University of British Columbia
CPSC 314 Computer Graphics
Jan-Apr 2010

Tamara Munzner

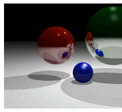
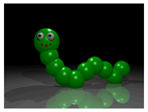
Advanced Rendering II, Clipping I

Week 8, Wed Mar 10

http://www.ugrad.cs.ubc.ca/~cs314/Vjan2010

News

- Project 3 out
  - due Fri Mar 26, 5pm
- raytracer
  - template code has significant functionality
  - clearly marked places where you need to fill in required code

News

- Project 2 F2F grading done
  - if you have not signed up, do so immediately with glj3 AT cs.ubc.ca
    - penalty already for being late
    - bigger penalty if we have to hunt you down

Reading for Advanced Rendering

- FCG Sec 8.2.7 Shading Frequency
- FCG Chap 4 Ray Tracing
- FCG Sec 13.1 Transparency and Refraction
  - (10.1-10.7 2nd ed)
- Optional - FCG Chap 24: Global Illumination

Review: Specifying Normals

- OpenGL state machine
  - uses last normal specified
  - if no normals specified, assumes all identical
- per-vertex normals

```
glNormal3f(1,1,1);
glVertex3f(3,4,5);
glNormal3f(1,1,0);
glVertex3f(10,5,2);
```

- per-face normals

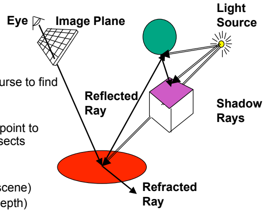
```
glNormal3f(1,1,1);
glVertex3f(3,4,5);
glVertex3f(10,5,2);
```

- normal interpreted as direction from vertex location
- can automatically normalize (computational cost)

```
glEnable(GL_NORMALIZE);
```


Review: Recursive Ray Tracing

- ray tracing can handle
  - reflection (chrome/mirror)
  - refraction (glass)
  - shadows
- one primary ray per pixel
- spawn secondary rays
  - reflection, refraction
    - if another object is hit, recurse to find its color
  - shadow
    - cast ray from intersection point to light source, check if intersects another object
  - termination criteria
    - no intersection (ray exits scene)
    - max bounces (recursion depth)
    - attenuated below threshold

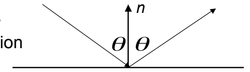


Review/Correction: Recursive Ray Tracing

RayTrace(r,scene)
obj := **FirstIntersection**(r,scene)
if (no obj) return BackgroundColor;
else begin
  if (**Reflect**(obj)) then
    reflect_color := **RayTrace**(**ReflectRay**(r,obj));
  else
    reflect_color := Black;
  if (**Transparent**(obj)) then
    refract_color := **RayTrace**(**RefractRay**(r,obj));
  else
    refract_color := Black;
  return **Shade**(reflect_color,refract_color,obj);
end;

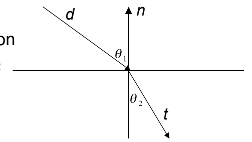
Review: Reflection and Refraction

- refraction: mirror effects
  - perfect specular reflection



- refraction: at boundary
- Snell's Law
  - light ray bends based on refractive indices c_1, c_2

$$c_1 \sin\theta_1 = c_2 \sin\theta_2$$

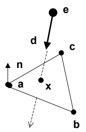


Review: Ray Tracing

- issues:
  - generation of rays
  - intersection of rays with geometric primitives
  - geometric transformations
  - lighting and shading
  - efficient data structures so we don't have to test intersection with *every* object

Ray-Triangle Intersection

- method in book is elegant but a bit complex
- easier approach: triangle is just a polygon
  - intersect ray with plane



$$\text{normal}: \mathbf{n} = (\mathbf{b}-\mathbf{a}) \times (\mathbf{c}-\mathbf{a})$$

$$\text{ray}: \mathbf{x} = \mathbf{e} + t\mathbf{d}$$

$$\text{plane}: (\mathbf{p}-\mathbf{x}) \cdot \mathbf{n} = 0 \Rightarrow \mathbf{x} = \frac{\mathbf{p}\cdot\mathbf{n}}{\mathbf{n}}$$

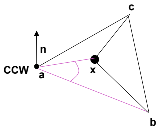
$$\frac{\mathbf{p}\cdot\mathbf{n}}{\mathbf{n}} = \mathbf{e} + t\mathbf{d} \Rightarrow t = -\frac{(\mathbf{e}-\mathbf{p})\cdot\mathbf{n}}{\mathbf{d}\cdot\mathbf{n}}$$

$\mathbf{p}$ is $\mathbf{a}$ or $\mathbf{b}$ or $\mathbf{c}$

  - check if ray inside triangle

Ray-Triangle Intersection

- check if ray inside triangle
  - check if point counterclockwise from each edge (to its left)
  - check if cross product points in same direction as normal (i.e. if dot is positive)



$$(\mathbf{b}-\mathbf{a}) \times (\mathbf{x}-\mathbf{a}) \cdot \mathbf{n} \ge 0$$
$$(\mathbf{c}-\mathbf{b}) \times (\mathbf{x}-\mathbf{b}) \cdot \mathbf{n} \ge 0$$
$$(\mathbf{a}-\mathbf{c}) \times (\mathbf{x}-\mathbf{c}) \cdot \mathbf{n} \ge 0$$

  - more details at
http://www.cs.cornell.edu/courses/cs465/2003fa/homeworks/raytri.pdf

Ray Tracing

- issues:
  - generation of rays
  - intersection of rays with geometric primitives
  - geometric transformations
  - lighting and shading
  - efficient data structures so we don't have to test intersection with *every* object

Geometric Transformations

- similar goal as in rendering pipeline:
  - modeling scenes more convenient using different coordinate systems for individual objects
- problem
  - not all object representations are easy to transform
    - problem is fixed in rendering pipeline by restriction to polygons, which are affine invariant
  - ray tracing has different solution
    - ray itself is always affine invariant
    - thus: transform ray into object coordinates!

Geometric Transformations

- ray transformation
  - for intersection test, it is only important that ray is in same coordinate system as object representation
  - transform all rays into object coordinates
    - transform camera point and ray direction by inverse of model/view matrix
  - shading has to be done in world coordinates (where light sources are given)
    - transform object space intersection point to world coordinates
    - thus have to keep both world and object-space ray

Ray Tracing

- issues:
  - generation of rays
  - intersection of rays with geometric primitives
  - geometric transformations
  - lighting and shading
  - efficient data structures so we don't have to test intersection with *every* object

Local Lighting

- local surface information (normal…)
  - for implicit surfaces $F(x,y,z)=0$: normal $\mathbf{n}(x,y,z)$ can be easily computed at every intersection point using the gradient

$$\mathbf{n}(x,y,z) = \begin{pmatrix} \partial F(x,y,z)/\partial x \\ \partial F(x,y,z)/\partial y \\ \partial F(x,y,z)/\partial z \end{pmatrix}$$

  - example: $F(x,y,z) = x^2 + y^2 + z^2 - r^2$

$$\mathbf{n}(x,y,z) = \begin{pmatrix} 2x \\ 2y \\ 2z \end{pmatrix}$$

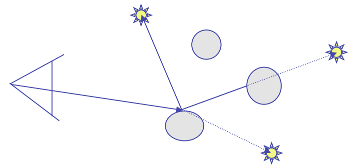
needs to be normalized!

Local Lighting

- local surface information
  - alternatively: can interpolate per-vertex information for triangles/meshes as in rendering pipeline
    - now easy to use Phong shading!
      - as discussed for rendering pipeline
  - difference with rendering pipeline:
    - interpolation cannot be done incrementally
    - have to compute barycentric coordinates for every intersection point (e.g plane equation for triangles)

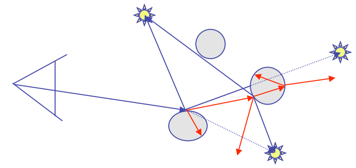
Global Shadows

- approach
  - to test whether point is in shadow, send out **shadow rays** to all light sources
    - if ray hits another object, the point lies in shadow



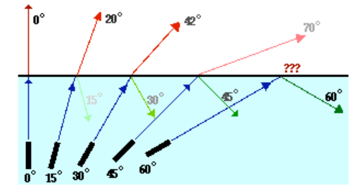
Global Reflections/Refractions

- approach
  - send rays out in reflected and refracted direction to gather incoming light
  - that light is multiplied by local surface color and added to result of local shading



Total Internal Reflection

As the angle of incidence increases from 0 to greater angles ...



...the refracted ray becomes dimmer (there is less refraction)
...the reflected ray becomes brighter (there is more reflection)
...the angle of refraction approaches 90 degrees until finally a refracted ray can no longer be seen.

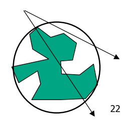
http://www.physicsclassroom.com/Class/refrn/U14L3b.html

Ray Tracing

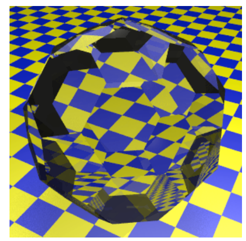
- issues:
  - generation of rays
  - intersection of rays with geometric primitives
  - geometric transformations
  - lighting and shading
  - efficient data structures so we don't have to test intersection with every object

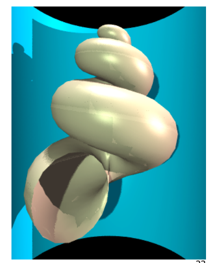
Optimized Ray-Tracing

- basic algorithm simple but very expensive
- optimize by reducing:
  - number of rays traced
  - number of ray-object intersection calculations
- methods
  - bounding volumes: boxes, spheres
  - spatial subdivision
    - uniform
    - BSP trees
- (more on this later with collision)



Example Images



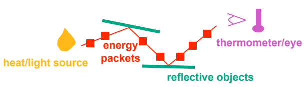


Radiosity

- radiosity definition
  - rate at which energy emitted or reflected by a surface
- radiosity methods
  - capture diffuse-diffuse bouncing of light
    - indirect effects difficult to handle with raytracing

Radiosity

- illumination as radiative heat transfer

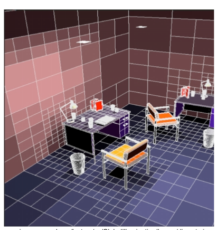


- conserve light energy in a volume
- model light transport as packet flow until convergence
- solution captures diffuse-diffuse bouncing of light

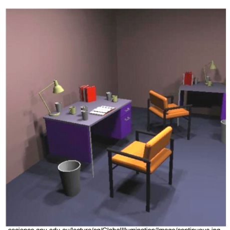
- view-independent technique
  - calculate solution for entire scene offline
  - browse from any viewpoint in realtime

Radiosity

- divide surfaces into small patches
- loop: check for light exchange between all pairs
  - form factor: orientation of one patch wrt other patch (n x n matrix)



escience.anu.edu.au/lecture/cg/GlobalIllumination/Image/discrete.jpg

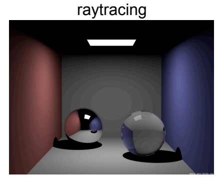


escience.anu.edu.au/lecture/cg/GlobalIllumination/Image/continuous.jpg

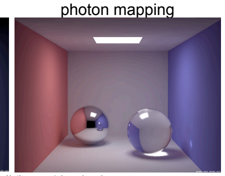
Better Global Illumination

- ray-tracing: great specular, approx. diffuse
  - view dependent
- radiosity: great diffuse, specular ignored
  - view independent, mostly-enclosed volumes
- photon mapping: superset of raytracing and radiosity
  - view dependent, handles both diffuse and specular well

raytracing



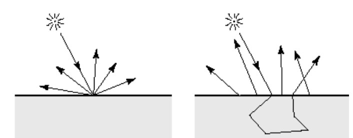
photon mapping



graphics.ucsd.edu/~henrik/images/cbox.html

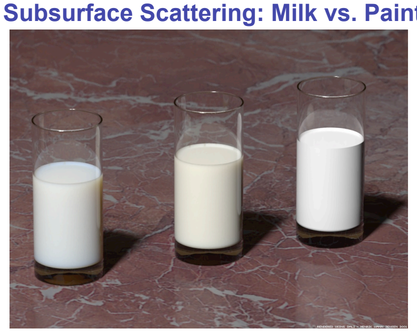
Subsurface Scattering: Translucency

- light enters and leaves at *different* locations on the surface
  - bounces around inside
- technical Academy Award, 2003
  - Jensen, Marschner, Hanrahan

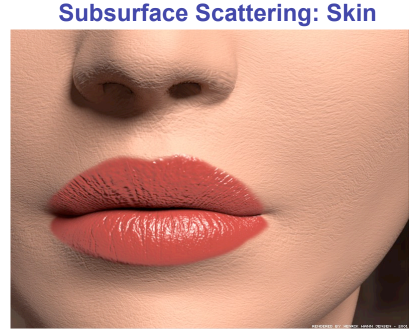


Subsurface Scattering: Marble

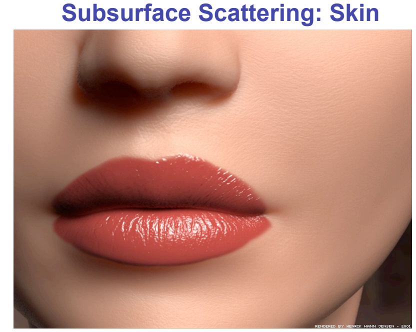
Subsurface Scattering: Milk vs. Paint



Subsurface Scattering: Skin

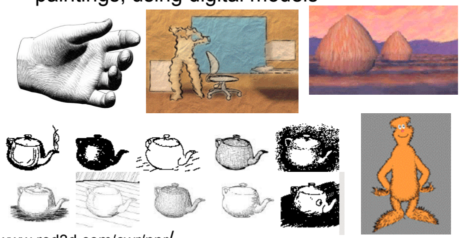


Subsurface Scattering: Skin



Non-Photorealistic Rendering

- simulate look of hand-drawn sketches or paintings, using digital models



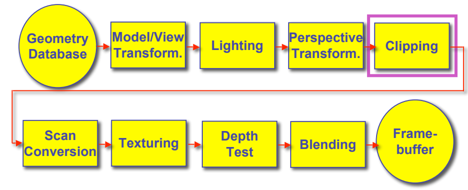
www.red3d.com/cwr/npr/

Clipping

Reading for Clipping

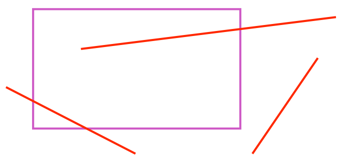
- FCG Sec 8.1.3-8.1.6 Clipping
- FCG Sec 8.4 Culling
  - (12.1-12.4 2nd ed)

Rendering Pipeline



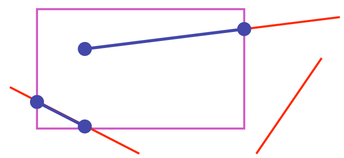
Next Topic: Clipping

- we've been assuming that all primitives (lines, triangles, polygons) lie entirely within the *viewport*
  - in general, this assumption will not hold:



Clipping

- analytically calculating the portions of primitives within the viewport



Why Clip?

- bad idea to rasterize outside of framebuffer bounds
- also, don't waste time scan converting pixels outside window
  - could be billions of pixels for very close objects!

Line Clipping

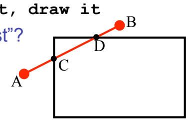
- 2D
  - determine portion of line inside an axis-aligned rectangle (screen or window)
- 3D
  - determine portion of line inside axis-aligned parallelpiped (viewing frustum in NDC)
  - simple extension to 2D algorithms

Clipping

- naïve approach to clipping lines:

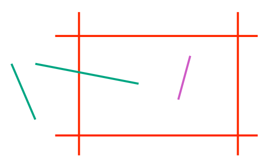
```
for each line segment
    for each edge of viewport
        find intersection point
        pick "nearest" point
  if anything is left, draw it
```

- what do we mean by "nearest"?
- how can we optimize this?



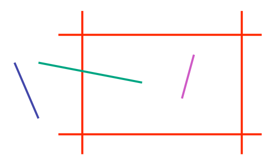
Trivial Accepts

- big optimization: trivial accept/rejects
  - Q: how can we quickly determine whether a line segment is entirely inside the viewport?
  - A: test both endpoints



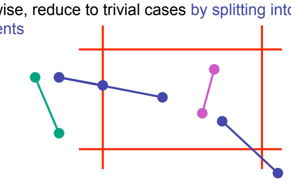
Trivial Rejects

- Q: how can we know a line is outside viewport?
- A: if both endpoints on wrong side of same edge, can trivially reject line



Clipping Lines To Viewport

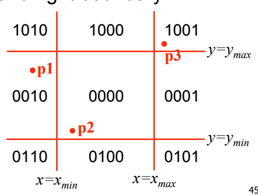
- combining trivial accepts/rejects
  - trivially accept lines with both endpoints inside all edges of the viewport
  - trivially reject lines with both endpoints outside the same edge of the viewport
  - otherwise, reduce to trivial cases by splitting into two segments



Cohen-Sutherland Line Clipping

- outcodes
  - 4 flags encoding position of a point relative to top, bottom, left, and right boundary

- *OC(p1)=0010*
- *OC(p2)=0000*
- *OC(p3)=1001*



Cohen-Sutherland Line Clipping

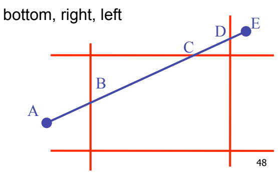
- assign outcode to each vertex of line to test
  - line segment: (**p1**,**p2**)
- trivial cases
  - OC(**p1**)== 0 && OC(**p2**)==0
    - both points inside window, thus line segment completely visible (trivial accept)
  - (OC(**p1**) & OC(**p2**))!= 0
    - there is (at least) one boundary for which both points are outside (same flag set in both outcodes)
    - thus line segment completely outside window (trivial reject)

Cohen-Sutherland Line Clipping

- if line cannot be trivially accepted or rejected, subdivide so that one or both segments can be discarded
- pick an edge that the line crosses (*how?*)
- intersect line with edge (*how?*)
- discard portion on wrong side of edge and assign outcode to new vertex
- apply trivial accept/reject tests; repeat if necessary

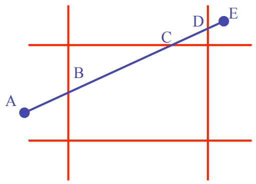
Cohen-Sutherland Line Clipping

- if line cannot be trivially accepted or rejected, subdivide so that one or both segments can be discarded
- pick an edge that the line crosses
  - check against edges in same order each time
    - for example: top, bottom, right, left



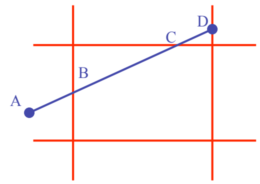
Cohen-Sutherland Line Clipping

- intersect line with edge



Cohen-Sutherland Line Clipping

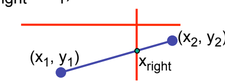
- discard portion on wrong side of edge and assign outcode to new vertex



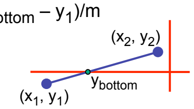
- apply trivial accept/reject tests and repeat if necessary

Viewport Intersection Code

- (x_1, y_1), (x_2, y_2) intersect vertical edge at x_{right}
  - $y_{intersect} = y_1 + m(x_{right} - x_1)$
  - $m=(y_2-y_1)/(x_2-x_1)$



- (x_1, y_1), (x_2, y_2) intersect horiz edge at y_{bottom}
  - $x_{intersect} = x_1 + (y_{bottom} - y_1)/m$
  - $m=(y_2-y_1)/(x_2-x_1)$



Cohen-Sutherland Discussion

- key concepts
  - use opcodes to quickly eliminate/include lines
    - best algorithm when trivial accepts/rejects are common
  - must compute viewport clipping of remaining lines
    - non-trivial clipping cost
    - redundant clipping of some lines
- basic idea, more efficient algorithms exist

Line Clipping in 3D

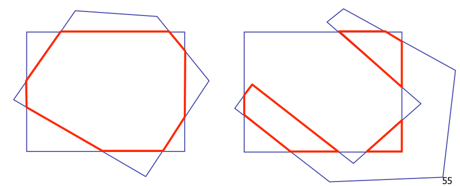
- approach
  - clip against parallelpiped in NDC
    - after perspective transform
  - means that clipping volume always the same
    - xmin=ymin= -1, xmax=ymax= 1 in OpenGL
  - boundary lines become boundary planes
    - but outcodes still work the same way
    - additional front and back clipping plane
      - zmin = -1, zmax = 1 in OpenGL

Polygon Clipping

- objective
  - 2D: clip polygon against rectangular window
    - or general convex polygons
    - extensions for non-convex or general polygons
  - 3D: clip polygon against parallelpiped

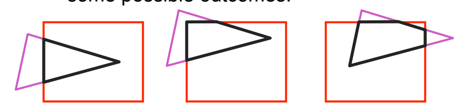
Polygon Clipping

- not just clipping all boundary lines
  - may have to introduce new line segments



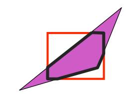
Why Is Clipping Hard?

- what happens to a triangle during clipping?
  - some possible outcomes:



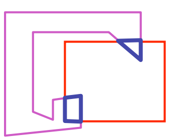
triangle to triangle   triangle to quad   triangle to 5-gon

- how many sides can result from a triangle?
  - seven



Why Is Clipping Hard?

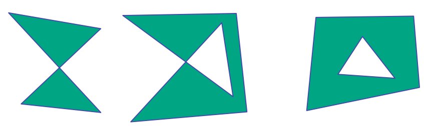
- a really tough case:



concave polygon to multiple polygons

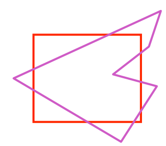
Polygon Clipping

- classes of polygons
  - triangles
  - convex
  - concave
  - holes and self-intersection



Sutherland-Hodgeman Clipping

- basic idea:
  - consider each edge of the viewport individually
  - clip the polygon against the edge equation
  - after doing all edges, the polygon is fully clipped



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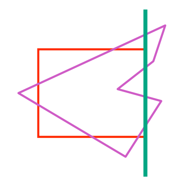

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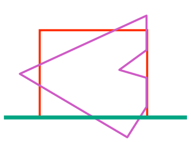

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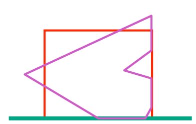

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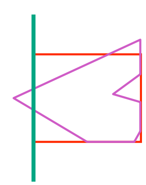

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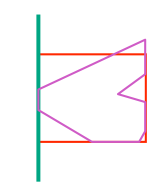

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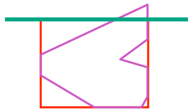

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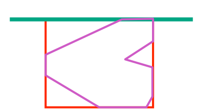

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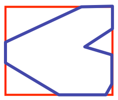
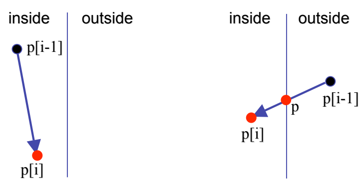


Sutherland-Hodgeman Algorithm

- input/output for whole algorithm
  - input: list of polygon vertices in order
  - output: list of clipped polygon vertices consisting of old vertices (maybe) and new vertices (maybe)
- input/output for each step
  - input: list of vertices
  - output: list of vertices, possibly with changes
- basic routine
  - go around polygon one vertex at a time
  - decide what to do based on 4 possibilities
    - is vertex inside or outside?
    - is previous vertex inside or outside?

Clipping Against One Edge

- p[i] inside: 2 cases

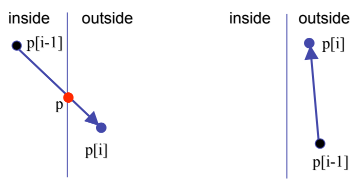


output: p[i]

output: p, p[i]

Clipping Against One Edge

- p[i] outside: 2 cases



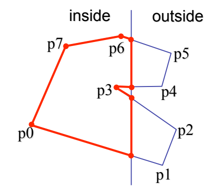
output: p

output: nothing

Clipping Against One Edge

```
clipPolygonToEdge( p[n], edge ) {
    for( i= 0 ; i< n ; i++ ) {
        if( p[i] inside edge ) {
            if( p[i-1] inside edge ) output p[i];      // p[-1]= p[n-1]
            else {
                p= intersect( p[i-1], p[i], edge ); output p, p[i];
            }
        } else {                                    // p[i] is outside edge
        if( p[i-1] inside edge ) {
            p= intersect(p[i-1], p[I], edge ); output p;
        }
    }
}
```


Sutherland-Hodgeman Example



Sutherland-Hodgeman Discussion

- similar to Cohen/Sutherland line clipping
  - inside/outside tests: outcodes
  - intersection of line segment with edge: window-edge coordinates
- clipping against individual edges independent
  - great for hardware (pipelining)
  - all vertices required in memory at same time
    - not so good, but unavoidable
    - another reason for using triangles only in hardware rendering