OpenGL®
Programming Guide

Seventh Edition

The Official Guide to Learning OpenGL®, Versions 3.0 and 3.1

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The Khronos OpenGL ARB Working Group

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Chapter 2

State Management and Drawing Geometric Objects

Chapter Objectives

After reading this chapter, you'll be able to do the following:

- Clear the window to an arbitrary color
- Force any pending drawing to complete
- Draw with any geometric primitive—point, line, or polygon—in two or three dimensions
- Turn states on and off and query state variables
- Control the display of geometric primitives—for example, draw dashed lines or outlined polygons
- Specify *normal vectors* at appropriate points on the surfaces of solid objects
- Use *vertex arrays* and *buffer objects* to store and access geometric data with fewer function calls
- Save and restore several state variables at once

Although you can draw complex and interesting pictures using OpenGL, they're all constructed from a small number of primitive graphical items. This shouldn't be too surprising—look at what Leonardo da Vinci accomplished with just pencils and paintbrushes.

At the highest level of abstraction, there are three basic drawing operations: clearing the window, drawing a geometric object, and drawing a raster object. Raster objects, which include such things as two-dimensional images, bitmaps, and character fonts, are covered in Chapter 8. In this chapter, you learn how to clear the screen and draw geometric objects, including points, straight lines, and flat polygons.

You might think to yourself, "Wait a minute. I've seen lots of computer graphics in movies and on television, and there are plenty of beautifully shaded curved lines and surfaces. How are those drawn if OpenGL can draw only straight lines and flat polygons?" Even the image on the cover of this book includes a round table and objects on the table that have curved surfaces. It turns out that all the curved lines and surfaces you've seen are approximated by large numbers of little flat polygons or straight lines, in much the same way that the globe on the cover is constructed from a large set of rectangular blocks. The globe doesn't appear to have a smooth surface because the blocks are relatively large compared with the globe. Later in this chapter, we show you how to construct curved lines and surfaces from lots of small geometric primitives.

This chapter has the following major sections:

- "A Drawing Survival Kit" explains how to clear the window and force drawing to be completed. It also gives you basic information about controlling the colors of geometric objects and describing a coordinate system.
- "Describing Points, Lines, and Polygons" shows you the set of primitive geometric objects and how to draw them.
- "Basic State Management" describes how to turn on and off some states (modes) and query state variables.
- "Displaying Points, Lines, and Polygons" explains what control you have over the details of how primitives are drawn—for example, what diameters points have, whether lines are solid or dashed, and whether polygons are outlined or filled.
- "Normal Vectors" discusses how to specify normal vectors for geometric objects and (briefly) what these vectors are for.

- "Vertex Arrays" shows you how to put large amounts of geometric data into just a few arrays and how, with only a few function calls, to render the geometry it describes. Reducing function calls may increase the efficiency and performance of rendering.
- "Buffer Objects" details how to use server-side memory buffers to store vertex array data for more efficient geometric rendering.
- "Vertex-Array Objects" expands the discussions of vertex arrays and buffer objects by describing how to efficiently change among sets of vertex arrays.
- "Attribute Groups" reveals how to query the current value of state variables and how to save and restore several related state values all at once.
- "Some Hints for Building Polygonal Models of Surfaces" explores the issues and techniques involved in constructing polygonal approximations to surfaces.

One thing to keep in mind as you read the rest of this chapter is that with OpenGL, unless you specify otherwise, every time you issue a drawing command, the specified object is drawn. This might seem obvious, but in some systems, you first make a list of things to draw. When your list is complete, you tell the graphics hardware to draw the items in the list. The first style is called *immediate-mode* graphics and is the default OpenGL style. In addition to using immediate mode, you can choose to save some commands in a list (called a *display list*) for later drawing. Immediate-mode graphics are typically easier to program, but display lists are often more efficient. Chapter 7 tells you how to use display lists and why you might want to use them.

Version 1.1 of OpenGL introduced vertex arrays.

In Version 1.2, scaling of surface normals (GL_RESCALE_NORMAL) was added to OpenGL. Also, **glDrawRangeElements()** supplemented vertex arrays.

Version 1.3 marked the initial support for texture coordinates for multiple texture units in the OpenGL core feature set. Previously, multitexturing had been an optional OpenGL extension.

In Version 1.4, fog coordinates and secondary colors may be stored in vertex arrays, and the commands **glMultiDrawArrays()** and **glMultiDrawElements()** may be used to render primitives from vertex arrays.

In Version 1.5, vertex arrays may be stored in buffer objects that may be able to use server memory for storing arrays and potentially accelerating their rendering.

Version 3.0 added support for vertex array objects, allowing all of the state related to vertex arrays to be bundled and activated with a single call. This, in turn, makes switching between sets of vertex arrays simpler and faster.

Version 3.1 removed most of the immediate-mode routines and added the primitive restart index, which allows you to render multiple primitives (of the same type) with a single drawing call.

A Drawing Survival Kit

This section explains how to clear the window in preparation for drawing, set the colors of objects that are to be drawn, and force drawing to be completed. None of these subjects has anything to do with geometric objects in a direct way, but any program that draws geometric objects has to deal with these issues.

Clearing the Window

Drawing on a computer screen is different from drawing on paper in that the paper starts out white, and all you have to do is draw the picture. On a computer, the memory holding the picture is usually filled with the last picture you drew, so you typically need to clear it to some background color before you start to draw the new scene. The color you use for the background depends on the application. For a word processor, you might clear to white (the color of the paper) before you begin to draw the text. If you're drawing a view from a spaceship, you clear to the black of space before beginning to draw the stars, planets, and alien spaceships. Sometimes you might not need to clear the screen at all; for example, if the image is the inside of a room, the entire graphics window is covered as you draw all the walls.

At this point, you might be wondering why we keep talking about *clearing* the window—why not just draw a rectangle of the appropriate color that's large enough to cover the entire window? First, a special command to clear a window can be much more efficient than a general-purpose drawing command. In addition, as you'll see in Chapter 3, OpenGL allows you to set the coordinate system, viewing position, and viewing direction arbitrarily, so it might be difficult to figure out an appropriate size and location for a window-clearing rectangle. Finally, on many machines, the graphics hardware consists of multiple buffers in addition to the buffer containing colors of the pixels that are displayed. These other buffers must be cleared from time to time, and it's convenient to have a single command that can clear any combination of them. (See Chapter 10 for a discussion of all the possible buffers.)

You must also know how the colors of pixels are stored in the graphics hardware known as *bitplanes*. There are two methods of storage. Either the red, green, blue, and alpha (RGBA) values of a pixel can be directly stored in the bitplanes, or a single index value that references a color lookup table is stored. RGBA color-display mode is more commonly used, so most of the examples in this book use it. (See Chapter 4 for more information about both display modes.) You can safely ignore all references to alpha values until Chapter 6.

As an example, these lines of code clear an RGBA mode window to black:

```
glClearColor(0.0, 0.0, 0.0, 0.0);
glClear(GL_COLOR_BUFFER_BIT);
```

The first line sets the clearing color to black, and the next command clears the entire window to the current clearing color. The single parameter to **glClear()** indicates which buffers are to be cleared. In this case, the program clears only the color buffer, where the image displayed on the screen is kept. Typically, you set the clearing color once, early in your application, and then you clear the buffers as often as necessary. OpenGL keeps track of the current clearing color as a state variable, rather than requiring you to specify it each time a buffer is cleared.

Chapter 4 and Chapter 10 discuss how other buffers are used. For now, all you need to know is that clearing them is simple. For example, to clear both the color buffer and the depth buffer, you would use the following sequence of commands:

```
glClearColor(0.0, 0.0, 0.0, 0.0);
glClearDepth(1.0);
glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);
```

In this case, the call to **glClearColor()** is the same as before, the **glClearDepth()** command specifies the value to which every pixel of the depth buffer is to be set, and the parameter to the **glClear()** command now consists of the bitwise logical OR of all the buffers to be cleared. The following summary of **glClear()** includes a table that lists the buffers that can be cleared, their names, and the chapter in which each type of buffer is discussed.

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

Sets the current clearing color for use in clearing color buffers in RGBA mode. (See Chapter 4 for more information on RGBA mode.) The *red*, *green*, *blue*, and *alpha* values are clamped if necessary to the range [0, 1]. The default clearing color is (0, 0, 0, 0), which is black.

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

Clears the specified buffers to their current clearing values. The *mask* argument is a bitwise logical OR combination of the values listed in Table 2-1.

Compatibility Extension

GL_ACCUM_ BUFFER_BIT

Buffer	**Name**	**Reference**
Color buffer	GL_COLOR_BUFFER_BIT	Chapter 4
Depth buffer	GL_DEPTH_BUFFER_BIT	Chapter 10
Accumulation buffer	GL_ACCUM_BUFFER_BIT	Chapter 10
Stencil buffer	GL_STENCIL_BUFFER_BIT	Chapter 10

Table 2-1 Clearing Buffers

Before issuing a command to clear multiple buffers, you have to set the values to which each buffer is to be cleared if you want something other than the default RGBA color, depth value, accumulation color, and stencil index. In addition to the **glClearColor()** and **glClearDepth()** commands that set the current values for clearing the color and depth buffers, **glClearIndex()**, **glClearAccum()**, and **glClearStencil()** specify the *color index*, accumulation color, and stencil index used to clear the corresponding buffers. (See Chapter 4 and Chapter 10 for descriptions of these buffers and their uses.)

OpenGL allows you to specify multiple buffers because clearing is generally a slow operation, as every pixel in the window (possibly millions) is touched, and some graphics hardware allows sets of buffers to be cleared simultaneously. Hardware that doesn't support simultaneous clears performs them sequentially. The difference between

```
glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);
```

and

```
glClear(GL_COLOR_BUFFER_BIT);
glClear(GL_DEPTH_BUFFER_BIT);
```

is that although both have the same final effect, the first example might run faster on many machines. It certainly won't run more slowly.

Specifying a Color

With OpenGL, the description of the shape of an object being drawn is independent of the description of its color. Whenever a particular geometric object is drawn, it's drawn using the currently specified coloring scheme. The coloring scheme might be as simple as "draw everything in fire-engine red" or as complicated as "assume the object is made out of blue plastic, that there's a yellow spotlight pointed in such and such a direction, and that there's a general low-level reddish-brown light everywhere else." In general, an OpenGL programmer first sets the color or coloring scheme and then draws the objects. Until the color or coloring scheme is changed, all objects are drawn in that color or using that coloring scheme. This method helps OpenGL achieve higher drawing performance than would result if it didn't keep track of the current color.

For example, the pseudocode

```
set_current_color(red);
draw_object(A);
draw_object(B);
set_current_color(green);
set_current_color(blue);
draw_object(C);
```

draws objects A and B in red, and object C in blue. The command on the fourth line that sets the current color to green is wasted.

Coloring, lighting, and shading are all large topics with entire chapters or large sections devoted to them. To draw geometric primitives that can be seen, however, you need some basic knowledge of how to set the current color; this information is provided in the next few paragraphs. (See Chapter 4 and Chapter 5 for details on these topics.)

To set a color, use the command **glColor3f()**. It takes three parameters, all of which are floating-point numbers between 0.0 and 1.0. The parameters are, in order, the red, green, and blue *components* of the color. You can think of these three values as specifying a "mix" of colors: 0.0 means don't use any of that component, and 1.0 means use all you can of that component. Thus, the code

```
glColor3f(1.0, 0.0, 0.0);
```

makes the brightest red the system can draw, with no green or blue components. All zeros makes black; in contrast, all ones makes white. Setting all three components to 0.5 yields gray (halfway between black and white). Here are eight commands and the colors they would set:

```
glColor3f(0.0, 0.0, 0.0);     /* black */
glColor3f(1.0, 0.0, 0.0);     /* red */
glColor3f(0.0, 1.0, 0.0);     /* green */
glColor3f(1.0, 1.0, 0.0);     /* yellow */
glColor3f(0.0, 0.0, 1.0);     /* blue */
glColor3f(1.0, 0.0, 1.0);     /* magenta */
glColor3f(0.0, 1.0, 1.0);     /* cyan */
glColor3f(1.0, 1.0, 1.0);     /* white */
```

You might have noticed earlier that the routine for setting the clearing color, **glClearColor()**, takes four parameters, the first three of which match the parameters for **glColor3f()**. The fourth parameter is the alpha value; it's covered in detail in "Blending" in Chapter 6. For now, set the fourth parameter of **glClearColor()** to 0.0, which is its default value.

Forcing Completion of Drawing

As you saw in "OpenGL Rendering Pipeline" in Chapter 1, most modern graphics systems can be thought of as an assembly line. The main central processing unit (CPU) issues a drawing command. Perhaps other hardware does geometric transformations. Clipping is performed, followed by shading and/or texturing. Finally, the values are written into the bitplanes for display. In high-end architectures, each of these operations is performed by a different piece of hardware that's been designed to perform its particular task quickly. In such an architecture, there's no need for the CPU to wait for each drawing command to complete before issuing the next one. While the CPU is sending a vertex down the pipeline, the transformation hardware is working on transforming the last one sent, the one before that is being clipped, and so on. In such a system, if the CPU waited for each command to complete before issuing the next, there could be a huge performance penalty.

In addition, the application might be running on more than one machine. For example, suppose that the main program is running elsewhere (on a machine called the client) and that you're viewing the results of the drawing on your workstation or terminal (the server), which is connected by a network to the client. In that case, it might be horribly inefficient to send each command over the network one at a time, as considerable overhead is often associated with each network transmission. Usually, the client gathers a collection of commands into a single network packet before sending it. Unfortunately, the network code on the client typically has no way of knowing that the graphics program is finished drawing a frame or scene. In the worst case, it waits forever for enough additional drawing commands to fill a packet, and you never see the completed drawing.

For this reason, OpenGL provides the command **glFlush()**, which forces the client to send the network packet even though it might not be full. Where there is no network and all commands are truly executed immediately on the server, **glFlush()** might have no effect. However, if you're writing a program that you want to work properly both with and without a network, include a call to **glFlush()** at the end of each frame or scene. Note that **glFlush()** doesn't wait for the drawing to complete—it just forces the drawing to begin execution, thereby guaranteeing that all previous commands *execute* in finite time even if no further rendering commands are executed.

There are other situations in which **glFlush()** is useful:

- Software renderers that build images in system memory and don't want to constantly update the screen.
- Implementations that gather sets of rendering commands to amortize start-up costs. The aforementioned network transmission example is one instance of this.

void **glFlush**(void);

Forces previously issued OpenGL commands to begin execution, thus guaranteeing that they complete in finite time.

A few commands—for example, commands that swap buffers in double-buffer mode—automatically flush pending commands onto the network before they can occur.

If **glFlush()** isn't sufficient for you, try **glFinish()**. This command flushes the network as **glFlush()** does and then waits for notification from the graphics hardware or network indicating that the drawing is complete in the framebuffer. You might need to use **glFinish()** if you want to synchronize tasks—for example, to make sure that your three-dimensional rendering is on the screen before you use Display PostScript to draw labels on top of the rendering. Another example would be to ensure that the drawing is complete before it begins to accept user input. After you issue a **glFinish()** command, your graphics process is blocked until it receives notification from the graphics hardware that the drawing is complete. Keep in mind that excessive use of **glFinish()** can reduce the performance of your application, especially if you're running over a network, because it requires round-trip communication. If **glFlush()** is sufficient for your needs, use it instead of **glFinish()**.

void **glFinish**(void);

Forces all previously issued OpenGL commands to complete. This command doesn't return until all effects from previous commands are fully realized.

Coordinate System Survival Kit

Whenever you initially open a window or later move or resize that window, the window system will send an event to notify you. If you are using GLUT, the notification is automated; whatever routine has been registered to **glutReshapeFunc()** will be called. You must register a callback function that will

- Reestablish the rectangular region that will be the new rendering canvas
- Define the coordinate system to which objects will be drawn

In Chapter 3, you'll see how to define three-dimensional coordinate systems, but right now just create a simple, basic two-dimensional coordinate system into which you can draw a few objects. Call **glutReshapeFunc**(**reshape**), where **reshape()** is the following function shown in Example 2-1.

Example 2-1 Reshape Callback Function

```
void reshape(int w, int h)
{
   glViewport(0, 0, (GLsizei) w, (GLsizei) h);
   glMatrixMode(GL_PROJECTION);
   glLoadIdentity();
   gluOrtho2D(0.0, (GLdouble) w, 0.0, (GLdouble) h);
}
```

The kernel of GLUT will pass this function two arguments: the width and height, in pixels, of the new, moved, or resized window. **glViewport()** adjusts the pixel rectangle for drawing to be the entire new window. The next three routines adjust the coordinate system for drawing so that the lower left corner is (0, 0) and the upper right corner is (*w*, *h*) (see Figure 2-1).

To explain it another way, think about a piece of graphing paper. The *w* and *h* values in **reshape()** represent how many columns and rows of squares are on your graph paper. Then you have to put axes on the graph paper. The **gluOrtho2D()** routine puts the origin, (0, 0), in the lowest, leftmost square, and makes each square represent one unit. Now, when you render the points, lines, and polygons in the rest of this chapter, they will appear on this paper in easily predictable squares. (For now, keep all your objects two-dimensional.)

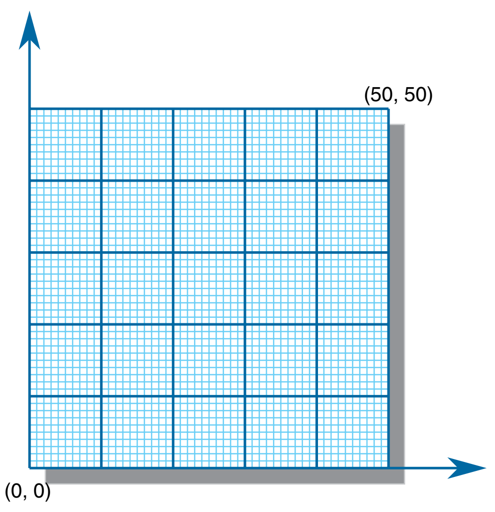


Figure 2-1 Coordinate System Defined by $w = 50$, $h = 50$

Describing Points, Lines, and Polygons

This section explains how to describe OpenGL geometric primitives. All geometric primitives are eventually described in terms of their *vertices*—coordinates that define the points themselves, the endpoints of line segments, or the corners of polygons. The next section discusses how these primitives are displayed and what control you have over their display.

What Are Points, Lines, and Polygons?

You probably have a fairly good idea of what a mathematician means by the terms *point*, *line*, and *polygon*. The OpenGL meanings are similar, but not quite the same.

One difference comes from the limitations of computer-based calculations. In any OpenGL implementation, floating-point calculations are of finite precision, and they have round-off errors. Consequently, the coordinates of OpenGL points, lines, and polygons suffer from the same problems.

A more important difference arises from the limitations of a raster graphics display. On such a display, the smallest displayable unit is a pixel, and although pixels might be less than 1/100 of an inch wide, they are still much larger than the mathematician's concepts of infinitely small (for points) and infinitely thin (for lines). When OpenGL performs calculations, it assumes that points are represented as vectors of floating-point numbers. However, a point is typically (but not always) drawn as a single pixel, and many different points with slightly different coordinates could be drawn by OpenGL on the same pixel.

Points

A point is represented by a set of floating-point numbers called a *vertex*. All internal calculations are done as if vertices are three-dimensional. Vertices specified by the user as two-dimensional (that is, with only *x*- and *y*-coordinates) are assigned a *z*-coordinate equal to zero by OpenGL.

Advanced

OpenGL works in the *homogeneous coordinates* of three-dimensional projective geometry, so for internal calculations, all vertices are represented with four floating-point coordinates (x, y, z, w). If w is different from zero, these coordinates correspond to the Euclidean, three-dimensional point (x/w, y/w, z/w). You can specify the w-coordinate in OpenGL commands, but this is rarely done. If the *w*-coordinate isn't specified, it is understood to be 1.0. (See Appendix C for more information about homogeneous coordinate systems.)

Lines

In OpenGL, the term *line* refers to a *line segment*, not the mathematician's version that extends to infinity in both directions. There are easy ways to specify a connected series of line segments, or even a closed, connected series of segments (see Figure 2-2). In all cases, though, the lines constituting the connected series are specified in terms of the vertices at their endpoints.

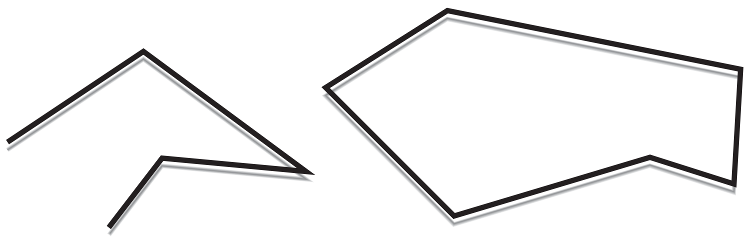


Figure 2-2 Two Connected Series of Line Segments

Polygons

Polygons are the areas enclosed by single closed loops of line segments, where the line segments are specified by the vertices at their endpoints. Polygons are typically drawn with the pixels in the interior filled in, but you can also draw them as outlines or a set of points. (See "Polygon Details" on page 60.)

In general, polygons can be complicated, so OpenGL imposes some strong restrictions on what constitutes a primitive polygon. First, the edges of OpenGL polygons can't intersect (a mathematician would call a polygon satisfying this condition a *simple polygon*). Second, OpenGL polygons must be *convex*, meaning that they cannot have indentations. Stated precisely, a region is convex if, given any two points in the interior, the line segment joining them is also in the interior. See Figure 2-3 for some examples of valid and invalid polygons. OpenGL, however, doesn't restrict the number of line segments making up the boundary of a convex polygon. Note that polygons with holes can't be described. They are *nonconvex*, and they can't be drawn with a boundary made up of a single closed loop. Be aware that if you present OpenGL with a nonconvex filled polygon, it might not draw it as you expect. For instance, on most systems, no more than the *convex hull* of the polygon would be filled. On some systems, less than the convex hull might be filled.

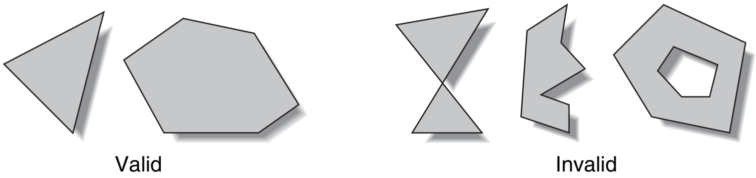


Figure 2-3 Valid and Invalid Polygons

The reason for the OpenGL restrictions on valid polygon types is that it's simpler to provide fast polygon-rendering hardware for that restricted class of polygons. Simple polygons can be rendered quickly. The difficult cases are hard to detect quickly, so for maximum performance, OpenGL crosses its fingers and assumes the polygons are simple.

Many real-world surfaces consist of nonsimple polygons, nonconvex polygons, or polygons with holes. Since all such polygons can be formed from unions of simple convex polygons, some routines to build more complex objects are provided in the GLU library. These routines take complex descriptions and tessellate them, or break them down into groups of the simpler OpenGL polygons that can then be rendered. (See "Polygon Tessellation" in Chapter 11 for more information about the *tessellation* routines.)

Since OpenGL vertices are always three-dimensional, the points forming the boundary of a particular polygon don't necessarily lie on the same plane in space. (Of course, they do in many cases—if all the z-coordinates are zero, for example, or if the polygon is a *triangle*.) If a polygon's vertices don't lie in the same plane, then after various rotations in space, changes in the viewpoint, and projection onto the display screen, the points might no longer form a simple convex polygon. For example, imagine a four-point *quadrilateral* where the points are slightly out of plane, and look at it almost edge-on. You can get a nonsimple polygon that resembles a bow tie, as shown in Figure 2-4, which isn't guaranteed to be rendered correctly. This situation isn't all that unusual if you approximate curved surfaces by quadrilaterals made of points lying on the true surface. You can always avoid the problem by using triangles, as any three points always lie on a plane.

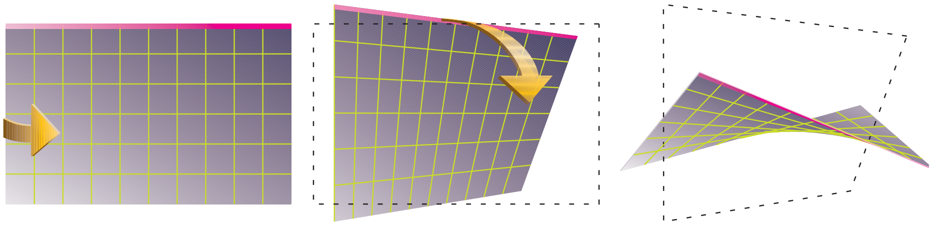


Figure 2-4 Nonplanar Polygon Transformed to Nonsimple Polygon

Rectangles

Since rectangles are so common in graphics applications, OpenGL provides a filled-rectangle drawing primitive, **glRect*()**. You can draw a rectangle as a polygon, as described in "OpenGL Geometric Drawing Primitives" on page 47, but your particular implementation of OpenGL might have optimized **glRect*()** for rectangles.

void **glRect**{sifd}(*TYPE x1*, *TYPE y1*, *TYPE x2*, *TYPE y2*);
void **glRect**{sifd}**v**(const *TYPE *v1*, const *TYPE *v2*);

Draws the rectangle defined by the corner points (*x1, y1*) and (*x2, y2*). The rectangle lies in the plane *z* = 0 and has sides parallel to the *x*- and *y*-axes. If the vector form of the function is used, the corners are given by two pointers to arrays, each of which contains an (*x, y*) pair.

Compatibility Extension
glRect

Note that although the rectangle begins with a particular orientation in three-dimensional space (in the *xy*-plane and parallel to the axes), you can change this by applying rotations or other transformations. (See Chapter 3 for information about how to do this.)

Curves and Curved Surfaces

Any smoothly curved line or surface can be approximated—to any arbitrary degree of accuracy—by short line segments or small polygonal regions. Thus, subdividing curved lines and surfaces sufficiently and then approximating them with straight line segments or flat polygons makes them appear curved (see Figure 2-5). If you're skeptical that this really works, imagine subdividing until each line segment or polygon is so tiny that it's smaller than a pixel on the screen.

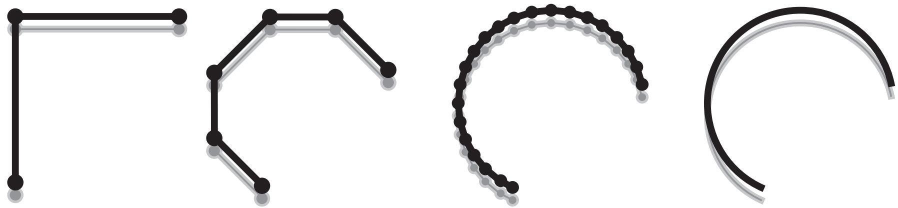


Figure 2-5 Approximating Curves

Even though curves aren't geometric primitives, OpenGL provides some direct support for subdividing and drawing them. (See Chapter 12 for information about how to draw curves and curved surfaces.)

Specifying Vertices

With OpenGL, every geometric object is ultimately described as an ordered set of vertices. You use the **glVertex*()** command to specify a vertex.

Compatibility Extension
glVertex

void **glVertex**[234]{sifd}(*TYPE coords*);
void **glVertex**[234]{sifd}v(const *TYPE* coords*);

Specifies a vertex for use in describing a geometric object. You can supply up to four coordinates (*x, y, z, w*) for a particular vertex or as few as two (*x, y*) by selecting the appropriate version of the command. If you use a version that doesn't explicitly specify *z* or *w*, *z* is understood to be 0, and *w* is understood to be 1. Calls to **glVertex*()** are effective only between a **glBegin()** and **glEnd()** pair.

Example 2-2 provides some examples of using **glVertex*()**.

Example 2-2 Legal Uses of glVertex*()

```
glVertex2s(2, 3);
glVertex3d(0.0, 0.0, 3.1415926535898);
glVertex4f(2.3, 1.0, -2.2, 2.0);

GLdouble dvect[3] = {5.0, 9.0, 1992.0};
glVertex3dv(dvect);
```

The first example represents a vertex with three-dimensional coordinates (2, 3, 0). (Remember that if it isn't specified, the *z*-coordinate is understood to be 0.) The coordinates in the second example are (0.0, 0.0, 3.1415926535898) (double-precision floating-point numbers). The third example represents the vertex with three-dimensional coordinates (1.15, 0.5, –1.1) as a homogenous coordinate. (Remember that the *x*-, *y*-, and *z*-coordinates are eventually divided by the *w*-coordinate.) In the final example, *dvect* is a pointer to an array of three double-precision floating-point numbers.

On some machines, the vector form of **glVertex*()** is more efficient, since only a single parameter needs to be passed to the graphics subsystem. Special hardware might be able to send a whole series of coordinates in a single batch. If your machine is like this, it's to your advantage to arrange your data so that the vertex coordinates are packed sequentially in memory. In this case, there may be some gain in performance by using the vertex array operations of OpenGL. (See "Vertex Arrays" on page 70.)

OpenGL Geometric Drawing Primitives

Now that you've seen how to specify vertices, you still need to know how to tell OpenGL to create a set of points, a line, or a polygon from those vertices. To do this, you bracket each set of vertices between a call to **glBegin()** and a call to **glEnd()**. The argument passed to **glBegin()** determines what sort of geometric primitive is constructed from the vertices. For instance, Example 2-3 specifies the vertices for the polygon shown in Figure 2-6.

Example 2-3 Filled Polygon

```
glBegin(GL_POLYGON);
   glVertex2f(0.0, 0.0);
   glVertex2f(0.0, 3.0);
   glVertex2f(4.0, 3.0);
   glVertex2f(6.0, 1.5);
   glVertex2f(4.0, 0.0);
glEnd();
```

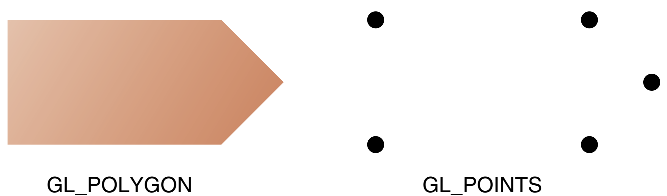


Figure 2-6 Drawing a Polygon or a Set of Points

If you had used GL_POINTS instead of GL_POLYGON, the primitive would have been simply the five points shown in Figure 2-6. Table 2-2 in the following function summary for **glBegin()** lists the 10 possible arguments and the corresponding types of primitives.

Compatibility Extension
glBegin
GL_QUADS
GL_QUAD_STRIP
GL_POLYGON

void **glBegin**(GLenum *mode*);

Marks the beginning of a vertex-data list that describes a geometric primitive. The type of primitive is indicated by *mode*, which can be any of the values shown in Table 2-2.

Value	Meaning
GL_POINTS	Individual points
GL_LINES	Pairs of vertices interpreted as individual line segments
GL_LINE_STRIP	Series of connected line segments
GL_LINE_LOOP	Same as above, with a segment added between last and first vertices
GL_TRIANGLES	Triples of vertices interpreted as triangles
GL_TRIANGLE_STRIP	Linked strip of triangles
GL_TRIANGLE_FAN	Linked fan of triangles
GL_QUADS	Quadruples of vertices interpreted as four-sided polygons
GL_QUAD_STRIP	Linked strip of quadrilaterals
GL_POLYGON	Boundary of a simple, convex polygon

Table 2-2 Geometric Primitive Names and Meanings

Compatibility Extension
glEnd

void **glEnd**(void);

Marks the end of a vertex-data list.

Figure 2-7 shows examples of all the geometric primitives listed in Table 2-2, with descriptions of the pixels that are drawn for each of the objects. Note that in addition to points, several types of lines and polygons are defined. Obviously, you can find many ways to draw the same primitive. The method you choose depends on your vertex data.

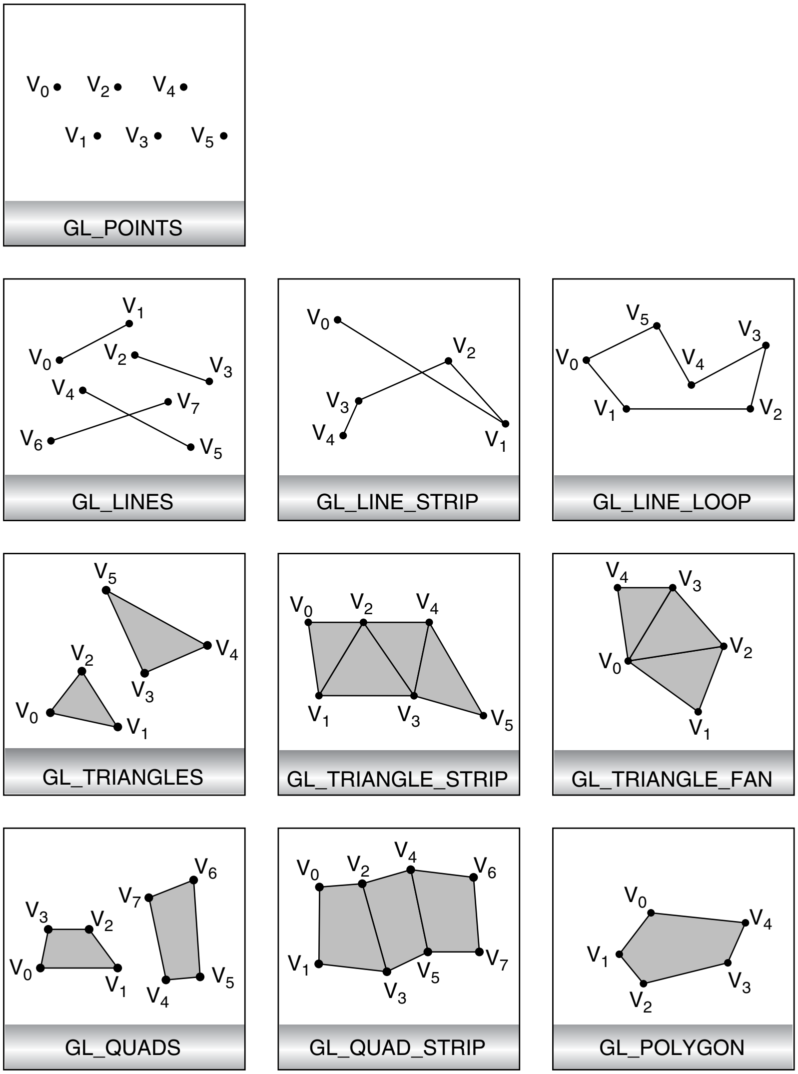


Figure 2-7 Geometric Primitive Types

As you read the following descriptions, assume that n vertices (v_0, v_1, v_2, ... , v_{n-1}) are described between a **glBegin()** and **glEnd()** pair.

GL_POINTS	Draws a point at each of the n vertices.
GL_LINES	Draws a series of unconnected line segments. Segments are drawn between v_0 and v_1, between v_2 and v_3, and so on. If n is odd, the last segment is drawn between v_{n-3} and v_{n-2}, and v_{n-1} is ignored.
GL_LINE_STRIP	Draws a line segment from v_0 to v_1, then from v_1 to v_2, and so on, finally drawing the segment from v_{n-2} to v_{n-1}. Thus, a total of $n - 1$ line segments are drawn. Nothing is drawn unless n is larger than 1. There are no restrictions on the vertices describing a line strip (or a line loop); the lines can intersect arbitrarily.
GL_LINE_LOOP	Same as GL_LINE_STRIP, except that a final line segment is drawn from v_{n-1} to v_0, completing a loop.
GL_TRIANGLES	Draws a series of triangles (three-sided polygons) using vertices v_0, v_1, v_2, then v_3, v_4, v_5, and so on. If n isn't a multiple of 3, the final one or two vertices are ignored.
GL_TRIANGLE_STRIP	Draws a series of triangles (three-sided polygons) using vertices v_0, v_1, v_2, then v_2, v_1, v_3 (note the order), then v_2, v_3, v_4, and so on. The ordering is to ensure that the triangles are all drawn with the same orientation so that the strip can correctly form part of a surface. Preserving the orientation is important for some operations, such as culling (see "Reversing and Culling Polygon Faces" on page 61). n must be at least 3 for anything to be drawn.
GL_TRIANGLE_FAN	Same as GL_TRIANGLE_STRIP, except that the vertices are v_0, v_1, v_2, then v_0, v_2, v_3, then v_0, v_3, v_4, and so on (see Figure 2-7).

GL_QUADS	Draws a series of quadrilaterals (four-sided polygons) using vertices v_0, v_1, v_2, v_3, then v_4, v_5, v_6, v_7, and so on. If *n* isn't a multiple of 4, the final one, two, or three vertices are ignored.
GL_QUAD_STRIP	Draws a series of quadrilaterals (four-sided polygons) beginning with v_0, v_1, v_3, v_2, then v_2, v_3, v_5, v_4, then v_4, v_5, v_7, v_6, and so on (see Figure 2-7). *n* must be at least 4 before anything is drawn. If *n* is odd, the final vertex is ignored.
GL_POLYGON	Draws a polygon using the points v_0, ... , v_{n-1} as vertices. *n* must be at least 3, or nothing is drawn. In addition, the polygon specified must not intersect itself and must be convex. If the vertices don't satisfy these conditions, the results are unpredictable.

Restrictions on Using glBegin() and glEnd()

The most important information about vertices is their coordinates, which are specified by the **glVertex*()** command. You can also supply additional vertex-specific data for each vertex—a color, a normal vector, texture coordinates, or any combination of these—using special commands. In addition, a few other commands are valid between a **glBegin()** and **glEnd()** pair. Table 2-3 contains a complete list of such valid commands.

Command	Purpose of Command	Reference
glVertex*()	set vertex coordinates	Chapter 2
glColor*()	set RGBA color	Chapter 4
glIndex*()	set color index	Chapter 4
glSecondaryColor*()	set secondary color for post-texturing application	Chapter 9
glNormal*()	set normal vector coordinates	Chapter 2
glMaterial*()	set material properties	Chapter 5
glFogCoord*()	set fog coordinates	Chapter 6

Table 2-3 Valid Commands between glBegin() and glEnd()

Command	Purpose of Command	Reference
glTexCoord*()	set texture coordinates	Chapter 9
glMultiTexCoord*()	set texture coordinates for multitexturing	Chapter 9
glVertexAttrib*()	set generic vertex attribute	Chapter 15
glEdgeFlag*()	control drawing of edges	Chapter 2
glArrayElement()	extract vertex array data	Chapter 2
glEvalCoord*(), glEvalPoint*()	generate coordinates	Chapter 12
glCallList(), glCallLists()	execute display list(s)	Chapter 7

Table 2-3 (continued) Valid Commands between glBegin() and glEnd()

No other OpenGL commands are valid between a **glBegin()** and **glEnd()** pair, and making most other OpenGL calls generates an error. Some vertex array commands, such as **glEnableClientState()** and **glVertexPointer()**, when called between **glBegin()** and **glEnd()**, have undefined behavior but do not necessarily generate an error. (Also, routines related to OpenGL, such as **glX*()** routines, have undefined behavior between **glBegin()** and **glEnd()**.) These cases should be avoided, and debugging them may be more difficult.

Note, however, that only OpenGL commands are restricted; you can certainly include other programming-language constructs (except for calls, such as the aforementioned **glX*()** routines). For instance, Example 2-4 draws an outlined circle.

Example 2-4 Other Constructs between glBegin() and glEnd()

```
#define PI 3.1415926535898
GLint circle_points = 100;
glBegin(GL_LINE_LOOP);
for (i = 0; i < circle_points; i++) {
   angle = 2*PI*i/circle_points;
   glVertex2f(cos(angle), sin(angle));
}
glEnd();
```

Note: This example isn't the most efficient way to draw a circle, especially if you intend to do it repeatedly. The graphics commands used are typically very fast, but this code calculates an angle and calls the **sin()** and **cos()** routines for each vertex; in addition, there's the loop overhead. (Another way to calculate the vertices of a circle is to use a GLU routine; see "Quadrics: Rendering Spheres, Cylinders, and Disks" in Chapter 11.) If you need to draw numerous circles, calculate the coordinates of the vertices once and save them in an array and create a display list (see Chapter 7), or use vertex arrays to render them.

Unless they are being compiled into a display list, all **glVertex*()** commands should appear between a **glBegin()** and **glEnd()** combination. (If they appear elsewhere, they don't accomplish anything.) If they appear in a display list, they are executed only if they appear between a **glBegin()** and a **glEnd()**. (See Chapter 7 for more information about display lists.)

Although many commands are allowed between **glBegin()** and **glEnd()**, vertices are generated only when a **glVertex*()** command is issued. At the moment **glVertex*()** is called, OpenGL assigns the resulting vertex the current color, texture coordinates, normal vector information, and so on. To see this, look at the following code sequence. The first point is drawn in red, and the second and third ones in blue, despite the extra color commands:

```
glBegin(GL_POINTS);
   glColor3f(0.0, 1.0, 0.0);                  /* green */
   glColor3f(1.0, 0.0, 0.0);                  /* red */
   glVertex(...);
   glColor3f(1.0, 1.0, 0.0);                  /* yellow */
   glColor3f(0.0, 0.0, 1.0);                  /* blue */
   glVertex(...);
   glVertex(...);
glEnd();
```

You can use any combination of the 24 versions of the **glVertex*()** command between **glBegin()** and **glEnd()**, although in real applications all the calls in any particular instance tend to be of the same form. If your vertex-data specification is consistent and repetitive (for example, **glColor***, **glVertex***, **glColor***, **glVertex***,...), you may enhance your program's performance by using vertex arrays. (See "Vertex Arrays" on page 70.)

Basic State Management

In the preceding section, you saw an example of a state variable, the current RGBA color, and how it can be associated with a primitive. OpenGL maintains many states and state variables. An object may be rendered with lighting, texturing, hidden surface removal, fog, and other states affecting its appearance.

By default, most of these states are initially inactive. These states may be costly to activate; for example, turning on texture mapping will almost certainly slow down the process of rendering a primitive. However, the image will improve in quality and will look more realistic, owing to the enhanced graphics capabilities.

To turn many of these states on and off, use these two simple commands:

void **glEnable**(GLenum *capability*);
void **glDisable**(GLenum *capability*);

glEnable() turns on a capability, and **glDisable()** turns it off. More than 60 enumerated values can be passed as parameters to **glEnable()** or **glDisable()**. Some examples are GL_BLEND (which controls blending of RGBA values), GL_DEPTH_TEST (which controls depth comparisons and updates to the depth buffer), GL_FOG (which controls fog), GL_LINE_STIPPLE (patterned lines), and GL_LIGHTING (you get the idea).

You can also check whether a state is currently enabled or disabled.

GLboolean **glIsEnabled**(GLenum *capability*)

Returns GL_TRUE or GL_FALSE, depending on whether or not the queried capability is currently activated.

The states you have just seen have two settings: on and off. However, most OpenGL routines set values for more complicated state variables. For example, the routine **glColor3f()** sets three values, which are part of the GL_CURRENT_COLOR state. There are five querying routines used to find out what values are set for many states:

void **glGetBooleanv**(GLenum *pname*, GLboolean **params*);
void **glGetIntegerv**(GLenum *pname*, GLint **params*);
void **glGetFloatv**(GLenum *pname*, GLfloat **params*);
void **glGetDoublev**(GLenum *pname*, GLdouble **params*);
void **glGetPointerv**(GLenum *pname*, GLvoid ***params*);

Obtains Boolean, integer, floating-point, double-precision, or pointer state variables. The *pname* argument is a symbolic constant indicating the state variable to return, and *params* is a pointer to an array of the indicated type in which to place the returned data. See the tables in Appendix B for the possible values for *pname*. For example, to get the current RGBA color, a table in Appendix B suggests you use **glGetIntegerv**(GL_CURRENT_COLOR, *params*) or **glGetFloatv**(GL_CURRENT_COLOR, *params*). A type conversion is performed, if necessary, to return the desired variable as the requested data type.

These querying routines handle most, but not all, requests for obtaining state information. (See "The Query Commands" in Appendix B for a list of all of the available OpenGL state querying routines.)

Displaying Points, Lines, and Polygons

By default, a point is drawn as a single pixel on the screen, a line is drawn solid and 1 pixel wide, and polygons are drawn solidly filled in. The following paragraphs discuss the details of how to change these default display modes.

Point Details

To control the size of a rendered point, use **glPointSize()** and supply the desired size in pixels as the argument.

void **glPointSize**(GLfloat *size*);

Sets the width in pixels for rendered points; *size* must be greater than 0.0 and by default is 1.0.

The actual collection of pixels on the screen that are drawn for various point widths depends on whether antialiasing is enabled. (Antialiasing is a technique for smoothing points and lines as they're rendered; see "Antialiasing" and "Point Parameters" in Chapter 6 for more detail.) If antialiasing is disabled (the default), fractional widths are rounded to integer widths, and a screen-aligned square region of pixels is drawn. Thus, if the width is 1.0, the square is 1 pixel by 1 pixel; if the width is 2.0, the square is 2 pixels by 2 pixels; and so on.

With antialiasing or multisampling enabled, a circular group of pixels is drawn, and the pixels on the boundaries are typically drawn at less than full intensity to give the edge a smoother appearance. In this mode, noninteger widths aren't rounded.

Most OpenGL implementations support very large point sizes. You can query the minimum and maximum sized for aliased points by using GL_ALIASED_POINT_SIZE_RANGE with **glGetFloatv()**. Likewise, you can obtain the range of supported sizes for antialiased points by passing GL_SMOOTH_POINT_SIZE_RANGE to **glGetFloatv()**. The sizes of supported antialiased points are evenly spaced between the minimum and maximum sizes for the range. Calling **glGetFloatv()** with the parameter GL_SMOOTH_POINT_SIZE_GRANULARITY will return how accurately a given antialiased point size is supported. For example, if you request **glPointSize(2.37)** and the granularity returned is 0.1, then the point size is rounded to 2.4.

Line Details

With OpenGL, you can specify lines with different widths and lines that are *stippled* in various ways—dotted, dashed, drawn with alternating dots and dashes, and so on.

Wide Lines

void **glLineWidth**(GLfloat *width*);

Sets the width, in pixels, for rendered lines; *width* must be greater than 0.0 and by default is 1.0.

Version 3.1 does not support values greater than 1.0, and will generate a GL_INVALID_VALUE error if a value greater than 1.0 is specified.

The actual rendering of lines is affected if either antialiasing or multisampling is enabled. (See "Antialiasing Points or Lines" on page 269 and "Antialiasing Geometric Primitives with Multisampling" on page 275.) Without antialiasing, widths of 1, 2, and 3 draw lines 1, 2, and 3 pixels wide. With antialiasing enabled, noninteger line widths are possible, and pixels on the boundaries are typically drawn at less than full intensity. As with point sizes, a particular OpenGL implementation might limit the width of nonantialiased lines to its maximum antialiased line width, rounded to the nearest integer value. You can obtain the range of supported aliased line widths by using GL_ALIASED_LINE_WIDTH_RANGE with **glGetFloatv()**. To determine the supported minimum and maximum sizes of antialiased line widths, and what granularity your implementation supports, call **glGetFloatv()**, with GL_SMOOTH_LINE_WIDTH_RANGE and GL_SMOOTH_LINE_WIDTH_GRANULARITY.

Note: Keep in mind that, by default, lines are 1 pixel wide, so they appear wider on lower-resolution screens. For computer displays, this isn't typically an issue, but if you're using OpenGL to render to a high-resolution plotter, 1-pixel lines might be nearly invisible. To obtain resolution-independent line widths, you need to take into account the physical dimensions of pixels.

Advanced

Advanced

With non-antialiased wide lines, the line width isn't measured perpendicular to the line. Instead, it's measured in the *y*-direction if the absolute value of the slope is less than 1.0; otherwise, it's measured in the *x*-direction. The rendering of an antialiased line is exactly equivalent to the rendering of a filled rectangle of the given width, centered on the exact line.

Stippled Lines

To make stippled (dotted or dashed) lines, you use the command **glLineStipple()** to define the *stipple* pattern, and then you enable line stippling with **glEnable()**.

```
glLineStipple(1, 0x3F07);
glEnable(GL_LINE_STIPPLE);
```

void **glLineStipple**(GLint *factor*, GLushort *pattern*);

Sets the current stippling pattern for lines. The *pattern* argument is a 16-bit series of 0s and 1s, and it's repeated as necessary to stipple a given line. A 1 indicates that drawing occurs, and a 0 that it does not, on a pixel-by-pixel basis, beginning with the low-order bit of the pattern. The pattern can be stretched out by using *factor*, which multiplies each subseries of consecutive 1s and 0s. Thus, if three consecutive 1s appear in the pattern, they're stretched to six if *factor* is 2. *factor* is clamped to lie between 1 and 256. Line stippling must be enabled by passing GL_LINE_STIPPLE to **glEnable()**; it's disabled by passing the same argument to **glDisable()**.

Compatibility Extension
glLineStipple **GL_LINE_STIPPLE**

With the preceding example and the pattern 0x3F07 (which translates to 0011111100000111 in binary), a line would be drawn with 3 pixels on, then 5 off, 6 on, and 2 off. (If this seems backward, remember that the low-order bit is used first.) If *factor* had been 2, the pattern would have been elongated: 6 pixels on, 10 off, 12 on, and 4 off. Figure 2-8 shows lines drawn with different patterns and repeat factors. If you don't enable line stippling, drawing proceeds as if *pattern* were 0xFFFF and *factor* were 1. (Use **glDisable()** with GL_LINE_STIPPLE to disable stippling.) Note that stippling can be used in combination with wide lines to produce wide stippled lines.

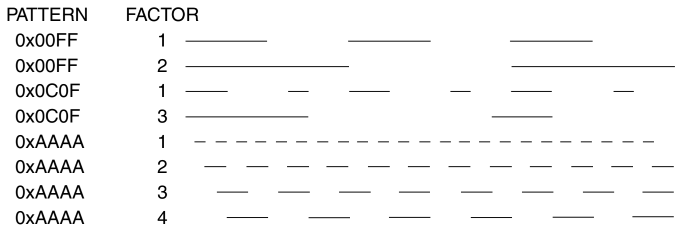


Figure 2-8 Stippled Lines

One way to think of the stippling is that as the line is being drawn, the pattern is shifted by 1 bit each time a pixel is drawn (or *factor* pixels are drawn, if *factor* isn't 1). When a series of connected line segments is drawn between a single **glBegin()** and **glEnd()**, the pattern continues to shift as one segment turns into the next. This way, a stippling pattern continues across a series of connected line segments. When **glEnd()** is executed, the pattern is reset, and if more lines are drawn before stippling is disabled the stippling restarts at the beginning of the pattern. If you're drawing lines with GL_LINES, the pattern resets for each independent line.

Example 2-5 illustrates the results of drawing with a couple of different stipple patterns and line widths. It also illustrates what happens if the lines are drawn as a series of individual segments instead of a single connected line strip. The results of running the program appear in Figure 2-9.

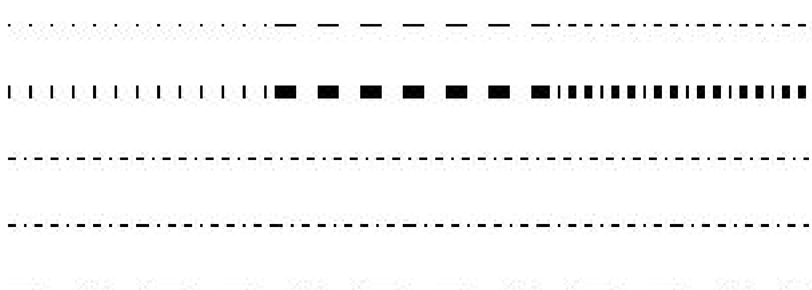


Figure 2-9 Wide Stippled Lines

Example 2-5 Line Stipple Patterns: lines.c

```
#define drawOneLine(x1,y1,x2,y2)  glBegin(GL_LINES);  \
   glVertex2f((x1),(y1)); glVertex2f((x2),(y2)); glEnd();

void init(void)
{
   glClearColor(0.0, 0.0, 0.0, 0.0);
   glShadeModel(GL_FLAT);
}

void display(void)
{
   int i;

   glClear(GL_COLOR_BUFFER_BIT);
/* select white for all lines  */
   glColor3f(1.0, 1.0, 1.0);

/* in 1st row, 3 lines, each with a different stipple  */
   glEnable(GL_LINE_STIPPLE);

   glLineStipple(1, 0x0101);  /*  dotted  */
   drawOneLine(50.0, 125.0, 150.0, 125.0);
   glLineStipple(1, 0x00FF);  /*  dashed  */
   drawOneLine(150.0, 125.0, 250.0, 125.0);
   glLineStipple(1, 0x1C47);  /*  dash/dot/dash  */
   drawOneLine(250.0, 125.0, 350.0, 125.0);

/* in 2nd row, 3 wide lines, each with different stipple */
   glLineWidth(5.0);
   glLineStipple(1, 0x0101);  /*  dotted  */
   drawOneLine(50.0, 100.0, 150.0, 100.0);
   glLineStipple(1, 0x00FF);  /*  dashed  */
   drawOneLine(150.0, 100.0, 250.0, 100.0);
   glLineStipple(1, 0x1C47);  /*  dash/dot/dash  */
   drawOneLine(250.0, 100.0, 350.0, 100.0);
   glLineWidth(1.0);

/* in 3rd row, 6 lines, with dash/dot/dash stipple  */
/* as part of a single connected line strip         */
   glLineStipple(1, 0x1C47);  /*  dash/dot/dash  */
   glBegin(GL_LINE_STRIP);
   for (i = 0; i < 7; i++)
      glVertex2f(50.0 + ((GLfloat) i * 50.0), 75.0);
   glEnd();
```

```
/* in 4th row, 6 independent lines with same stipple  */
   for (i = 0; i < 6; i++) {
      drawOneLine(50.0 + ((GLfloat) i * 50.0), 50.0,
                  50.0 + ((GLfloat)(i+1) * 50.0), 50.0);
   }

/* in 5th row, 1 line, with dash/dot/dash stipple    */
/* and a stipple repeat factor of 5                   */
   glLineStipple(5, 0x1C47);  /*  dash/dot/dash  */
   drawOneLine(50.0, 25.0, 350.0, 25.0);

   glDisable(GL_LINE_STIPPLE);
   glFlush();
}

void reshape(int w, int h)
{
   glViewport(0, 0, (GLsizei) w, (GLsizei) h);
   glMatrixMode(GL_PROJECTION);
   glLoadIdentity();
   gluOrtho2D(0.0, (GLdouble) w, 0.0, (GLdouble) h);
}

int main(int argc, char** argv)
{
   glutInit(&argc, argv);
   glutInitDisplayMode(GLUT_SINGLE | GLUT_RGB);
   glutInitWindowSize(400, 150);
   glutInitWindowPosition(100, 100);
   glutCreateWindow(argv[0]);
   init();
   glutDisplayFunc(display);
   glutReshapeFunc(reshape);
   glutMainLoop();
   return 0;
}
```

Polygon Details

Polygons are typically drawn by filling in all the pixels enclosed within the boundary, but you can also draw them as outlined polygons or simply as points at the vertices. A filled polygon might be solidly filled or stippled with a certain pattern. Although the exact details are omitted here, filled polygons are drawn in such a way that if adjacent polygons share an edge or vertex, the pixels making up the edge or vertex are drawn exactly once—they're included in only one of the polygons. This is done so that partially transparent polygons don't have their edges drawn twice, which would make those edges appear darker (or brighter, depending on what color you're drawing with). Note that it might result in narrow polygons having no filled pixels in one or more rows or columns of pixels.

To antialias filled polygons, multisampling is highly recommended. For details, see "Antialiasing Geometric Primitives with Multisampling" in Chapter 6.

Polygons as Points, Outlines, or Solids

A polygon has two sides—front and back—and might be rendered differently depending on which side is facing the viewer. This allows you to have cutaway views of solid objects in which there is an obvious distinction between the parts that are inside and those that are outside. By default, both front and back faces are drawn in the same way. To change this, or to draw only outlines or vertices, use **glPolygonMode()**.

void **glPolygonMode**(GLenum *face*, GLenum *mode*);

Controls the drawing mode for a polygon's front and back faces. The parameter *face* can be GL_FRONT_AND_BACK, GL_FRONT, or GL_BACK; *mode* can be GL_POINT, GL_LINE, or GL_FILL to indicate whether the polygon should be drawn as points, outlined, or filled. By default, both the front and back faces are drawn filled.

Version 3.1 only accepts GL_FRONT_AND_BACK as a value for *face*, and renders polygons the same way regardless of whether they're front- or back-facing.

Compatibility Extension

GL_FRONT
GL_BACK

For example, you can have the *front faces* filled and the *back faces* outlined with two calls to this routine:

```
glPolygonMode(GL_FRONT, GL_FILL);
glPolygonMode(GL_BACK, GL_LINE);
```

Reversing and Culling Polygon Faces

By convention, polygons whose vertices appear in counterclockwise order on the screen are called *front-facing*. You can construct the surface of any "reasonable" solid—a mathematician would call such a surface an orientable manifold (spheres, donuts, and teapots are orientable; Klein bottles and Möbius strips aren't)—from polygons of consistent orientation. In other words, you can use all clockwise polygons or all counterclockwise polygons. (This is essentially the mathematical definition of *orientable*.)

Suppose you've consistently described a model of an orientable surface but happen to have the clockwise orientation on the outside. You can swap what OpenGL considers the back face by using the function **glFrontFace()**, supplying the desired orientation for front-facing polygons.

void **glFrontFace**(GLenum *mode*);

Controls how front-facing polygons are determined. By default, *mode* is GL_CCW, which corresponds to a counterclockwise orientation of the ordered vertices of a projected polygon in window coordinates. If *mode* is GL_CW, faces with a clockwise orientation are considered front-facing.

Note: The orientation (clockwise or counterclockwise) of the vertices is also known as its *winding*.

In a completely enclosed surface constructed from opaque polygons with a consistent orientation, none of the back-facing polygons are ever visible—they're always obscured by the front-facing polygons. If you are outside this surface, you might enable *culling* to discard polygons that OpenGL determines are back-facing. Similarly, if you are inside the object, only back-facing polygons are visible. To instruct OpenGL to discard front- or back-facing polygons, use the command **glCullFace()** and enable culling with **glEnable()**.

void **glCullFace**(GLenum *mode*);

Indicates which polygons should be discarded (culled) before they're converted to screen coordinates. The mode is either GL_FRONT, GL_BACK, or GL_FRONT_AND_BACK to indicate front-facing, back-facing, or all polygons. To take effect, culling must be enabled using **glEnable()** with GL_CULL_FACE; it can be disabled with **glDisable()** and the same argument.

Advanced

Advanced

In more technical terms, deciding whether a face of a polygon is front- or back-facing depends on the sign of the polygon's area computed in window coordinates. One way to compute this area is

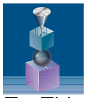
$$a = \frac{1}{2}\sum_{i=0}^{n-1} x_i \, y_{i\oplus 1} - x_{i\oplus 1} \, y_i$$

where x_i and y_i are the x and y window coordinates of the ith vertex of the n-vertex polygon and

$$i \oplus 1 \text{ is } (i+1) \bmod n.$$

Assuming that GL_CCW has been specified, if $a > 0$, the polygon corresponding to that vertex is considered to be front-facing; otherwise, it's back-facing. If GL_CW is specified and if $a < 0$, then the corresponding polygon is front-facing; otherwise, it's back-facing.

Try This


Try This

Modify Example 2-5 by adding some filled polygons. Experiment with different colors. Try different polygon modes. Also, enable culling to see its effect.

Stippling Polygons

By default, filled polygons are drawn with a solid pattern. They can also be filled with a 32-bit by 32-bit *window-aligned* stipple pattern, which you specify with **glPolygonStipple()**.

Compatibility Extension

glPolygonStipple
GL_POLYGON_STIPPLE

void **glPolygonStipple**(const GLubyte **mask*);

Defines the current stipple pattern for filled polygons. The argument *mask* is a pointer to a 32 × 32 bitmap that's interpreted as a mask of 0s and 1s. Where a 1 appears, the corresponding pixel in the polygon is drawn, and where a 0 appears, nothing is drawn. Figure 2-10 shows how a stipple pattern is constructed from the characters in *mask*. Polygon stippling is enabled and disabled by using **glEnable()** and **glDisable()** with GL_POLYGON_STIPPLE as the argument. The interpretation of the *mask* data is affected by the **glPixelStore*()** GL_UNPACK* modes. (See "Controlling Pixel-Storage Modes" in Chapter 8.)

In addition to defining the current polygon stippling pattern, you must enable stippling:

```
glEnable(GL_POLYGON_STIPPLE);
```

Use **glDisable()** with the same argument to disable polygon stippling.

Figure 2-11 shows the results of polygons drawn unstippled and then with two different stippling patterns. The program is shown in Example 2-6. The reversal of white to black (from Figure 2-10 to Figure 2-11) occurs because the program draws in white over a black background, using the pattern in Figure 2-10 as a stencil.

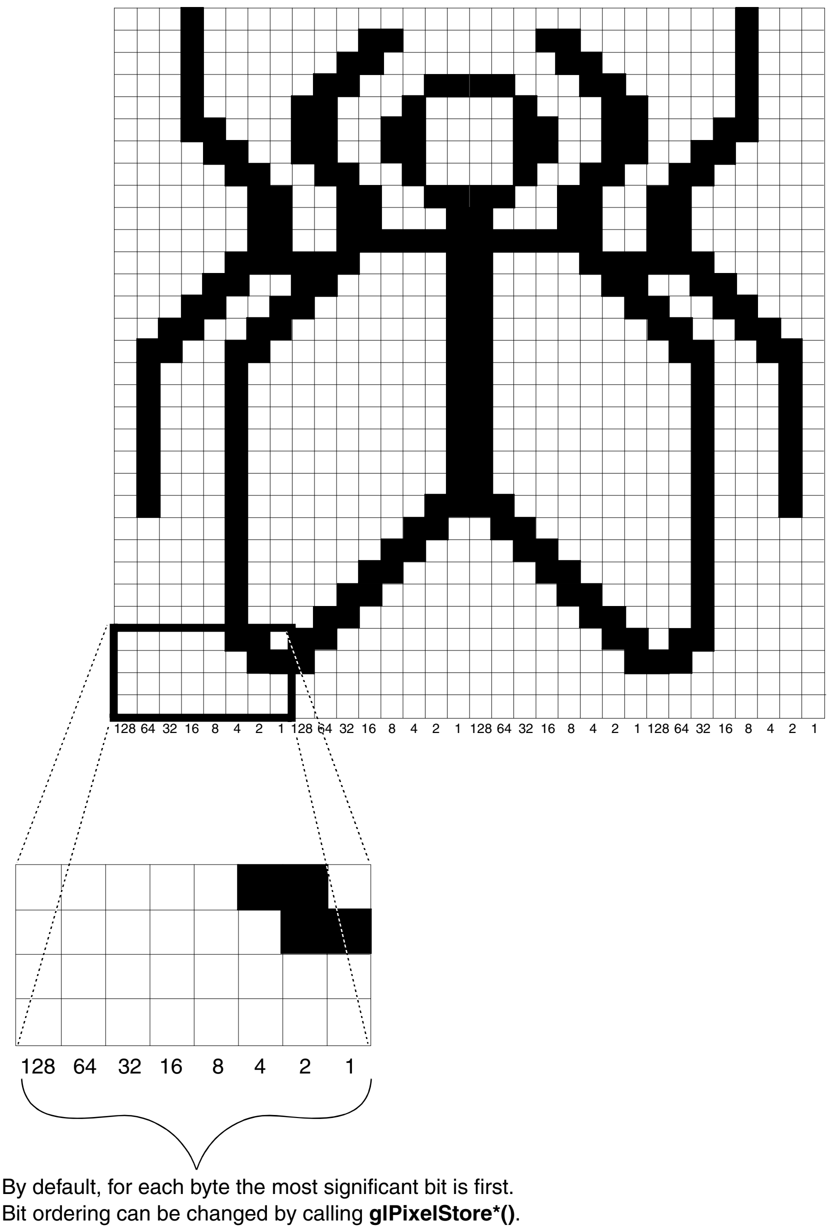


Figure 2-10 Constructing a Polygon Stipple Pattern

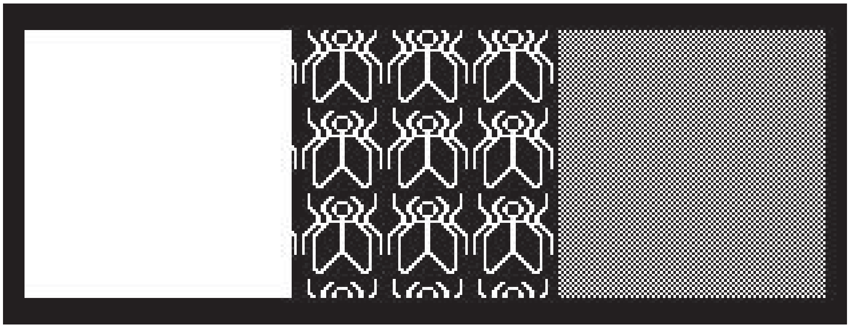


Figure 2-11 Stippled Polygons

Example 2-6 Polygon Stipple Patterns: polys.c

```
void display(void)
{
   GLubyte fly[] = {
      0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00,
      0x03, 0x80, 0x01, 0xC0, 0x06, 0xC0, 0x03, 0x60,
      0x04, 0x60, 0x06, 0x20, 0x04, 0x30, 0x0C, 0x20,
      0x04, 0x18, 0x18, 0x20, 0x04, 0x0C, 0x30, 0x20,
      0x04, 0x06, 0x60, 0x20, 0x44, 0x03, 0xC0, 0x22,
      0x44, 0x01, 0x80, 0x22, 0x44, 0x01, 0x80, 0x22,
      0x44, 0x01, 0x80, 0x22, 0x44, 0x01, 0x80, 0x22,
      0x44, 0x01, 0x80, 0x22, 0x44, 0x01, 0x80, 0x22,
      0x66, 0x01, 0x80, 0x66, 0x33, 0x01, 0x80, 0xCC,
      0x19, 0x81, 0x81, 0x98, 0x0C, 0xC1, 0x83, 0x30,
      0x07, 0xe1, 0x87, 0xe0, 0x03, 0x3f, 0xfc, 0xc0,
      0x03, 0x31, 0x8c, 0xc0, 0x03, 0x33, 0xcc, 0xc0,
      0x06, 0x64, 0x26, 0x60, 0x0c, 0xcc, 0x33, 0x30,
      0x18, 0xcc, 0x33, 0x18, 0x10, 0xc4, 0x23, 0x08,
      0x10, 0x63, 0xC6, 0x08, 0x10, 0x30, 0x0c, 0x08,
      0x10, 0x18, 0x18, 0x08, 0x10, 0x00, 0x00, 0x08};

   GLubyte halftone[] = {
      0xAA, 0xAA, 0xAA, 0xAA, 0x55, 0x55, 0x55, 0x55,
      0xAA, 0xAA, 0xAA, 0xAA, 0x55, 0x55, 0x55, 0x55,
      0xAA, 0xAA, 0xAA, 0xAA, 0x55, 0x55, 0x55, 0x55,
      0xAA, 0xAA, 0xAA, 0xAA, 0x55, 0x55, 0x55, 0x55,
      0xAA, 0xAA, 0xAA, 0xAA, 0x55, 0x55, 0x55, 0x55,
      0xAA, 0xAA, 0xAA, 0xAA, 0x55, 0x55, 0x55, 0x55,
      0xAA, 0xAA, 0xAA, 0xAA, 0x55, 0x55, 0x55, 0x55,
      0xAA, 0xAA, 0xAA, 0xAA, 0x55, 0x55, 0x55, 0x55,
```

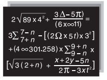
```
      0xAA, 0xAA, 0xAA, 0xAA, 0x55, 0x55, 0x55, 0x55,
      0xAA, 0xAA, 0xAA, 0xAA, 0x55, 0x55, 0x55, 0x55,
      0xAA, 0xAA, 0xAA, 0xAA, 0x55, 0x55, 0x55, 0x55,
      0xAA, 0xAA, 0xAA, 0xAA, 0x55, 0x55, 0x55, 0x55,
      0xAA, 0xAA, 0xAA, 0xAA, 0x55, 0x55, 0x55, 0x55,
      0xAA, 0xAA, 0xAA, 0xAA, 0x55, 0x55, 0x55, 0x55,
      0xAA, 0xAA, 0xAA, 0xAA, 0x55, 0x55, 0x55, 0x55,
      0xAA, 0xAA, 0xAA, 0xAA, 0x55, 0x55, 0x55, 0x55};

   glClear(GL_COLOR_BUFFER_BIT);
   glColor3f(1.0, 1.0, 1.0);
/*  draw one solid, unstippled rectangle,       */
/*  then two stippled rectangles                */
   glRectf(25.0, 25.0, 125.0, 125.0);
   glEnable(GL_POLYGON_STIPPLE);
   glPolygonStipple(fly);
   glRectf(125.0, 25.0, 225.0, 125.0);
   glPolygonStipple(halftone);
   glRectf(225.0, 25.0, 325.0, 125.0);
   glDisable(GL_POLYGON_STIPPLE);
   glFlush();
}

void init(void)
{
   glClearColor(0.0, 0.0, 0.0, 0.0);
   glShadeModel(GL_FLAT);
}

void reshape(int w, int h)
{
   glViewport(0, 0, (GLsizei) w, (GLsizei) h);
   glMatrixMode(GL_PROJECTION);
   glLoadIdentity();
   gluOrtho2D(0.0, (GLdouble) w, 0.0, (GLdouble) h);
}

int main(int argc, char** argv)
{
   glutInit(&argc, argv);
   glutInitDisplayMode(GLUT_SINGLE | GLUT_RGB);
   glutInitWindowSize(350, 150);
   glutCreateWindow(argv[0]);
   init();
   glutDisplayFunc(display);
```

```
   glutReshapeFunc(reshape);
   glutMainLoop();
   return 0;
}
```

You might want to use display lists to store polygon stipple patterns to maximize efficiency. (See "Display List Design Philosophy" in Chapter 7.)

Marking Polygon Boundary Edges

Advanced



Advanced

OpenGL can render only convex polygons, but many nonconvex polygons arise in practice. To draw these nonconvex polygons, you typically subdivide them into convex polygons—usually triangles, as shown in Figure 2-12—and then draw the triangles. Unfortunately, if you decompose a general polygon into triangles and draw the triangles, you can't really use **glPolygonMode()** to draw the polygon's outline, as you get all the triangle outlines inside it. To solve this problem, you can tell OpenGL whether a particular vertex precedes a boundary edge; OpenGL keeps track of this information by passing along with each vertex a bit indicating whether that vertex is followed by a boundary edge. Then, when a polygon is drawn in GL_LINE mode, the nonboundary edges aren't drawn. In Figure 2-12, the dashed lines represent added edges.

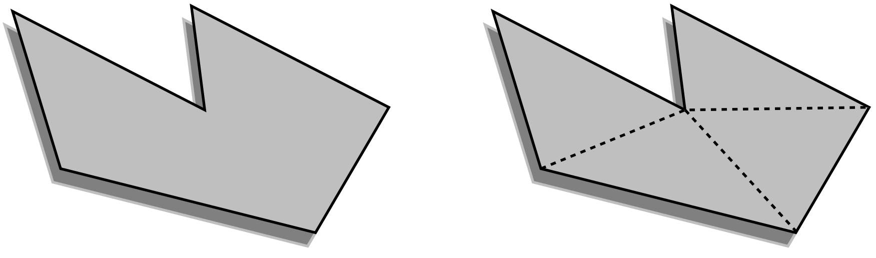


Figure 2-12 Subdividing a Nonconvex Polygon

By default, all vertices are marked as preceding a boundary edge, but you can manually control the setting of the *edge flag* with the command **glEdgeFlag*()**. This command is used between **glBegin()** and **glEnd()** pairs, and it affects all the vertices specified after it until the next **glEdgeFlag()** call is made. It applies only to vertices specified for polygons, triangles, and quads, not to those specified for strips of triangles or quads.

Compatibility Extension

glEdgeFlag

void **glEdgeFlag**(GLboolean *flag*);
void **glEdgeFlagv**(const GLboolean **flag*);

Indicates whether a vertex should be considered as initializing a boundary edge of a polygon. If *flag* is GL_TRUE, the edge flag is set to TRUE (the default), and any vertices created are considered to precede boundary edges until this function is called again with *flag* being GL_FALSE.

For instance, Example 2-7 draws the outline shown in Figure 2-13.

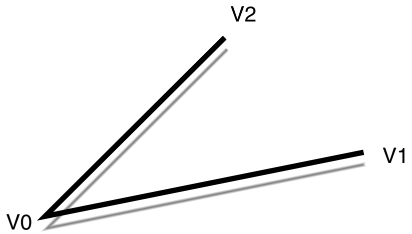


Figure 2-13 Outlined Polygon Drawn Using Edge Flags

Example 2-7 Marking Polygon Boundary Edges

```
glPolygonMode(GL_FRONT_AND_BACK, GL_LINE);
glBegin(GL_POLYGON);
    glEdgeFlag(GL_TRUE);
    glVertex3fv(V0);
    glEdgeFlag(GL_FALSE);
    glVertex3fv(V1);
    glEdgeFlag(GL_TRUE);
    glVertex3fv(V2);
glEnd();
```

Normal Vectors

A *normal vector* (or *normal*, for short) is a vector that points in a direction that's perpendicular to a surface. For a flat surface, one perpendicular direction is the same for every point on the surface, but for a general curved surface, the normal direction might be different at each point on the surface. With OpenGL, you can specify a normal for each polygon or for each vertex. Vertices of the same polygon might share the same normal (for a flat surface) or have different normals (for a curved surface). You can't assign normals anywhere other than at the vertices.

An object's normal vectors define the orientation of its surface in space—in particular, its orientation relative to light sources. These vectors are used by OpenGL to determine how much light the object receives at its vertices. Lighting—a large topic by itself—is the subject of Chapter 5, and you might want to review the following information after you've read that chapter. Normal vectors are discussed briefly here because you define normal vectors for an object at the same time you define the object's geometry.

You use **glNormal*()** to set the current normal to the value of the argument passed in. Subsequent calls to **glVertex*()** cause the specified vertices to be assigned the current normal. Often, each vertex has a different normal, which necessitates a series of alternating calls, as in Example 2-8.

Example 2-8 Surface Normals at Vertices

```
glBegin (GL_POLYGON);
   glNormal3fv(n0);
   glVertex3fv(v0);
   glNormal3fv(n1);
   glVertex3fv(v1);
   glNormal3fv(n2);
   glVertex3fv(v2);
   glNormal3fv(n3);
   glVertex3fv(v3);
glEnd();
```

void **glNormal3**{bsidf}(*TYPE nx*, *TYPE ny*, *TYPE nz*);
void **glNormal3**{bsidf}**v**(const *TYPE* *v);

Sets the current normal vector as specified by the arguments. The nonvector version (without the **v**) takes three arguments, which specify an (*nx, ny, nz*) vector that's taken to be the normal. Alternatively, you can use the vector version of this function (with the **v**) and supply a single array of three elements to specify the desired normal. The **b**, **s**, and **i** versions scale their parameter values linearly to the range [–1.0, 1.0].

Compatibility Extension
glNormal

There's no magic to finding the normals for an object—most likely, you have to perform some calculations that might include taking derivatives—but there are several techniques and tricks you can use to achieve certain effects. Appendix H, "Calculating Normal Vectors,"[1] explains how to find normal vectors for surfaces. If you already know how to do this, if you can count on always being supplied with normal vectors, or if you don't want to use the OpenGL lighting facilities, you don't need to read this appendix.

[1] This appendix is available online at `http://www.opengl-redbook.com/appendices/`.

Note that at a given point on a surface, two vectors are perpendicular to the surface, and they point in opposite directions. By convention, the normal is the one that points to the outside of the surface being modeled. (If you get inside and outside reversed in your model, just change every normal vector from (x, y, z) to $(-x, -y, -z)$).

Also, keep in mind that since normal vectors indicate direction only, their lengths are mostly irrelevant. You can specify normals of any length, but eventually they have to be converted to a length of 1 before lighting calculations are performed. (A vector that has a length of 1 is said to be of unit length, or *normalized*.) In general, you should supply normalized normal vectors. To make a normal vector of unit length, divide each of its x-, y-, z-components by the length of the normal:

$$\sqrt{x^2 + y^2 + z^2}$$

Normal vectors remain normalized as long as your model transformations include only rotations and translations. (See Chapter 3 for a discussion of transformations.) If you perform irregular transformations (such as scaling or multiplying by a shear matrix), or if you specify nonunit-length normals, then you should have OpenGL automatically normalize your normal vectors after the transformations. To do this, call **glEnable(GL_NORMALIZE)**.

Compatibility Extension
GL_NORMALIZE
GL_RESCALE_NORMAL

If you supply unit-length normals, and you perform only uniform scaling (that is, the same scaling value for x, y, and z), you can use **glEnable(GL_RESCALE_NORMAL)** to scale the normals by a constant factor, derived from the modelview transformation matrix, to return them to unit length after transformation.

Note that automatic normalization or rescaling typically requires additional calculations that might reduce the performance of your application. Rescaling normals uniformly with GL_RESCALE_NORMAL is usually less expensive than performing full-fledged normalization with GL_NORMALIZE. By default, both automatic normalizing and rescaling operations are disabled.

Vertex Arrays

You may have noticed that OpenGL requires many function calls to render geometric primitives. Drawing a 20-sided polygon requires at least 22 function calls: one call to **glBegin()**, one call for each of the vertices, and a final call to **glEnd()**. In the two previous code examples, additional information (polygon boundary edge flags or surface normals) added function calls for each vertex. This can quickly double or triple the number of function calls required for one geometric object. For some systems, function calls have a great deal of overhead and can hinder performance.

An additional problem is the redundant processing of vertices that are shared between adjacent polygons. For example, the cube in Figure 2-14 has six faces and eight shared vertices. Unfortunately, if the standard method of describing this object is used, each vertex has to be specified three times: once for every face that uses it. Therefore, 24 vertices are processed, even though eight would be enough.

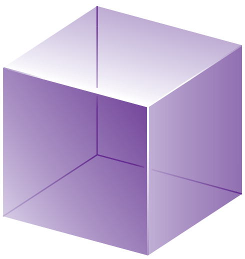


Figure 2-14 Six Sides, Eight Shared Vertices

OpenGL has vertex array routines that allow you to specify a lot of vertex-related data with just a few arrays and to access that data with equally few function calls. Using vertex array routines, all 20 vertices in a 20-sided polygon can be put into one array and called with one function. If each vertex also has a surface normal, all 20 surface normals can be put into another array and also called with one function.

Arranging data in vertex arrays may increase the performance of your application. Using vertex arrays reduces the number of function calls, which improves performance. Also, using vertex arrays may allow reuse of already processed shared vertices.

Note: Vertex arrays became standard in Version 1.1 of OpenGL. Version 1.4 added support for storing fog coordinates and secondary colors in vertex arrays.

There are three steps to using vertex arrays to render geometry:

1. Activate (enable) the appropriate arrays, with each storing a different type of data: vertex coordinates, surface normals, RGBA colors, secondary colors, color indices, fog coordinates, texture coordinates, polygon edge flags, or vertex attributes for use in a vertex shader.

2. Put data into the array or arrays. The arrays are accessed by the addresses of (that is, pointers to) their memory locations. In the client-server model, this data is stored in the client's address space, unless you choose to use buffer objects (see "Buffer Objects" on page 91), for which the arrays are stored in server memory.

3. Draw geometry with the data. OpenGL obtains the data from all activated arrays by dereferencing the pointers. In the client-server model, the data is transferred to the server's address space. There are three ways to do this:

   - Accessing individual array elements (randomly hopping around)
   - Creating a list of individual array elements (methodically hopping around)
   - Processing sequential array elements

   The dereferencing method you choose may depend on the type of problem you encounter. Version 1.4 added support for multiple array access from a single function call.

Interleaved vertex array data is another common method of organization. Instead of several different arrays, each maintaining a different type of data (color, surface normal, coordinate, and so on), you may have the different types of data mixed into a single array. (See "Interleaved Arrays" on page 88.)

Step 1: Enabling Arrays

The first step is to call **glEnableClientState()** with an enumerated parameter, which activates the chosen array. In theory, you may need to call this up to eight times to activate the eight available arrays. In practice, you'll probably activate up to six arrays. For example, it is unlikely that you would activate both GL_COLOR_ARRAY and GL_INDEX_ARRAY, as your program's display mode supports either RGBA mode or color-index mode, but probably not both simultaneously.

Compatibility Extension
glEnableClientState

void **glEnableClientState**(GLenum *array*)

Specifies the array to enable. The symbolic constants GL_VERTEX_ARRAY, GL_COLOR_ARRAY, GL_SECONDARY_COLOR_ARRAY, GL_INDEX_ARRAY, GL_NORMAL_ARRAY, GL_FOG_COORD_ARRAY, GL_TEXTURE_COORD_ARRAY, and GL_EDGE_FLAG_ARRAY are acceptable parameters.

Note: Version 3.1 supports only vertex array data stored in buffer objects (see "Buffer Objects" on page 91 for details).

If you use lighting, you may want to define a surface normal for every vertex. (See "Normal Vectors" on page 68.) To use vertex arrays for that case, you activate both the surface normal and vertex coordinate arrays:

```
glEnableClientState(GL_NORMAL_ARRAY);
glEnableClientState(GL_VERTEX_ARRAY);
```

Suppose that you want to turn off lighting at some point and just draw the geometry using a single color. You want to call **glDisable()** to turn off lighting states (see Chapter 5). Now that lighting has been deactivated, you also want to stop changing the values of the surface normal state, which is wasted effort. To do this, you call

```
glDisableClientState(GL_NORMAL_ARRAY);
```

void **glDisableClientState**(GLenum *array*);

Specifies the array to disable. It accepts the same symbolic constants as **glEnableClientState()**.

Compatibility Extension

glDisableClientState

You might be asking yourself why the architects of OpenGL created these new (and long) command names, like **gl*ClientState()**, for example. Why can't you just call **glEnable()** and **glDisable()**? One reason is that **glEnable()** and **glDisable()** can be stored in a display list, but the specification of vertex arrays cannot, because the data remains on the client's side.

If multitexturing is enabled, enabling and disabling client arrays affects only the active texturing unit. See "Multitexturing" on page 467 for more details.

Step 2: Specifying Data for the Arrays

There is a straightforward way by which a single command specifies a single array in the client space. There are eight different routines for specifying arrays—one routine for each kind of array. There is also a command that can specify several client-space arrays at once, all originating from a single interleaved array.

Compatibility Extension

glVertexPointer

void **glVertexPointer**(GLint *size*, GLenum *type*, GLsizei *stride*,
const GLvoid **pointer*);

Specifies where spatial coordinate data can be accessed. *pointer* is the memory address of the first coordinate of the first vertex in the array. *type* specifies the data type (GL_SHORT, GL_INT, GL_FLOAT, or GL_DOUBLE) of each coordinate in the array. *size* is the number of coordinates per vertex, which must be 2, 3, or 4. *stride* is the byte offset between consecutive vertices. If *stride* is 0, the vertices are understood to be tightly packed in the array.

To access the other seven arrays, there are seven similar routines:

Compatibility Extension

glColorPointer
glSecondaryColorPointer
glIndexPointer
glNormalPointer
glFogCoordPointer
glTexCoordPointer
glEdgeFlagPointer

void **glColorPointer**(GLint *size*, GLenum *type*, GLsizei *stride*,
const GLvoid **pointer*);
void **glSecondaryColorPointer**(GLint *size*, GLenum *type*, GLsizei *stride*,
const GLvoid **pointer*);
void **glIndexPointer**(GLenum *type*, GLsizei *stride*, const GLvoid **pointer*);
void **glNormalPointer**(GLenum *type*, GLsizei *stride*,
const GLvoid **pointer*);
void **glFogCoordPointer**(GLenum *type*, GLsizei *stride*,
const GLvoid **pointer*);
void **glTexCoordPointer**(GLint *size*, GLenum *type*, GLsizei *stride*,
const GLvoid **pointer*);
void **glEdgeFlagPointer**(GLsizei *stride*, const GLvoid **pointer*);

Note: Additional vertex attributes, used by programmable shaders, can be stored in vertex arrays. Because of their association with shaders, they are discussed in Chapter 15, "The OpenGL Shading Language," on page 720. For Version 3.1, only generic vertex arrays are supported for storing vertex data.

The main difference among the routines is whether size and type are unique or must be specified. For example, a surface normal always has three components, so it is redundant to specify its size. An edge flag is always a single Boolean, so neither size nor type needs to be mentioned. Table 2-4 displays legal values for size and data types.

For OpenGL implementations that support multitexturing, specifying a texture coordinate array with **glTexCoordPointer()** only affects the currently active texture unit. See "Multitexturing" on page 467 for more information.

Command	Sizes	Values for ***type*** Argument
glVertexPointer	2, 3, 4	GL_SHORT, GL_INT, GL_FLOAT, GL_DOUBLE
glColorPointer	3, 4	GL_BYTE, GL_UNSIGNED_BYTE, GL_SHORT, GL_UNSIGNED_SHORT, GL_INT, GL_UNSIGNED_INT, GL_FLOAT, GL_DOUBLE
glSecondaryColorPointer	3	GL_BYTE, GL_UNSIGNED_BYTE, GL_SHORT, GL_UNSIGNED_SHORT, GL_INT, GL_UNSIGNED_INT, GL_FLOAT, GL_DOUBLE
glIndexPointer	1	GL_UNSIGNED_BYTE, GL_SHORT, GL_INT, GL_FLOAT, GL_DOUBLE
glNormalPointer	3	GL_BYTE, GL_SHORT, GL_INT, GL_FLOAT, GL_DOUBLE
glFogCoordPointer	1	GL_FLOAT, GL_DOUBLE
glTexCoordPointer	1, 2, 3, 4	GL_SHORT, GL_INT, GL_FLOAT, GL_DOUBLE
glEdgeFlagPointer	1	no type argument (type of data must be GLboolean)

Table 2-4 Vertex Array Sizes (Values per Vertex) and Data Types

Example 2-9 uses vertex arrays for both RGBA colors and vertex coordinates. RGB floating-point values and their corresponding (*x*, *y*) integer coordinates are loaded into the GL_COLOR_ARRAY and GL_VERTEX_ARRAY.

Example 2-9 Enabling and Loading Vertex Arrays: varray.c

```
static GLint vertices[] = {25, 25,
                          100, 325,
                          175, 25,
                          175, 325,
                          250, 25,
                          325, 325};
static GLfloat colors[] = {1.0, 0.2, 0.2,
                          0.2, 0.2, 1.0,
                          0.8, 1.0, 0.2,
                          0.75, 0.75, 0.75,
                          0.35, 0.35, 0.35,
                          0.5, 0.5, 0.5};
```

```
glEnableClientState(GL_COLOR_ARRAY);
glEnableClientState(GL_VERTEX_ARRAY);

glColorPointer(3, GL_FLOAT, 0, colors);
glVertexPointer(2, GL_INT, 0, vertices);
```

Stride

The *stride* parameter for the **gl*Pointer()** routines tells OpenGL how to access the data you provide in your pointer arrays. Its value should be the number of bytes between the starts of two successive pointer elements, or zero, which is a special case. For example, suppose you stored both your vertex's RGB and (*x*, *y*, *z*) coordinates in a single array, such as the following:

```
static GLfloat intertwined[] =
      {1.0, 0.2, 1.0, 100.0, 100.0, 0.0,
       1.0, 0.2, 0.2,   0.0, 200.0, 0.0,
       1.0, 1.0, 0.2, 100.0, 300.0, 0.0,
       0.2, 1.0, 0.2, 200.0, 300.0, 0.0,
       0.2, 1.0, 1.0, 300.0, 200.0, 0.0,
       0.2, 0.2, 1.0, 200.0, 100.0, 0.0};
```

To reference only the color values in the *intertwined* array, the following call starts from the beginning of the array (which could also be passed as *&intertwined[0]*) and jumps ahead 6 * **sizeof**(GLfloat) bytes, which is the size of both the color and vertex coordinate values. This jump is enough to get to the beginning of the data for the next vertex:

```
glColorPointer(3, GL_FLOAT, 6*sizeof(GLfloat), &intertwined[0]);
```

For the vertex coordinate pointer, you need to start from further in the array, at the fourth element of *intertwined* (remember that C programmers start counting at zero):

```
glVertexPointer(3,GL_FLOAT, 6*sizeof(GLfloat), &intertwined[3]);
```

If your data is stored similar to the *intertwined* array above, you may find the approach described in "Interleaved Arrays" on page 88 more convenient for storing your data.

With a stride of zero, each type of vertex array (RGB color, color index, vertex coordinate, and so on) must be tightly packed. The data in the array must be homogeneous; that is, the data must be all RGB color values, all vertex coordinates, or all some other data similar in some fashion.

Step 3: Dereferencing and Rendering

Until the contents of the vertex arrays are dereferenced, the arrays remain on the client side, and their contents are easily changed. In Step 3, contents of the arrays are obtained, sent to the server, and then sent down the graphics processing pipeline for rendering.

You can obtain data from a single array element (indexed location), from an ordered list of array elements (which may be limited to a subset of the entire vertex array data), or from a sequence of array elements.

Dereferencing a Single Array Element

void **glArrayElement**(GLint *ith*)

Obtains the data of one (the *ith*) vertex for all currently enabled arrays. For the vertex coordinate array, the corresponding command would be **glVertex**[*size*][*type*]**v()**, where *size* is one of [2, 3, 4], and *type* is one of [s,i,f,d] for GLshort, GLint, GLfloat, and GLdouble, respectively. Both size and type were defined by **glVertexPointer()**. For other enabled arrays, **glArrayElement()** calls **glEdgeFlagv()**, **glTexCoord**[*size*][*type*]**v()**, **glColor**[*size*][*type*]**v()**, **glSecondaryColor3**[*type*]**v()**, **glIndex**[*type*]**v()**, **glNormal3**[*type*]**v()**, and **glFogCoord**[*type*]**v()**. If the vertex coordinate array is enabled, the **glVertex*v()** routine is executed last, after the execution (if enabled) of up to seven corresponding array values.

Compatibility Extension

glArrayElement

glArrayElement() is usually called between **glBegin()** and **glEnd()**. (If called outside, **glArrayElement()** sets the current state for all enabled arrays, except for vertex, which has no current state.) In Example 2-10, a triangle is drawn using the third, fourth, and sixth vertices from enabled vertex arrays. (Again, remember that C programmers begin counting array locations with zero.)

Example 2-10 Using glArrayElement() to Define Colors and Vertices

```
glEnableClientState(GL_COLOR_ARRAY);
glEnableClientState(GL_VERTEX_ARRAY);
glColorPointer(3, GL_FLOAT, 0, colors);
glVertexPointer(2, GL_INT, 0, vertices);

glBegin(GL_TRIANGLES);
glArrayElement(2);
glArrayElement(3);
glArrayElement(5);
glEnd();
```

When executed, the latter five lines of code have the same effect as

```
glBegin(GL_TRIANGLES);
glColor3fv(colors + (2 * 3));
glVertex2iv(vertices + (2 * 2));
glColor3fv(colors + (3 * 3));
glVertex2iv(vertices + (3 * 2));
glColor3fv(colors + (5 * 3));
glVertex2iv(vertices + (5 * 2));
glEnd();
```

Since **glArrayElement()** is only a single function call per vertex, it may reduce the number of function calls, which increases overall performance.

Be warned that if the contents of the array are changed between **glBegin()** and **glEnd()**, there is no guarantee that you will receive original data or changed data for your requested element. To be safe, don't change the contents of any array element that might be accessed until the primitive is completed.

Dereferencing a List of Array Elements

glArrayElement() is good for randomly "hopping around" your data arrays. Similar routines, **glDrawElements()**, **glMultiDrawElements()**, and **glDrawRangeElements()**, are good for hopping around your data arrays in a more orderly manner.

void **glDrawElements**(GLenum *mode*, GLsizei *count*, GLenum *type*,
const GLvoid **indices*);

Defines a sequence of geometric primitives using *count* number of elements, whose indices are stored in the array *indices*. *type* must be one of GL_UNSIGNED_BYTE, GL_UNSIGNED_SHORT, or GL_UNSIGNED_INT, indicating the data type of the *indices* array. *mode* specifies what kind of primitives are constructed and is one of the same values that is accepted by **glBegin()**; for example, GL_POLYGON, GL_LINE_LOOP, GL_LINES, GL_POINTS, and so on.

The effect of **glDrawElements()** is almost the same as this command sequence:

```
glBegin(mode);
for (i = 0; i < count; i++)
   glArrayElement(indices[i]);
glEnd();
```

glDrawElements() additionally checks to make sure *mode*, *count*, and *type* are valid. Also, unlike the preceding sequence, executing **glDrawElements()** leaves several states indeterminate. After execution of **glDrawElements()**, current RGB color, secondary color, color index, normal coordinates, fog coordinates, texture coordinates, and edge flag are indeterminate if the corresponding array has been enabled.

With **glDrawElements()**, the vertices for each face of the cube can be placed in an array of indices. Example 2-11 shows two ways to use **glDrawElements()** to render the cube. Figure 2-15 shows the numbering of the vertices used in Example 2-11.

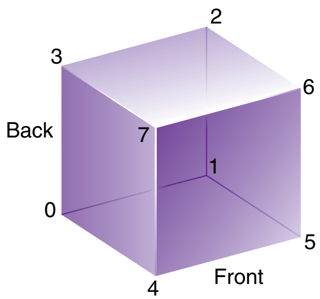


Figure 2-15 Cube with Numbered Vertices

Example 2-11 Using glDrawElements() to Dereference Several Array Elements

```
static GLubyte frontIndices[] = {4, 5, 6, 7};
static GLubyte rightIndices[] = {1, 2, 6, 5};
static GLubyte bottomIndices[] = {0, 1, 5, 4};
static GLubyte backIndices[] = {0, 3, 2, 1};
static GLubyte leftIndices[] = {0, 4, 7, 3};
static GLubyte topIndices[] = {2, 3, 7, 6};

glDrawElements(GL_QUADS, 4, GL_UNSIGNED_BYTE, frontIndices);
glDrawElements(GL_QUADS, 4, GL_UNSIGNED_BYTE, rightIndices);
glDrawElements(GL_QUADS, 4, GL_UNSIGNED_BYTE, bottomIndices);
glDrawElements(GL_QUADS, 4, GL_UNSIGNED_BYTE, backIndices);
glDrawElements(GL_QUADS, 4, GL_UNSIGNED_BYTE, leftIndices);
glDrawElements(GL_QUADS, 4, GL_UNSIGNED_BYTE, topIndices);
```

Note: It is an error to encapsulate **glDrawElements()** between a **glBegin()/glEnd()** pair.

With several primitive types (such as GL_QUADS, GL_TRIANGLES, and GL_LINES), you may be able to compact several lists of indices together into a single array. Since the GL_QUADS primitive interprets each group of four vertices as a single polygon, you may compact all the indices used in Example 2-11 into a single array, as shown in Example 2-12:

Example 2-12 Compacting Several glDrawElements() Calls into One

```
static GLubyte allIndices[] = {4, 5, 6, 7, 1, 2, 6, 5,
                               0, 1, 5, 4, 0, 3, 2, 1,
                               0, 4, 7, 3, 2, 3, 7, 6};

glDrawElements(GL_QUADS, 24, GL_UNSIGNED_BYTE, allIndices);
```

For other primitive types, compacting indices from several arrays into a single array renders a different result. In Example 2-13, two calls to **glDrawElements()** with the primitive GL_LINE_STRIP render two line strips. You cannot simply combine these two arrays and use a single call to **glDrawElements()** without concatenating the lines into a single strip that would connect vertices #6 and #7. (Note that vertex #1 is being used in both line strips just to show that this is legal.)

Example 2-13 Two glDrawElements() Calls That Render Two Line Strips

```
static GLubyte oneIndices[] = {0, 1, 2, 3, 4, 5, 6};
static GLubyte twoIndices[] = {7, 1, 8, 9, 10, 11};

glDrawElements(GL_LINE_STRIP, 7, GL_UNSIGNED_BYTE, oneIndices);
glDrawElements(GL_LINE_STRIP, 6, GL_UNSIGNED_BYTE, twoIndices);
```

The routine **glMultiDrawElements()** was introduced in OpenGL Version 1.4 to enable combining the effects of several **glDrawElements()** calls into a single call.

void **glMultiDrawElements**(GLenum *mode*, GLsizei **count*,
GLenum *type*, const GLvoid ***indices*,
GLsizei *primcount*);

Calls a sequence of *primcount* (a number of) **glDrawElements()** commands. *indices* is an array of pointers to lists of array elements. *count* is an array of how many vertices are found in each respective array element list. *mode* (primitive type) and *type* (data type) are the same as they are in **glDrawElements()**.

The effect of **glMultiDrawElements()** is the same as

```
for (i = 0; i < primcount; i++) {
   if (count[i] > 0)
      glDrawElements(mode, count[i], type, indices[i]);
}
```

The calls to **glDrawElements()** in Example 2-13 can be combined into a single call of **glMultiDrawElements()**, as shown in Example 2-14:

Example 2-14 Use of glMultiDrawElements(): mvarray.c

```
static GLubyte oneIndices[] = {0, 1, 2, 3, 4, 5, 6};
static GLubyte twoIndices[] = {7, 1, 8, 9, 10, 11};
static GLsizei count[] = {7, 6};
static GLvoid * indices[2] = {oneIndices, twoIndices};

glMultiDrawElements(GL_LINE_STRIP, count, GL_UNSIGNED_BYTE,
                    indices, 2);
```

Like **glDrawElements()** or **glMultiDrawElements()**, **glDrawRangeElements()** is also good for hopping around data arrays and rendering their contents. **glDrawRangeElements()** also introduces the added restriction of a range of legal values for its indices, which may increase program performance. For optimal performance, some OpenGL implementations may be able to prefetch (obtain prior to rendering) a limited amount of vertex array data. **glDrawRangeElements()** allows you to specify the range of vertices to be prefetched.

void **glDrawRangeElements**(GLenum *mode*, GLuint *start*,
GLuint *end*, GLsizei *count*,
GLenum *type*, const GLvoid **indices*);

Creates a sequence of geometric primitives that is similar to, but more restricted than, the sequence created by **glDrawElements().** Several parameters of **glDrawRangeElements()** are the same as counterparts in **glDrawElements()**, including *mode* (kind of primitives), *count* (number of elements), *type* (data type), and *indices* (array locations of vertex data). **glDrawRangeElements()** introduces two new parameters: *start* and *end,* which specify a range of acceptable values for *indices*. To be valid, values in the array *indices* must lie between *start* and *end,* inclusive.

It is a mistake for vertices in the array *indices* to reference outside the range [*start, end*]. However, OpenGL implementations are not required to find or report this mistake. Therefore, illegal index values may or may not generate an OpenGL error condition, and it is entirely up to the implementation to decide what to do.

You can use **glGetIntegerv()** with GL_MAX_ELEMENTS_VERTICES and GL_MAX_ELEMENTS_INDICES to find out, respectively, the recommended maximum number of vertices to be prefetched and the maximum number of indices (indicating the number of vertices to be rendered) to be referenced. If *end – start + 1* is greater than the recommended maximum of prefetched vertices, or if *count* is greater than the recommended maximum of indices, **glDrawRangeElements()** should still render correctly, but performance may be reduced.

Not all vertices in the range [*start, end*] have to be referenced. However, on some implementations, if you specify a sparsely used range, you may unnecessarily process many vertices that go unused.

With **glArrayElement()**, **glDrawElements()**, **glMultiDrawElements()**, and **glDrawRangeElements()**, it is possible that your OpenGL implementation caches recently processed (meaning transformed, lit) vertices, allowing your application to "reuse" them by not sending them down the transformation pipeline additional times. Take the aforementioned cube, for example, which has six faces (polygons) but only eight vertices. Each vertex is used by exactly three faces. Without **gl*Elements()**, rendering all six faces would require processing 24 vertices, even though 16 vertices are redundant. Your implementation of OpenGL may be able to minimize redundancy and process as few as eight vertices. (Reuse of vertices may be limited to all vertices within a single **glDrawElements()** or **glDrawRangeElements()** call, a single index array for **glMultiDrawElements()**, or, for **glArrayElement()**, within one **glBegin()/glEnd()** pair.)

Dereferencing a Sequence of Array Elements

While **glArrayElement()**, **glDrawElements()**, and **glDrawRangeElements()** "hop around" your data arrays, **glDrawArrays()** plows straight through them.

void **glDrawArrays**(GLenum *mode*, GLint *first*, GLsizei *count*);

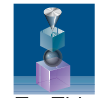
Constructs a sequence of geometric primitives using array elements starting at *first* and ending at *first + count – 1* of each enabled array. *mode* specifies what kinds of primitives are constructed and is one of the same values accepted by **glBegin()**; for example, GL_POLYGON, GL_LINE_LOOP, GL_LINES, GL_POINTS, and so on.

The effect of **glDrawArrays()** is almost the same as this command sequence:

```
glBegin (mode);
for (i = 0; i < count; i++)
   glArrayElement(first + i);
glEnd();
```

As is the case with **glDrawElements()**, **glDrawArrays()** also performs error checking on its parameter values and leaves the current RGB color, secondary color, color index, normal coordinates, fog coordinates, texture coordinates, and edge flag with indeterminate values if the corresponding array has been enabled.

Try This


Try This

Change the icosahedron drawing routine in Example 2-19 on page 115 to use vertex arrays.

Similar to **glMultiDrawElements()**, the routine **glMultiDrawArrays()** was introduced in OpenGL Version 1.4 to combine several **glDrawArrays()** calls into a single call.

void **glMultiDrawArrays**(GLenum *mode*, GLint **first*, GLsizei **count*
GLsizei *primcount*);

Calls a sequence of *primcount* (a number of) **glDrawArrays()** commands. *mode* specifies the primitive type with the same values as accepted by **glBegin()**. *first* and *count* contain lists of array locations indicating where to process each list of array elements. Therefore, for the *i*th list of array elements, a geometric primitive is constructed starting at *first[i]* and ending at *first[i]* + *count[i]* – *1*.

The effect of **glMultiDrawArrays()** is the same as

```
for (i = 0; i < primcount; i++) {
   if (count[i] > 0)
      glDrawArrays(mode, first[i], count[i]);
}
```

Restarting Primitives

As you start working with larger sets of vertex data, you are likely to find that you need to make numerous calls to the OpenGL drawing routines, usually rendering the same type of primitive (such as GL_TRIANGLE_STRIP, for example) that you used in the previous drawing call. Of course, you can use the **glMultiDraw*()** routines, but they require the overhead of maintaining the arrays for the starting index and length of each primitive.

OpenGL Version 3.1 added the ability to restart primitives within the same drawing call by specifying a special value, the *primitive restart index*, which is specially processed by OpenGL. When the primitive restart index is encountered in a draw call, a new rendering primitive of the same type is started with the vertex following the index. The primitive restart index is specified by the **glPrimitiveRestartIndex()** routine.

void **glPrimitiveRestartIndex**(GLuint *index*);

Specifies the vertex array element index used to indicate that a new primitive should be started during rendering. When processing of vertex array element indices encounters a value that matches *index*, no vertex data is processed, the current graphics primitive is terminated, and a new one of the identical type is started.

Primitive restarting is controlled by calling **glEnable()** or **glDisable()** and specifying GL_PRIMITIVE_RESTART, as demonstrated in Example 2-15.

Example 2-15 Using glPrimitiveRestartIndex() to Render Multiple Triangle Strips: primrestart.c.

```
#define BUFFER_OFFSET(offset) ((GLvoid *) NULL + offset)

#define XStart      -0.8
#define XEnd         0.8
#define YStart      -0.8
#define YEnd         0.8

#define NumXPoints          11
#define NumYPoints          11
#define NumPoints           (NumXPoints * NumYPoints)
#define NumPointsPerStrip   (2*NumXPoints)
#define NumStrips           (NumYPoints-1)
#define RestartIndex        0xffff

void
init()
{
    GLuint    vbo, ebo;
    GLfloat   *vertices;
    GLushort  *indices;

    /* Set up vertex data */
    glGenBuffers(1, &vbo);
    glBindBuffer(GL_ARRAY_BUFFER, vbo);
    glBufferData(GL_ARRAY_BUFFER, 2*NumPoints*sizeof(GLfloat),
        NULL, GL_STATIC_DRAW);
```

```
vertices = glMapBuffer(GL_ARRAY_BUFFER, GL_WRITE_ONLY);

if (vertices == NULL) {
    fprintf(stderr, "Unable to map vertex buffer\n");
    exit(EXIT_FAILURE);
}
else {
    int       i, j;
    GLfloat  dx = (XEnd - XStart) / (NumXPoints - 1);
    GLfloat  dy = (YEnd - YStart) / (NumYPoints - 1);
    GLfloat  *tmp = vertices;
    int n = 0;

    for (j = 0; j < NumYPoints; ++j) {
        GLfloat y = YStart + j*dy;

        for (i = 0; i < NumXPoints; ++i) {
            GLfloat x = XStart + i*dx;
            *tmp++ = x;
            *tmp++ = y;
        }
     }

     glUnmapBuffer(GL_ARRAY_BUFFER);
     glVertexPointer(2, GL_FLOAT, 0, BUFFER_OFFSET(0));
     glEnableClientState(GL_VERTEX_ARRAY);
}

/* Set up index data */
glGenBuffers(1, &ebo);
glBindBuffer(GL_ELEMENT_ARRAY_BUFFER, ebo);

/* We allocate an extra restart index because it simplifies
**   the element-array loop logic */
glBufferData( GL_ELEMENT_ARRAY_BUFFER,
    NumStrips*(NumPointsPerStrip+1)*sizeof(GLushort),
    NULL, GL_STATIC_DRAW );
indices = glMapBuffer(GL_ELEMENT_ARRAY_BUFFER,
    GL_WRITE_ONLY);

if (indices == NULL) {
    fprintf(stderr, "Unable to map index buffer\n");
    exit(EXIT_FAILURE);
}
else {
    int       i, j;
    GLushort  *index = indices;
```

```
        for (j = 0; j < NumStrips; ++j) {
            GLushort  bottomRow = j*NumYPoints;
            GLushort  topRow = bottomRow + NumYPoints;

            for (i = 0; i < NumXPoints; ++i) {
                *index++ = topRow + i;
                *index++ = bottomRow + i;
            }
            *index++ = RestartIndex;
        }

        glUnmapBuffer(GL_ELEMENT_ARRAY_BUFFER);
    }

    glPrimitiveRestartIndex(RestartIndex);
    glEnable(GL_PRIMITIVE_RESTART);
}

void
display()
{
    int  i, start;

    glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);

    glColor3f(1, 1, 1);
    glDrawElements(GL_TRIANGLE_STRIP,
        NumStrips*(NumPointsPerStrip + 1),
        GL_UNSIGNED_SHORT, BUFFER_OFFSET(0));

    glutSwapBuffers();
}
```

Instanced Drawing

Advanced

Advanced

OpenGL Version 3.1 (specifically, GLSL version 1.40) added support for *instanced drawing*, which provides an additional value—`gl_InstanceID`, called the *instance ID*, and accessible only in a vertex shader—that is monotonically incremented for each group of primitives specified.

glDrawArraysInstanced() operates similarly to **glMultiDrawArrays()**, except that the starting index and vertex count (as specified by *first* and *count*, respectively) are the same for each call to **glDrawArrays()**.

void **glDrawArraysInstanced**(GLenum *mode*, GLint *first*, GLsizei *count*, GLsizei *primcount*);

Effectively calls **glDrawArrays()** *primcount* times, setting the GLSL vertex shader value gl_InstanceID before each call. *mode* specifies the primitive type. *first* and *count* specify the range of array elements that are passed to **glDrawArrays()**.

glDrawArraysInstanced() has the same effect as this call sequence (except that your application cannot manually update `gl_InstanceID`):

```
for (i = 0; i < primcount; i++) {
    gl_InstanceID = i;
    glDrawArrays(mode, first, count);
}
gl_InstanceID = 0;
```

Likewise, **glDrawElementsInstanced()** performs the same operation, but allows random-access to the data in the vertex array:

void **glDrawElementsInstanced**(GLenum *mode*, GLsizei *count*, GLenum *type*, const void **indicies*, GLsizei *primcount*);

Effectively calls **glDrawElements()** *primcount* times, setting the GLSL vertex shader value gl_InstanceID before each call. *mode* specifies the primitive type. *type* indicates the data type of the array *indices* and must be one of the following: GL_UNSIGNED_BYTE, GL_UNSIGNED_SHORT, or GL_UNSIGNED_INT. *indicies* and *count* specify the range of array elements that are passed to **glDrawElements()**.

The implementation of **glDrawElementsInstanced()** is shown here:

```
for (i = 0; i < primcount; i++) {
    gl_InstanceID = i;
    glDrawElements(mode, count, type, indicies);
}
gl_InstanceID = 0;
```

Interleaved Arrays

Advanced

Advanced

Earlier in this chapter (see "Stride" on page 76), the special case of interleaved arrays was examined. In that section, the array *intertwined*, which interleaves RGB color and 3D vertex coordinates, was accessed by calls to **glColorPointer()** and **glVertexPointer()**. Careful use of *stride* helped properly specify the arrays:

```
static GLfloat intertwined[] =
      {1.0, 0.2, 1.0, 100.0, 100.0, 0.0,
       1.0, 0.2, 0.2, 0.0, 200.0, 0.0,
       1.0, 1.0, 0.2, 100.0, 300.0, 0.0,
       0.2, 1.0, 0.2, 200.0, 300.0, 0.0,
       0.2, 1.0, 1.0, 300.0, 200.0, 0.0,
       0.2, 0.2, 1.0, 200.0, 100.0, 0.0};
```

There is also a behemoth routine, **glInterleavedArrays()**, that can specify several vertex arrays at once. **glInterleavedArrays()** also enables and disables the appropriate arrays (so it combines "Step 1: Enabling Arrays" on page 72 and "Step 2: Specifying Data for the Arrays" on page 73). The array *intertwined* exactly fits one of the 14 data-interleaving configurations supported by **glInterleavedArrays()**. Therefore, to specify the contents of the array *intertwined* into the RGB color and vertex arrays and enable both arrays, call

```
glInterleavedArrays(GL_C3F_V3F, 0, intertwined);
```

This call to **glInterleavedArrays()** enables GL_COLOR_ARRAY and GL_VERTEX_ARRAY. It disables GL_SECONDARY_COLOR_ARRAY, GL_INDEX_ARRAY, GL_NORMAL_ARRAY, GL_FOG_COORD_ARRAY, GL_TEXTURE_COORD_ARRAY, and GL_EDGE_FLAG_ARRAY.

This call also has the same effect as calling **glColorPointer()** and **glVertexPointer()** to specify the values for six vertices in each array. Now you are ready for Step 3: calling **glArrayElement()**, **glDrawElements()**, **glDrawRangeElements()**, or **glDrawArrays()** to dereference array elements.

Note that **glInterleavedArrays()** does not support edge flags.

The mechanics of **glInterleavedArrays()** are intricate and require reference to Example 2-16 and Table 2-5. In that example and table, you'll see e_t, e_c, and e_n, which are the Boolean values for the enabled or disabled texture coordinate, color, and normal arrays; and you'll see s_t, s_c, and s_v, which are the sizes (numbers of components) for the texture coordinate, color, and void **glInterleavedArrays**(GLenum *format*, GLsizei *stride*, const GLvoid **pointer*)

Compatibility Extension

glInterleavedArrays

Initializes all eight arrays, disabling arrays that are not specified in *format*, and enabling the arrays that are specified. *format* is one of 14 symbolic constants, which represent 14 data configurations; Table 2-5 displays *format* values. *stride* specifies the byte offset between consecutive vertices. If *stride* is 0, the vertices are understood to be tightly packed in the array. *pointer* is the memory address of the first coordinate of the first vertex in the array.

If multitexturing is enabled, **glInterleavedArrays()** affects only the active texture unit. See "Multitexturing" on page 467 for details.

vertex arrays. t_c is the data type for RGBA color, which is the only array that can have nonfloating-point interleaved values. p_c, p_n, and p_v are the calculated strides for jumping into individual color, normal, and vertex values; and s is the stride (if one is not specified by the user) to jump from one array element to the next.

The effect of **glInterleavedArrays()** is the same as calling the command sequence in Example 2-16 with many values defined in Table 2-5. All pointer arithmetic is performed in units of **sizeof**(GLubyte).

Example 2-16 Effect of glInterleavedArrays(format, stride, pointer)

```
int str;
/*  set et, ec, en, st, sc, sv, tc, pc, pn, pv, and s
 *  as a function of Table 2-5 and the value of format
 */

str = stride;
if (str == 0)
   str = s;

glDisableClientState(GL_EDGE_FLAG_ARRAY);
glDisableClientState(GL_INDEX_ARRAY);
glDisableClientState(GL_SECONDARY_COLOR_ARRAY);
glDisableClientState(GL_FOG_COORD_ARRAY);

if (et) {
   glEnableClientState(GL_TEXTURE_COORD_ARRAY);
   glTexCoordPointer(st, GL_FLOAT, str, pointer);
}
else
```

```
   glDisableClientState(GL_TEXTURE_COORD_ARRAY);
if (e_c) {
   glEnableClientState(GL_COLOR_ARRAY);
   glColorPointer(s_c, t_c, str, pointer+p_c);
}
else
   glDisableClientState(GL_COLOR_ARRAY);

if (e_n) {
   glEnableClientState(GL_NORMAL_ARRAY);
   glNormalPointer(GL_FLOAT, str, pointer+p_n);
}
else
   glDisableClientState(GL_NORMAL_ARRAY);

glEnableClientState(GL_VERTEX_ARRAY);
glVertexPointer(s_v, GL_FLOAT, str, pointer+p_v);
```

In Table 2-5, T and F are True and False. f is **sizeof**(GLfloat). c is 4 times **sizeof**(GLubyte), rounded up to the nearest multiple of f.

Format	e_t	e_c	e_n	s_t	s_c	s_v	t_c	p_c	p_n	p_v	s
GL_V2F	F	F	F			2				0	2f
GL_V3F	F	F	F			3				0	3f
GL_C4UB_V2F	F	T	F		4	2	GL_UNSIGNED_BYTE	0		c	c+2f
GL_C4UB_V3F	F	T	F		4	3	GL_UNSIGNED_BYTE	0		c	c+3f
GL_C3F_V3F	F	T	F		3	3	GL_FLOAT	0		3f	6f
GL_N3F_V3F	F	F	T			3			0	3f	6f
GL_C4F_N3F_V3F	F	T	T		4	3	GL_FLOAT	0	4f	7f	10f
GL_T2F_V3F	T	F	F	2		3				2f	5f
GL_T4F_V4F	T	F	F	4		4				4f	8f
GL_T2F_C4UB_V3F	T	T	F	2	4	3	GL_UNSIGNED_BYTE	2f		c+2f	c+5f
GL_T2F_C3F_V3F	T	T	F	2	3	3	GL_FLOAT	2f		5f	8f
GL_T2F_N3F_V3F	T	F	T	2		3			2f	5f	8f
GL_T2F_C4F_N3F_V3F	T	T	T	2	4	3	GL_FLOAT	2f	6f	9f	12f
GL_T4F_C4F_N3F_V4F	T	T	T	4	4	4	GL_FLOAT	4f	8f	11f	15f

Table 2-5 Variables That Direct glInterleavedArrays()

Start by learning the simpler formats, GL_V2F, GL_V3F, and GL_C3F_V3F. If you use any of the formats with C4UB, you may have to use a struct data type or do some delicate type casting and pointer math to pack four unsigned bytes into a single 32-bit word.

For some OpenGL implementations, use of interleaved arrays may increase application performance. With an interleaved array, the exact layout of your data is known. You know your data is tightly packed and may be accessed in one chunk. If interleaved arrays are not used, the *stride* and size information has to be examined to detect whether data is tightly packed.

Note: **glInterleavedArrays()** only enables and disables vertex arrays and specifies values for the vertex-array data. It does not render anything. You must still complete "Step 3: Dereferencing and Rendering" on page 77 and call **glArrayElement()**, **glDrawElements()**, **glDrawRangeElements()**, or **glDrawArrays()** to dereference the pointers and render graphics.

Buffer Objects

Advanced

Advanced

There are many operations in OpenGL where you send a large block of data to OpenGL, such as passing vertex array data for processing. Transferring that data may be as simple as copying from your system's memory down to your graphics card. However, because OpenGL was designed as a client-server model, any time that OpenGL needs data, it will have to be transferred from the client's memory. If that data doesn't change, or if the client and server reside on different computers (distributed rendering), that data transfer may be slow, or redundant.

Buffer objects were added to OpenGL Version 1.5 to allow an application to explicitly specify which data it would like to be stored in the graphics server.

Many different types of buffer objects are used in the current versions of OpenGL:

- Vertex data in arrays can be stored in server-side buffer objects starting with OpenGL Version 1.5. They are described in "Using Buffer Objects with Vertex-Array Data" on page 102 of this chapter.
- Support for storing pixel data, such as texture maps or blocks of pixels, in buffer objects was added into OpenGL Version 2.1 It is described in "Using Buffer Objects with Pixel Rectangle Data" in Chapter 8.

- Version 3.1 added *uniform buffer objects* for storing blocks of uniform-variable data for use with shaders.

You will find many other features in OpenGL that use the term "objects," but not all apply to storing blocks of data. For example, texture objects (introduced in OpenGL Version 1.1) merely encapsulate various state settings associated with texture maps (See "Texture Objects" on page 437). Likewise, vertex-array objects, added in Version 3.0, encapsulate the state parameters associated with using vertex arrays. These types of objects allow you to alter numerous state settings with many fewer function calls. For maximum performance, you should try to use them whenever possible, once you're comfortable with their operation.

Note: An object is referred to by its name, which is an unsigned integer identifier. Starting with Version 3.1, all names must be generated by OpenGL using one of the **glGen*()** routines; user-defined names are no longer accepted.

Creating Buffer Objects

In OpenGL Version 3.0, any nonzero unsigned integer may used as a buffer object identifier. You may either arbitrarily select representative values or let OpenGL allocate and manage those identifiers for you. Why the difference? By having OpenGL allocate identifiers, you are guaranteed to avoid an already used buffer object identifier. This helps to eliminate the risk of modifying data unintentionally. In fact, OpenGL Version 3.1 requires that all object identifiers be generated, disallowing user-defined names.

To have OpenGL allocate buffer objects identifiers, call **glGenBuffers()**.

void **glGenBuffers**(GLsizei *n*, GLuint **buffers*);

Returns *n* currently unused names for buffer objects in the array *buffers*. The names returned in *buffers* do not have to be a contiguous set of integers.

The names returned are marked as used for the purposes of allocating additional buffer objects, but only acquire a valid state once they have been bound.

Zero is a reserved buffer object name and is never returned as a buffer object by **glGenBuffers()**.

You can also determine whether an identifier is a currently used buffer object identifier by calling **glIsBuffer()**.

GLboolean **glIsBuffer**(GLuint *buffer*);

Returns GL_TRUE if *buffer* is the name of a buffer object that has been bound, but has not been subsequently deleted. Returns GL_FALSE if *buffer* is zero or if *buffer* is a nonzero value that is not the name of a buffer object.

Making a Buffer Object Active

To make a buffer object active, it needs to be bound. Binding selects which buffer object future operations will affect, either for initializing data or using that buffer for rendering. That is, if you have more than one buffer object in your application, you'll likely call **glBindBuffer()** multiple times: once to initialize the object and its data, and then subsequent times either to select that object for use in rendering or to update its data.

To disable use of buffer objects, call **glBindBuffer()** with zero as the buffer identifier. This switches OpenGL to the default mode of not using buffer objects.

void **glBindBuffer**(GLenum *target*, GLuint *buffer*);

Specifies the current active buffer object. *target* must be set to one of GL_ARRAY_BUFFER, GL_ELEMENT_ARRAY_BUFFER, GL_PIXEL_PACK_BUFFER, GL_PIXEL_UNPACK_BUFFER, GL_COPY_READ_BUFFER, GL_COPY_WRITE_BUFFER, GL_TRANSFORM_FEEDBACK_BUFFER, or GL_UNIFORM_BUFFER. *buffer* specifies the buffer object to be bound to.

glBindBuffer() does three things: 1. When using *buffer* of an unsigned integer other than zero for the first time, a new buffer object is created and assigned that name. 2. When binding to a previously created buffer object, that buffer object becomes the active buffer object. 3. When binding to a *buffer* value of zero, OpenGL stops using buffer objects.

Allocating and Initializing Buffer Objects with Data

Once you've bound a buffer object, you need to reserve space for storing your data. This is done by calling **glBufferData()**.

void **glBufferData**(GLenum *target*, GLsizeiptr *size*, const GLvoid **data*, GLenum *usage*);

Allocates *size* storage units (usually bytes) of OpenGL server memory for storing vertex array data or indices. Any previous data associated with the currently bound object will be deleted.

target may be either GL_ARRAY_BUFFER for vertex data; GL_ELEMENT_ARRAY_BUFFER for index data; GL_PIXEL_UNPACK_BUFFER for pixel data being passed into OpenGL; GL_PIXEL_PACK_BUFFER for pixel data being retrieved from OpenGL; GL_COPY_READ_BUFFER and GL_COPY_WRITE_BUFFER for data copied between buffers; GL_TEXTURE_BUFFER for texture data stored as a texture buffer; GL_TRANSFORM_FEEDBACK_BUFFER for results from executing a transform feedback shader; or GL_UNIFORM_BUFFER for uniform variable values.

size is the amount of storage required for storing the respective data. This value is generally number of elements in the data multiplied by their respective storage size.

data is either a pointer to a client memory that is used to initialize the buffer object or NULL. If a valid pointer is passed, *size* units of storage are copied from the client to the server. If NULL is passed, *size* units of storage are reserved for use, but are left uninitialized.

usage provides a hint as to how the data will be read and written after allocation. Valid values are GL_STREAM_DRAW, GL_STREAM_READ, GL_STREAM_COPY, GL_STATIC_DRAW, GL_STATIC_READ, GL_STATIC_COPY, GL_DYNAMIC_DRAW, GL_DYNAMIC_READ, GL_DYNAMIC_COPY.

glBufferData() will generate a GL_OUT_OF_MEMORY error if the requested *size* exceeds what the server is able to allocate. It will generate a GL_INVALID_VALUE error if usage is not one of the permitted values.

glBufferData() first allocates memory in the OpenGL server for storing your data. If you request too much memory, a GL_OUT_OF_MEMORY error will be set. Once the storage has been reserved, and if the *data* parameter is not NULL, *size* units of storage (usually bytes) are copied from the client's memory into the buffer object. However, if you need to dynamically load the data at some point after the buffer is created, pass NULL in for the *data* pointer. This will reserve the appropriate storage for your data, but leave it uninitialized.

The final parameter to **glBufferData()**, *usage*, is a performance hint to OpenGL. Based upon the value you specify for *usage*, OpenGL may be able to optimize the data for better performance, or it can choose to ignore the hint. There are three operations that can be done to buffer object data:

1. Drawing—the client specifies data that is used for rendering.
2. Reading—data values are read from an OpenGL buffer (such as the framebuffer) and used in the application in various computations not immediately related to rendering.
3. Copying—data values are read from an OpenGL buffer and then used as data for rendering.

Additionally, depending upon how often you intend to update the data, there are various operational hints for describing how often the data will be read or used in rendering:

- Stream mode—you specify the data once, and use it only a few times in drawing or other operations.
- Static mode—you specify the data once, but use the values often.
- Dynamic mode—you may update the data often and use the data values in the buffer object many times as well.

Possible values for *usage* are described in Table 2-6.

Parameter	Meaning
GL_STREAM_DRAW	Data is specified once and used at most a few times as the source of drawing and image specification commands.
GL_STREAM_READ	Data is copied once from an OpenGL buffer and is used at most a few times by the application as data values.
GL_STREAM_COPY	Data is copied once from an OpenGL buffer and is used at most a few times as the source for drawing or image specification commands.
GL_STATIC_DRAW	Data is specified once and used many times as the source of drawing or image specification commands.
GL_STATIC_READ	Data is copied once from an OpenGL buffer and is used many times by the application as data values.

Table 2-6 Values for *usage* Parameter of glBufferData()

Parameter	Meaning
GL_STATIC_COPY	Data is copied once from an OpenGL buffer and is used many times as the source for drawing or image specification commands.
GL_DYNAMIC_DRAW	Data is specified many times and used many times as the source of drawing and image specification commands.
GL_DYNAMIC_READ	Data is copied many times from an OpenGL buffer and is used many times by the application as data values.
GL_DYNAMIC_COPY	Data is copied many times from an OpenGL buffer and is used many times as the source for drawing or image specification commands.

Table 2-6 (continued) Values for *usage* Parameter of glBufferData()

Updating Data Values in Buffer Objects

There are two methods for updating data stored in a buffer object. The first method assumes that you have data of the same type prepared in a buffer in your application. **glBufferSubData()** will replace some subset of the data in the bound buffer object with the data you provide.

void **glBufferSubData**(GLenum *target*, GLintptr *offset*, GLsizeiptr *size*, const GLvoid **data*);

Update *size* bytes starting at *offset* (also measured in bytes) in the currently bound buffer object associated with *target* using the data pointed to by *data*. *target* must be one of GL_ARRAY_BUFFER, GL_ELEMENT_ARRAY_BUFFER, GL_PIXEL_UNPACK_BUFFER, GL_PIXEL_PACK_BUFFER, GL_COPY_READ_BUFFER, GL_COPY_WRITE_BUFFER, GL_TRANSFORM_FEEDBACK_BUFFER, or GL_UNIFORM_BUFFER.

glBufferSubData() will generate a GL_INVALID_VALUE error if *size* is less than zero or if *size* + *offset* is greater than the original size specified when the buffer object was created.

The second method allows you more control over which data values are updated in the buffer. **glMapBuffer()** and **glMapBufferRange()** return a pointer to the buffer object memory, into which you can write new values (or simply read the data, depending on your choice of memory access permissions), just as if you were assigning values to an array. When you've completed updating the values in the buffer, you call **glUnmapBuffer()** to signify that you've completed updating the data.

glMapBuffer() provides access to the entire set of data contained in the buffer object. This approach is useful if you need to modify much of the data in buffer, but may be inefficient if you have a large buffer and need to update only a small portion of the values.

GLvoid ***glMapBuffer**(GLenum *target*, GLenum *access*);

Returns a pointer to the data storage for the currently bound buffer object associated with *target*, which must be one of GL_ARRAY_BUFFER, GL_ELEMENT_ARRAY_BUFFER, GL_PIXEL_PACK_BUFFER, GL_PIXEL_UNPACK_BUFFER, GL_COPY_READ_BUFFER, GL_COPY_WRITE_BUFFER, GL_TRANSFORM_FEEDBACK_BUFFER, or GL_UNIFORM_BUFFER. *access* must be either GL_READ_ONLY, GL_WRITE_ONLY, or GL_READ_WRITE, indicating the operations that a client may do on the data.

glMapBuffer() will return NULL either if the buffer cannot be mapped (setting the OpenGL error state to GL_OUT_OF_MEMORY) or if the buffer was already mapped previously (where the OpenGL error state will be set to GL_INVALID_OPERATION).

When you've completed accessing the storage, you can unmap the buffer by calling **glUnmapBuffer()**.

GLboolean **glUnmapBuffer**(GLenum *target*);

Indicates that updates to the currently bound buffer object are complete, and the buffer may be released. *target* must be one of GL_ARRAY_BUFFER, GL_ELEMENT_ARRAY_BUFFER, GL_PIXEL_PACK_BUFFER, GL_PIXEL_UNPACK_BUFFER, GL_COPY_READ_BUFFER, GL_COPY_WRITE_BUFFER, GL_TRANSFORM_FEEDBACK_BUFFER, or GL_UNIFORM_BUFFER.

As a simple example of how you might selectively update elements of your data, we'll use **glMapBuffer()** to obtain a pointer to the data in a buffer object containing three-dimensional positional coordinates, and then update only the *z*-coordinates.

```
GLfloat* data;

data = (GLfloat*) glMapBuffer(GL_ARRAY_BUFFER, GL_READ_WRITE);

if (data != (GLfloat*) NULL) {
    for( i = 0; i < 8; ++i )
        data[3*i+2] *= 2.0;  /* Modify Z values */
    glUnmapBuffer(GL_ARRAY_BUFFER);
} else {
    /* Handle not being able to update data */
}
```

If you need to update only a relatively small number of values in the buffer (as compared to its total size), or small contiguous ranges of values in a very large buffer object, it may be more efficient to use **glMapBufferRange()**. It allows you to map only the range of data values you need.

GLvoid ***glMapBufferRange**(GLenum *target*, GLintptr *offset*, GLsizeiptr *length*, GLbitfield *access*);

Returns a pointer into the data storage for the currently bound buffer object associated with *target*, which must be one of GL_ARRAY_BUFFER, GL_ELEMENT_ARRAY_BUFFER, GL_PIXEL_PACK_BUFFER, GL_PIXEL_UNPACK_BUFFER, GL_COPY_READ_BUFFER, GL_COPY_WRITE_BUFFER, GL_TRANSFORM_FEEDBACK_BUFFER, or GL_UNIFORM_BUFFER. *offset* and *length* specify the range to be mapped. *access* is a bitmask composed of GL_MAP_READ_BIT, GL_MAP_WRITE_BIT, which indicate the operations that a client may do on the data, and optionally GL_MAP_INVALIDATE_RANGE_BIT, GL_MAP_INVALIDATE_BUFFER_BIT, GL_MAP_FLUSH_EXPLICIT_BIT, or GL_MAP_UNSYNCHRONIZED_BIT, which provide hints on how OpenGL should manage the data in the buffer.

glMapBufferRange() will return NULL if an error occurs. GL_INVALID_VALUE is generated if *offset* or *length* are negative, or *offset+length* is greater than the buffer size. GL_OUT_OF_MEMORY error is generated if adequate memory cannot be obtained to map the buffer. GL_INVALID_OPERATION is generated if any of the following occur: The buffer is already mapped; *access* does not have either GL_MAP_READ_BIT or GL_MAP_WRITE_BIT set; *access* has GL_MAP_READ_BIT set and any of GL_MAP_INVALIDATE_RANGE_BIT, GL_MAP_INVALIDATE_BUFFER_BIT, or GL_MAP_UNSYNCHRONIZED_BIT is also set; or both GL_MAP_WRITE_BIT and GL_MAP_FLUSH_EXPLICIT_BIT are set in *access*.

Using **glMapBufferRange()**, you can specify optional hints by setting additional bits within *access*. These flags describe how the OpenGL server needs to preserve data that was originally in the buffer before you mapped it. The hints are meant to aid the OpenGL implementation in determining which data values it needs to retain, or for how long, to keep any internal copies of the data correct and consistent.

Parameter	**Meaning**
GL_MAP_INVALIDATE_RANGE_BIT	Specify that the previous values in the mapped range may be discarded, but preserve the other values within the buffer. Data within this range are undefined unless explicitly written. No OpenGL error is generated if later OpenGL calls access undefined data, and the results of such calls are undefined (but may cause application or system errors). This flag may not be used in conjunction with the GL_READ_BIT.
GL_MAP_INVALIDATE_BUFFER_BIT	Specify that the previous values of the entire buffer may be discarded, and all values with the buffer are undefined unless explicitly written. No OpenGL error is generated if later OpenGL calls access undefined data, and the results of such calls are undefined (but may cause application or system errors). This flag may not be used in conjunction with the GL_READ_BIT.
GL_MAP_FLUSH_EXPLICIT_BIT	Indicate that discrete ranges of the mapped region may be updated, that the application will signal when modifications to a range should be considered completed by calling **glFlushMappedBufferRange()**. No OpenGL error is generated if a range of the mapped buffer is updated but not flushed, however, the values are undefined until flushed. Using this option will require any modified ranges to be explicitly flushed to the OpenGL server—**glUnmapBuffer()** will not automatically flush the buffer's data.

Table 2-7 Values for the *access* Parameter of glMapBufferRange()

Parameter	Meaning
GL_MAP_UNSYNCHRONIZED_BIT	Specify that OpenGL should not attempt to synchronize pending operations on a buffer (e.g., updating data with a call to **glBufferData()**, or the application is trying to use the data in the buffer for rendering) until the call to **glMapBufferRange()** has completed. No OpenGL errors are generated for the pending operations that access or modify the mapped region, but the results of those operations is undefined.

Table 2-7 (continued) Values for the *access* Parameter of glMapBufferRange()

As described in Table 2-7, specifying GL_MAP_FLUSH_EXPLICIT_BIT in the access flags when mapping a buffer region with **glMapBufferRange()** requires ranges modified within the mapped buffer to be indicated to the OpenGL by a call to **glFlushMappedBufferRange().**

GLvoid **glFlushMappedBufferRange**(GLenum *target*, GLintptr *offset*, GLsizeiptr *length*);

Signal that values within a mapped buffer range have been modified, which may cause the OpenGL server to update cached copies of the buffer object. *target* must be one of the following: GL_ARRAY_BUFFER, GL_ELEMENT_ARRAY_BUFFER, GL_PIXEL_PACK_BUFFER, GL_PIXEL_UNPACK_BUFFER, GL_COPY_READ_BUFFER, GL_COPY_WRITE_BUFFER, GL_TRANSFORM_FEEDBACK_BUFFER, or GL_UNIFORM_BUFFER. *offset* and *length* specify the range of the mapped buffer region, relative to the beginning of the mapped range of the buffer.

A GL_INVALID_VALUE error is generated if *offset* or *length* is negative or if *offset+length* is greater than the size of the mapped region. A GL_INVALID_OPERATION error is generated if there is no buffer bound to *target* (i.e., zero was specified as the buffer to be bound in a call to **glBindBuffer()** for *target*), or if the buffer bound to *target* is not mapped, or if it is mapped without having set the GL_MAP_FLUSH_EXPLICIT_BIT.

Copying Data Between Buffer Objects

On some occasions, you may need to copy data from one buffer object to another. In versions of OpenGL prior to Version 3.1, this would be a two-step process:

1. Copy the data from the buffer object into memory in your application. You would do this either by mapping the buffer and copying it into a local memory buffer, or by calling **glGetBufferSubData()** to copy the data from the server.
2. Update the data in another buffer object by binding to the new object and then sending the new data using **glBufferData()** (or **glBufferSubData()** if you're replacing only a subset). Alternatively, you could map the buffer, and then copy the data from a local memory buffer into the mapped buffer.

In OpenGL Version 3.1, the **glCopyBufferSubData()** command copies data without forcing it to make a temporary stop in your application's memory.

void **glCopyBufferSubData**(GLenum *readbuffer*, GLenum *writebuffer*,
GLintptr *readoffset*, GLintptr *writeoffset*,
GLsizeiptr *size*);

Copy data from the buffer object associated with *readbuffer* to the buffer object bound to *writebuffer*. *readbuffer* and *writebuffer* must be one of GL_ARRAY_BUFFER, GL_COPY_READ_BUFFER, GL_COPY_WRITE_BUFFER, GL_ELEMENT_ARRAY_BUFFER, GL_PIXEL_PACK_BUFFER, GL_PIXEL_UNPACK_BUFFER, GL_TEXTURE_BUFFER, GL_TRANSFORM_FEEDBACK_BUFFER, or GL_UNIFORM_BUFFER.

readoffset and *size* specify the amount of data copied into the destination buffer object, replacing the same size of data starting at *writeoffset*.

Numerous situations will cause a GL_INVALID_VALUE error to be generated: *readoffset*, *writeoffset*, or *size* being negative; *readoffset* + *size* exceeding the extent of the buffer object bound to *readbuffer*; *writeoffset* + *size* exceeding the extent of the buffer object bound to *writebuffer*; or if *readbuffer* and *writebuffer* are bound to the same object, and the regions specified by *readoffset* and *size* overlap the region defined by *writeoffset* and *size*.

A GL_INVALID_OPERATION error is generated if either *readbuffer* or *writebuffer* is bound to zero, or either buffer is currently mapped.

Cleaning Up Buffer Objects

When you're finished with a buffer object, you can release its resources and make its identifier available by calling **glDeleteBuffers()**. Any bindings to currently bound objects that are deleted are reset to zero.

void **glDeleteBuffers**(GLsizei *n*, const GLuint **buffers*);

Deletes *n* buffer objects, named by elements in the array *buffers*. The freed buffer objects may now be reused (for example, by **glGenBuffers()**).

If a buffer object is deleted while bound, all bindings to that object are reset to the default buffer object, as if **glBindBuffer()** had been called with zero as the specified buffer object. Attempts to delete nonexistent buffer objects or the buffer object named zero are ignored without generating an error.

Using Buffer Objects with Vertex-Array Data

To store your vertex-array data in buffer objects, you will need to add a few steps to your application.

1. (Optional) Generate buffer object identifiers.
2. Bind a buffer object, specifying that it will be used for either storing vertex data or indices.
3. Request storage for your data, and optionally initialize those data elements.
4. Specify offsets relative to the start of the buffer object to initialize the vertex-array functions, such as **glVertexPointer()**.
5. Bind the appropriate buffer object to be utilized in rendering.
6. Render using an appropriate vertex-array rendering function, such as **glDrawArrays()** or **glDrawElements()**.

If you need to initialize multiple buffer objects, you will repeat steps 2 through 4 for each buffer object.

Both "formats" of vertex-array data are available for use in buffer objects. As described in "Step 2: Specifying Data for the Arrays," vertex, color, lighting normal, or any other type of associated vertex data can be stored in a buffer object. Additionally, interleaved vertex array data, as described in "Interleaved Arrays," can also be stored in a buffer object. In either case, you would create a single buffer object to hold all of the data to be used as vertex arrays.

As compared to specifying a memory address in the client's memory where OpenGL should access the vertex-array data, you specify the offset in machine units (usually bytes) to the data in the buffer. To help illustrate computing the offset, and to frustrate the purists in the audience, we'll use the following macro to simplify expressing the offset:

```
#define BUFFER_OFFSET(bytes)  ((GLubyte*) NULL + (bytes))
```

For example, if you had floating-point color and position data for each vertex, perhaps represented as the following array

```
GLfloat vertexData[][6] = {
    { R0, G0, B0, X0, Y0, Z0 },
    { R1, G1, B1, X1, Y1, Z1 },
    ...
    { Rn, Gn, Bn, Xn, Yn, Zn }
};
```

that were used to initialize the buffer object, you could specify the data as two separate vertex array calls, one for colors and one for vertices:

```
glColorPointer(3, GL_FLOAT, 6*sizeof(GLfloat),BUFFER_OFFSET(0));
glVertexPointer(3, GL_FLOAT, 6*sizeof(GLfloat),
                BUFFER_OFFSET(3*sizeof(GLfloat));
glEnableClientState(GL_COLOR_ARRAY);
glEnableClientState(GL_VERTEX_ARRAY);
```

Conversely, since the data in *vertexData* matches a format for an interleaved vertex array, you could use **glInterleavedArrays()** for specifying the vertex-array data:

```
glInterleavedArrays(GL_C3F_V3F, 0, BUFFER_OFFSET(0));
```

Putting this all together, Example 2-17 demonstrates how buffer objects of vertex data might be used. The example creates two buffer objects, one containing vertex data and the other containing index data.

Example 2-17 Using Buffer Objects with Vertex Data

```
#define VERTICES     0
#define INDICES      1
#define NUM_BUFFERS  2
```

```
GLuint  buffers[NUM_BUFFERS];

GLfloat vertices[][3] = {
    { -1.0, -1.0, -1.0 },
    {  1.0, -1.0, -1.0 },
    {  1.0,  1.0, -1.0 },
    { -1.0,  1.0, -1.0 },
    { -1.0, -1.0,  1.0 },
    {  1.0, -1.0,  1.0 },
    {  1.0,  1.0,  1.0 },
    { -1.0,  1.0,  1.0 }
};

GLubyte indices[][4] = {
    { 0, 1, 2, 3 },
    { 4, 7, 6, 5 },
    { 0, 4, 5, 1 },
    { 3, 2, 6, 7 },
    { 0, 3, 7, 4 },
    { 1, 5, 6, 2 }
};

glGenBuffers(NUM_BUFFERS, buffers);

glBindBuffer(GL_ARRAY_BUFFER, buffers[VERTICES]);
glBufferData(GL_ARRAY_BUFFER, sizeof(vertices), vertices,
             GL_STATIC_DRAW);
glVertexPointer(3, GL_FLOAT, 0, BUFFER_OFFSET(0));
glEnableClientState(GL_VERTEX_ARRAY);

glBindBuffer(GL_ELEMENT_ARRAY_BUFFER, buffers[INDICES]);
glBufferData(GL_ELEMENT_ARRAY_BUFFER, sizeof(indices), indices
             GL_STATIC_DRAW);

glDrawElements(GL_QUADS, 24, GL_UNSIGNED_BYTE,
               BUFFER_OFFSET(0));
```

Vertex-Array Objects

As your programs grow larger and use more models, you will probably find that you switch between multiple sets of vertex arrays each frame. Depending on how many vertex attributes you're using for each vertex, the number of calls—such as to **glVertexPointer()—**may start to become large.

Vertex-array objects bundle collections of calls for setting the vertex array's state. After being initialized, you can quickly change between different sets of vertex arrays with a single call.

To create a vertex-array object, first call **glGenVertexArrays()**, which will create the requested number of uninitialized objects:

void **glGenVertexArrays**(GLsizei *n*, GLuint **arrays*);

Returns *n* currently unused names for use as vertex-array objects in the array *arrays*. The names returned are marked as used for the purposes of allocating additional buffer objects, and initialized with values representing the default state of the collection of uninitialized vertex arrays.

After creating your vertex-array objects, you'll need to initialize the new objects, and associate the set of vertex-array data that you want to enable with the individual allocated objects. You do this with the **glBindVertexArray()** routine. Once you initialize all of your vertex-array objects, you can use **glBindVertexArray()** to switch between the different sets of vertex arrays that you've set up.

GLvoid **gBindVertexArray**(GLuint *array*);

glBindVertexArray() does three things. When using the value *array* that is other than zero and was returned from **glGenVertexArrays()**, a new vertex-array object is created and assigned that name. When binding to a previously created vertex-array object, that vertex array object becomes active, which additionally affects the vertex array state stored in the object. When binding to an *array* value of zero, OpenGL stops using vertex-array objects and returns to the default state for vertex arrays.

A GL_INVALID_OPERATION error is generated if *array* is not a value previously returned from **glGenVertexArrays()**, or if it is a value that has been released by **glDeleteVertexArrays()**, or if any of the **gl*Pointer()** routines are called to specify a vertex array that is not associated with a buffer object while a non-zero vertex-array object is bound (i.e., using a client-side vertex array storage).

Example 2-18 demonstrates switching between two sets of vertex arrays using vertex-arrays objects.

Example 2-18 Using Vertex-Array Objects: vao.c

```
#define BUFFER_OFFSET(offset)  ((GLvoid*) NULL + offset)
#define NumberOf(array)        (sizeof(array)/sizeof(array[0]))

typedef struct {
    GLfloat x, y, z;
} vec3;


typedef struct {
    vec3     xlate;   /* Translation */
    GLfloat  angle;
    vec3     axis;
} XForm;

enum { Cube, Cone, NumVAOs };
GLuint   VAO[NumVAOs];
GLenum   PrimType[NumVAOs];
GLsizei  NumElements[NumVAOs];
XForm    Xform[NumVAOs] = {
    { { -2.0, 0.0, 0.0 }, 0.0, { 0.0, 1.0, 0.0 } },
    { {  0.0, 0.0, 2.0 }, 0.0, { 1.0, 0.0, 0.0 } }
};
GLfloat  Angle = 0.0;

void
init()
{
    enum { Vertices, Colors, Elements, NumVBOs };
    GLuint  buffers[NumVBOs];

    glGenVertexArrays(NumVAOs, VAO);

    {
        GLfloat  cubeVerts[][3] = {
            { -1.0, -1.0, -1.0 },
            { -1.0, -1.0,  1.0 },
            { -1.0,  1.0, -1.0 },
            { -1.0,  1.0,  1.0 },
            {  1.0, -1.0, -1.0 },
            {  1.0, -1.0,  1.0 },
            {  1.0,  1.0, -1.0 },
            {  1.0,  1.0,  1.0 },
        };
```

```
    GLfloat  cubeColors[][3] = {
        {  0.0,  0.0,  0.0 },
        {  0.0,  0.0,  1.0 },
        {  0.0,  1.0,  0.0 },
        {  0.0,  1.0,  1.0 },
        {  1.0,  0.0,  0.0 },
        {  1.0,  0.0,  1.0 },
        {  1.0,  1.0,  0.0 },
        {  1.0,  1.0,  1.0 },
    };

    GLubyte  cubeIndices[] = {
        0, 1, 3, 2,
        4, 6, 7, 5,
        2, 3, 7, 6,
        0, 4, 5, 1,
        0, 2, 6, 4,
        1, 5, 7, 3
    };

    glBindVertexArray(VAO[Cube]);
    glGenBuffers(NumVBOs, buffers);
    glBindBuffer(GL_ARRAY_BUFFER, buffers[Vertices]);
    glBufferData(GL_ARRAY_BUFFER, sizeof(cubeVerts),
        cubeVerts, GL_STATIC_DRAW);
    glVertexPointer(3, GL_FLOAT, 0, BUFFER_OFFSET(0));
    glEnableClientState(GL_VERTEX_ARRAY);

    glBindBuffer(GL_ARRAY_BUFFER, buffers[Colors]);
    glBufferData(GL_ARRAY_BUFFER, sizeof(cubeColors),
        cubeColors, GL_STATIC_DRAW);
    glColorPointer(3, GL_FLOAT, 0, BUFFER_OFFSET(0));
    glEnableClientState(GL_COLOR_ARRAY);

    glBindBuffer(GL_ELEMENT_ARRAY_BUFFER,
        buffers[Elements]);
    glBufferData(GL_ELEMENT_ARRAY_BUFFER,
        sizeof(cubeIndices), cubeIndices, GL_STATIC_DRAW);

    PrimType[Cube] = GL_QUADS;
    NumElements[Cube] = NumberOf(cubeIndices);
}

{
    int i, idx;
    float  dTheta;
```

```
#define NumConePoints  36
        /* We add one more vertex for the cone's apex */
        GLfloat  coneVerts[NumConePoints+1][3] = {
            {0.0, 0.0, 1.0}
        };
        GLfloat  coneColors[NumConePoints+1][3] = {
            {1.0, 1.0, 1.0}
        };
        GLubyte  coneIndices[NumConePoints+1];

        dTheta = 2*M_PI / (NumConePoints - 1);
        idx = 1;
        for (i = 0; i < NumConePoints; ++i, ++idx) {
            float theta = i*dTheta;
            coneVerts[idx][0] = cos(theta);
            coneVerts[idx][1] = sin(theta);
            coneVerts[idx][2] = 0.0;

            coneColors[idx][0] = cos(theta);
            coneColors[idx][1] = sin(theta);
            coneColors[idx][2] = 0.0;

            coneIndices[idx] = idx;
        }

        glBindVertexArray(VAO[Cone]);
        glGenBuffers(NumVBOs, buffers);
        glBindBuffer(GL_ARRAY_BUFFER, buffers[Vertices]);
        glBufferData(GL_ARRAY_BUFFER, sizeof(coneVerts),
            coneVerts, GL_STATIC_DRAW);
        glVertexPointer(3, GL_FLOAT, 0, BUFFER_OFFSET(0));
        glEnableClientState(GL_VERTEX_ARRAY);

        glBindBuffer(GL_ARRAY_BUFFER, buffers[Colors]);
        glBufferData(GL_ARRAY_BUFFER, sizeof(coneColors),
            coneColors, GL_STATIC_DRAW);
        glColorPointer(3, GL_FLOAT, 0, BUFFER_OFFSET(0));
        glEnableClientState(GL_COLOR_ARRAY);

        glBindBuffer(GL_ELEMENT_ARRAY_BUFFER,
            buffers[Elements]);
        glBufferData(GL_ELEMENT_ARRAY_BUFFER,
            sizeof(coneIndices), coneIndices, GL_STATIC_DRAW);

        PrimType[Cone] = GL_TRIANGLE_FAN;
        NumElements[Cone] = NumberOf(coneIndices);
    }

    glEnable(GL_DEPTH_TEST);
}
```

```
void
display()
{
    int  i;

    glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);

    glPushMatrix();
    glRotatef(Angle, 0.0, 1.0, 0.0);

    for (i = 0; i < NumVAOs; ++i) {
        glPushMatrix();
        glTranslatef(Xform[i].xlate.x, Xform[i].xlate.y,
            Xform[i].xlate.z);
        glRotatef(Xform[i].angle, Xform[i].axis.x,
            Xform[i].axis.y, Xform[i].axis.z);
        glBindVertexArray(VAO[i]);
        glDrawElements(PrimType[i], NumElements[i],
            GL_UNSIGNED_BYTE, BUFFER_OFFSET(0));
        glPopMatrix();
    }

    glPopMatrix();
    glutSwapBuffers();
}
```

To delete vertex-array objects and release their names for reuse, call **glDeleteVertexArrays()**. If you're using buffer objects for storing data, they are not deleted when the vertex-array object referencing them is deleted. They continue to exist (until you delete them). The only change that occurs is if the buffer objects were currently bound when you deleted the vertex-array object, they become unbound.

void **glDeleteVertexArrays**(GLsizei *n*, GLuint **arrays*);

Deletes the *n* vertex-arrays objects specified in *arrays*, enabling the names for reuse as vertex arrays later. If a bound vertex array is deleted, the bindings for that vertex array become zero (as if you had called **glBindBuffer()** with a value of zero), and the default vertex array becomes the current one. Unused names in arrays are released, but no changes to the current vertex array state are made.

Finally, if you need to determine whether a particular value might represent an allocated (but not necessarily initialized) vertex-array object, you can check by calling **glIsVertexArray().**

GLboolean **glIsVertexArray**(GLuint *array*);

Returns GL_TRUE if *array* is the name of a vertex-array object that was previously generated with **glGenVertexArrays()**, but has not been subsequently deleted. Returns GL_FALSE if *array* is zero or a nonzero value that is not the name of a vertex-array object.

Attribute Groups

In "Basic State Management" you saw how to set or query an individual state or state variable. You can also save and restore the values of a collection of related state variables with a single command.

OpenGL groups related state variables into an *attribute group*. For example, the GL_LINE_BIT attribute consists of five state variables: the line width, the GL_LINE_STIPPLE enable status, the line stipple pattern, the line stipple repeat counter, and the GL_LINE_SMOOTH enable status. (See "Antialiasing" in Chapter 6.) With the commands **glPushAttrib()** and **glPopAttrib()**, you can save and restore all five state variables at once.

Some state variables are in more than one attribute group. For example, the state variable GL_CULL_FACE is part of both the polygon and the enable attribute groups.

In OpenGL Version 1.1, there are now two different attribute stacks. In addition to the original attribute stack (which saves the values of server state variables), there is also a client attribute stack, accessible by the commands **glPushClientAttrib()** and **glPopClientAttrib()**.

In general, it's faster to use these commands than to get, save, and restore the values yourself. Some values might be maintained in the hardware, and getting them might be expensive. Also, if you're operating on a remote client, all the attribute data has to be transferred across the network connection and back as it is obtained, saved, and restored. However, your OpenGL implementation keeps the attribute stack on the server, avoiding unnecessary network delays.

There are about 20 different attribute groups, which can be saved and restored by **glPushAttrib()** and **glPopAttrib()**. There are two client attribute groups, which can be saved and restored by **glPushClientAttrib()** and **glPopClientAttrib()**. For both server and client, the attributes are stored on a stack, which has a depth of at least 16 saved attribute groups. (The actual stack depths for your implementation can be obtained using GL_MAX_ATTRIB_STACK_DEPTH and GL_MAX_CLIENT_ATTRIB_STACK_DEPTH with **glGetIntegerv()**.) Pushing a full stack or popping an empty one generates an error.

(See the tables in Appendix B to find out exactly which attributes are saved for particular mask values—that is, which attributes are in a particular attribute group.)

void **glPushAttrib**(GLbitfield *mask*);
void **glPopAttrib**(void);

glPushAttrib() saves all the attributes indicated by bits in *mask* by pushing them onto the attribute stack. **glPopAttrib()** restores the values of those state variables that were saved with the last **glPushAttrib()**. Table 2-8 lists the possible mask bits that can be logically ORed together to save any combination of attributes. Each bit corresponds to a collection of individual state variables. For example, GL_LIGHTING_BIT refers to all the state variables related to lighting, which include the current material color; the ambient, diffuse, specular, and emitted light; a list of the lights that are enabled; and the directions of the spotlights. When **glPopAttrib()** is called, all these variables are restored.

The special mask GL_ALL_ATTRIB_BITS is used to save and restore all the state variables in all the attribute groups.

Mask Bit	Attribute Group
GL_ACCUM_BUFFER_BIT	accum-buffer
GL_ALL_ATTRIB_BITS	—
GL_COLOR_BUFFER_BIT	color-buffer
GL_CURRENT_BIT	current
GL_DEPTH_BUFFER_BIT	depth-buffer

Table 2-8 Attribute Groups

Compatibility Extension

glPushAttrib
glPopAttrib
GL_ACCUM_BUFFER_BIT
GL_ALL_ATTRIB_BITS
GL_COLOR_BUFFER_BIT
GL_CURRENT_BIT
GL_DEPTH_BUFFER_BIT
GL_ENABLE_BIT
GL_EVAL_BIT
GL_FOG_BIT
GL_HINT_BIT
GL_LIGHTING_BIT
GL_LINE_BIT
GL_LIST_BIT
GL_MULTISAMPLE_BIT
GL_PIXEL_MODE_BIT
GL_POINT_BIT
GL_POLYGON_BIT
GL_POLYGON_STIPPLE_BIT
GL_SCISSOR_BIT
GL_STENCIL_BUFFER_BIT
GL_TEXTURE_BIT
GL_TRANSFORM_BIT
GL_VIEWPORT_BIT

Mask Bit	Attribute Group
GL_ENABLE_BIT	enable
GL_EVAL_BIT	eval
GL_FOG_BIT	fog
GL_HINT_BIT	hint
GL_LIGHTING_BIT	lighting
GL_LINE_BIT	line
GL_LIST_BIT	list
GL_MULTISAMPLE_BIT	multisample
GL_PIXEL_MODE_BIT	pixel
GL_POINT_BIT	point
GL_POLYGON_BIT	polygon
GL_POLYGON_STIPPLE_BIT	polygon-stipple
GL_SCISSOR_BIT	scissor
GL_STENCIL_BUFFER_BIT	stencil-buffer
GL_TEXTURE_BIT	texture
GL_TRANSFORM_BIT	transform
GL_VIEWPORT_BIT	viewport

Table 2-8 (continued) Attribute Groups

Compatibility Extension

glPushClientAttrib
glPopClientAttrib
GL_CLIENT_PIXEL_STORE_BIT
GL_CLIENT_VERTEX_ARRAY_BIT
GL_CLIENT_ALL_ATTRIB_BITS

void **glPushClientAttrib**(GLbitfield *mask*);
void **glPopClientAttrib**(void);

glPushClientAttrib() saves all the attributes indicated by bits in *mask* by pushing them onto the client attribute stack. **glPopClientAttrib()** restores the values of those state variables that were saved with the last **glPushClientAttrib()**. Table 2-9 lists the possible mask bits that can be logically ORed together to save any combination of client attributes.

Two client attribute groups, feedback and select, cannot be saved or restored with the stack mechanism.

Mask Bit	Attribute Group
GL_CLIENT_PIXEL_STORE_BIT	pixel-store
GL_CLIENT_VERTEX_ARRAY_BIT	vertex-array
GL_CLIENT_ALL_ATTRIB_BITS	--
can't be pushed or popped	feedback
can't be pushed or popped	select

Table 2-9 Client Attribute Groups

Some Hints for Building Polygonal Models of Surfaces

Following are some techniques that you can use as you build polygonal approximations of surfaces. You might want to review this section after you've read Chapter 5 on lighting and Chapter 7 on display lists. The lighting conditions affect how models look once they're drawn, and some of the following techniques are much more efficient when used in conjunction with display lists. As you read these techniques, keep in mind that when lighting calculations are enabled, normal vectors must be specified to get proper results.

Constructing polygonal approximations to surfaces is an art, and there is no substitute for experience. This section, however, lists a few pointers that might make it a bit easier to get started.

- Keep polygon orientations (windings) consistent. Make sure that when viewed from the outside, all the polygons on the surface are oriented in the same direction (all clockwise or all counterclockwise). Consistent orientation is important for polygon culling and two-sided lighting. Try to get this right the first time, as it's excruciatingly painful to fix the problem later. (If you use **glScale*()** to reflect geometry around some axis of symmetry, you might change the orientation with **glFrontFace()** to keep the orientations consistent.)
- When you subdivide a surface, watch out for any nontriangular polygons. The three vertices of a triangle are guaranteed to lie on a plane; any polygon with four or more vertices might not. Nonplanar

polygons can be viewed from some orientation such that the edges cross each other, and OpenGL might not render such polygons correctly.

- There's always a trade-off between the display speed and the quality of the image. If you subdivide a surface into a small number of polygons, it renders quickly but might have a jagged appearance; if you subdivide it into millions of tiny polygons, it probably looks good but might take a long time to render. Ideally, you can provide a parameter to the subdivision routines that indicates how fine a subdivision you want, and if the object is farther from the eye, you can use a coarser subdivision. Also, when you subdivide, use large polygons where the surface is relatively flat, and small polygons in regions of high curvature.
- For high-quality images, it's a good idea to subdivide more on the silhouette edges than in the interior. If the surface is to be rotated relative to the eye, this is tougher to do, as the silhouette edges keep moving. Silhouette edges occur where the normal vectors are perpendicular to the vector from the surface to the viewpoint—that is, when their vector dot product is zero. Your subdivision algorithm might choose to subdivide more if this dot product is near zero.
- Try to avoid T-intersections in your models (see Figure 2-16). As shown, there's no guarantee that the line segments AB and BC lie on exactly the same pixels as the segment AC. Sometimes they do, and sometimes they don't, depending on the transformations and orientation. This can cause cracks to appear intermittently in the surface.

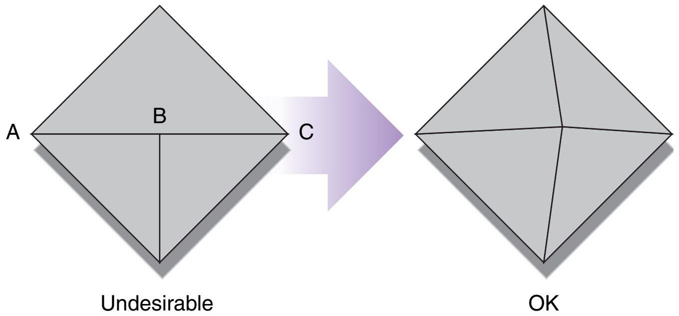


Figure 2-16 Modifying an Undesirable T-Intersection

- If you're constructing a closed surface, be sure to use exactly the same numbers for coordinates at the beginning and end of a closed loop, or you can get gaps and cracks due to numerical round-off. Here's an example of bad code for a two-dimensional circle:

  ```
  /* don't use this code */
  #define PI 3.14159265
  #define EDGES 30

  /* draw a circle */
  glBegin(GL_LINE_STRIP);
  for (i = 0; i <= EDGES; i++)
      glVertex2f(cos((2*PI*i)/EDGES), sin((2*PI*i)/EDGES));
  glEnd();
  ```

  The edges meet exactly only if your machine manages to calculate exactly the same values for the sine and cosine of 0 and of (2*PI*EDGES/EDGES). If you trust the floating-point unit on your machine to do this right, the authors have a bridge they'd like to sell you… To correct the code, make sure that when *i* == EDGES, you use 0 for the sine and cosine, not 2*PI*EDGES/EDGES. (Or simpler still, use GL_LINE_LOOP instead of GL_LINE_STRIP, and change the loop termination condition to *i* < EDGES.)

An Example: Building an Icosahedron

To illustrate some of the considerations that arise in approximating a surface, let's look at some example code sequences. This code concerns the vertices of a regular icosahedron (which is a Platonic solid composed of 20 faces that span 12 vertices, the face of each being an equilateral triangle). An icosahedron can be considered a rough approximation of a sphere. Example 2-19 defines the vertices and triangles making up an icosahedron and then draws the icosahedron.

Example 2-19 Drawing an Icosahedron

```
#define X .525731112119133606
#define Z .850650808352039932

static GLfloat vdata[12][3] = {
   {-X, 0.0, Z}, {X, 0.0, Z}, {-X, 0.0, -Z}, {X, 0.0, -Z},
   {0.0, Z, X}, {0.0, Z, -X}, {0.0, -Z, X}, {0.0, -Z, -X},
   {Z, X, 0.0}, {-Z, X, 0.0}, {Z, -X, 0.0}, {-Z, -X, 0.0}
};
```

```
static GLuint tindices[20][3] = {
  {1,4,0}, {4,9,0}, {4,5,9}, {8,5,4}, {1,8,4},
  {1,10,8}, {10,3,8}, {8,3,5}, {3,2,5}, {3,7,2},
  {3,10,7}, {10,6,7}, {6,11,7}, {6,0,11}, {6,1,0},
  {10,1,6}, {11,0,9}, {2,11,9}, {5,2,9}, {11,2,7}
};

int i;

glBegin(GL_TRIANGLES);
for (i = 0; i < 20; i++) {
   /* color information here */
   glVertex3fv(&vdata[tindices[i][0]][0]);
   glVertex3fv(&vdata[tindices[i][1]][0]);
   glVertex3fv(&vdata[tindices[i][2]][0]);
}
glEnd();
```

The strange numbers *X* and *Z* are chosen so that the distance from the origin to any of the vertices of the icosahedron is 1.0. The coordinates of the 12 vertices are given in the array *vdata[][]*, where the zeroth vertex is {*–X, 0.0, Z*}, the first is {*X, 0.0, Z*}, and so on. The array *tindices[][]* tells how to link the vertices to make triangles. For example, the first triangle is made from the zeroth, fourth, and first vertices. If you take the vertices for triangles in the order given, all the triangles have the same orientation.

The line that mentions color information should be replaced by a command that sets the color of the *i*th face. If no code appears here, all faces are drawn in the same color, and it will be impossible to discern the three-dimensional quality of the object. An alternative to explicitly specifying colors is to define surface normals and use lighting, as described in the next subsection.

Note: In all the examples described in this section, unless the surface is to be drawn only once, you should probably save the calculated vertex and normal coordinates so that the calculations don't need to be repeated each time the surface is drawn. This can be done using your own data structures or by constructing display lists (see Chapter 7).

Calculating Normal Vectors for a Surface

If a surface is to be lit, you need to supply the vector normal to the surface. Calculating the normalized cross product of two vectors on that surface provides their normal vector. With the flat surfaces of an icosahedron, all three vertices defining a surface have the same normal vector. In this case, the normal needs to be specified only once for each set of three vertices. The code in Example 2-20 can replace the “color information here” line in Example 2-19 for drawing the icosahedron.

Example 2-20 Generating Normal Vectors for a Surface

```
GLfloat d1[3], d2[3], norm[3];
for (j = 0; j < 3; j++) {
   d1[j] = vdata[tindices[i][0]][j] - vdata[tindices[i][1]][j];
   d2[j] = vdata[tindices[i][1]][j] - vdata[tindices[i][2]][j];
}
normcrossprod(d1, d2, norm);
glNormal3fv(norm);
```

The function **normcrossprod()** produces the normalized cross product of two vectors, as shown in Example 2-21.

Example 2-21 Calculating the Normalized Cross Product of Two Vectors

```
void normalize(float v[3])
{
   GLfloat d = sqrt(v[0]*v[0]+v[1]*v[1]+v[2]*v[2]);
   if (d == 0.0) {
      error(“zero length vector”);
      return;
   }
   v[0] /= d;
   v[1] /= d;
   v[2] /= d;
}

void normcrossprod(float v1[3], float v2[3], float out[3])
{
   out[0] = v1[1]*v2[2] - v1[2]*v2[1];
   out[1] = v1[2]*v2[0] - v1[0]*v2[2];
   out[2] = v1[0]*v2[1] - v1[1]*v2[0];
   normalize(out);
}
```

If you’re using an icosahedron as an approximation for a shaded sphere, you’ll want to use normal vectors that are perpendicular to the true surface of the sphere, rather than perpendicular to the faces. For a sphere, the normal vectors are simple; each points in the same direction as the vector from the origin to the corresponding vertex. Since the icosahedron vertex data is for an icosahedron of radius 1, the normal data and vertex data are identical. Here is the code that would draw an icosahedral approximation of a smoothly shaded sphere (assuming that lighting is enabled, as described in Chapter 5):

```
glBegin(GL_TRIANGLES);
for (i = 0; i < 20; i++) {
      glNormal3fv(&vdata[tindices[i][0]][0]);
      glVertex3fv(&vdata[tindices[i][0]][0]);
      glNormal3fv(&vdata[tindices[i][1]][0]);
      glVertex3fv(&vdata[tindices[i][1]][0]);
      glNormal3fv(&vdata[tindices[i][2]][0]);
      glVertex3fv(&vdata[tindices[i][2]][0]);
}
glEnd();
```

Improving the Model

A 20-sided approximation to a sphere doesn't look good unless the image of the sphere on the screen is quite small, but there's an easy way to increase the accuracy of the approximation. Imagine the icosahedron inscribed in a sphere, and subdivide the triangles as shown in Figure 2-17. The newly introduced vertices lie slightly inside the sphere, so push them to the surface by normalizing them (dividing them by a factor to make them have length 1). This subdivision process can be repeated for arbitrary accuracy. The three objects shown in Figure 2-17 use 20, 80, and 320 approximating triangles, respectively.

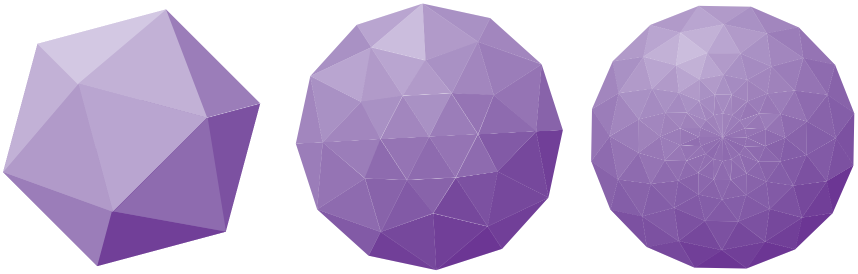


Figure 2-17 Subdividing to Improve a Polygonal Approximation to a Surface

Example 2-22 performs a single subdivision, creating an 80-sided spherical approximation.

Example 2-22 Single Subdivision

```
void drawtriangle(float *v1, float *v2, float *v3)
{
   glBegin(GL_TRIANGLES);
      glNormal3fv(v1);
      glVertex3fv(v1);
      glNormal3fv(v2);
      glVertex3fv(v2);
      glNormal3fv(v3);
      glVertex3fv(v3);
   glEnd();
}



void subdivide(float *v1, float *v2, float *v3)
{
   GLfloat v12[3], v23[3], v31[3];
   GLint i;

   for (i = 0; i < 3; i++) {
      v12[i] = (v1[i]+v2[i])/2.0;
      v23[i] = (v2[i]+v3[i])/2.0;
      v31[i] = (v3[i]+v1[i])/2.0;
   }
   normalize(v12);
   normalize(v23);
   normalize(v31);
   drawtriangle(v1, v12, v31);
   drawtriangle(v2, v23, v12);
   drawtriangle(v3, v31, v23);
   drawtriangle(v12, v23, v31);
}

for (i = 0; i < 20; i++) {
   subdivide(&vdata[tindices[i][0]][0],
             &vdata[tindices[i][1]][0],
             &vdata[tindices[i][2]][0]);
}
```

Example 2-23 is a slight modification of Example 2-22 that recursively subdivides the triangles to the proper depth. If the depth value is 0, no subdivisions are performed, and the triangle is drawn as is. If the depth is 1, a single subdivision is performed, and so on.

Example 2-23 Recursive Subdivision

```
void subdivide(float *v1, float *v2, float *v3, long depth)
{
   GLfloat v12[3], v23[3], v31[3];
   GLint i;

   if (depth == 0) {
      drawtriangle(v1, v2, v3);
      return;
   }
   for (i = 0; i < 3; i++) {
      v12[i] = (v1[i]+v2[i])/2.0;
      v23[i] = (v2[i]+v3[i])/2.0;
      v31[i] = (v3[i]+v1[i])/2.0;
   }
   normalize(v12);
   normalize(v23);
   normalize(v31);
   subdivide(v1, v12, v31, depth-1);
   subdivide(v2, v23, v12, depth-1);
   subdivide(v3, v31, v23, depth-1);
   subdivide(v12, v23, v31, depth-1);
}
```

Generalized Subdivision

A recursive subdivision technique such as the one described in Example 2-23 can be used for other types of surfaces. Typically, the recursion ends if either a certain depth is reached or some condition on the curvature is satisfied (highly curved parts of surfaces look better with more subdivision).

To look at a more general solution to the problem of subdivision, consider an arbitrary surface parameterized by two variables, *u[0]* and *u[1]*. Suppose that two routines are provided:

```
void surf(GLfloat u[2], GLfloat vertex[3], GLfloat normal[3]);
float curv(GLfloat u[2]);
```

If *u[]* is passed to **surf()**, the corresponding three-dimensional vertex and normal vectors (of length 1) are returned. If *u[]* is passed to **curv()**, the curvature of the surface at that point is calculated and returned. (See an introductory textbook on differential geometry for more information about measuring surface curvature.)

Example 2-24 shows the recursive routine that subdivides a triangle until either the maximum depth is reached or the maximum curvature at the three vertices is less than some cutoff.

Example 2-24 Generalized Subdivision

```
void subdivide(float u1[2], float u2[2], float u3[2],
                float cutoff, long depth)
{
   GLfloat v1[3], v2[3], v3[3], n1[3], n2[3], n3[3];
   GLfloat u12[2], u23[2], u32[2];
   GLint i;

   if (depth == maxdepth || (curv(u1) < cutoff &&
       curv(u2) < cutoff && curv(u3) < cutoff)) {
      surf(u1, v1, n1);
      surf(u2, v2, n2);
      surf(u3, v3, n3);
      glBegin(GL_POLYGON);
         glNormal3fv(n1); glVertex3fv(v1);
         glNormal3fv(n2); glVertex3fv(v2);
         glNormal3fv(n3); glVertex3fv(v3);
      glEnd();
      return;
   }

   for (i = 0; i < 2; i++) {
      u12[i] = (u1[i] + u2[i])/2.0;
      u23[i] = (u2[i] + u3[i])/2.0;
      u31[i] = (u3[i] + u1[i])/2.0;
   }
   subdivide(u1, u12, u31, cutoff, depth+1);
   subdivide(u2, u23, u12, cutoff, depth+1);
   subdivide(u3, u31, u23, cutoff, depth+1);
   subdivide(u12, u23, u31, cutoff, depth+1);
}
```

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