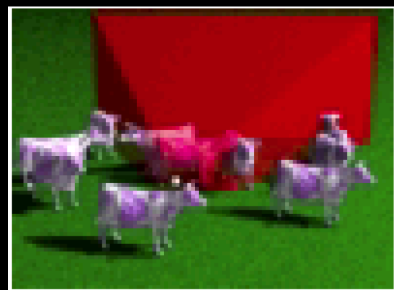
Why do clipping?

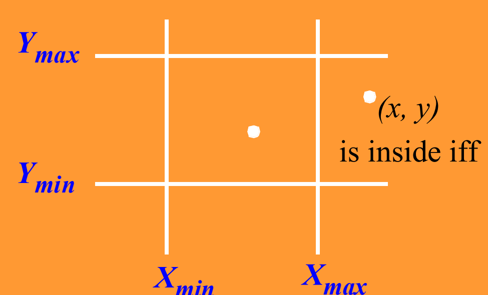
- Clipping is a visibility preprocess. In real-world scene clipping can remove a substantial percentage of the environment from consideration.
- Clipping offers an important optimization
- Also need to avoid setting pixel values outside of the range.



What is clipping, two views

- Clipping *spatially partitions* geometric primitives, according to their containment within some region. Clipping can be used to:
  - Distinguish whether geometric primitives are inside or outside of a *viewing frustum* or *picking frustum*
  - Detect intersections between primitives
- Clipping *subdivides* geometric primitives. Several other potential applications.
  - Binning geometric primitives into spatial data structures
  - computing analytical shadows.

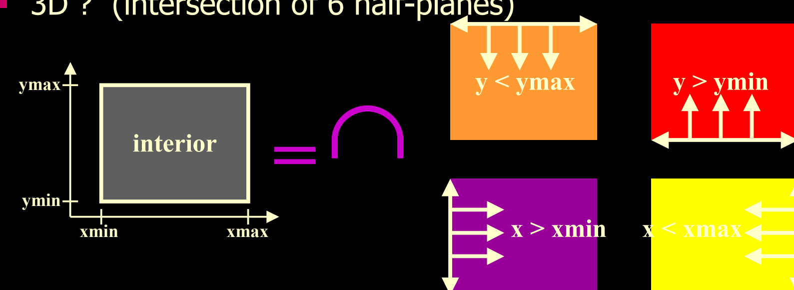
Point Clipping



$$X_{min} \le x \le X_{max} \text{ AND } Y_{min} \le y \le Y_{max}$$

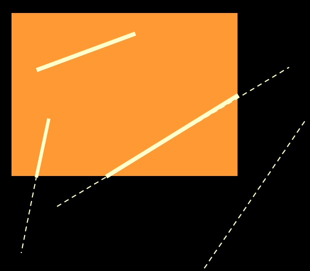
Line Clipping - Half Plane Tests

- Modify endpoints to lie in rectangle
- "Interior" of rectangle?
- Answer: intersection of 4 half-planes
- 3D ? (intersection of 6 half-planes)



Line Clipping

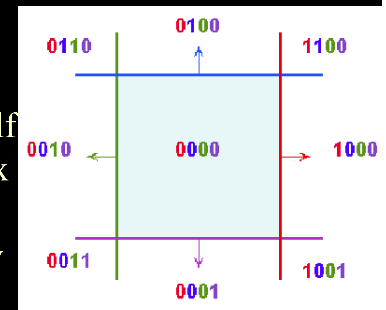
- Is end-point inside a clip region? - half-plane test
- If outside, calculate intersection between line and the clipping rectangle and make this the new end point



- **Both endpoints inside: trivial accept**
- **One inside: find intersection and clip**
- **Both outside: either clip or reject (tricky case)**

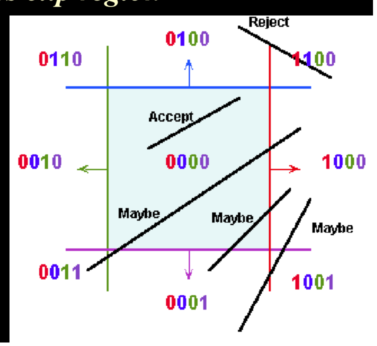
Cohen-Sutherland Algorithm (Outcode clipping)

- Classifies each vertex of a primitive, by generating an *outcode*. An outcode identifies the appropriate half space location of each vertex relative to all of the clipping planes. Outcodes are usually stored as bit vectors.



Cohen-Sutherland Algorithm (Outcode clipping)

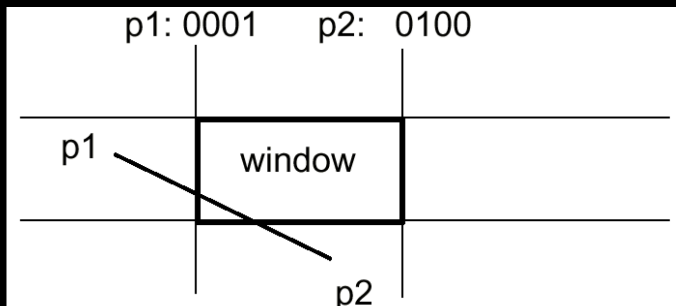
if (outcode1 == '0000' and outcode2 == '0000') then
    line segment is inside
else
  if ((outcode1 AND outcode2) == 0000) then
      line segment potentially crosses clip region
  else
      line is entirely outside of clip region
  endif
endif



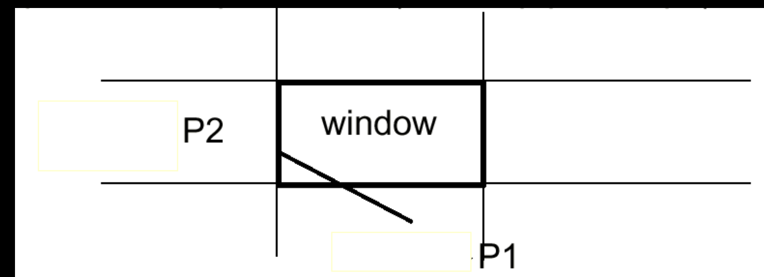
The Maybe cases?

- If neither trivial accept nor reject:
  - Pick an outside endpoint (with nonzero outcode)
  - Pick an edge that is crossed (nonzero bit of outcode)
  - Find line's intersection with that edge
  - Replace outside endpoint with intersection point
  - Repeat until trivial accept or reject

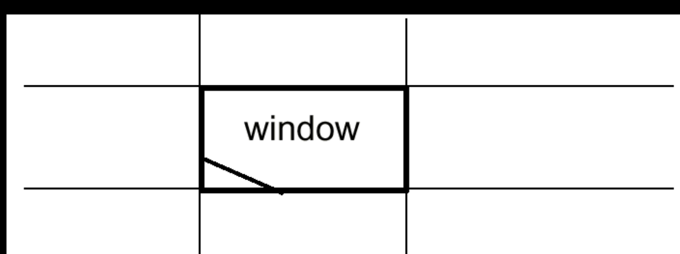
The Maybe case



The Maybe Case



The Maybe Case



Difficulty

- This clipping will handle most cases. However, there is one case in general that cannot be handled this way.
  - Parts of a primitive lie both in front of and behind the viewpoint. This complication is caused by our projection stage.
  - It has the nasty habit of mapping objects in behind the viewpoint to positions in front of it.

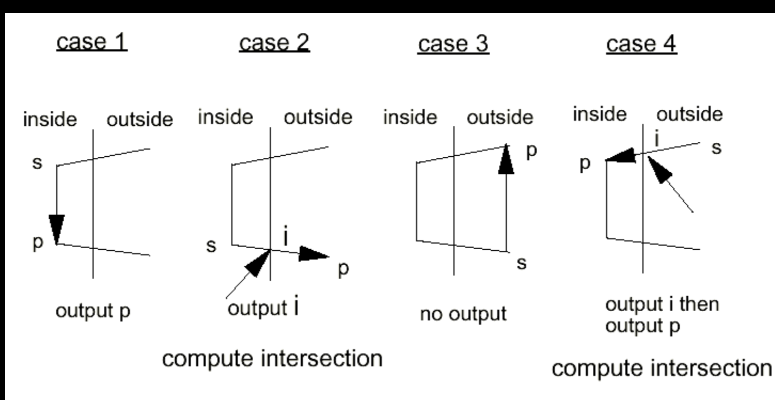
One Plane At a Time Clipping

- (a.k.a. Sutherland-Hodgeman Clipping)
- The Sutherland-Hodgeman triangle clipping algorithm uses a *divide-and-conquer* strategy.
- Clip a triangle against a single plane. Each of the clipping planes are applied in succession to every triangle.
- There is minimal storage requirements for this algorithm, and it is well suited for pipelining.
- It is often used in hardware implementations.

Sutherland-Hodgman Polygon Clipping Algorithm

- Clip a polygon (input: vertex list) against a single clip edges
- Output the vertex list(s) for the resulting clipped polygon(s)
- Clip against all four planes
  - Generalizes to 3D (6 planes)
  - Generalizes to clip against any convex polygon/polyhedron
- Used in viewing transforms

Sutherland-Hodgman Polygon Clipping Algorithm



Sutherland-Hodgman

```
SHclippedge(var: ilist, olist: list; ilen, olen, edge : integer)

    s = ilist[ilen];    olen = 0;
    for i = 1 to ilen do
     d := ilist[i];
     if (inside(d, edge) then
       if (inside(s, edge) then               -- case 1 just add d
         addlist(d, olist);    olen := olen + 1;
       else                                   -- case 4 add new intersection pt. and d
         n := intersect(s, d, edge);
         addlist(n, olist);   addlist(d, olist);   olen = olen + 2;
       else if (inside(s, edge) then          -- case 2 add new intersection pt.
         n := intersect(s, d, edge); addlist(n, olist);  olen ++; s = d;
    end_for;
```

Clip input polygon *ilist* to the edge, ***edge***, and ouput the new polygon.

Sutherland-Hodgman

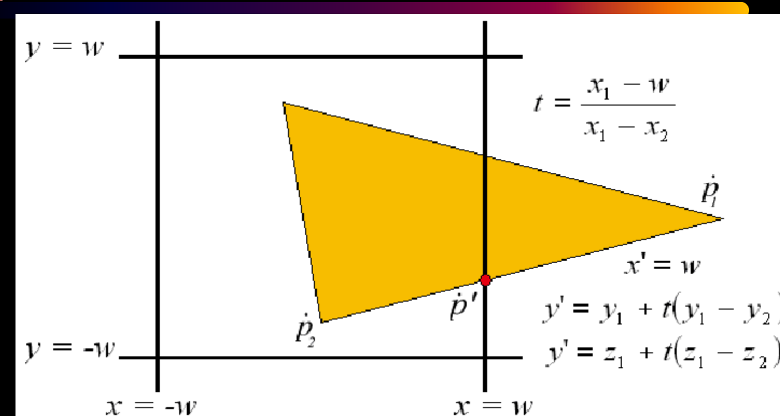
```
SHclip(var: ilist, olist: list; ilen, olen : integer)
{
    SHclippedge(ilist, tmplist1, ilen, tlen1, RIGHT);
    SHclippedge(tmplist1, tmplist2, tlen1, tlen2, BOTTOM);
    SHclippedge(tmplist2, tmplist1, tlen2, tlen1, LEFT);
    SHclippedge(tmplist1, olist, tlen1, olen, TOP);
}
```

Pictorial Example

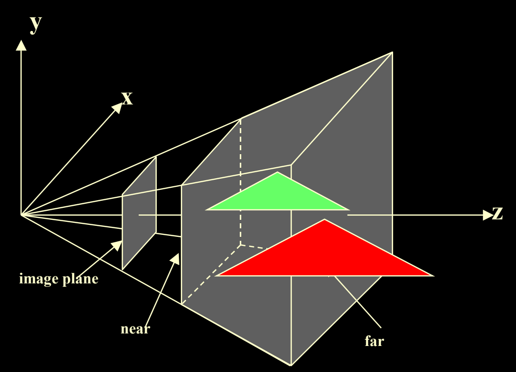
Sutherland-Hodgman

- Advantages:
  - Elegant (few special cases)
  - Robust (handles boundary and edge conditions well)
  - Well suited to hardware
  - Canonical clipping makes fixed-point implementations manageable
- Disadvantages:
  - Only works for convex clipping volumes
  - Often generates more than the minimum number of triangles needed
  - Requires a divide per edge

Interpolating Parameters



3D Clipping (Planes)



4D Polygon Clip

- Use Sutherland Hodgman algorithm
- Use arrays for input and output lists
- There are six planes of course !

4D Clipping

- OpenGL uses -1<=x<=1, -1<=y<=1, -1<=z<=1
- We use: -1<=x<=1, -1<=y<=1, -1<=z <=0
- Must clip in homogeneous coordinates:
  - w>0: -w<=x<=w, -w<=y<=w, -w<=z<=0
  - w<0: -w>=x>=w, -w>=y>=w, -w>=z>=0
- Consider each case separately
- What issues arise ?

4D Clipping

- Point A is inside, Point B is outside. Clip edge AB

  $x = Ax + t(Bx – Ax)$

  $y = Ay + t(By – Ay)$

  $z = Az + t(Bz – Az)$

  $w = Aw + t(Bw – Aw)$
- Clip boundary: x/w = 1 i.e. (x–w=0);

  $w-x = Aw – Ax + t(Bw – Aw – Bx + Ax) = 0$

Solve for t.

Why Homogeneous Clipping

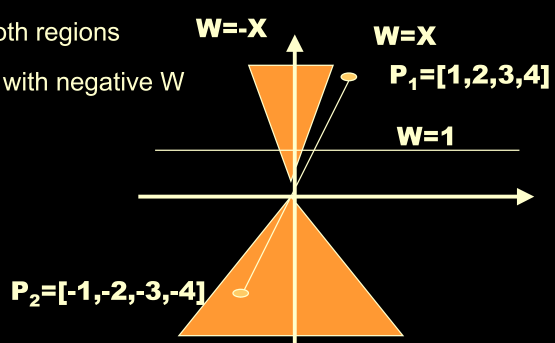
- Efficiency/Uniformity: A single clip procedure is typically provided in hardware, optimized for canonical view volume.
- The perspective projection canonical view volume can be transformed into a parallel-projection view volume, so the same clipping procedure can be used.
- But for this, clipping must be done in homogenous coordinates (and not in 3D). Some transformations can result in negative W : 3D clipping would not work.

Difficulty (revisit)

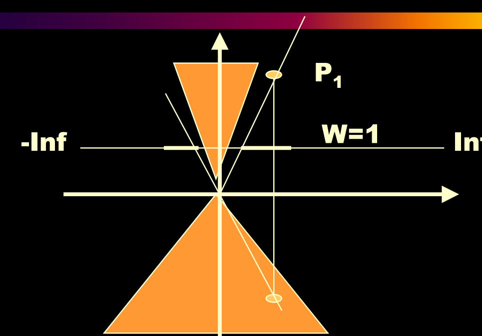
- Clipping will handle most cases. However, there is one case in general that cannot be handled this way.
  - Parts of a primitive lie both in front of and behind the viewpoint. This complication is caused by our projection stage.
  - It has the nasty habit of mapping objects in behind the viewpoint to positions in front of it.
- Solution: clip in homogeneous coordinate

4D Clipping Issues

- P_1 and P_2 map to same physical point !
- Solution:
  - Clip against both regions
  - Negate points with negative W



4D Clipping Issues



- Line straddles both regions
- After projection one gets two line segments
- How to do this? Only before the perspective division

Additional Clipping Planes

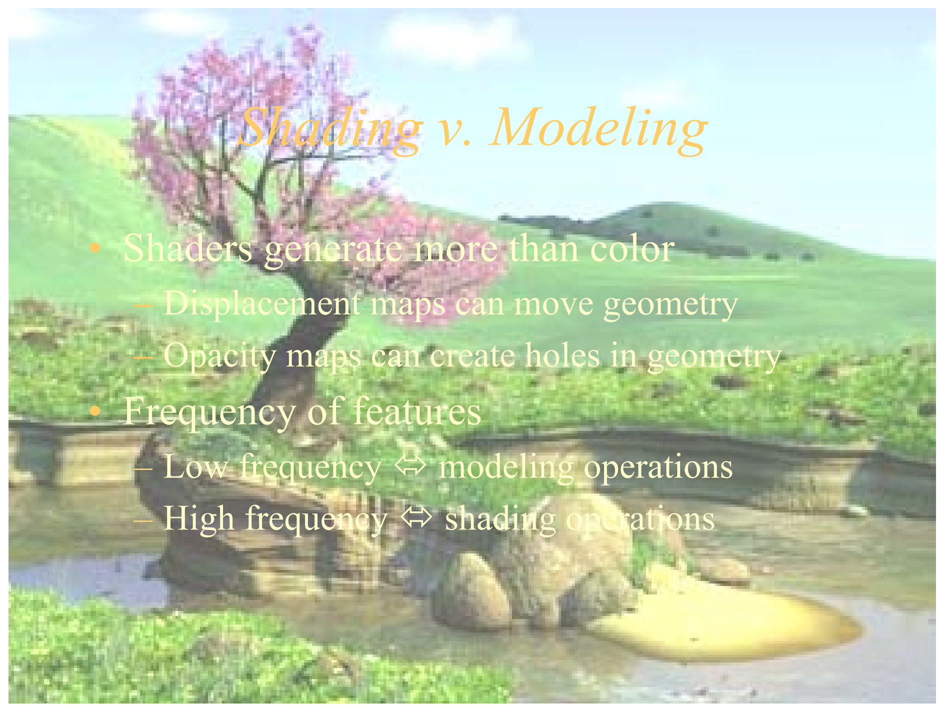
- At least 6 more clipping planes available
- Good for cross-sections
- Modelview matrix moves clipping plane
- $Ax + By + Cz + D < 0$ clipped
- `glEnable( GL_CLIP_PLANEi )`
- `glClipPlane( GL_CLIP_PLANEi, GLdouble* coeff )`

Reversing Coordinate Projection

- Screen space back to world space
- `glGetIntegerv( GL_VIEWPORT, GLint viewport[4] )`
- `glGetDoublev( GL_MODELVIEW_MATRIX, GLdouble mvmatrix[16] )`
- `glGetDoublev( GL_PROJECTION_MATRIX, GLdouble projmatrix[16] )`
- `gluUnProject( GLdouble winx, winy, winz, mvmatrix[16], projmatrix[16], GLint viewport[4], GLdouble *objx, *objy, *objz )`
- `gluProject` goes from world to screen space

Shaders

- Local illumination quite complex
  - Reflectance models
  - Procedural texture
  - Solid texture
  - Bump maps
  - Displacement maps
  - Environment maps
- Need ability to collect into a single shading description called a *shader*
- Shaders also describe
  - lights, e.g. spotlights
  - atmosphere, e.g. fog

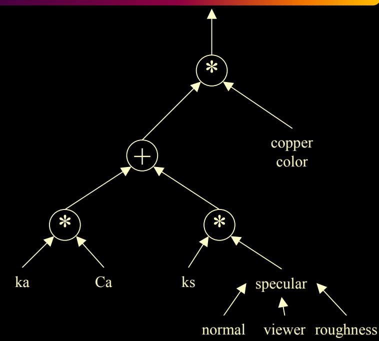


Shading v. Modeling

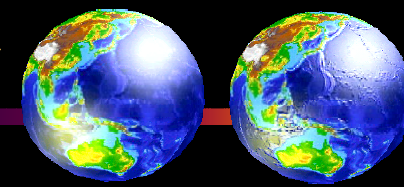
- Shaders generate more than color
  - Displacement maps can move geometry
  - Opacity maps can create holes in geometry
- Frequency of features
  - Low frequency ⇔ modeling operations
  - High frequency ⇔ shading operations

Shade Trees

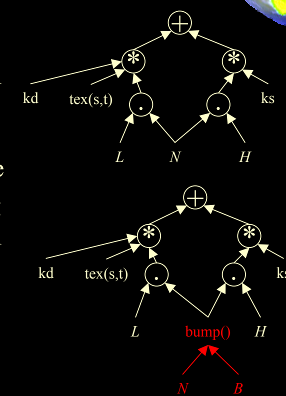
- Cook, SIGGRAPH 84
- Hierarchical organization of shading
- Breaks a shading expression into simple components
- Visual programming
- Modular
- Drag-n-drop shading components

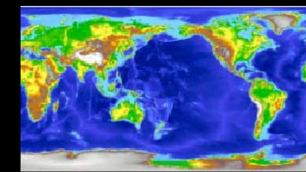


Texture v. Bump Mapping



- Texture mapping simulates detail with a color that varies across a surface
- Bump mapping simulates detail with a surface normal that varies across a surface





Problems with Shade Trees

- Shaders can get *very* complex
- Sometimes need higher-level constructs than simple expression trees
  - Variables
  - Iteration
- Need to compile a program instead of evaluate an expression

Renderman Shading Language

- Hanrahan & Lawson, SIGGRAPH 90
- High level little language
- Special purpose variables useful for shading
  - P – surface position
  - N – surface normal
- Special purpose functions useful for shading
  - smoothstep(x_0,x_1,a) – smoothly interpolates from x_0 to x_1 as a varies from 0 to 1
  - specular(N,V,m) – computes specular reflection given normal N, view direction V and roughness m.

Types

- Colors
  - Multiplication is componentwise
  - e.g. Cd*(La + Ld) + Cs*Ls + Ct*Lt
- Points
  - Built in dot (L.N) and cross (N^L) products
  - Transform to other coordinate systems: "raster," "screen," "camera," "world," and "object"
- Variables
  - Uniform – independent of position
  - Varying – changes across surface

Lighting

- Constructs
  - illuminate() – point source with cone spread
  - solar() – directional source
- Variables
  - L – direction of light (independent)
  - Cl – color of light (dependent)
- Types
  - ambient – non-directional (but can vary with position)
  - point – equal in all directions
  - spot – focused around a given direction
  - shadowed – modulated by texture/shadow map
  - distant –directional source
  - environment map – distant source modulated by texture

Local Illumination

- Construct
  - illuminance()
- Variables
  - L – incoming light direction
  - Cl – incoming light color
  - C – output color
- Example (hair diffuse)

```
color C = 0;
illuminance(P,N,Pi/2) {
    L = normalize(L);
    C += Kd * Cd * Cl * length(L^T);
}
```

Texture Functions

- texture() returns float/color based on texture coordinates
- bump() returns normal perturbation based on texture coordinates
- environment() returns float/color based on a direction passed to it
- shadow() returns a float indicating the percentage a point's position is shadowed

Renderman Example

```
Surface dent(float Ks=.4, Kd=.5, Ka=.1, roughness=.25, dent=.4) {
    float turbulence;
    point Nf, V;
    float I, freq;
    /* Transform to solid texture coordinate system */
    V = transform("shader",P);
    /* Sum 6 octaves of noise to form turbulence */
    turbulence = 0; freq = 1.0;
    for (i = 0; i < 6; i += 1) {
        turbulence += 1/freq + abs(0.5*noise(4*freq*V));
        freq *= 2;
    }
    /* sharpen turbulence */
    turbulence *= turbulence * turbulence;
    turbulence *= dent;
    /* Displace surface and compute normal */
    P -= turbulence * normalize(N);
    Nf = faceforward(normalize(calculatenormal(P)),I);
    V = normalize(-I);
    /* Perform shading calculations */
    Oi = 1 – smoothstep(0.03,0.05,turbulence);
    Ci = Oi*Cs*(Ka*ambient() + Ks*specular(Nf,V,roughness));
}
```

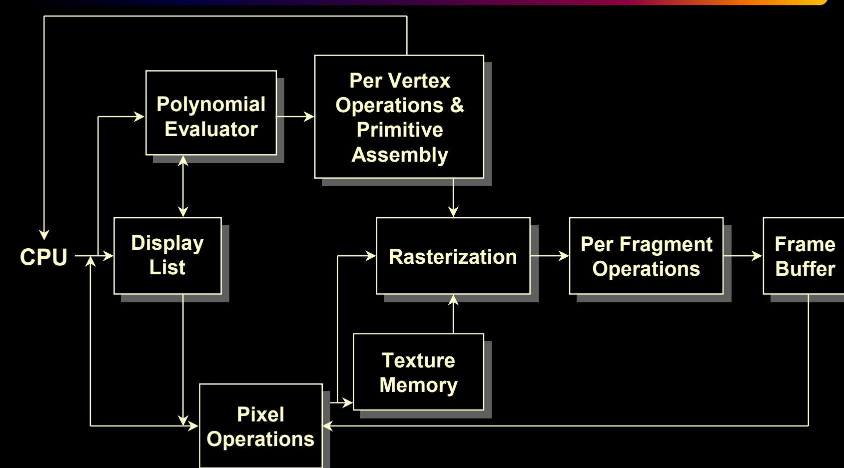
Try It Yourself

- Photorealistic Renderman
  - Based on REYES polygon renderer
  - Uses shadow maps
- Blue Moon Rendering Tools
  - Free
  - Uses ray tracer
  - No displacement maps
  - http://www.exluna.com/products/bmrt/

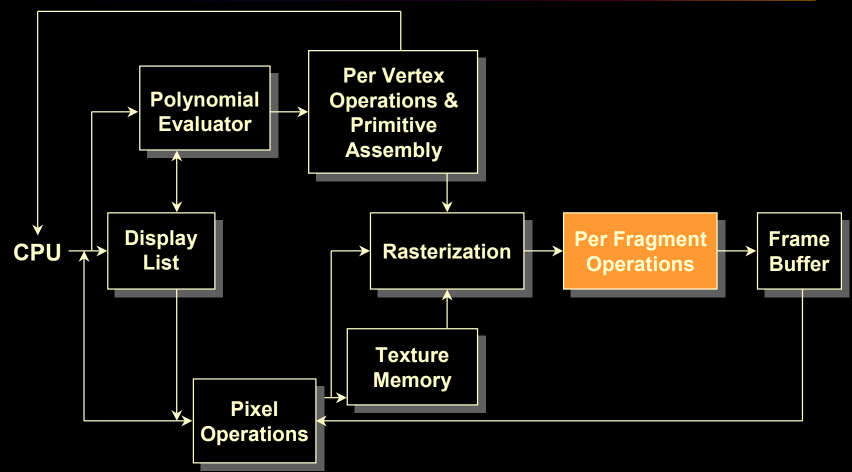
Deferred Shading

- Makes procedural shading more efficient
- Why apply shader to entire surface if only small portion is actually visible
- Separate rendering into two passes
  - Pass 1: Render geometry using Z-buffer
    - But rather than storing color in frame buffer
    - Store shading parameters instead
  - Pass 2: Shade frame buffer
    - Apply shading procedure to frame buffer
    - Replaces shading parameters with color
- Problem: Fat framebuffer

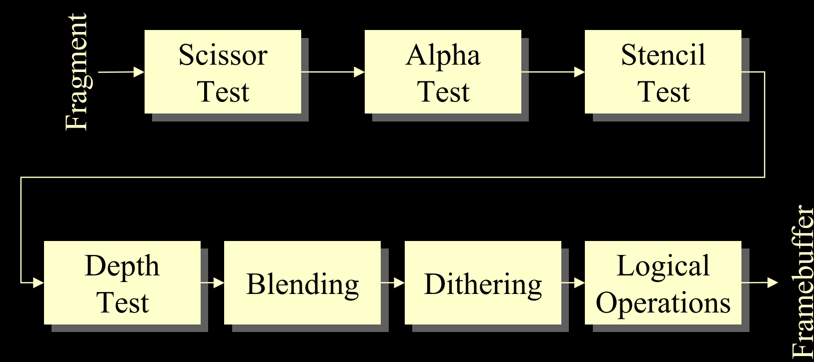
OpenGL Architecture



Per-Fragment Operations



Getting to the Framebuffer



Scissor Box

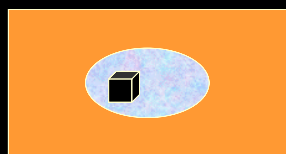
- Additional Clipping Test
  - `glScissor( x, y, w, h )`
  - – any fragments outside of box are clipped
  - – useful for updating a small section of a viewport
    - affects **`glClear()`** operations

Alpha Test

- Reject pixels based on their alpha value
  - `glAlphaFunc( func, value )`
  - `glEnable( GL_ALPHA_TEST )`
  - – use alpha as a mask in textures

Stencil Buffer

- Used to control drawing based on values in the stencil buffer
  - Fragments that fail the stencil test are not drawn
  - Example: create a mask in stencil buffer and draw only objects not in mask area



Stencil Testing

- Now broadly supports by both major APIs
  - OpenGL
  - DirectX 6
- RIVA TNT and other consumer cards now supporting full 8-bit stencil
- Opportunity to achieve new cool effects and improve scene quality

What is Stenciling?

- Per-pixel test, similar to depth buffering.
- Tests against value from stencil buffer; rejects fragment if stencil test fails.
- Distinct stencil operations performed when
  - Stencil test fails
  - Depth test fails
  - Depth test passes
- Provides fine grain control of pixel update

OpenGL API

- glEnable/glDisable(GL_STENCIL_TEST);
- glStencilFunc(function, reference, mask);
- glStencilOp(stencil_fail,
  depth_fail, depth_pass);
- glStencilMask(mask);
- glClear(… | GL_STENCIL_BUFFER_BIT);

Controlling Stencil Buffer

- `glStencilFunc( func, ref, mask )`
  - compare value in buffer with **`ref`** using **`func`**
  - only applied for bits in **`mask`** which are 1
  - **`func`** is one of standard comparison functions
- `glStencilOp( fail, zfail, zpass )`
  - Allows changes in stencil buffer based on passing or failing stencil and depth tests: **`GL_KEEP, GL_INCR`**

Request a Stencil Buffer

- If using stencil, request sufficient bits of stencil
- Implementations may support from zero to 32 bits of stencil
- 8, 4, or 1 bit are common possibilities
- Easy for GLUT programs:

```
glutInitDisplayMode(GLUT_DOUBLE | GLUT_RGB |
    GLUT_DEPTH | GLUT_STENCIL);
glutCreateWindow("stencil example");
```

Stencil Test

- Compares reference value to pixel's stencil buffer value
- Same comparison functions as depth test:
  - NEVER, ALWAYS
  - LESS, LEQUAL
  - GREATER, GEQUAL
  - EQUAL, NOTEQUAL
- Bit mask controls comparison
  ((ref & mask) op (svalue & mask))

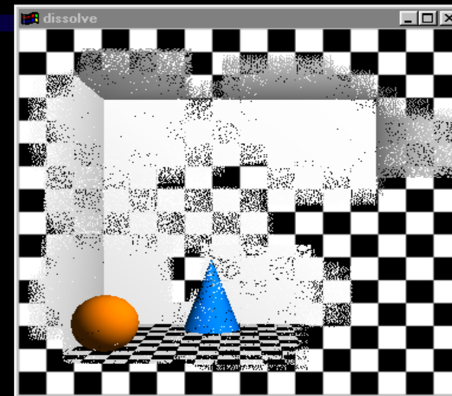
Stencil Operations

- Stencil side effects of
  - Stencil test fails
  - Depth test fails
  - Depth test passes
- Possible operations
  - Increment, Decrement (saturates)
  - Increment, Decrement (wrap, DX6 option)
  - Keep, Replace
  - Zero, Invert
- Way stencil buffer values are controlled

Stencil Write Mask

- Bit mask for controlling write back of stencil value to the stencil buffer
- Applies to the clear too!
- Stencil compare & write masks allow stencil values to be treated as sub-fields

Very Complex Clip Window



Digital Dissolve

Creating a Mask

- `gluInitDisplayMode(…|GLUT_STENCIL|…);`
- `glEnable( GL_STENCIL_TEST );`
- `glClearStencil( 0x0 );`
- `glStencilFunc( GL_ALWAYS, 0x1, 0x1 );`
- `glStencilOp( GL_REPLACE, GL_REPLACE, GL_REPLACE );`
- *draw mask*

Using Stencil Mask

- Draw objects where stencil = 1
  - `glStencilFunc( GL_EQUAL, 0x1, 0x1 )`
- Draw objects where stencil != 1
  - `glStencilFunc( GL_NOTEQUAL, 0x1, 0x1 );`
  - `glStencilOp( GL_KEEP, GL_KEEP, GL_KEEP );`
-

Performance

- With today's 32-bit graphics accelerator modes, 24-bit depth and 8-bit stencil packed in *same* memory word
- RIVA TNT is an example
- Performance implication:

  if using depth testing, stenciling is at NO PENALTY

Repeating that!

- On card like RIVA TNT2 in 32-bit mode

  if using depth testing, stenciling has NO PENALTY

- Do not treat stencil as "expensive" -- in fact, treat stencil as "free" when already depth testing

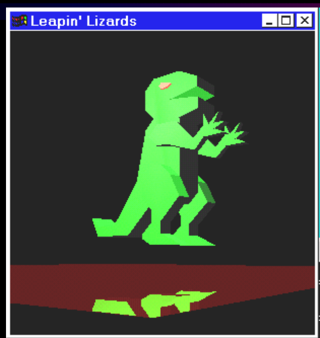
Pseudo Global Lighting Effects

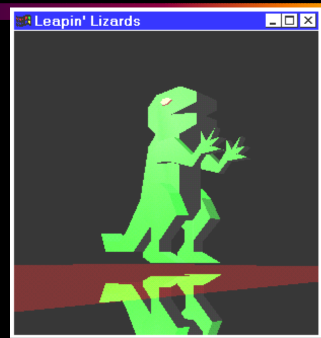
- OpenGL's light model is a "local" model
  - Light source parameters
  - Material parameters
  - Nothing else enters the equation
- Global illumination is fancy word for real-world light interactions
  - Shadows, reflections, refractions, radiosity, etc.
- Pseudo global lighting is about clever hacks

Planar Reflections

Dinosaur is reflected by the planar floor. Easy hack, draw dino twice, second time has `glScalef(1,-1,1)` to reflect through the floor

Compare Two Versions

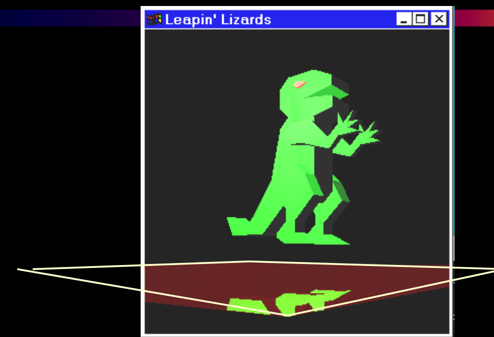




Good. **Bad.**

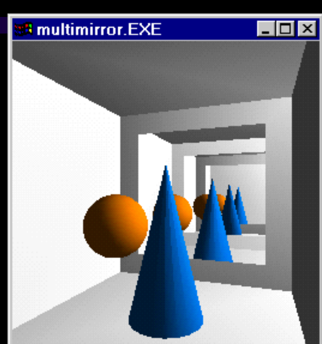
Notice right image's reflection falls off the floor!

Stencil Maintains the Floor



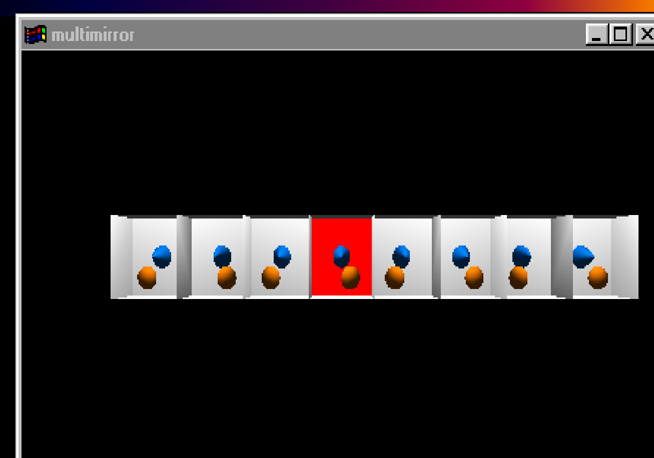
Clear stencil to zero.
Draw floor polygon with stencil set to one.
Only draw reflection where stencil is one.

Recursive Planar Mirrors

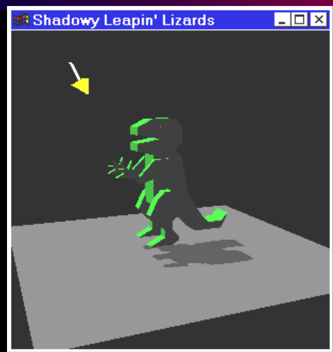


Basic idea of planar reflections can be applied recursively. Requires more stencil bits.

The Trick (bird's eye view)



Next: Planar Shadows



Shadow is projected into the plane of the floor.

Constructing a Shadow Matrix

```
void shadowMatrix(GLfloat shadowMat[4][4], GLfloat groundplane[4], GLfloat lightpos[4])
{
  GLfloat dot;
  /* Find dot product between light position vector and ground plane normal. */
  dot = groundplane[X] * lightpos[X] +
   groundplane[Y] * lightpos[Y] +
   groundplane[Z] * lightpos[Z] +
   groundplane[W] * lightpos[W];
  shadowMat[0][0] = dot - lightpos[X] * groundplane[X];
  shadowMat[1][0] = 0.f - lightpos[X] * groundplane[Y];
  shadowMat[2][0] = 0.f - lightpos[X] * groundplane[Z];
  shadowMat[3][0] = 0.f - lightpos[X] * groundplane[W];
  shadowMat[X][1] = 0.f - lightpos[Y] * groundplane[X];
  shadowMat[1][1] = dot - lightpos[Y] * groundplane[Y];
  shadowMat[2][1] = 0.f - lightpos[Y] * groundplane[Z];
  shadowMat[3][1] = 0.f - lightpos[Y] * groundplane[W];
  shadowMat[X][2] = 0.f - lightpos[Z] * groundplane[X];
  shadowMat[1][2] = 0.f - lightpos[Z] * groundplane[Y];
  shadowMat[2][2] = dot - lightpos[Z] * groundplane[Z];
  shadowMat[3][2] = 0.f - lightpos[Z] * groundplane[W];
  shadowMat[X][3] = 0.f - lightpos[W] * groundplane[X];
  shadowMat[1][3] = 0.f - lightpos[W] * groundplane[Y];
  shadowMat[2][3] = 0.f - lightpos[W] * groundplane[Z];
  shadowMat[3][3] = dot - lightpos[W] * groundplane[W];
}
```

How to Render the Shadow

```
 /* Render 50% black shadow color on top of whatever
     the floor appearance is. */
glEnable(GL_BLEND);
glBlendFunc(GL_SRC_ALPHA,
     GL_ONE_MINUS_SRC_ALPHA);
glDisable(GL_LIGHTING);  /* Force the 50% black. */
glColor4f(0.0, 0.0, 0.0, 0.5);

glPushMatrix();
  /* Project the shadow. */
  glMultMatrixf((GLfloat *) floorShadow);
  drawDinosaur();
glPopMatrix();
```

Note Quite So Easy (1)

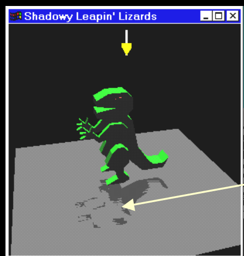
Without stencil to avoid double blending of the shadow pixels:

Notice darks spots on the planar shadow.

Solution: Clear stencil to zero. Draw floor with stencil of one. Draw shadow if stencil is one. If shadow's stencil test passes, set stencil to two. No double blending.

Note Quite So Easy (2)

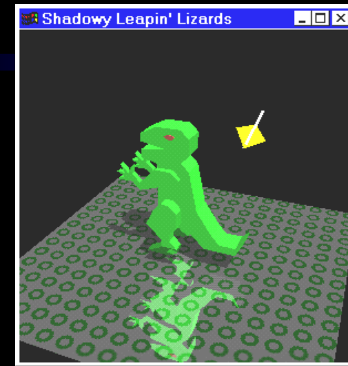
There's still another problem even if using stencil to avoid double blending.



depth buffer Z fighting artifacts

Shadow fights with depth values from the floor plane. Use polygon offset to raise shadow polygons slightly in Z.

Everything All At Once

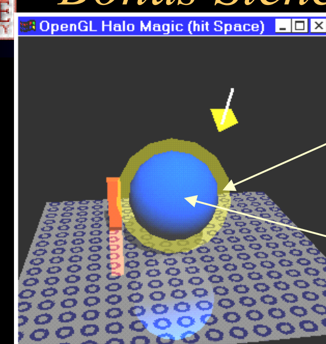


Lighting, texturing, planar shadows, and planar reflections all at one time. Stencil & polygon offset eliminate aforementioned artifacts.

Pseudo Global Lighting

- Planar reflections and shadows add more than simplistic local lighting model
- Still not really global
  - Techniques more about hacking common cases based on knowledge of geometry
  - Not really modeling underlying physics of light
- Techniques are "multipass"
  - Geometry is rendered multiple times to improve the rendered visual quality

Bonus Stenciled Halo Effect



Halo is blended with objects behind haloed object.

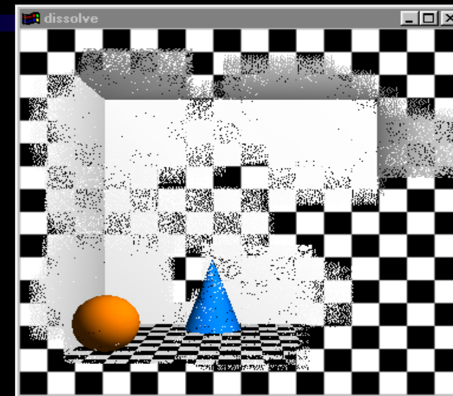
Halo does not obscure or blend with the haloed object.

Clear stencil to zero. Render object, set stencil to one where object is. Scale up object with glScalef. Render object again, but not where stencil is one.

Other Stencil Uses

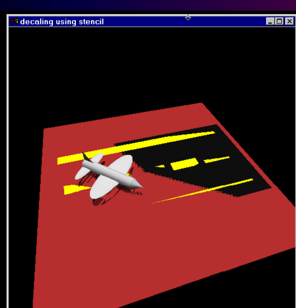
- Digital dissolve effects
- Handling co-planar geometry such as decals
- Measuring depth complexity
- Constructive Solid Geometry (CSG)

Digital Dissolve

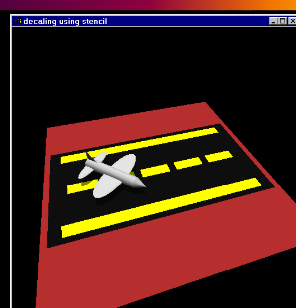


Stencil buffer holds dissolve pattern.
Stencil test two scenes against the pattern

Co-planar Geometry



Shows "Z fighting" of co-planar geometry



Stencil testing fixes "Z fighting"

Visualizing Depth Complexity

Use stencil to count pixel updates, then color code results.

Dithering

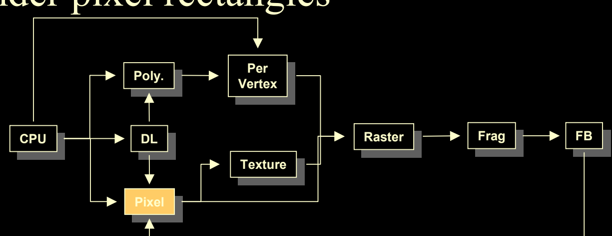
- `glEnable( GL_DITHER )`
- Dither colors for better looking results
  - Used to simulate more available colors

Logical Operations on Pixels

- Combine pixels using bitwise logical operations
  - `glLogicOp( mode )`
  - Common modes
    - **`GL_XOR – Rubberband user-interface.`**
    - **`GL_AND`**
  - Others
    - GL_CLEAR, GL_SET , GL_COPY,
    - GL_COPY_INVERTED, GL_NOOP, GL_INVERT
    - GL_AND, GL_NAND, GL_OR
    - GL_NOR, GL_XOR, GL_AND_INVERTED
    - GL_AND_REVERSE, GL_EQUIV, GL_OR_REVERSE
    - GL_OR_INVERTED

Imaging and Raster Primitives

- Describe OpenGL’s raster primitives: bitmaps and image rectangles
- Demonstrate how to get OpenGL to read and render pixel rectangles

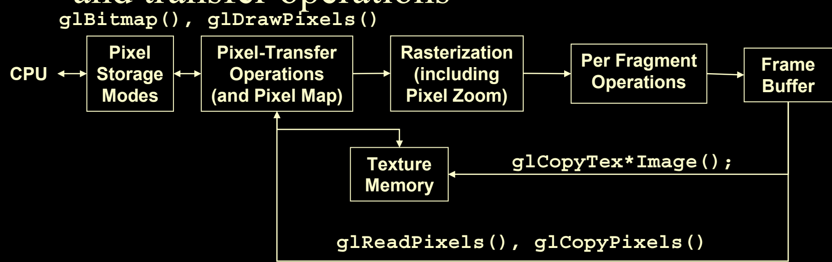


Pixel-based primitives

- Bitmaps
  - 2D array of bit masks for pixels
    - update pixel color based on current color
- Images
  - 2D array of pixel color information
    - complete color information for each pixel
- OpenGL doesn’t understand image formats

Pixel Pipeline

- Programmable pixel storage and transfer operations

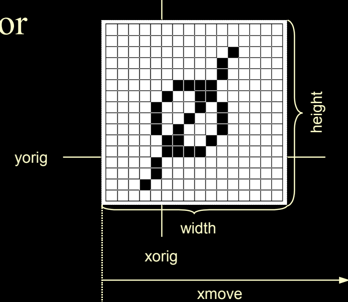


Positioning Image Primitives

- `glRasterPos3f( x, y, z )`
  - raster position transformed like geometry
  - discarded if raster position is outside of viewport
    - may need to fine tune viewport for desired results

Rendering Bitmaps

- `glBitmap( width, height, xorig, yorig, xmove, ymove, bitmap )`
  - render bitmap in current color at $(\lfloor x - xorig \rfloor \quad \lfloor y - yorig \rfloor)$
  - advance raster position by $(xmove \quad ymove)$ after rendering



Rendering Fonts using Bitmaps

- OpenGL uses bitmaps for font rendering
  - each character is stored in a display list containing a bitmap
  - window system specific routines to access system fonts
    - **`glXUseXFont()`**
    - **`wglUseFontBitmaps()`**

Rendering Images

- `glDrawPixels( width, height, format, type, pixels )`
  - render pixels with lower left of image at current raster position
  - numerous formats and data types for specifying storage in memory
    - best performance by using format and type that matches hardware

Reading Pixels

- `glReadPixels( x, y, width, height, format, type, pixels )`
  - read pixels from specified *(x,y)* position in framebuffer
  - pixels automatically converted from framebuffer format into requested format and type
- Framebuffer pixel copy
  - `glCopyPixels( x, y, width, height, type )`

Pixel Zoom

- `glPixelZoom( x, y )`
  - expand, shrink or reflect pixels around current raster position
  - fractional zoom supported

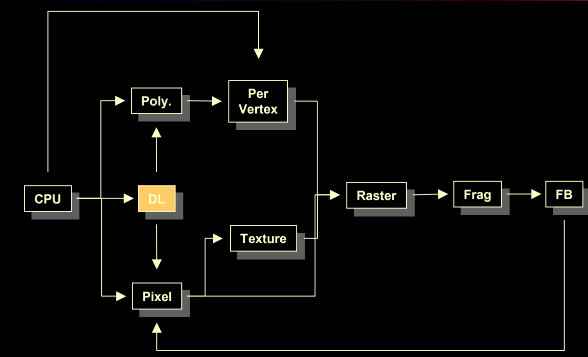
Storage and Transfer Modes

- Storage modes control accessing memory
  - byte alignment in host memory
  - extracting a subimage
- Transfer modes allow modify pixel values
  - scale and bias pixel component values
  - replace colors using pixel maps

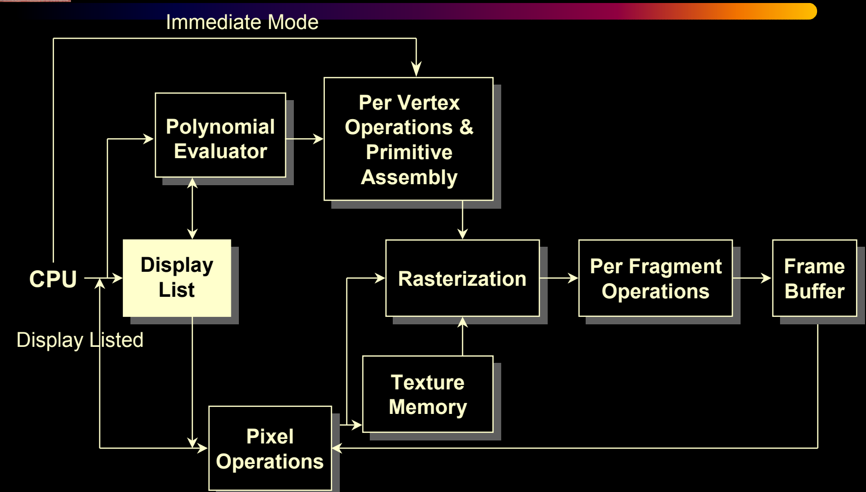
Immediate Mode versus Display Listed Rendering

- Immediate Mode Graphics
  - Primitives are sent to pipeline and display right away
  - No memory of graphical entities
- Display Listed Graphics
  - Primitives placed in display lists
  - Display lists kept on graphics server
  - Can be redisplayed with different state
  - Can be shared among OpenGL graphics contexts

Display Lists



Immediate Mode versus Display Lists



Display Lists

- Creating a display list

```
GLuint id;
void init( void )
{
   id = glGenLists( 1 );
   glNewList( id, GL_COMPILE );
   /* other OpenGL routines */
   glEndList();
}
```

- Call a created list

```
void display( void )
{
   glCallList( id );
}
```

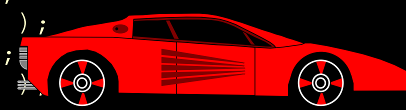
Display Lists

- Not all OpenGL routines can be stored in display lists
- State changes persist, even after a display list is finished
- Display lists can call other display lists
- Display lists are not editable, but you can fake it
  - make a list (A) which calls other lists (B, C, and D)
  - delete and replace B, C, and D, as needed

Display Lists and Hierarchy

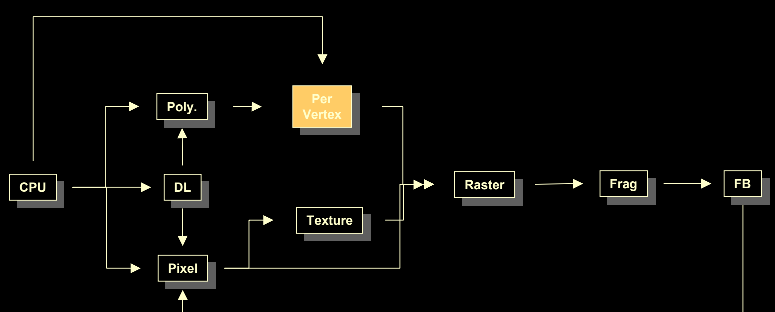
- Consider model of a car
  - Create display list for chassis
  - Create display list for wheel

```
glNewList( CAR, GL_COMPILE );
    glCallList( CHASSIS );
    glTranslatef( … );
    glCallList( WHEEL );
    glTranslatef( … );
    glCallList( WHEEL );
        …
glEndList();
```



Advanced Primitives

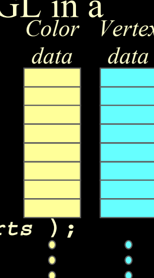
- Vertex Arrays



Vertex Arrays

- Pass arrays of vertices, colors, etc. to OpenGL in a large chunk

```
glVertexPointer( 3, GL_FLOAT, 0, coords )
glColorPointer( 4, GL_FLOAT, 0, colors )
glEnableClientState( GL_VERTEX_ARRAY )
glEnableClientState( GL_COLOR_ARRAY )
glDrawArrays( GL_TRIANGLE_STRIP, 0, numVerts );
```



- All active arrays are used in rendering

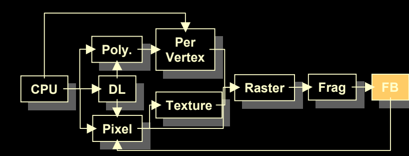
Why use Display Lists or Vertex Arrays?

- May provide better performance than immediate mode rendering
  - Avoid function call overheads and small packet sends.
- Display lists can be shared between multiple OpenGL context
  - reduce memory usage for multi-context applications
- Vertex arrays may format data for better memory access

Alpha: the 4th Color Component

- Measure of Opacity
  - simulate translucent objects
    - glass, water, etc.
  - composite images
  - antialiasing
  - ignored if blending is not enabled

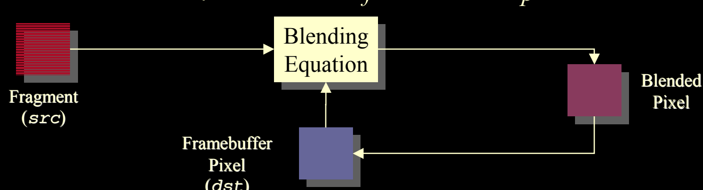
```
glEnable( GL_BLEND )
```



Blending

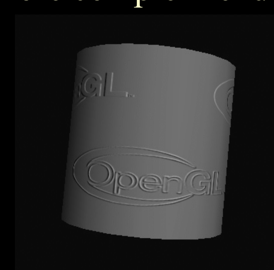
- Combine pixels with what's in already in the framebuffer
  - `glBlendFunc( src, dst )`

$$\vec{C}_r = src\ \vec{C}_f + dst\ \vec{C}_p$$



Multi-pass Rendering

- Blending allows results from multiple drawing passes to be combined together
  - enables more complex rendering algorithms



Example of bump-mapping done with a multi-pass OpenGL algorithm