Special Topics in OpenGL

Rasterization

What is Rasterization?

- Is a process by which a primitive is converted to a 2D image
  - Determine which squares of an integer grid in window coordinates are occupied by the primitive
  - Assign a color and a depth value to each square
- A grid square along with its assigned color and depth is called a fragment
- The results of the process are passed to the next stage of per-fragment operations

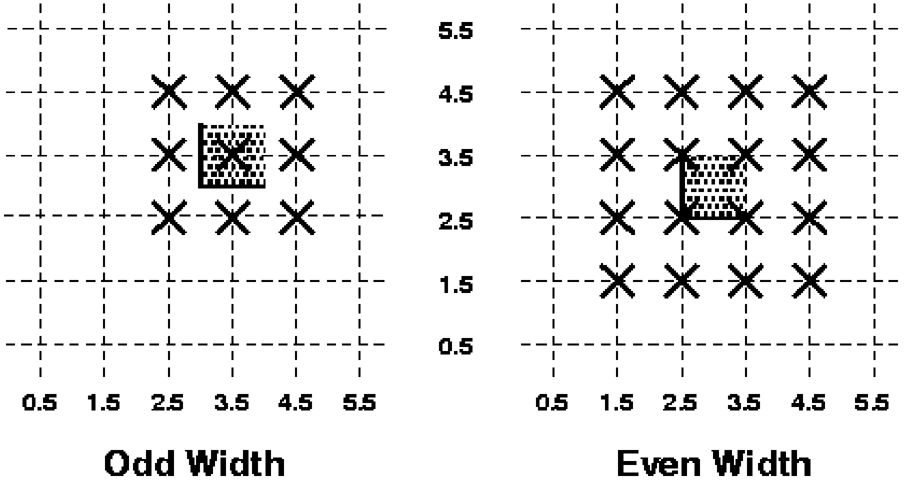
Point Rasterization

- Point is rasterized as a single fragment truncating its (x_w, y_w) coordinates to integers

- For wide points, fragment centers are at

$$\left(\lfloor x_w \rfloor + \frac{1}{2}, \lfloor y_w \rfloor + \frac{1}{2}\right) \quad \text{(Odd)}$$

$$\left(\left\lfloor x_w + \frac{1}{2}\right\rfloor, \left\lfloor y_w + \frac{1}{2}\right\rfloor\right) \quad \text{(Even)}$$



- The data associated with each rasterized fragment is the same as that of the vertex

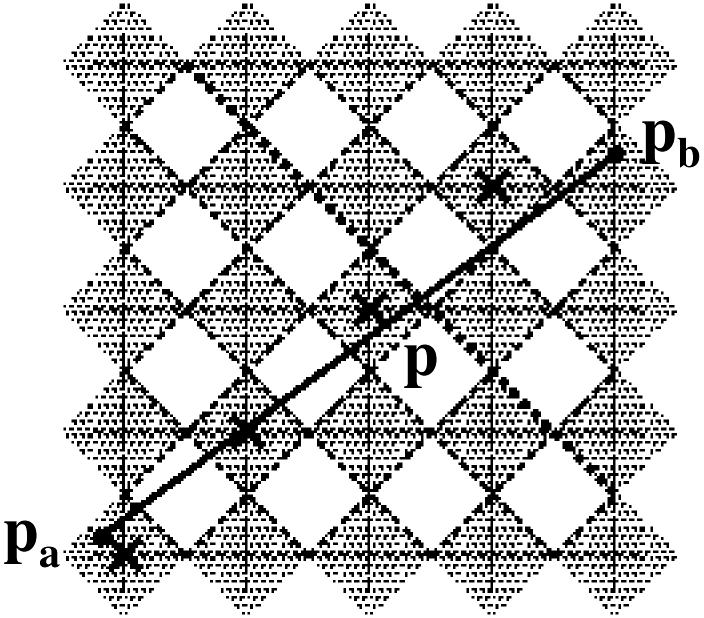
Line Segment Rasterization

- Diamond-exit rule to determine the fragments produced by rasterization

- Specify the data associate with each rasterized fragment

$$f = \frac{(1-t)f_a/w_a + tf_b/w_b}{(1-t)/w_a + t/w_b}$$

Where $t = \dfrac{(p-p_a)\bullet(p_b-p_a)}{|p_b-p_a|^2}$



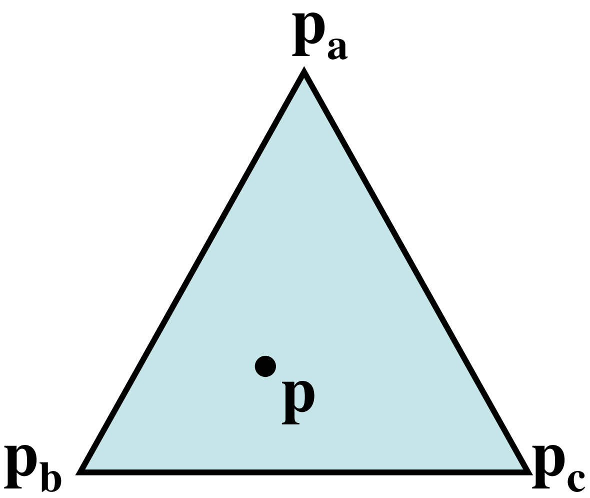
Polygon Rasterization

- Point sampling
  - Rasterized fragment centers lie inside the projected polygon
  - If two or more polygons share the same fragment, it is rasterized by one of them

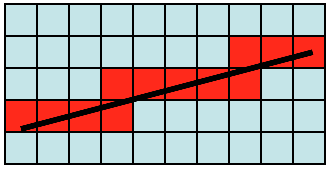
- Specify the data associated with each rasterized fragment

$$f = \frac{af_a / w_a + bf_b / w_b + cf_c / w_c}{a / w_a + b / w_b + c / w_c}$$

$p = ap_a + bp_b + cp_c$ defines any point in a triangle with barycentric coordinates (a, b, and c)



Antialiasing



- Lines (nearly horizontal or vertical) appear zagged
- Reducing this zaggedness is called antialiasing
  - Calculates a coverage value for each fragment based on the fraction of the pixel square on the screen that it would occur
  - Multiplies the fragment's alpha by its coverage
  - Use the resulting alpha to blend the fragment with the corresponding pixel already in the frame buffer
- Antialising points or lines or polygons

  Pass GL_POINT_SMOOTH or GL_LINE_SMOOTH or GL_POLYGON_SMOOTH to **glEnable()**

  Enable blending

  Example: Aliased and antialiased lines

Framebuffer

What is Framebuffer

- Each fragment has coordinate data which correspond to a pixel, as well as color and depth values

- Buffers (storages) to hold the various kinds of information of pixels

- OpenGL implementation supports the following buffers
  - Color buffer
  - Depth buffer
  - Stencil buffer
  - Accumulation buffer

  The buffers are used to perform special tasks before pixels are finally written to the viewable color buffer

- A collection of these buffers is called framebuffer

Color Buffers

- Color buffers are the ones to which you draw
  - They contain RGBA data

- Stereoscopic viewing needs left and right color buffers for the left and right stereo images

- Double-buffered systems have front and back color buffers

- Non-displayable auxiliary color buffers can be used

- Minimum requirement is a front-left color buffer

Other Buffers

- Depth buffer (*z*-buffer):
  - Stores a depth value for each pixel
  - Depth is usually measured in terms of distance to the eye
  - Used for a hidden-surface removal

- Stencil buffer:
  - Stores the information to restrict drawing to certain portions of the screen

- Accumulation buffer:
  - Holds RGBA color data for accumulating a series of images into a final, composite image
  - When accumulation is finished, the result is copied back into the color buffer for viewing
  - Used for scene antialiasing, motion blur, simulating depth of field, and calculating soft shadows

Clearing Buffers

- Clearing the screen (or any of the buffers) is expensive
  - Hardware can clear more than one buffer at once

- First, specify the current clearing values for each buffer

  void **glClearColor**(GLclampf *red*, GLclampf *green*, GLclampf *blue*, GLclampf *alpha*);

  void **glClearDepth**(GLclampf *depth*);

  void **glClearStencil**(GLuint *s*);

  void **glClearAccum**(GLclampf *red*, GLclampf *green*, GLclampf *blue*, GLclampf *alpha*);

- Then issue a single clear command

  void **glClear**(GLbitfield *mask*);

  mask is the bitwise logical OR of some combination of GL_COLOR_BUFFER_BIT, GL_DEPTH_BUFFER_BIT, GL_STECIL_BUFFER_BIT, and GL_ACCUM_BUFFER_BIT

Color Buffers for Writing and Reading

- void **glDrawBuffer**(GLenum *mode*);
  - Selects the color buffers enabled for writing or clearing
  - *mode* can be GL_FRONT, GL_BACK, GL_LEFT, GL_RIGHT, GL_FRONT_LEFT, etc.
  - Default mode is GL_FRONT for single-buffered contexts and GL_BACK for double-buffered contexts

- void **glReadBuffer**(GLenum *mode*);
  - Selects the color buffer enabled as the source for reading pixels

Masking Buffers

- Sets the masks used to control writing into the indicated buffers

- void **glColorMask**(GLboolean *red*, GLboolean *green*, GLboolean *blue*, GLboolean *alpha*);
  - The *red, green, blue* and *alpha* values control whether corresponding component is written

- void **glDepthMask**(Glboolean *flag*);
  - *flag* is GL_TRUE for writing in depth buffer

- void **glStencilMask**(Gluint *mask*);
  - mask = 1 for writing the bit

Testing and Operating on Fragments

- After fragments are generated, several processing stages occur determining how and whether a given fragment is drawn as pixel into the framebuffer

- Set of tests:
    - Scissor test
    - Alpha test
    - Depth test
    - Stencil test
    - Blending
    - Dithering
    - Logical operation

Scissor Test

- void **glScissor**(Glint *x*, Glint *y*, GLsizei *width*, GLsizei *height*);
  - Sets the location and size of the scissor rectangle or box
  - By default, the rectangle matches the window
  - Drawing occurs only inside the rectangle: pixels lying inside the rectangle pass the scissor test

  - Needs enabling

    glEnable(GL_SCISSOR_TEST);

Alpha Test

- void **glAlphaFunc**(GLenum *func*, GLclampf *ref*);
  - Sets the reference value and comparison function for the alpha test
  - In RGBA mode, a fragment is accepted or rejected by the alpha test on its alpha value
  - By default, *ref* is zero, and *func* is GL_ALWAYS
  - *func* can be GL_ALWAYS, GL_NEVER, GL_LESS, GL_EQUAL, GL_LEQUAL, GL_GEQUAL, GL_GREATER or GL_NOTEQUAL

  - Needs enabling

    glEnable(GL_ALPHA_TEST);

Depth Test

- **glDepthFunc**(GLenum *func*);
  - Sets the comparison function for the depth test
  - An incoming fragment passes the depth test if its *z* value has specified relation to the value already stored in the depth buffer
  - By default, *func* is GL_LESS

    Pixels with larger depth-buffer values are overwritten by pixels with smaller values
  - *func* can be GL_ALWAYS, GL_EQUAL, GL_GREATER, etc.
  - Needs enabling

    glEnable(GL_DEPTH_TEST);

Stencil Test

- The stencil test takes place only if there is a stencil buffer
  - It compares a reference value with the value stored at a pixel in the buffer
  - Depending on the test result, the value in the stencil buffer is modified

- void **glStencilFunc**(GLenum *func*, GLint *ref*, GLuint *mask*);
  - Sets the comparison *func*, reference *ref* and *mask* for the test

    Comparison applies to those bits for which bits of the mask are 1
  - *func* can be GL_ALWAYS, GL_LESS, etc.
  - Needs enabling: **glEnable**(GL_STENCIL);

- **glStencilOp**(GLenum *fail*, GLenum *zfail*, GLenum *zpass*);
  - Specifies how the data in the stencil buffer is modified when a fragment passes or fails the stencil test
  - *fail, zfail, zpass* can be GL_KEEP, GL_ZERO, GL_REPLACE, GL_INCR, GL_DECR, GL_INVERT

    fail = failed stencil test; *zfail* = failed *z* test; *zpass* = passed *z* test

Other Operations

- Blending
  - Combines the incoming fragment's R, G, B and A values with those of the pixel already stored at the location
- Dithering
  - Dither the values of red, green and blue on neighboring pixels for the perception of a wide range of colors

  Needs enabling with GL_DITHER
- Logical Operations
  - Are applied between the incoming fragment's color and the color stored at the corresponding location in the framebuffer
  - The result replaces the value in the framebuffer for that fragment

  void **glLogicOp**(GLenum *opcode*);

  opcode can be GL_CLEAR, GL_COPY, GL_AND, etc

  Needs enabling with GL_COLOR_LOGIC

Blending

What Blending?

- Combining colors from a source (incoming fragment) and destination (the corresponding pixel) to achieve such effects as making objects appear translucent

- The source and destination factors are RGBA quadruplets:
  - ➢ (Sr, Sg, Sb, Sa) and (Dr, Dg, Db, Da)

- Blended RGBA values are
  - ➢ (RsSr + RdDr, GsSg + GdDg, BsSb+BdDb, AsSa+AdDa)

Where (Rs,Gs,Bs,As) and (Rd,Gd,Bd,Ad) are the RGBA values of source and destination

How to Specify?

- void **glBlendFunc**(GLenum *sfactor*, GLenum *dfactor*);
  - Controls how color values in the fragment being processed (the source) are combined with those already stored in the framebuffer (the destination)
  - *sfactor* (*dfactor*) indicates how to compute a source (destination) blending factor

    GL_ONE: (1,1,1,1)

    GL_SRC_ALPHA: (As,As,As,As)

    GL_ONE_MINUS_SRC_ALPHA: (1,1,1,1)-(As,As,As,As)

  - Needs enabling

    glEinable(GL_BEND);

3D Blending with the Depth Buffer

- For 3D objects, the appearance depends on whether you draw the polygons from back to front or from front to back
  - drawing order
- Consider the effect of the depth buffer in determining the order
  - If an opaque object hides other objects, eliminate the more distant objects
- If the translucent object is closer, blend it with the opaque object
- **Example: Sphere inside a Cube**

Animation

Pictures That Move

- Animation is an important part of computer graphics
- Seeing all sides of a mechanical part designed
- Learning to fly an airplane using a simulation
- Viewing molecular dynamics
- Viewing vector data

Motion = Redraw + Swap

- OpenGL provides double buffering (two color buffers)
  - One is displayed while the other is being drawn
  - When drawing of a frame is complete, the two buffers are swapped
  - Like a movie projector with only two frames in a loop

- void **glutSwapBuffers**(void);
  - Swap the viewable and drawable buffers
  - Waits until one frame is completely drawn and other is completely displayed
  - For a system with display refresh rate of 60 times per second, the fastest frame rate can be 60 frames per second

- void **glutInitDisplayMode**(GLUT_DOUBLE | GLUT_RGB);
  - Set double buffered window mode

Example: Solar System

```
void display (void) {
    glClear (GL_COLOR_BUFFER_BIT |GL_DEPTH_BUFFER_BIT);
    glColor3f (1.0, 1.0, 1.0);
    glPushMatrix ();
    glRotatef (year, 0.0, 1.0, 0.0);
    glutSolidSphere (1.0, 80, 64);
    glTranslatef (2.0, 0.0, 0.0);
    glRotatef (day, 0.0, 1.0, 0.0);
    glutSolidSphere (0.2, 80, 64);
    glPopMatrix ();
    glutSwapBuffers ();
}
glutInitDisplayMode (GLUT_DOUBLE | GLUT_RGB);
```

- Sun is rotating about its own axis; planet is orbiting around the sun as well as rotating about its own axis

  The graphics remain idle between the frames

Hidden-Surface Removal

Hidden Surface?

- In a scene composed of 3D objects, some of them might obscure all or parts of others
- The obscuring relationship changes with viewpoint and needs to be properly maintained
- Hidden-surface removal is elimination of parts of solid objects that are obscured by others
- Otherwise, the objects are drawn in the order the drawing commands appear in the code
- Hidden-surface removal increases performance

Use of Depth Buffer

- Use of depth buffer (*z-buffer*) to achieve hidden surface removal
- Graphical calculations convert each surface (before drawing) to a set of corresponding pixels on the window and also compute depth value for each pixel
- A comparison is done with the depth value already stored at that pixel to accept the pixel only if it has a smaller depth
- Color and depth information of the incoming pixel with greater depth is discarded

How to Specify?

- In void **glDepthFunc**(Glenum *func*);

  Defualt value of *func* is used: GL_LESS used

  glEnable(GL_DEPTH_TEST);

- **glutInitDisplayMode** (GLUT_RGB | GLUT_DEPTH);

- Before drawing, each time you need to clear the depth buffer and draw objects in any order

  glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);

  glClear() clears both color and depth buffers

- **Planet hides behind the sun in solar system example**

Drawing Pixel Data

Geometric Versus Pixel Data

- Rendering of geometric data (arrays of vertices)
  - points, lines, polygons

- Rendering of pixel data (arrays of pixels)
  - Bitmaps
    - Characters in fonts
    - Array of 0s and 1s(1 = the pixel is affected)
    - Serves as drawing mask for overlying another image
  - Image data
    - A photograph that is scanned or an image calculated by some program in memory by pixels or an image first drawn and then read back pixel by pixel
    - Several pieces of data per pixel (R,G,B,A values)
    - Simply overwrites in the framebuffer

Current Raster Position

- void **glRasterPos**{234}{sifd}(*TYPE x*, *TYPE y*, *TYPE z*, *TYPE w*);
    - Sets the current raster position where the next bitmap (or image) is to be drawn
    - The raster position coordinates are subject to the modelview and projection transformations in the same way as the vertex coordinates

- To specify the raster position directly in the screen coordinates, only 2D version of transformations need to be specified

Drawing Bitmaps

- void **glBitmap**(GLsizei *width*, GLsizei *height*, GLfloat x_{bo}, GLfloat y_{bo}, GLfloat x_{bi}, GLfloat y_{bi}, const Glubyte **bitmap*);
  - Draws the bitmap specified by *bitmap*
  - *Width and height* define size of the bitmap
  - Subscript *bo* means the origin of the bitmap
  - Subscript *bi* means increment to the current raster position after the bitmap is rasterized

Manipulating Images

- void **glReadPixels**(GLint *x*, GLint *y*, GLsizei *width*, GLsizei *height*, GLenum *format*, GLenum *type*, GLvoid **pixels*)
  - Reads pixel data from the *specified* framebuffer rectangle and stores data in the array pointed by *pixels*
  - *format* can be GL_RGBA, GL_RED, GL_ALPHA, GL_DEPTH_COMPONENT
  - *type* can be s, u, i, f, etc.

- void **glDrawPixels**(GLsizei *width*, GLsizei *height*, GLenum *format*, GLenum *type*, GLvoid **pixels*)
  - Draws a rectangle of pixel data with dimensions *width* and *height*
  - Pixel rectangle has its lower-left corner at the current raster position

- void **glCopyPixels**(GLint *x*, GLint *y*, GLsizei *width*, GLsizei *height*, GLenum *buffer*)
  - Copies pixel data from the specified framebuffer rectangle
  - Buffer can be GL_COLOR, GL_DEPTH, GL_STENCIL

Example: Drawing Image

- Make a checkerboard image

- Define raster position

- Draw an pixel rectangle of the image

Texture Mapping

What is Texture Mapping?

- Gluing an image (such as scanned photograph) to a polygon
  - Bricks on wall
  - Ground in flight simulation
  - Vegetation

- Textures are rectangular arrays of data (colors, luminace)
  - Individual values are called texels

- Textures can be manipulated with transformations
  - Repeat textures in different directions to cover the surface
  - Apply textures in different shapes and sizes

Steps in Texturing

- Create a texture object and specify a texture for the object
- Indicate how the texture is to be applied to each pixel
- Enable texture mapping
- Draw the scene by supplying both texture and geometric coordinates

Sample Example

- Checkboard texture is generated

  makeCheckImage()

- All texture mapping initialization occurs in **init**()

  glGenTextures(1, &texName);

  glBindTexture(GL_TEXTURE_2D, texName);

- Single, full resolution texture map is specified

  glTexImage2D(GL_TEXTURE_2D, 0, GL_RGBA, checkImageWidth, checkImageHeight, 0, GL_RGBA, GL_UNSIGNED_BYTE, checkImage);

- Specify how the texture to be wrapped and how the colors are to be filtered if there is not an exact match between texels and pixels

  glTexParameteri(GL_TEXTURE_2D,GL_TEXTURE_WRAP_S,GL_REPEAT);

  glTexParameteri(GL_TEXTURE_2D,GL_TEXTURE_MAG_FILTER,GL_NEAREST);

More on Example

- In **display**(void), texture is turned on

  glEnable(GL_TEXTURE_2D);

- Drawing mode is set so as to draw the textured polygons using the colors from the texture map

  glTexEnvf(GL_TEXTURE_ENV, GL_TEXTURE_ENV_MODE, GL_REPLACE);

- Two polygons are drawn by specifying texture coordinates along with vertex coordinates

  glTexCoord2f(0.0,0.0); **glVertex3f**(-2.0,-1.0,0.0);

  …..

- Texture is finally turned off

  glDisable(GL_TEXTURE_2D);

3D Textures

- 3D textures are used in scientific visualization
  - e.g. volume rendering
- Defining a 3D texture:
  - **glTexImage3D**(GL_TEXTURE_3D, 0, GL_RGB, iWidth, iHeight, iDepth, 0, GL_RGB, GL_UNSIGNED_BYTE, image);
- Replace all or some of the texels of a 3D texture
- Using compressed texture images
- Mipmaps: Multiple levels of detail
- Filtering
- Texture objects
- Texturing functions

Display Lists

What and Why Display List?

- In many cases, you may need to execute the same set of OpenGL commands multiple times

- Drawing a tricycle:
  - ➢ Two wheels on the back are the same size but are offset from each other. The front wheel is larger and in a different location
  - ➢ An efficient way to render the wheels on the tricycle is store the geometry for one wheel in a list and then execute the list three times by setting the appropriate modelview matrix each time before executing the list

- Several other examples: Solar system, molecular dynamics

What and Why Display List?

- A display list is a group of OpenGL commands that have been stored for later execution
- You can define the geometry and/or state changes once and execute them multiple times by providing a number that uniquely specifies the display list
- Display lists improve performance by caching commands which are reused many times

Naming and Creating a Display List

- Each display list is identified as a unique, system-generated integer index or ID

- GLuint **glGenLists** (GLsizei *range*);
  - Allocates *range* number of contiguous, previously unallocated display list indices
  - The integer returned is the index that marks the beginning of a contiguous block of empty display list indices

  If returned integer is *n*, then indices *n, n+1, ……, n + range -1* are available

  `listIndex` = **glGenLists**(1);

  Generates one new display list ID and store it in variable `listIndex`

  glIsList(Gluint *list*) to check whether a specific index is in use. It returns GL_TRUE if the *list* is already used

  glDeleteLists(Gluint *list*, GLsizei *range*) to delete *range* display lists starting at the index specified by *list*

Naming and Creating a Display List

- void **glNewList**(GLuint *list*, GLenum *mode*);
  - Specifies the start of a display list.
  - The argument *list* is a nonzero positive integer that uniquely identifies the display list
  - The possible values for *mode* are GL_COMPILE and COMPILE_EXECUTE
- void **glEndList**(void);
  - Marks the end of a display list

```
glNewList (listIndex, GL_COMPILE);
        .......
glEndList();
```

Executing a Display List

- Void **glCallList**(GLint *list*);
  - Executes the display list specified by *list* which is the index for the display list
  - Commands in the display list are executed, just as if they were issued

- You can execute the same display list many times

- You can mix display lists and immediate-mode graphics

Example

- The display list contains OpenGL commands to draw a triangle

- The display list is executed multiple times

- A rectangle is drawn in immediate mode.

Hierarchical Display Lists

- A hierarchical display list executes another display list in it by calling **glCallList**() between a **glNewList**() and **glEndList**() pair
  - A display list to render a tricycle:

```
glNewList(listIndex, GL_COMPLIE);
        glCallList(handlebars);
        glCallList(frame);
        glTranslatef(1.0,0.0,0.0);
        glCallList(wheel);
        glTranslatef(3.0,0.0,0.0);
        glCallList(wheel);
        glTranslatef(3.0,0.0,0.0);
        glScalef(1.5,1.5,1.5);
        glCallList(wheel);
glEndList();
```

Multiple Display Lists

- void **glListBase**(GLuint *base*);
  - Specifies the offset that's added to the display-list indices in glCallLists() to obtain the final display-list indices

- void **glCallLists**(GLsizei *n*, GLenum *type*, const GLvoid **lists*);
  - Executes *n* display lists
  - **lists* is a pointer that points to an array of offsets
  - Nesting level of display lists is at least 64

Managing State Variables

- A display list can contain calls that change the value of OpenGL state variables
- The changes persist after execution of the display list is completed
- Use **glPushAttrib()** to save a group of state variables and **glPopAttrib()** to restore the values later
- Use **glPushMatrix()** and **glPopMatrix()** to save and restore the current matrix

Selection

Interactive Applications

- Allows user to select a region of the scene or pick an object drawn on the screen

- Selection mode
  - First draw scene, then use selection mode, and redraw the scene
  - Screen remains frozen while OpenGL is in selection mode
  - On exiting from selection mode, OpenGL returns a list of primitives that intersect the viewing volume
  - Each primitive within the viewing volume causes a selection hit

Basic Steps

- Specify the array to be used for the returned hit records with **glSelectBuffer()**
- Enter selection mode by specifying GL_SELECT with **glRenderMode()**
- Initialize the name stack using **glInitNames**()
- Define viewing volume to be used for selection
- Exit selection mode and process the hit records

Commands

- void **glSelectBuffer**(GLsizei **size**, GLuint **buffer*);
  - Specifies the array to be used for the returned selection data
  - *buffer* is a pointer to the array of the given *size*

- void **glRenderMode**(GLenum *mode*);
  - Controls whether the application is in rendering, selection, or feedback mode
  - *mode* is GL_RENDER, GL_SELECT or GL_FEEDBACK
  - *mode* remains unchanged until glRenderMode() is called again with different argument

Creating the Name Stack

- void **glInitNames**(void);
  - Clears the name stack so that it's empty
- void **glPushName**(Gluint *mode*);
  - Pushes name onto the name stack
  - The stack contain at least 64 names
- void **glPopName(**void);
  - Pops one name off the top of the name stack
- void **glLoadName**(GLuint *name*);
  - Replaces the value on the top of the name stack with name

Hit Record

- A primitive that intersects the viewing volume causes a selection hit
- OpenGL writes a hit record into the selection array if there is a hit
- Each hit record consists of the following items
    - Number of names on the name stack when the hit is occurred
    - Minimum and maximum window coordinate depth (z) values of all selected primitives
    - Contents of the name stack at the time of the hit

Picking

- Use selection mode to determine if the object are picked
- Picking is triggered by an input device (mouse click)
- Use a special picking matrix in conjunction with the projection matrix

  void **glPickMatrix**(GLdouble *x*, GLdouble *y*, GLdouble *width*, GLdouble *height*, GLint *viewport*[4]);

  - Creats a projection matrix that restricts drawing to a small region of the viewport and multiplies that matrix onto current matrix stack
  - *x,y* define the center of picking region (or cursor location)
  - *width and height* define the size of the picking region
  - *viewport*[] indicates the current viewport boundaries.

Evaluators

What is Evaluators?

- Provide way to describe curves and surfaces by using few parameters or control points
- Use a polynomial mapping to produce vertex, normal, and texture coordinates, and colors
- Precision and storage efficient

One-Dimensional Evaluators

A vector-valued function (called Bezier curve) of one variable is

$$C(u) = [X(u), Y(u), Z(u)] = \sum_{i=0}^{n} B_i^n(u) P_i$$

Example: distance traveled by a body as a function of time

Where P_i represent a set of n control points (3D) for vertices, colors or normals, and

$$B_i^n(u) = \binom{n}{i} u^i (1-u)^{n-i}$$

is ith Bernstein polynomial of degree n

Domain for variable u is [0.0,1.0].

But if it is $[u_1, u_2]$, the function at u is evaluated as

$$C\left(\frac{u-u_1}{u_2-u_1}\right)$$

Defining

- void **glMap1**{fd}(GLenum *target*, *TYPE* u_1, *TYPE* u_2, GLint *stride*, GLint *order*, const *TYPE *points*);
  - ➢ Defines 1D evaluator
  - ➢ *target:* what control point represent and how many values need to be supplied in points

    GL_MAP1_VERTEX_3,GL_MAP1_COLOR_4,GL_MAP1_NORMAL

  - ➢ u_1 and u_2: range for variable u
  - ➢ *stride*: an offset value between the beginning of one control point and the beginning of the next
  - ➢ *order*: *degree* + 1

    glMap1f(GL_MAP1_VERTEX_3, 0.0, 1.0, 3, 4, &cntrlpoints[0][0]);

    glEnable(GL_MAP1_VERTEX_3);

Evaluating

- void **glEvalCoord1**{fd}(*TYPE u*);
  - Causes evaluation of the enabled 1D maps
  - *u* is the domain coordinate
  - Call does not affect the current values for color and normal vectors
  - Call appears between **glBegin()** and **glEnd()** pair

- More than one evaluator can be evaluated at a time
  - Define and enable both GL_MAP1_VERTEX_3 and GL_MAP1_COLOR_4

    so that a single call to **glEvalCoord1**() generate both position and color along the curve

Defining Evenly Spaced *u* Values

- Use a 1D grid of *u* values for evaluation of function
- void **MapGrid1**{fd}(GLint *n*, *TYPE* u_1, *TYPE* u_2);
  - Define a grid that goes from u_1 and u_2 in *n* steps, which are evenly spaced
- void **glEvalMesh1**(GLenum *mode*, GLint p_1, GLint p_2);
  - Applies currently defined map grid to all enabled evaluators
  - Mode: GL_POINT or GL_LINE
  - p_1 and p_2 defines the range of steps

Two-Dimensional Evaluators

A vector-valued function (called Bezier surface) of two variables (*u* and *v*) is

$$C(u,v) = [X(u,v), Y(u,v), Z(u,v)] = \sum_{i=0}^{n} \sum_{j=0}^{m} B_i^n(u) B_j^m(v) P_{ij}$$

Where P_{ij} represents a set of $m*n$ control points (3D), and *B's* are Bernstein polynomials

Procedure to use 2D evaluators:

1. Define evaluator with **glMap2()**
2. Enable them by passing appropriate value to **glEnable()**
3. Invoke them either by **glEvalCoord2()** between **glBegin()** and **glEnd()** pair or

   By specifying and applying a mesh with **glMapGrid2()** and **glEvalMesh2()**

2D Evaluators Command

- Void **glMap2**{fd}(GLenum *target*, *TYPE* u_1, *TYPE* u_2, GLint *ustride*, GLint *uorder*, *TYPE* v_1, *TYPE* v_2, GLint *vstride*, GLint *vorder*, const *TYPE *points*);

- void **glEvalCoord2**{fd}(*TYPE u*, *TYPE v*);

- void **glMapGrid2**{fd}(GLint *nu*, *TYPE* u_1, *TYPE* u_2, GLint *nv*, *TYPE* v_1, *TYPE* v_2);

  void **glEvalMesh2**(GLenum *mode*, GLint i_1, GLint i_2, GLint j_1, GLint j_2);

  mode can be GL_POINT, GL_LINE, GL_FILL

- Normal to the surface can be computed with **glEnable**(GL_AUTO_NORMAL)

Tessellators, Quadrics, NURBs

Polygon Tessellation

- Process of subdividing non-simple polygons (such as concave polygons, polygons with holes, polygons with intersecting edges) into simple convex polygons

- Steps in polygon tessellation:
  - Create a new tessellation object with **gluNewTess**()
  - Use **gluTessCallback**() to register callback functions to perform operations during the tessellation
  - Specify tessellation properties by calling **gluTessProperty**()
  - Create and render tessellated polygons by the contours
  - Delete tessellation object with **gluDeleteTess**()

Quadrics

- Rendering spheres, cylinders, and disks:
  - Quadric surfaces are defined by

$$a_1x^2 + a_2y^2 + a_3z^2 + a_4xy + a_5yz + a_6xz + a_7x + a_8y + a_9z + a_{10} = 0$$

- Steps in using quadrics object
  - Use **gluNewQuadric()** to create a quadrics object
  - Specifying rendering attributes with **gluQuadricOrientation**(), **gluQuadricDrawstyle(), gluQuadricNormals()**
  - Invoke the rendering routines for different quadric objects: **gluSphere(), gluCylinder(), gluDisk()**
  - Delete the quadric object with **gluDeleteQuadric()**

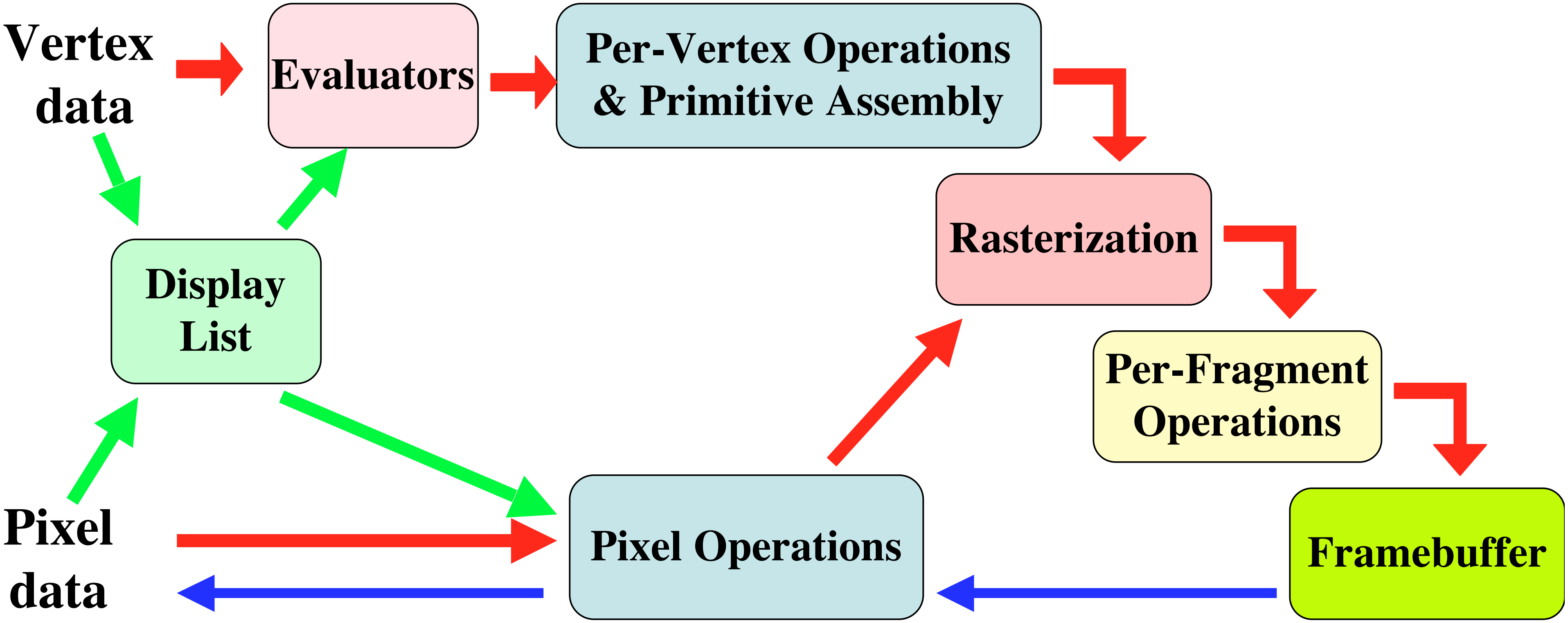
NURBS Interface

- GLU provides a NURBS (Non-Uniform-Rational-B-Spline) interfaces

- Steps to draw NURBS curves or surfaces
  - Use **gluNewNurbsRender()** to create a NURBS object
  - Start your curve or surface by calling **gluBeginCurve**() or **gluBeginSurface**()
  - Generate and render curve or surface with call to **gluNurbsCurve() or gluNurbsSurface()**
  - Call **gluNurbsProperty()** to choose rendering values such as number of polygons used
  - Call **gluNurbsCallback()** for different functions
  - Use lighting with **glEnable**(GL_AUTO_NORMAL)
  - Complete drawing with **gluEndCurve**() or **gluEndSurface**()

Summary

OpenGL Rendering Pipeline



Vertex data

Evaluators

Per-Vertex Operations & Primitive Assembly

Display List

Rasterization

Per-Fragment Operations

Pixel data

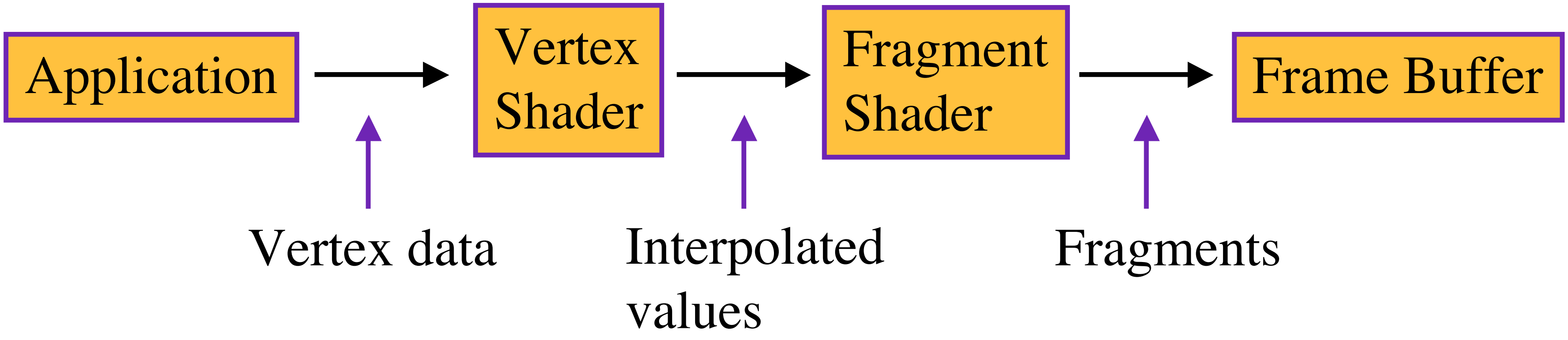
Pixel Operations

Framebuffer

Programmable Pipeline

- Graphics processors (GPUs) are programmable
  - Functionality of some of major units in the graphics pipeline can be altered by user programs which are executed in GPU
- Vertex shader
  - User programs to manipulate vertex properties
- Fragment shader
  - User programs to alter the processing of fragments
- Shading languages
  - The OpenGL Shading Language based on C
  - C for graphics: Cg

Programmable Pipeline: A Simple View



Application

Vertex Shader

Fragment Shader

Frame Buffer

Vertex data

Interpolated values

Fragments

- All data (vertex, interpolated values and fragments) pass through a non-programmable part of the hardware
  - ➢ GPU registers store and transfer the data.

What Have We Covered?

- OpenGL Basics
  - ➢ openGL and related libraries, window management
- Drawing
  - ➢ Geometric primitive objects, veretx arrays, normal vectors, polygonal models of surfaces
- Viewing
  - ➢ Modelview transformations, projection transformations, viewport transformation, clipping, matrix stacks
- Color
  - ➢ Color perception, color functions, shading
- Lighting
  - ➢ Light sources, ligthing models, material properties
- Special topics
  - ➢ Rasterization, framebuffer, animation, hidden-surface removal, blending, drawing pixel data, texture mapping, display lists, evaluators, selection
  - ➢ GPU programming