GPU Graphics Pipeline

Introduction to Computer Graphics

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Recap.

Object Space
(Local Space)

World Space — After applying world transform (translation, scaling, rotation)

Camera Space
(View, Eye Space) — After applying camera transform

Clip Space — After applying projection

Normalized Device Coordinate (NDC) — After applying perspective division
XYZ in the range [-1, 1]
The Z component is kept for depth comparison
(closest surface to the camera)

Screen Space

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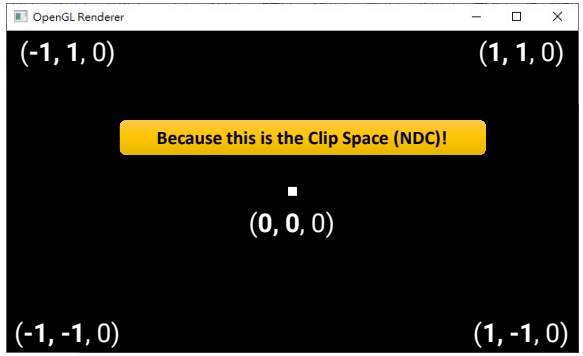
Recap. (cont.)



What about the *z* coordinate? You can find the point will only be visible if its *z* value is within ***[-1, 1]***

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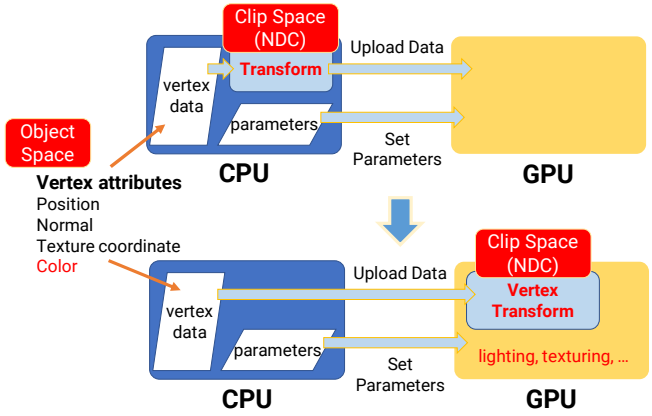
Recap. (cont.)



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GPU Graphics Pipeline

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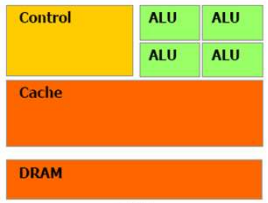
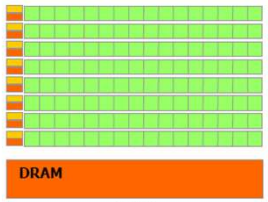
CPU v.s. GPU





Good at
- Serial processing
- Control (branching)
- Larger cache

Good at
- Parallel processing
- SIMD
- Higher throughput

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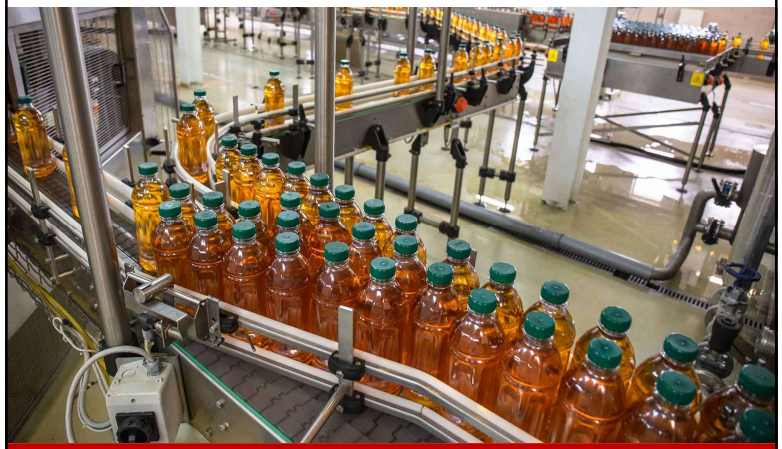
Pipeline



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GPU Graphics Pipeline Overview

- Responsible for the fixed routines of bringing triangles to pixels
- Can be roughly categorized into 4 stages

- Physical simulation
- Animation
- Collision detection
- Global acceleration
- etc.

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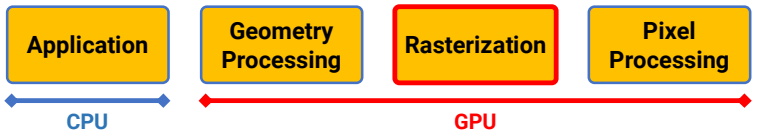
GPU Graphics Pipeline Overview (cont.)

- Responsible for the fixed routines of bringing triangles to pixels
- Can be roughly categorized into 4 stages

- Vertex transform and projection
- Vertex lighting and shading (rarely used now)
- Geometry assembly
- Clipping
- Culling

GPU Graphics Pipeline Overview (cont.)

- Responsible for the fixed routines of bringing triangles to pixels
- Can be roughly categorized into 4 stages

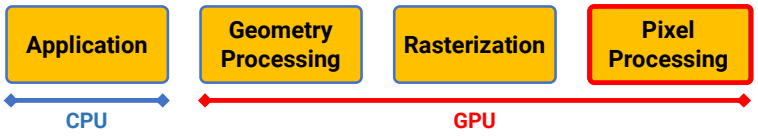


- Triangle setup
- Fragments (pixels) generation
  - Attribute interpolation

from continuous to discrete

GPU Graphics Pipeline Overview (cont.)

- Responsible for the fixed routines of bringing triangles to pixels
- Can be roughly categorized into 4 stages



- Pixel shading / Texturing
- Depth testing
- Alpha blending

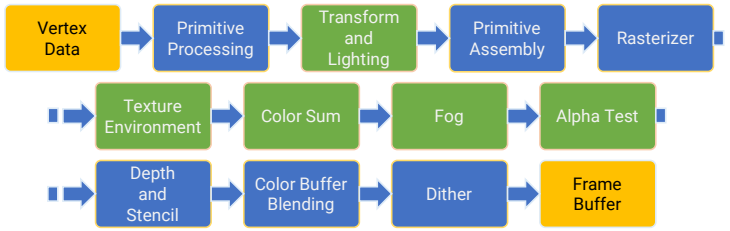
GPU Graphics Pipeline Overview (cont.)

- In the slides, we will first introduce the GPU rendering pipeline revealed in ***OpenGL 1.x***
- After that, we will show why (and how) some stages become **programmable** in ***OpenGL 2.0***

OpenGL Graphics Pipeline 1.x

OpenGL (1.x) Fixed Function Pipeline

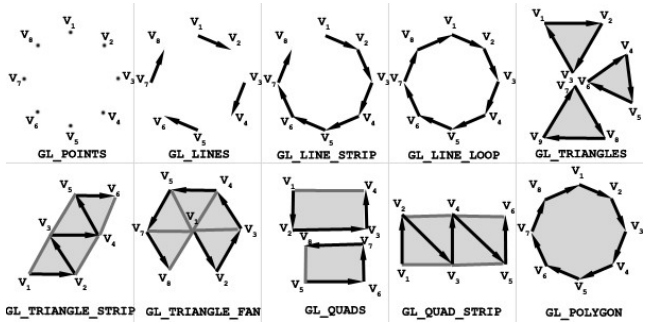
- Used when OpenGL was first introduced
- All the functions performed by OpenGL are **fixed** and **could not** be modified except through the manipulation of the **rendering states**
- The stages shown in green have been replaced by **shaders**



OpenGL (1.x) Fixed Function Pipeline (cont.)

- **Vertex Data**
  - Send the vertex data to the GPU
  - **Vertex attributes** include vertex position, vertex normal, texture coordinate, vertex color, fog coordinate, etc.
  - The vertex data processed by the GPU is referred to as the **vertex stream**
- **Primitive Processing**
  - Vertex stream is processed **per primitive**
  - OpenGL supports several types of primitives, including points, lines, triangles, ~~quads, and polygons~~ (deprecated after OpenGL 3.1)

OpenGL (1.x) Fixed Function Pipeline (cont.)



primitive types in OpenGL 1.1

OpenGL (1.x) Fixed Function Pipeline (cont.)

```
glBegin(GL_POINTS); //starts drawing of points
  glVertex3f(1.0f,1.0f,0.0f);//upper-right corner
  glVertex3f(-1.0f,-1.0f,0.0f);//lower-left corner
glEnd();//end drawing of points
```

```
glBegin(GL_TRIANGLES);//start drawing triangles
  glVertex3f(-1.0f,-0.25f,0.0f);//triangle one first vertex
  glVertex3f(-0.5f,-0.25f,0.0f);//triangle one second vertex
  glVertex3f(-0.75f,0.25f,0.0f);//triangle one third vertex
  //drawing a new triangle
  glVertex3f(0.5f,-0.25f,0.0f);//triangle two first vertex
  glVertex3f(1.0f,-0.25f,0.0f);//triangle two second vertex
  glVertex3f(0.75f,0.25f,0.0f);//triangle two third vertex
glEnd();//end drawing of triangles
```

```
glBegin(GL_POLYGON);//begin drawing of polygon
  glVertex3f(-0.5f,0.5f,0.0f);//first vertex
  glVertex3f(0.5f,0.5f,0.0f);//second vertex
  glVertex3f(1.0f,0.0f,0.0f);//third vertex
  glVertex3f(0.5f,-0.5f,0.0f);//fourth vertex
  glVertex3f(-0.5f,-0.5f,0.0f);//fifth vertex
  glVertex3f(-1.0f,0.0f,0.0f);//sixth vertex
glEnd();//end drawing of polygon
```

primitive drawing in OpenGL 1.1

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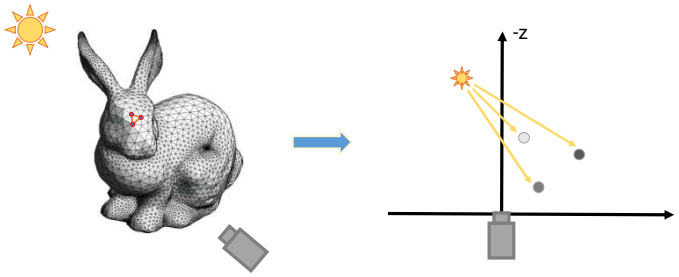
OpenGL (1.x) Fixed Function Pipeline (cont.)

- **Transform and Lighting**
  - Vertex is transformed to camera space by the current ***ModelView*** matrix
  - Lighting is computed at each vertex (Gouraud shading)



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OpenGL (1.x) Fixed Function Pipeline (cont.)

- **Transform and Lighting in OpenGL 1.x**

```
void display(void)
{
   glClear (GL_COLOR_BUFFER_BIT);
   glColor3f (1.0, 1.0, 1.0);
   glLoadIdentity ();             /* clear the matrix */
           /* viewing transformation  */
   gluLookAt (0.0, 0.0, 5.0, 0.0, 0.0, 0.0, 0.0, 1.0, 0.0);
   glScalef (1.0, 2.0, 1.0);      /* modeling transformation */
   glutWireCube (1.0);
   glFlush ();
}

void reshape (int w, int h)
{
   glViewport (0, 0, (GLsizei) w, (GLsizei) h);
   glMatrixMode (GL_PROJECTION);
   glLoadIdentity ();
   glFrustum (-1.0, 1.0, -1.0, 1.0, 1.5, 20.0);
   glMatrixMode (GL_MODELVIEW);
}
```


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OpenGL (1.x) Fixed Function Pipeline (cont.)

- **Transform and Lighting in OpenGL 1.x**

```
void init(void)
{
   GLfloat mat_specular[] = { 1.0, 1.0, 1.0, 1.0 };
   GLfloat mat_shininess[] = { 50.0 };
   GLfloat light_position[] = { 1.0, 1.0, 1.0, 0.0 };
   glClearColor (0.0, 0.0, 0.0, 0.0);
   glShadeModel (GL_SMOOTH);

   glMaterialfv(GL_FRONT, GL_SPECULAR, mat_specular);
   glMaterialfv(GL_FRONT, GL_SHININESS, mat_shininess);
   glLightfv(GL_LIGHT0, GL_POSITION, light_position);

   glEnable(GL_LIGHTING);
   glEnable(GL_LIGHT0);
   glEnable(GL_DEPTH_TEST);
}
```


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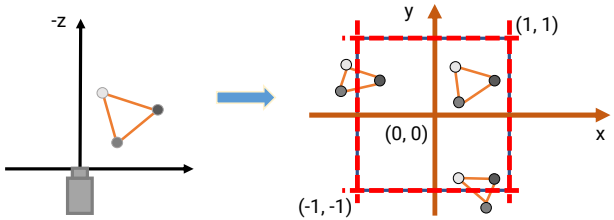
OpenGL (1.x) Fixed Function Pipeline (cont.)

- **Primitive Assembly**
  - Convert primitives from the basic primitive types (e.g., triangle strip) into triangles
  - Triangles are transformed to NDC and got **clipped** to fit within the viewport boundaries
  - Perform **back-face culling** if enabled



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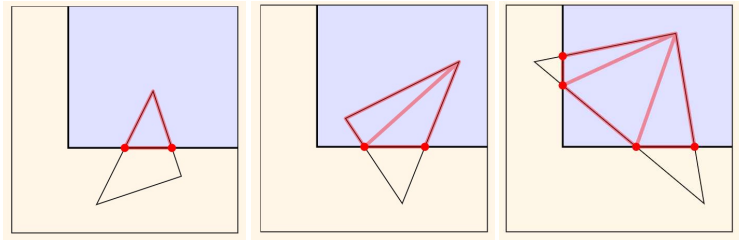
Clipping

- In OpenGL, clipping is performed by adding new vertices and triangulation
- Automatically performed in NDC



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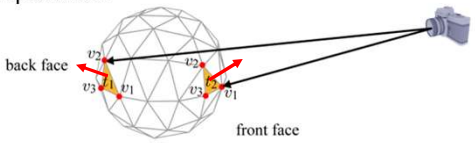
Back-face Culling

- If a triangle is facing away from the camera, it will never be seen
- We can cull these back-facing triangles for saving unnecessary computation

we can only see three faces from six!



How about this case?

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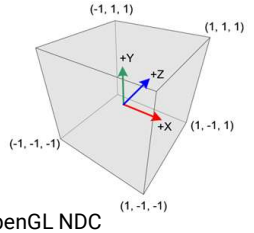
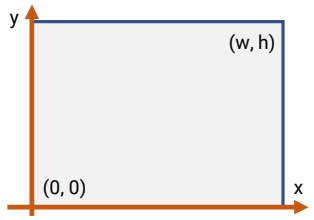
OpenGL (1.x) Fixed Function Pipeline (cont.)

- **Screen mapping (OpenGL will handle this!)**



OpenGL NDC



OpenGL Screen Space

$$x_s = w(x_{ndc} + 1)/2$$
$$y_s = h(y_{ndc} + 1)/2$$
$$z_s = (z_{ndc} + 1)/2$$
$$w_s = w_{ndc}$$

+ screen location

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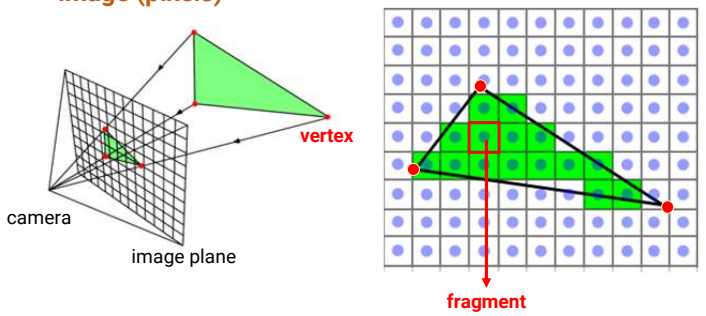
OpenGL (1.x) Fixed Function Pipeline (cont.)

- **Rasterizer**
  - Convert **triangles** (**continuous**) into **fragments** (**discrete**, which eventually become the individual **screen pixels**)
  - Vertex attributes are **interpolated** across the face, including
    - (Lighting) color — used for per-vertex lighting
    - Texture coordinate
    - Position ┐ used for per-fragment lighting (after OpenGL 2.0)
    - Normal ┘
    - Anything you want to interpolate

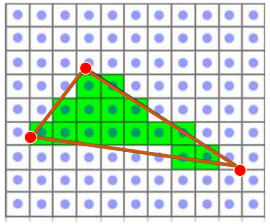
Rasterization

- The task of taking an **image described in vector graphics format (shapes)** and converting it into a **bitmapped/raster image (pixels)**



Rasterization (cont.)

- The task of taking an **image described in vector graphics format (shapes)** and converting it into a **bitmapped/raster image (pixels)**
- **Triangle setup**
  - Setup the properties of a triangle using the vertices data
    - E.g., the equations of edges

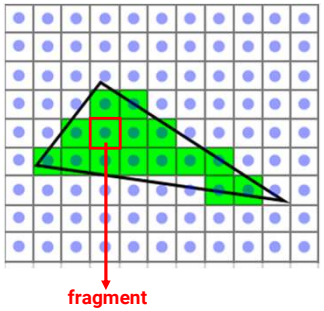


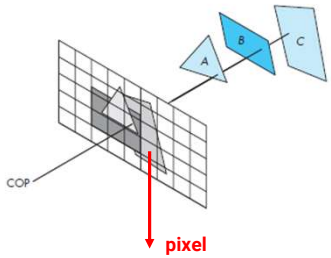
Rasterization (cont.)

- The task of taking an **image described in vector graphics format (shapes)** and converting it into a **bitmapped/raster image (pixels)**
- **Triangle setup**
  - Setup the properties of a triangle using the vertices data
    - E.g., the equations of edges
- **Fragment generation**
  - For each pixel that is inside the triangle in the screen space, generate a **fragments**
  - Obtain **per-fragment data** using **interpolation**

Rasterization (cont.)

- Fragment != Pixel





Rasterization (cont.)

- https://www.youtube.com/watch?v=t7Ztio8cwqM

Digital Differential Analyzer (DDA)

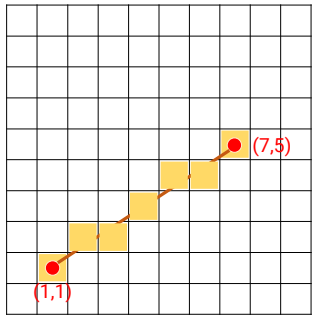
- Draw a line segment passing through $(x_1, y_1) = (1, 1)$ and $(x_2, y_2) = (7, 5)$

$$y = mx + b$$

$$m = \text{slope} = \frac{y_2 - y_1}{x_2 - x_1} = \frac{\Delta y}{\Delta x}$$

$$\Delta y = m\Delta x = m \quad (\text{if } \Delta x = 1)$$

$x_a = 2 \rightarrow y_a = y_1 + m = 1.667 \rightarrow (2, 1.667)$ (2, 2)
$x_b = 3 \rightarrow y_b = y_a + m = 2.333 \rightarrow (3, 2.333)$ (3, 2)
$x_c = 4 \rightarrow y_c = y_b + m = 3.000 \rightarrow (4, 3.000)$ (4, 3)
$x_d = 5 \rightarrow y_d = y_c + m = 3.667 \rightarrow (5, 3.667)$ (5, 4)
$x_e = 6 \rightarrow y_e = y_d + m = 4.333 \rightarrow (6, 4.333)$ (6, 4)



floating-point addition / comparison

Bresenham Algorithm

- Draw a line segment passing through $(x_1, y_1) = (1, 1)$ and $(x_2, y_2) = (7, 5)$

$$y = mx + b$$

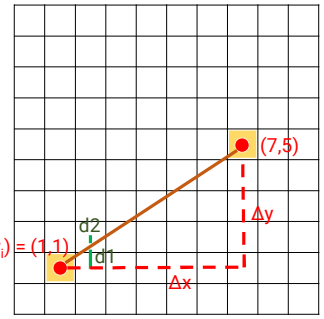
$$m = \frac{y_2 - y_1}{x_2 - x_1} = \frac{\Delta y}{\Delta x}$$

$$d1 = y - y_i = (m(x_i + 1) + b) - y_i$$

$$d2 = (y_i + 1) - y_i = y_i + 1 - (m(x_i + 1) + b)$$

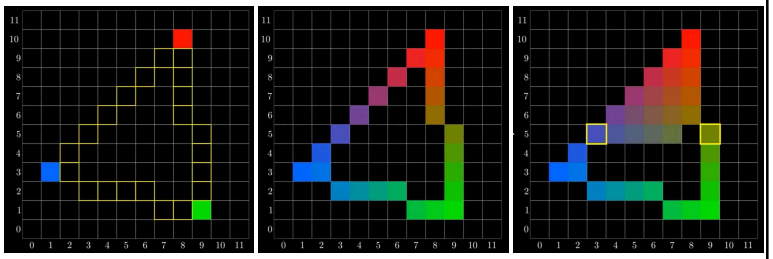
$$d1 - d2 = 2m(x_i + 1) - 2y_i + 2b - 1$$

$$\Delta x(d1 - d2) = 2\Delta y x_i - 2\Delta x y_i + c$$



integer multiplication / comparison

Scanline Rasterization

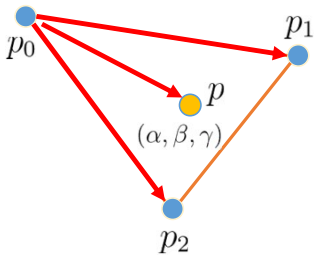


Attributes interpolation of edge pixels using vertices

Attributes interpolation of inner pixels using edge points

Barycentric Coordinates

- Barycentric coordinates inside a triangle



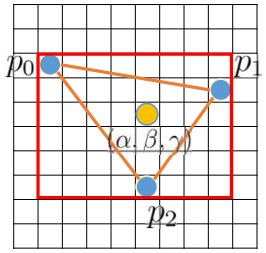
$$p = p_0 + \beta(p_1 - p_0) + \gamma(p_2 - p_0)$$
$$= (1 - \beta - \gamma)p_0 + \beta p_1 + \gamma p_2$$
$$= \alpha p_0 + \beta p_1 + \gamma p_2$$
$$\alpha + \beta + \gamma = 1$$

The values $\alpha, \beta, \gamma \in [0, 1]$ **if and only if p is inside the triangle**

Barycentric Coordinates (cont.)

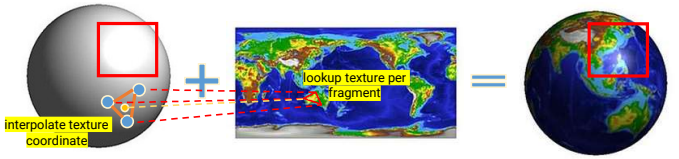
- Compute the 2D bounding box of the 2D triangle
- For each pixel inside the bounding box, compute its barycentric coordinates
- If the coordinates are all ≥ 0 and ≤ 1, the pixel is covered by the triangle

The barycentric coordinates α, β, γ can be used to interpolate vertex attributes directly



OpenGL (1.x) Fixed Function Pipeline (cont.)

- **Texture Environment**
  - Apply the textures to the fragments
- **Color Sum**
  - Used to add-in a secondary color to the geometry after the textures have been applied



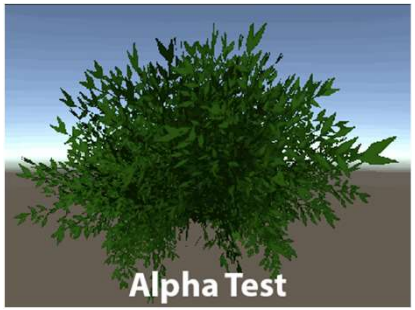
3D object | texture | texture mapped object (color = lighting × texture)

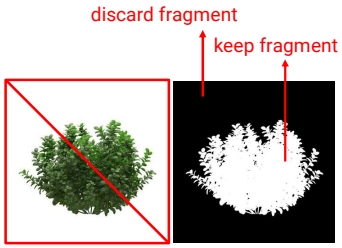
OpenGL (1.x) Fixed Function Pipeline (cont.)

- **Fog**
  - Simulate the effect of geometry fadeout as dimmed by fog
  - Linearly blend the fragment color with the fog color

OpenGL (1.x) Fixed Function Pipeline (cont.)

- **Alpha Test**
  - Discard fragments if their alpha values are below a certain threshold



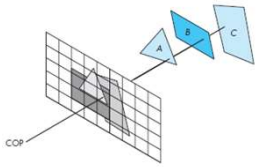


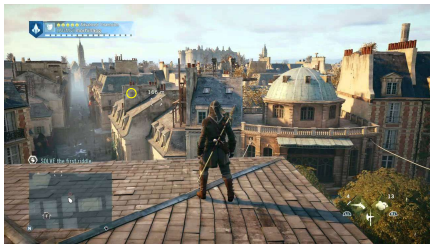
albedo texture (usually combined in an RGBA texture)

alpha mask

OpenGL (1.x) Fixed Function Pipeline (cont.)

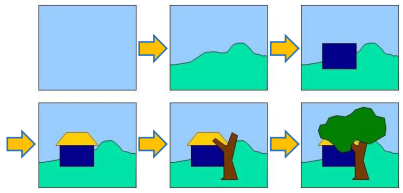
- **Depth Test**
  - Used for **hidden surface removal**
    - Only show the **closest** surfaces to the camera at each pixel

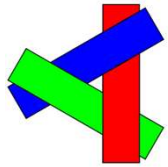




OpenGL (1.x) Fixed Function Pipeline (cont.)

- **Depth Test**
  - Used for **hidden surface removal**
    - Only show the **closest** surfaces to the camera at each pixel
  - Earlier approach: painter's algorithm

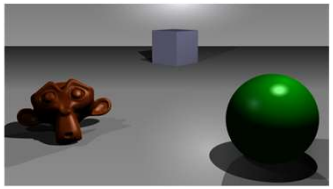




How about this?
(cyclical overlapping)

OpenGL (1.x) Fixed Function Pipeline (cont.)

- **Depth Test**
  - **Z-buffer**
    - An additional buffer used to maintain the z value of the closest surface to a pixel
    - Discard fragments if they have larger depth values than the ones stored in their corresponding positions in the Z buffer

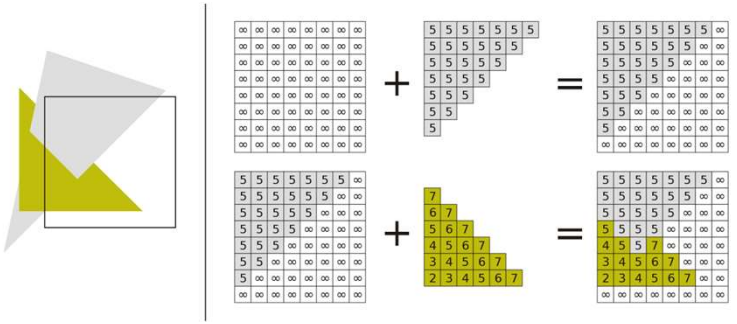


color frame buffer

Z (depth) buffer

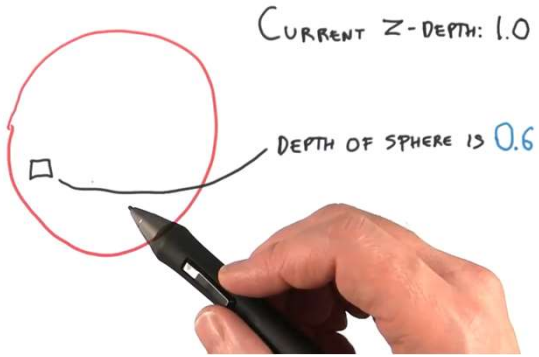
Z-Buffer

- Z-buffer update



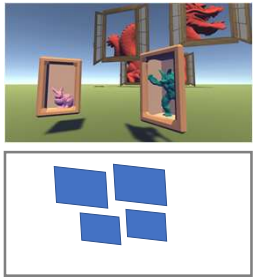
Z-Buffer (cont.)

- https://www.youtube.com/watch?v=yhwg_O5HBwQ



OpenGL (1.x) Fixed Function Pipeline (cont.)

- **Stencil Test**
  - Used to discard fragments that fail a stencil comparison, based on the content of the stencil buffer

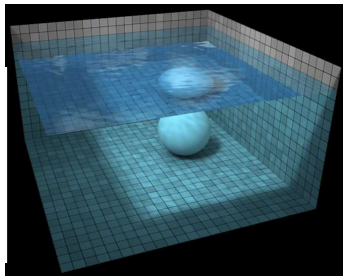


stencil buffer

OpenGL (1.x) Fixed Function Pipeline (cont.)

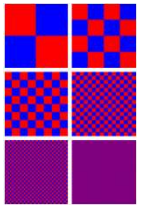
- **Color Buffer Blending**
  - Blend the color of fragments with the previous results in the frame buffer based on the **alpha values** of the current fragments, as well as the **blend function** and the **blend equations**





OpenGL (1.x) Fixed Function Pipeline (cont.)

- **Dither**
  - If a color palette is used, OpenGL will try to simulate a larger color palette by mixing colors in close proximity
  - Areas of a single color are replaced by a pattern of dots of several different colors, in such a way that optical mixing in the eye produces a color close to the desired one

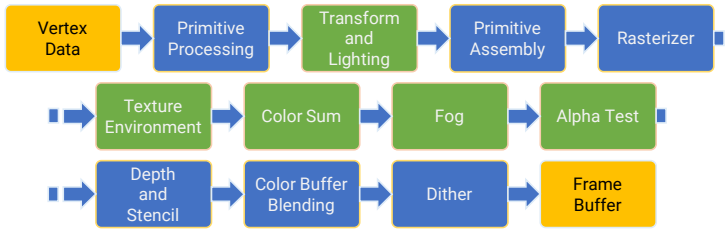

Summary of Fixed Function Pipeline

- An 3D object will come to the screen with a series of "fixed" steps
  - Fixed transformation (MVP matrix)
  - **Fixed (Phong) lighting model on vertices**
  - **Fixed modulation of lighting color and texture color**
    - Color = Lighting $\times$ Texture
- **We would like more flexibility!**

OpenGL Graphics Pipeline 2.0

Recap: OpenGL (1.x) Fixed Function Pipeline

- All the functions performed by OpenGL are **fixed** and **could not** be modified except through the manipulation of the **rendering states**
- The stages shown in green have been replaced by **shaders**



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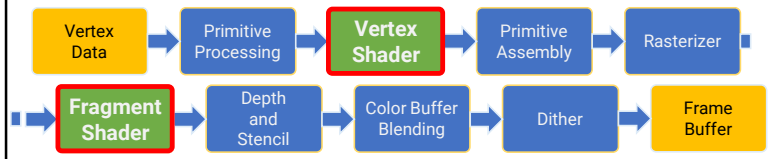
OpenGL (2.0) Graphics Pipeline

- Released in 2004
- Provide the ability to **programmatically** define the vertex transformation and lighting and the fragment operations (with small GPU programs called **shaders**)



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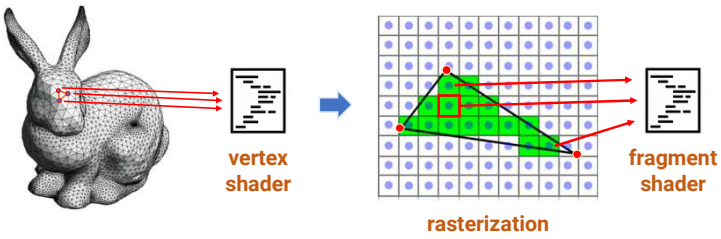
Vertex Shader and Fragment Shader

- **Important concepts**
  - The vertex shader runs **per vertex**
  - The fragment shader runs **per (rasterized) fragment**



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Vertex Shader (Run per Vertex)

- Give the programmers more **flexibility** regarding
  - **How the vertices are transformed**
    - We can also choose not to transform the vertices at all
  - **How the lighting is computed**
    - We can also choose to compute lighting in the fragment shader (per-fragment lighting)
- However, ***with great power, comes great responsibility***
  - Programmers have to implement the functions provided by the fixed pipeline on their own
  - The primary responsibility of the vertex shader program is to **transform the vertex position into Clip Space**
    - Commonly, this is done by multiplying the vertex with the **model-view-projection** matrix

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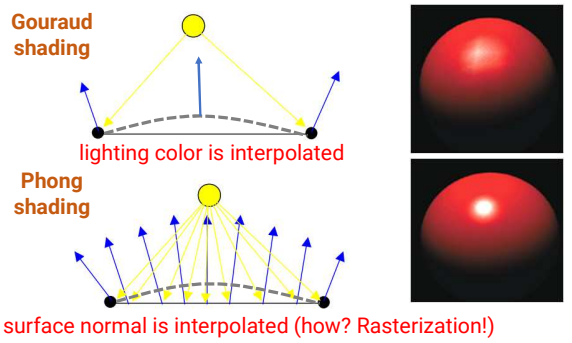
Fragment Shader (Run per Fragment)

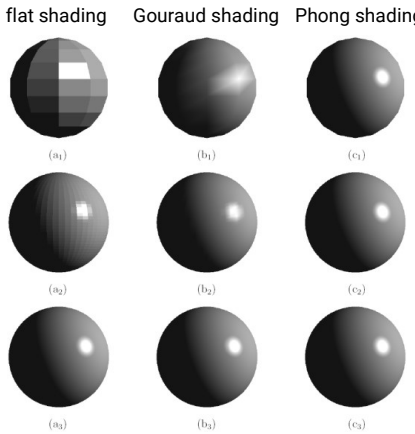
- Replace the texture blending, color sum, fog, and alpha test operations from the fixed function pipeline
- Graphics programmers have to write a fragment program to perform these operations (of course, you can omit them if you do not care!)
- The primary responsibility of the fragment program is to **determine the final color of the fragment**
- Allow different lighting and fog model, as well as an arbitrary combination of lighting and texture
- Allow for techniques such as per-pixel lighting, bump, normal mapping, etc.

Per-Fragment Shading

- Problem with Gouraud shading
- Phong shading (instead of Gouraud shading)



Per-Fragment Shading (cont.)



Per-Fragment Shading (cont.)

- Normal mapping

We will talk about this when introducing Textures

Modern Graphics Pipeline

- Modern graphics pipeline comprised more programmable (shader) stages, such as
  - **Geometry shader** in OpenGL 3.2
  - **Tessellation control shader** and **tessellation evaluation shader** in OpenGL 4.0
  - **Compute shader** in OpenGL 4.3
  - **Mesh shader** in OpenGL ?
- Hopefully, we could have time to introduce these shaders later in this semester

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Any Questions?

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