Intro to OpenGL

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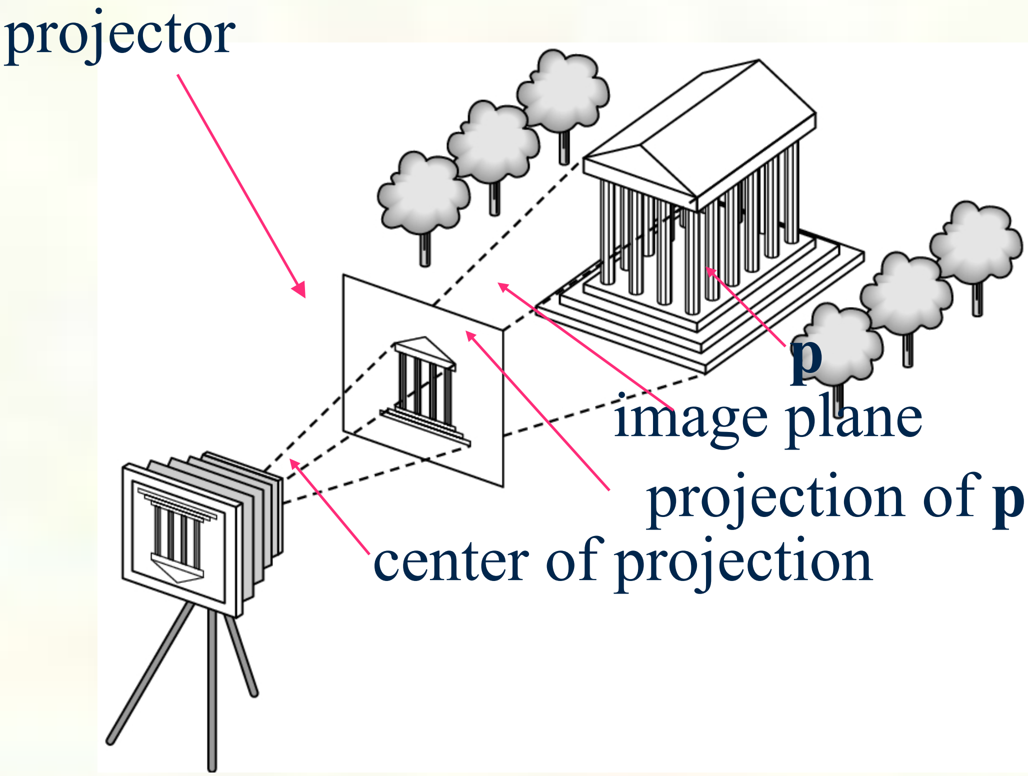
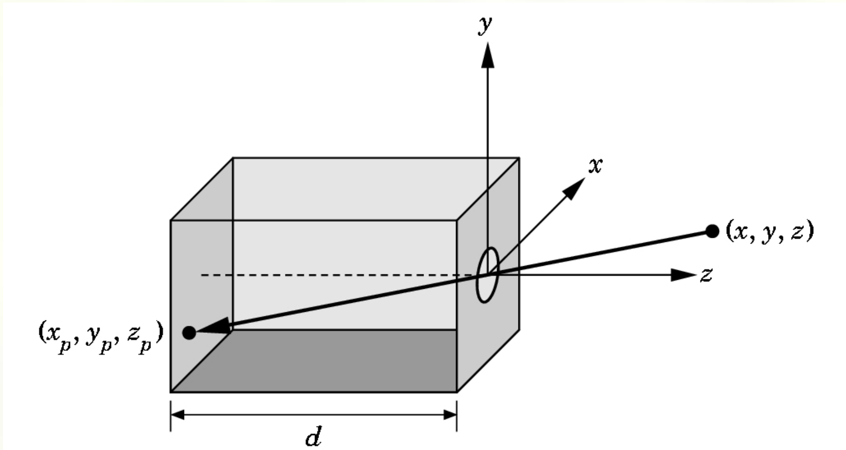
Synthetic Camera Model



Pinhole Camera

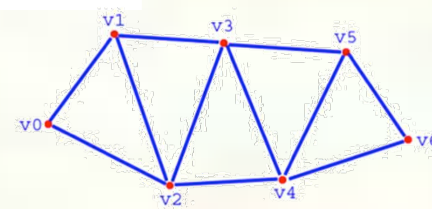


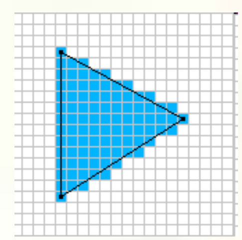
Use similar triangles to find perspective projection of point at (x,y,z)

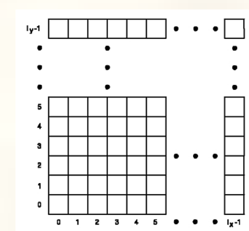
$x_p = -x/z/d$ $y_p = -y/z/d$ $z_p = d$

Objects and Scenes

- Programmers want to render “objects”
  - Say a fire truck or molecule
  - Arranged relative to other objects (a scene) & then viewed
- Graphics pipeline approach—used by OpenGL and GPUs
  - Break objects into geometry batches
    - Batches may be meshes or “patches”
  - Batches reduce to polygonal primitives
    - Typically triangles
    - But also lines, points, bitmaps, or images
  - Geometric primitives are specified by vertices
    - So vertices are assembled into primitives
  - Primitives are rasterized into fragments
  - Fragments are shaded
  - Raster operations take shaded fragments and update the framebuffer







Advantages

- Separation of objects, viewer, light sources
- Two-dimensional graphics is a special case of three-dimensional graphics
- Leads to simple software API
  - Specify objects, lights, camera, attributes
  - Let implementation determine image
- Leads to fast hardware implementation

What is OpenGL?

- The OpenGL Graphics System
  - Not just for 3D graphics; imaging too
  - "GL" standard for "Graphics Library"
  - "Open" means industry standard meant for broad adoption with liberal licensing
- Standardized in 1992
  - By Silicon Graphics
  - And others: Compaq, DEC, Intel, IBM, Microsoft
  - Originally meant for Unix and Windows workstations
- Now *de facto* graphics acceleration standard
  - Now managed by the Khronos industry consortium
  - Available everywhere, from supercomputers to cell phones
  - Alternative: Direct3D provides similar functionality with a very different API for Microsoft Windows platforms

Student's View of OpenGL

- You can learn OpenGL gradually
  - Lots of its can be ignored for now
  - The "classic" API is particularly nice
    - "Deprecation" has ruined the pedagogical niceness of OpenGL; ignore deprecation
- Plenty of documentation and sample code
- Makes concrete the abstract graphics pipeline for rasterization

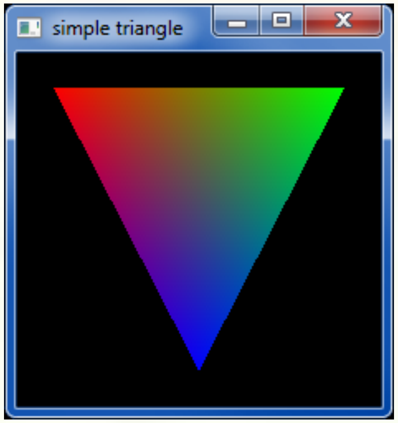
OpenGL API Example

```
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)

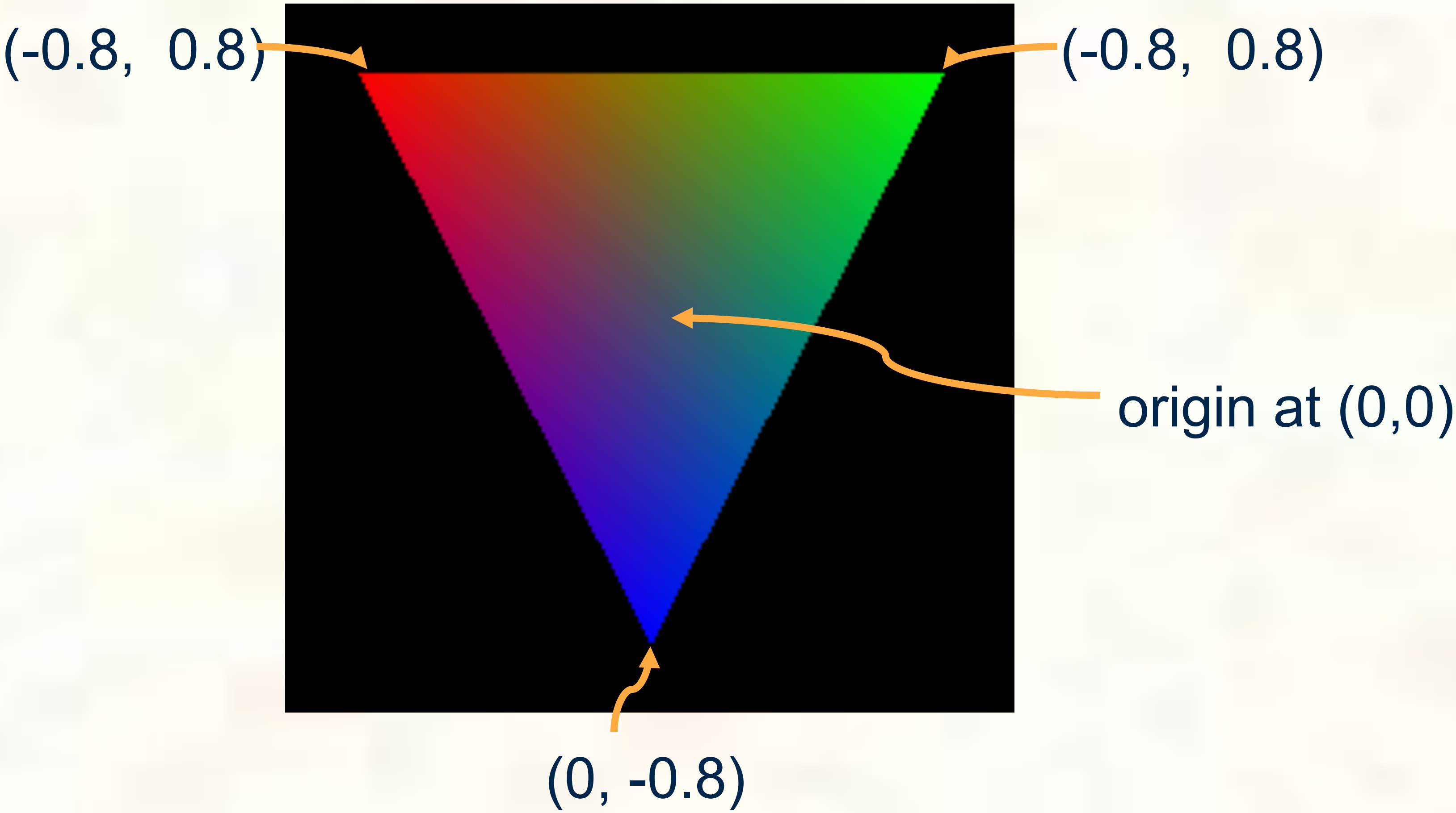
  glColor4ub(0, 255, 0, 255);    // RGBA=(0,1,0,100%)
  glVertex3f( 0.8,  0.8, -0.2);  // XYZ=(8/10,8/10,-2/10)

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



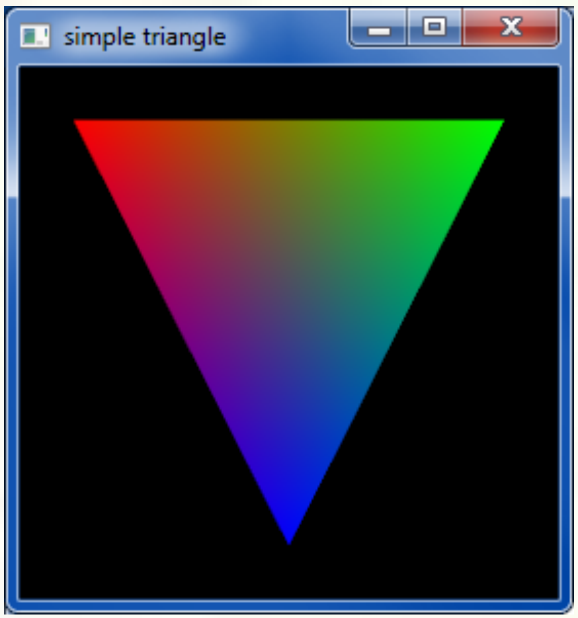
Initial Logical Coordinate System

- Think of drawing into a $[-1,+1]^3$ cube

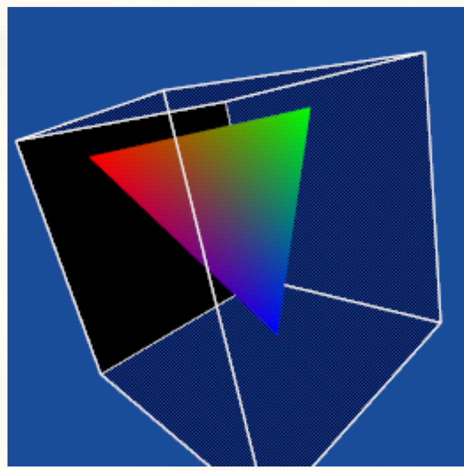


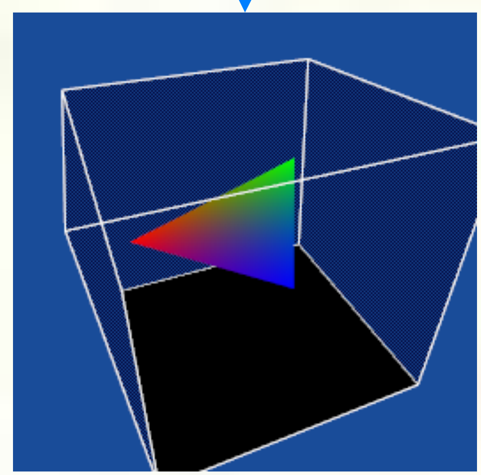
Normalized Device Coordinates

- What does this simple triangle look like with the $[-1,+1]^3$ cube's coordinate system?
  - We call this coordinate system "Normalize Device Coordinate" or NDC space



Wire frame cube shows boundaries of NDC space

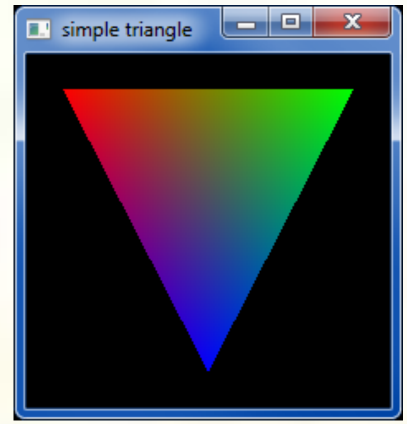




From NDC views, you can see triangle isn't "flat" in the Z direction

Two vertices have Z of -0.2—third has Z of 0.3

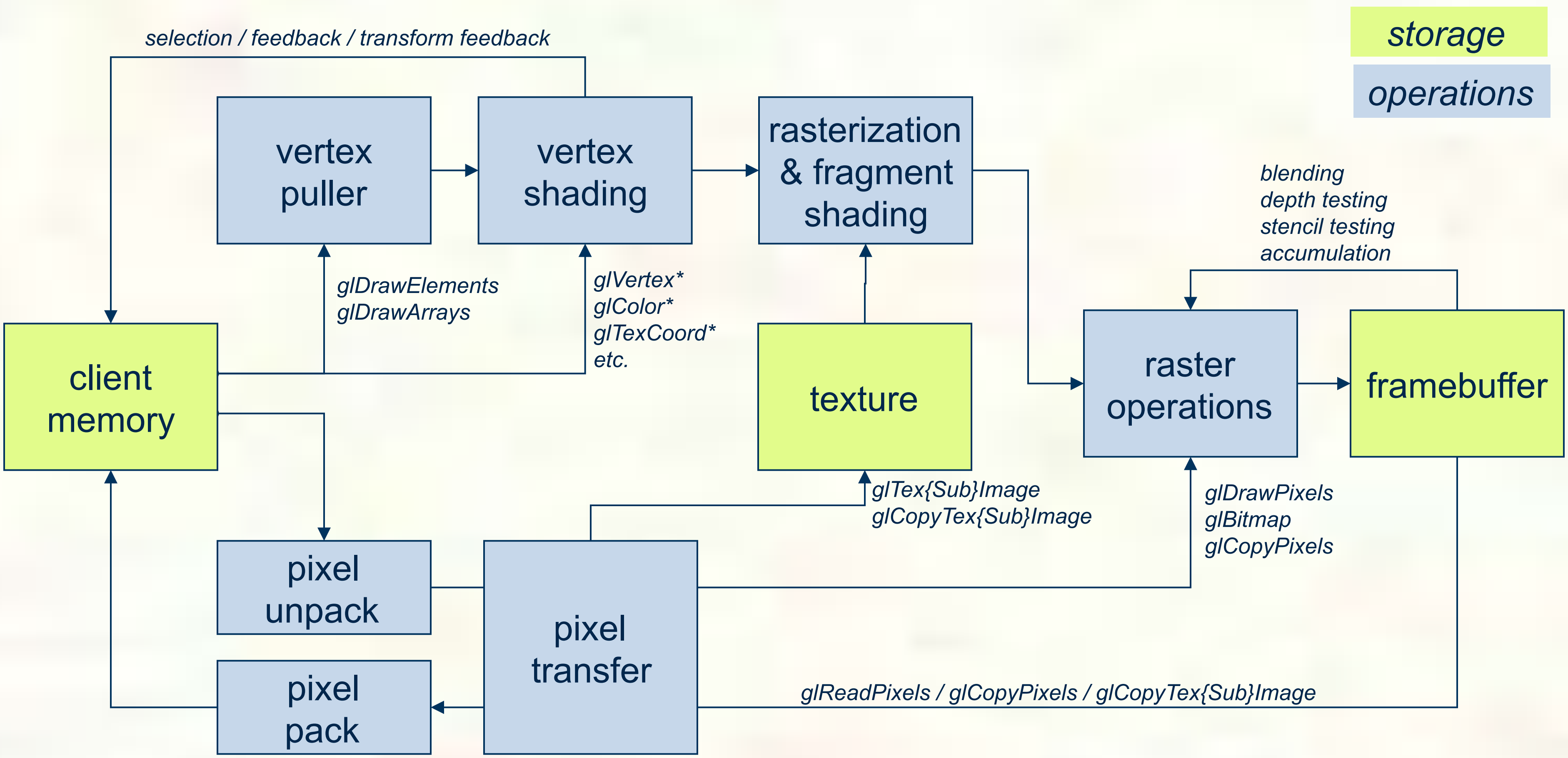
GLUT API Example




```
#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();
}
```

OpenGL Data Flow



Simplified Graphics Pipeline

Application

Vertex batching & assembly

OpenGL API

Clipping

NDC to window space

Rasterization

Fragment shading

Depth testing ↔ Depth buffer

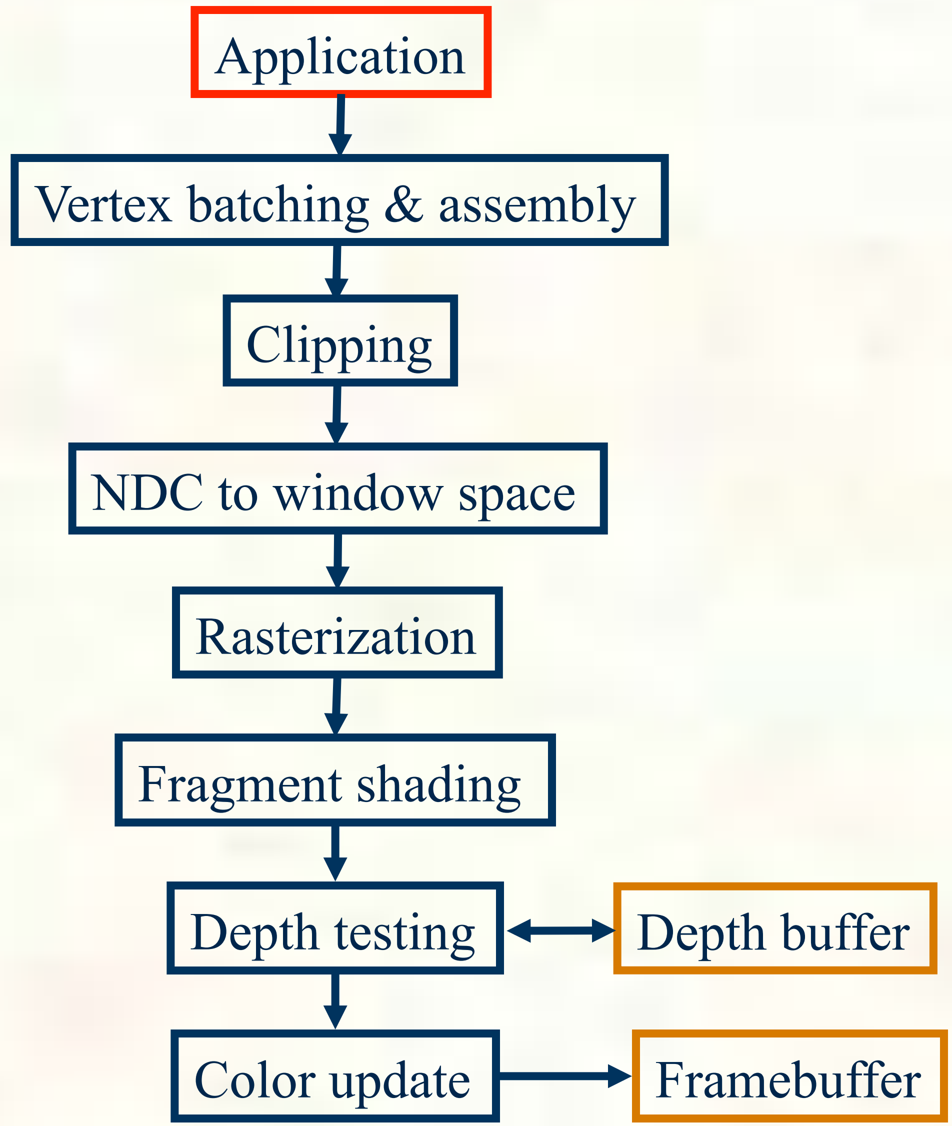
Color update → Framebuffer →

NDC = Normalized Device Coordinates, this is a $[-1,+1]^3$ cube

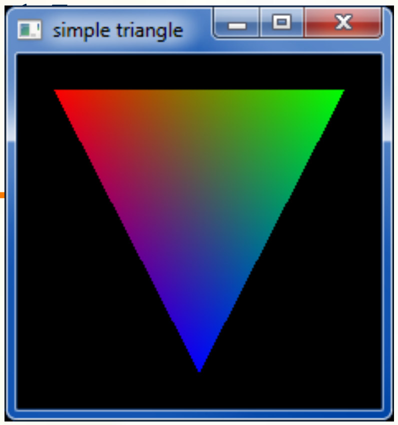
Really lots more steps than this but these are the non-trivial operations in our simple triangle example

Application

- What's the app do?
  - Running on the CPU
- Initializes app process
  - Creates graphics resources such as
    - OpenGL context
    - Windows
- Handles events
  - Input events, resize windows, etc.
  - Crucial event for graphics: **Redisplay**
    - Window needs to be drawn—so do it
    - GPU gets involved at this point



App Stuff



- GLUT is doing the heavy lifting
  - Talking to Win32, Cocoa, or Xlib for you
  - Other alternatives: SDL, etc.

```
#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();
}
```

display function is being registered as a "callback"

Rendering - the *display* Callback

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

Graphics state setting

```
glClear(GL_COLOR_BUFFER_BIT|GL_DEPTH_BUFFER_BIT);
```

Framebuffer buffer clearing

```
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)

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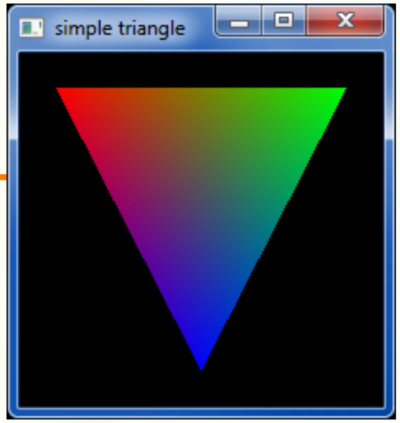
} glEnd();
```

Triangle rendering

Graphics State Setting



- Within the draw routine

```
glShadeModel(GL_SMOOTH);   // smooth color interpolation
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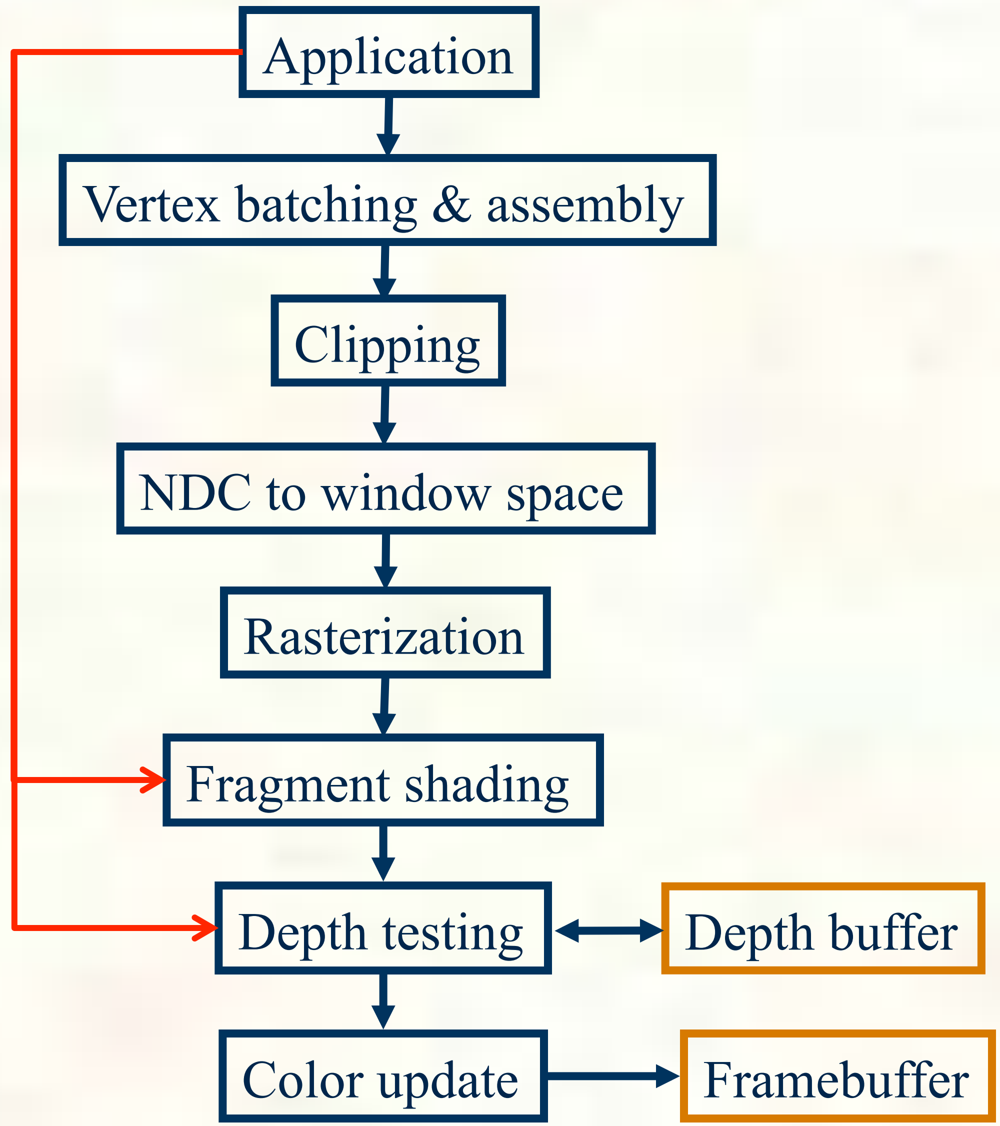
  glVertex3f( 0.0, -0.8, -0.2);   // XYZ=(0,-8/10,-2/10)
} glEnd();
```

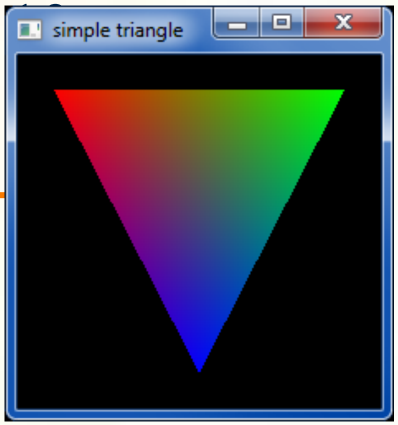
graphics context state is "stateful" (sticky) so technically doesn't need to be done every time display is called

State Updates

- ShadeModel(SMOOTH) requests smooth color interpolation
  - changes fragment shading state
  - alternative is "flat shading"
- Enable(DEPTH_TEST) enables depth buffer-based hidden surface removal algorithm
- State updates happen in command sequence order
- In fact, all OpenGL commands are in a stream that must complete in order



Clearing the buffers



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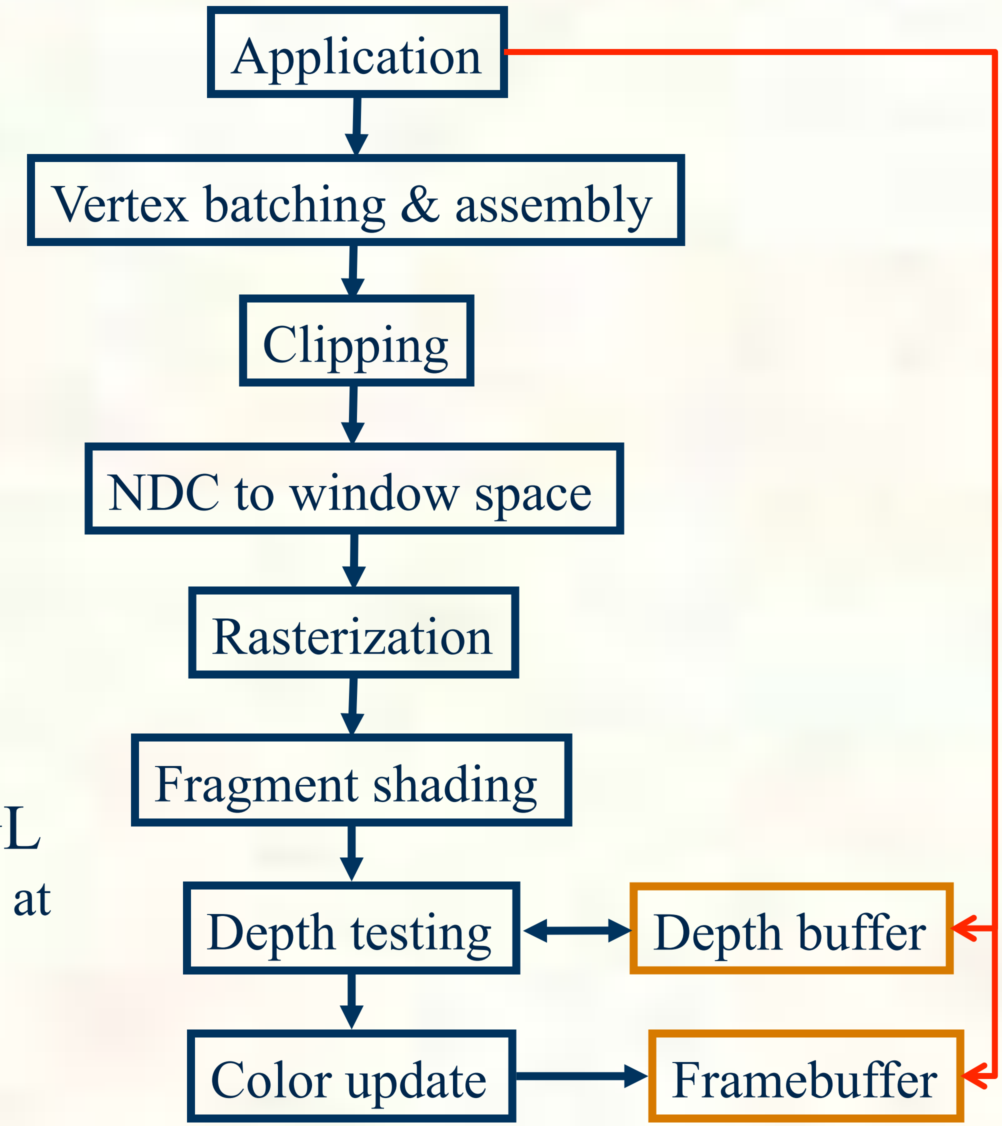
glEnd();
```

Buffer Clearing

- New frame needs to reset entire color buffer to "background" or "clear" color
  - Avoids having remnants of prior frame persist
    - Needed if can't guarantee every pixel is touched every frame
- Depth buffer needs to be cleared to "farthest value"
  - More about depth buffering later
- Special operation in OpenGL
  - Hardware wants clears to run at memory-saturating speeds
  - Still in-band with command stream

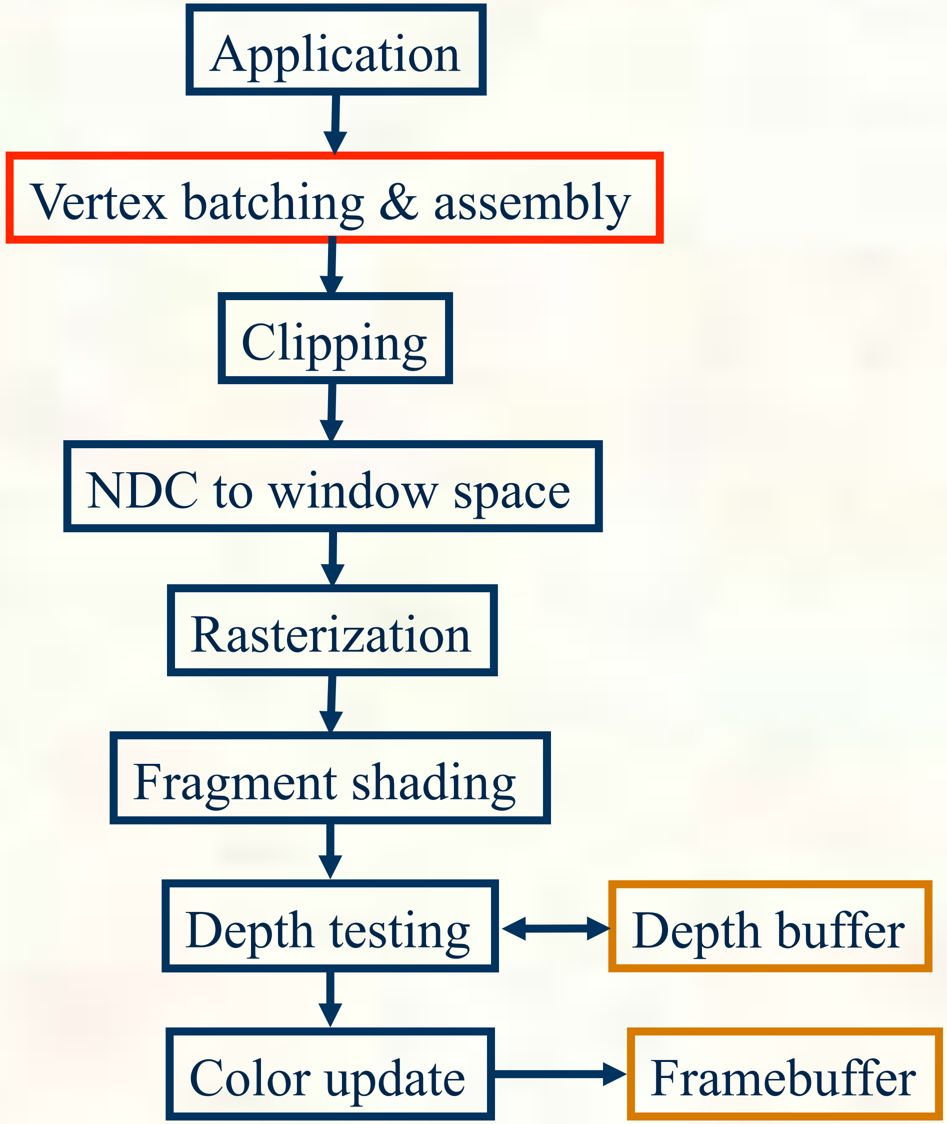


Clear Values and Operations

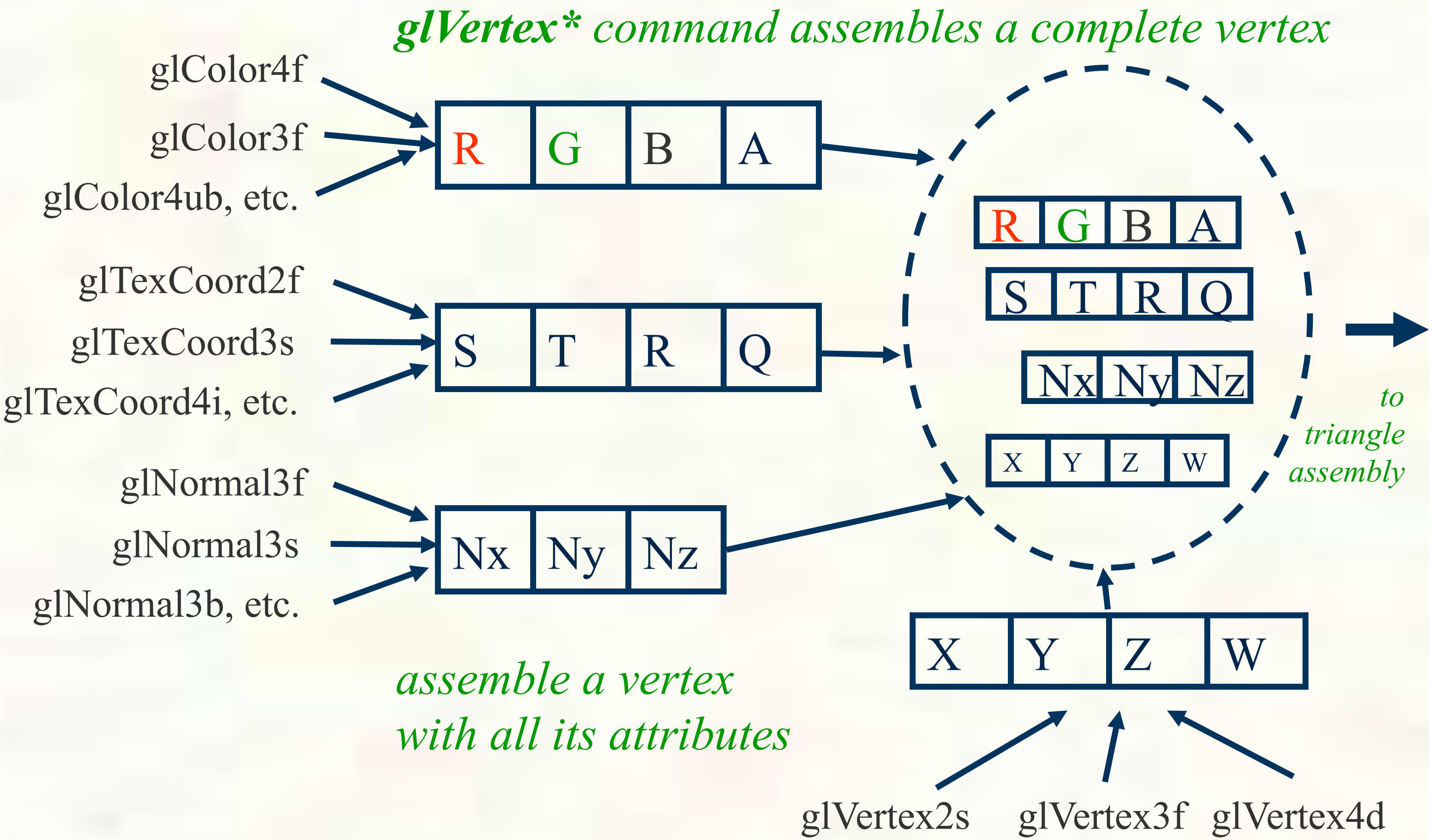
- OpenGL commands to set clear values
  - glClearColor for RGBA color buffers
    - **Example:** glClearColor(0,0,0,1);
      - Clear to black with 100% opacity
      - Initial clear value is (0,0,0,0) so black with 0% opacity
  - glClearDepth for depth buffers
    - **Example**: glClearDepth(1.0);
      - Clear to farthest depth value, for [0,1] range
      - Initial depth clear value is 1.0 so farthest depth value
  - Neither commands does the actual clear operation…
- That's done by glClear(mask)
  - Mask parameter indicates buffers to clear
    - GL_COLOR_BUFFER_BIT, GL_DEPTH_BUFFER_BIT
    - Bitwise-OR (|) them together
    - Also GL_STENCIL_BUFFER_BIT, GL_ACCUM_BUFFER_BIT
  - Allows multiple buffers (e.g. depth <u>&</u> color) to be cleared in single operation, possibly in parallel

Batching and Assembling Vertices

- glBegin and glEnd designate a batch of primitives
  - Begin mode of GL_TRIANGLES means every 3 vertexes = triangle
- Various vertex attributes
  - Position attribute sent with glVertex* commands
  - Also colors, texture coordinates, normals, etc.
- glVertex* assembles a vertex and puts it into the primitive batch
  - Other vertex attribute commands such as glColor* have their attributes "latched" when glVertex* assembles a vertex



Assembling a Vertex



Vertex Attribute Commands

- OpenGL vertex attribute commands follow a regular pattern
  - gl-prefix :: common to all OpenGL API calls
  - Vertex, Normal, TexCoord, Color, SecondaryColor, FogCoord, VertexAttrib, etc.
    - Name the semantic meaning of the attribute
    - VertexAttrib is for generic attributes
      - Used by vertex shaders where the shader determines "meaning" of attributes
      - Attribute zero & Vertex are "special"—they latch the assembly of a vertex
  - 1, 2, 3, 4 :: Number of components for the attribute
    - For an attribute with more components than the number, sensible defaults apply
      - For example, 3 for Color means Red, Green, Blue & Alpha assumed 1.0
  - f, i, s, b, d, ub, us, ui
    - Type of components: float, integer, short, byte, double, unsigned byte, unsigned short, unsigned integer
  - v :: means parameters are passed by a pointer
    - Instead of immediate values

Example

- Consider glColor4ub and glVertex3fv

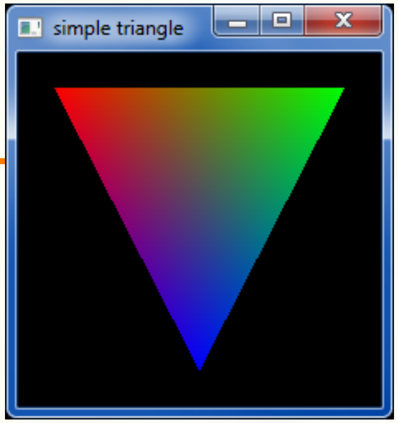
glColor4ub(red, green, blue, alpha);

Belongs to OpenGL | *Meaning of attribute* | *Number of components* | *Type of components*

glVertex3fv(const GLfloat v[3]);

Vector arguments

Assemble a Triangle



- Within the draw routine

```
glBegin(GL_TRIANGLES);

  glColor4ub(255, 0, 0, 255);
  glVertex3f(-0.8,  0.8,  0.3);

  glColor4ub(0, 255, 0, 255);
  glVertex3f( 0.8,  0.8, -0.2);

  glColor4ub(0, 0, 255, 255);
  glVertex3f( 0.0, -0.8, -0.2);

glEnd();
```

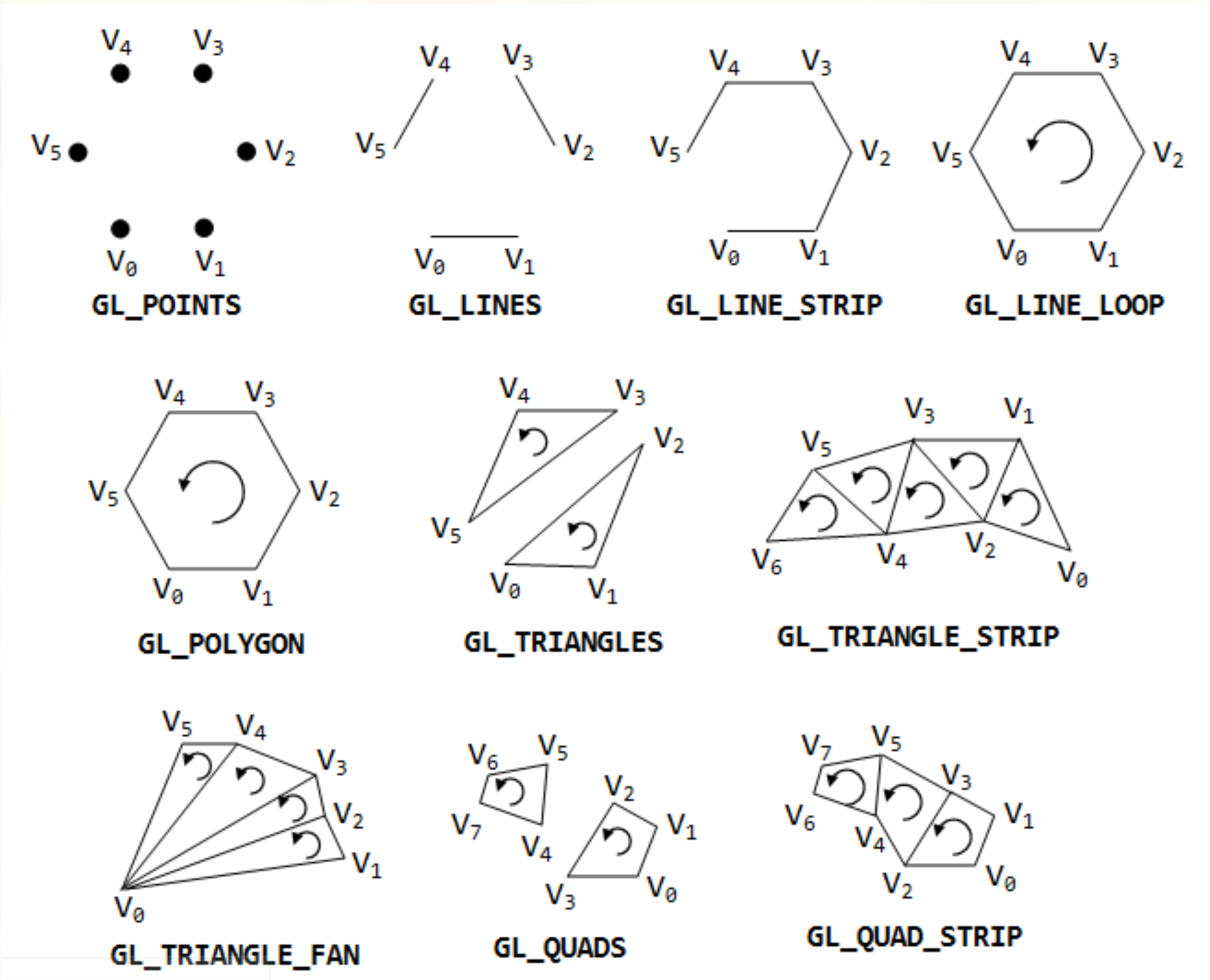
First vertex

Second vertex

Third vertex

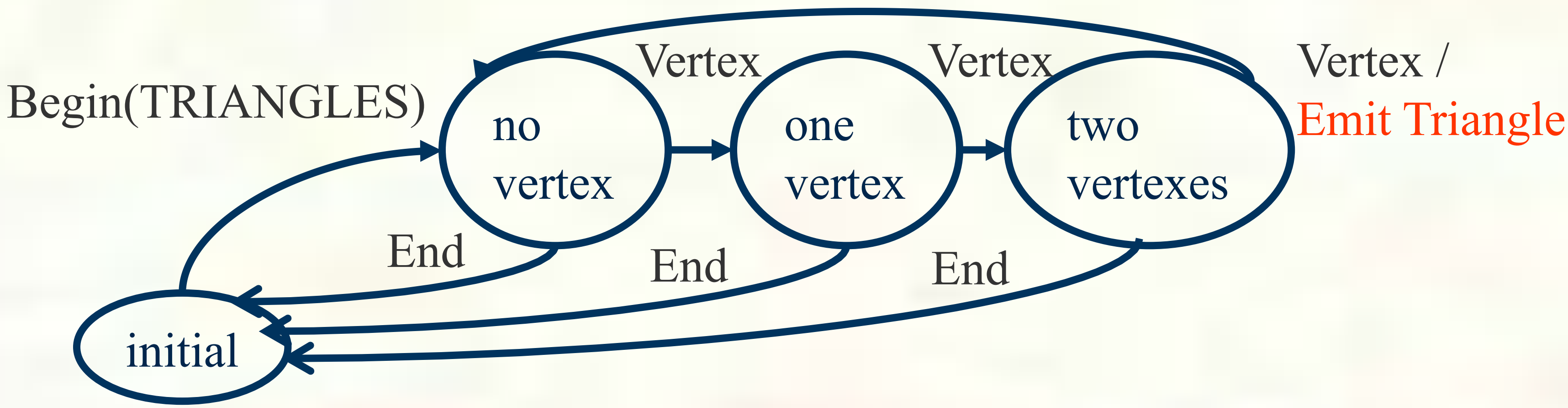
First triangle

glBegin Primitive Batch Types

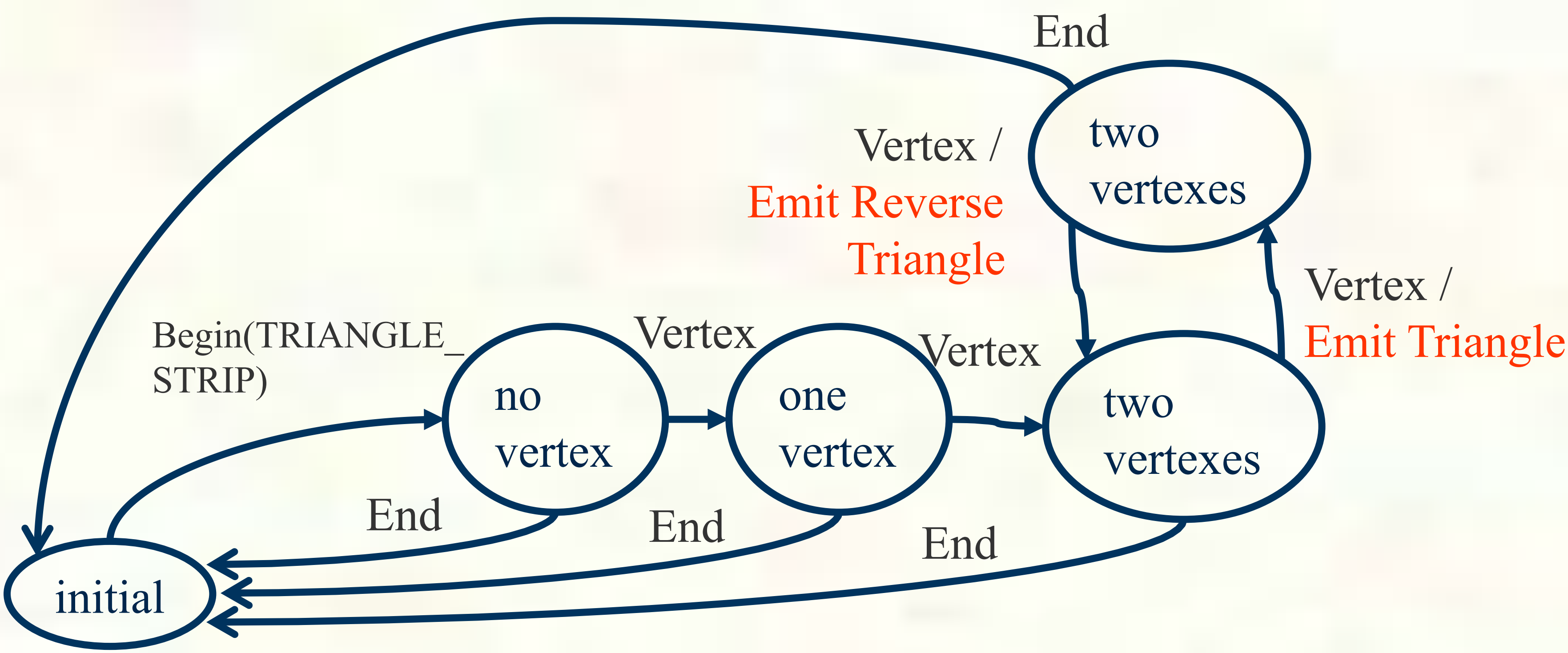


Assembly State Machines

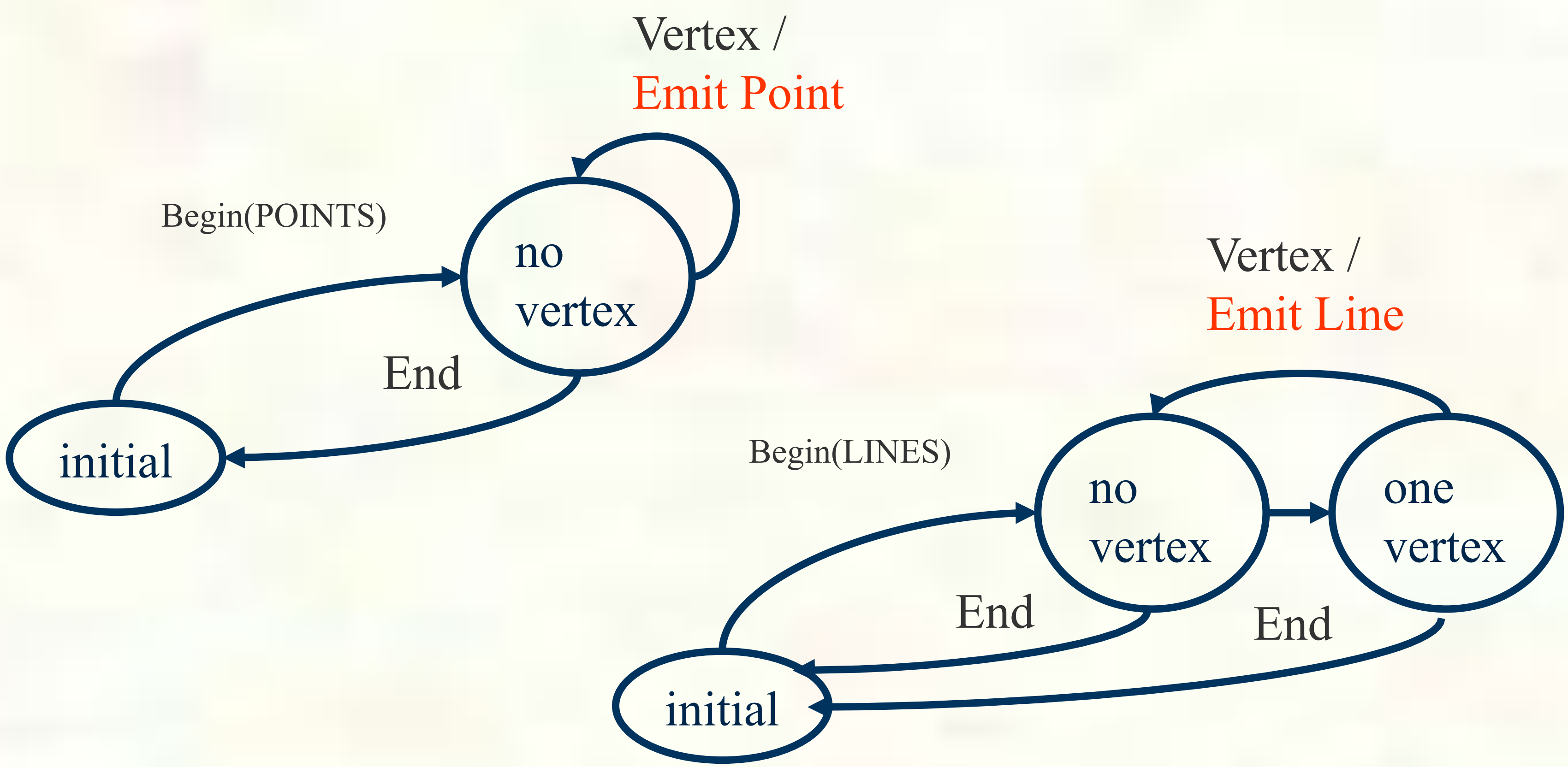
- Fixed-function hardware performs primitive assembly
  - Based on glBegin's mode
- State machine for GL_TRIANGLES



GL_TRIANGLE_STRIP



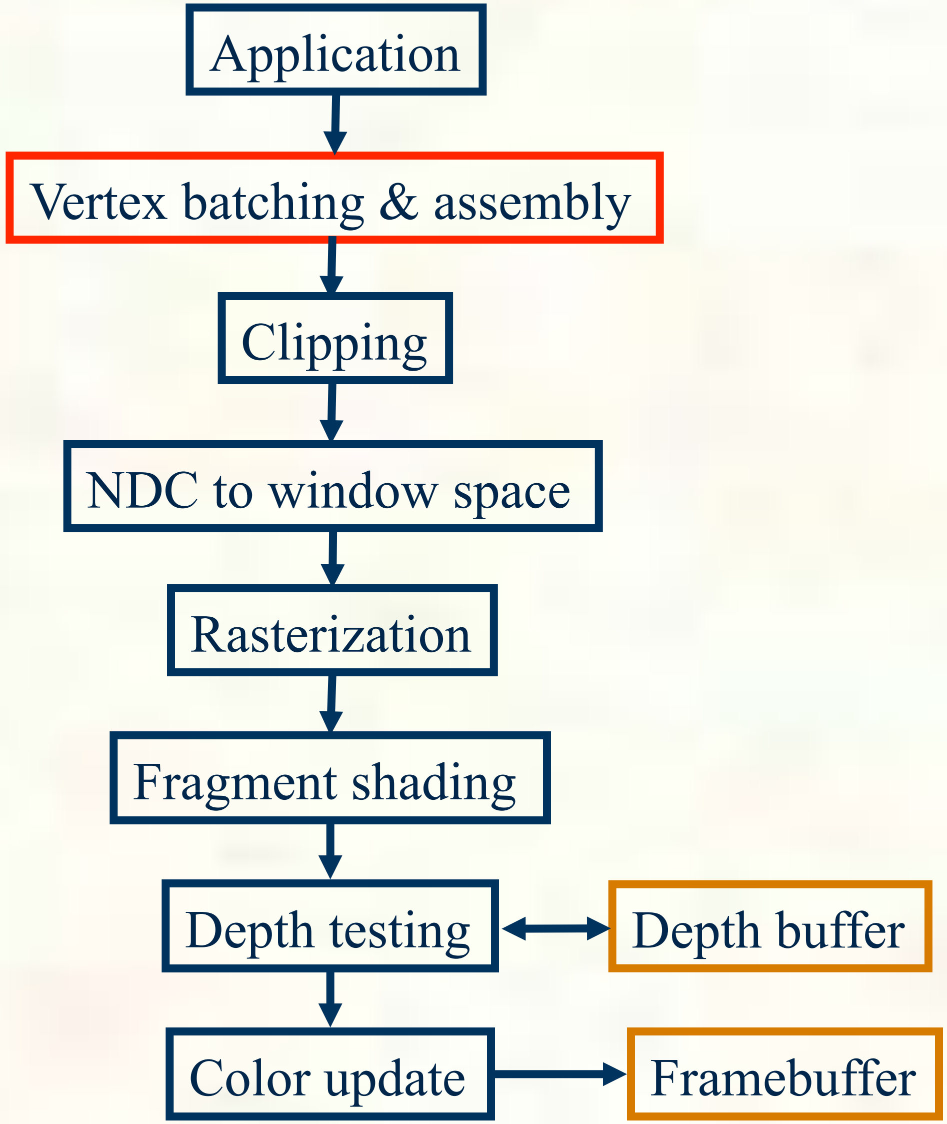
GL_POINTS and GL_LINES



Actual hardware state machine handles all OpenGL begin modes, so rather complex

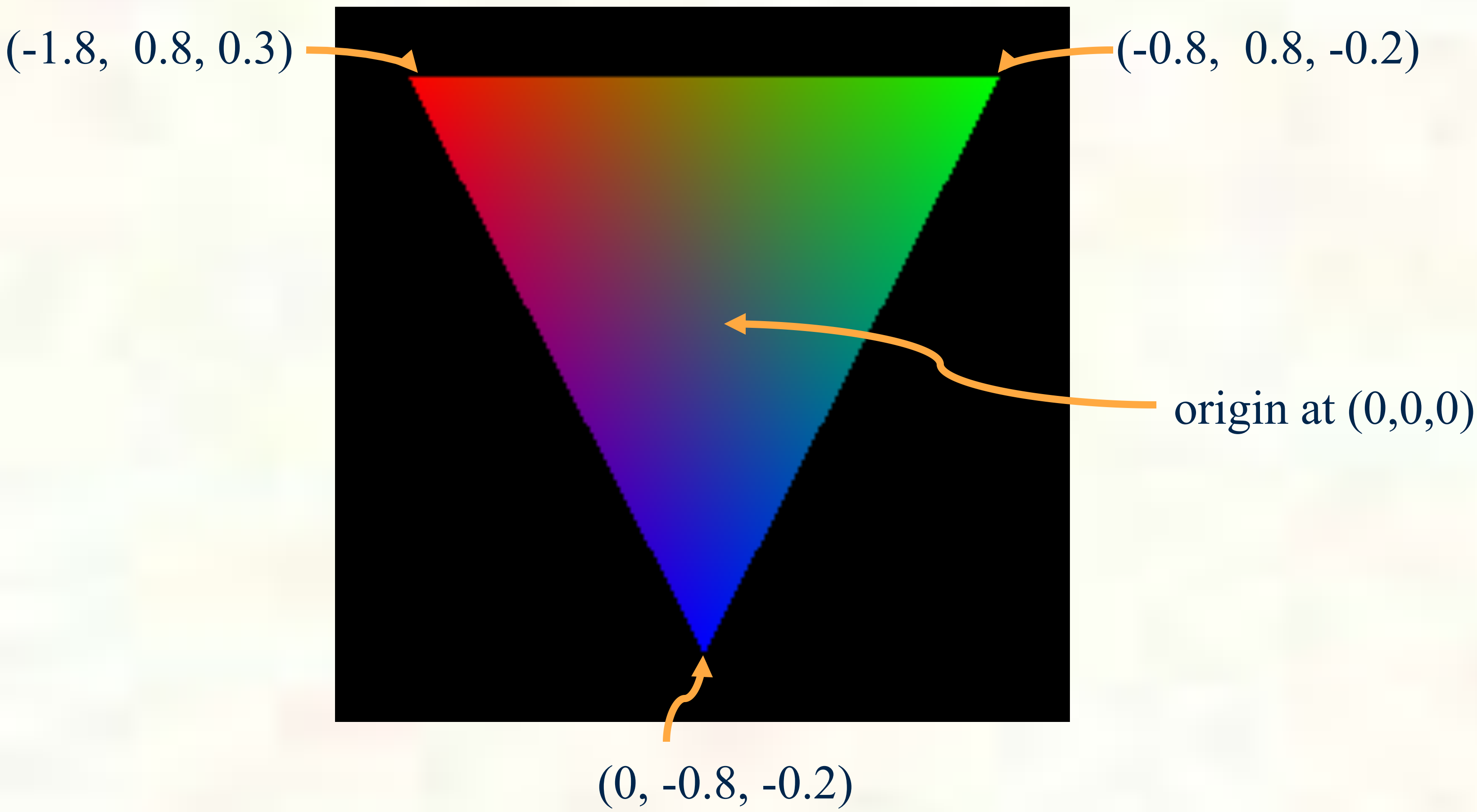
Triangle Assembly

- Now we have a triangle assembled
- Later, we'll generalize how the vertex positions get transformed
  - And other attributes might be processed too
- For now, just assume the XYZ position passed to glVertex3f position is in NDC space



Our Newly Assembled Triangle

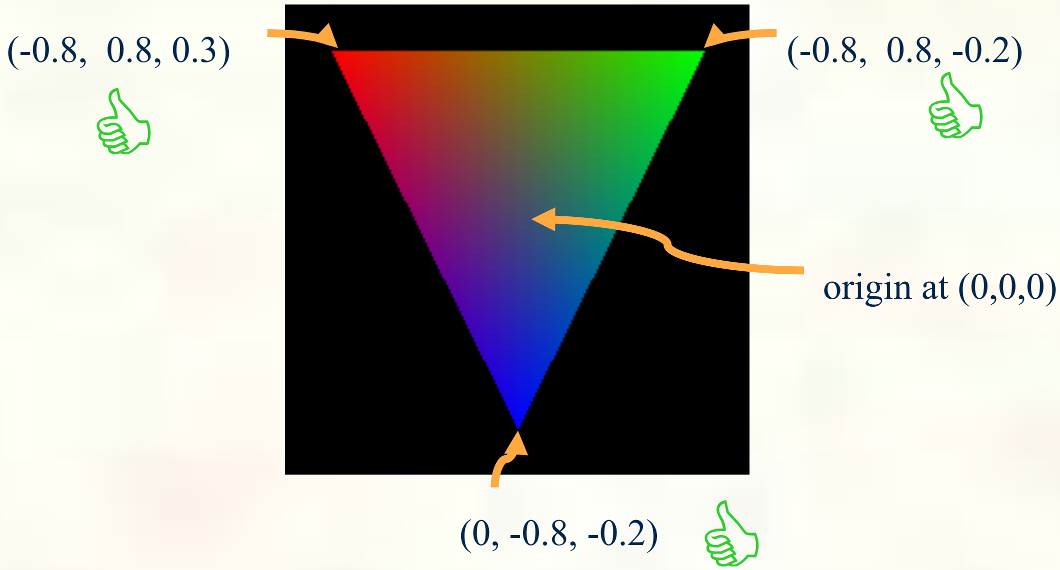
- Think of drawing into a $[-1,+1]^3$ cube



Clipping

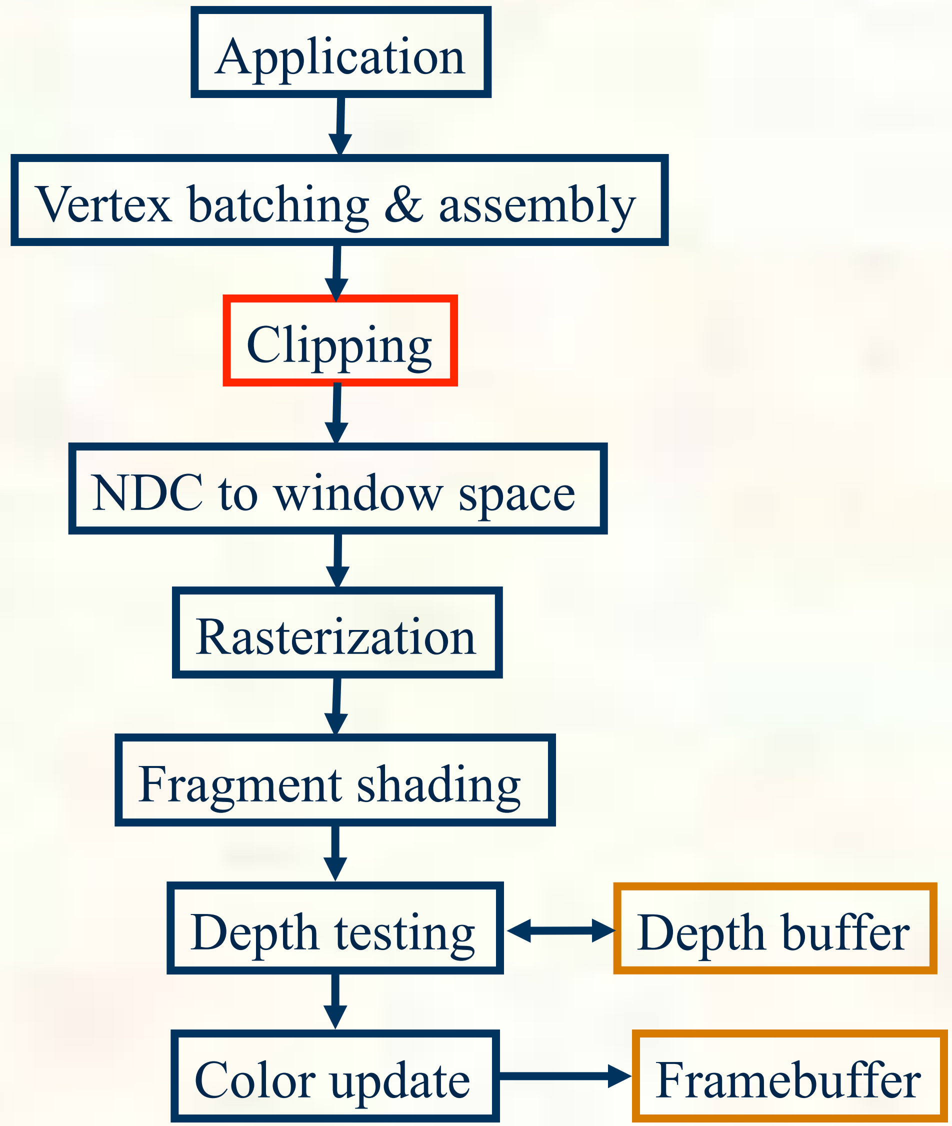
- What if any portion of our triangle extended beyond the NDC range of the $[-1,+1]^3$ cube?
  - Only regions of the triangle $[-1,+1]^3$ cube should be rasterized!
- No clipping for our simple triangle
  - This situation is known as "trivial accept"
  - Because all 3 vertices in the $[-1,+1]^3$ cube

Triangles are convex, so entire triangle must also be in the cube if the vertexes are



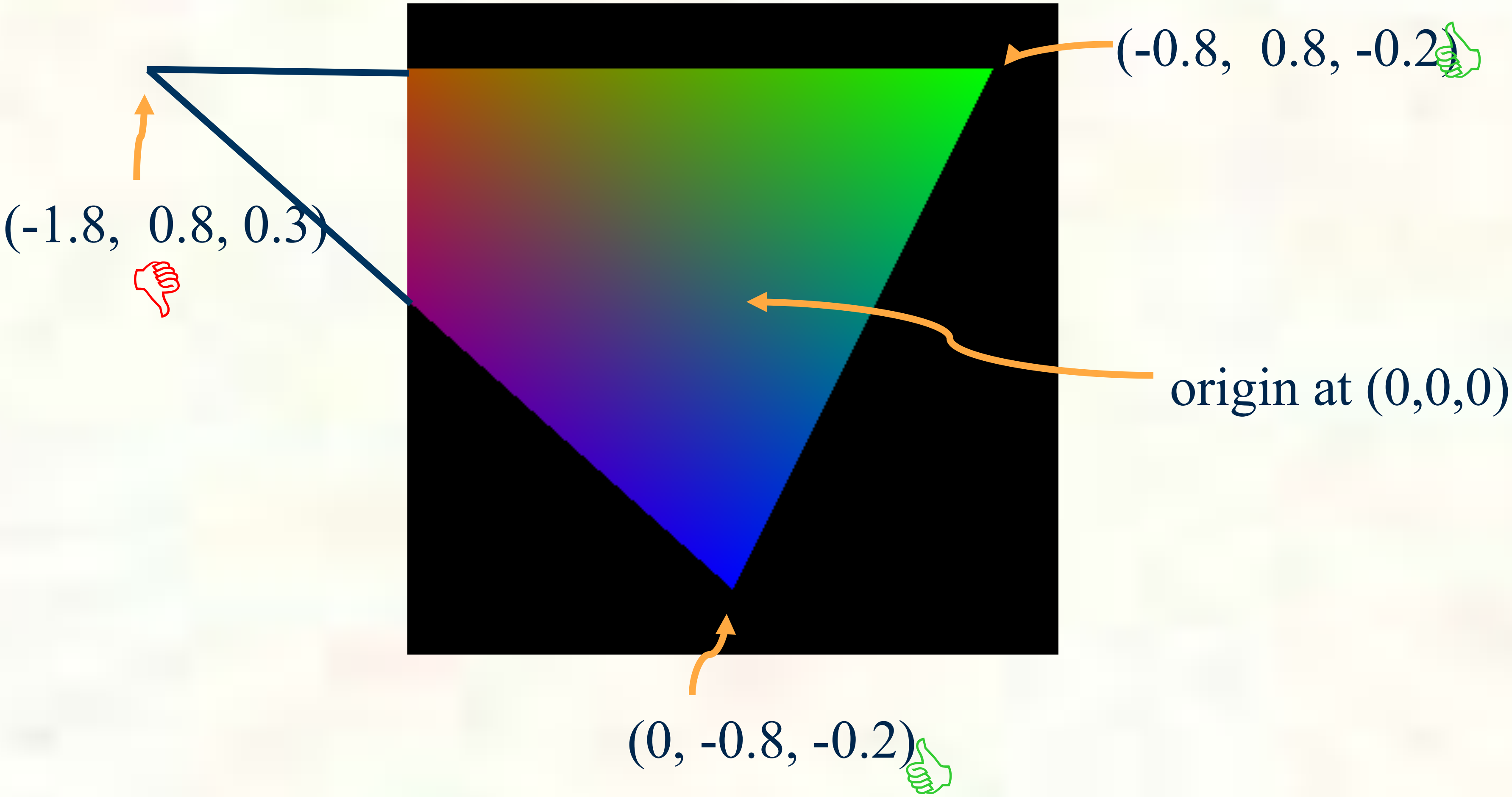
Triangle Clipping

- Triangles can straddle the NDC cube
  - Happens with lines too
- In this case, we must “clip” the triangle to the NDC cube
  - This is an involved process but one that must be done

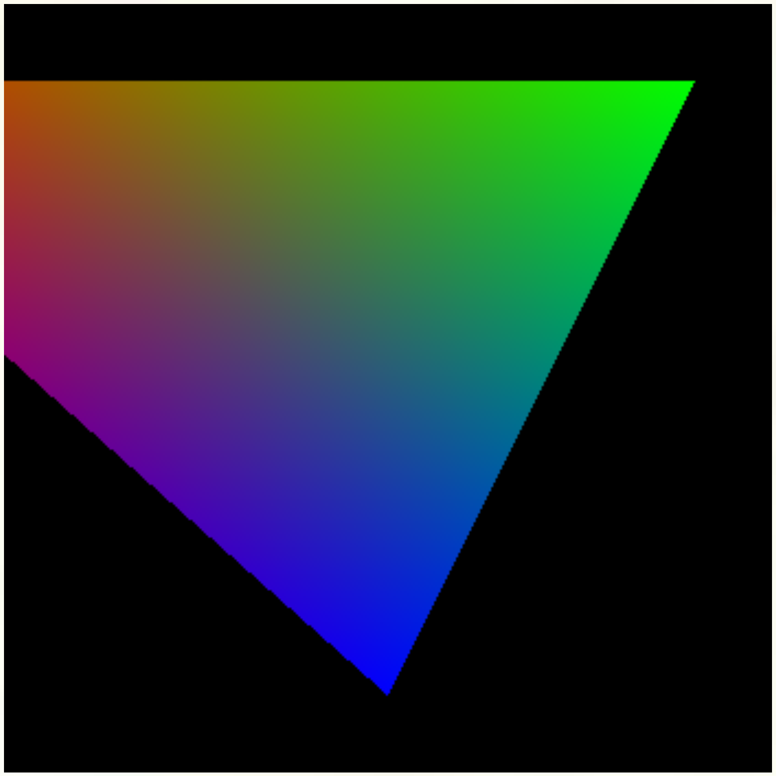


Consider a Different Triangle

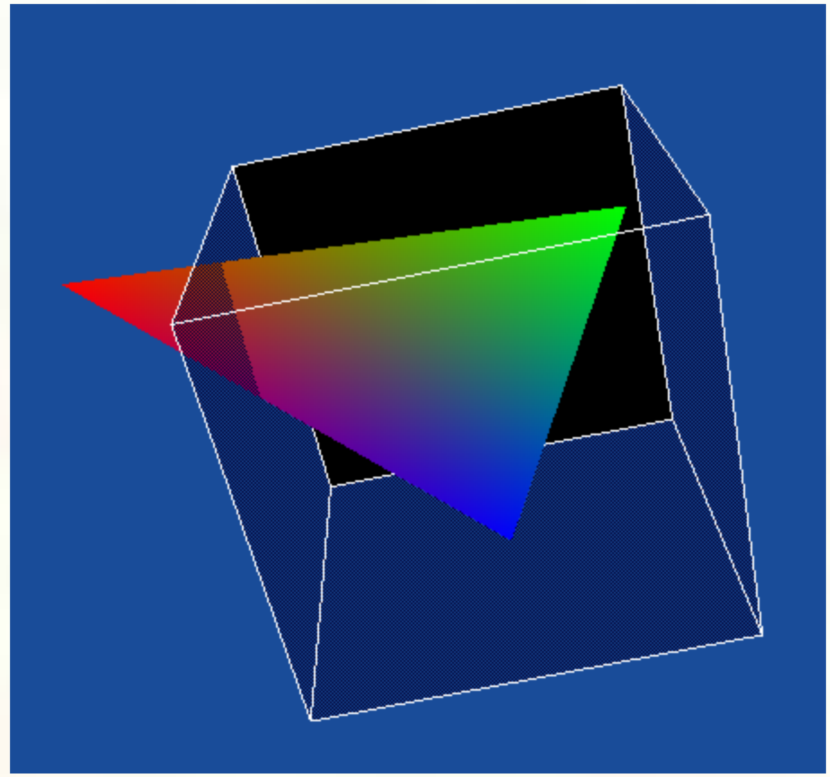
- Move left vertex so it's X = -1.8
  - Result is a clipped triangle



Clipped Triangle Visualized



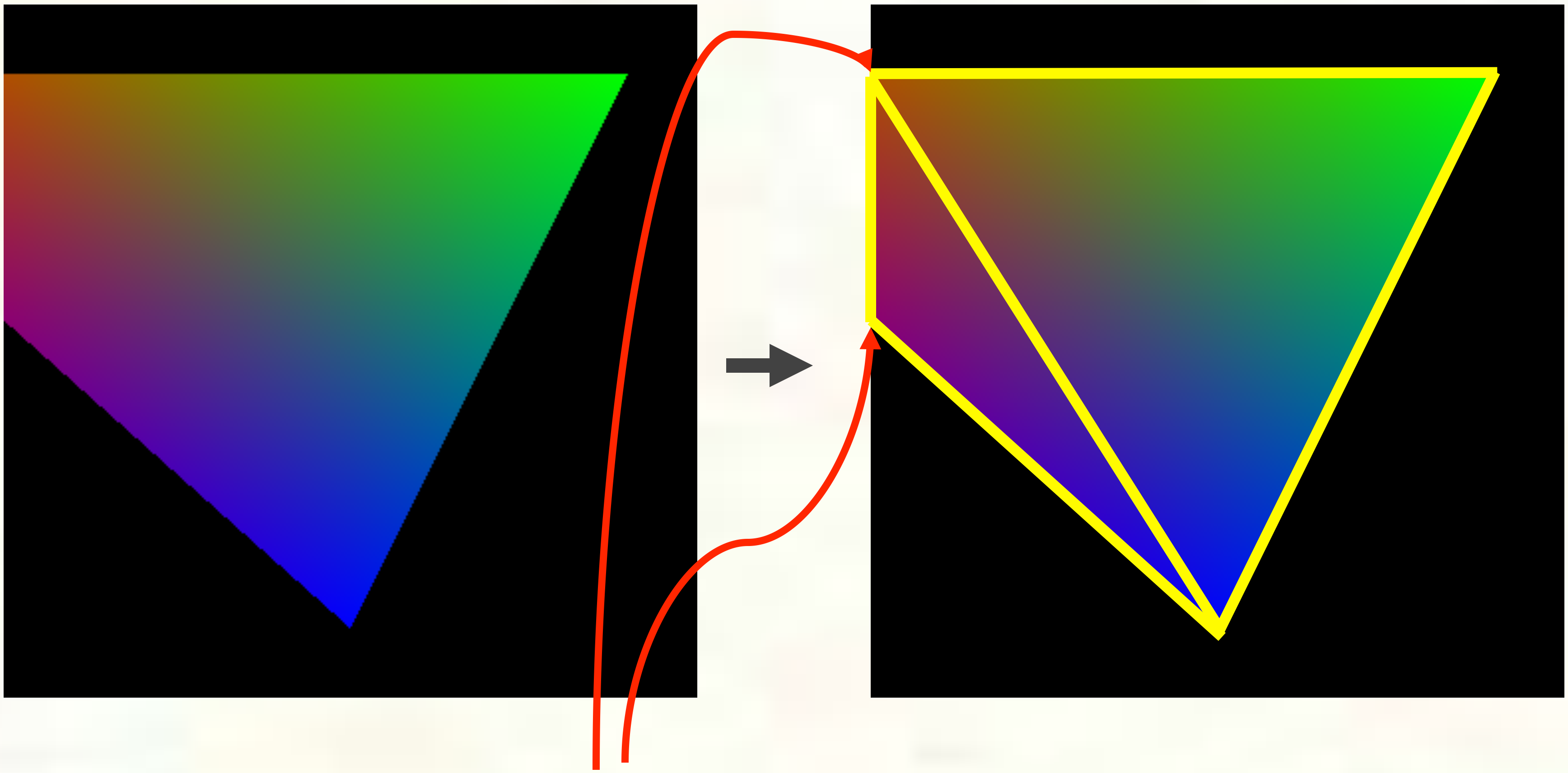
Clipped and Rasterized Normally



Visualization of NDC space

Notice triangle is “poking out” of the cube; this is the reason that should be clipped

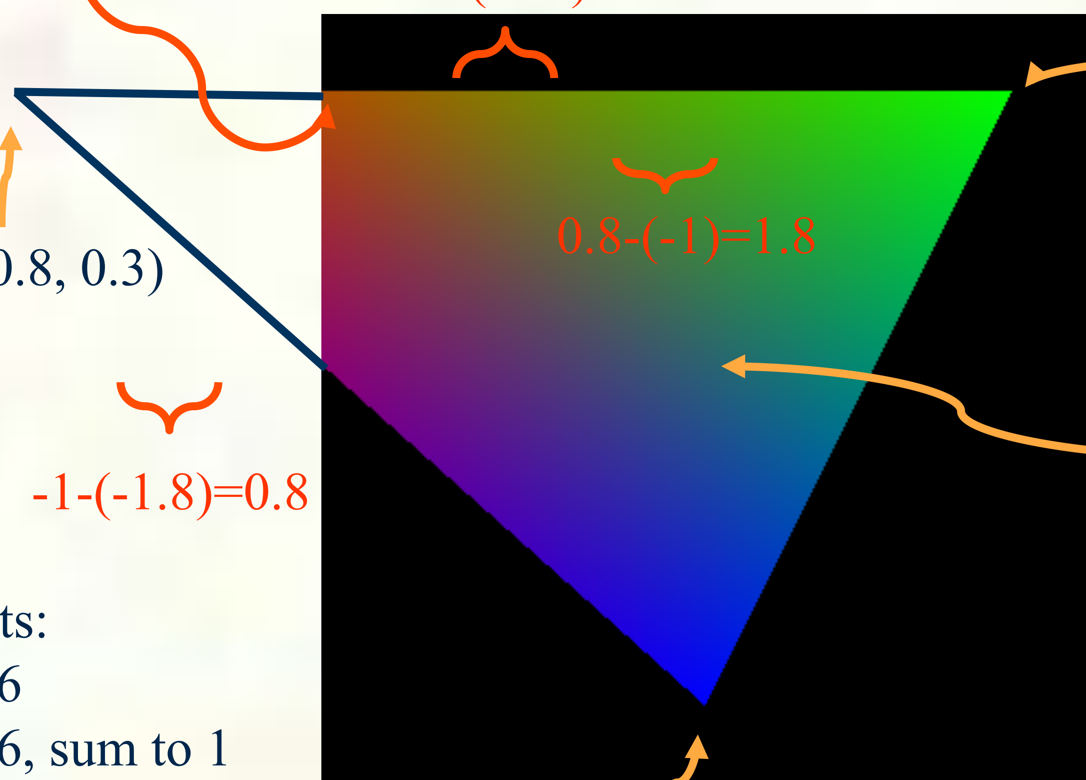
New triangles out



But how do we find these “new” vertices?

The edge clipping the triangle is the line at $X = -1$
so we know $X = -1$ at these points—but what about Y?

Use Ratios to Interpolate Clipped Positions



Weights:
1.8/2.6
0.8/2.6, sum to 1

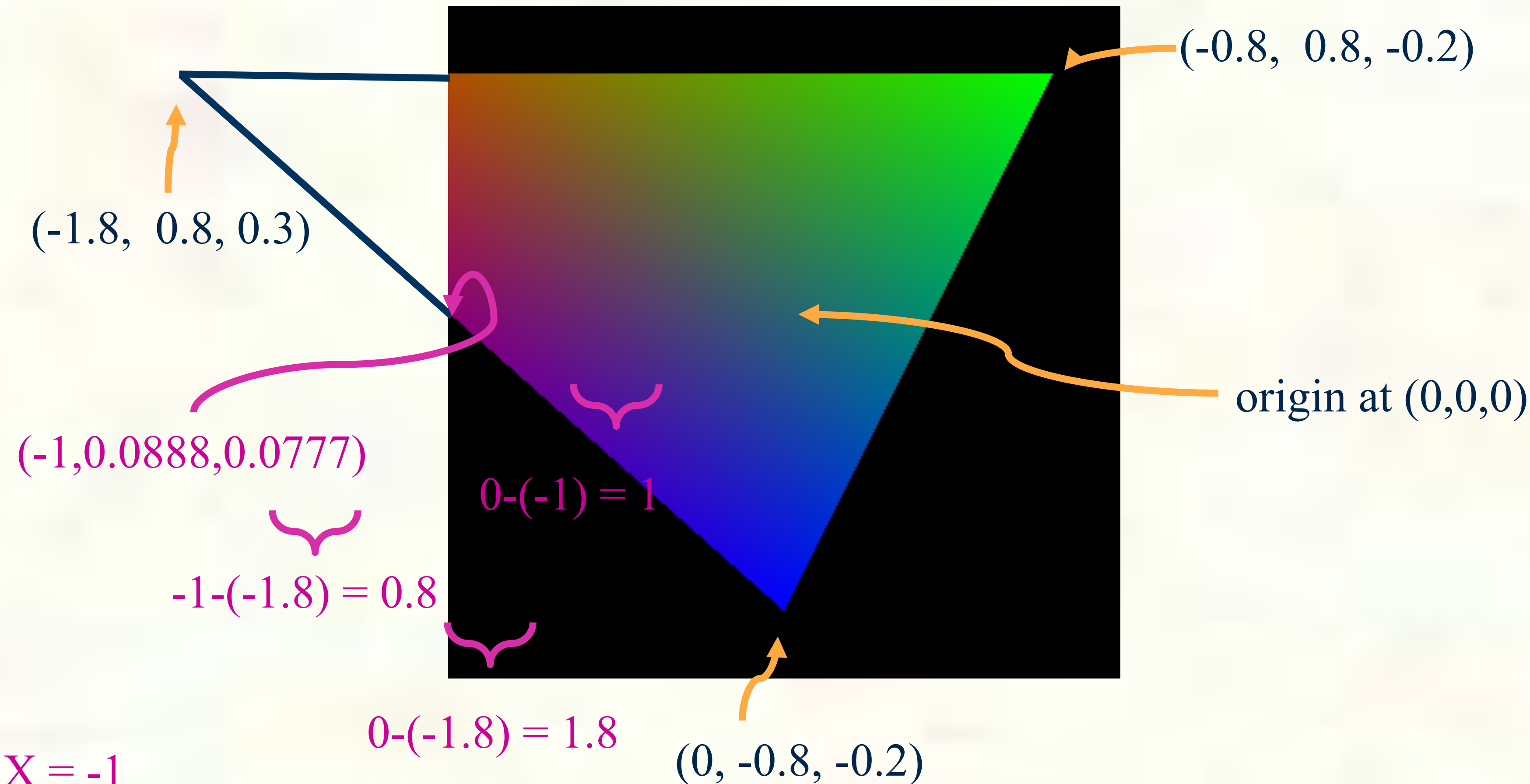
Straightforward because
all the edges are orthogonal

$X = -1$

$Y = (1.8/2.6)\times 0.8 + (0.8/2.6)\times 0.8$
$= 0.8$

$Z = (1.8/2.6)\times 0.3 + (0.8/2.6)\times -0.2$
$= 0.1461538$

Use Ratios to Interpolate Clipped Positions



X = -1

Y = (1/1.8)×0.8 + (0.8/1.8)×-0.8

= 0.08888…

Z = (1/1.8)×0.3 + (0.8/1.8)×-0.2

= 0.07777…

Weights:

1/1.8

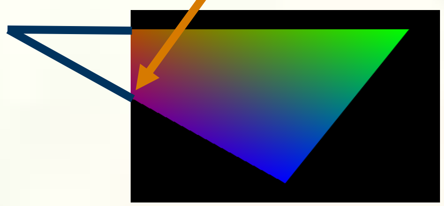
0.8/1.8, sum to 1

Clipping Complications

- Given primitive may be clipped by multiple cube faces
  - Potentially clipping by all 6 faces!
- Approach
  - Four possibilities
    - Face doesn't actually result in any clipping of a triangle
      - Triangle is unaffected by this plane then
    - Clipping eliminates a triangle completely
      - All 3 vertices on "wrong" side of the face's plane
    - Triangle "tip" clipped away
      - Leaving two triangles
    - Triangle "base" is clipped away
      - Leaving a single triangle
  - **Strategy**: implement <u>recursive</u> clipping process
    - "Two triangle" case means resulting two triangles must be clipped by all remaining planes

Attribute Interpolation

- When splitting triangles for clipping, must also interpolate new attributes
  - For example, color
  - Also texture coordinates
- Back to our example
  - BLUE×0.8/1.8 + RED×1/1.8
    - (0,0,1,1)×0.8/1.8 + (1,0,0,1)×1/1.8
    - (0.444,0,.555,1) or MAGENTA

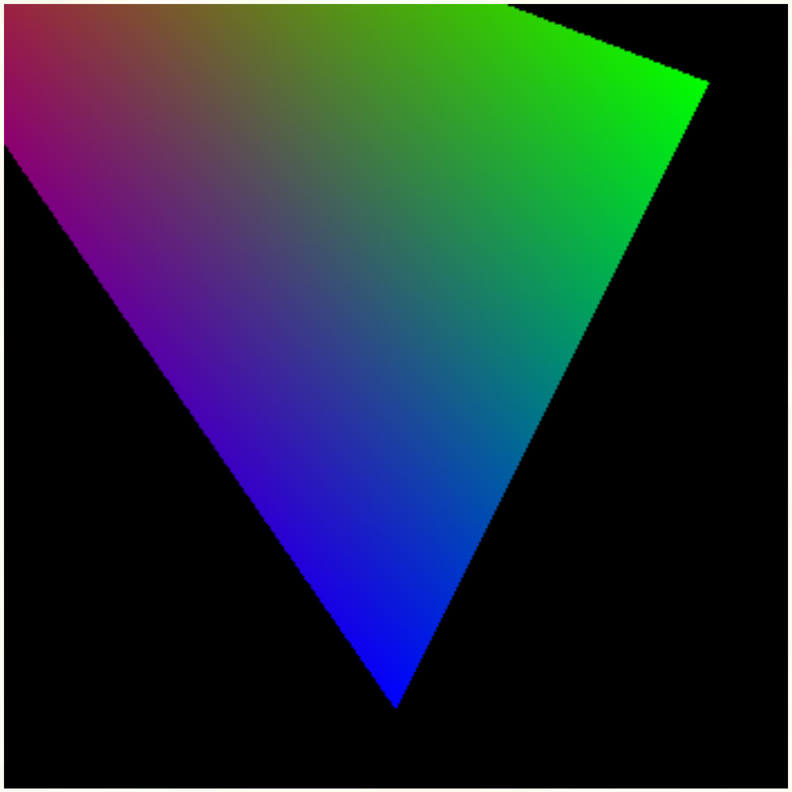


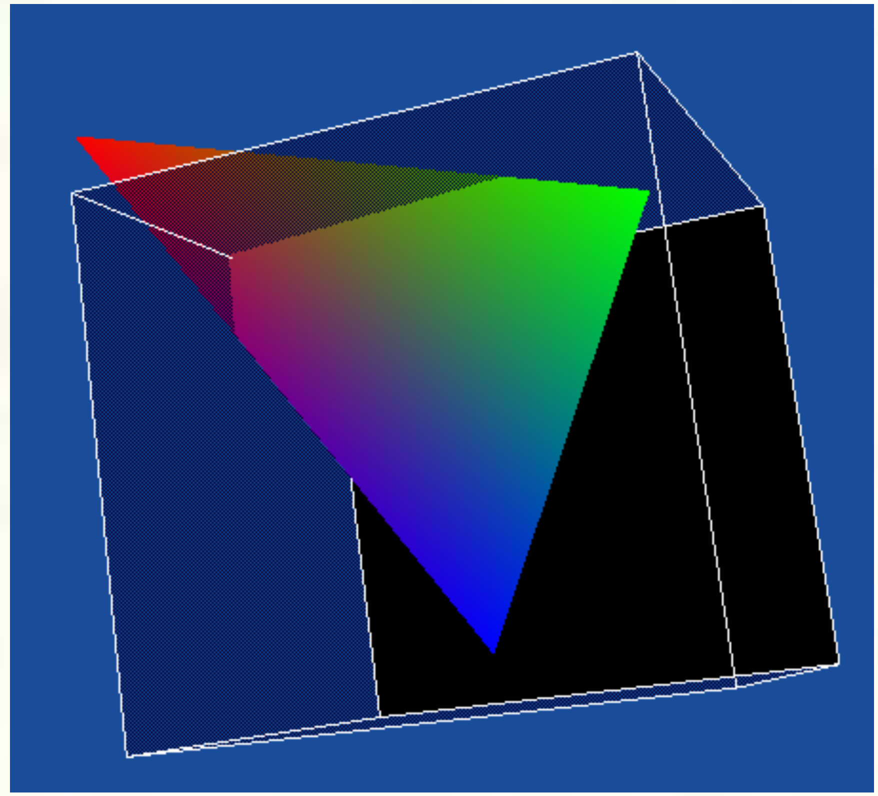
Weights:
1/1.8
0.8/1.8, sum to 1

What to do about this?

- Several possibilities
  - Require applications to <u>never</u> send primitives that require clipping
    - Wishful thinking
    - And a cop-out—makes clipping <u>their</u> problem
  - Rasterize into larger space than normal and discard pixels outsize the NDC cube
    - Increases useless rasterizer work
      - Requires additional math precision in the rasterizer
    - Worse, creates problems when rendering into a projective clip space (needed for perspective)
      - Something for a future lecture
  - Break clipped triangles into smaller triangles that tessellate the clipped region…

Triangle clipped by Two Planes

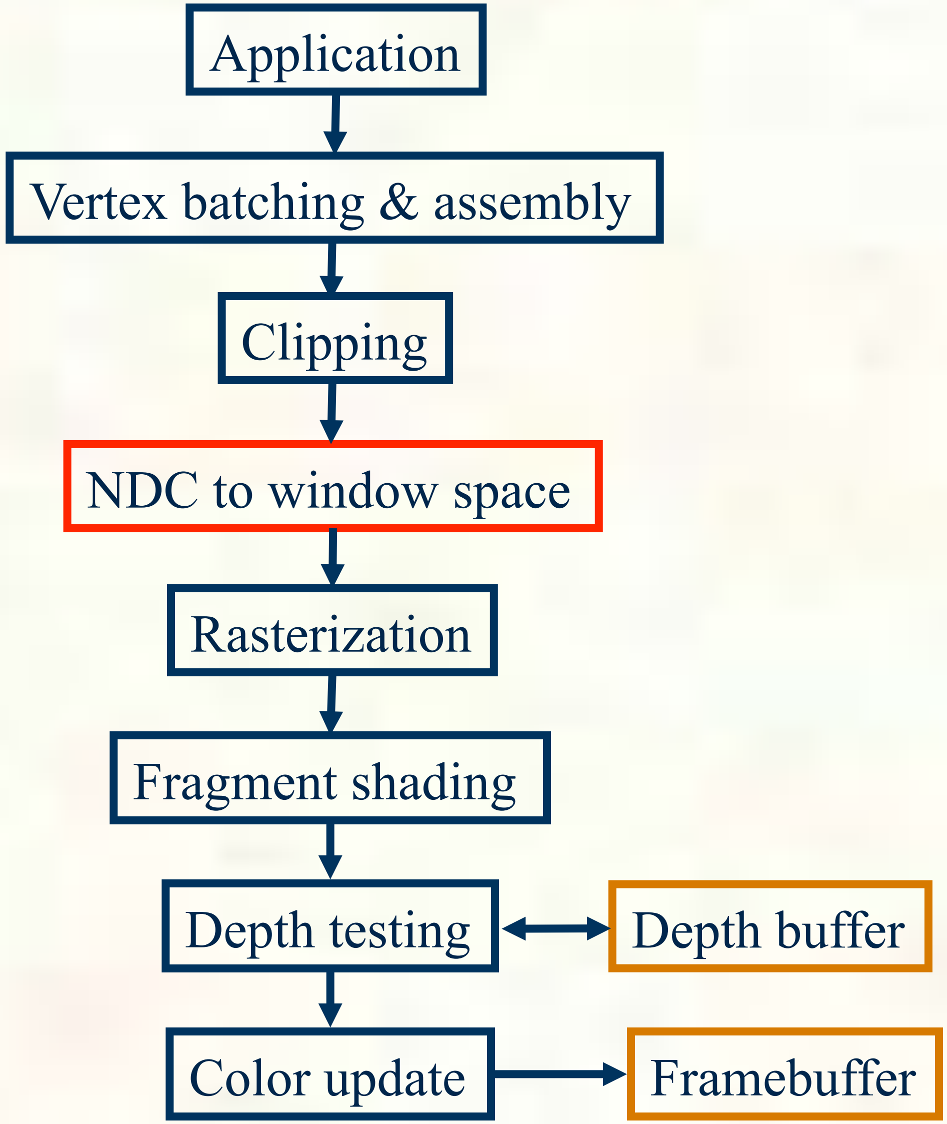




Recursive process can make 4 triangles
And it gets worse with more non-trivial clipping

NDC to Window Space

- NDC is "normalized" to the $[-1,+1]^3$ cube
  - Nice for clipping
  - But doesn't yet map to pixels on the screen
- **Next:** a transform from NDC space to window space



Viewport and Depth Range

- OpenGL has 2 commands to configure the state to map NDC space to window space
  - glViewport(GLint vx, GLint vy, GLsizei w, GLsizei h);
    - Typically programmed to the window's width and height for *w* & *h* and zero for both *vx* & *vy*
    - **Example:** glViewport(0, 0, window_width, window_height);
  - glDepthRange(GLclampd n, GLclampd f);
    - *n* for near depth value, *f* for far depth value
    - Normally set to glDepthRange(0,1)
      - Which is an OpenGL context's initial depth range state
- The mapping from NDC space to window space depends on *vx*, *vy*, *w*, *h*, *n*, and *d*

OpenGL Data Type Naming

- The OpenGL specification allow an implementation to specify how language data types map to OpenGL API data types
  - GLfloat is usually typedef'ed to float but this isn't necessarily true
    - Same for GLint, GLshort, GLdouble
    - But is true in practice
  - GLbyte is byte-sized so expected it to be a char
  - GLubyte, GLushort, and GLuint are unsigned versions of GLbyte, GLshort, and GLint
- Certain names clue you into their parameter usage
  - GLsizei is an integer parameter that is not allowed to be negative
    - An GL_INVALID_VALUE is generated if a GLsizei parameter is ever negative
  - GLclampd and GLclampf are the same as GLfloat and GLdouble, but indicate the parameter will be clamped automatically to the [0,1] range
- Notice
  - glViewport uses GLsizei for width and height
  - glDepthRange uses GLclampd for near and far

OpenGL Errors

- OpenGL reports asynchronously from your commands
  - Effectively, you must explicitly call glGetError to find if any prior command generated an error or was otherwise used incorrectly
  - glGetError returns GL_NO_ERROR if there is no error
    - Otherwise an error such as GL_INVALID_VALUE is returned
- Rationale
  - OpenGL commands are meant to be executed in a pipeline so the error might not be identified until after the command's function has returned
    - Errors might be detected by hardware that isn't actually the CPU
  - Also forcing applications to check return codes of functions is slow
    - It's inappropriate for a high-performance API such as OpenGL
- So if you suspect errors, you have to poll for them
  - Learn to do this while you are debugging your code
  - If something fails to happen, suspect there's an OpenGL errors
- Also commands that generated an error are ignored
  - The only exception is GL_OUT_OF_MEMORY which results in undefined state

Mapping NDC to Window Space

- Assume (x,y,z) is the NDC coordinate that's passed to glVertex3f in our simple_triangle example
- Then window-space (w_x,w_y,w_z) location is
  - $w_x = (w/2)\times x + v_x + w/2$
  - $w_y = (h/2)\times y + v_y + h/2$
  - $w_z = [(f-n)/2]\times z + (n+f)/2$

$\times$ *means scalar multiplication here*

Where is glViewport set?

- The simple_triangle program never calls glViewport
  - That's OK because GLUT will call glViewport for you if you don't register your own per-window callback to handle when a window is reshaped (resized)
  - Without a reshape callback registered, GLUT will simply call glViewport(0, 0, window_width, window_height);
- Alternatively, you can use glReshapeFunc to register a callback
  - Then calling glViewport or otherwise tracking the window height becomes your application's responsibility
  - Example reshape callback:

    ```
    void reshape(int w, int h) {
      glViewport(0, 0, w, h);
    }
    ```
  - Example registering a reshape callback:

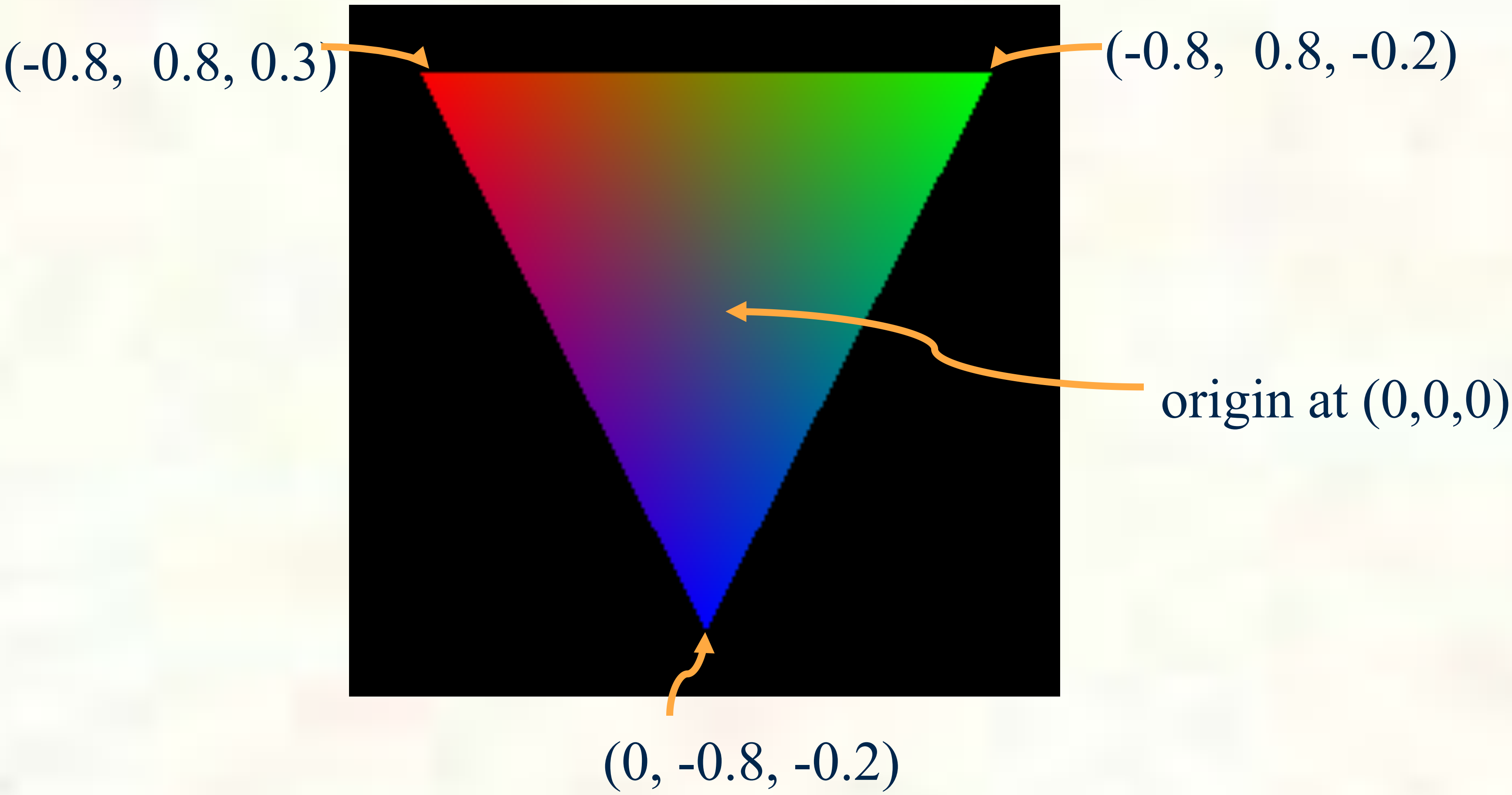
    ```
    glReshapeFunc(reshape);
    ```
- **FYI**: OpenGL maintains a lower-left window-space origin
  - Whereas most 2D graphics APIs use upper-left

What about glDepthRange?

- Simple applications don't normally need to call glDepthRange
  - Notice the simple_triangle program never calls glDepthRange
- Rationale
  - The initial depth range of [0,1] is fine for most application
  - It says the entire available depth buffer range should be used
- When the depth range is [0,1] the equation for window-space z simplifies to $wz = \frac{1}{2} \times z + \frac{1}{2}$

Triangle Vertices in Window Space

- Assume the window is 500x500 pixels
  - So glViewport(0,0,500,500) has been called



Apply the Transforms

- First vertex :: (-0.8, 0.8, 0.3)
  - $w_x = (w/2)\times x + v_x + w/2 = 250\times(-0.8) + 250 = 50$
  - $w_y = (h/2)y + v_y + h/2 = 250\times(0.8) + 250 = 450$
  - $w_z = [(f-n)/2]\times z + (n+f)/2 = 0.65$
- Second vertex :: (0.8, 0.8, -0.2)
  - $w_x = (w/2)\times x + v_x + w/2 = 250\times(-0.8) + 250 = 50$
  - $w_y = (h/2)y + v_y + h/2 = 250\times(0.8) + 250 = 450$
  - $w_z = [(f-n)/2]\times z + (n+f)/2 = 0.4$
- Third vertex :: (0, -0.8, -0.2)
  - $w_x = (w/2)\times x + v_x + w/2 = 250\times 0 + 250 = 250$
  - $w_y = (h/2)y + v_y + h/2 = 250\times(-0.8) + 250 = 50$
  - $w_z = [(f-n)/2]\times z + (n+f)/2 = 0.4$

Still Left to Do

- Rasterize the clipped triangle
  - But our triangle's vertexes are in window space so we are ready
- Interpolate color values over the triangle
- Depth test the triangle
- Update pixel locations
- Swap buffers
- Next lecture!

Next Lecture

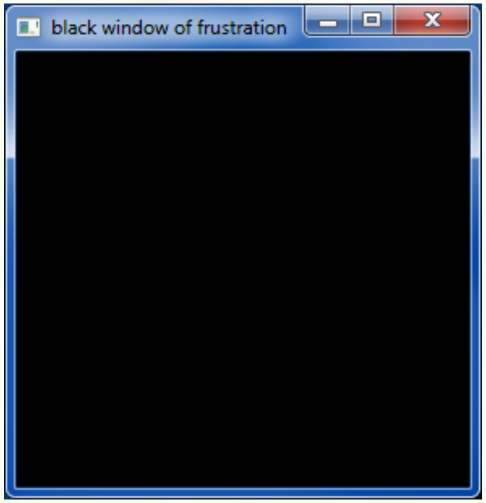
- Graphics Pipeline
  - *What are the operations in the so-called "graphics pipeline"?*
  - As usual, expect a short quiz on today's lecture
    - Know how to map clip space to NDC space to window space

- Assignments
  - Reading from "Interactive Computer Graphics" (Angel)
    - Chapter 2, pages 43-107
  - Homework (a.k.a. Project Zero), **deadline** January 25th
    - Get the ZIP for the "simple triangle" and "clip space" example programs
    - Learn how to compile and run them on your CS account
    - Modify either program to
      - Change the clear color to burnt orange
      - Change the title of the window to your name
      - Instead of drawing a single triangle, make a simple arrangement of polygons forming a letter from your name
    - Use the **turnin** system to submit your modified source code and a screenshot image of your modified example

Purpose
Gain familiarity
with OpenGL programming
and submitting
projects

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