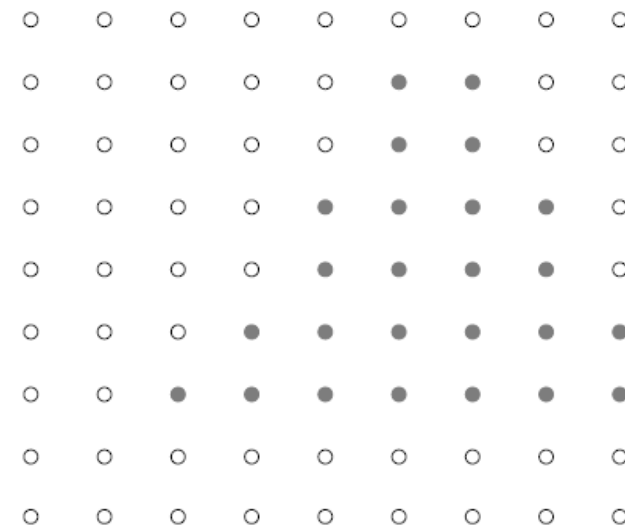
Color buffer contents

Grayscale value of sample point
used to indicate distance

White = large distance

Black = small distance

Red = sample passed depth test

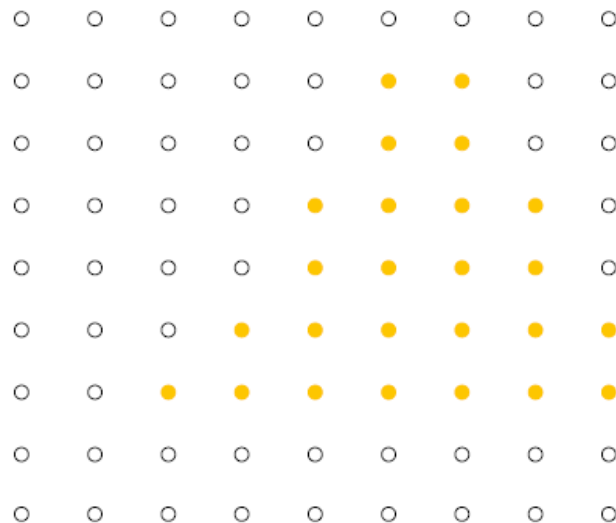


Depth buffer contents

Depth-test in pixel-fill

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

Processing blue triangle:
depth = 0.75



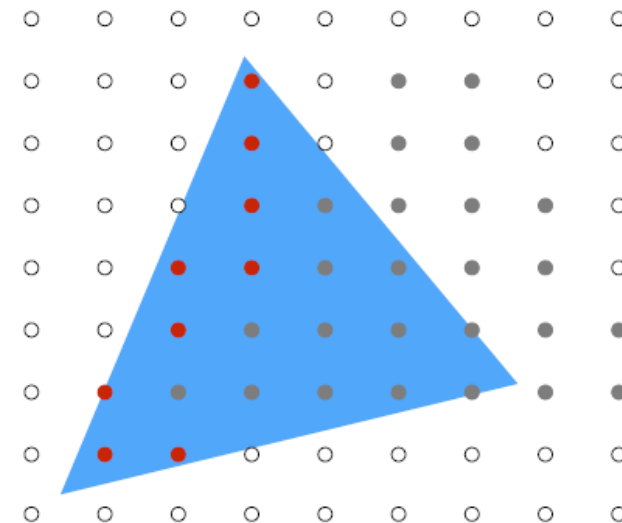
Color buffer contents

Grayscale value of sample point
used to indicate distance

White = large distance

Black = small distance

Red = sample passed depth test

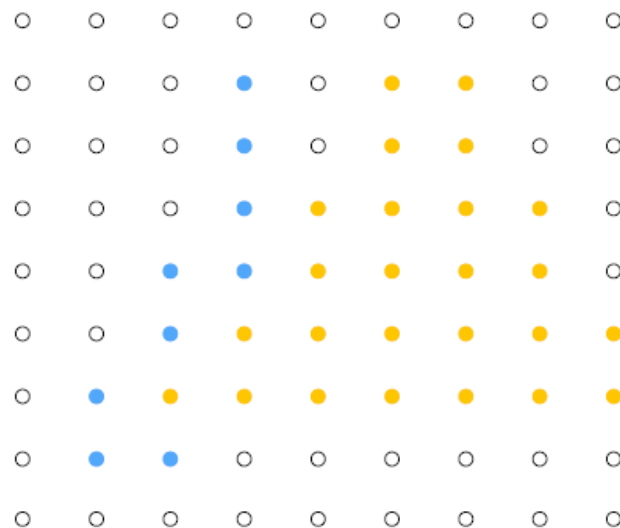


Depth buffer contents

Depth-test in pixel-fill

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

After processing blue triangle:



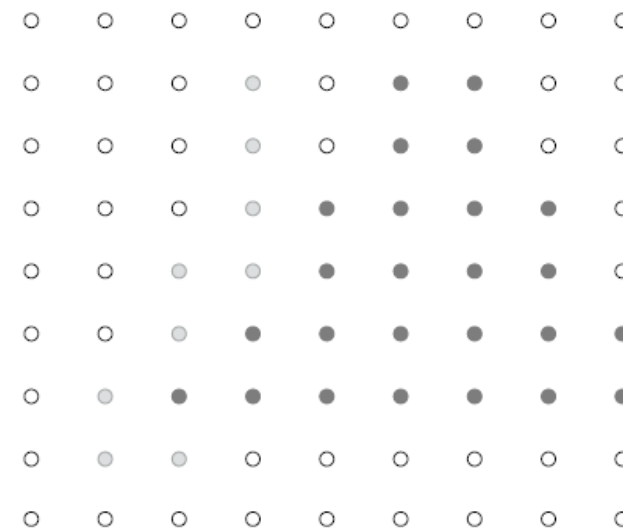
Color buffer contents

Grayscale value of sample point
used to indicate distance

White = large distance

Black = small distance

Red = sample passed depth test

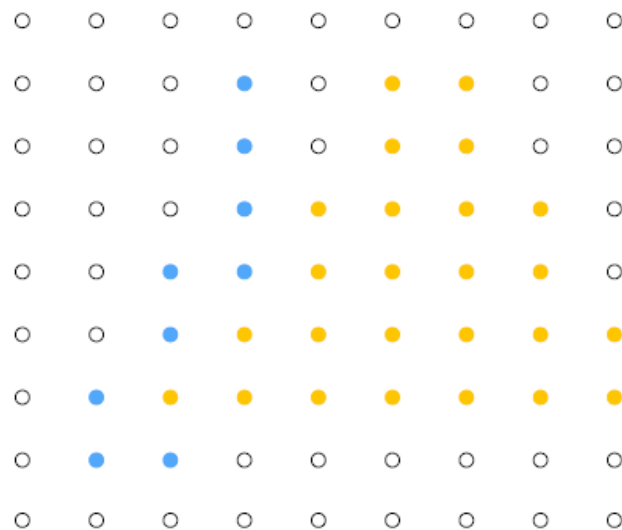


Depth buffer contents

Depth-test in pixel-fill

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

Processing red triangle:
depth = 0.25



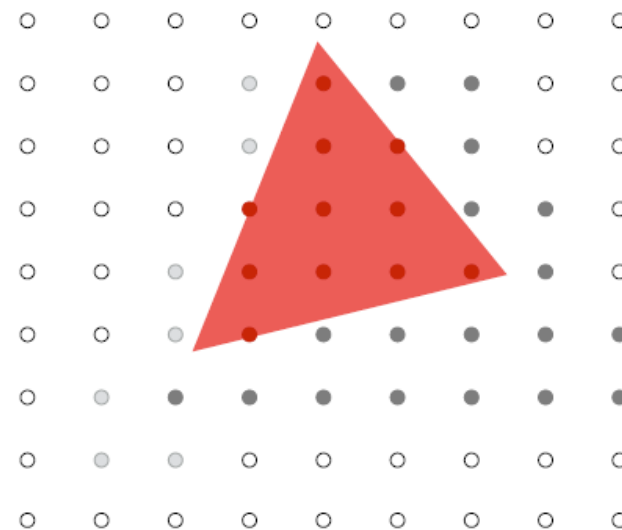
Color buffer contents

Grayscale value of sample point
used to indicate distance

White = large distance

Black = small distance

Red = sample passed depth test

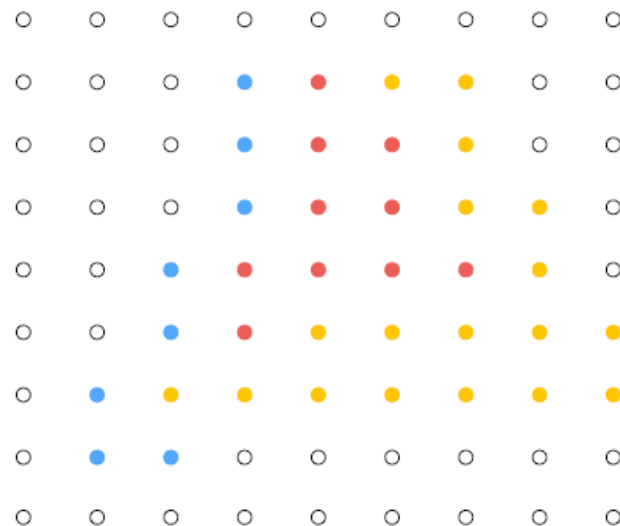


Depth buffer contents

Depth-test in pixel-fill

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

After processing red triangle:



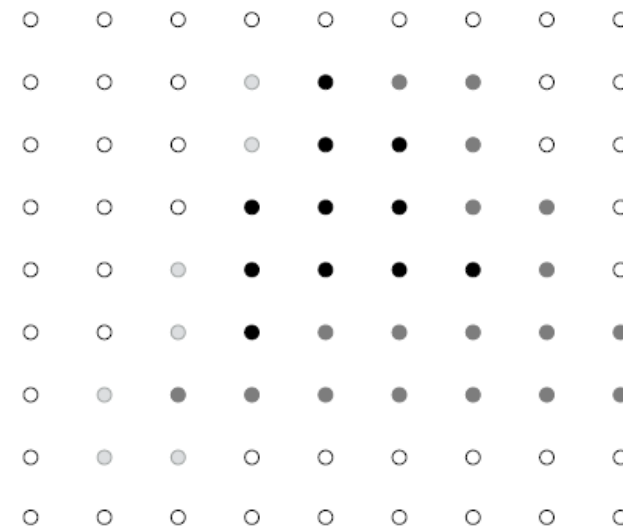
Color buffer contents

Grayscale value of sample point
used to indicate distance

White = large distance

Black = small distance

Red = sample passed depth test



Depth buffer contents

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);

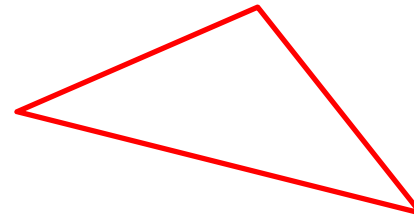
    //add your OpenGL rendering calls here

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

Wired v.s. filled polygons

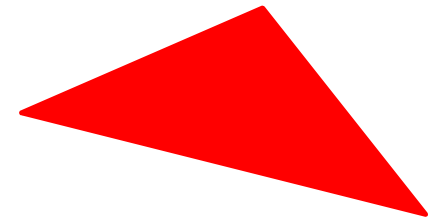
- **Wired triangle**

- 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

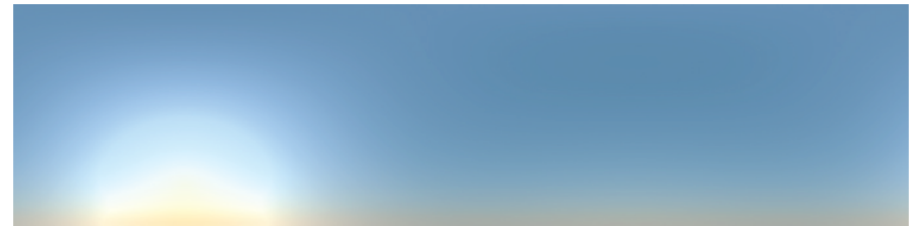
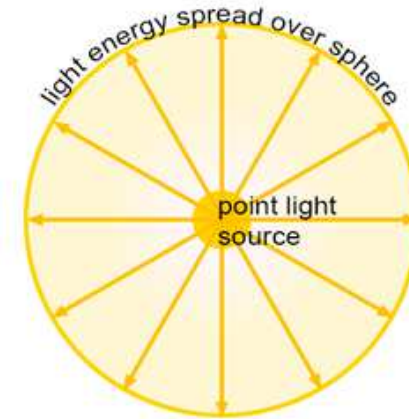
Shading

- **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

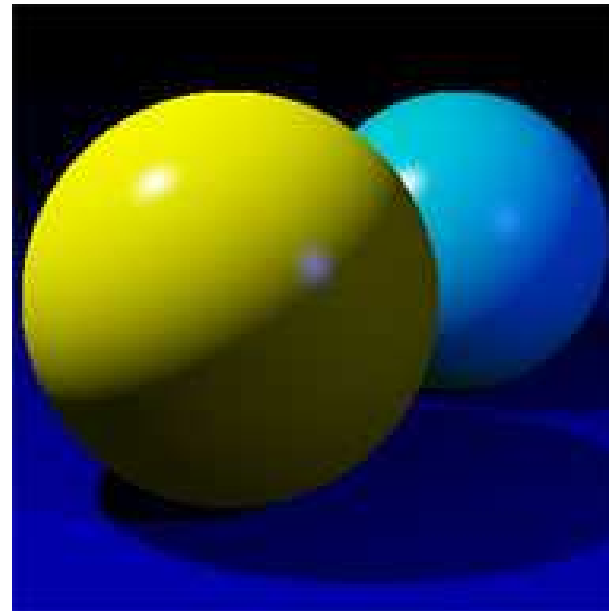
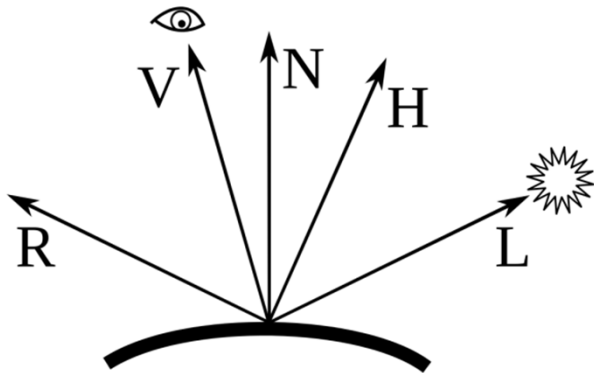
- **The sources to illuminate light**
 - Point/parallel/spot light sources
 - Area light sources
 - Environmental light sources



Environment light map

Lighting model

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

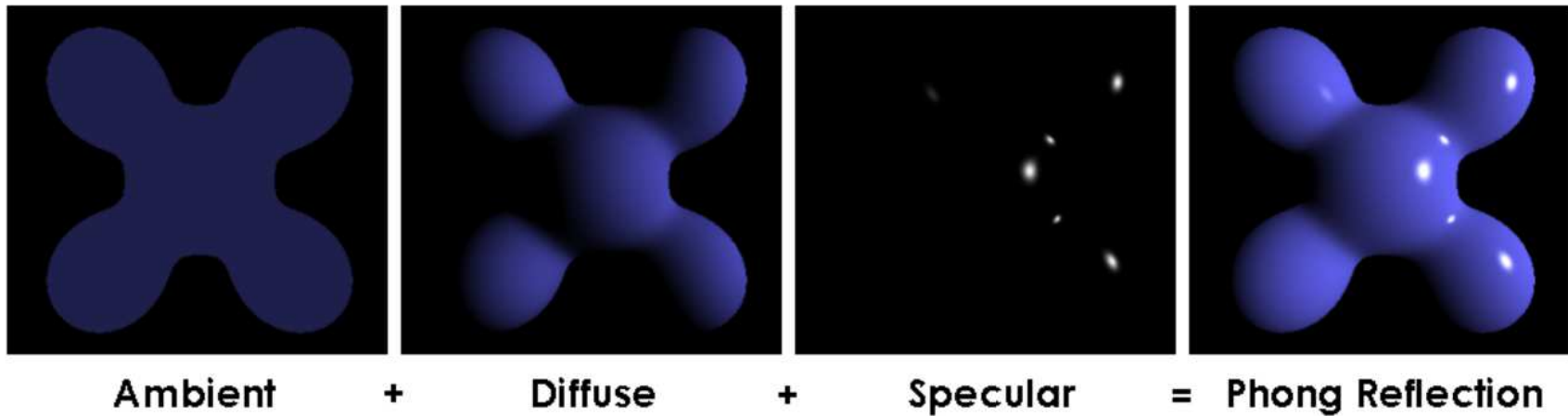


Lighting model

- **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



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

$$I_p = k_a i_a + \sum_{m \in \text{lights}} (k_d (\hat{L}_m \cdot \hat{N}) i_{m,d} + k_s (\hat{R}_m \cdot \hat{V})^\alpha i_{m,s})$$

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);
```

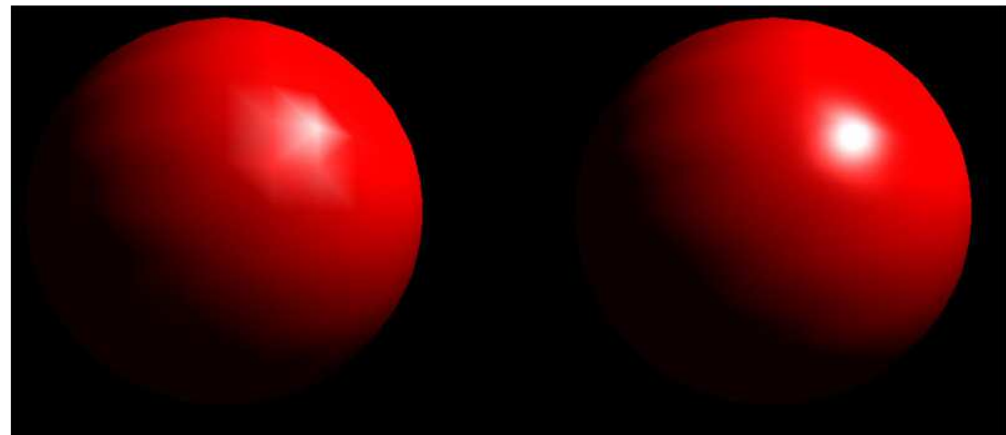
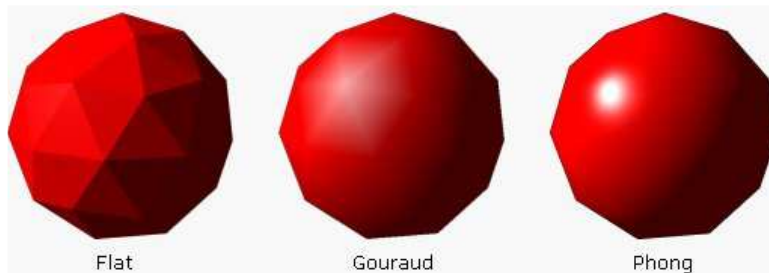
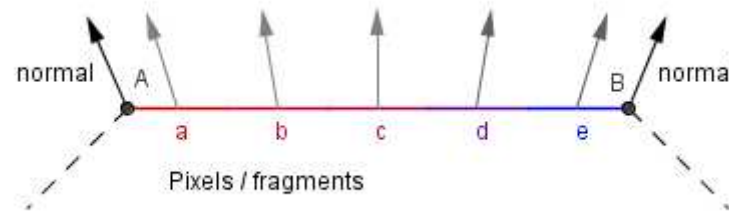
```
GLfloat specular[] = { 1.0f, 1.0f, 1.0f };  
glMaterialfv(GL_FRONT, GL_SPECULAR, specular);
```

- **Enable smooth shading**

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

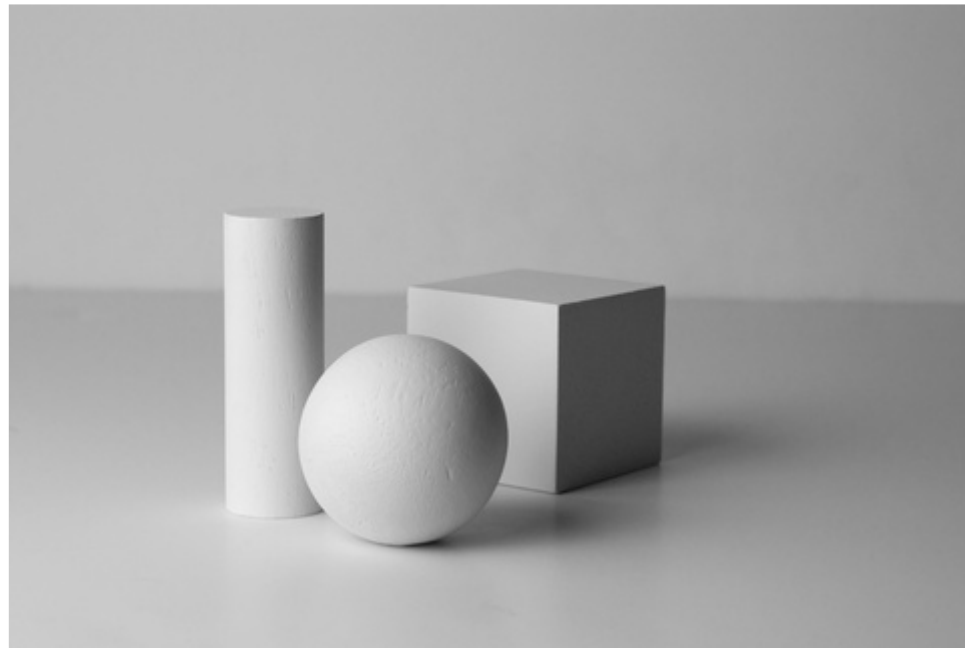
Shading model

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



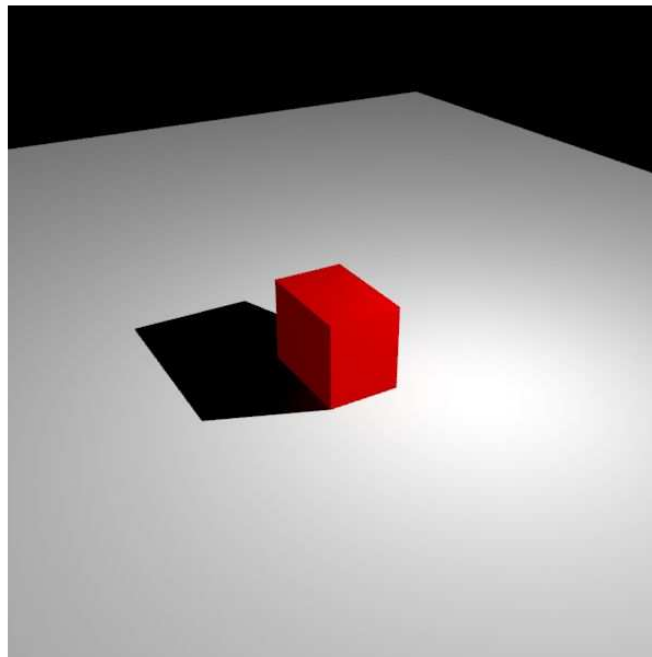
Shadow

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



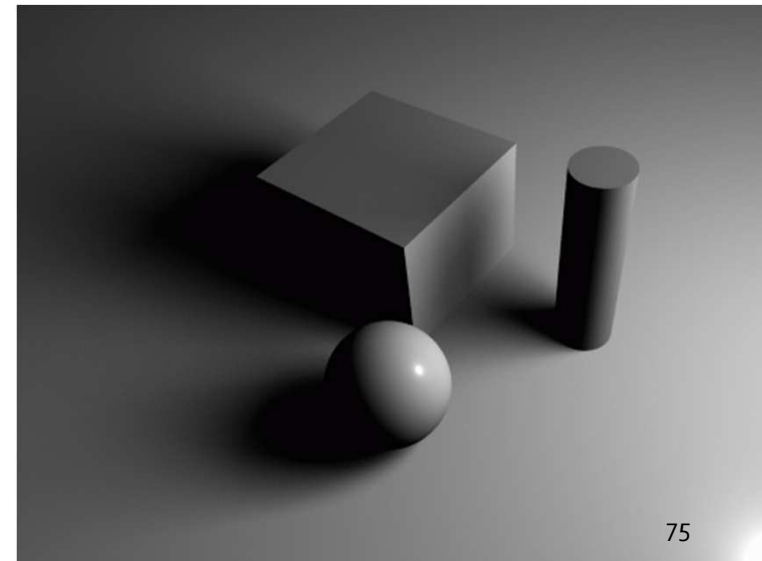
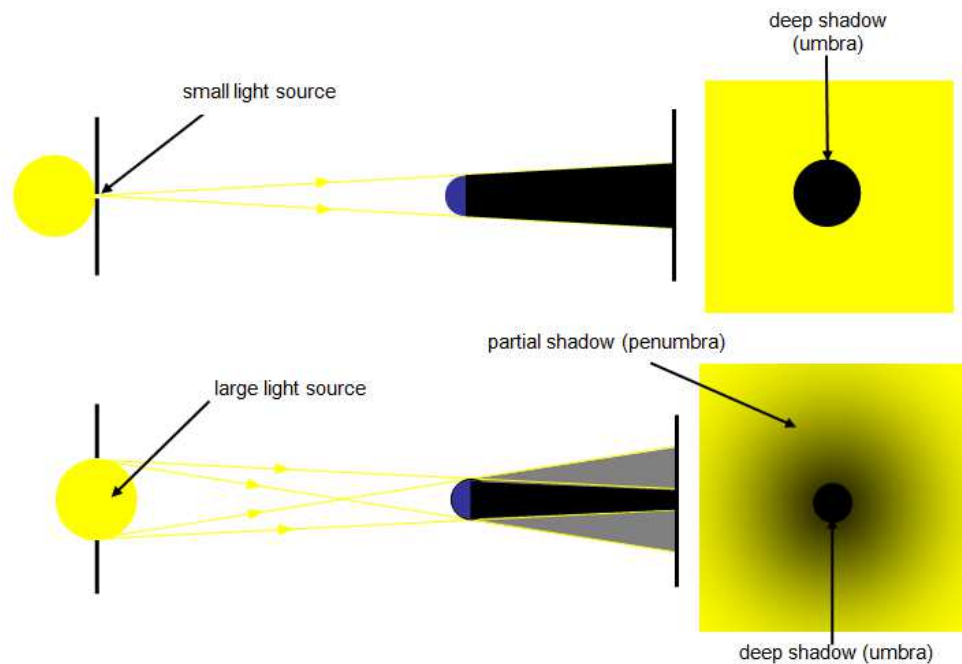
Shadow

- **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

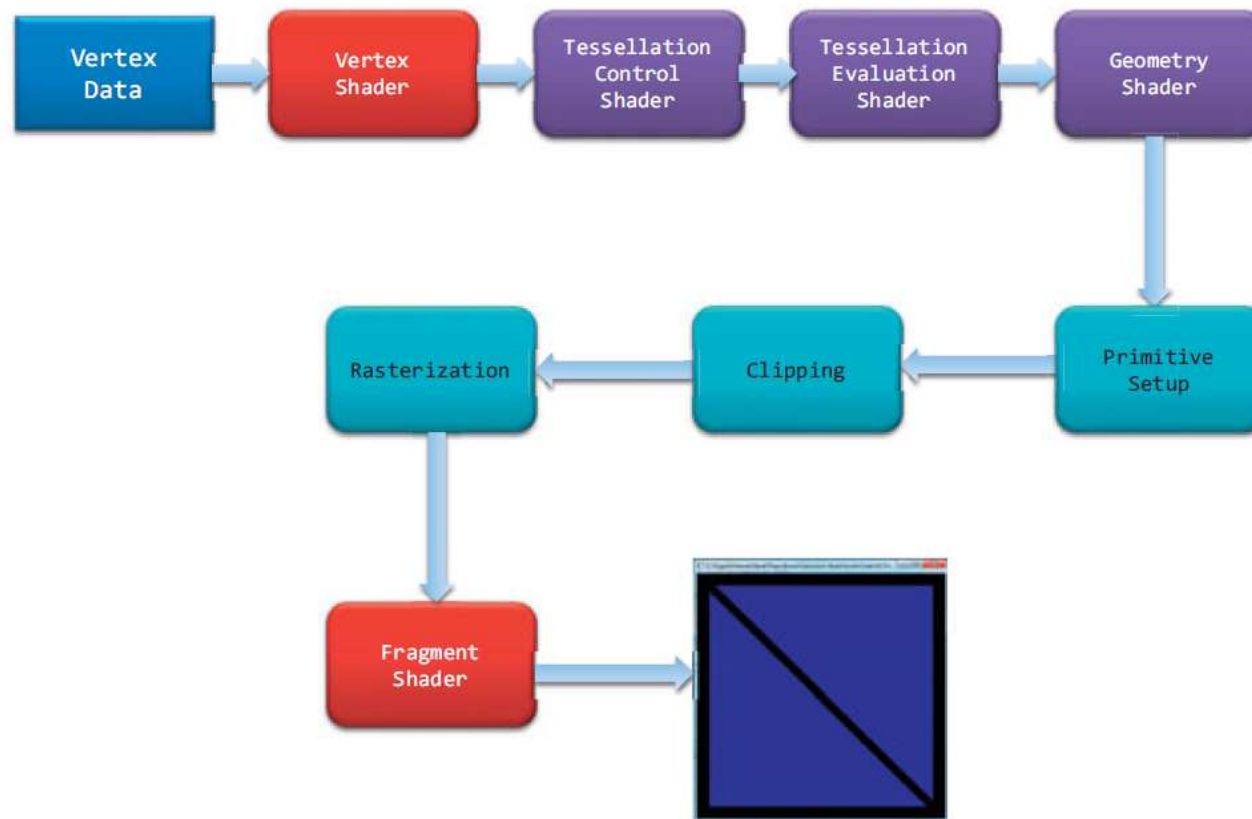
- **Texture map**
 - A texture map is an image applied (mapped) to the surface of a shape (mesh)
- **Texture mapping**
 - A mapping from image space to projection space



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;

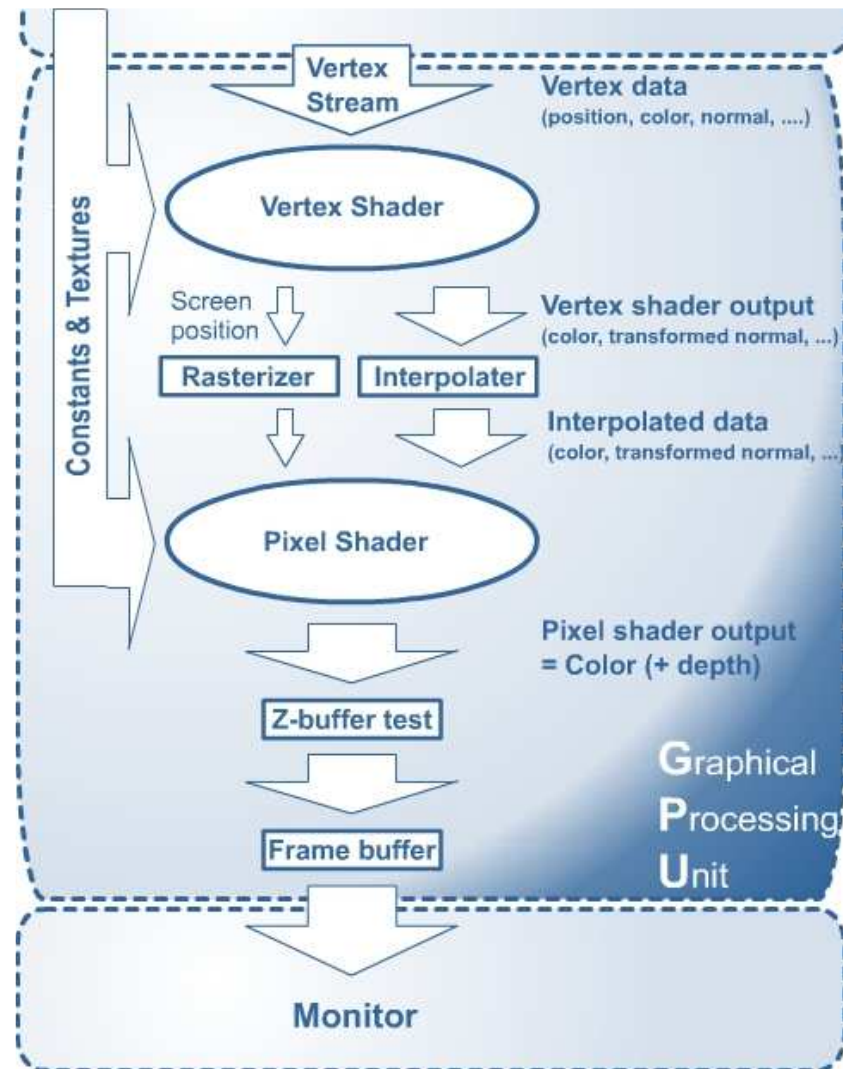
        /* get the shader info log */
        glGetShaderiv(shader, GL_INFO_LOG_LENGTH, &length);
        log = malloc(length);
        glGetShaderInfoLog(shader, length, &result, log);

        /* 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**