Intro to OpenGL III

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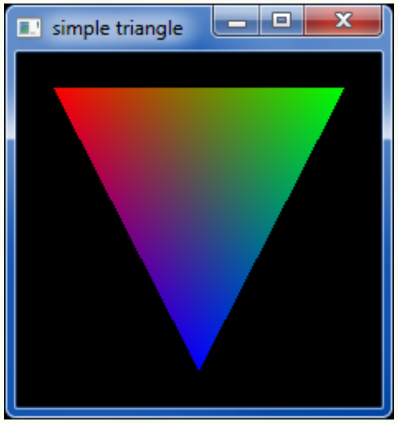
Where are we?

- Continuing the OpenGL basic pipeline

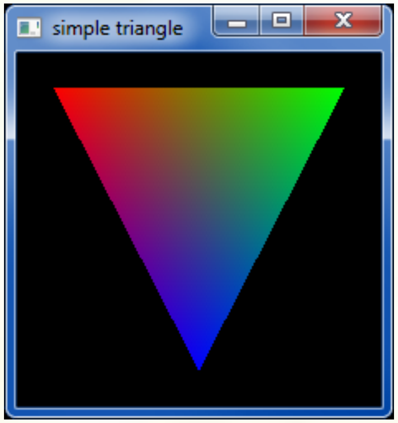
OpenGL API Example

```
glShadeModel(GL_SMOOTH);  // smooth color interpolation
glEnable(GL_DEPTH_TEST);  // enable hidden surface removal

glClear(GL_COLOR_BUFFER_BIT|GL_DEPTH_BUFFER_BIT);
glBegin(GL_TRIANGLES);  // every 3 vertexes makes a triangle
  glColor4ub(255, 0, 0, 255);    // RGBA=(1,0,0,100%)
  glVertex3f(-0.8,  0.8,  0.3);  // XYZ=(-8/10,8/10,3/10)

  glColor4ub(0, 255, 0, 255);    // RGBA=(0,1,0,100%)
  glVertex3f( 0.8,  0.8, -0.2);  // XYZ=(8/10,8/10,-2/10)

  glColor4ub(0, 0, 255, 255);    // RGBA=(0,0,1,100%)
  glVertex3f( 0.0, -0.8, -0.2);  // XYZ=(0,-8/10,-2/10)
glEnd();
```



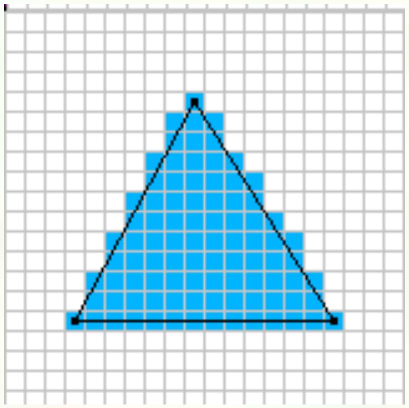
GLUT API Example

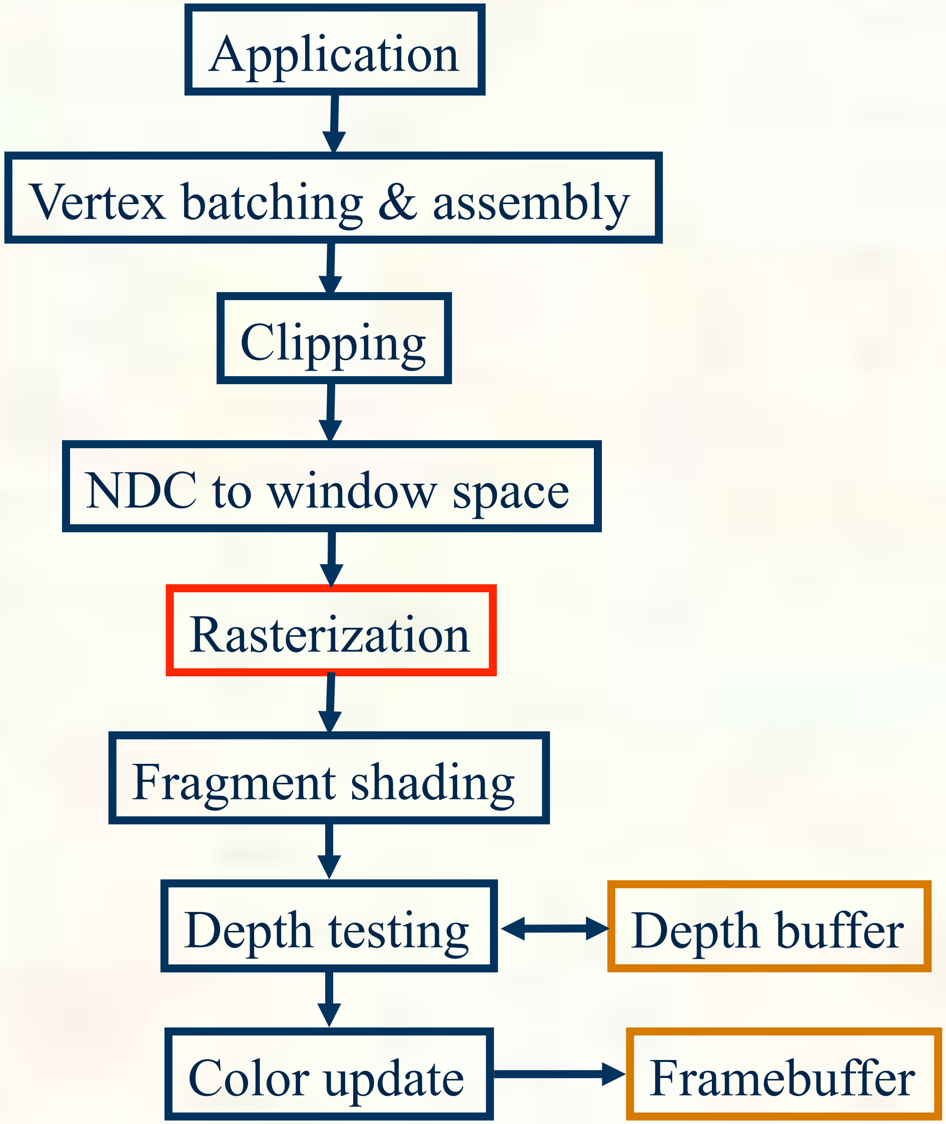
```
#include <GL/glut.h>  // includes necessary OpenGL headers

void display() {
  // << insert code on prior slide here >>
  glutSwapBuffers();
}
void main(int argc, char **argv) {
  // request double-buffered color window with depth buffer
  glutInitDisplayMode(GLUT_RGBA | GLUT_DOUBLE | GLUT_DEPTH);
  glutInit(&argc, argv);
  glutCreateWindow("simple triangle");
  glutDisplayFunc(display); // function to render window
  glutMainLoop();
}
```



Rasterization

- Last time we covered how rasterization is done. Lots of linear interpolation in special-purpose hardware, so it’s fast.





Application

Vertex batching & assembly

Clipping

NDC to window space

Rasterization

Fragment shading

Depth testing

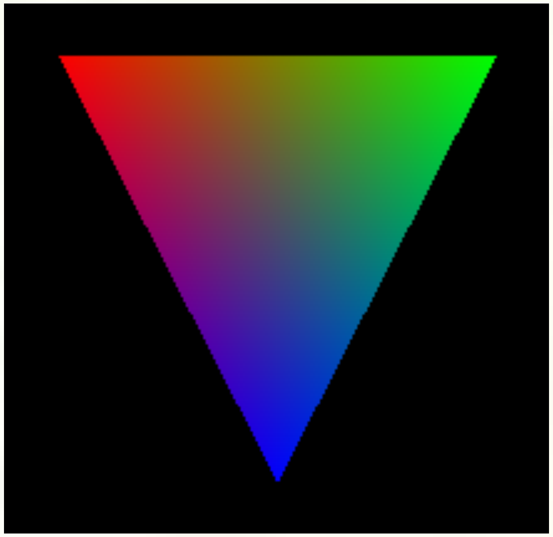
Depth buffer

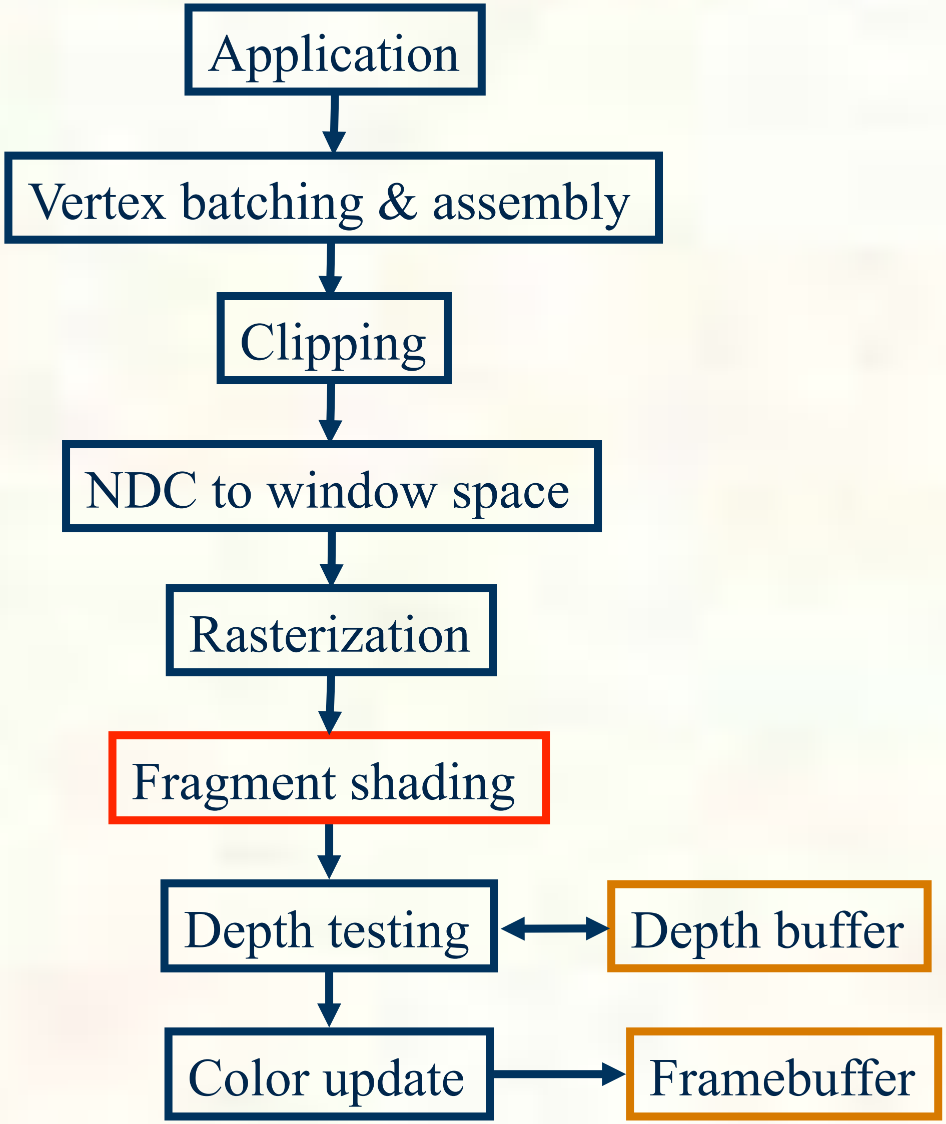
Color update

Framebuffer

Simple Fragment Shading

- We also talked a little about fragment shading, that is, the simple interpolated color shading that can be done in the rasterizer. There's much more to come.





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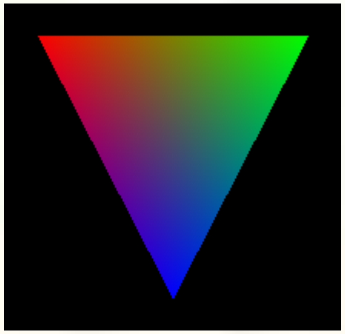
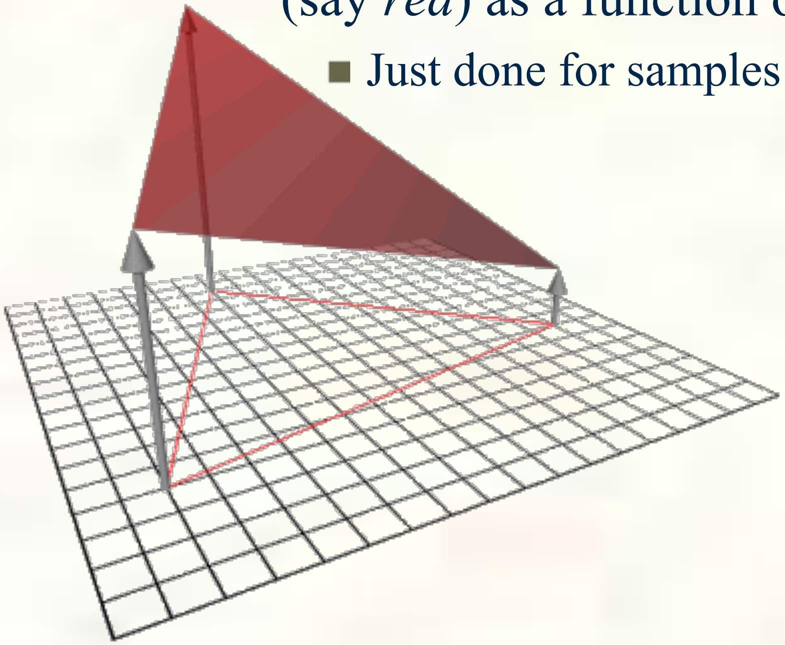
Color Interpolation

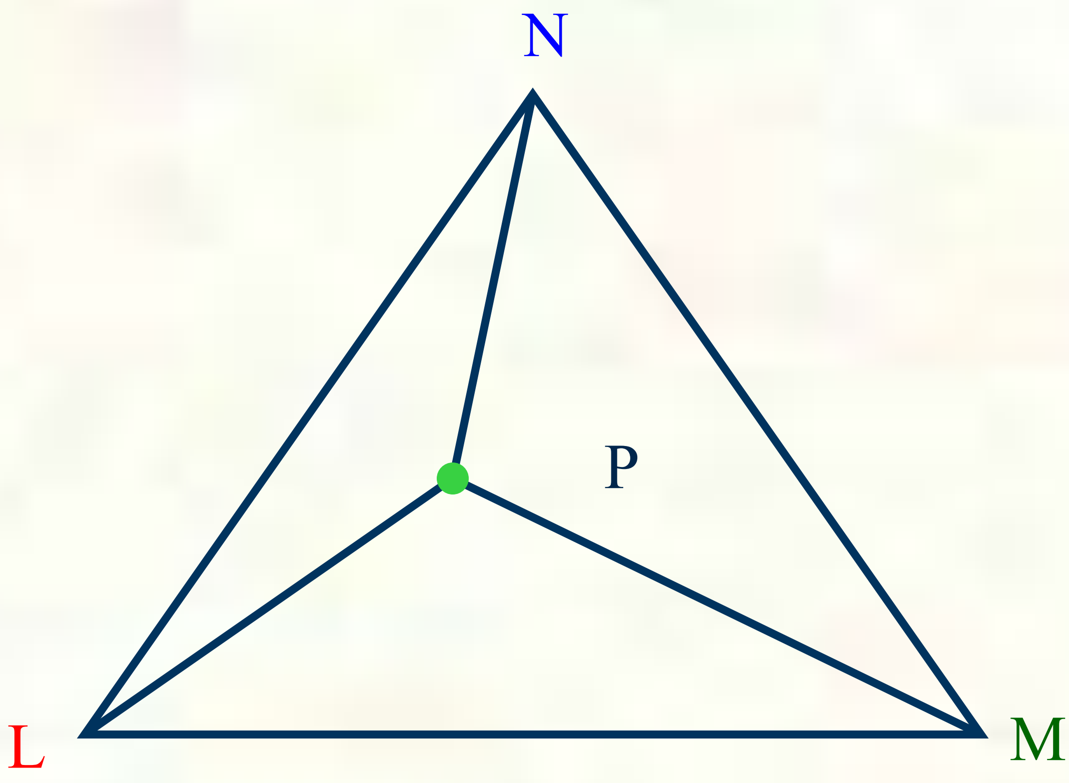


- Our simple triangle is drawn with smooth color interpolation
  - Recall: glShadeModel(GL_SMOOTH)
- How is color interpolated?
  - Think of a plane equation to computer each color component (say *red*) as a function of (x,y)
    - Just done for samples positions within the triangle



$$"redness" = A_{red}x + B_{red}y + C_{red}$$

Barycentric Coordinates



$$\frac{\text{Area}(PMN)}{\text{Area}(LMN)} = \alpha$$

$$\frac{\text{Area}(LPN)}{\text{Area}(LMN)} = \beta$$

$$\frac{\text{Area}(LMP)}{\text{Area}(LMN)} = \gamma$$

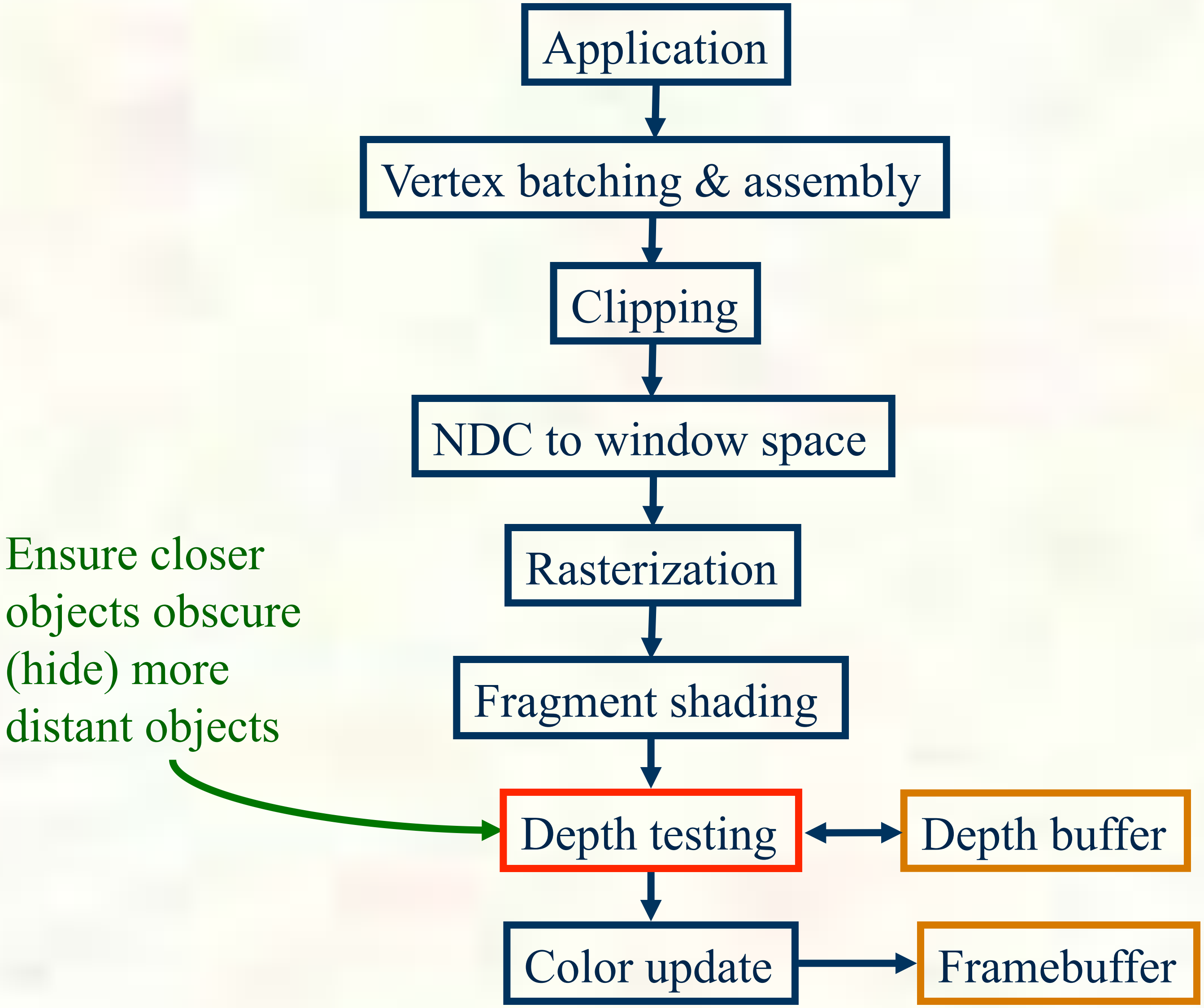
Note: $\alpha + \beta + \gamma = 0$ by construction

$$\text{attribute}(P) = \alpha\times\text{attribute}(L) + \beta\times\text{attribute}(M) + \gamma\times\text{attribute}(N)$$

Hardware Triangle Rendering Rates

- Top GPUs can setup over a billion triangles per second for rasterization
- Triangle setup & rasterization is just one of the (many, many) computation steps in GPU rendering

A Simplified Graphics Pipeline



Ensure closer objects obscure (hide) more distant objects

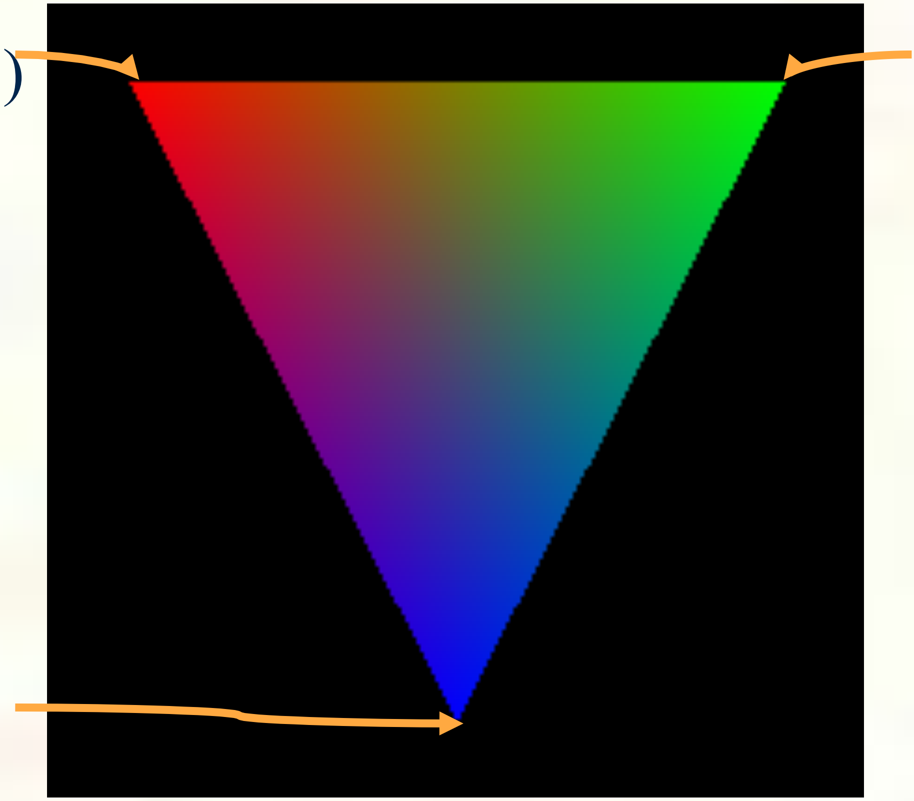
Interpolating Window Space Z

- Plane equation coefficients (A, B, C) generated by multiplying inverse matrix by vector of per-vertex attributes

$$\begin{bmatrix} L_x & L_y & 1 \\ M_x & M_y & 1 \\ N_x & N_y & 1 \end{bmatrix}^{-1} \begin{bmatrix} L_z \\ M_z \\ N_z \end{bmatrix} = \begin{bmatrix} A_z \\ B_z \\ C_z \end{bmatrix}$$

Simple Triangle Vertex Depth

- Assume glViewport(0,0,500,500) has been called
  - And glDepthRange(0,1)



L=(50, 450, 0.65)

N=(450,450,0.4)

M=(250,50,0.4)

$L_z = 0.65$
$M_z = 0.40$
$N_z = 0.40$

Interpolating Window Space Z

- Substitute per-vertex (x,y) and Z values for the L, M, and N vertexes

$$\begin{bmatrix} 50 & 450 & 1 \\ 250 & 50 & 1 \\ 450 & 450 & 1 \end{bmatrix}^{-1} \begin{bmatrix} 0.65 \\ 0.4 \\ 0.4 \end{bmatrix} = \begin{bmatrix} A_z \\ B_z \\ C_z \end{bmatrix}$$

A_z= -0.000625

B_z = 0.0003125

C_z = 0.540625

Complete Z plane equation

Z(x,y) = -0.000625*x + 0.0003125*y + 0.540625

Depth Buffer Algorithm

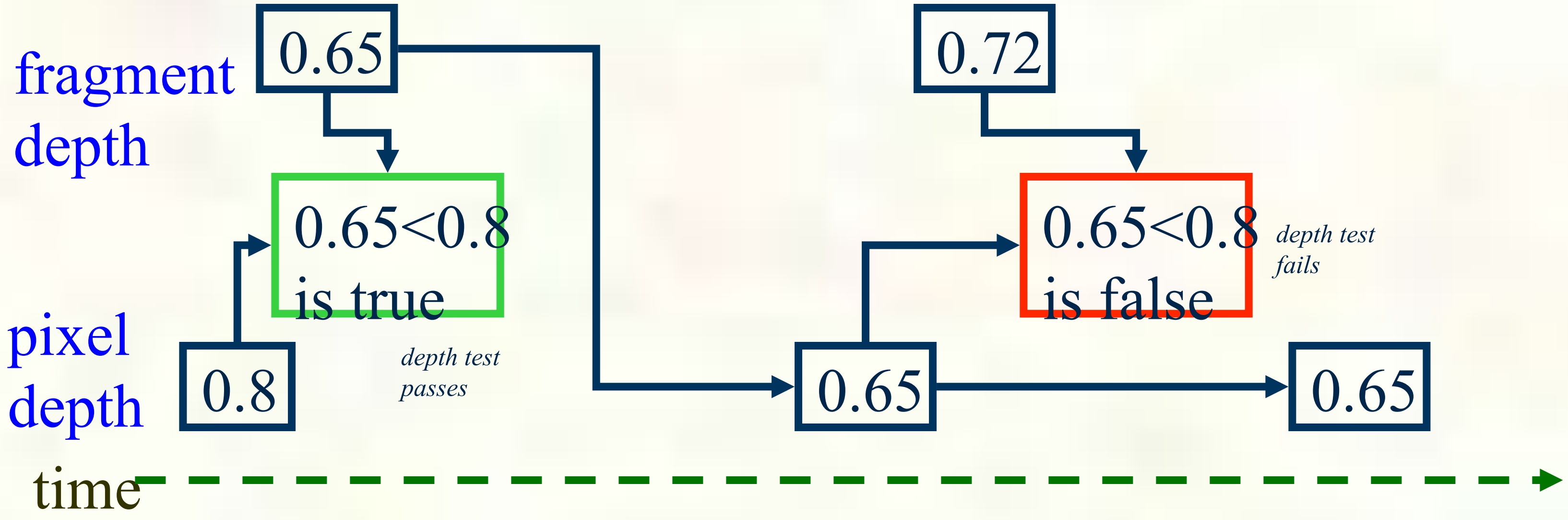
- Simple, brute force
  - Every color sample in framebuffer has corresponding depth sample
  - Discrete, solves occlusion in pixel space
  - Memory intensive, but fast for hardware
- Basic algorithm
  - Clear the depth buffer to its “maximum far” value (generally 1.0)
  - Interpolate fragment’s Z
  - Read fragment’s corresponding depth buffer sample Z value
  - If interpolated Z is less than (closer) than Z from depth buffer
    - Then replace the depth buffer Z with the fragment’s Z
      - And also allow the fragment’s shaded color to update the corresponding color value in color buffer
    - Otherwise discard fragment
      - Do <u>not</u> update depth or color buffer

Depth Buffer Example

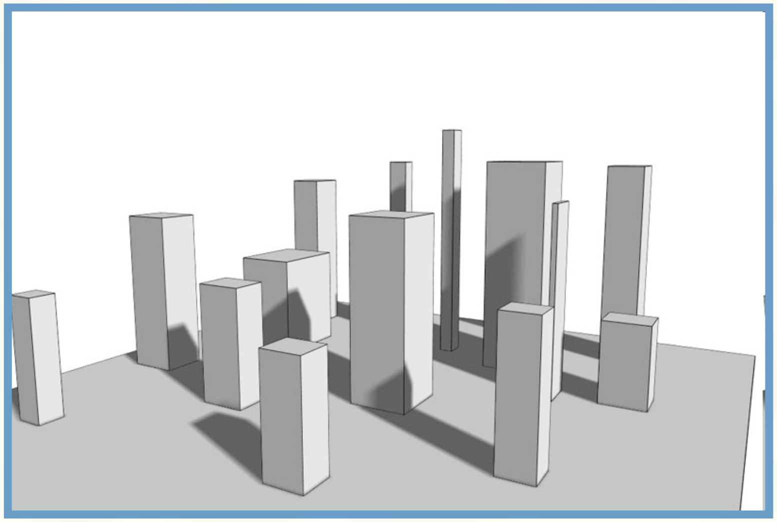
- Fragment gets rasterized
- Fragment's Z value is interpolated
  - Resulting Z value is 0.65
- Read the corresponding pixel's Z value
  - Reads the value 0.8
- Evaluate depth function
  - 0.65 GL_LESS 0.8 is **true**
  - So 0.65 replaces 0.8 in the depth buffer

- Second primitive rasterizes same pixel
- Fragment's Z value is interpolated
  - Resulting Z value is 0.72
- Read the corresponding pixel's Z value
  - Reads the value 0.65
- Evaluate depth function
  - 0.72 GL_LESS 0.65 is **false**
  - So the fragment' s depth value and color value are discarded

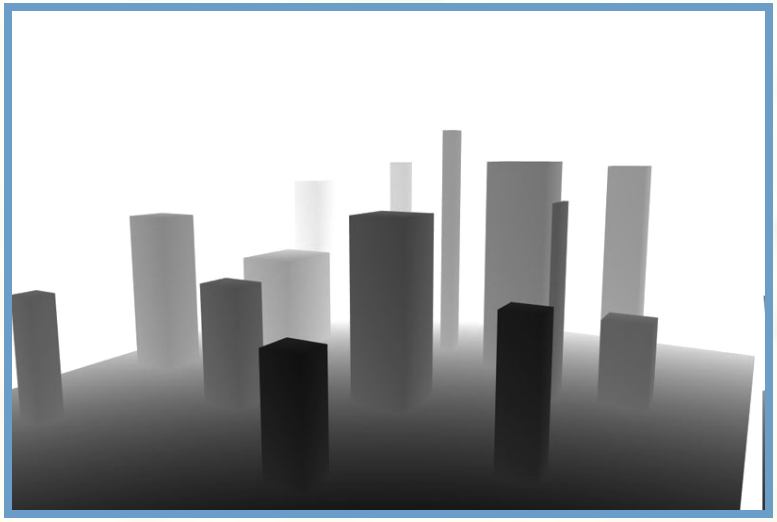
Depth Test Operation



Depth Buffer Visualized



Depth-tested
3D scene



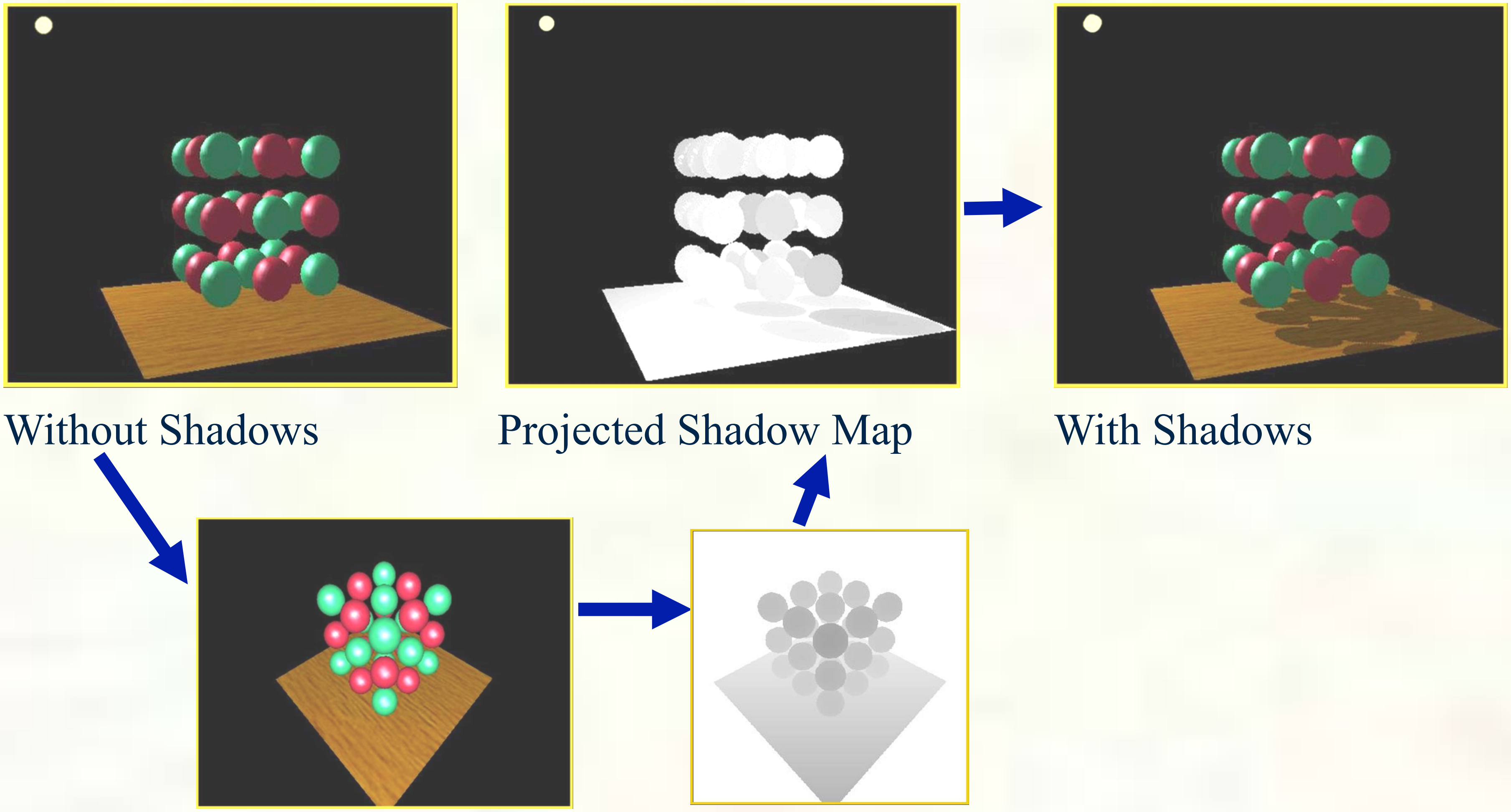
Z or depth values
white = 1.0 (far), black = 0.0 (near)

OpenGL API for Depth Testing

- Simple to use
  - Most applications just "enable" depth testing and hidden surfaces are removed
  - Enable it: glEnable(GL_DEPTH_TEST)
    - Disabled by default
    - **Must** have depth buffer allocated for it to work
      - **Example:** glutInitDisplayMode(GLUT_RGBA | GLUT_DOUBLE | GLUT_DEPTH)
- More control
  - Clearing the depth buffer
    - glClear(GL_DEPTH_BUFFER_BIT | otherBits)
    - glClearDepth(*zvalue*)
      - Initial value is 1.0, the maximum Z value in the depth buffer
  - glDepthFunc(*zfunc*)
    - *zfunc* is one of GL_LESS, GL_GREATER, GL_EQUAL, GL_GEQUAL, GL_LEQUAL, GL_ALWAYS, GL_NEVER, GL_NOTEQUAL
    - Initial value is GL_LESS
  - glDepthMask(*boolean*)
    - True means write depth value if depth test passes; if false, don't write
    - Initial value is GL_TRUE
  - glDepthRange
    - Maps NDC Z values to window-space Z values
    - Initially [0,1], mapping to the entire available depth range

Not Just for View Occlusion

Depth Buffers also Useful for Shadow Generation



Without Shadows

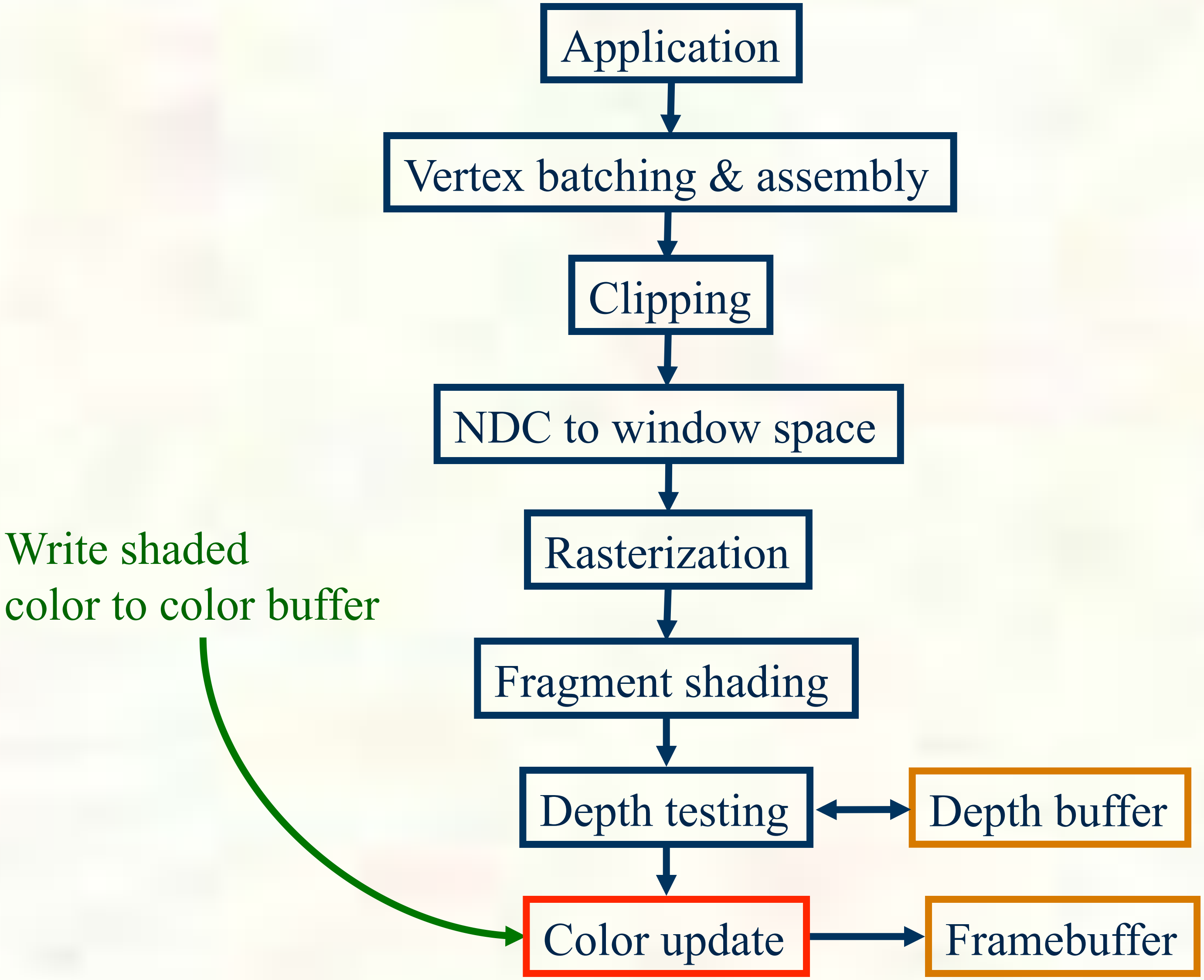
Projected Shadow Map

With Shadows

Light’ s View

Light’ s View Depth

A Simplified Graphics Pipeline



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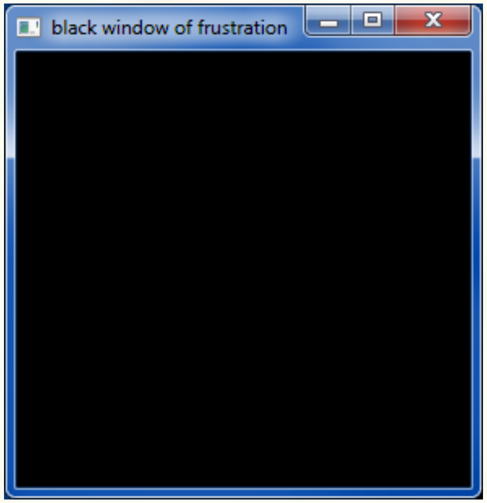
Write shaded color to color buffer

Next Lecture

- Graphics Math, Transforms
  - *Interpolation, vector math, and number representations for computer graphics*

Programming tips

- 3D graphics, whether OpenGL or Direct3D or any other API, can be frustrating
  - You write a bunch of code and the result is



Nothing but black window; where did your rendering go??

Things to Try

- Set your clear color to something other than black!
  - It is easy to draw things black accidentally so don’t make black the clear color
  - But black is the initial clear color
- Did you draw something for one frame, but the next frame draws nothing?
  - Are you using depth buffering? Did you forget to clear the depth buffer?
- Remember there are near and far clip planes so clipping in Z, not just X & Y
- Have you checked for glGetError?
  - Call glGetError once per frame while debugging so you can see errors that occur
  - For release code, take out the glGetError calls
- Not sure what state you are in?
  - Use glGetIntegerv or glGetFloatv or other query functions to make sure that OpenGL’s state is what you think it is
- Use glutSwapBuffers to flush your rendering and show to the visible window
  - Likewise glFinish makes sure all pending commands have finished
- Try reading
  - http://www.slideshare.net/Mark_Kilgard/avoiding-19-common-opengl-pitfalls
  - This is well worth the time wasted debugging a problem that could be avoided

Thanks

- Presentation approach and figures from
  - David Luebke [2003]
  - Brandon Lloyd [2007]
  - *Geometric Algebra for Computer Science* [Dorst, Fontijne, Mann]
  - via Mark Kilgard