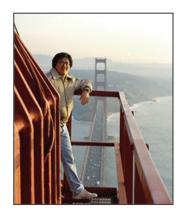
3-D ROTATION USING A 2-D INPUT DEVICE

One essential part of any 3-D graphics application is the ability to turn an object so that it can be viewed from different sides. This article describes a user interface technique called the Virtual Sphere that allows you to perform continuous 3-D rotation using a 2-D input device such as a mouse. For those who have played with my Rotation Controller application and have been waiting for source code, here it is! For others, this article is a good way to learn something about interactive 3-D graphics and user interfaces for 3-D.



MICHAEL CHEN

There are many situations in which users might want to view a 3-D graphics object from different sides. They might want to do so while constructing an object or rearranging objects in a scene. Or they may be viewing a multimedia document and want to turn around a 3-D object that's embedded in the page. Whatever the context, it's important to provide a simple, intuitive interface for the task that's available to a wide user base.

The problem of 3-D rotation has been approached in many ways. Some people have designed their applications to use higher-degrees-of-freedom input devices such as 3-D mice, 3-D trackballs, the 6-D Spaceball, and the 6-D Polhemus. These devices let you control values for x, y, and z (and perhaps roll, pitch, and yaw) at the same time. Unfortunately, these input devices incur extra cost and must be available on the machine currently being used. The user must also learn how to use the device and possibly learn a new interface paradigm.

Other applications have stayed with 2-D input devices because of their familiarity and availability. However, many of these applications will let you perform rotation only about the x, y, or z axis, while others will let you use the mouse to perform only "2-D rotations," in which the user must specify an axis of rotation lying on, say, the x-y plane. In both cases, the user needs to change tools or hold down modifier keys (or mouse buttons) to specify rotations about other axes. This is cumbersome, but

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The Virtual Sphere controller is a user interface tool developed to solve the problem of 3-D rotation using a 2-D input device. The controller allows continuous rotation about an arbitrary axis in three-dimensional space. Because the controller works with a 2-D input device, the interface can be used on a wide range of machines with a mouse, trackball, touch screen, or similar device. (This article will assume the use of a mouse.) An important part of the design effort was user testing. Not only must the controller be technologically sound, it must also be easy to learn and use. Testing results will be discussed later.

USING THE VIRTUAL SPHERE INTERFACE

Before getting into the design and implementation of the Virtual Sphere interface, let's first play a bit with the sample application. You'll need to use a machine running System 7 or a System 6 machine with 32-Bit QuickDraw. Find and launch the application VirtualSphereSample, provided on this issue's CD. As shown in Figure 1, you'll see a 3-D house enclosed by the circular Virtual Sphere controller (hereafter called the *cue*).

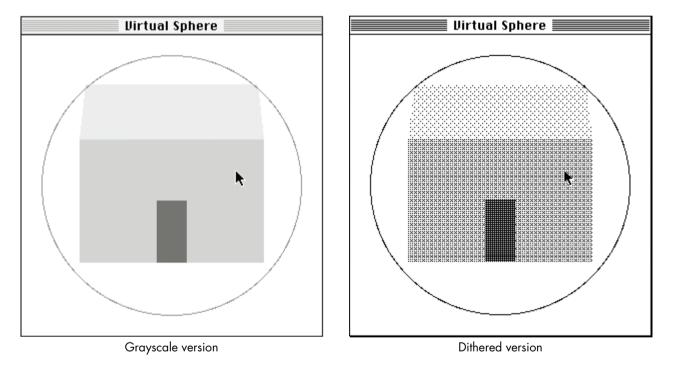


Figure 1

The Initial Window, in Grayscale and With Dithering

"Someday, someone is gonna figure out how you can read music without wondering what those tiny little notes are on the page."* 41

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You'll see a color, grayscale, or dithered rendering of the house, depending on your monitor and bit depth. To rotate the house, move the pointer inside the cue and then drag the pointer around. Observe what happens to the house when you drag in the following directions:

- left and right, beginning with the pointer at the center of the cue
- up and down, beginning with the pointer at the center of the cue
- around the edge of or outside the cue

See if you can position the house in a desired orientation.

The Virtual Sphere controller simulates the mechanics of a physical 3-D trackball that can freely rotate about any arbitrary axis in three-dimensional space. The user can imagine the cue to be a glass sphere that's encasing the object to be rotated. Rotation is a matter of rolling the sphere and therefore the object with the pointer. Up-and-down and left-and-right movement at the center of the cue is equivalent to "rolling" the imaginary sphere at its apex and produces rotation about an axis lying on the plane of the screen. Movement along (or completely outside) the edge of the cue is equivalent to rolling the sphere at the edge and produces rotation about the axis perpendicular to the screen.

The Virtual Sphere is unusual in the sense that you seem to be able to squeeze an extra degree of freedom out of a 2-D input device. The action of rolling the Virtual Sphere lets you specify an arbitrary rotation axis in three-dimensional space, with the advantage that you don't need to think about the rotation axis. You just roll, and the object turns in the expected way.

To validate the usefulness of the Virtual Sphere interface, two colleagues and I designed an experiment to compare the performance of different rotational interfaces in a matching task. In the experiment, the computer displays a house at a certain orientation, and the user has to use the given rotational interface to match that orientation. The performance measurement is based on time and accuracy. The result showed that the Virtual Sphere was indeed easy to use and was fastest for complex rotations. If you're interested in the details of the other rotational interfaces and the experiment, they're described in "A Study in Interactive 3-D Rotation Using 2-D Control Devices" (see "Recommended Reading" at the end of this article). A version of the rotation controllers and computer experiment is available on this issue's CD.

HOW THE VIRTUAL SPHERE INTERFACE WORKS

The general idea of this interface is that the Virtual Sphere cue is drawn around the object to be rotated. The cue is centered over the object's center of rotation and should be just large enough to enclose the object. When the user drags over the cue, the successive x-y locations of the pointer are used to incrementally rotate the object. The next few paragraphs delve into the mathematics of this process. Those of you

with an aversion to vectors and trigonometry may want to skip ahead to the next section.

The orientation of the object is represented in the sample code by a 4 x 4 rotation matrix. At each movement of the pointer, an incremental rotation matrix is computed, using the Virtual Sphere algorithm. This matrix is then concatenated with the object's matrix, and the object is redisplayed. This process is repeated until the user releases the mouse button.

The incremental rotation matrix is computed using the Virtual Sphere algorithm as follows: Figure 2 shows a cue as it appears on the screen and also gives the corresponding 3-D view. The cue is conceptually a hemisphere protruding from the screen. When the pointer is moved from point p to point q on the screen, we think of it as moving from point p' to point q' on the surface of the imaginary hemisphere. We compute the points p' and q' by projecting points p and q upward (that is, straight out from the screen) from the circle to the surface of the hemisphere. To simplify the math, we'll assume that the cue and hemisphere each have a radius of 1.

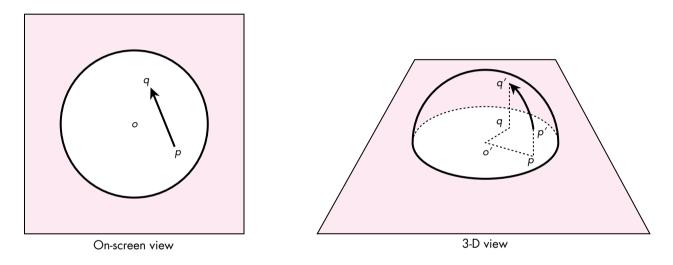


Figure 2

The Virtual Sphere Cue and Its Corresponding 3-D Hemisphere

Given that we now have points p' and q', we create vectors from the center of the hemisphere, o', calling them vectors $\overrightarrow{o'p'}$ and $\overrightarrow{o'q'}$. The axis of rotation, \overrightarrow{a} , is perpendicular to the two vectors and can be computed using the vector cross-product (see Figure 3):

$$\overrightarrow{a} = \overrightarrow{o'p'} \times \overrightarrow{o'q'}$$

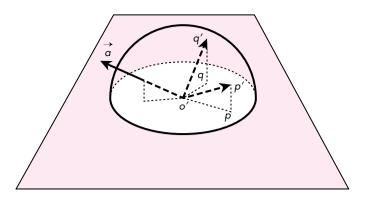


Figure 3 Computing the Axis of Rotation

The amount of rotation, θ , is the angle between the vectors, and is computed from the arc sine of the length of $\vec{a:}$

 $\theta = \sin^{-1} |\vec{a}|$

The corresponding 4 x 4 incremental rotation matrix is

$ta_x^2 + c$	$ta_x a_y + sa_z$	ta_xa_z -say	0
ta _x a _y -sa _z	$ta_y^2 + c$	$ta_ya_z + sa_x$	0
$ta_xa_z+sa_y$	$ta_y a_z$ -s a_x	ta_z^2 +c	0
0	0	0	0 0 0 1

where

- a_x, a_y , and a_z are the components of \vec{a}
- $s = \sin \theta = |\overrightarrow{a}|$ • $c = \cos \theta = \overrightarrow{o'p'} \cdot \overrightarrow{o'q'}$ (vector dot-product of $\overrightarrow{o'p'}$ and $\overrightarrow{o'q'}$) • t = 1 - c

Note that we have a choice here for computing the matrix. We can first compute the angle of rotation and then use the sine and cosine functions to obtain *s* and *c*. However, knowing vector $\overrightarrow{o'p'}$ and $\overrightarrow{o'q'}$, we can also compute *s* and *c* using the length of \overrightarrow{a} and the dot-product. The latter approach allows us to compute the matrix efficiently without using any trigonometric calculations, which are expensive.

The Virtual Sphere algorithm just described is an improvement over the one described in the paper "A Study in Interactive 3-D Rotation Using 2-D Control Devices." The paper used a three-step procedure to convert movement of a 2-D input device into a 3-D rotation matrix. However, it turns out that if we first convert the 2-D input to 3-D, the Virtual Sphere calculation can be done much more efficiently.

IMPLEMENTING THE VIRTUAL SPHERE INTERFACE

The preceding description of the Virtual Sphere algorithm probably sounds more complicated than it is. The actual implementation is really quite simple. In fact, the VirtualSphere module contains only one externally visible routine:

First, the routine PointOnUnitSphere is used to convert p and q (the previous and current locations of the mouse) into the vectors $\overrightarrow{o'p'}$ and $\overrightarrow{o'q'}$. The routine SetRotationMatrix then computes the 4 x 4 incremental rotation matrix as described in the previous section. The parameters cueCenter and cueRadius define the location of the cue circle in the window. Integer is a macro for long, and CPoint3D is a structure of three doubles.

USING THE VIRTUAL SPHERE INTERFACE

Let's look at how we use the VirtualSphere routine to rotate a 3-D object interactively.

```
Point
            sphereCenter;
            sphereRadius;
Integer
            tempMatrix;
Matrix4D
Matrix4D
            rotationMatrix;
p = event->where;
GlobalToLocal (&p);
                        /* Get mouse-down point in local coordinates.*/
/* Figure out where to place the Virtual Sphere cue. */
sphereCenter.h = kSphereCenterH;
sphereCenter.v = kSphereCenterV;
sphereRadius = kSphereRadius;
while (StillDown()) {
   GetMouse (&q);
   dx = q.h - p.h;
   dy = q.v - p.v;
   if (dx != 0 || dy != 0) {
      VirtualSphere (p, q, sphereCenter, sphereRadius, rotationMatrix);
      MultiplyMatrix (objectMatrix, rotationMatrix, tempMatrix);
      CopyMatrix (tempMatrix, objectMatrix);
      DrawWindow (window);
                                 /* Update the window. */
      p = q;
              /* Remember previous mouse point for next iteration.*/
   }
}
```

When DoRotation is called, the 3-D object's current matrix is passed in as objectMatrix. In the sample application, the Virtual Sphere cue is always centered on the window and has a fixed size. Thus, sphereCenter and sphereRadius are assigned with constants. In a general application, you'll need to determine which object is selected and figure out the size and location of the cue (in the window's coordinates) to surround the object. In any case, while the mouse button is still down and the mouse has moved, we call VirtualSphere to obtain the incremental rotation matrix. This matrix is concatenated onto the 3-D object's current matrix using MultiplyMatrix and CopyMatrix. We then redraw the window to display the object at its new orientation. This process is repeated until the mouse button is released.

CREATING A SIMPLE 3-D GRAPHICS SYSTEM

}

The real point of this article and the sample code is to demonstrate the Virtual Sphere interface. However, it turned out that a large part of the effort involved went into creating a simple 3-D graphics system. It was much more work than the implementation of the Virtual Sphere algorithm itself! I wanted to provide a simple system that would be accessible by the majority of Macintosh programmers and would allow even low-end Macintosh models to do interactive 3-D graphics.

The graphics system I came up with is based on Graf3D. Graf3D is a simple library for drawing 3-D graphics using a fixed-point interface to QuickDraw's integer coordinates. I chose Graf3D because it's included in the THINK C and MPW environments. It uses fixed-point math and runs reasonably quickly even on a Macintosh SE! This means that the sample code should be quite usable for all *develop* readers.

One major caveat is that the Graf3D library is unsupported. Most people doing 3-D graphics on the Macintosh probably won't care about this point, because they write their own 3-D software and will simply port the Virtual Sphere code to their system. I've provided the sample code using Graf3D to show how the whole system works. Also, it's nice to be able to show that Graf3D is not as brain dead as some people might think.

GRAPHICS SYSTEM SPECIFICATION

The graphics system we need is extremely simple. It needs to be able to display only one relatively simple 3-D object at the center of a window. We'll assume that the entire object is visible so that we won't have to worry about 3-D polygon clipping (which, unfortunately, is left as an exercise for the students in most 3-D graphics courses). The object should be displayed with perspective projection. The displayed object can only be rotated. We predefine the center of rotation to be the center of the object.

On the display screen, we define the origin of the 3-D coordinate system at the center of the screen, the x axis as extending to the right, the y axis as extending upward, and the z axis as coming out of the screen toward the viewer. Note that in the QuickDraw coordinate system, the y axis extends in the opposite direction.

For the sake of cosmetics, the graphics system should adapt to the monitor bit depth so that the graphics can be shown on color, grayscale, and black-and-white displays. The system must use double buffering to eliminate screen flicker.

To make the Virtual Sphere implementation easier to understand, I've used floatingpoint math to compute the axis of rotation, the angle of rotation, and the 4 x 4 rotation matrix. However, we'll take advantage of the fixed-point math used in Graf3D to speed up graphics drawing.

SETTING UP GRAF3D

To implement our simple graphics system using Graf3D, we create and associate a Port3D to the grafPort in which the 3-D object is to be displayed. We place the camera at some distance on the positive z axis, looking at the origin. We draw the object centered at the origin. With this setup, we have the 3-D view as specified above.

EXTENDING GRAF3D TO DRAW POLYGONS

Graf3D provides only two calls, MoveTo3D and LineTo3D, to perform line drawings in 3-D. These calls are analogous to the 2-D MoveTo and LineTo calls, except that the 3-D calls require an additional *z* parameter. Graf3D doesn't have calls to draw 3-D polygons. However, that doesn't mean we have to write our own routine from scratch. We'll take advantage of the fact that MoveTo3D and LineTo3D, after performing the math to project 3-D onto 2-D, will call MoveTo and LineTo to draw the line on-screen (of course, it helps to have access to the source code for Graf3D). Hence, drawing a polygon projected from 3-D is no more difficult than drawing a regular 2-D polygon: we use the standard QuickDraw polygon routines. Here's an example that draws a filled 3-D triangle:

```
polyHdl= OpenPoly ();
   MoveTo3D (Long2Fix(0),Long2Fix(0),Long2Fix(0)); /* 1st point */
   LineTo3D (Long2Fix(2),Long2Fix(5),Long2Fix(0)); /* 2nd point */
   LineTo3D (Long2Fix(5),Long2Fix(1),Long2Fix(0)); /* 3rd point */
   LineTo3D (Long2Fix(0),Long2Fix(0),Long2Fix(0)); /* 1st point again */
   ClosePoly ();
   PolyColor (&rGBColor);
   FillPoly (polyHdl, lgPolyShade);
   KillPoly (polyHdl);
```

PolyColor is a new routine for specifying the color of the polygon; lgPolyShade specifies the polygon's fill pattern. These two items are explained in the next section.

DEALING WITH BLACK-AND-WHITE AND COLOR QUICKDRAW

In general, if you want to take advantage of a grayscale or color display when available, you have to write parallel code. You also need to worry about different versions of QuickDraw so that you don't make the mistake of making Color QuickDraw calls on machines with black-and-white QuickDraw. (See the Graphical Truffles column in this issue for a discussion of the different possible QuickDraw versions.) In our simple graphics system, we want to be able to draw in color when we can and draw in simulated grays using dither patterns when we have a 1-bit display. Parallel code is eliminated by hiding all the complexity of different QuickDraw versions inside the routine PolyColor.

```
static ConstPatternParam lgPolyShade;
pascal void PolyColor (const RGBColor *rGBColor)
{
    if (gDrawInColor) {
        lgPolyShade = qd.black;
        RGBForeColor (rGBColor);
    } else {
        /* Convert rGBColor to a dither pattern. */
        unsigned long index;
```

```
index = RGBToGrayscale (rGBColor, (**lgDitherPatterns).patListSize);
lgPolyShade = (**lgDitherPatterns).patList [index];
ForeColor (blackColor);
}
```

```
}
```

PolyColor takes an RGBColor as an argument. If we're drawing in color (the global variable gDrawInColor is true), PolyColor simply calls RGBForeColor, and lgPolyShade is set to a black pattern. When FillPoly(polyHdl, lgPolyShade) is eventually called, the polygon will get drawn in that color. If we're drawing in black and white, PolyColor makes the foreground color black and converts the RGB value to one of 65 dither patterns (including white), which is assigned to lgPolyShade (see "Converting RGB Color to a Grayscale Value"). When FillPoly(polyHdl, lgPolyShade) is called, the polygon will be filled with that dither pattern. Note that lgDitherPatterns is just a (locked) handle to a PAT# resource. We're limited to 65 possible dither patterns because the Pattern data structure is 8 x 8.

CONVERTING RGB COLOR TO A GRAYSCALE VALUE

The conversion from an RGB value to a grayscale value can be done in a number of ways. The most obvious way is to have the R, G, and B components each contribute equally to the gray value. However, this implies that, for example, pure red, green, and blue colors will all map to one value, which might not be desirable. In the sample code, the conversion routine RGBToGrayscale employs a set of often-used weighting factors for the RGB components. The routine returns an integer value from 0 to maxGrayValue-1:

```
unsigned long RGBToGrayscale (const RGBColor *rGBColor, Integer
                             maxGrayValue)
{
   #define kRWeight
                          3
   #define kGWeight
                           6
   #define kBWeight
                          1
   #define kTotalWeight (kRWeight + kGWeight + kBWeight)
  unsigned long intensity;
  unsigned long index;
  intensity = kRWeight*rGBColor->red + kGWeight*rGBColor->green +
                  kBWeight*rGBColor->blue;
  index = intensity * maxGrayValue/ kTotalWeight / (USHRT MAX+1);
                          /* Note integer math. Order matters. */
  return (index);
}
```



DEALING WITH ROTATION

In Graf3D, the Port3D data structure contains a 4 x 4 xForm matrix that defines how the object is to be transformed before it's displayed. Recall that in our DoRotation routine we compute the object's rotation matrix directly. Thus, all we need to do is copy this matrix to xForm before we display the object. However, we need to do some number conversions since the rotation matrix is in floating point and the xForm matrix is in fixed point. The routine Matrix2XfMatrix does the necessary conversion:

```
pascal void Matrix2XfMatrix (Matrix4D fromMatrix, XfMatrix toMatrix)
{
    Integer i, j;
    for (i=3; i>=0; i--) {
        for (j=3; j>=0; j--) {
            toMatrix[i][j]= X2Fix (fromMatrix[i][j]);
        }
    }
}
```

DOUBLE BUFFERING

The sample code contains a module for off-screen drawing that uses GWorlds to eliminate drawing flicker. The use of GWorlds means that graphics acceleration comes for free if it's available in hardware. This module provides a very simple way of dealing with GWorlds. It contains only five routines:

pascal OSErr	InitializeOffscreen (Boolean *gWorldAvailable);
pascal void	<pre>FreeOffscreen (GWorldPtr offscreenGWorld);</pre>
pascal QDErr	CheckOffscreenForWindow (GWorldPtr *offscreenGWorld,
	<pre>short pixelDepth, WindowPtr window);</pre>
pascal void	BeginDrawingOffscreen (GWorldPtr offscreenGWorld,
	WindowPtr window);
pascal void	EndDrawingOffscreen (GWorldPtr offscreenGWorld,
	WindowPtr window);

The routine InitializeOffscreen determines whether GWorlds are available on a particular machine and internally remembers whether System 6 or 7 is running. The latter is needed because there are subtle differences between the GWorld calls in System 6 and those in System 7 (see Offscreen.c and *Inside Macintosh* Volume VI, page 21-19).

The routine CheckOffscreenForWindow checks to see whether a GWorld has the proper bit depth and memory boundary aligned for efficient transfer using CopyBits. If a GWorld hasn't been allocated, a new one is created. If an existing GWorld has the wrong bit depth or isn't memory aligned, it's reallocated. This routine hides the subtle differences between the Toolbox NewGWorld and UpdateGWorld calls. You

should call this routine when a window has just been created *and* whenever you think the GWorld is out of sync with the screen.

The routine BeginDrawingOffscreen redirects drawing to the GWorld. The routine EndDrawingOffscreen ends the redirection and copies the off-screen buffer onto the window. The routine FreeOffscreen frees the GWorld when it's no longer needed.

The basic calling sequence for this module is as follows:

```
InitOffscreen (...);
window = GetNewWindow (...);
gWorld = nil;
CheckOffscreenForWindow (&gWorld, window, ...);
. . .
while (still not done with drawing) {
   CheckOffscreenForWindow (&gWorld, window, ...);
   BeginDrawingOffscreen (&gWorld, window);
   /* Draw something */
   EndDrawingOffscreen (&gWorld, window);
}
FreeOffscreen (&gWorld);
```

In the actual code, CheckOffscreenForWindow is called only when there's an update event that could have been generated when the user changed the monitor bit depth. It's not necessary to call CheckOffscreenForWindow during the loop when the mouse is interacting with the object.

CODE OPTIMIZATION

I didn't optimize the sample code because it would have detracted from presenting a clear implementation of the Virtual Sphere algorithm and the 3-D graphics system. For example, we deal only with 3-D rotation in this program, so we don't really need to have a general 4 x 4 matrix when a 3 x 3 matrix would do. Even if we were willing to waste storage, some of the math routines (such as CopyMatrix, MultiplyMatrix, SetRotationMatrix, and Matrix2XfMatrix) could have been optimized to use only the upper left 3 x 3 cells of the 4 x 4 matrix. It might also be worthwhile to do a full fixed-point implementation of the Virtual Sphere algorithm.

MPW C VERSUS THINK C

One of my objectives in creating this sample code was to make sure that it could be used in both the MPW and THINK C environments. I also wanted to allow the option of compiling the application using SANE or a hardware floating-point unit (FPU). This turned out to be a learning experience in itself. Here are a few things I picked up from the process:

- The main difference between the two environments is the way in which floating-point numbers are handled. MPW provides an easy way of switching between SANE and a hardware FPU simply by switching compile flags and by including the proper versions of the math libraries. The header files need not be changed. With THINK C, the SANE and ANSI math libraries aren't integrated. You must include either SANE.h or Math.h, but not both.
- In THINK C, some of the transcendental functions (for example, asin and atan2) are not available when SANE is used.
- In THINK C, there are five floating-point formats. Some of the fixed-point/floating-point conversion routines (such as X2Fix and Fix2X) are incompatible when native floating-point format is used.

I created the files MyMath.h and MyMath.c to hide all the ugliness of floating-point math from the rest of the code.

Compiling the code in both environments requires more careful coding. A version that compiled fine in one environment would get errors and warnings in the other. In general, MPW C is a bit pickier about type checking.

On my wish list is a common pragma structure for changing compile options in the source code. I wanted to display an error message if the user launched a version of the sample application compiled for a hardware FPU on a non-floating-point machine. Here's an example of the gymnastics I had to go through to make sure the routine MessageAlert could be executed on all processors:

```
#ifdef applec
#pragma push
                              /* MPW: save compiler flags
                                                                         */
#pragma processor 68000
                              /* Generate 68000 instructions only
                                                                         */
#endif
pascal void MessageAlert (Str255 message)
{
   #ifdef THINK C
                              /* THINK C: Generate 68020 instructions...*/
   #pragma options(!mc68020) /* NOT! Silly way of saying 68000
                                                                         */
   #endif
                              /* instructions only. Note this pragma
                                                                         */
                              /* is defined only until end of routine. */
   SetCursor (&gd.arrow);
   ParamText (message, "", "", "");
   SysBeep (10);
   (void) Alert (rMessageAlert, nil);
}
#ifdef applec
#pragma pop
                              /* MPW: restore compiler flags
                                                                         */
#endif
```

Why should the processor pragma matter for such a simple routine? The reason is that MPW C with the -68020 flag will generate an RTD (not available on a 68000 machine) instead of an RTS instruction for returning to the calling routine. This would cause the resulting sample application to crash on a 68000 machine instead of putting up an alert message. THINK C doesn't seem to generate the RTD instruction even when asked to generate 68020 code. However, I put the pragma in for THINK C just in case.

GOING ON FROM HERE

I hope this article has whetted your appetite for 3-D graphics and 3-D user interfaces. Several companies have released commercial programs that improve on the Virtual Sphere concept. Silicon Graphics' Inventor Toolkit contains a version with three orthogonal "ribbons" around the sphere to provide constrained-axis rotation. Virtus Walkthrough contains a version with momentum — the object continues to spin in the direction of the pointer movement when the mouse button is released.

The Virtual Sphere interface introduces a new interaction technique that was backed with user testing. If you're doing new interface development, I encourage you to use the same process: design followed by testing with iterations. Remember to keep the big picture in mind. 3-D rotation is just one small task that the user has to do in a 3-D application. All the interaction techniques for manipulating objects must work together and must be appropriate for the 3-D task the user wants to perform.

RECOMMENDED READING

- "A Study in Interactive 3-D Rotation Using 2-D Control Devices" by Michael Chen, S. Joy Mountford, and Abigail Sellen (ACM Siggraph '88 Proceedings, Volume 22, Number 4, August 1988, pages 121–129). An electronic version of this paper is available on this issue's CD.
- "A Technique for Specifying Rotations in Three Dimensions Using a 2-D Input Device" by Michael Chen and K. C. Smith (*Proceedings IEEE Montech '87* — *Compint '87*, November 1987, pages 118–120).
- "An Object-Oriented 3D Graphics Toolkit" by Paul Strauss and Rikk Carey (ACM Siggraph '92 Proceedings, Volume 26, Number 2, July 1992, pages 341–349).
- "Tablet Based Valuators That Provide One, Two or Three Degrees of Freedom" by K. B. Evans, Peter P.

Tanner, and M. Wein (*ACM Siggraph '81 Proceedings*, Volume 15, Number 3, August 1988, pages 91–97).

- "Iterative Design of an Interface for Easy 3-D Direct Manipulation" by Stephanie Houde (ACM CHI '92 Proceedings, May 1992, pages 135–142).
- "Three-Dimensional Widgets" by B. Conner, S. Snibbe, K. Herndon, D. Robbins, R. Zeleznik, and A. Van Dam (Proceedings of the 1992 Symposium on Interactive 3D Graphics, pages 183–188).
- "Understanding Graf3D" by Scott Berfield (The Essential MacTutor Volume 3, pages 230–238).
- Computer Graphics: Principles and Practice, 2nd ed., by J. D. Foley, A. Van Dam, S. K. Feiner, and J. F. Hughes (Addison-Wesley, 1990).

THANKS TO OUR TECHNICAL REVIEWERS Michael Chmilar, Forrest Tanaka, Dan Venolia*