# Intro to OpenGL II

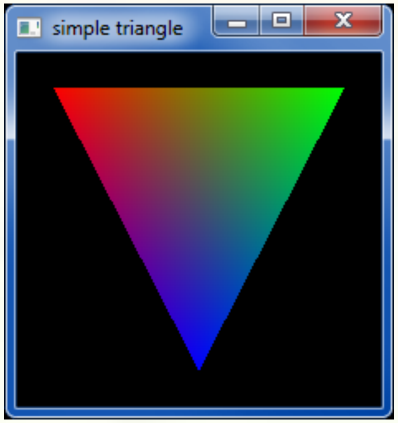
Don Fussell
Computer Science Department
The University of Texas at Austin

# Where are we?

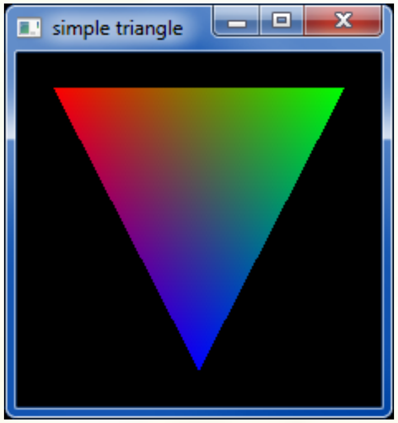
- Last lecture, we started the OpenGL pipeline with our example code
- This lecture we'll continue that

# 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();
```



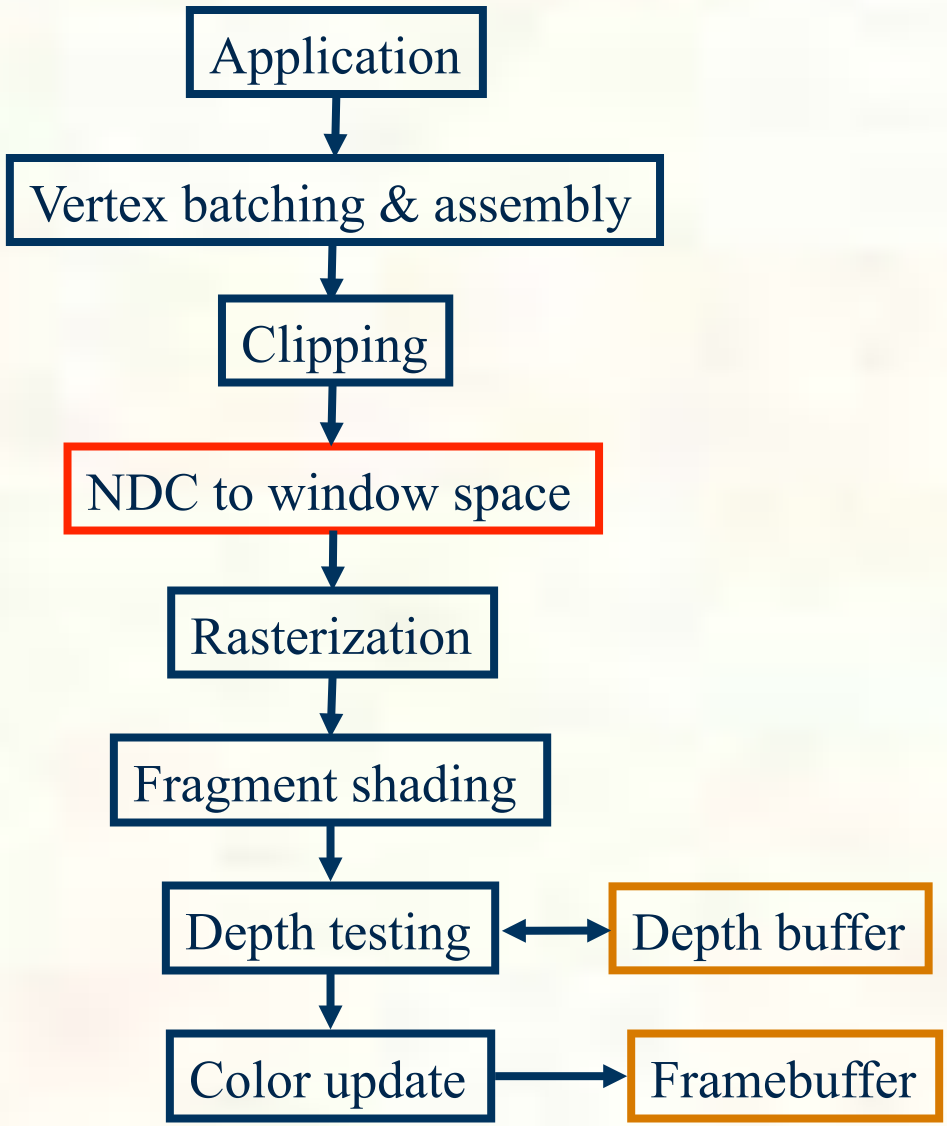
# GLUT API Example




```
#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();
}
```

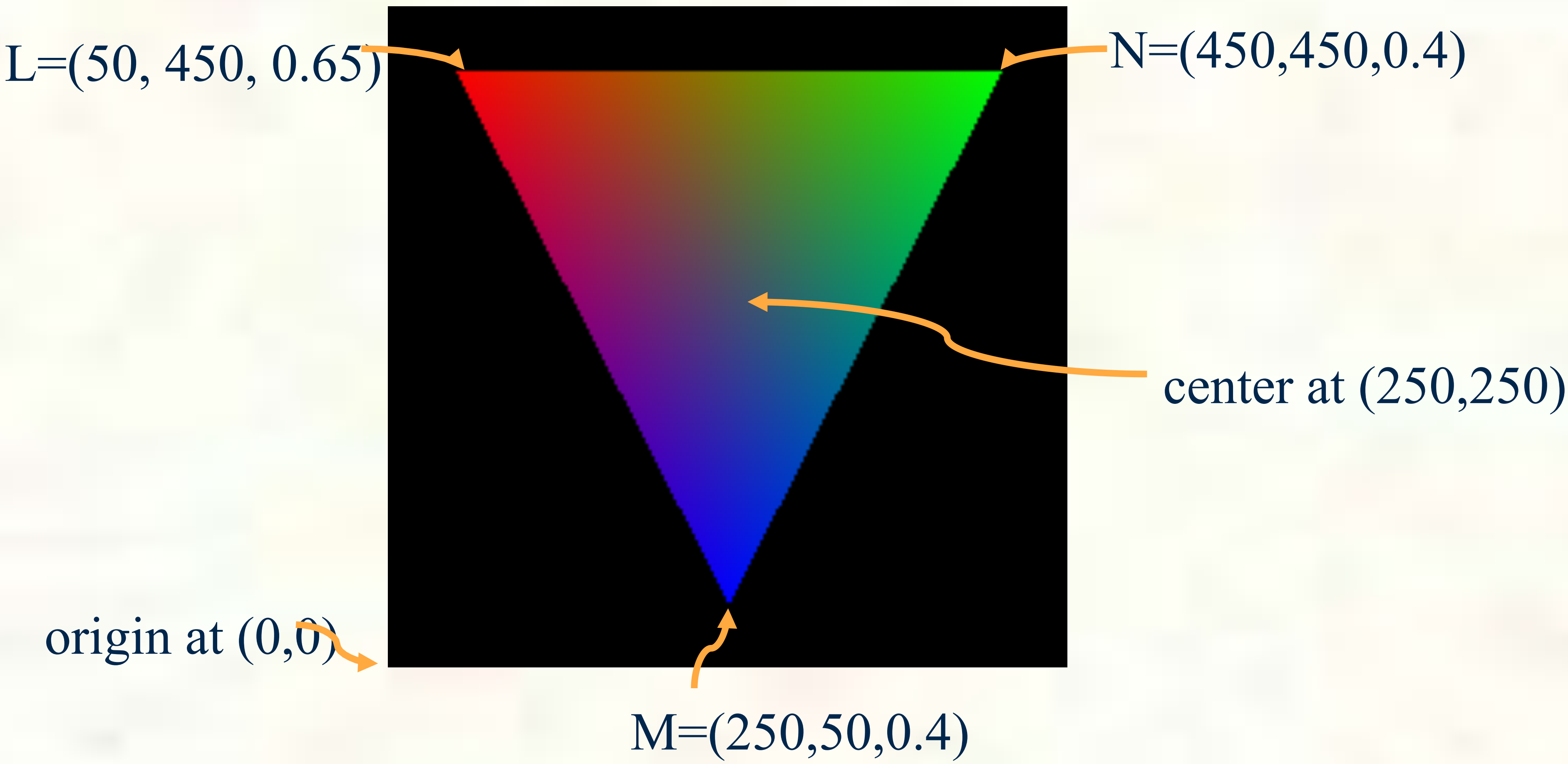
# NDC to Window Space

- Done transforming from NDC space to window space
- Next: Rasterize, then shade pixels (fragments)



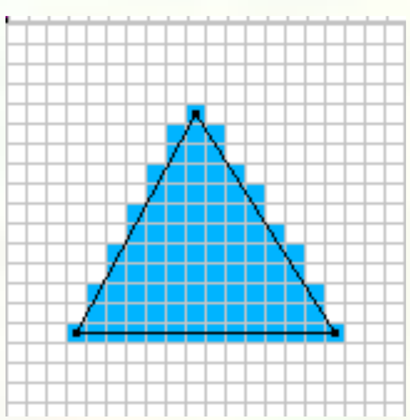
# Screen Space Coordinates of Triangle

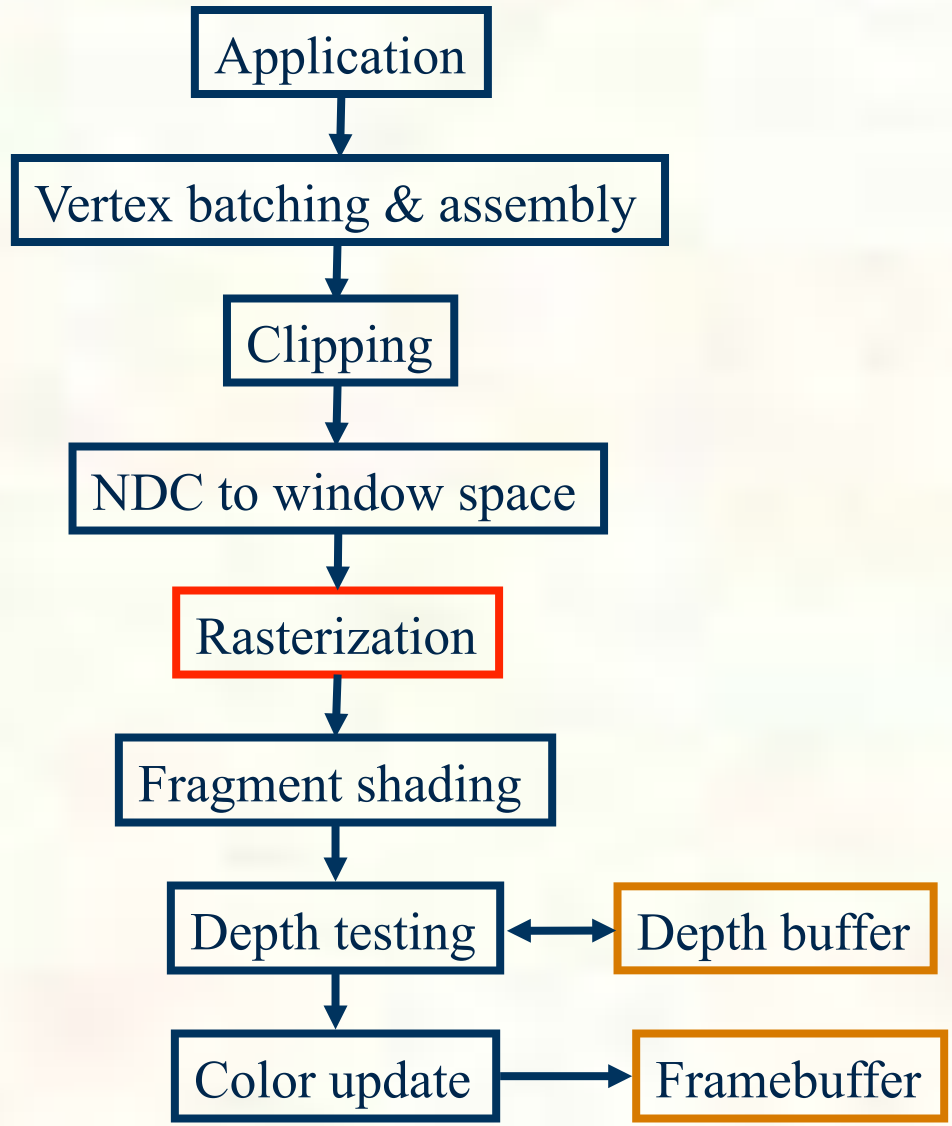
- Assume the window is 500x500 pixels
  - So glViewport(0,0,500,500) has been called



# Rasterization

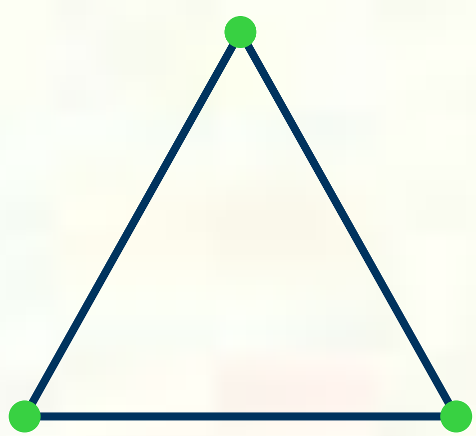
- Process of converting a clipped triangle into a set of sample locations covered by the triangle
  - Also can rasterize points and lines



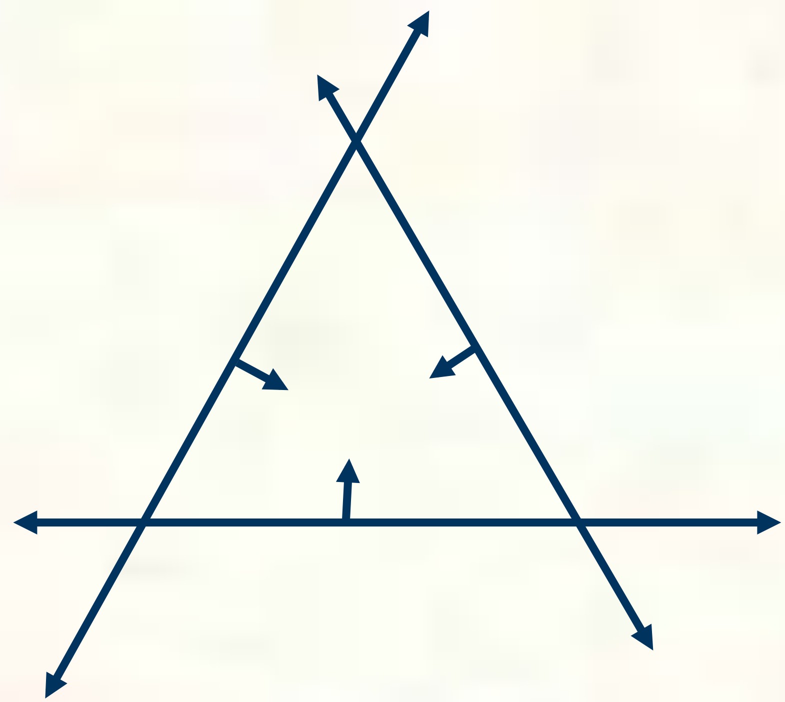


# Determining a Triangle

- **Classic view**: 3 points determine a triangle
  - Given 3 vertex positions, we determine a triangle
  - Hence glVertex3f/glVertex3f/glVertex3f

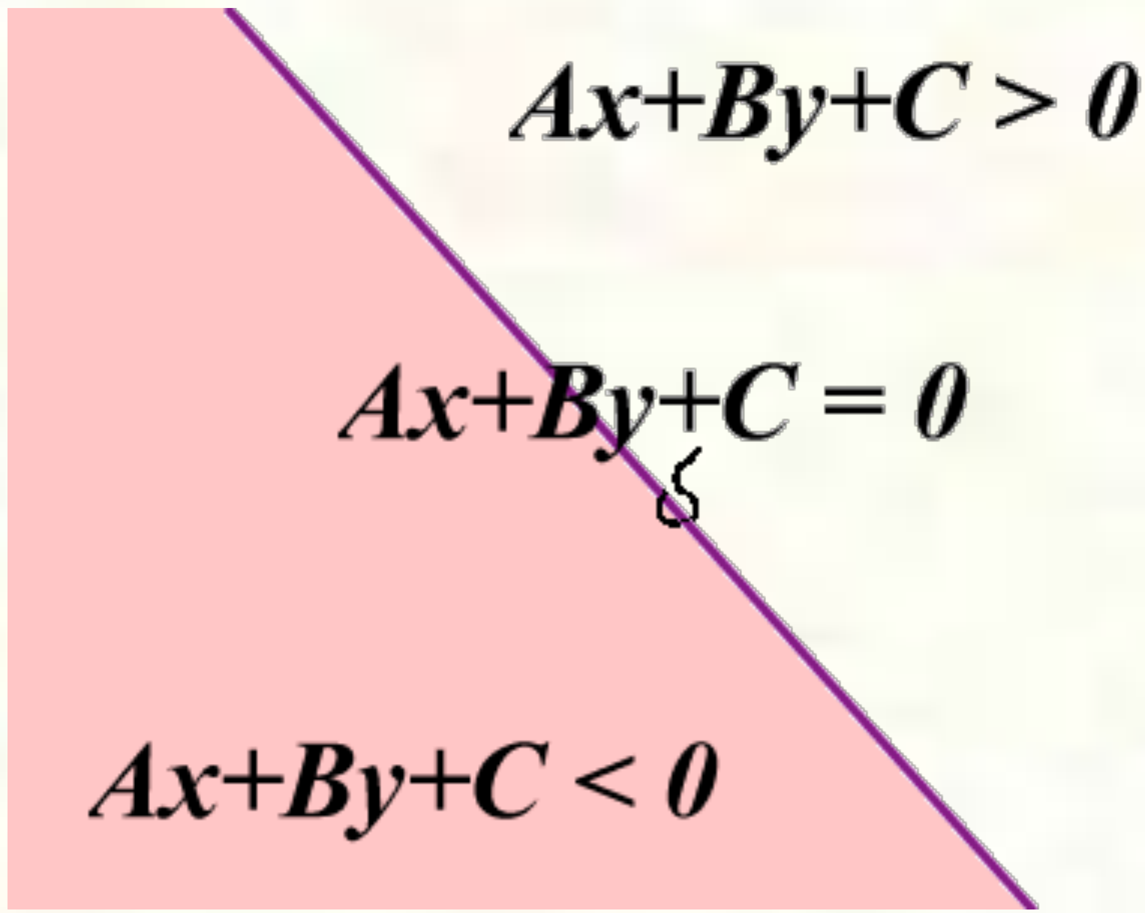


- **Rasterization view**: 3 oriented edge equations determine a triangle

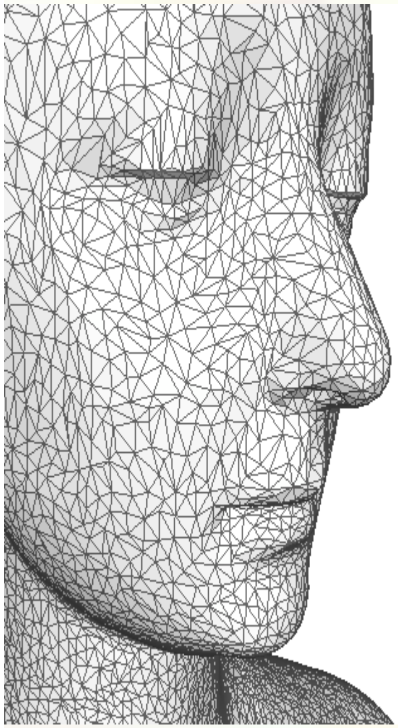


Each oriented edge equation in form:
$A*x + B*y + C \geq 0$

# Oriented Edge Equations



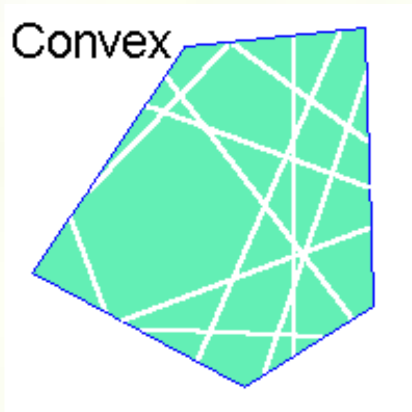
# Step back: Why Triangles?

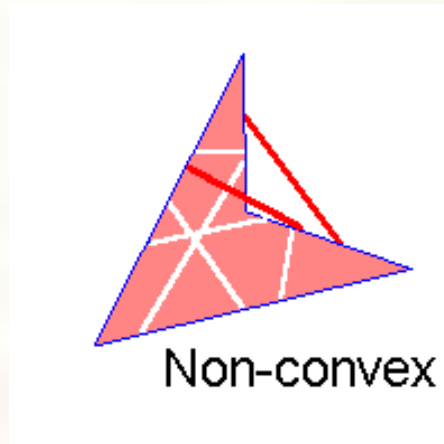


*Face meshed with triangles*

- Simplest linear primitive with area
  - If it got any simpler, the primitive would be a line (just 2 vertexes)
  - Guaranteed to be planar (flat) and convex (not concave)
- Triangles are compact
  - 3 vertexes, 9 scalar values in affine 3D, determine a triangle
  - When in a mesh, vertex positions can be "shared" among adjacent triangles
- Triangles are simple
  - Simplicity and generality of triangles facilitates elegant, hardware-amenable algorithms
- Triangles lacks curvature
  - BUT with enough triangles, we can piecewise approximate just about any manifold
- We can subdivide regions of high curvature until we reach flat regions to represent as a triangle

# Concave vs. Convex

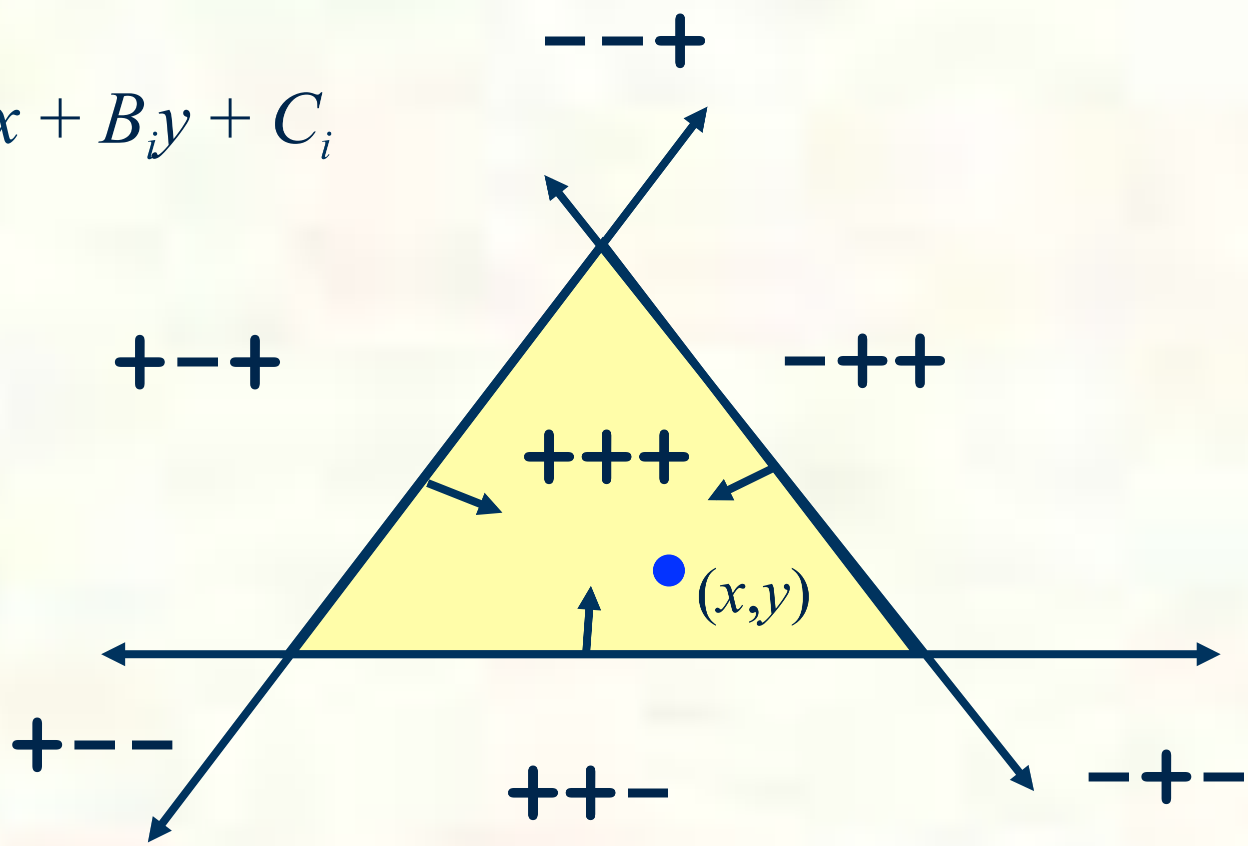



- Region is convex if any two points can be connected by a line segment where all points on this segment are also in the region
  - Opposite is non-convex
- Concave means the region is connected but NOT convex
  - Connected means there's some path (not necessarily a line) from every two points in the region that is entirely in the region

# 7 Cases

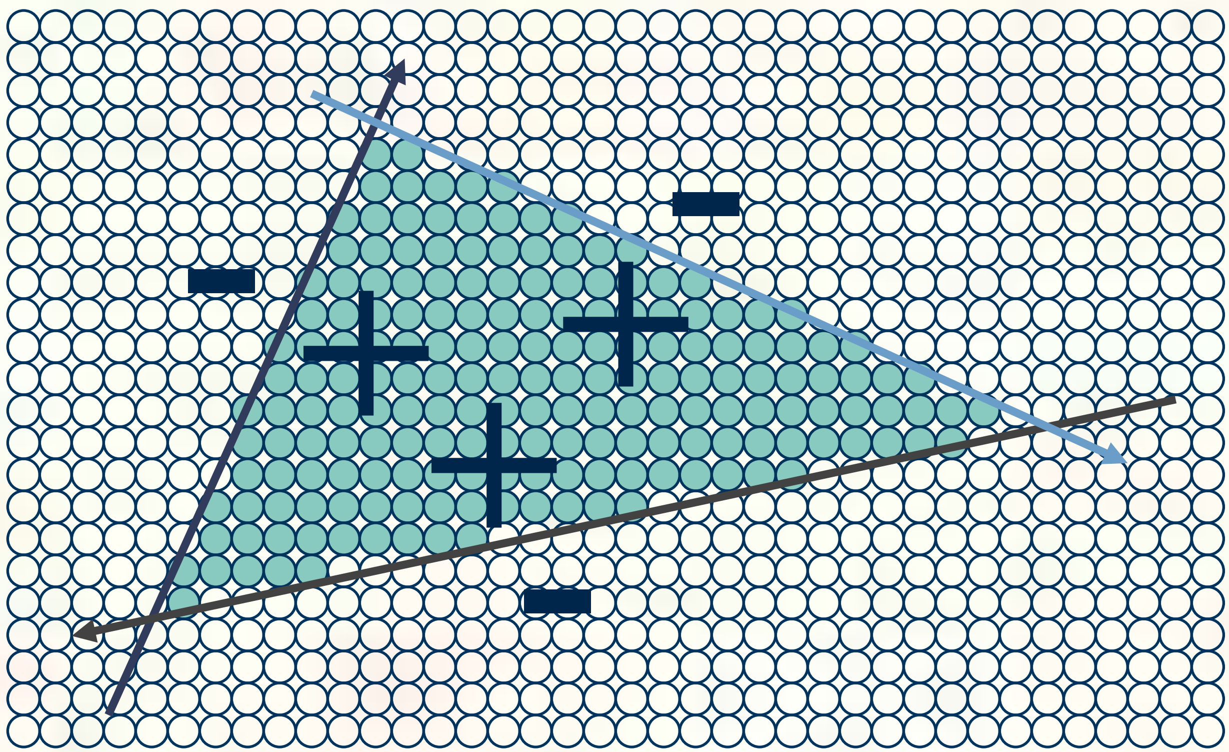
$$E_i(x,y) = A_i x + B_i y + C_i$$



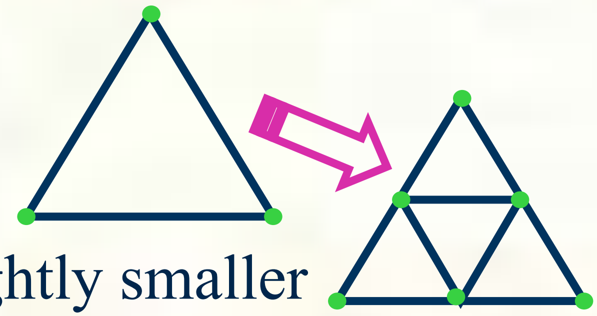
# Inside Triangle Test

- Evaluate edge equations at grid of sample points
  - If sample position is "inside" all 3 edge equations, the position is "within" the triangle
  - Implicitly parallel—all samples can be tested at once

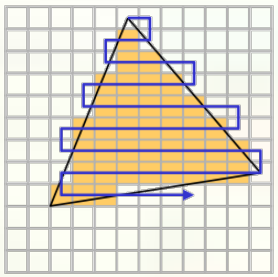
- Good for hardware implementation
  - Pixel-planes
  - Pineda tiled extension



# Other Rasterization Approaches

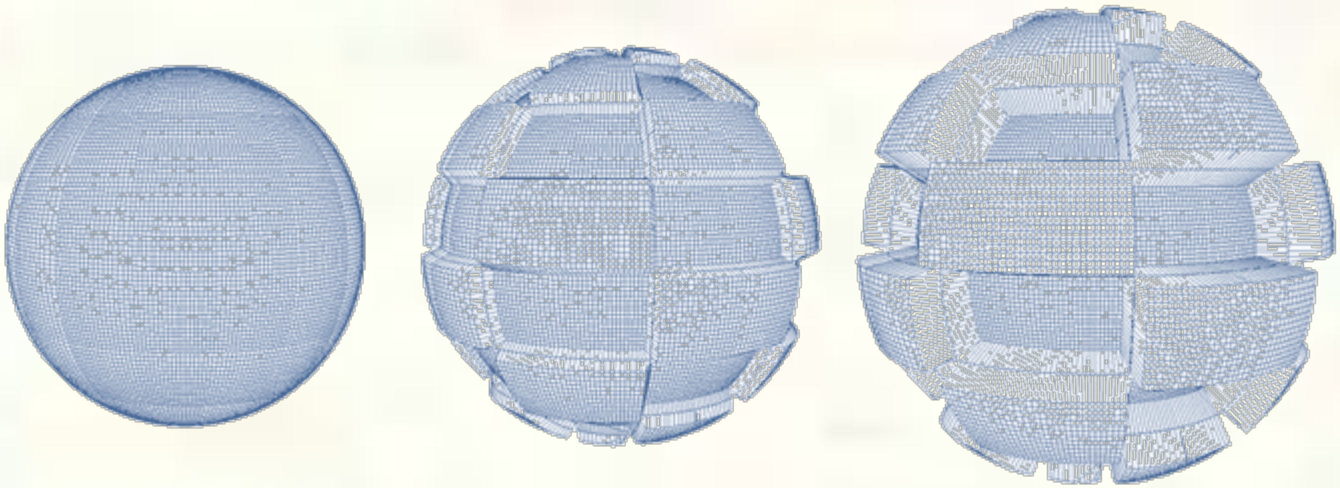


- Subdivision approaches
  - Easy to split a triangle into 4 triangles
  - Keep splitting triangles until they are slightly smaller than your samples
    - Often called micro-polygon rendering
    - Chief advantage is being able to apply displacements during the subdivision
- Edge walking approaches
  - Often used by CPU-based rasterizers
  - Much more sequential than Pineda approach
  - Work efficient and amendable to fixed-point implementation



# Micropolygons

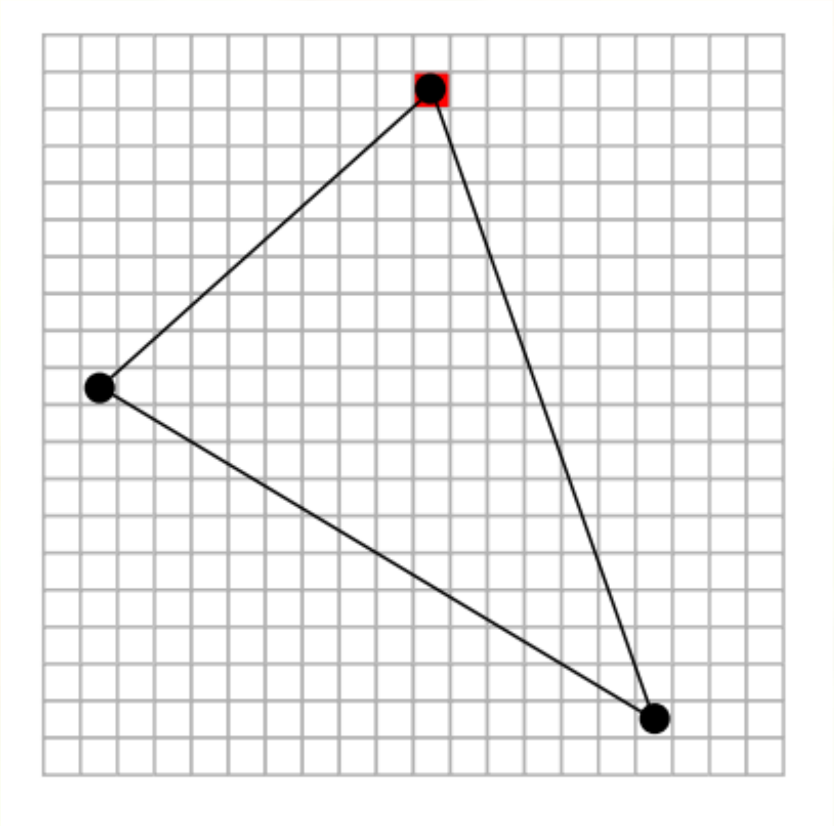
- Rasterization becomes a geometry dicing process
  - Approach taken by Pixar
    - For production rendering when scene detail and quality is at a premium; interactivity, not so much
  - High-level representation is generally patches rather than mere triangles



*Displacement mapping of a meshed sphere [Pixar, RenderMan]*

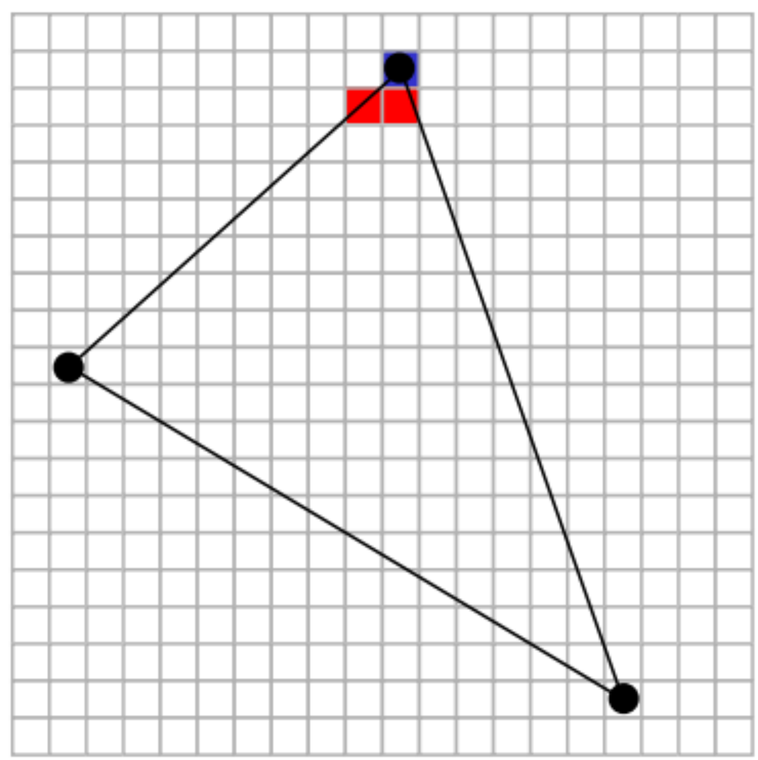
# Scanline Rasterization

- Find a "top" to the triangle
  - Now walk down edges



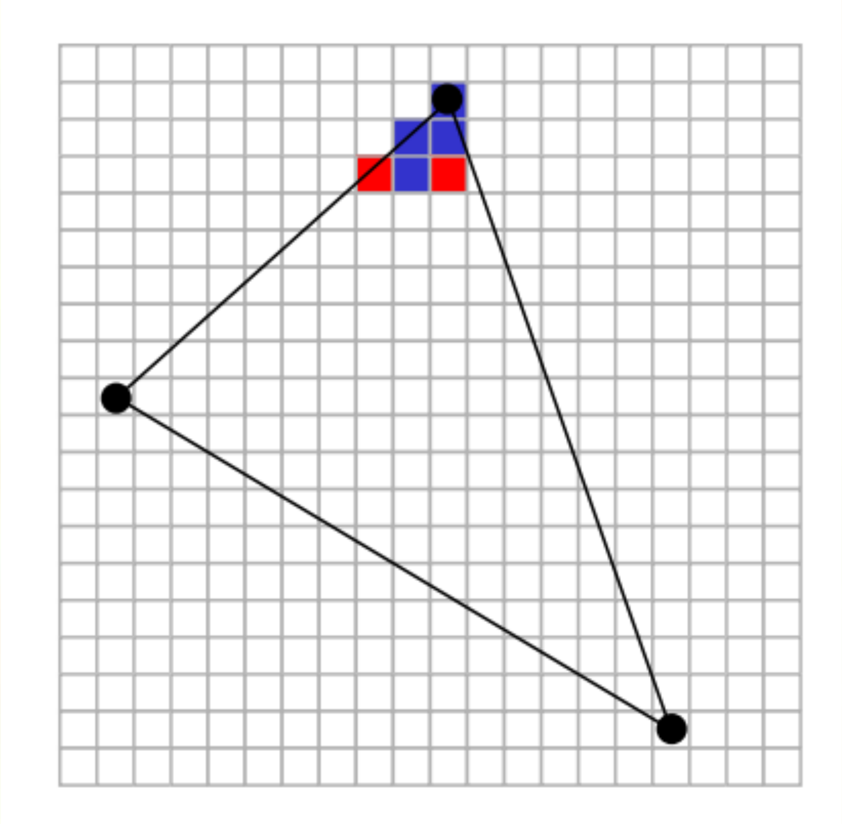
# Scanline Rasterization

- Move down a scan-line, keeping track of the left and right ends of the triangle



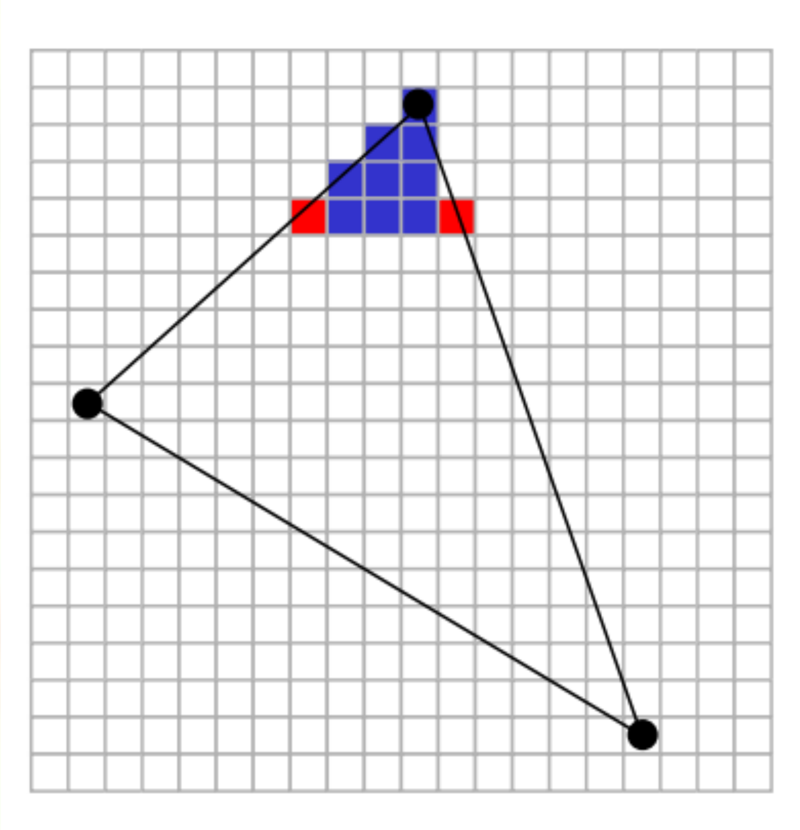
# Scanline Rasterization

- Repeat, moving down a scanline
  - Cover the samples between the left and right ends of the triangle in the scan-line



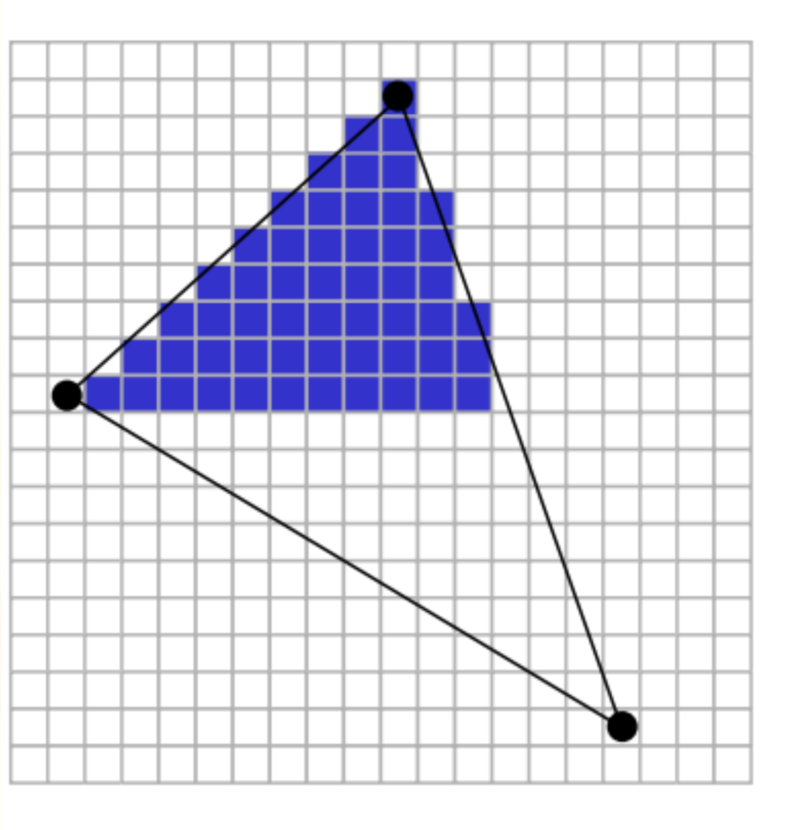
# Scanline Rasterization

- Process repeats for each scanline
  - Easy to “step” down to the next scanline based on the slopes of two edges



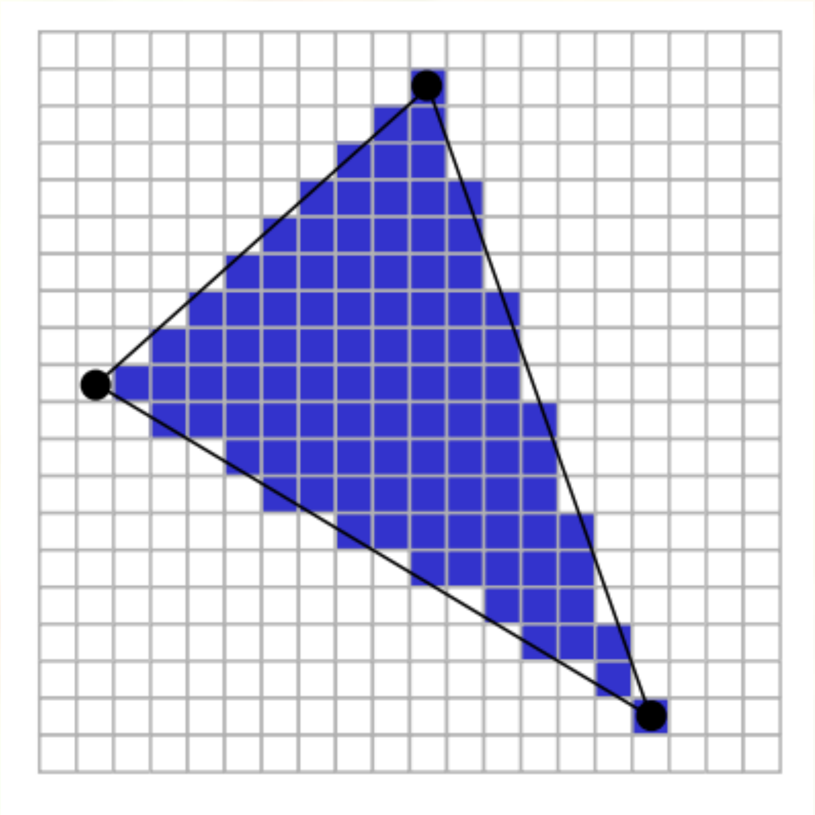
# Scanline Rasterization

- Eventually reach a vertex
  - Transition to a different edge and continue filling the span within the triangle



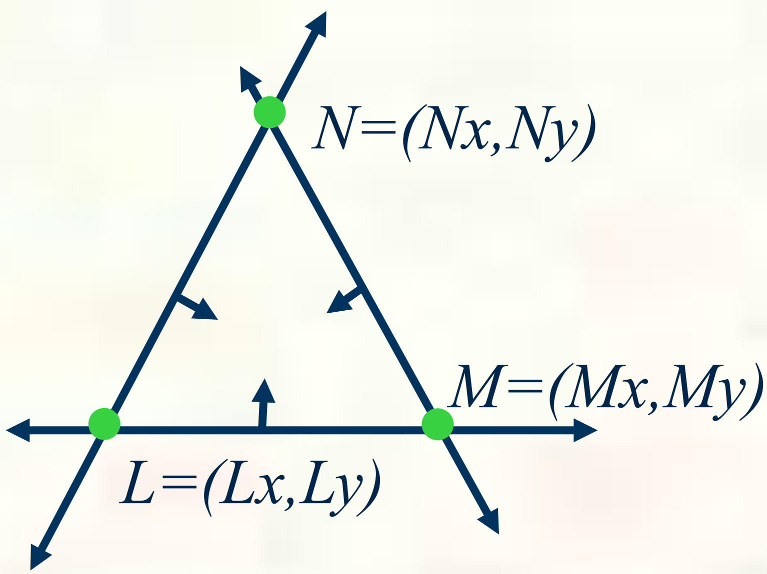
# Scanline Rasterization

- Until you finish the triangle
  - Friendly for how CPU memory arranges an image as a 2D array with horizontal locality
  - Layout is good for raster scan-out too



# Creating Edge Equations

- Triangle rasterization need edge equations
  - How do we make edge equations?
- An edge is a line so determined by two points
  - Each of the 3 triangle edges is determined by two of the 3 triangle vertexes (L, M, N)




How do we get

$$A^*x + B^*y + C \geq 0$$

for each edge from L, M, and N?

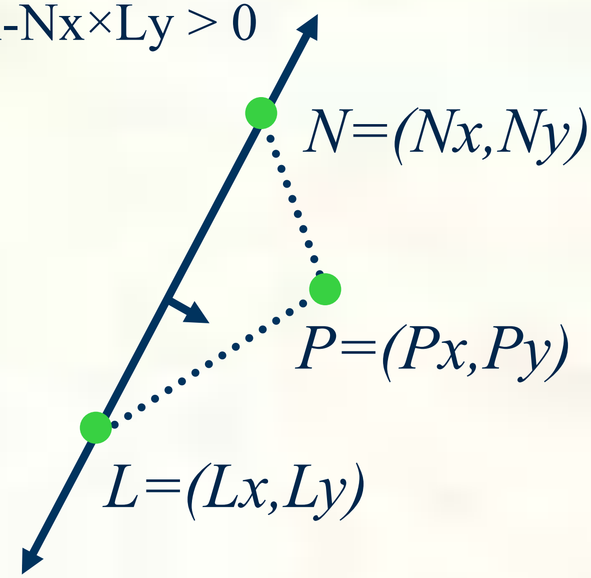
# Edge Equation Setup

- How do you get the coefficients A, B, and C?
- Determinants help—consider the LN edge:

*P is an arbitrary point*

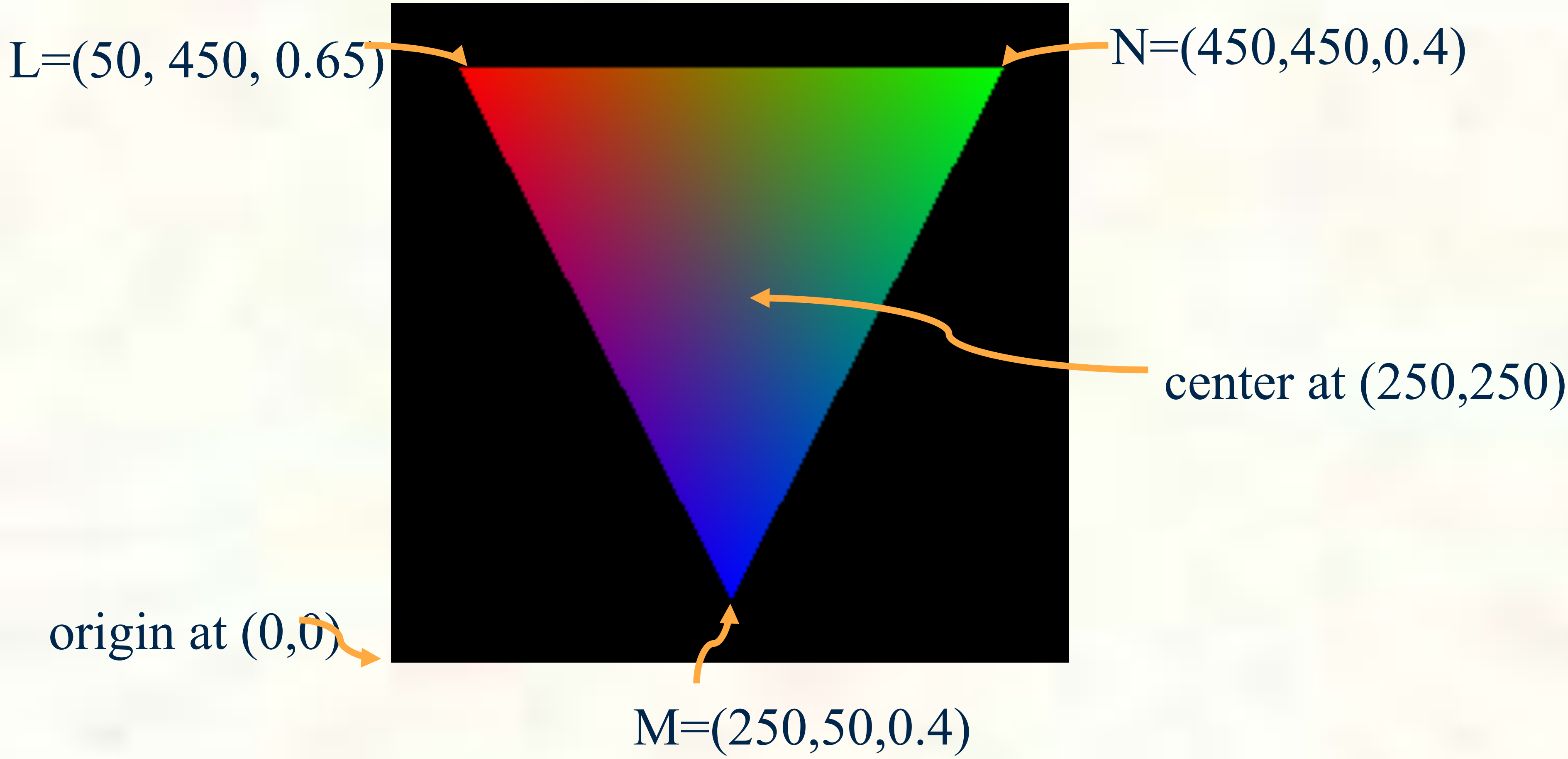
$$\begin{vmatrix} N_x - L_x & N_y - L_y \\ P_x - L_x & P_y - L_y \end{vmatrix} > 0 \quad \text{or more succinctly} \quad \begin{vmatrix} N - L \\ P - L \end{vmatrix} > 0$$

- **Expansion:** $(Ly-Ny) \times Px + (Nx-Lx) \times Py + Ny \times Lx - Nx \times Ly > 0$
  - $A_{LN} = Ly-Ny$
  - $B_{LN} = Nx-Lx$
  - $C_{LN} = Ny \times Lx - Nx \times Ly$
- **Geometric interpretation:** twice signed area of the triangle LPN



# Screen Space Coordinates of Triangle

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



# Look at the LN edge

- **Expansion:**
  $(Ly\text{-}Ny)\times Px + (Nx\text{-}Lx)\times Py + Ny\times Lx\text{-}Nx\times Ly > 0$
  - $A_{LN} = Ly\text{-}Ny = 450\text{-}450 = 0$
  - $B_{LN} = Nx\text{-}Lx = 50\text{-}450 = -400$
  - $C_{LN} = Ny\times Lx\text{-}Nx\times Ly = 180{,}000$
- Is center at (250,250) in the triangle?
  - $A_{LN} \times 250 + B_{LN} \times 250 + C_{LN} = ???$
  - $0 \times 250 - 400 \times 250 + 180{,}000 = 80{,}000$
    - 80,000 > 0 so (250,250) is <u>in</u> the triangle

# All Three Edge Equations

- All three triangle edge equations:

$$\begin{vmatrix} M-N \\ P-N \end{vmatrix} > 0 \qquad \begin{vmatrix} N-L \\ P-L \end{vmatrix} > 0 \qquad \begin{vmatrix} L-M \\ P-M \end{vmatrix} > 0$$

- Satisfy all 3 and P is in the triangle
  - And then rasterize at sample location P
- **Caveat:** if $\begin{vmatrix} N-L \\ M-L \end{vmatrix} < 0$ reverse the comparison sense

# Water Tight Rasterization

- Two triangles often share a common edge
  - Indeed in closed polygonal meshes, every triangle shares its edges with as many as three other triangles
    - Called adjacent or "shared edge" triangles
- Crucial rasterization property
  - No double sampling (hitting) along the shared edge
  - No sample gaps (pixel fall-out) along the shared edge
  - Samples along the shared edge must be belong to exactly one of the two triangles
    - Not both, not neight
- Water tight rasterization is crucial to many higher-level algorithms; otherwise, rendering artifacts
  - Possible artifact: if pixels hit twice on an edge, the pixel could be double blended
  - Example application: Stenciled Shadow Volumes (SSV)

# Water Tight Rasterization Solution

- First “snap” vertex positions to a grid
  - Grid can (and should) be sub-pixel samples
  - Results in fixed-point vertex positions
- Fixed-point math allows exact edge computations
  - **Surprising? E**nsuring robustness requires discarding excess precision
- Problem
  - What happens when edge equation evaluates to exactly zero at a sample position?
  - Need a consistent tie breaker

# Tie Breaker Rule

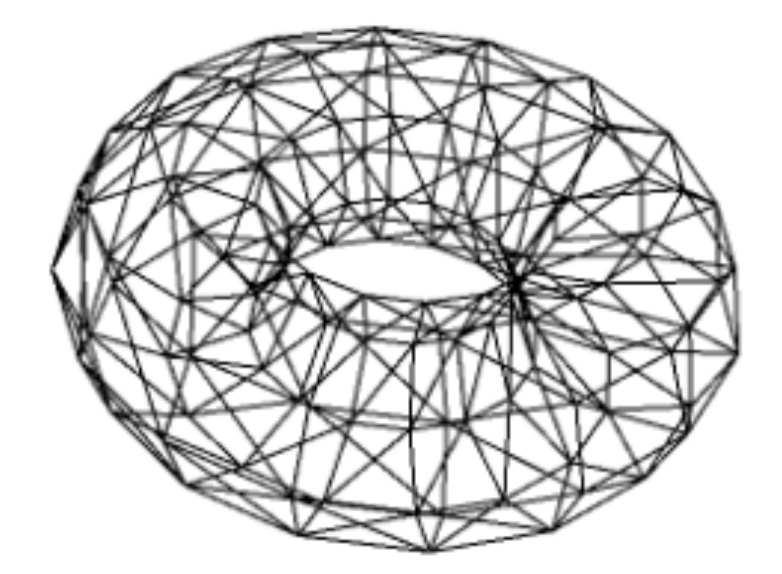
- Look at edge equation coefficients
- Tie-breaker rule when edge equation evaluates to zero
  - "Inside" edge when edge equation is zero <u>and</u> $A > 0$ when $A \neq 0$, or $B > 0$ when $A = 0$
- Complete coverage determination rule
  - if (E(x,y) > 0 || (E(x,y)==0 && (A != 0 ? A > 0 : B > 0)))

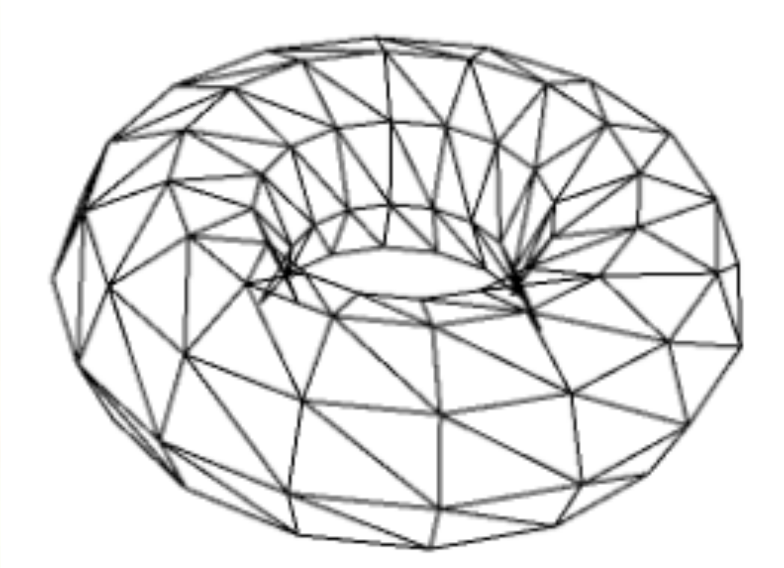
    sample at (x,y) is inside edge

# Zero Area Triangles

- We reverse the edge equation comparison sense if the (signed) area of the triangle is negative
- What if the area is zero?
  - Linear algebra indicates a singular matrix
  - Need to cull the primitive
- Also useful to cull primitives when area is negative
  - OpenGL calls this face culling
    - Enabled with glEnable(GL_CULL_FACE)
  - When drawing closed meshes, back face culling can avoid drawing primitives assured to be occluded by front faces

# Back Face Culling Example





Torus drawn in wire-frame
without back face culling

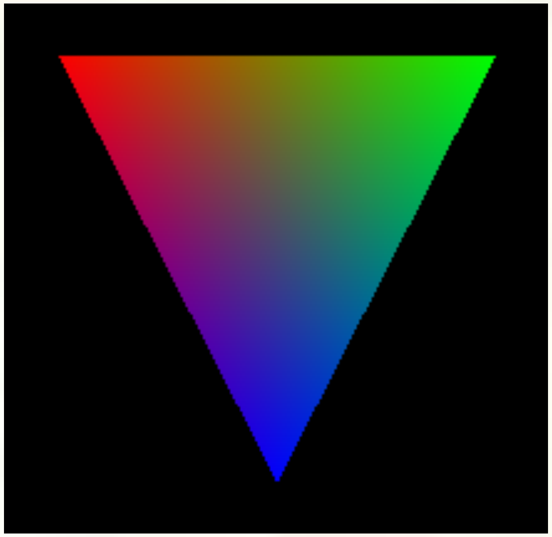
Notice considerable extraneous triangles that would normally be occluded

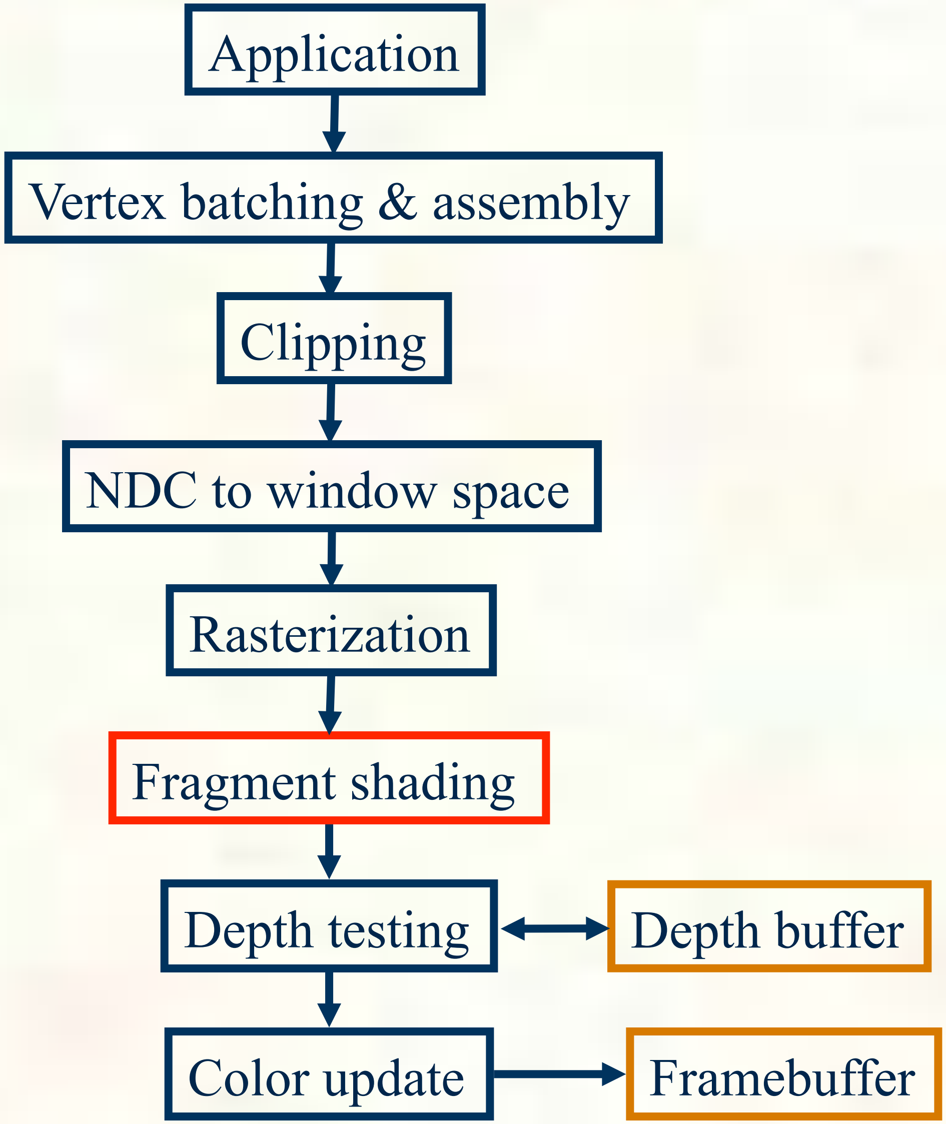
Torus drawn in wire-frame
**with** back face culling

By culling back-facing (negative signed area) triangles, fewer triangles are rasterized

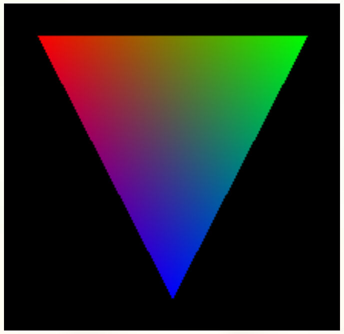
# Simple Fragment Shading

- For all samples (pixels) within the triangle, evaluate the interpolated color
  - Requires having math to determine color at the sample (x,y) location

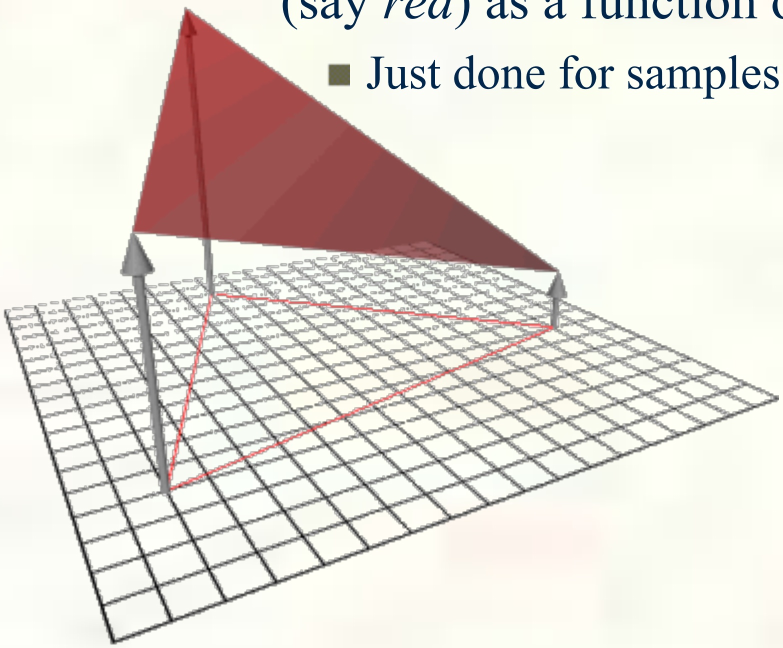




# Color Interpolation



- 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



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

# Setup Plane Equation

- Setup plane equation to solve for "red" as a function of (x,y)

Setup system of equations

$$\begin{bmatrix} L_{red} \\ M_{red} \\ N_{red} \end{bmatrix} = \begin{bmatrix} L_x & L_y & 1 \\ M_x & M_y & 1 \\ N_x & N_y & 1 \end{bmatrix} \begin{bmatrix} A_{red} \\ B_{red} \\ C_{red} \end{bmatrix}$$

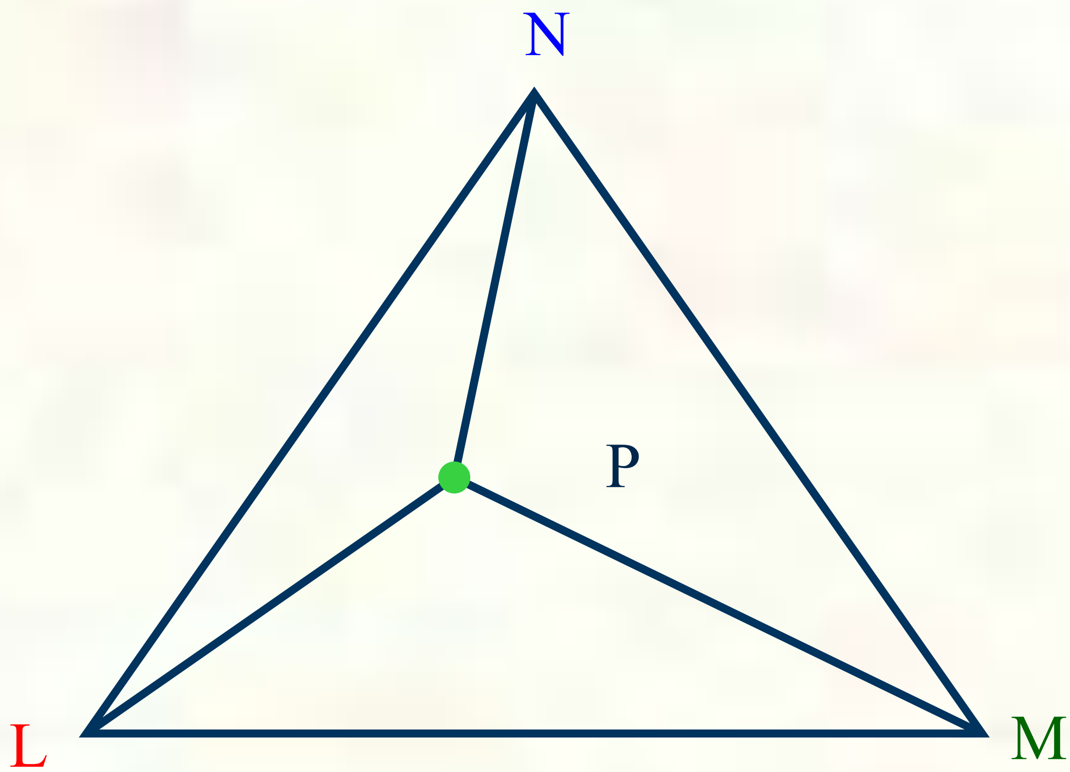
Solve for plane equation coefficients A, B, C

$$\begin{bmatrix} L_x & L_y & 1 \\ M_x & M_y & 1 \\ N_x & N_y & 1 \end{bmatrix}^{-1} \begin{bmatrix} L_{red} \\ M_{red} \\ N_{red} \end{bmatrix} = \begin{bmatrix} A_{red} \\ B_{red} \\ C_{red} \end{bmatrix}$$

*Do the same for green, blue, and alpha (opacity)…*

# More Intuitive Way to Interpolate

- 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

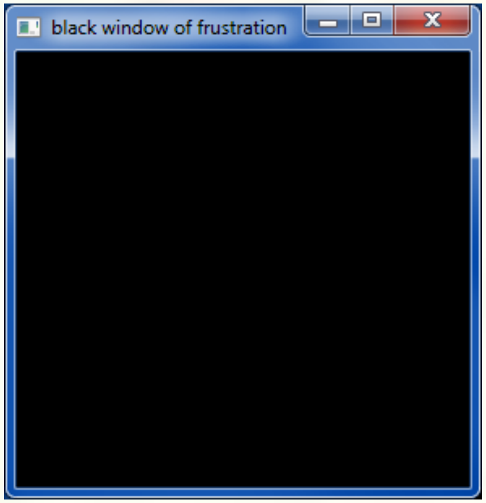
# Remaining Steps

- Depth interpolation
- Color update
- Scan-out to the display

- *Next time…*

# 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

# Next Lecture

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

# Thanks

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