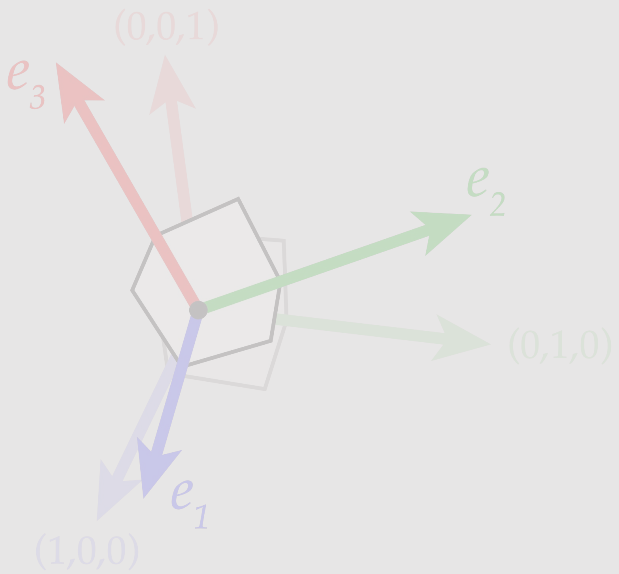
Midterm Review

Midterm Overview

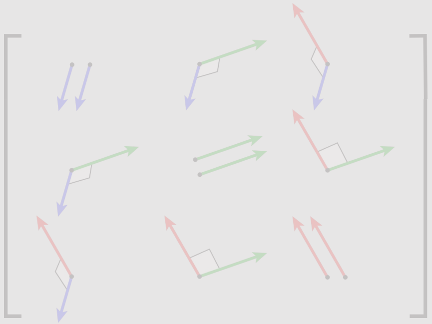
- 80 minutes, during class next Thursday
  - Basic mathematical questions, no intense calculation
  - Know your definitions and be able to apply them!
  - No pseudocode
  - Review slides are a good hint as to what might be on the exam :)
- Cheat sheet: one 3x3 inch note (about the size of a post it note) front and back
- **Please bring a blue/black pen to write your solutions**

3D Inverse Rotations



$$\overbrace{\begin{bmatrix} — e_1^T — \\ — e_2^T — \\ — e_3^T — \end{bmatrix}}^{R^T} \overbrace{\begin{bmatrix} | & | & | \\ e_1 & e_2 & e_3 \\ | & | & | \end{bmatrix}}^{R}$$

$=$



$$= \begin{bmatrix} e_1^T e_1 & e_1^T e_2 & e_1^T e_3 \\ e_2^T e_1 & e_2^T e_2 & e_2^T e_3 \\ e_3^T e_1 & e_3^T e_2 & e_3^T e_3 \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$R^T R = I \Rightarrow R^T = R^{-1}$$

If you need to review any slides more in depth,
look here for which lecture it came from

- Transformations Review
- Rasterization Review
- Geometry Review
- Spatial Data Structures Review

Transformations

- Homogeneous coordinates
- 3D Translation
- 3D Scale
- 3D Rotation
    - Axis-Aligned rotation
    - Axis-Angle rotation
    - Rotations from orthonormal bases

3D Transforms in Homogeneous Coordinate

$$\begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

[point in 3D]

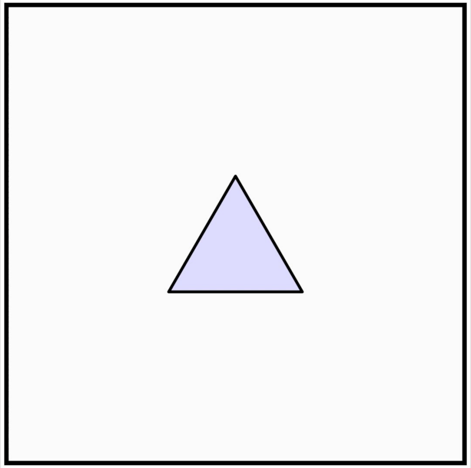
Matrix representations of 3D linear transformations just get an additional identity row/column:

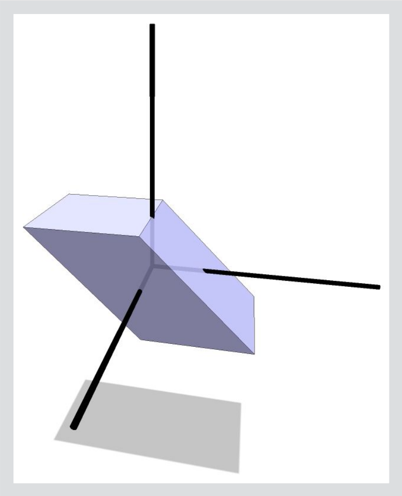
$$\begin{bmatrix} \cos\theta & 0 & \sin\theta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\theta & 0 & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & s & 0 \\ 0 & 1 & t & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} a & 0 & 0 & 0 \\ 0 & b & 0 & 0 \\ 0 & 0 & c & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & u \\ 0 & 1 & 0 & v \\ 0 & 0 & 1 & w \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

[rotate around y by θ] [shear by z in (s,t) direction] [scale by a,b,c] [translate by (u,v,w)]

Translation in Homogeneous Coordinates

- A 2D translation is similar to a 3D shear
  - Moving a slice up/down the shear moves the shape





- Recall shear is written as:

$$f_{\mathbf{u},\mathbf{v}}(\mathbf{x}) = \mathbf{x} + \langle \mathbf{v}, \mathbf{x} \rangle \mathbf{u}$$

$$f_{\mathbf{u},\mathbf{v}}(\mathbf{x}) = \left(I + \mathbf{u}\mathbf{v}^{\mathsf{T}}\right)\mathbf{x}$$

- In our case, $v = (0,0,1)$, so**

$$\begin{bmatrix} 1 & 0 & u_1 \\ 0 & 1 & u_2 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} cp_1 \\ cp_2 \\ c \end{bmatrix} = \begin{bmatrix} c(p_1 + u_1) \\ c(p_2 + u_2) \\ c \end{bmatrix} \xRightarrow{1/c} \begin{bmatrix} p_1 + u_1 \\ p_2 + u_2 \end{bmatrix}$$

**most often in this class we will also use c = 1

Non-Uniform Scaling

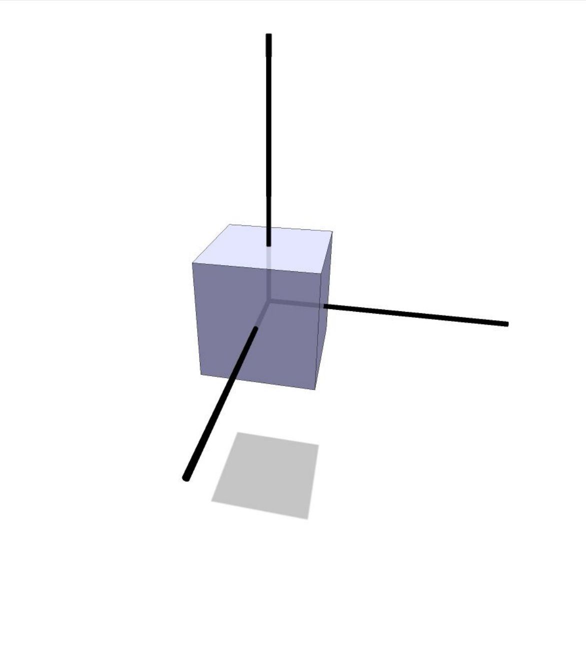
- To scale a vector u by a non-uniform amount (a, b, c):

$$\begin{bmatrix} a & 0 & 0 \\ 0 & b & 0 \\ 0 & 0 & c \end{bmatrix}\begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} = \begin{bmatrix} au_1 \\ bu_2 \\ cu_3 \end{bmatrix}$$

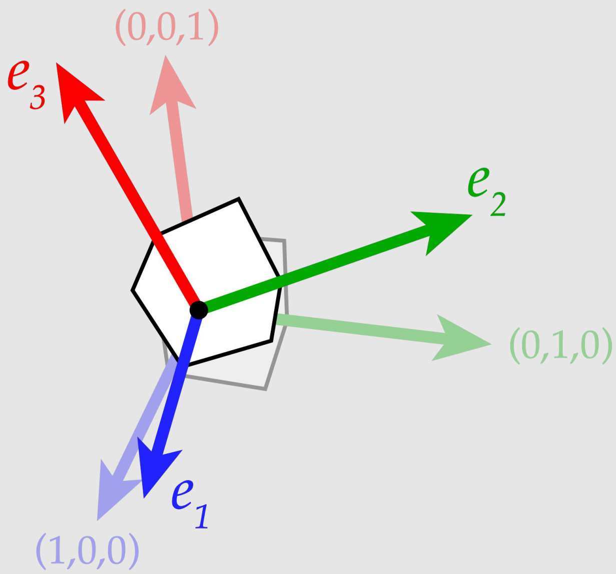
- The above works only if scaling is axis-aligned. What if it isn't?
- Idea:
  - Rotate to a new axis R
  - Perform axis-aligned scaling D
  - Rotate back to original axis R^T

$$A \coloneqq R^T D R$$

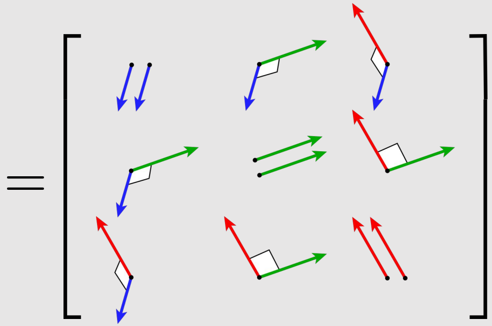
  - Resulting transform A is a symmetric matrix



3D Inverse Rotations



$$\overset{R^{\mathsf{T}}}{\begin{bmatrix} - & e_1^T & - \\ - & e_2^T & - \\ - & e_3^T & - \end{bmatrix}} \overset{R}{\begin{bmatrix} | & | & | \\ e_1 & e_2 & e_3 \\ | & | & | \end{bmatrix}}$$

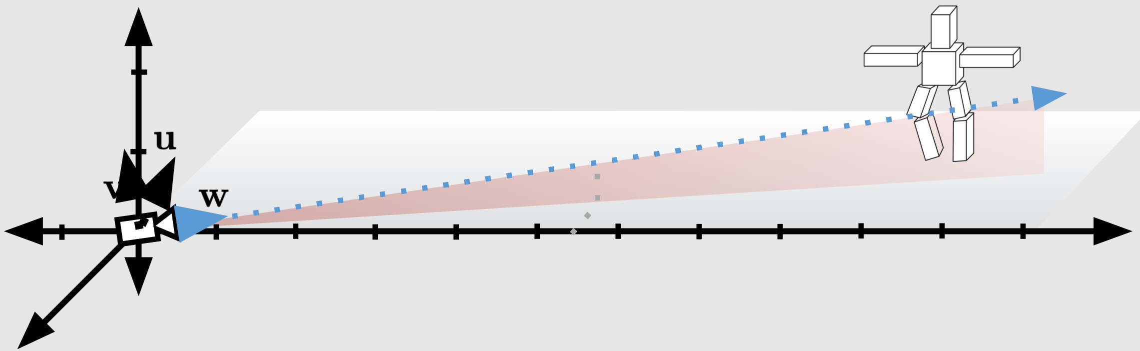


$$= \begin{bmatrix} e_1^T e_1 & e_1^T e_2 & e_1^T e_3 \\ e_2^T e_1 & e_2^T e_2 & e_2^T e_3 \\ e_3^T e_1 & e_3^T e_2 & e_3^T e_3 \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\boldsymbol{R^T R = I \;\; \Rightarrow \;\; R^T = R^{-1}}$$

Rotations From Orthonormal Bases



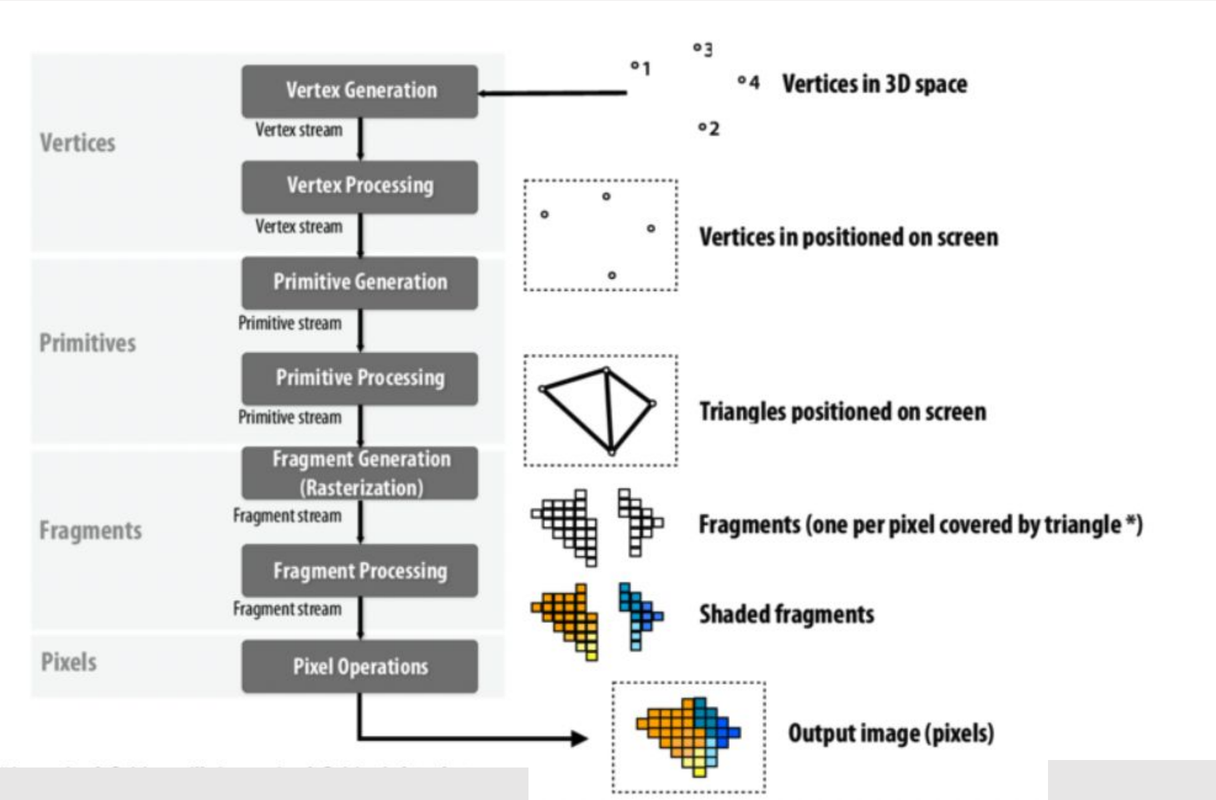
$$R = \begin{bmatrix} -u_x & v_x & -w_x \\ -u_y & v_y & -w_y \\ -u_z & v_z & -w_z \end{bmatrix} \qquad R^{-1} = \begin{bmatrix} -u_x & -u_y & -u_z \\ v_x & v_y & v_z \\ -w_x & -w_y & -w_z \end{bmatrix}$$

- Transformations Review
- Rasterization Review
- Geometry Review
- Spatial Data Structures Review

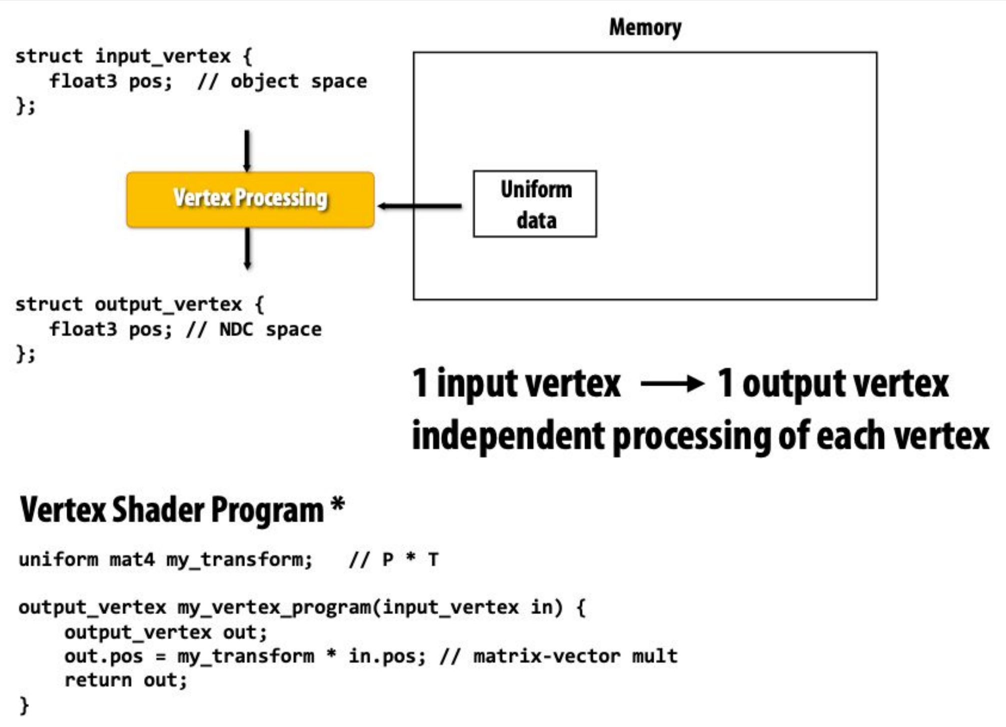
Rasterization

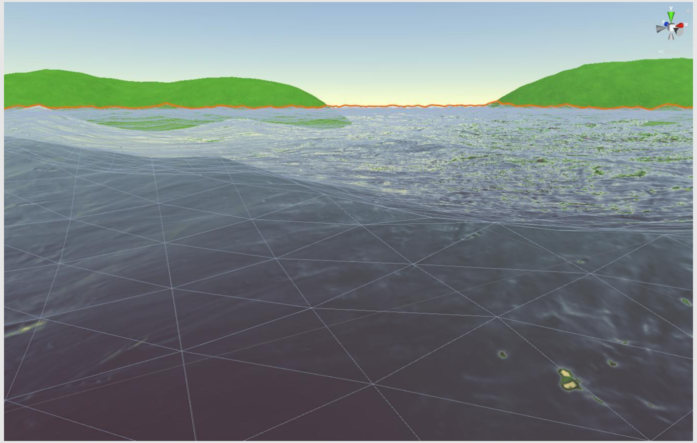
- The “simpler” graphics pipeline
- Scene graph
- Clipping
- Rasterization
    - Sampling
    - Point-in-triangle tests
    - Barycentric coordinates
- Textures
- Depth and Alpha blending

The Graphics Pipeline



Vertex Shader

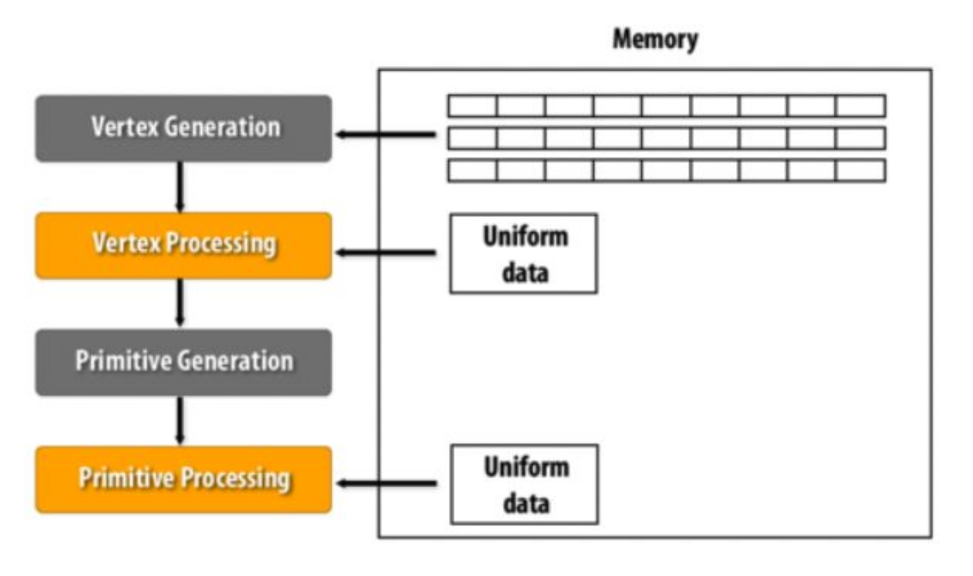


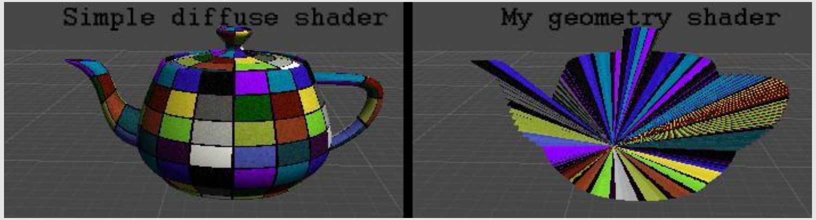


ers provide per-vertex operations that change
vertices such as their positions and normal
e: fluid simulation

* (Note this is pseudocode, not GLSL syntax)

Geometry Shader



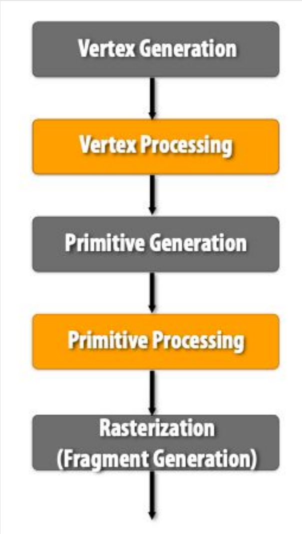


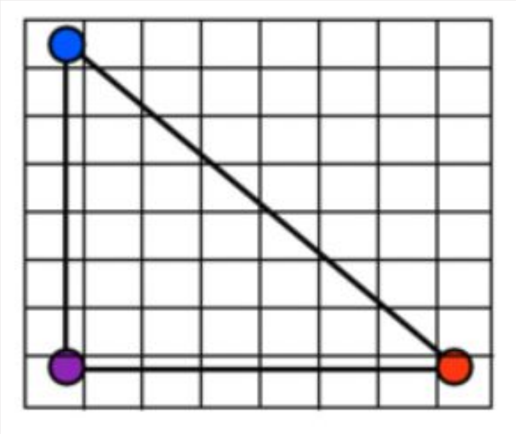
Some guy in Unity having a hard time with geometry shaders (2014)

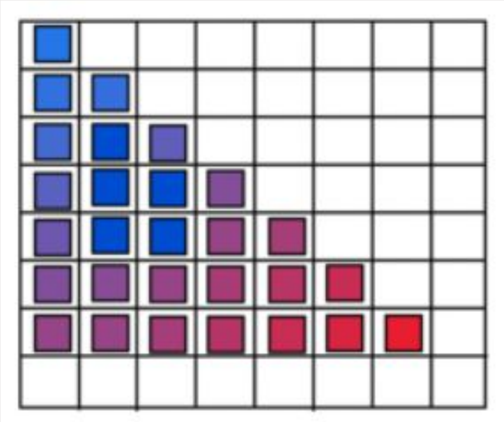
- Recently added to OpenGL in 2007
  - As such, not many people use it
- Allows user to retarget the connectivity of their geometry by specifying tessellation operations or adding in additional geometry
  - Example: computing vertex shader on coarse geometry and then subdividing a surface in the geometry shader

* "Geometry Shader" in OpenGL/Direct3D/Metal terminology

Fragment Shader







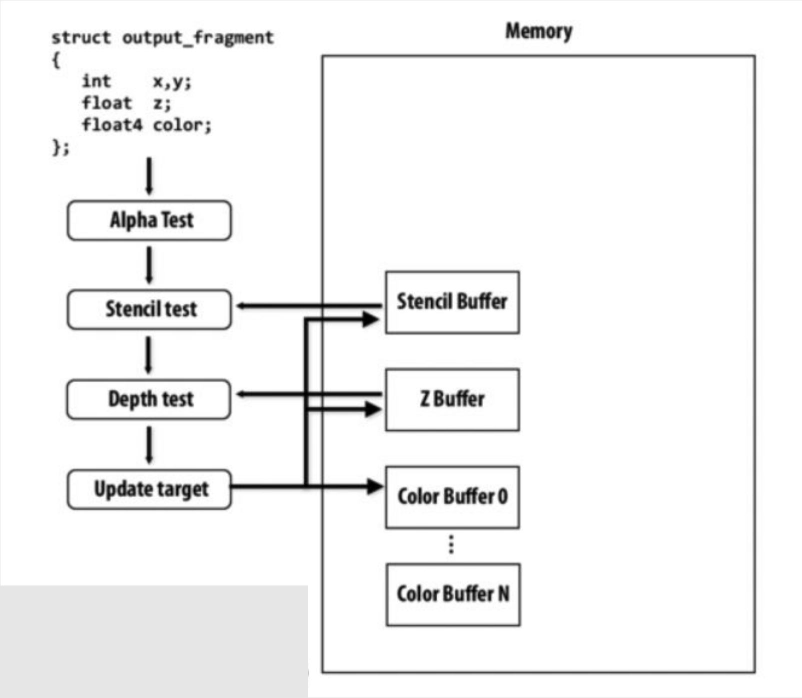
```
struct fragment      // note similarity to output_vertex from before
{
   float  x,y;       // screen pixel coordinates (sample point location)
   float  z;         // depth of triangle at sample point

   float3 normal;    // interpolated application-defined attribs
   float2 texcoord;  // (e.g., texture coordinates, surface normal)

}
```

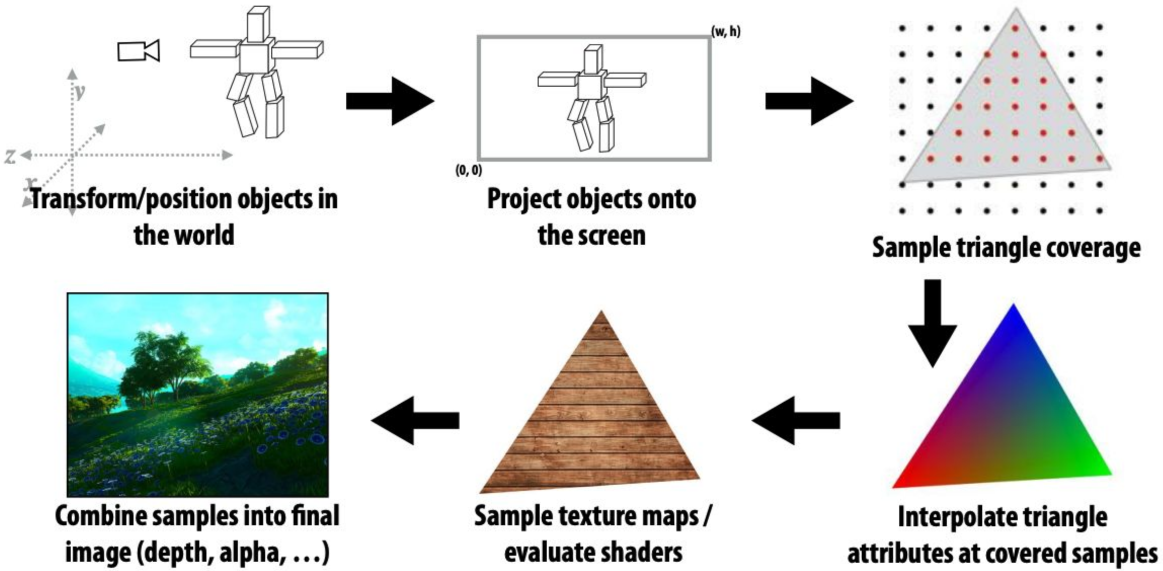
- Separate triangles into fragments
- For each fragment, compute the output RGBA

Frame-Buffer Operations

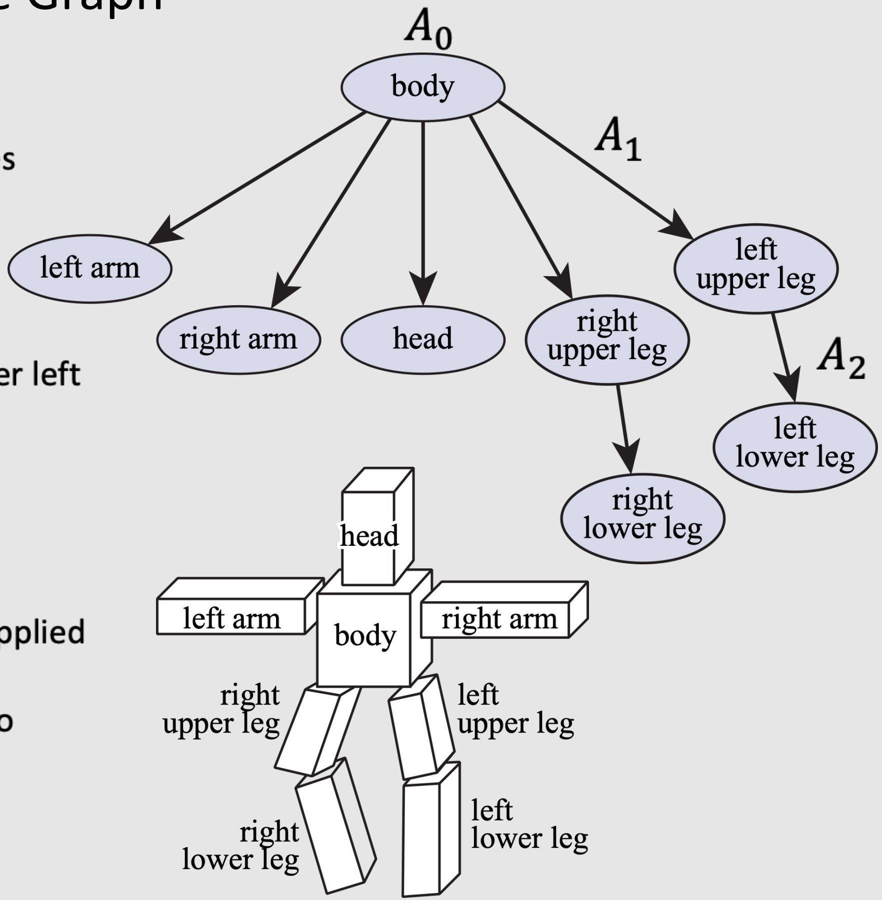


- **Alpha Test**
  - Allows fragments with alpha value greater/less than a constant specified by the user to pass
- **Stencil Test**
  - Allows fragments that pass a user-defined per-pixel function to pass
    - Stored in stencil buffer
    - Example: mattes + masking
- **Depth Test**
  - Allows fragments that are closest in depth to pass
    - Stored in Z-buffer
- **Update Target**
  - If pixel passes, modify stencil depth and color buffers
  - Reads can be done in parallel, writes require locking
    - We'll look at techniques later to accelerate this

The “Simpler” Graphics Pipeline



Scene Graph



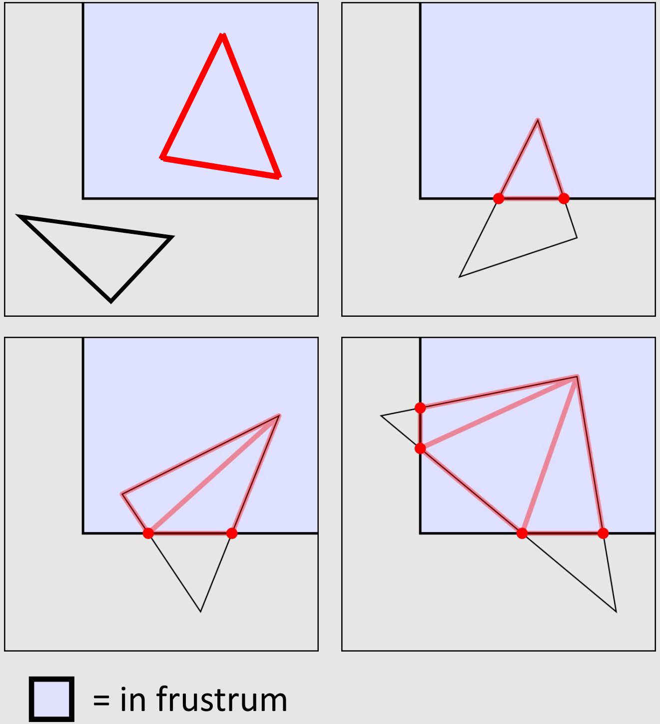
- Suppose we want to build a skeleton out of cubes
- **Idea:** transform cubes in world space
  - Store transform of each cube
- **Problem:** If we rotate the left upper leg, the lower left leg won't track with it
  - **Better Idea:** store a hierarchy of transforms
    - Known as a scene graph
    - Each edge (+root) stores a linear transformation
    - Composition of transformations gets applied to nodes
      - Keep transformations on a stack to reduce redundant multiplication
- **Lower left leg transform:** $A_2 A_1 A_0$

Clipping

- Clipping eliminates triangles not visible to the camera (not in view frustum)
  - Don't waste time rasterizing primitives you can't see!
  - Discarding individual fragments is expensive
    - "Fine granularity"
  - Makes more sense to toss out whole primitives
    - "Coarse granularity"

- What if a primitive is **partially clipped?**
  - Partially enclosed primitives are triangulated into non-overlapping smaller triangles that fit in the frustum

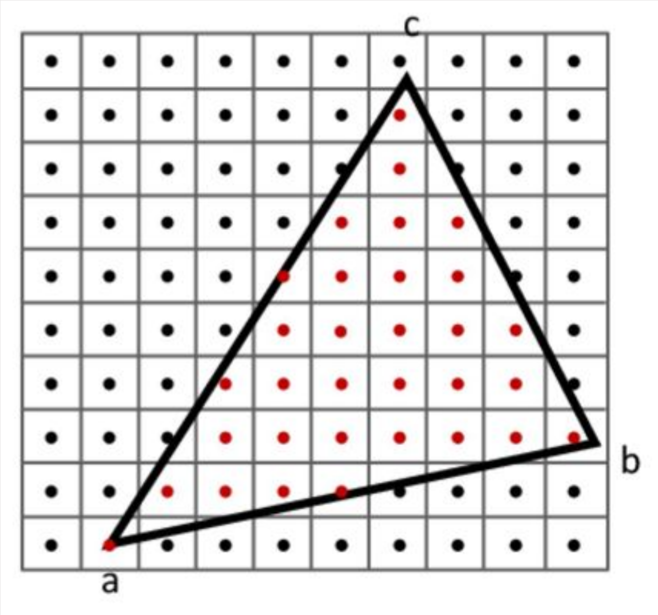
- If part of a triangle is outside the frustum, it means at least one of its vertices are outside the frustum
  - **Idea:** check which side of halfspaces the vertices are at



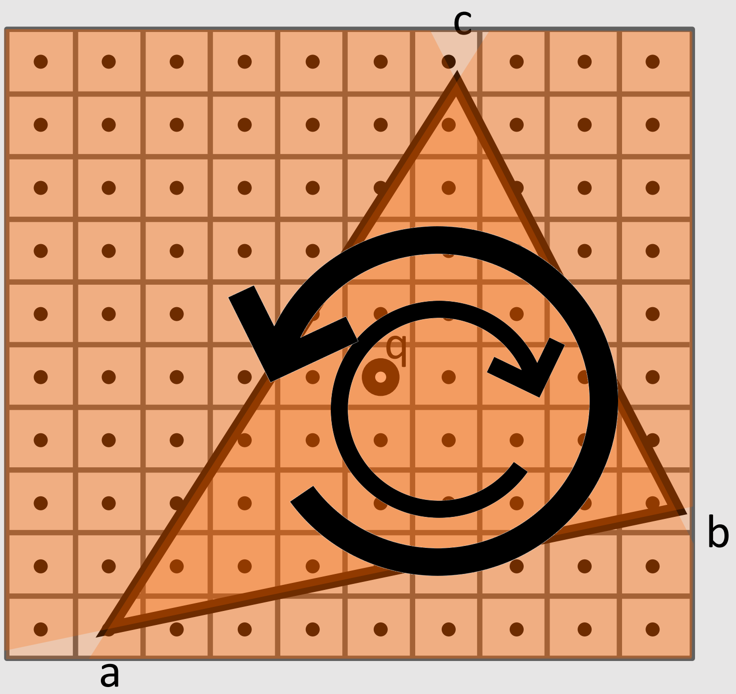
Rasterization

- Triangle
  - Bounding box
  - Incremental triangle traversal
  - Hierarchical coverage

- For each **Primitive** (Triangle):
  - For each **Pixel**:
    - If **Pixel** in **Primitive**:
      - Pixel color = Interpolated triangle color



Point-In-Triangle Test



- **Measurements must all either be positive or negative** for point to be in triangle

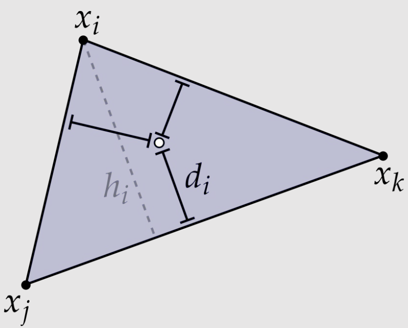
$$(\overrightarrow{ac} \times \overrightarrow{ab}) \cdot (\overrightarrow{ac} \times \overrightarrow{aq}) > 0 \,\&\&$$
$$(\overrightarrow{cb} \times \overrightarrow{ca}) \cdot (\overrightarrow{cb} \times \overrightarrow{cq}) > 0 \,\&\&$$
$$(\overrightarrow{ba} \times \overrightarrow{bc}) \cdot (\overrightarrow{ba} \times \overrightarrow{bq}) > 0$$

OR

$$(\overrightarrow{ab} \times \overrightarrow{ac}) \cdot (\overrightarrow{ac} \times \overrightarrow{aq}) < 0 \,\&\&$$
$$(\overrightarrow{ca} \times \overrightarrow{cb}) \cdot (\overrightarrow{cb} \times \overrightarrow{cq}) < 0 \,\&\&$$
$$(\overrightarrow{bc} \times \overrightarrow{ba}) \cdot (\overrightarrow{ba} \times \overrightarrow{bq}) < 0$$

- Orientation no longer matters
  - Just be consistent!

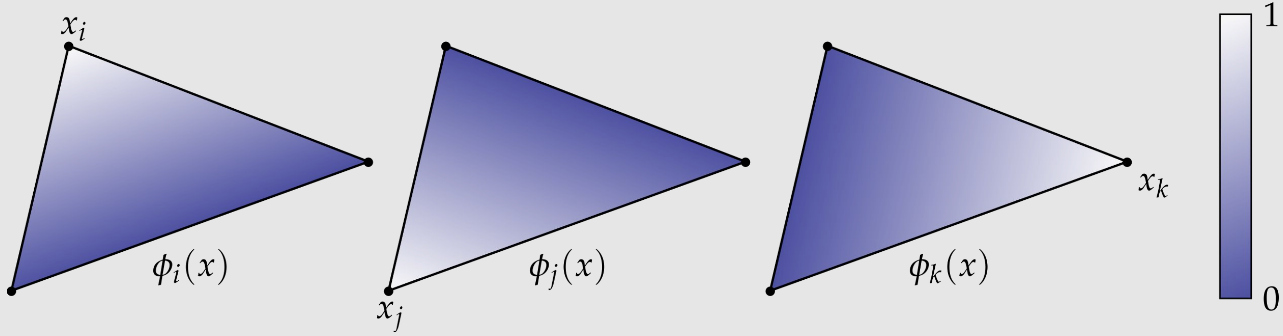
Barycentric Coordinates



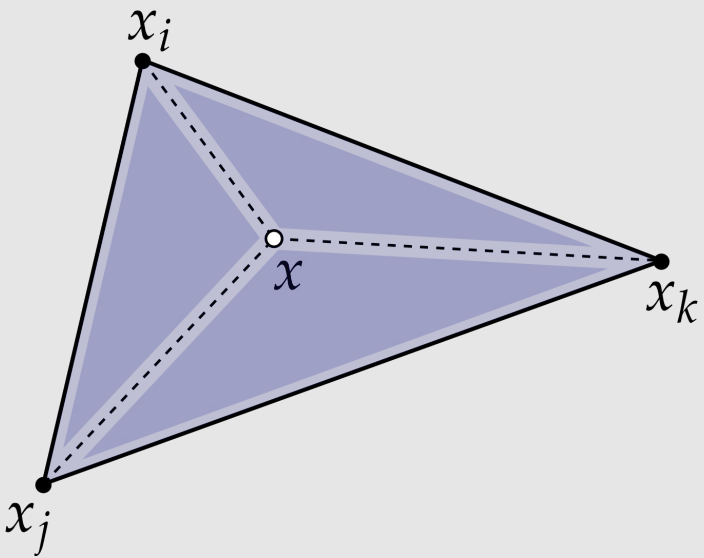
- Inversely proportional to the signed distance between the target point and a point within the triangle
- Can be computed as:

$$\phi_i(x) = d_i(x)/h_i$$

- How would you compute h_i? $d_i(x)$?



Barycentric Coordinates [Another Way]



- Directly proportional to the signed area created by the triangle composed of the other two target points and a point within the triangle

- Can be computed as:

$$\phi_i(x) = \frac{\mathrm{area}(x, x_j, x_k)}{\mathrm{area}(x_i, x_j, x_k)}$$

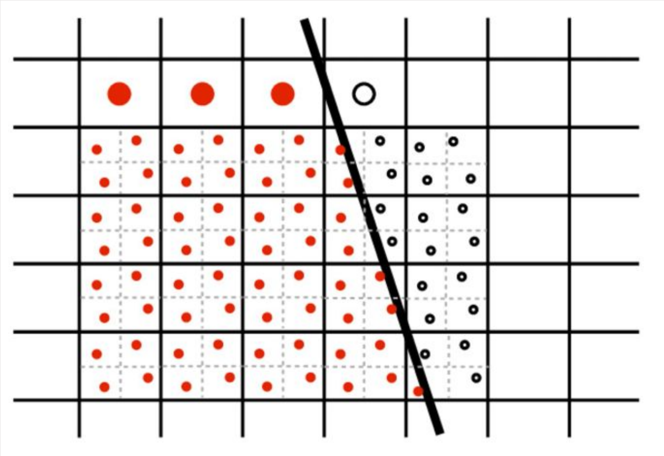
- Note that signed distance / area implies barycentric coordinates can be negative, but they will still sum to 1! (if on the same plane, otherwise we project point to the plane containing our triangle)

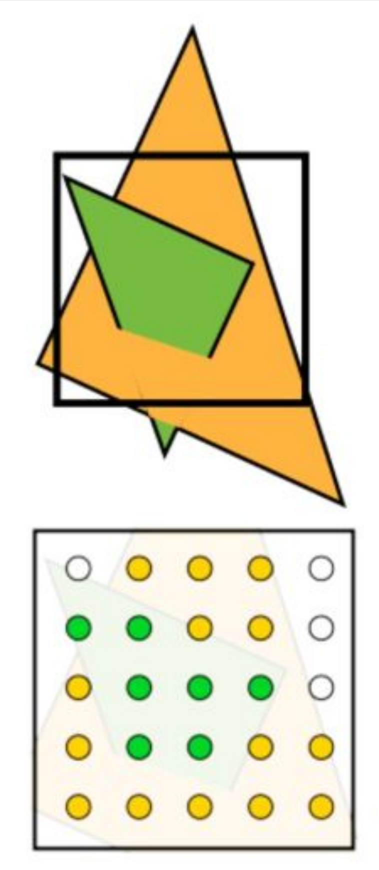
** Interesting read of barycentric coordinates for n-gons: https://www.inf.usi.ch/hormann/barycentric/

Coverage via Samples

- Sample : Discrete measurement of a signal
  - Multisampling vs Supersampling

- Approximate the coverage of the area of a pixel by taking *n* samples
  - Per sample coverage & depth test + texture lookup + alpha blending



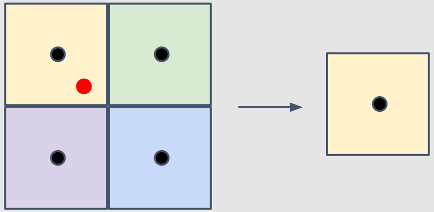


Nearest Neighbor Sampling

- **Idea:** Grab texel nearest to requested location in texture
- **Requires:**
  - 1 memory lookup
  - 0 linear interpolations

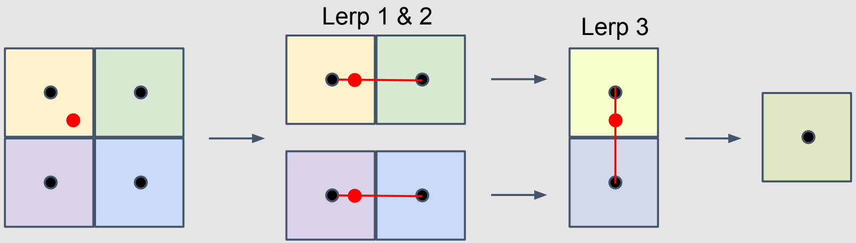
$$x' \leftarrow round(x - 0.5), \qquad y' \leftarrow round(y) - 0.5$$

$$t \leftarrow tex.lookup(x', y')$$



Bilinear Interpolation Sampling

- **Idea:** Grab nearest 4 texels and blend them together based on their inverse distance from the requested location
  - Blend two sets of pixels along one axis, then blend the remaining pixels
- **Requires:**
  - 4 memory lookup
  - 3 linear interpolations



$$x' \leftarrow floor(x - 0.5), \qquad y' \leftarrow floor(y - 0.5)$$

$$\Delta x \leftarrow (x - 0.5) - x'$$
$$\Delta y \leftarrow (y - 0.5) - y'$$

$$t_{(x,y)} \leftarrow tex.lookup(x', y')$$
$$t_{(x+1,y)} \leftarrow tex.lookup(x' + 1, y')$$
$$t_{(x,y+1)} \leftarrow tex.lookup(x', y' + 1)$$
$$t_{(x+1,y+1)} \leftarrow tex.lookup(x', +1\ y' + 1)$$

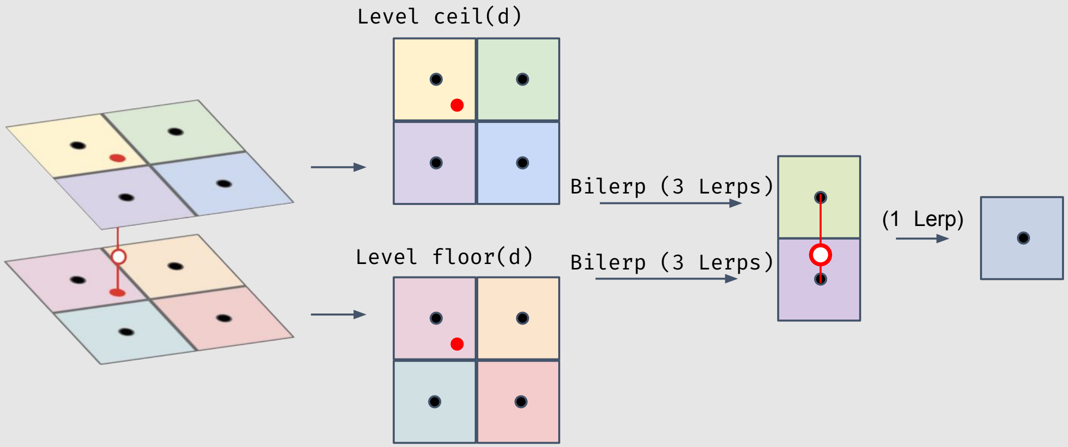
$$t_x \leftarrow (1 - \Delta x) * t_{(x,y)} + \Delta x * t_{(x+1,y)}$$
$$t_y \leftarrow (1 - \Delta x) * t_{(x,y+1)} + \Delta x * t_{(x+1,y+1)}$$

$$t \leftarrow (1 - \Delta y) * t_x + \Delta y * t_y$$

Trilinear Interpolation Sampling

- **Idea:** Perform bilinear interpolation on two layers of the mip-map that represents proper minification/magnification, blending the results together

- **Requires:**
  - 8 memory lookup
  - 7 linear interpolations



$$L_x{}^2 \leftarrow \frac{du}{dx}^2 + \frac{dv}{dx}^2$$
$$L_y{}^2 \leftarrow \frac{du}{dy}^2 + \frac{dv}{dy}^2$$

$$L \leftarrow \sqrt{\max(L_x{}^2, L_y{}^2)}$$
$$d \leftarrow log_2 L$$

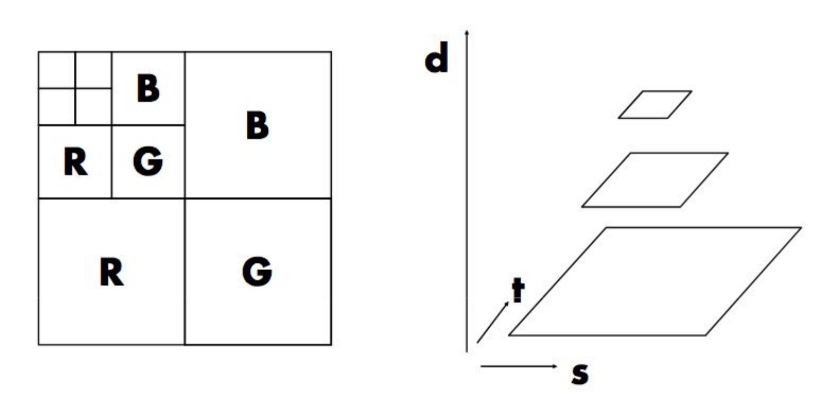
$$d' \leftarrow floor(d)$$
$$\Delta d \leftarrow d - d'$$

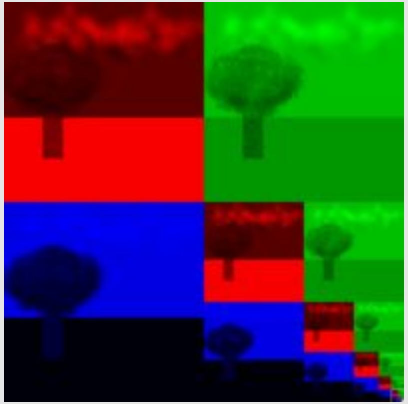
$$t_d \leftarrow tex[d'].bilinear(x,y)$$
$$t_{d+1} \leftarrow tex[d'+1].bilinear(x,y)$$
$$t \leftarrow (1-\Delta d) * t_d + \Delta d * t_{d+1}$$

Mip-Map [L. Williams ‘83]

- Storing an RGB Mip-Map can be fit into an image twice the width and twice the height of the original image
  - See diagram for proof :)
  - Does not work as nicely for RGBA!

- **Issue:** bad spatial locality
  - Requesting a texel requires lookup in 3 very different regions of an image





Anisotropic Filtering

- **Anisotropic** filtering is dependent on direction
  - ***an* – not, iso – same, *tropic* – direction**

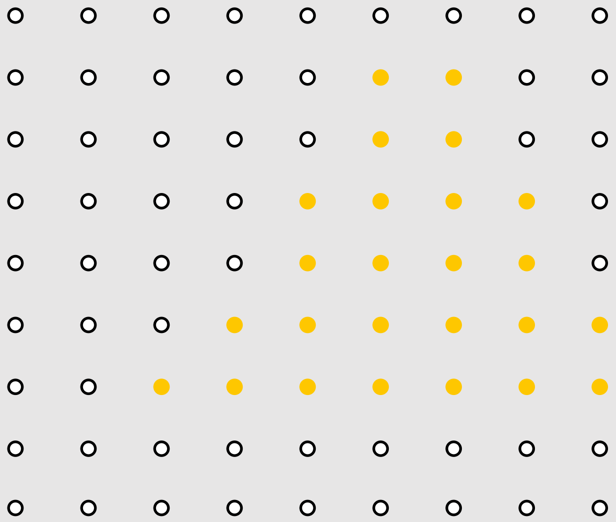
- **Idea:** create a new texture map that downsamples the x and y axis by 2 separately
  - Instead of taking the max, use each coordinate to index into correct location in map

$$L = \cancel{\sqrt{\max(L_x^2, L_y^2)}}$$

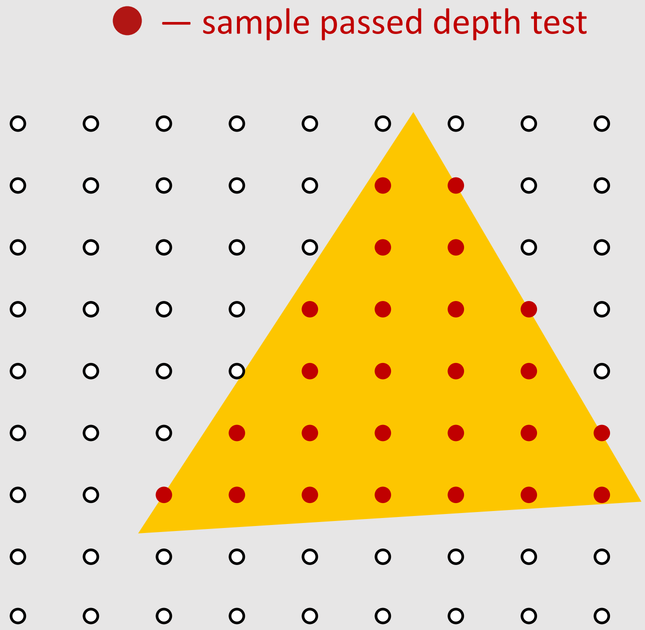
$$(d_x, d_y) = (\log_2\sqrt{L_x^2}, \log_2\sqrt{L_y^2})$$

- Texture map is now a grid of downsampled textures
  - Known as a RipMap

Depth Buffer (Z-buffer)

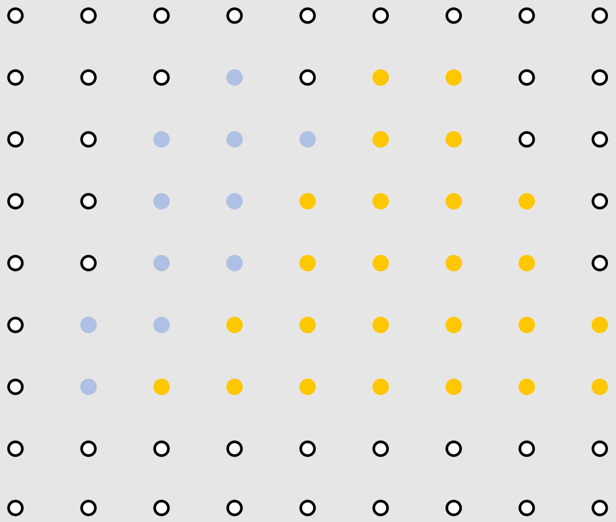


[color buffer]

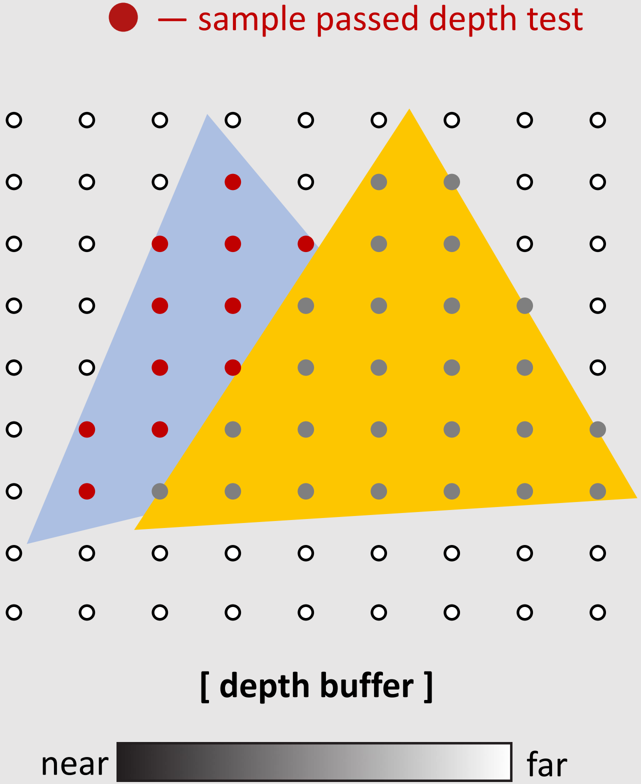


[depth buffer]

Depth Buffer (Z-buffer)

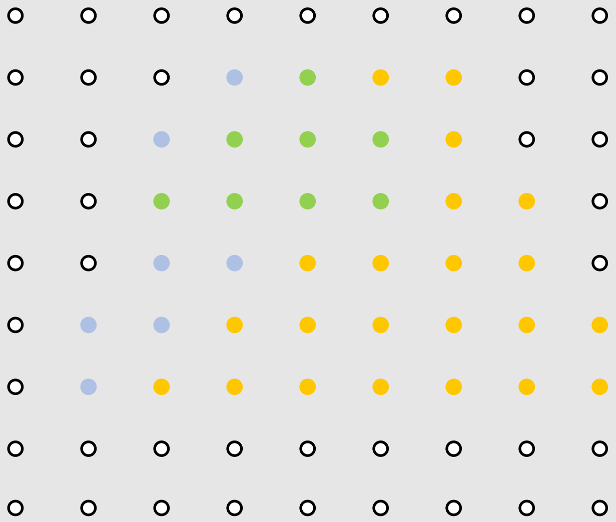


[color buffer]



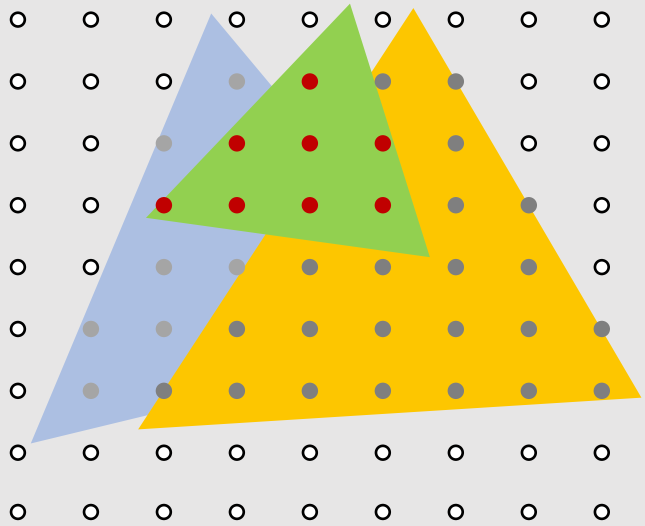
[depth buffer]

Depth Buffer (Z-buffer)



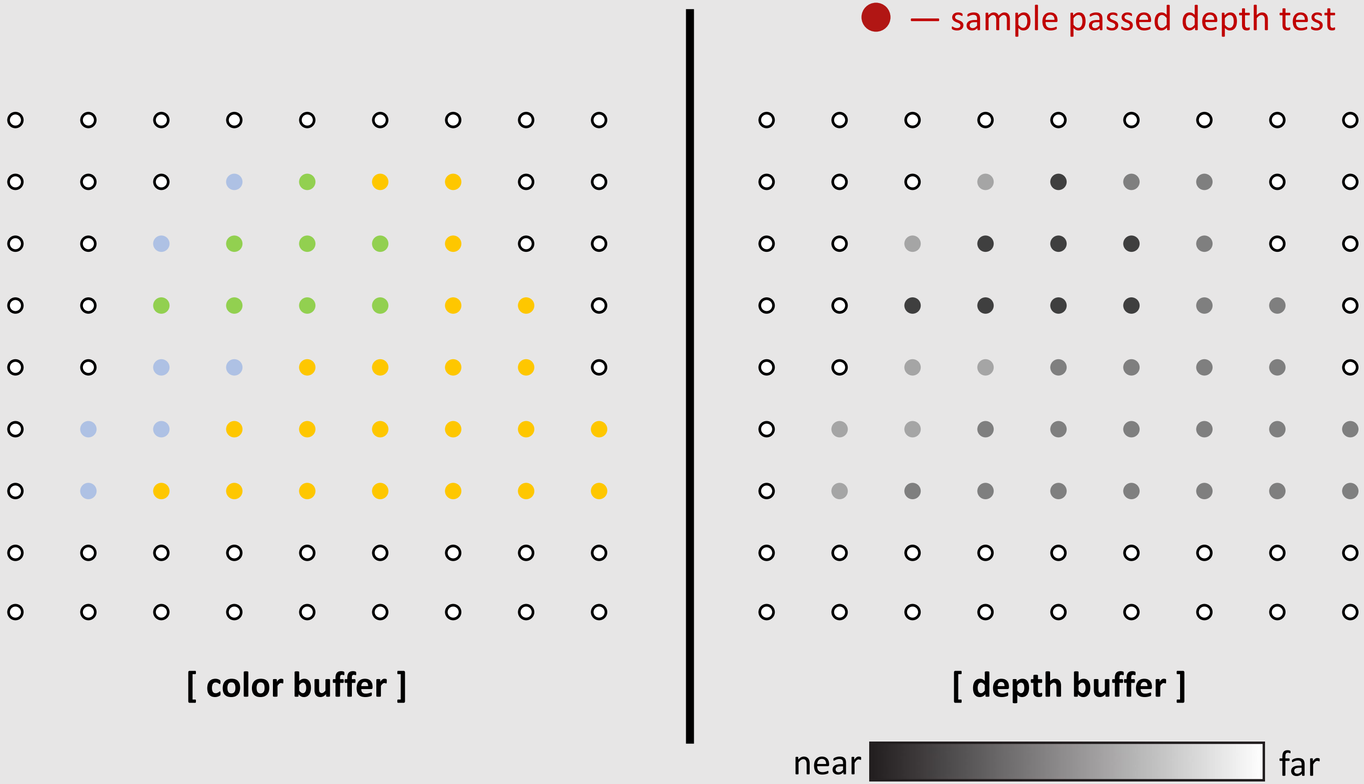
[color buffer]

— sample passed depth test



[depth buffer]

Depth Buffer (Z-buffer)

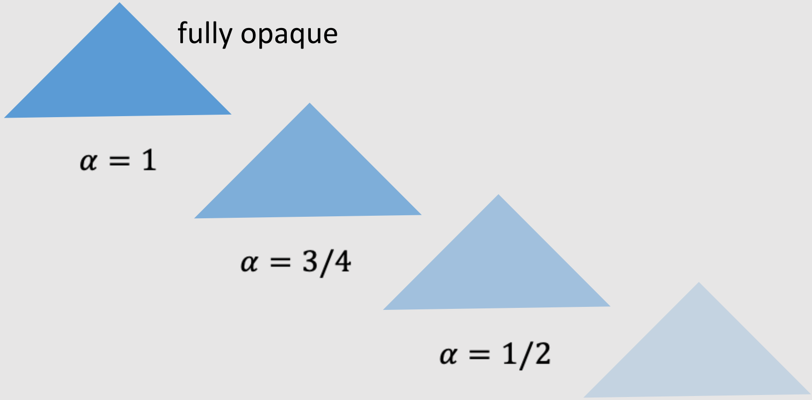


Alpha Values

- Common image format: RGBA
  - Alpha channel specifies ‘opacity’/transparency of object
  - Most common encoding is 8-bits per channel
- Compositing A over B != B over A
  - Consider the extreme case of two opaque objects…
- Non-premultiplied alpha vs Premultiplied alpha

$C = \alpha_B B + (1 - \alpha_B)\alpha_A A$

$C' = B' + (1 - \alpha_B)A'$



[koala over nyc]

[nyc over…koala?]

where is the koala…

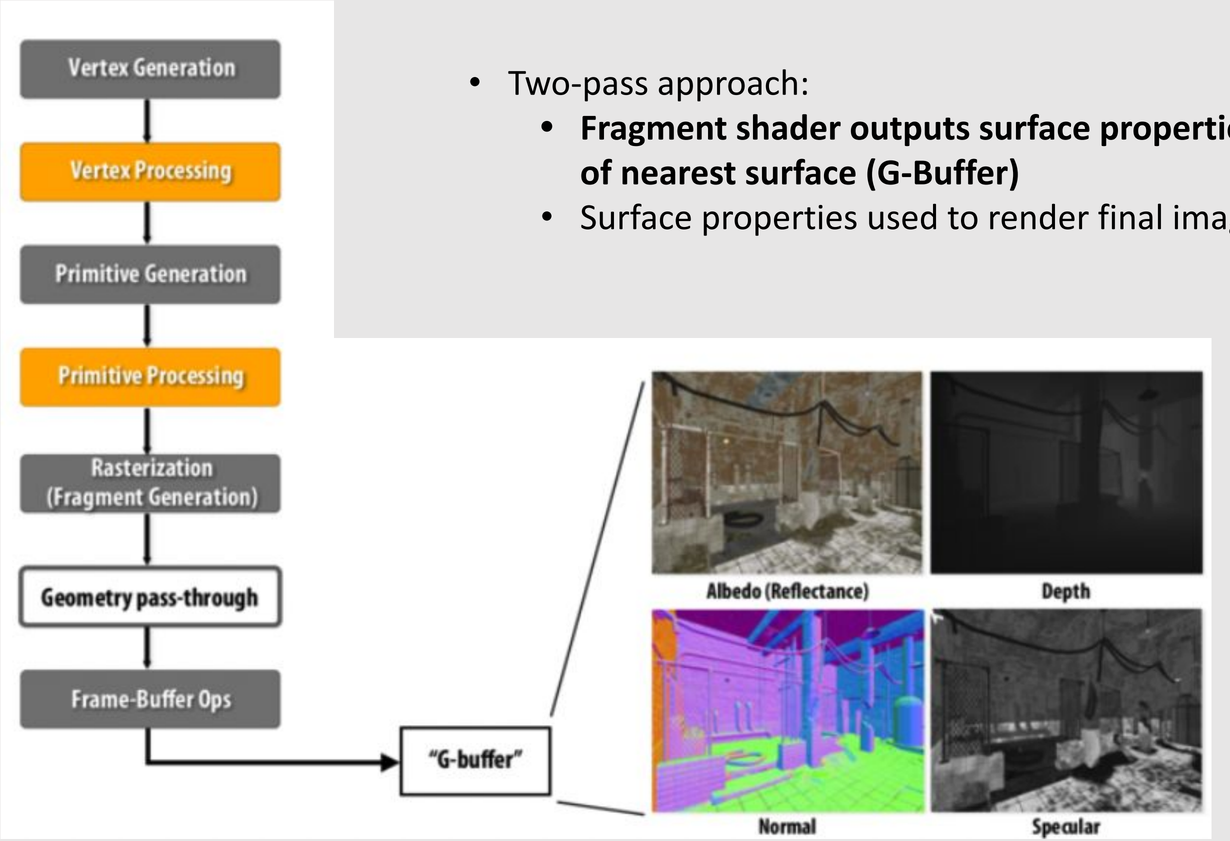
Deferred Shading

- Popular algorithm for rendering in modern games
- **Idea:** restructure the rendering pipeline to perform shading **after** all occlusions have been resolved
- Not a new idea. Implemented in several classic graphics systems, but not directly supported in most high-end GPUs
  - But modern graphics pipeline provides mechanism to allow applications to implement deferred shading efficiently

Assassin's Creed III (2012) Ubisoft

Shrek (2001) Digital Illusions Canada

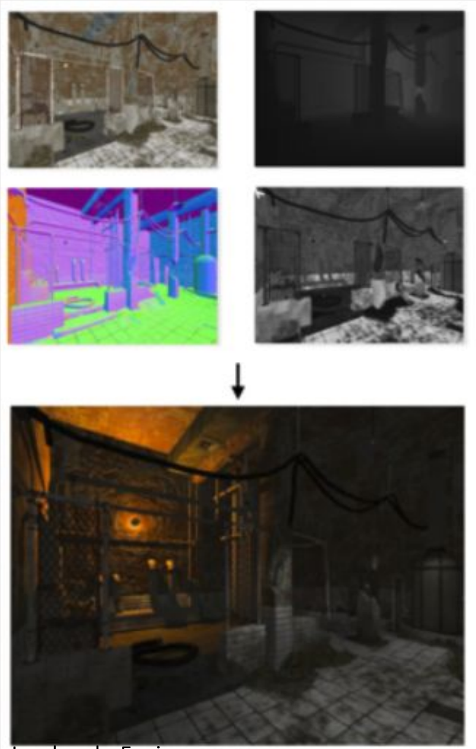
Deferred Shading



- Two-pass approach:
  - **Fragment shader outputs surface properties of nearest surface (G-Buffer)**
  - Surface properties used to render final image

Two-Pass Algorithm

- **Pass 1: Geometry Pass**
  - Render scene geometry using traditional pipeline
  - Write visible geometry information to G-Buffer
- **Pass 2: Shading Pass**
  - For each G-Buffer sample, compute shading
  - Read G-Buffer data for current sample
  - Accumulate contribution of all lights
  - Output final surface color for sample

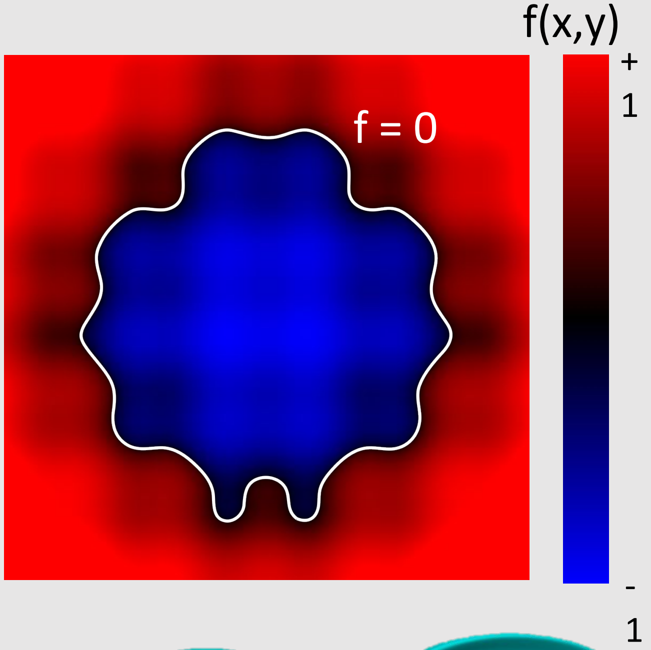


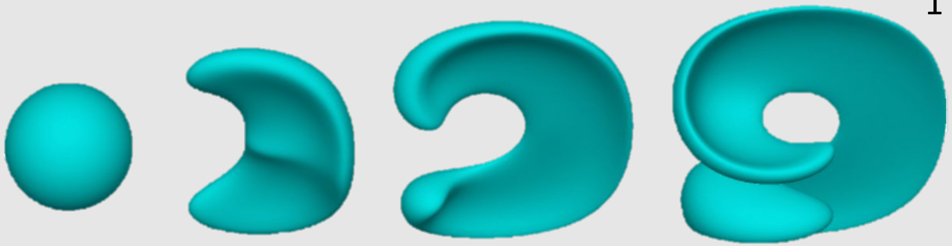
Leadwerks Engine

- Transformations Review
- Rasterization Review
- Geometry Review
- Spatial Data Structures Review

Implicit Geometry

- Points aren't known directly, but satisfy some relationship
  - Example: unit sphere is all points such that $x^2+y^2+z^2=1$
- More generally, in the form $f(x,y,z) = 0$
- Finding example points is **<u>hard</u>**
  - Requires solving equation
- Checking if points are inside/outside is **<u>easy</u>**
  - Just evaluate the function with a given point



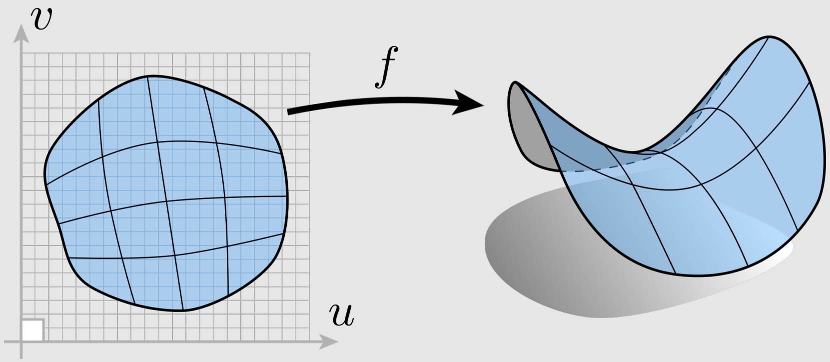


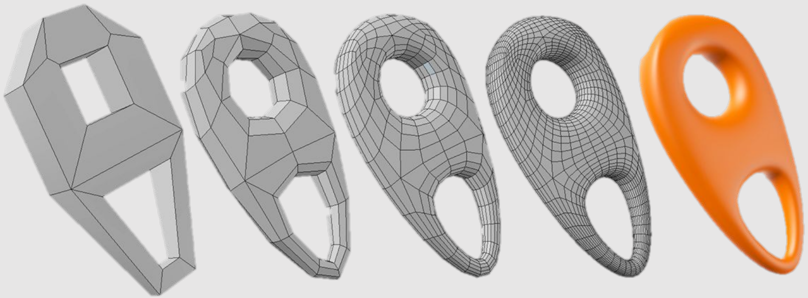
Explicit Geometry

- All points are given directly
  - The polygons we were given during rasterization is an example of explicit geometry
- More generally:

$$f : \mathbb{R}^2 \to \mathbb{R}^3; (u, v) \mapsto (x, y, z)$$

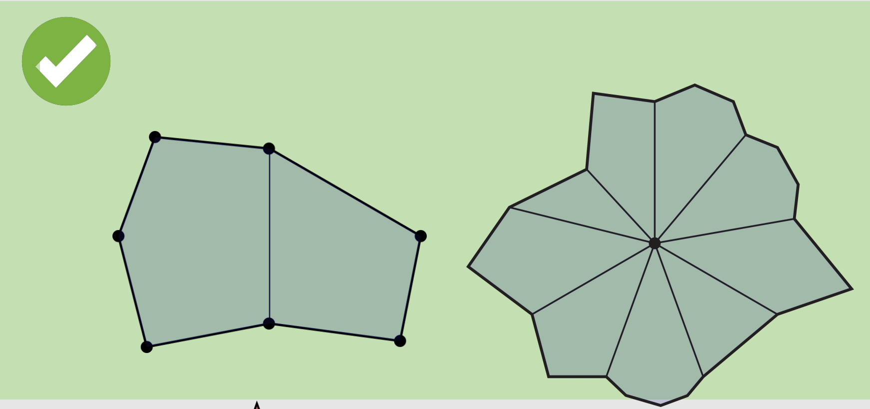
  - Given any (u, v), we can find a point on the surface
  - Can limit (u, v) to some range
    - Example: triangle with barycentric coordinates
- Finding example points is **easy**
  - We are given them for free
- Checking if points are inside/outside is **hard**
  - We are given the output values and need to find input values that satisfy the geometry

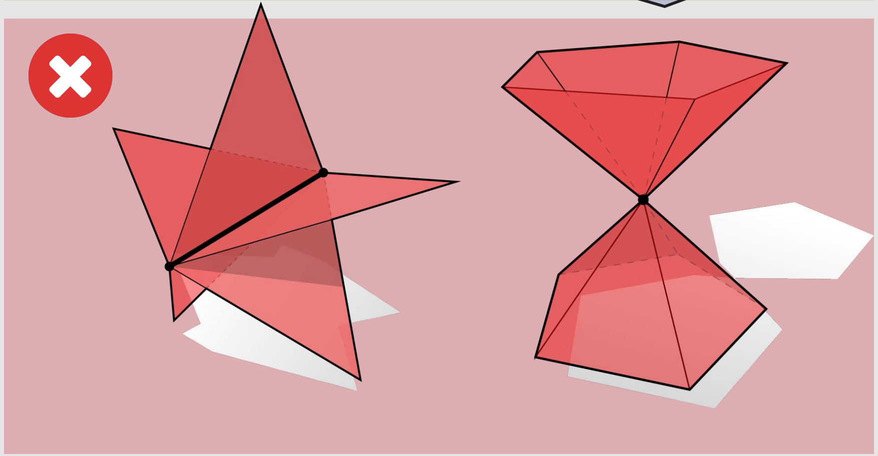




Manifold Properties

- For polygonal surfaces, we will check for **“fins”** and **”fans”**
- Every edge is contained in only two polygons (no **“fins”**)
    - The extra 3rd or 4th or 5th or so forth polygon is the fin of a fish
- The polygons containing each vertex make a single **“fan”**
    - We should be able to loop around the faces around a vertex in a clear way





Geometry Types

- What is implicit geometry
  - Algebraic surfaces
  - Constructive solid geometry
  - Signed distance fields
- What is explicit geometry
  - Point clouds
  - Triangle meshes
- Be able to compare the pros and cons of implicit and explicit geometry
- Manifold mesh requirements

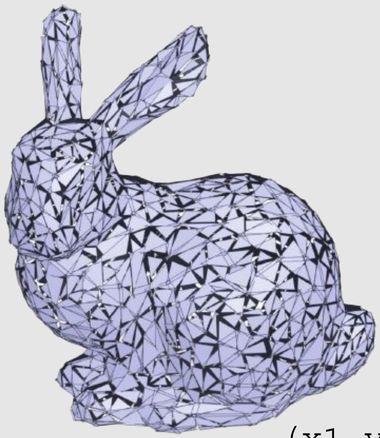
What are some ways to describe the connectivity of geometry?

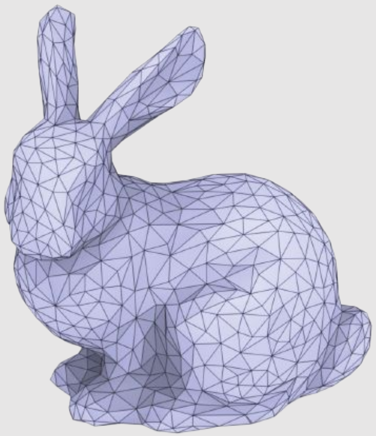
Polygon Soup

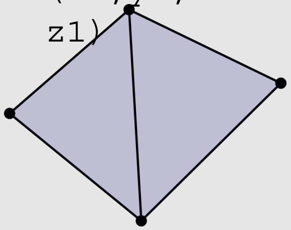
- Most basic idea imaginable:
  - For each triangle, just store three coordinates
  - No other information about connectivity
  - Not much different from point cloud
    - A “Triangle cloud”?

- **Pros:**
  - [+] Really stupid simple

- **Cons:**
  - [-] Really stupid
  - [-] Redundant storage of vertices
  - [-] Very difficult to find neighboring polygons



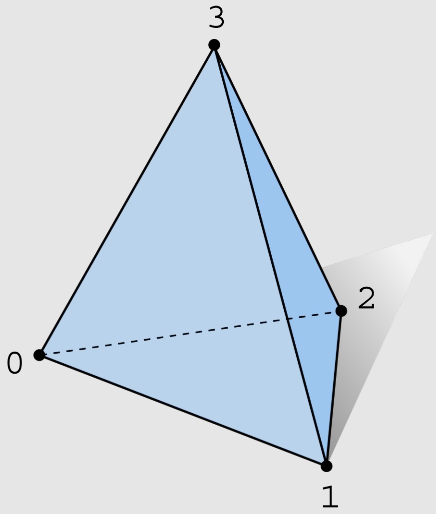





```
x0,y0,z0  x1,y1,z1
x3,y3,z3
x1,y1,z1  x2,y2,z2
x3,y3,z3
```

Adjacency List

- A little more complicated:
  - Store triples of coordinates (x,y,z)
  - Store tuples of indices referencing the coordinates needed to build each triangle
- **Pros:**
  - [+] No duplicate coordinates
  - [+] Lower memory footprint
  - [+] Easy to keep geometry manifold
  - [+] Supports nonmanifold geometry
  - [+] Easy to change connectivity of geometry
- **Cons:**
  - [-] Very difficult to find neighboring polygons
  - [-] Difficult to add/remove mesh elements

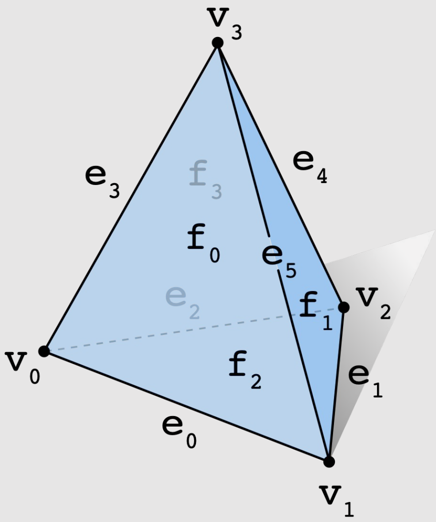


Incidence Matrices

- If we want to know our neighbors, let's store them:
  - Store triples of coordinates (x,y,z)
  - Store incidence matrix between vertices + edges, and edges + faces
    - 1 means touch, 0 means no touch
    - Store as sparse matrix

- **Pros:**
  - [+] No duplicate coordinates
  - [+] Finding neighbors is O(1)
  - [+] Easy to keep geometry manifold
  - [+] Supports nonmanifold geometry

- **Cons:**
  - [-] Larger memory footprint
  - [-] Hard to change connectivity with fixed indices
  - [-] Difficult to add/remove mesh elements



Halfedge Mesh

- What are the components of a halfedge mesh?
- How to traverse around a vertex? A face? An edge?
- Why can we not represent a non-manifold mesh using halfedge geometry?
- What makes a good mesh?

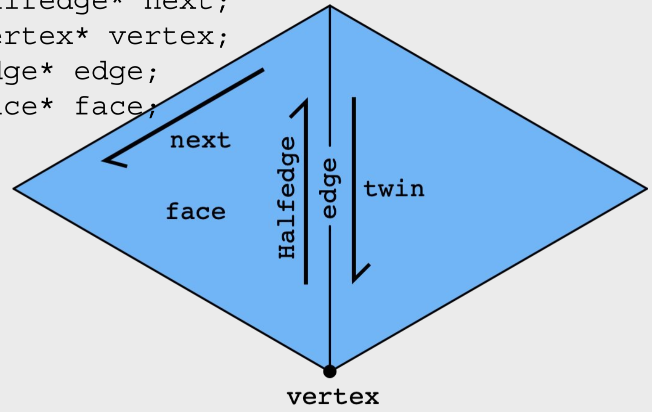
Halfedge Data Structure

- Let's store a little, but not a lot, about our neighbors:
  - Halfedge data structure added to our geometry
  - Each edge gets 2 halfedges
    - Each halfedge "glues" an edge to a face

- **Pros:**
  - [+] No duplicate coordinates
  - [+] Finding neighbors is O(1)
  - [+] Easy to traverse geometry
  - [+] Easy to change mesh connectivity
  - [+] Easy to add/remove mesh elements
  - [+] Easy to keep geometry manifold

- **Cons:**
  - [-] Does not support nonmanifold geometry

```
struct Halfedge
{
   Halfedge* twin;
   Halfedge* next;
   Vertex* vertex;
   Edge* edge;
   Face* face;
};
```



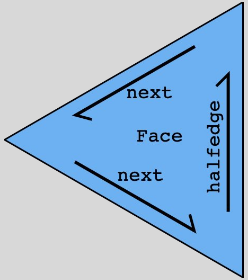
Halfedge Data Structure

- Makes mesh traversal easy
  - Use “twin” and “next” pointers to move around the mesh
  - Use “vertex”, “edge”, and “face” pointers to grab element

```
struct Halfedge
{
   Halfedge* twin;
   Halfedge* next;
   Vertex* vertex;
   Edge* edge;
   Face* face;
};
```

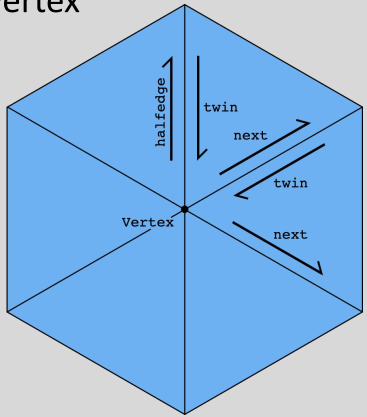
Example: visit all vertices in a face

```
Halfedge* h = f->halfedge;
do {
   h = h->next;
   // do something w/ h->vertex
}
while( h != f->halfedge );
```



Example: visit all neighbors of a vertex

```
Halfedge* h = v->halfedge;
do {
   h = h->twin->next;
}
while( h != v->halfedge );
```



Note: only makes sense if mesh is manifold!

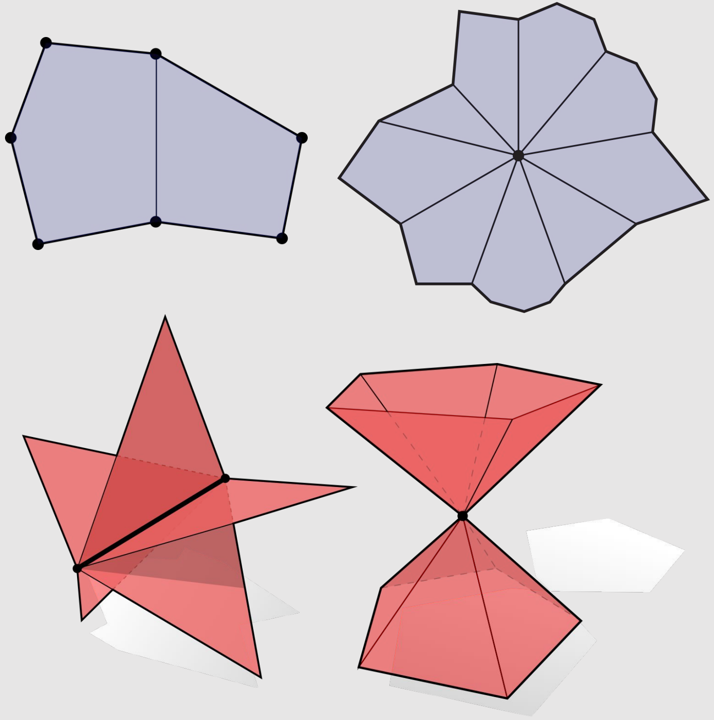
Halfedge Data Structure

- Halfedge meshes are always manifold!
- Halfedge data structures have the following constraints:

```
h->twin->twin == h // my twin's twin is me
h->twin != h // I am not my own twin
h2->next = h //every h's is someone's "next"
```

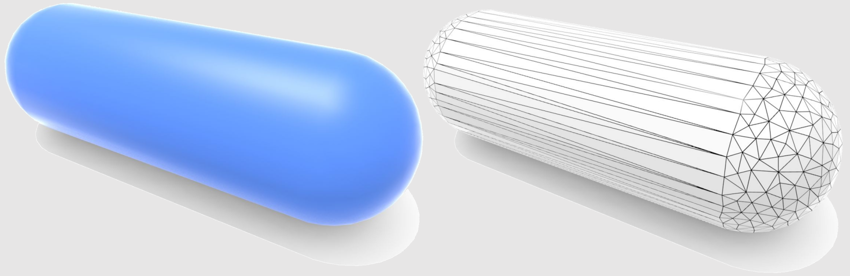
- Keep following **next** and you'll traverse a face
- Keep following **twin** and you'll traverse an edge
- Keep following **next->twin** and you'll traverse a vertex

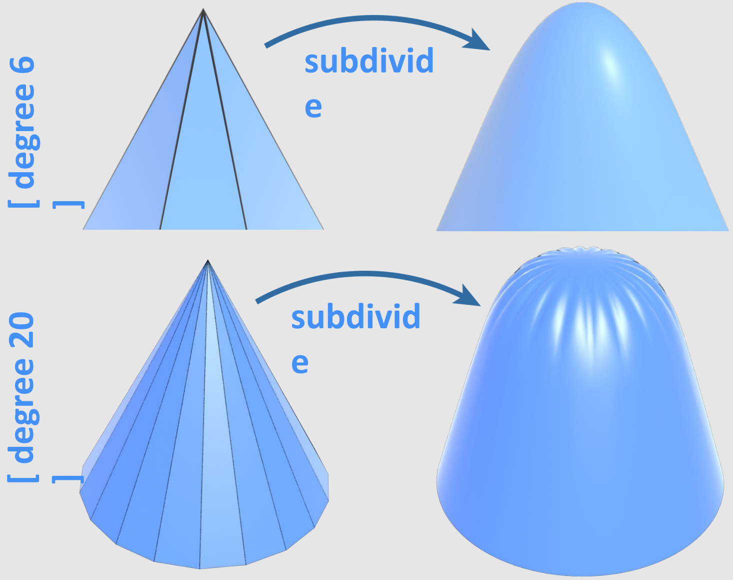
- Q: Why, therefore, is it impossible to encode the red figures?
  - First shape violates first 2 conditions
  - Second shape violates 3rd condition

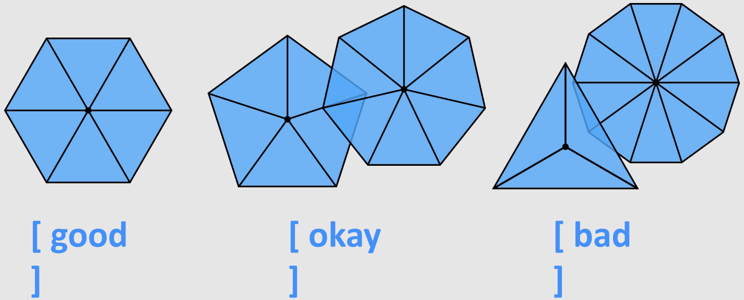


A Good Mesh Has…

- Good approximation of original shape
  - Keep only elements that contribute information about shape
  - More elements where curvature is high
- Regular vertex degree
  - Degree 6 for triangle mesh, 4 for quad mesh
    - Better polygon shape
    - More regular computation
    - Smoother subdivision

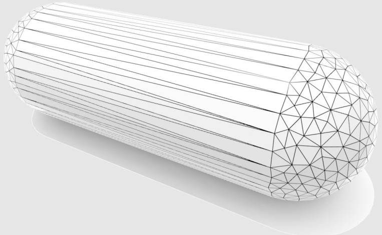


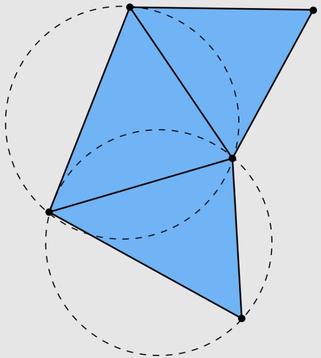




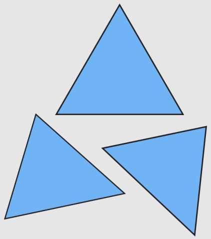
A Good Mesh Has…

- Good triangle shape
    - All angles close to 60 degrees
- More sophisticated condition: Delaunay
    - For every triangle, the unique circumcircle (circle passing through all vertices of the triangle) does not encase any other vertices
    - Many nice properties:
        - Maximizes minimum angle
        - Smoothest interpolation
- **Tradeoff:** sometimes a mesh can be approximated best with long & skinny triangles
    - Doesn't make the mesh Delaunay anymore
    - Example: cylinder





[delaunay]



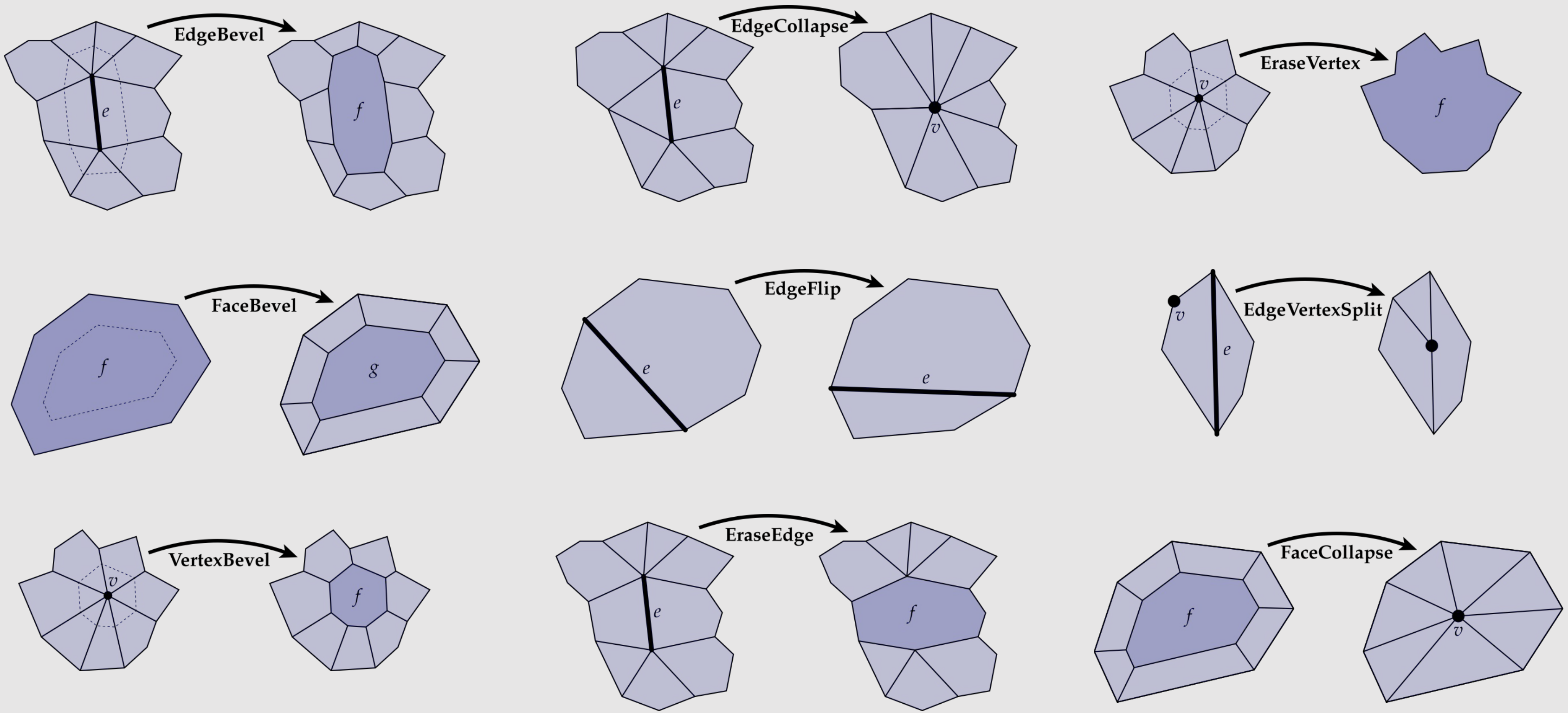
[good]

[bad]

Halfedge Mesh Operations

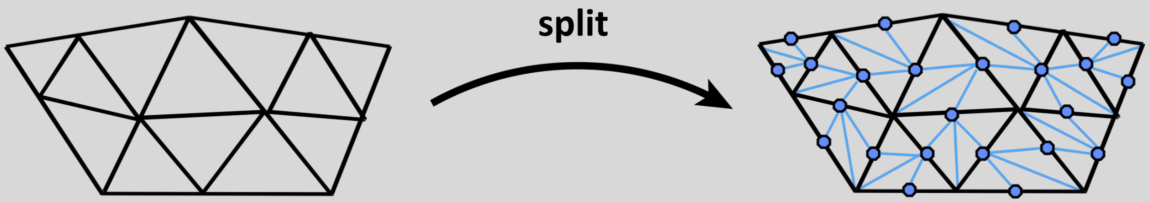
- Local Operations
  - EdgeBevel
  - EdgeCollapse
  - EraseVertex
  - FaceBevel
  - EdgeFlit
  - EdgeVertexSplit
  - VertexBevel
  - EraseEdge
  - FaceCollapse
  - …
- Global Operations
  - Loop Subdivision
  - Isotropic Remeshing
  - Simplification
  - …

Local Operations

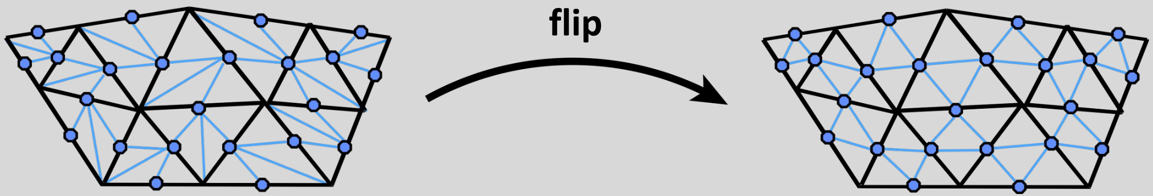


Loop Subdivision Using Local Ops

Step 1:
Split all edges in any order

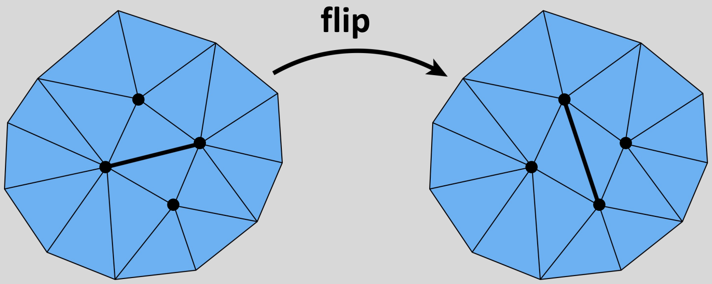


Step 2:
Flip new edges until they touch two new vertices

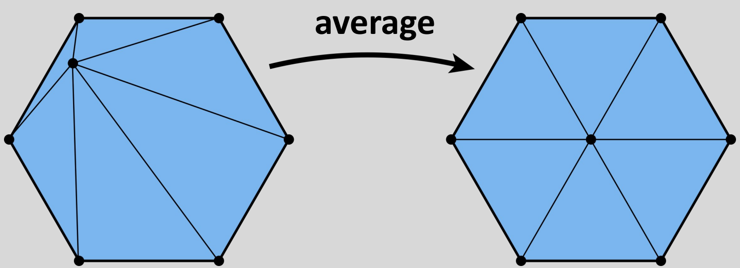


Isotropic Remeshing

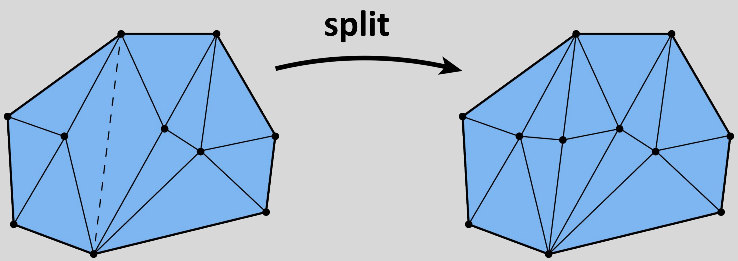
Step 1:



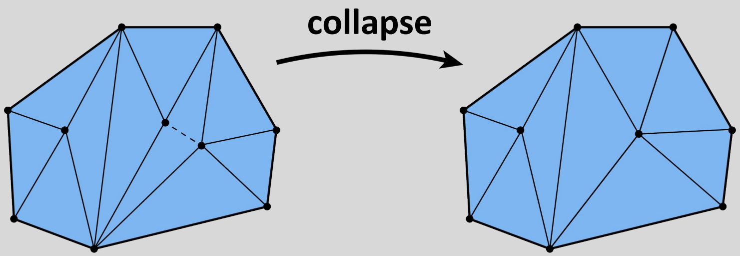
Step 2:



Step 3:



Step 4:



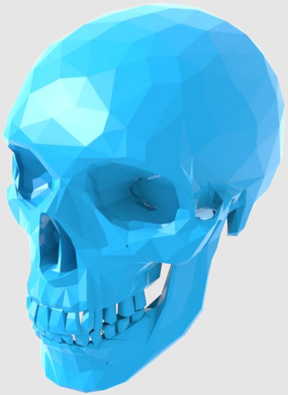
Simplification Algorithm Basics

- Greedy Algorithm:
  - Assign each edge a cost
  - Collapse edge with least cost
  - Repeat until target number of elements is reached

- Particularly effective cost function: quadric error metric**

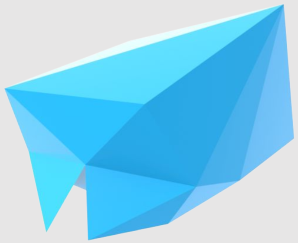
No need to remember the specific metric!

[30,000 triangles]



[3,000 triangles]

[300 triangles]



[30 triangles]

**invented at CMU (Garland & Heckbert 1997)

- Transformations Review
- Rasterization Review
- Geometry Review
- Spatial Data Structures Review

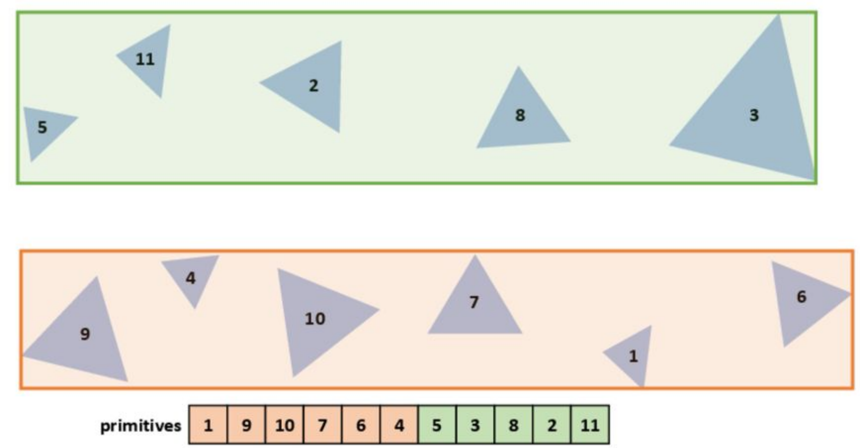
Spatial Data Structures

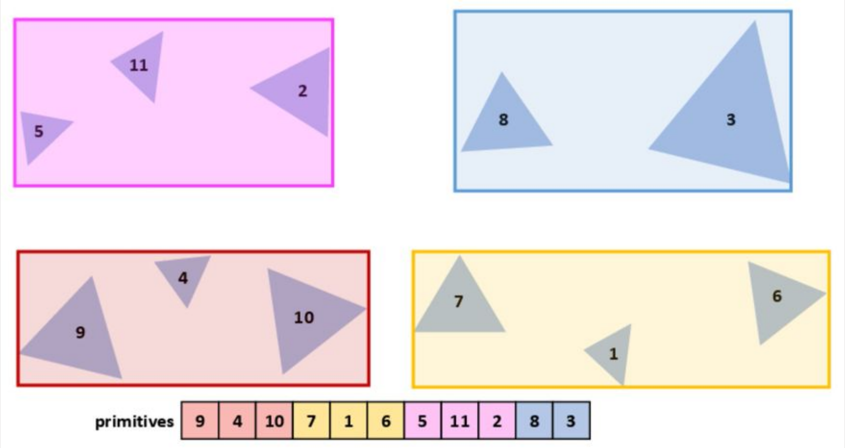
- Primitive-partitioning acceleration structure:
  - Partitions node's primitives into disjoint sets (but sets may overlap in space)
  - Bounding Volume Hierarchy
    - How to construct a BVH
    - How to traverse a BVH
    - Axis-aligned vs non-axis aligned BVHs

- Space-partitioning acceleration structures:
  - Partitions space into disjoint regions (but primitives may be contained in multiple regions)
  - K-D Trees
  - Uniform Grids
  - Quad/OctTreees

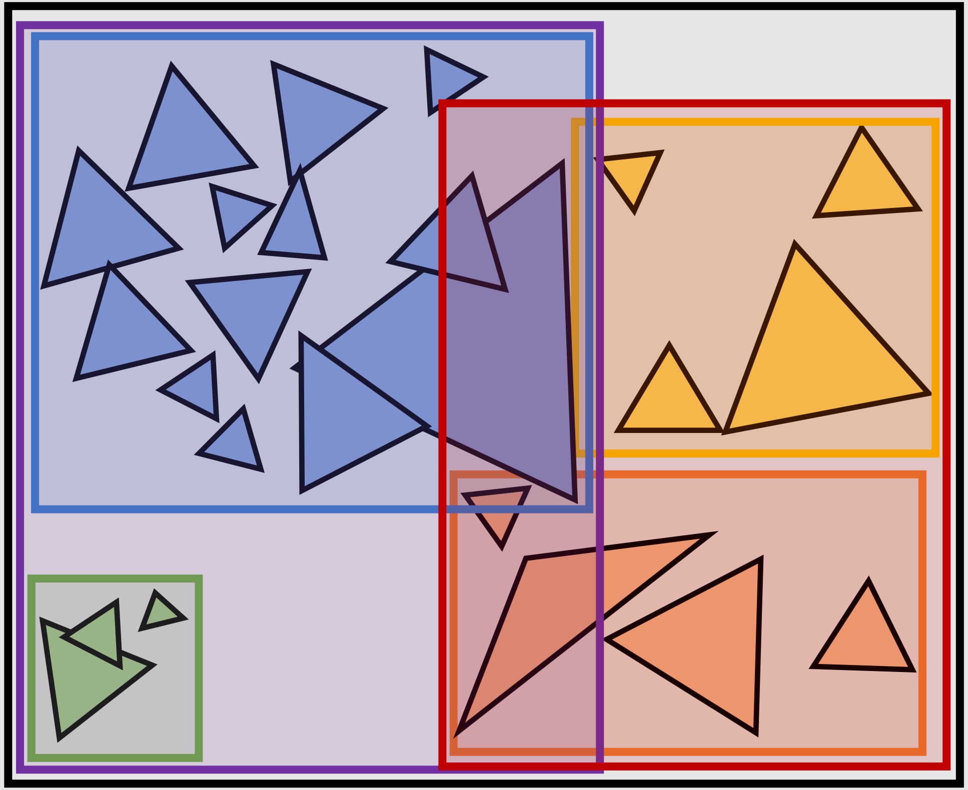
BVH Construction

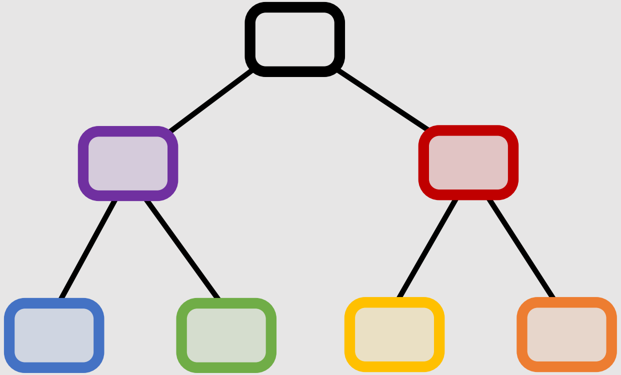
```
For axis x,y,z:
    Initialize buckets
    For each primitive p in node:
        B = compute_bucket(p.centroid)
        B.bbox.enclose(p.bbox)
        B.prim_count++
    For each of |B| - 1 possible partitions
        Evaluate cost (SAH), keep track of lowest cost partition
Recurse on lowest cost partition found (or make node leaf)
```





BVH Example





Bounding boxes will sometimes intersect!

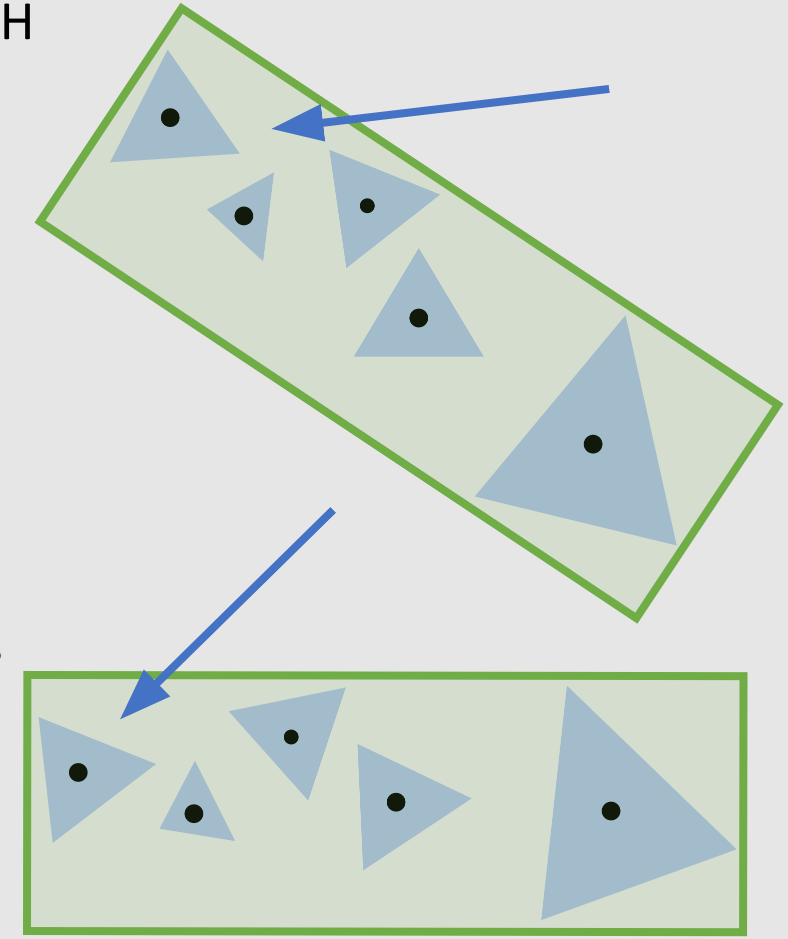
Axis-Aligned BVH

- **Are non-axis-aligned BVHs actually faster?**
  - Yes, and no.

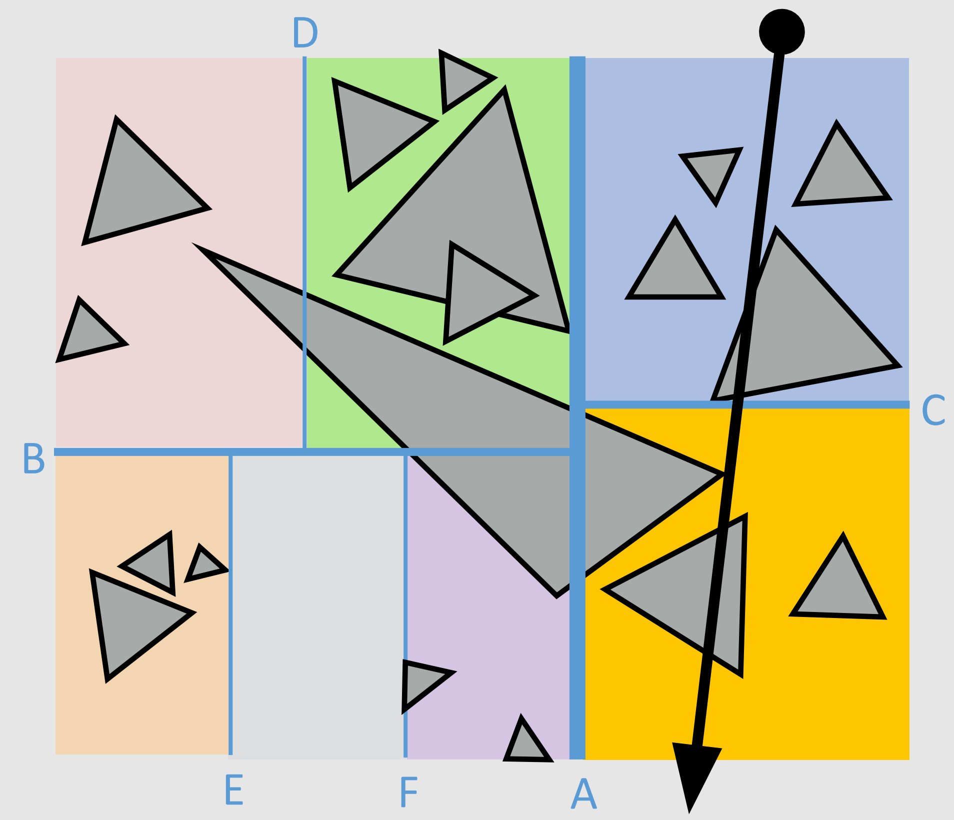
$$C = C_{trav} + \frac{S_A}{S_C} N_A C_{tri} + \frac{S_B}{S_C} N_B C_{tri}$$

  - Surface area ratio $\frac{S_A}{S_C}$ decreases with better-fitting bboxes
  - Bounding box intersection cost C_{trav} increases with more compute required to check unaligned bbox

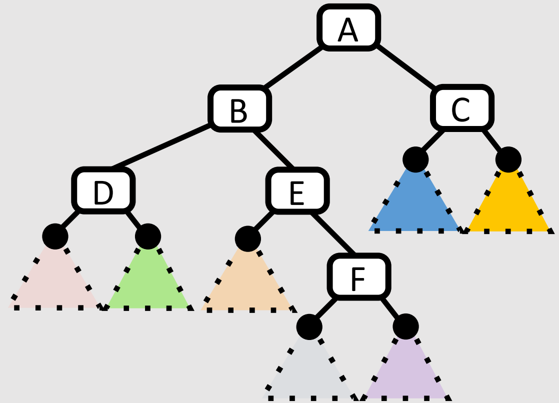
- **How to check for intersection with non-axis-aligned bbox?**
  - Bbox now has an extra transform matrix T taking it from its <u>local</u> space <u>to</u> its <u>parent</u> space
    - Apply the **inverse** transform to the **ray** and compute axis-aligned intersections
  - Larger memory overhead, now need to store the transform with each node



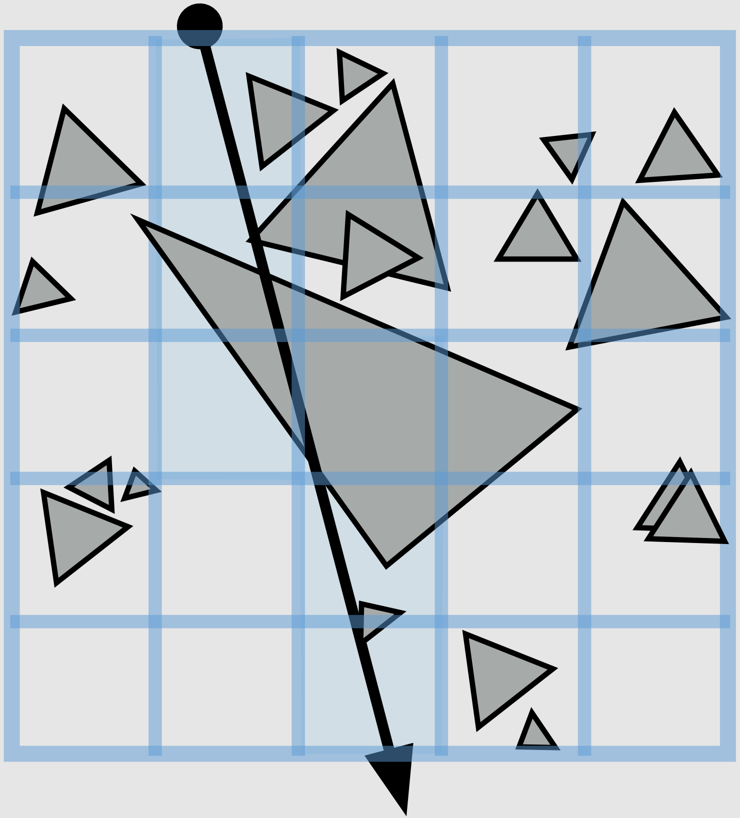
K-D Trees



- Recursively partition space via axis-aligned partitioning planes
  - Interior nodes correspond to spatial splits
  - Node traversal proceeds in front-to-back order
  - Unlike BVH, can terminate search after first hit is found
  - Still $O(\log(N))$ performance



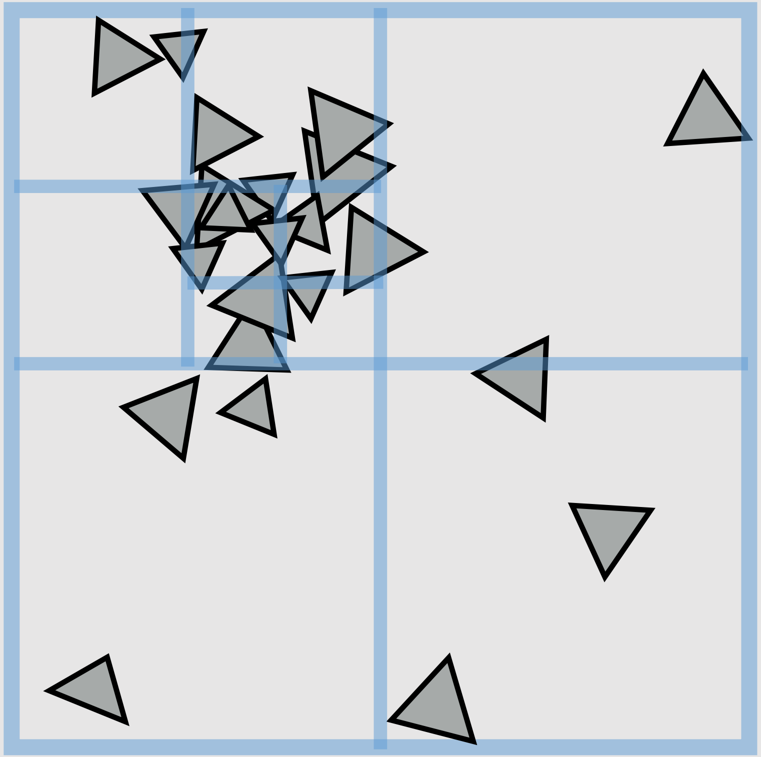
Uniform Grid



- Partition space into equal sized volumes (volume-elements or “voxels”)
- Each grid cell contains primitives that overlap voxel. (very cheap to construct acceleration structure)
- Walk ray through volume in order
  - Very efficient implementation possible (think: 3D line rasterization)
  - Only consider intersection with primitives in voxels the ray intersects

- What is a good number of voxels?
  - Should be proportional to total number of primitives N
  - Number of cells traversed is proportional to $O(\sqrt[3]{N})$
    - A line going through a cube is a cubed root
    - Still not as good as $O(\log(N))$

Quad-Tree/Octree



- Like uniform grid, easy to build
- Has greater ability to adapt to location of scene geometry than uniform grid
  - Still not as good adaptability as K-D tree

- **Quad-tree:** nodes have 4 children
  - Partitions 2D space
- **Octree:** nodes have 8 children
  - Partitions 3D space


good luck