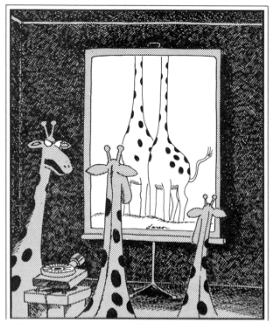
The Traditional Graphics Pipeline

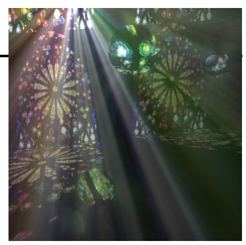

"Oh, lovely — just the hundredth time you've managed to cut everyone's head off."

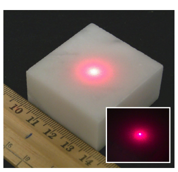
Final Projects

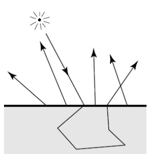
- Proposals due Thursday 4/8
  - Proposed project summary
  - At least 3 related papers (read & summarized)
  - Description of series of test cases
  - Timeline & initial task assignment
    - [Homework 4 due: Thursday 4/22]
    - Final project progress post on LMS due: Monday 4/26
    - [Quiz 2: Fri 4/30]
    - In class work sessions: Tuesday 5/4 & Friday 5/7 (TA will meet with each group)
    - Reports Due: Monday 5/10
    - Presentations: *Wednesday 5/12, 1-5pm?*

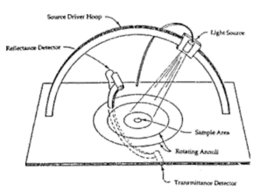
Last Time?

- Participating Media
- Measuring BRDFs
- 3D Digitizing & Scattering
- BSSRDFs
  - Monte Carlo Simulation
  - Dipole Approximation









Today

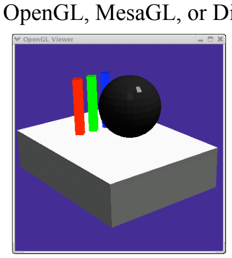
- Ray Casting / Tracing vs. Scan Conversion
- Traditional Graphics Pipeline
- Clipping
- Rasterization/Scan Conversion

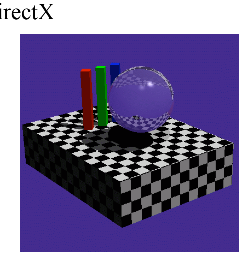
Ray Casting / Tracing

- Advantages?
  - Smooth variation of normal, silhouettes
  - Generality: can render anything that can be intersected with a ray
  - Atomic operation, allows recursion
- Disadvantages?
  - Time complexity (N objects, R pixels)
  - Usually too slow for interactive applications
  - Hard to implement in hardware (lacks computation coherence, must fit entire scene in memory)

How Do We Render Interactively?

- Use graphics hardware (the graphics pipeline), via OpenGL, MesaGL, or DirectX


Graphics Pipeline (OpenGL)

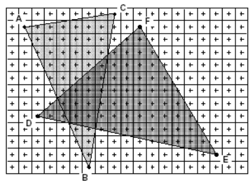

Ray Tracing

- Most global effects available in ray tracing will be sacrificed, but some can be approximated

Scan Conversion

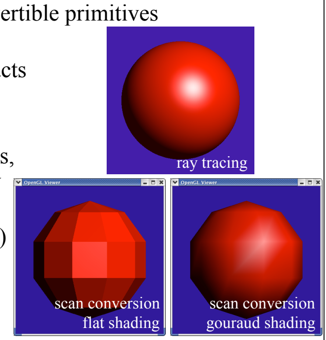
- Given a primitive's vertices & the illumination at each vertex:
- Figure out which pixels to "turn on" to render the primitive
- Interpolate the illumination values to "fill in" the primitive
- At each pixel, keep track of the closest primitive (z-buffer)

```
glBegin(GL_TRIANGLES)
glNormal3f(...)
glVertex3f(...)
glVertex3f(...)
glVertex3f(...)
glEnd();
```



Limitations of Scan Conversion

- Restricted to scan-convertible primitives
  - Object polygonization
- Faceting, shading artifacts
- Effective resolution is hardware dependent
- No handling of shadows, reflection, transparency
- Problem of overdraw (high depth complexity)
- What if there are many more triangles than pixels?



Ray Casting vs. Rendering Pipeline

Ray Casting

```
For each pixel
   For each object
```

Send pixels into the scene

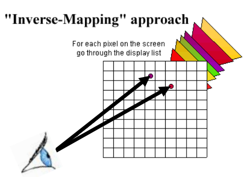
Discretize first

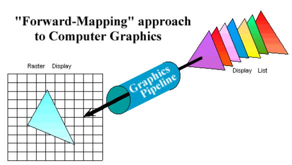
Rendering Pipeline

```
For each triangle
   For each pixel
```

Project scene to the pixels

Discretize last





Ray Casting vs. Rendering Pipeline

Ray Casting

```
For each pixel
   For each object
```

- Whole scene must be in memory
- Depth complexity: no computation for hidden parts
- Atomic computation
- More general, more flexible
  - Primitives, lighting effects, adaptive antialiasing

Rendering Pipeline

```
For each triangle
   For each pixel
```

- Primitives processed one at a time
- Coherence: geometric transforms for vertices only
- Early stages involve analytic processing
- Computation increases with depth of the pipeline
  - Good bandwidth/computation ratio
- Sampling occurs late in the pipeline
- Minimal state required

Questions?

Today

- Ray Casting / Tracing vs. Scan Conversion
- Traditional Graphics Pipeline
- Clipping
- Rasterization/Scan Conversion

The Graphics Pipeline

- Modeling Transformations
- Illumination (Shading)
- Viewing Transformation (Perspective / Orthographic)
- Clipping
- Projection (to Screen Space)
- Scan Conversion (Rasterization)
- Visibility / Display

Input:
Geometric model:
Description of all object, surface, and light source geometry and transformations
Lighting model:
Computational description of object and light properties, interaction (reflection)
Synthetic Viewpoint (or *Camera*):
Eye position and viewing frustum
Raster Viewport:
Pixel grid onto which image plane is mapped

Output:
Colors/Intensities suitable for framebuffer display
(For example, 24-bit RGB value at each pixel)

The Graphics Pipeline

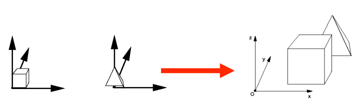
- Modeling Transformations
- Illumination (Shading)
- Viewing Transformation (Perspective / Orthographic)
- Clipping
- Projection (to Screen Space)
- Scan Conversion (Rasterization)
- Visibility / Display

- Primitives are processed in a series of stages
- Each stage forwards its result on to the next stage
- The pipeline can be drawn and implemented in different ways
- Some stages may be in hardware, others in software
- Optimizations & additional programmability are available at some stages

Modeling Transformations

- Modeling Transformations
- Illumination (Shading)
- Viewing Transformation (Perspective / Orthographic)
- Clipping
- Projection (to Screen Space)
- Scan Conversion (Rasterization)
- Visibility / Display

- 3D models defined in their own coordinate system (object space)
- Modeling transforms orient the models within a common coordinate frame (world space)

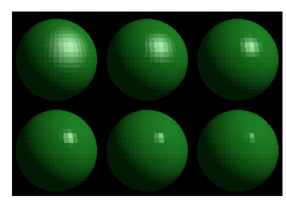


Object space World space

Illumination (Shading) (Lighting)

- Modeling Transformations
- Illumination (Shading)
- Viewing Transformation (Perspective / Orthographic)
- Clipping
- Projection (to Screen Space)
- Scan Conversion (Rasterization)
- Visibility / Display

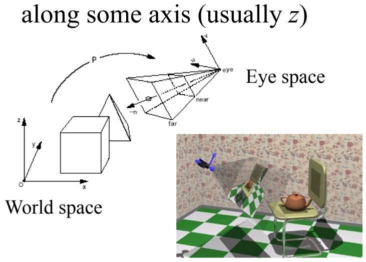
- Vertices lit (shaded) according to material properties, surface properties (normal) and light sources
- Local lighting model (Diffuse, Ambient, Phong, etc.)



Viewing Transformation

- Modeling Transformations
- Illumination (Shading)
- Viewing Transformation (Perspective / Orthographic)
- Clipping
- Projection (to Screen Space)
- Scan Conversion (Rasterization)
- Visibility / Display

- Maps world space to eye space
- Viewing position is transformed to origin & direction is oriented along some axis (usually z)



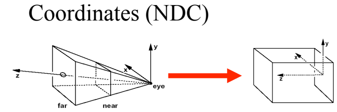
Eye space

World space

Clipping

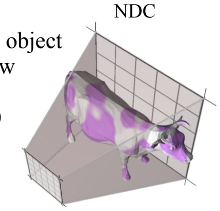
- Modeling Transformations
- Illumination (Shading)
- Viewing Transformation (Perspective / Orthographic)
- Clipping
- Projection (to Screen Space)
- Scan Conversion (Rasterization)
- Visibility / Display

- Transform to Normalized Device Coordinates (NDC)



Eye space NDC

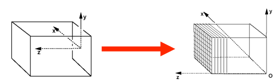
- Portions of the object outside the view volume (view frustum) are removed



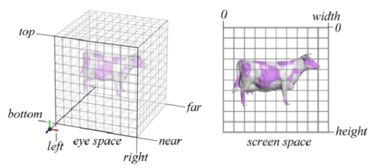
Projection

- Modeling Transformations
- Illumination (Shading)
- Viewing Transformation (Perspective / Orthographic)
- Clipping
- Projection (to Screen Space)
- Scan Conversion (Rasterization)
- Visibility / Display

- The objects are projected to the 2D image place (screen space)



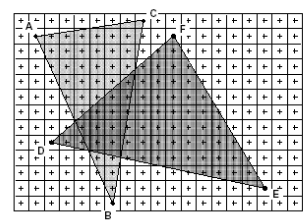
NDC Screen Space



Scan Conversion (Rasterization)

- Modeling Transformations
- Illumination (Shading)
- Viewing Transformation (Perspective / Orthographic)
- Clipping
- Projection (to Screen Space)
- Scan Conversion (Rasterization)
- Visibility / Display

- Rasterizes objects into pixels
- Interpolate values as we go (color, depth, etc.)



Visibility / Display

- Modeling Transformations
- Illumination (Shading)
- Viewing Transformation (Perspective / Orthographic)
- Clipping
- Projection (to Screen Space)
- Scan Conversion (Rasterization)
- Visibility / Display

- Each pixel remembers the closest object (depth buffer)

- Almost every step in the graphics pipeline involves a change of coordinate system. Transformations are central to understanding 3D computer graphics.

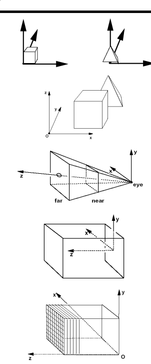
Questions?

Today

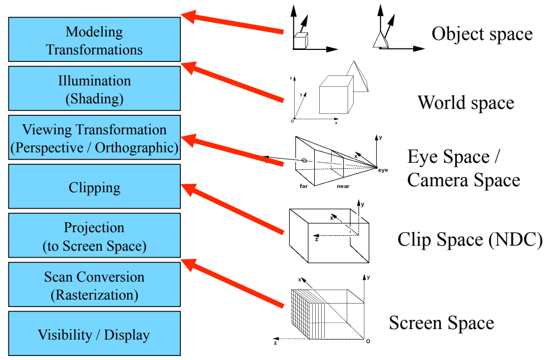
- Ray Casting / Tracing vs. Scan Conversion
- Traditional Graphics Pipeline
- Clipping
  - Coordinate Systems
- Rasterization/Scan Conversion

Common Coordinate Systems

- Object space
  - local to each object
- World space
  - common to all objects
- Eye space / Camera space
  - derived from view frustum
- Clip space / Normalized Device Coordinates (NDC)
  - $[-1,-1,-1] \rightarrow [1,1,1]$
- Screen space
  - indexed according to hardware attributes

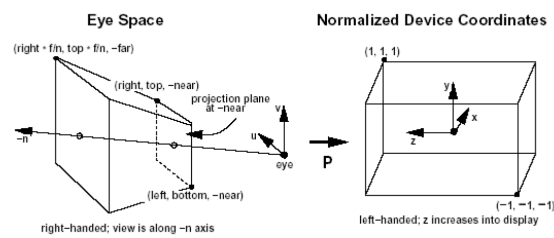


Coordinate Systems in the Pipeline

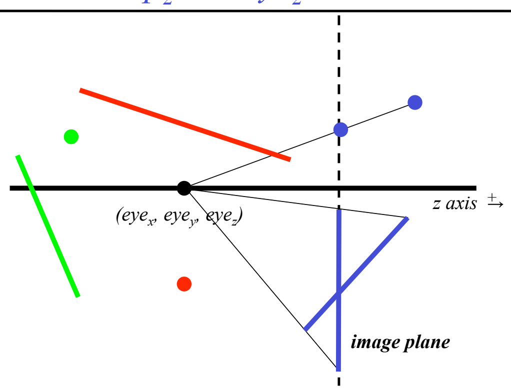


Normalized Device Coordinates

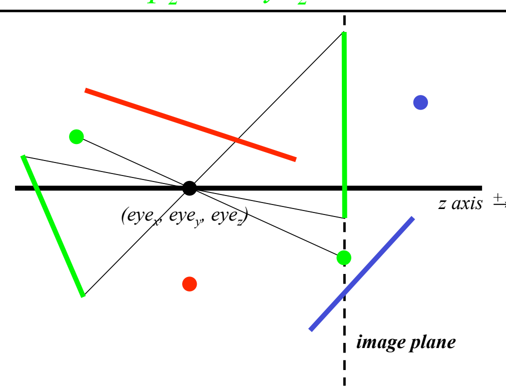
- Clipping is more efficient in a rectangular, axis-aligned volume: (-1,-1,-1) → (1,1,1) *OR* (0,0,0) → (1,1,1)



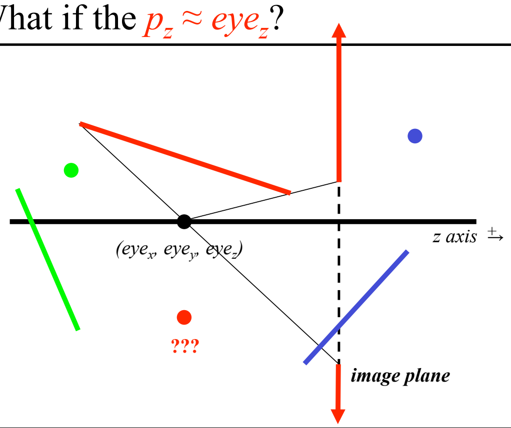
What if the p_z is > eye_z?



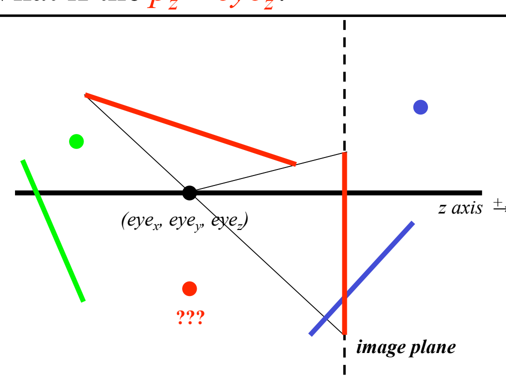
What if the p_z is < eye_z?



What if the $p_z \approx eye_z$?

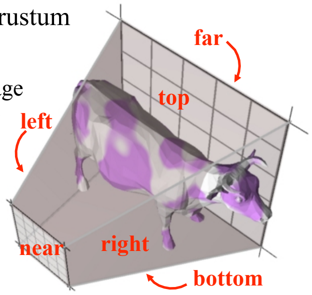


What if the $p_z \approx eye_z$?



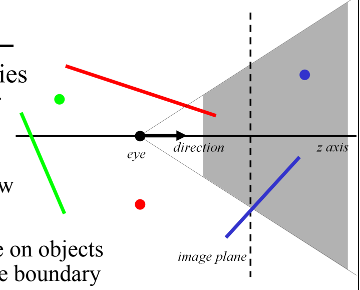
Clipping

- Eliminate portions of objects outside the viewing frustum
- View Frustum
  – boundaries of the image plane projected in 3D
  – a near & far clipping plane
- User may define additional clipping planes



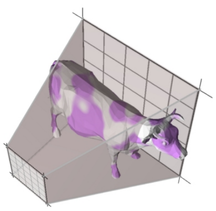
Why Clip?

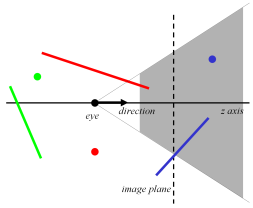
- Avoid degeneracies
  – Don't draw stuff behind the eye
  – Avoid division by 0 and overflow
- Efficiency
  – Don't waste time on objects outside the image boundary
- Other graphics applications (often non-convex)
  – Hidden-surface removal, Shadows, Picking, Binning, CSG (Boolean) operations (2D & 3D)



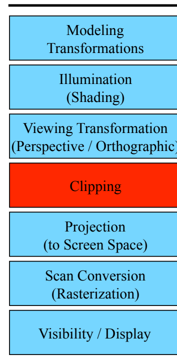
Clipping Strategies

- Don't clip (and hope for the best)
- Clip on-the-fly during rasterization
- Analytical clipping: alter input geometry





The Graphics Pipeline



- Former hardware relied on full clipping
- Modern hardware mostly avoids clipping
  – Only with respect to plane z=0
- In general, it is useful to learn clipping because it is similar to many geometric algorithms

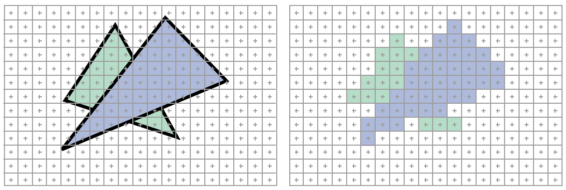
Questions?

Today

- Ray Casting / Tracing vs. Scan Conversion
- Traditional Graphics Pipeline
- Clipping
- Rasterization/Scan Conversion
  – Line Rasterization
  – Triangle Rasterization

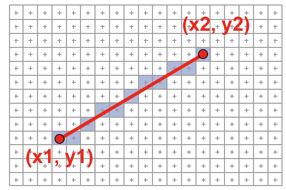
2D Scan Conversion

- Geometric primitives
  (point, line, polygon, circle, polyhedron, sphere...)
- Primitives are continuous; screen is discrete
- Scan Conversion: algorithms for *efficient* generation of the samples comprising this approximation



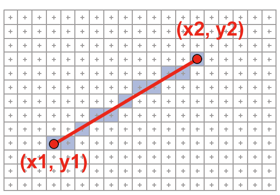
Scan Converting 2D Line Segments

- Given:
  - Segment endpoints (integers x1, y1; x2, y2)
- Identify:
  - Set of pixels (x, y) to display for segment



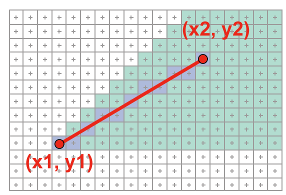
Line Rasterization Requirements

- Transform **continuous** primitive into **discrete** samples
- Uniform thickness & brightness
- Continuous appearance
- No gaps
- Accuracy
- Speed



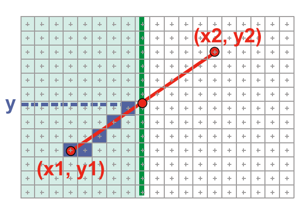
Algorithm Design Choices

- Assume:
  - m = dy/dx, 0 < m < 1
- Exactly one pixel per column
  - fewer → disconnected, more → too thick



Naive Line Rasterization Algorithm

- Simply compute y as a function of x
  - Conceptually: move vertical scan line from x1 to x2
  - What is the expression of y as function of x?
  - Set pixel (x, round (y(x)))



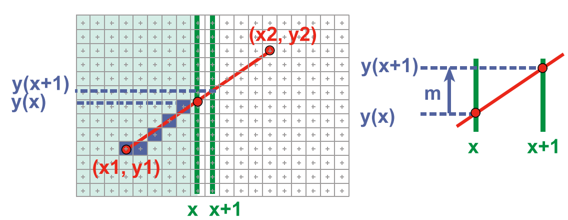
$$y = y1 + \frac{x - x1}{x2 - x1}(y2 - y1)$$

$$= y1 + m(x - x1)$$

$$m = \frac{dy}{dx}$$

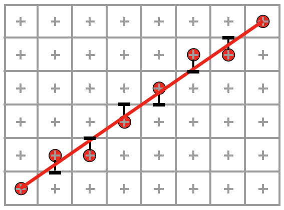
Efficiency

- Computing y value is expensive
  $y = y1 + m(x - x1)$
- Observe: y += m at each x step ($m = dy/dx$)



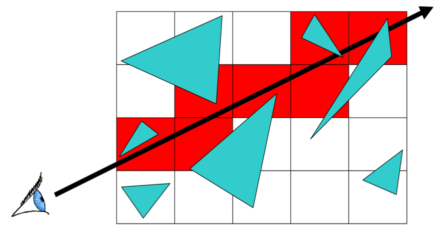
Bresenham's Algorithm (DDA)

- Select pixel vertically closest to line segment
  - intuitive, efficient, pixel center always within 0.5 vertically
- Generalize to handle all eight octants using symmetry
- Can be modified to use only integer arithmetic



Line Rasterization & Grid Marching

- Can be used for ray-casting acceleration
- March a ray through a grid

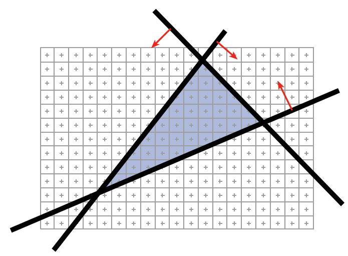


- Collect *all* grid cells, not just 1 per column (or row)

Questions?

Brute force solution for triangles

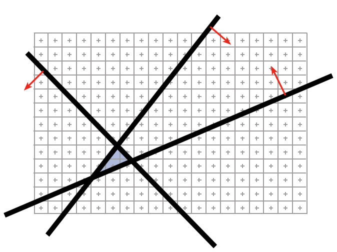
- For each pixel
  - Compute line equations at pixel center
  - "clip" against the triangle



Problem?

Brute force solution for triangles

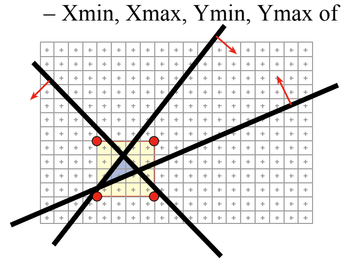
- For each pixel
  - Compute line equations at pixel center
  - "clip" against the triangle



Problem?
If the triangle is small, a lot of useless computation

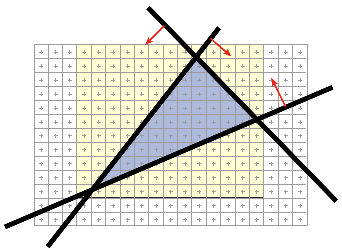
Brute force solution for triangles

- Improvement: Compute only for the *screen bounding box* of the triangle
- How do we get such a bounding box?
  - Xmin, Xmax, Ymin, Ymax of the triangle vertices



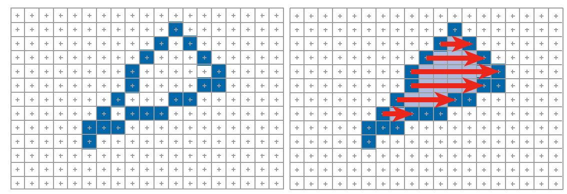
Can we do better? Kind of!

- We compute the line equation for many useless pixels
- What could we do?



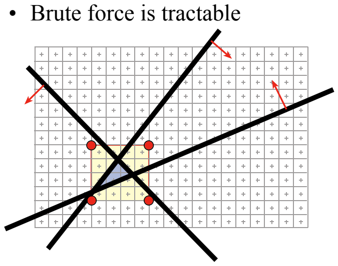
Scan-line Rasterization

- Compute the boundary pixels
- Fill the spans
- Interpolate vertex color along the edges & spans!



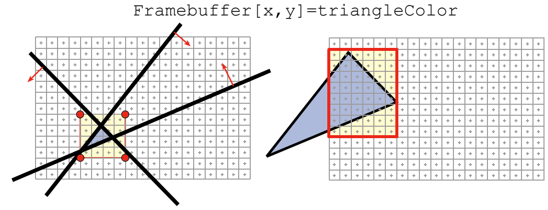
But These Days…

- Triangles are usually very small
- Setup cost are becoming more troublesome
- Clipping is annoying
- Brute force is tractable



Modern Rasterization

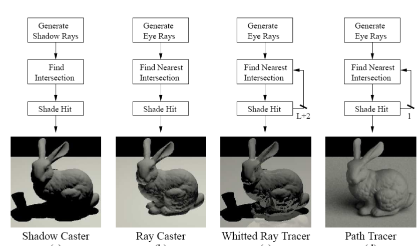
```
For every triangle
   ComputeProjection
   Compute bbox, clip bbox to screen limits
   For all pixels in bbox
      Compute line equations
      If all line equations>0  //pixel [x,y] in triangle
            Framebuffer[x,y]=triangleColor
```



Questions?

Reading for Today:

- "Ray Tracing on Programmable Graphics Hardware Purcell", Buck, Mark, & Hanrahan SIGGRAPH 2002



Post a comment or question on the LMS discussion by 10am on Tuesday 3/18

Reading for Friday:

- "Shadow Algorithms for Computer Graphics", Frank Crow, SIGGRAPH 1977