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SOFTWARE ENGINEERING SPECIAL ISSUE

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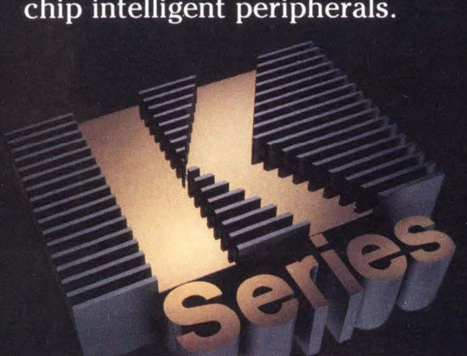

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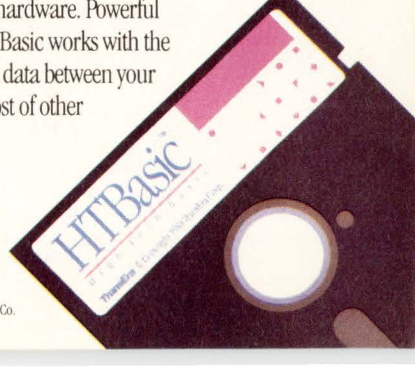

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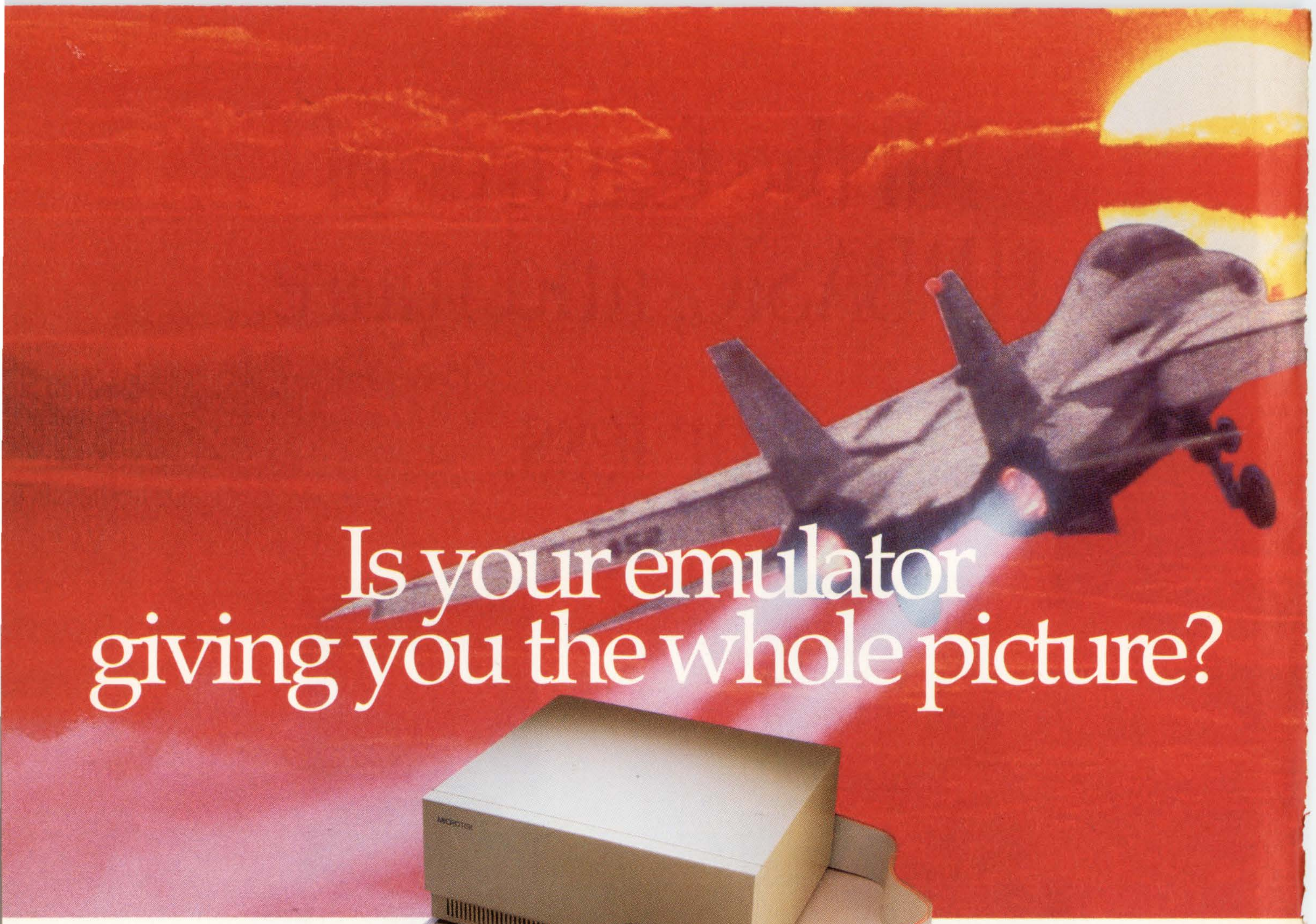

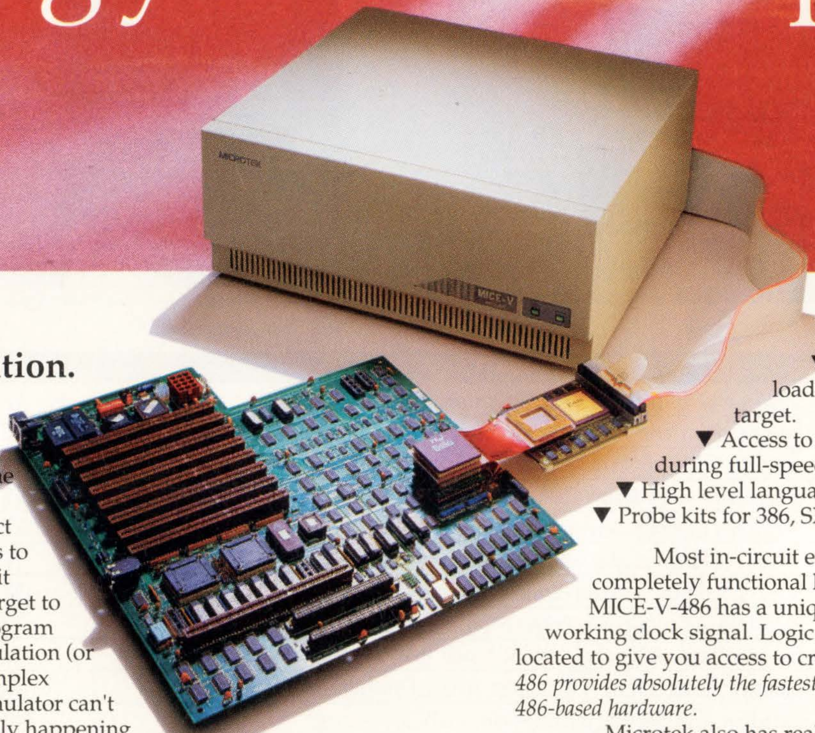

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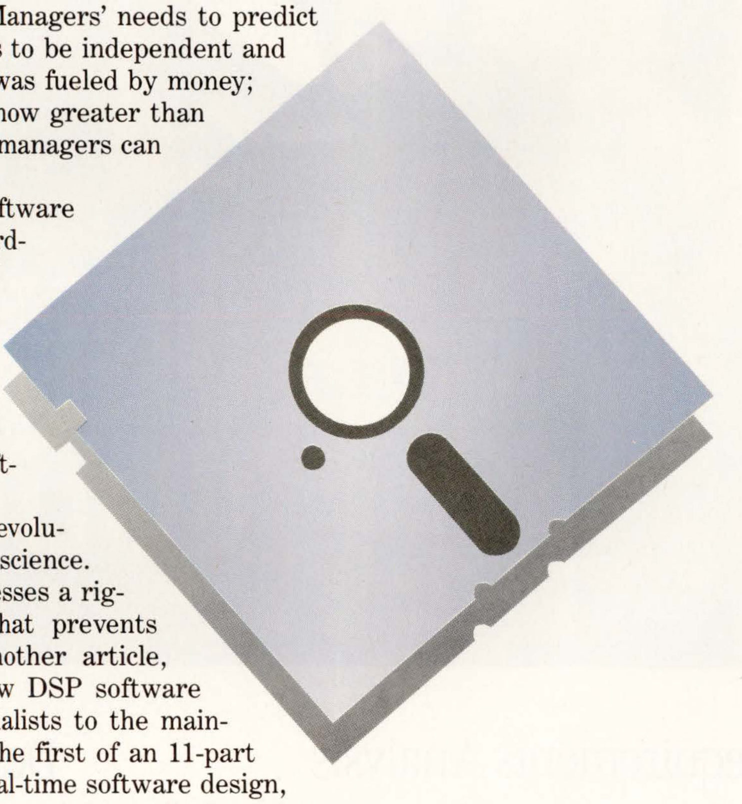
Art becomes science

Not so very long ago, software development was more an art than a science. The best programmers were those brilliant individuals who could disappear into small cubicles, work their creative magic, and then reappear some weeks or months later with programs of dazzling cleverness. Often, though, the programs were so clever no one could understand them. Sometimes they did what they were designed to do, but were designed to do the wrong thing. The fact that a program did the wrong thing with dazzling cleverness was usually of some satisfaction to the programmer, but very little to the programmer's manager.

So it happened that software development—mostly an art—led to software engineering—mostly a science. Managers' needs to predict results won out over programmers' desires to be independent and creative. As with many changes, this one was fueled by money; the value of software in most products is now greater than the value of the hardware, a fact that few managers can afford to overlook.

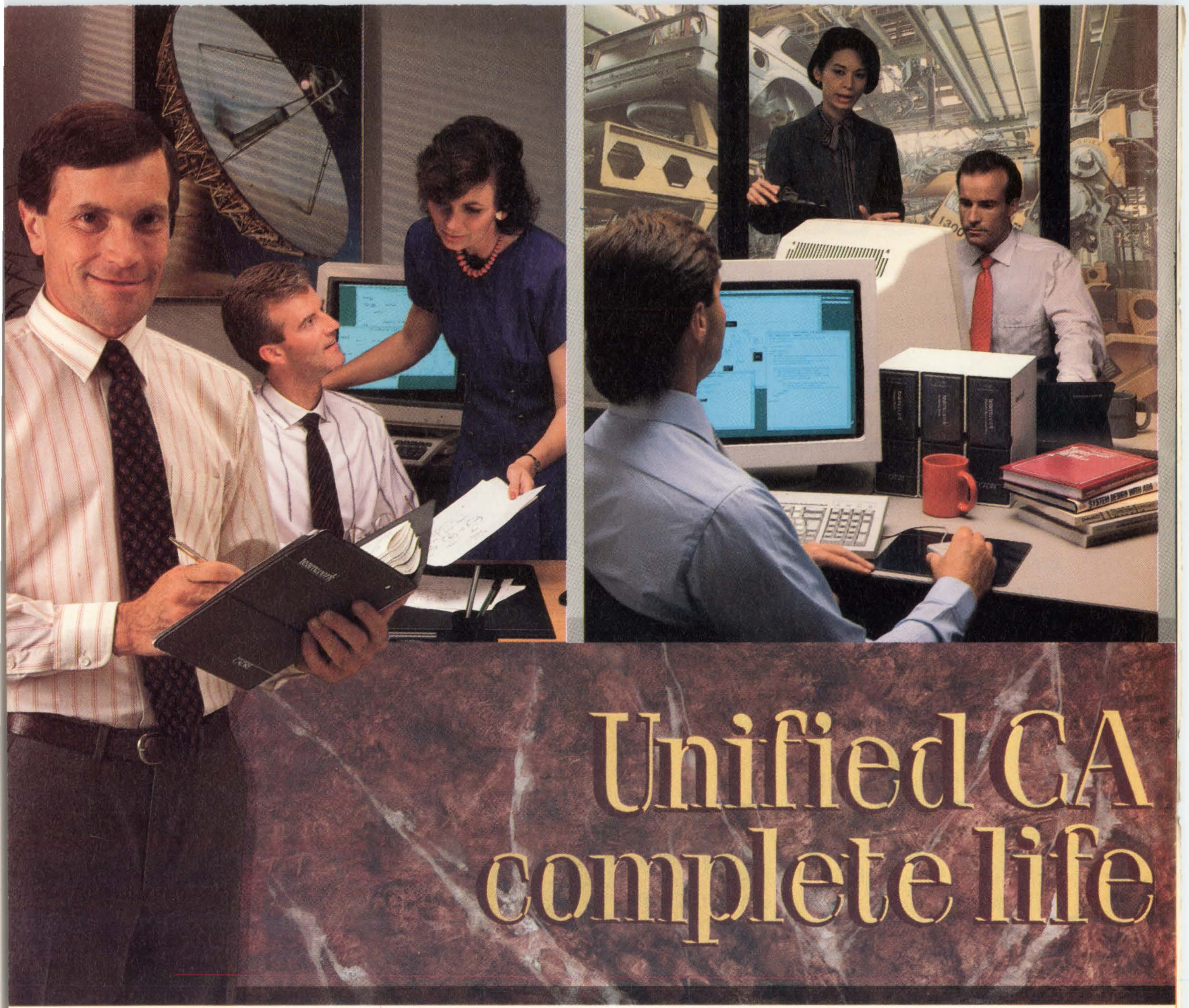


Software's growing importance and software engineering's increasing overlap with hardware engineering have led the editors of EDN, over the years, to increase their software coverage. In this special issue, we give you nothing but software. It's not software in a vacuum, though; rather, it's the kind of software that also involves hardware, the kind of software EDN readers are involved with.

The articles included here all reflect the evolution of software development from art to science. An article on debugging, for example, stresses a rigorous approach to designing software that prevents many problems from ever occurring. Another article, on DSP software development, shows how DSP software is moving from an esoteric group of specialists to the mainstream of software development. And in the first of an 11-part series, we begin a no-nonsense guide to real-time software design, previously one of the blackest black magics of them all. Rounding out the list of technical articles are a practical guide to developing OS/2 applications and some useful techniques for combining C and assembly language.

You could view these articles as a few small components in the enormous structure that is software-as-science. In science, you have a knowledge base to build on; you don't have to waste creative energy reestablishing what others have already done. But creativity is as essential to science as it is to art, and the rules of science should help us, not hinder us; if they don't, we should break them. Rules were made to be broken, after all, and even science should be fun. If programmers lose the spirit that existed when software was more an avocation than a vocation, when it was more an art than a science, then we will all feel the loss.

Gary Legg
Special Projects Editor



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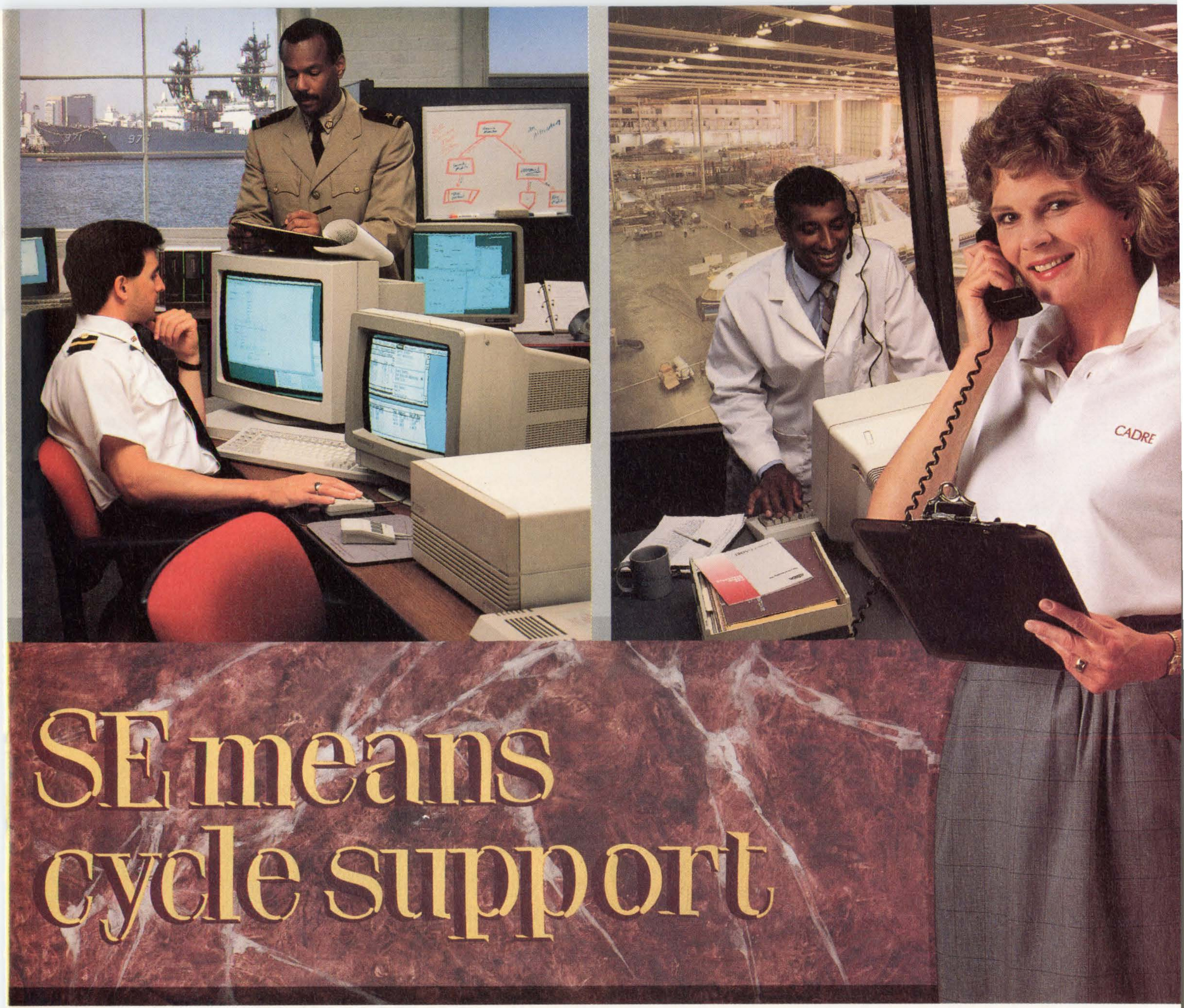

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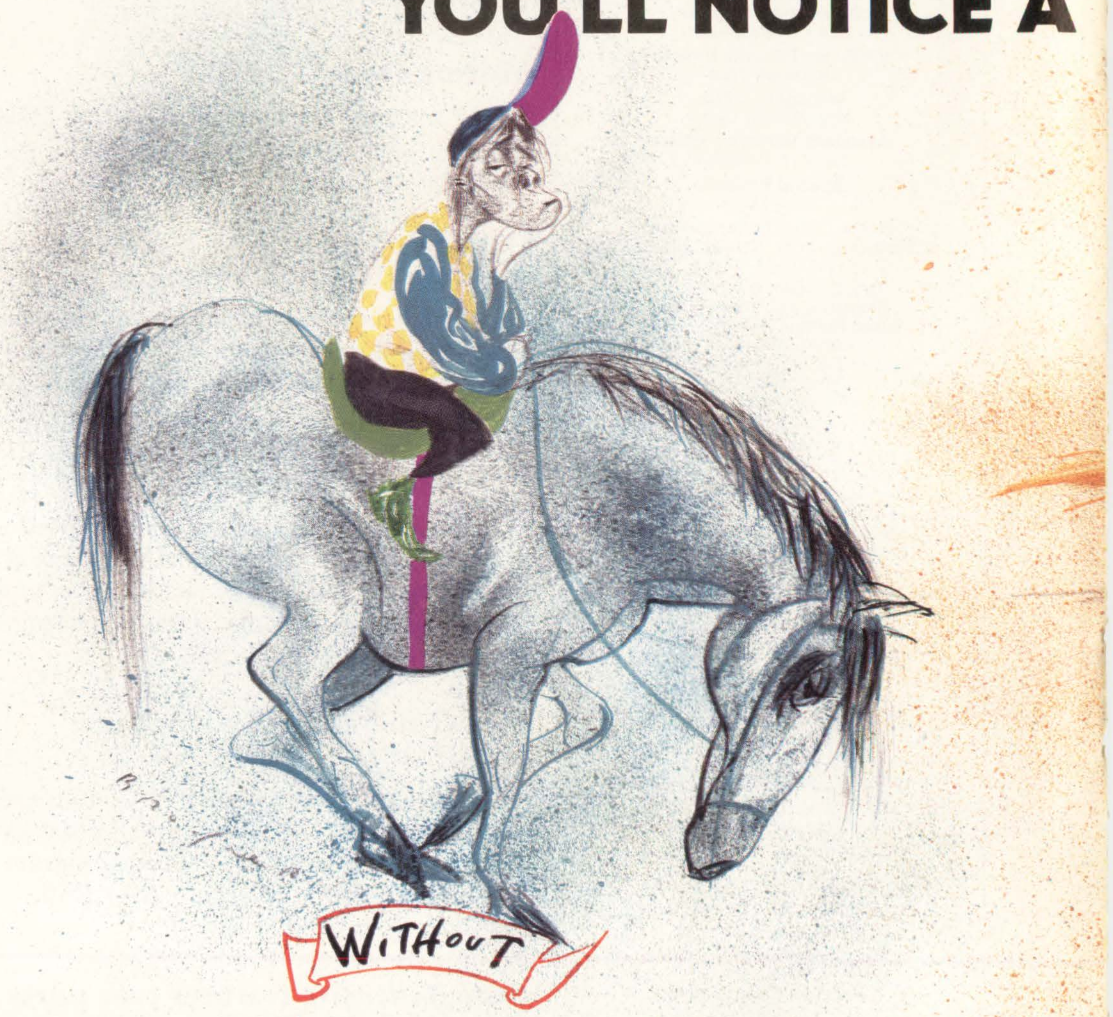

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68030 PERFORMANCE SUMMARY

Access Clocks	*DRAM Speed*	*Frequency (Mhz)*
4-2-2-2	70 ns	20
5-2-2-2	120 ns	20
5-2-2-2	80 ns	25
6-2-2-2	120 ns	25
6-2-2-2	80 ns	33
7-2-2-2	100 ns	33

68040 PERFORMANCE SUMMARY

Access Clocks	*DRAM Speed*	*Frequency (Mhz)*
3-2-2-2	80 ns	25
5-2-2-2	100 ns	25
6-2-2-2	120 ns	25
5-2-2-2	80 ns	33
6-2-2-2	100 ns	33

design time, since it means you don't need additional glue logic.

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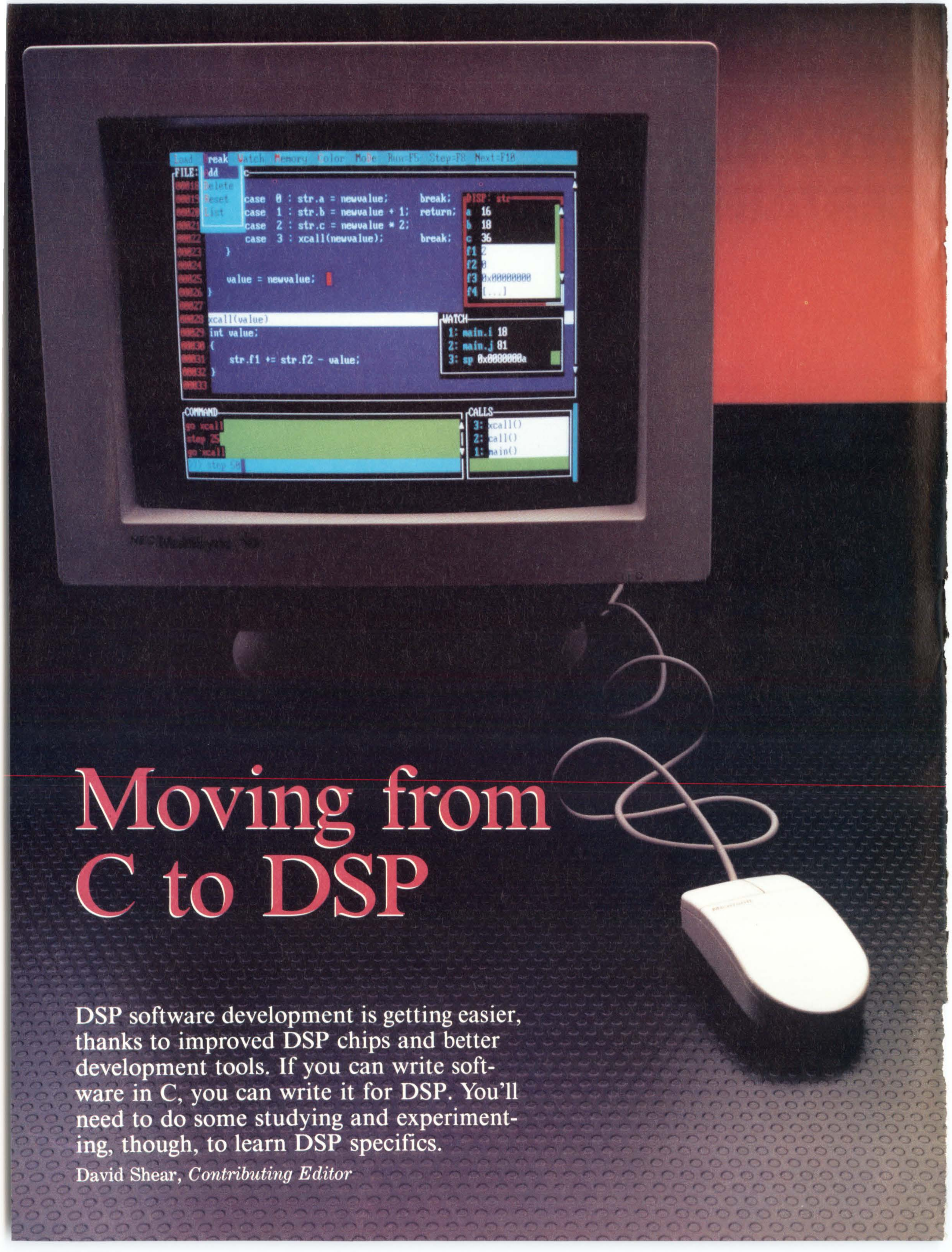


```
        case  0 : str.a = newvalue;       break;
        case  1 : str.b = newvalue + 1;   return;
        case  2 : str.c = newvalue * 2;
        case  3 : xcall(newvalue);        break;
    }

    value = newvalue;
}

xcall(value)
int value;
{
    str.f1 += str.f2 - value;
}
```

```
a  16
b  18
c  36
f1 2
f2 0
f3 0x00000000
f4 [...]
```

```
1: main.i 18
2: main.j 81
3: sp 0x0000000a
```

```
go xcall
step 25
go xcall
step 50
```

```
3: xcall()
2: call()
1: main()
```

Moving from C to DSP

DSP software development is getting easier, thanks to improved DSP chips and better development tools. If you can write software in C, you can write it for DSP. You'll need to do some studying and experimenting, though, to learn DSP specifics.

David Shear, *Contributing Editor*

Digital signal processing (DSP) is moving into the mainstream. Low-cost DSP chips are going into products ranging from games to cellular telephones and from modems to electronic test equipment. When—not if—you face a DSP software project, you must know how to tackle it. Fortunately, new chips and their supporting development tools are making that task easier than it was a few years ago. For experienced C programmers, DSP projects require only a few new skills.

Advice for getting started in DSP ranges from "hire an expert" to "just open a book and have at it." Warren Cope, senior applications engineer at Spectrum Signal Processing, suggests starting with literature, routines, and application libraries from manufacturers and the public domain. "Call all the chip vendors and get whatever application literature they have," he says. "Just because you're using a TI chip doesn't mean you can't read Motorola's books. The algorithms still work no matter what chip you're using."

Ray Simar, principal architect and program manager for Texas Instruments' TMS320C30 and TMS320C40, echoes Cope's advice. For information on any of TI's DSP products, he suggests calling the Texas Instruments hot line ((713) 274-2320). In addition to customer-support phone lines, major chip vendors have computer-accessible bulletin boards with DSP information and program listings. Many textbooks also include DSP algorithms and listings in Fortran or C. Whatever method you use to acquire it, a general understanding of DSP is essential for developing DSP software (see **box,** "A DSP definition").

With some knowledge of DSP in hand, you'll want to learn about development tools for different DSP chips. The availability and quality of development tools should influence your decision about which DSP chip to use, because most DSP projects are software intensive. Some chips have few or no tools, and others have an impressive variety. Texas Instruments leads the industry in tools and assistance; Analog Devices, AT&T, and Motorola also offer a number of tools. Look closely at the tools available for a particular DSP chip before selecting it; the effort you waste when you don't have good tools can be enormous.

Because first-generation DSP chips had novel architectures, development tools for them were difficult to create and, therefore,

C source-level debuggers, like the TMS320C30 C Source Debugger from Texas Instruments (left), are changing the way you debug DSP software. You no longer have to look at an assembly listing to figure out what the compiler has done with your high-level code.

New hardware and software tools are changing the way DSP programs are developed.

scarce. These early chips had architectures optimized for DSP, and little else; capabilities for running the general-purpose part of a program were very limited. Modern DSP chips, however, are capable general-purpose processors, and the hardware and software tools for them are changing the way DSP programs are developed. Now, developing a DSP program resembles the development of other real-time programs.

The tools for a particular DSP chip used to include only an assembler and a simulator. Today, some DSP chips have an optimizing C or Ada compiler, a source-level debugger, a real-time emulator, a block-level-language programming system, a variety of code generators, and extensive DSP function libraries. Several vendors offer complete, dedicated DSP development systems that include all these tools. There's even a real-time multitasking operating system especially for DSP chips—Spox from Spectron Microsystems.

C vs assembly code

In addition to development tools, you must also consider the language in which you'll write your DSP programs. The advantages of C over assembly language are the same for a DSP chip as for a general-purpose μP: ease of programming, code readability, and reduced maintenance costs. Likewise, C has the same

A DSP definition

The definition of digital signal processing (DSP) is changing. Originally, DSP was defined as the processing of signals by digital means, as opposed to analog means. A signal was just that: a received sonar or radar pulse, an acoustic signal, a signal on aphone line.

Now a signal can be just about anything. It is simply a continuous stream of information. A common signal is the music that travels through your stereo. Data about the price of a stock over some period of time can be a signal. Any block of related data can be a signal.

Processing a signal means modifying the signal so you can understand the information it contains. In a stereo, the bass and treble controls process the signal to accurately reproduce the music. A sonar system processes a received signal to identify the location of targets. You can analyze the performance of a stock to identify trends. A modem processes transmitted and received signals so computers can communicate over phone lines. Any time a signal gets modified, signal processing occurs.

Signals can be processed by analog or digital techniques. Digital techniques began to develop when affordable digital computers became available in the 1960s. But the number and size of computers required for the digital approach limited its use to research and very specialized applications. The cost of using DSP has declined, however, and the number of available algorithms has increased to a point where you may soon be called upon to use DSP.

The signals you process with DSP don't have to be analog. For example, DSP can be helpful any time you need to crunch numbers. By arranging your data in the most beneficial way and using an appropriate algorithm, you can often manipulate your data very quickly.

Algorithms are problem-solving procedures that generally involve repetition of an operation. The FFT, or fast Fourier transform, is a common DSP algorithm that converts data from the time domain to the frequency domain or vice versa. A signal that looks very complex in the time domain may look simple in the frequency domain. If you use an oscilloscope to view a signal representing the noise from a machine, the scope trace probably won't make much sense. In the frequency domain, however, the signal may appear as only a few separate frequencies mixed together. The FFT conversion from the time domain to the frequency domain makes the data easier to understand.

DSP algorithms often change a large amount of complex data into a form that is easier to deal with. A vision system, for example, examines and identifies objects—perhaps good and defective products on a conveyer belt—and may reduce an incredible amount of data to a simple pass/fail result.

The algorithms you need for a project may be given to you, or you may have to dig into DSP literature to find them. You shouldn't have any trouble finding algorithms, though; many people make careers out of creating new algorithms and publishing them.

Listing 1—DSP program written in C

```
#include <stdio.h>
#include <libap.h>
#define N 1024              /* Number of points in the window */
#define M 10                /* log2(N), N = 2^M */

main ()
{
     static float freq_array[N/2];

     /* The other part of your program goes here. When you need
          to use the spectrum analyzer, use the following
          function call. */

     get_spectrum (freq_array);

     /* Use the frequency domain data acquired by get_spectrum */
}

/* get_spectrum  -  spectrum analyzer
                 This routine will read the input from an ADC,
                 perform a Hanning window on the data, do an
                 FFT, and convert the resulting complex data
                 into floating point amplitude.  Data returned
                 is an array of amplitude of type float in the
                 frequency domain.  The function read_adc will
                 cause the hardware controlling the ADC to gather
                 data at precise time intervals.
*/

get_spectrum (freq_array)
{
     register float *data, real, imaginary, ampsqrd, *freq;
     register int i;
     static float data_array[2*N];

     data = data_array;
     for (i = 0; i < N; i++)           /* read buffer full of data */
     {
          *data++ = read_adc();
          *data++ = 0.0;               /* all complex values = 0 */
     }
     chann0 (N,M,data_array);          /* complex Hanning window */
     fft (N,M,data_array);             /* FFT of the data */
     data = data_array;
     freq = freq_array;
     for (i = 0; i < N/2; i++)         /* get the amplitude */
     {
          real = *data++;
          imaginary = *data++;
          ampsqrd = (real * real) + (imaginary * imaginary);
          *freq++ = sqrt(ampsqrd);
     }
}
```

disadvantages: increased execution time and program size. You'll probably want to use C as much as possible and assembly language only for those sections that require greater speed.

Depending on your application, you may be able to program an entire project in C. **Listing 1**, for example, shows a simple DSP program that performs a spectrum-analyzer function. The program makes function calls to an application library of optimized assembly-language routines.

Unfortunately, it is difficult to determine how much a high-level language will degrade your system's performance. Optimizing compilers—available from Analog Devices, AT&T, Intermetrics, Motorola, and Texas Instruments—are an improvement over standard C compilers, but they still don't produce code that's as efficient as that written by an experienced assembly-language programmer.

To begin DSP programming, you don't even need a DSP chip. You can compile and run algorithms on your PC. They won't run as fast on a PC's general-purpose μP, but they'll give you some useful insight. After experimenting with DSP algorithms on a PC, you can increase capability by adding a plug-in board that has a DSP chip. Many companies make such boards. Texas Instruments, for example, sells the $995 EVM, a PC card with a TMS320C30 DSP chip, memory, an ADC, and a DAC. The EVM works with all of TI's software development tools. An assembler/linker and source-level debugger come with the card; a C compiler is optional.

You can also gain DSP experience by using a DSP function library written in C, such as DSPL from Sonitech International. Its algorithms won't run as fast as assembly-language versions, but they're easier to understand. If the routines aren't fast enough for your final product, you can still use them for prototyping and then optimize some of the code as you become more familiar with the DSP chip you're using.

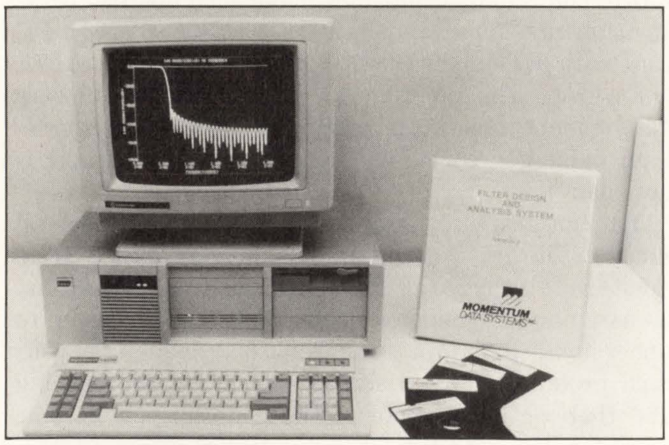
Another helpful tool for learning about the signal-processing aspect of DSP is filter-design software. Many available packages will accept your specification

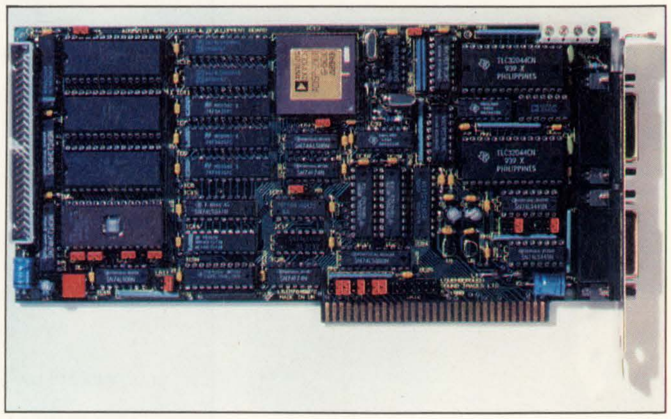
Depending on your application, you may be able to program an entire DSP project in C.

for a filter and then calculate the coefficients to create the filter. The Filter Design and Analysis System (FDAS) from Momentum Data Systems will even create assembly-language code to implement filter algorithms on a variety of DSP chips. Momentum president Jerry Purcell says the code-generation option for FDAS is very popular. "You can do a working program the minute you get the software," he says. "It gives you a big confidence boost and saves a week or two of trying to read through the manufacturer's manual to get a program running."

William Meshach, a consulting engineer for Loughborough Sound Images, recommends starting with C to learn DSP algorithms without the added confusion of real-time constraints. "Actually sit down with a setup where you can run something," he says. "Just write a C program that will record some stuff into memory, and then write a C program that scrambles it up somehow. Last of all, do simple math functions just to see how the waveforms are brought in, how they're stored, and how you manage the memory buffers."

Spectrum's Warren Cope believes you should familiarize yourself with DSP by taking three or four weeks to get a small practice design up and running, even if you have to borrow that time from your actual project. "I know that seems like a lot of time if you only have six months to do a design project," Cope says, but he stresses that you do eventually need to learn how to use a DSP chip and its tools, and you can get a jump on your project by first learning how to do all the parts of a design.


A filter-design software package can aid your introduction to DSP. The Filter Design and Analysis System (FDAS) from Momentum Data Systems helps you design and analyze filters and will even generate the program code needed to create the filter.


A DSP board can turn your PC into a prototype development system. This board from Spectrum Signal Processing contains Analog Devices' ADSP-2101 DSP chip, plus memory, analog I/O, and digital I/O.

By doing a small design first, you'll see where you need further help. You'll discover whether your assembler actually runs on your computer, whether your simulator runs in the available memory, and whether the simulator is fast enough to be useful. You can also find out if your compiler will compile and if your application library will link. You'll make sure everything works together and get some valuable experience on the way.

After writing a complete DSP program in C, you have to determine whether it's fast enough as is or if you need to rewrite the speed-demanding sections of code in assembly language. The simulators now available for DSP chips can help you determine which sections of code need additional work.

Before throwing any compiler-generated code out the window, though, make sure your expectations are realistic. Remember when you look at the code that a DSP chip is a RISC (reduced-instruction-set computer) processor. The code will look inefficient if you're used to looking at the assembly language for a CISC (complex-instruction-set computer) machine, but the microcode within a CISC machine hides many tasks that you have to explicitly tell a RISC machine to do.

You may find that C is helpful even if a state-of-the-art C compiler won't produce code that runs fast enough for the task you have at hand. Many companies use C as a development tool, even when they know their final product will contain only hand-generated assembly-language code; they use C to verify the functionality of their DSP algorithms, and then they turn to assembly language for speed.

Intelledex, a manufacturer of robots and vision systems in Corvallis, OR, is one company that takes this approach. The vision systems R&D group, headed by John McGarry, combines four AT&T DSP32C chips to make its algorithms run faster. McGarry explains that the group begins software development with a C compiler on a PC. In the next step, it uses AT&T's C cross-compiler to produce code for the DSP chips. The resulting program works, but is slow; a by-product, however, is an assembly-language listing that is helpful in understanding details of the program's operation. Next, the group writes a rough assembly-language version using the C code as a model. The final step is to optimize this program by taking advantage of the particular architectures of the DSP chips.

If you don't take advantage of your DSP chip's architecture, you won't get the speed the chip was designed for (see **box,** "Speed in the real world"). You have to understand the chip's parallel architecture to get the most out of your compiler. If you write code the way you always have, your compiler may not be able to optimize it. Every compiler has guidelines you should follow to get efficient code, so read the documentation carefully.

The way you use memory for data and program storage is one facet of DSP software design that can affect your program's execution speed. Many DSP chips have several separate memories that serve different purposes; if you use the memories improperly, your DSP chip won't work efficiently. For example, if you're multiplying two numbers together and you have to retrieve them both from the same memory, you'll need two sequential memory-read operations to fetch them. If, on the other hand, you have the numbers in separate memories, the processor can fetch them—as well as an instruction from a third memory—all at the same time. You must understand the memory-mapping features of the compiler and the architecture of the DSP chip to know where to place data for highest execution speed.

Another way to take full advantage of a DSP chip's speed is to use a DSP function library that's written in assembly language. Unlike C libraries, these libraries contain highly optimized assembly-language functions you call from C. A good one will give you the speed you need without making you write in assembly language.

Speed in the real world

A DSP program is a cross between a program for a supercomputer and a program for a real-time embedded system. The number-crunching algorithms that ran on supercomputers a few years ago now run on DSP chips and, in addition, must respond quickly to interrupts from real-world events. A DSP program is unacceptable if some part of it runs even a microsecond longer than the maximum allowable time.

Often you have to squeeze out every drop of performance to make your program fast enough. You can literally spend months shaving off instructions to increase speed. DSP chip architectures and instruction sets are designed to do some things—but not all things—very quickly. To get optimal performance, you must thoroughly understand your architecture and instruction set.

Speed is the only reason for using a DSP chip. Speed is also why programming a DSP chip is more difficult than programming a general-purpose μP. For a DSP chip to be fast, it has to perform many operations at the same time, so most DSP chips have a parallel architecture that makes their instruction sets very complex. A single instruction doesn't do just one thing; some operations of one instruction may even prepare for future operations. For example, while a DSP chip is multiplying two numbers from memory, the registers that point to the numbers can be incrementing to point to the next two numbers to be multiplied.

Keeping track of what a DSP chip is doing at any one time can be difficult. Because most of the chips are pipelined, a latency exists between an operation and the availability of the operation's results. If you're writing DSP programs in assembly language, you may have to wait a few cycles for results. Rather than wasting those cycles with no-ops, you can use instructions to accomplish something that may not even be related to the first instruction. The resulting code can get confusing. If you're writing in a high-level language, the assembly code produced by your compiler can be even more confusing.

Start your DSP experience by getting a small practice design up and running, even if you have to borrow the time from your actual project.

Analog Devices increases DSP speed by extending standard C. DSP/C is the company's implementation of an extended ANSI C standard being developed by the Numeric C Extensions Group, a working group of the ANSI X3J11 committee. In addition to increasing C's speed for DSP, DSP/C's nonproprietary extended features make DSP applications easier to write. "We believe the efficiency will be such that no one would ever be compelled to write an assembly-language subroutine or even in-line assembly code," says Kevin Leary, an Analog Devices staff engineer. Because DSP/C is a vector language instead of a scaler language, Leary continues, it can operate on vectors directly.

Debugging software for a DSP chip used to be a nightmare. There were no DSP debuggers or emulators on the market; you were on your own. The current availability of source-level debuggers for DSP chips is a major milestone. Without them, you would have to debug your program in assembly language and then try to figure out what the compiler did. This problem is even more serious with optimizing compilers, because the assembly code they produce looks so bizarre.

The ease of DSP programming depends on development tools and customer support. Texas Instruments currently leads the industry in the level of support and the number of tools it offers.

The first high-level-language source-level debugger, the TMS320C30 C Source Debugger from Texas Instruments, supports mixed C and assembly languages. You can look at the C code as it runs or at the assembly code as it runs. You can observe your application from a C perspective or an assembler perspective or even look at them both at the same time. If you have the assembly-language window open when you single step through the C code, the debugger highlights not only the line of C code, but also the assembly-language lines that implement the C line. You can display C variables by name, C structures, your link list (the list of all modules linked in your program), and other data. The debugger works on TI's XDS development system, EVM evaluation module, and C30 simulator.

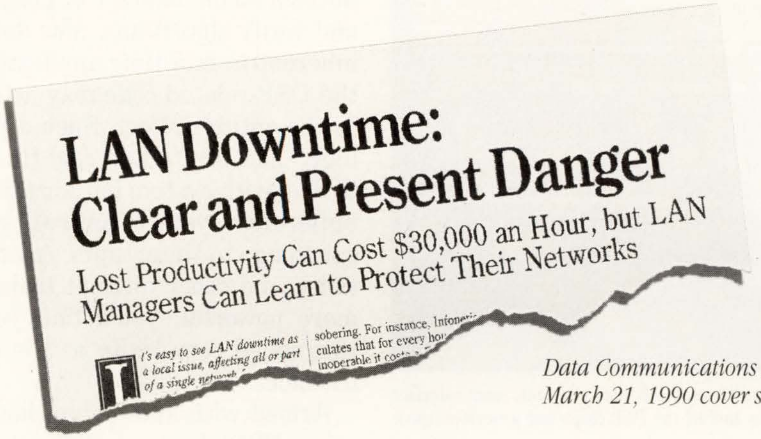
Another source-level debugger, the XDB from Intermetrics, will be available this fall, according to the company. The debugger and an optimizing C compiler will support the Motorola 96002. Otherwise similar to TI's debugger, the XDB doesn't use a mouse, and its windows aren't as convenient to use. It does have the same user interface as other debuggers from Intermetrics, so if you're using another μP as your system host, all your debugging tools can look the same. The Intermetrics tools run on a wide variety of computers.

When you develop and debug a program for a DSP chip, you'll run into the same types of problems you see in other real-time applications. Much of the advice you hear will also sound familiar. Analog Devices' Leary cautions against ignoring your runtime structure. He says his company's customers spend more time fixing runtime problems than anticipated.

You also need to understand the operation of on-chip peripherals. For example, many DSP chips have very capable, but complex, serial interfaces. Once you set up these interfaces, they're easy to use, but you have to learn how they operate in order to set them up.

Communications is another area that can cause trouble. Most of the time, a DSP chip does not work alone; complex systems have several DSP chips or at least a host controller. Designers often fail to examine bandwidth requirements for these systems, says Spectrum's Cope. "It can take a considerable amount of time for a DSP chip to send and receive data," he says. "A lot of people think they can just throw data to this other guy. They don't realize that [communication] kills a lot of your CPU cycles."

Your next embedded real-time system damn well better be bullet-proof.



LAN Downtime: Clear and Present Danger

Lost Productivity Can Cost $30,000 an Hour, but LAN Managers Can Learn to Protect Their Networks

It's easy to see LAN downtime as a local issue, affecting all or part of a single network

sobering. For instance, Infonetics calculates that for every hou inoperable it costs

Data Communications Magazine
March 21, 1990 cover story

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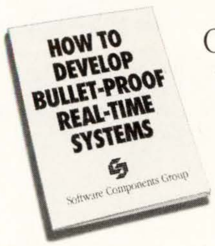
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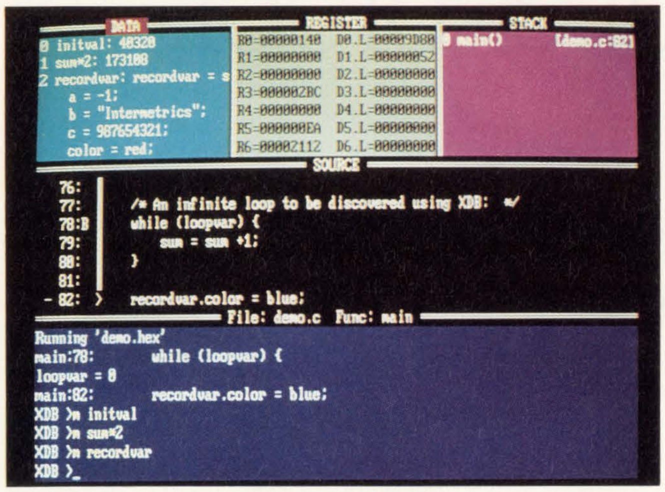
BULLET-PROOF REAL-TIME TECHNOLOGY

Many companies use C to verify DSP algorithms' functionality and then turn to assembly language for speed.



```
DATA                              REGISTER                      STACK
0 inital: 48320               R0=00000140  D0.L=00009D80   0 main()      [demo.c:82]
1 sum*2: 173188               R1=00000000  D1.L=00000052
2 recordvar: recordvar = s    R2=00000000  D2.L=00000000
   a = -1;                    R3=000002BC  D3.L=00000000
   b = "Intermetrics";        R4=00000000  D4.L=00000000
   c = 987654321;             R5=000000EA  D5.L=00000000
   color = red;               R6=00002112  D6.L=00000000
                              SOURCE
   76:
   77:      /* An infinite loop to be discovered using XDB:  */
   78:B      while (loopvar) {
   79:         sum = sum +1;
   80:      }
   81:
 - 82: >    recordvar.color = blue;
                      File: demo.c  Func: main
Running 'demo.hex'
main:78:        while (loopvar) {
loopvar = 0
main:82:        recordvar.color = blue;
XDB >m inital
XDB >m sum*2
XDB >m recordvar
XDB >_
```

A source-level debugger from Intermetrics, XDB uses the same user interface for all the host computers it runs on and all the DSP chips and general-purpose µPs it supports.

Your system design affects the difficulty of implementing the overall program. If your DSP chip is a coprocessor to another µP, you might be able to avoid real-time interrupt handling, sampling data at exact intervals, or interlacing your algorithms with real-time control of your system. A coprocessor usually accepts data from the host µP, then processes it and flags the host when it's done; there are few surprises. You can debug your program simply by feeding it known data and verifying the results.

A stand-alone application, on the other hand, produces a whole new set of problems. You have to create and verify algorithms, plus deal with all the difficulties inherent to real-time applications. The effort to create the DSP-related code may actually be minor compared to the entire project. Such a project may look surprisingly like any other real-time application. You have to deal with system initialization, data acquisition, data buffering, system control, running algorithms, responding to interrupts, memory-management functions, and other difficult tasks. As DSP chips become more powerful, you'll find your programs taking on this added complexity as the need for a separate host µP fades.

Armed with knowledge, however, you shouldn't find using DSP chips too difficult. The increasing number of development tools helps, especially if you're already familiar with similar tools for general-purpose µPs. The continued evolution of DSP chips makes the job easier. And the ever increasing number of function libraries keeps you from reinventing the wheel. EDN

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For more information . . .

For more information on DSP chips and development tools discussed in this article, circle the appropriate numbers on the Information Retrieval Service card, or use EDN's Express Request service. When you contact the manufacturers directly, please let them know you saw their products in EDN.

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Costa Mesa, CA 92626
(714) 557-6884
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Microprocessor Products Group
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Austin, TX 78735
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Wellesley, MA 02181
(617) 235-6824
Circle No. 655

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Santa Barbara, CA 93111
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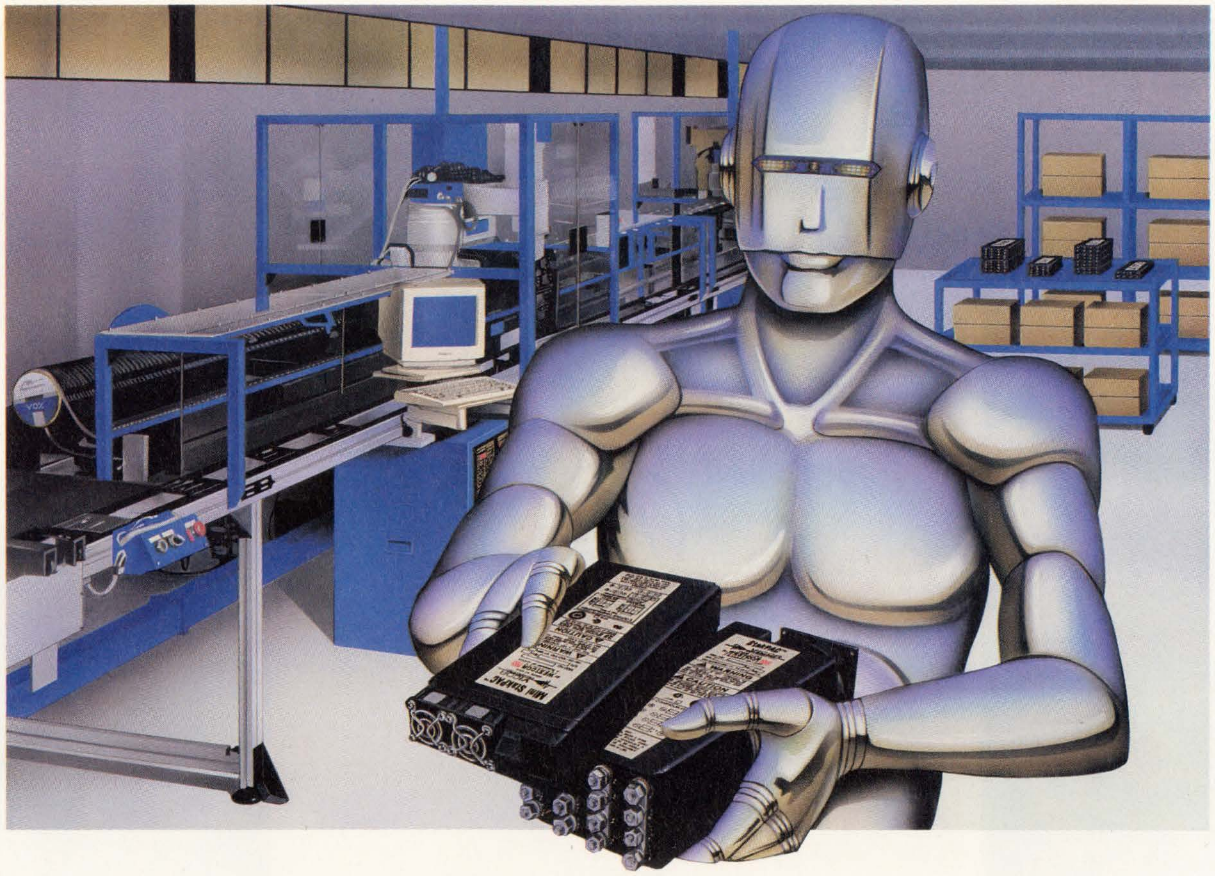

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SP1-1604	15 @ 80				
SP1-1605	24 @ 50				
SP1-1606	28 @ 42				
SP1-1607	48 @ 25				
Dual Output					
SP2-1801	2 @ 120	5 @ 120			
SP2-1802	5 @ 120	5 @ 120			
SP2-1803	5 @ 120	12 @ 66			
SP2-1804	12 @ 66	12 @ 66			
SP2-1805	15 @ 53	15 @ 53			
Triple Output					
SP3-1801	5 @ 180	12 @ 16	12 @ 16		
SP3-1802	5 @ 150	12 @ 33	12 @ 16		
SP3-1803	5 @ 180	15 @ 13	15 @ 13		
SP3-1804	5 @ 150	15 @ 26	15 @ 13		
Quad Output					
SP4-1801	5 @ 150	12 @ 16	12 @ 16	5 @ 30	
SP4-1802	5 @ 150	15 @ 13	15 @ 13	5 @ 30	
SP4-1803	5 @ 150	12 @ 16	12 @ 16	24 @ 8	
SP4-1804	5 @ 150	15 @ 13	15 @ 13	24 @ 8	
Five Output					
SP5-1801	5 @ 120	12 @ 16	12 @ 16	5 @ 30	24 @ 8
SP5-1802	5 @ 120	15 @ 13	15 @ 13	5 @ 30	24 @ 8
Seven Output					
SP7-1801	5 @ 60	12 @ 16	12 @ 16	24 @ 8	24 @ 8
	#6	#7			
	5.2 @ 28	2 @ 30			

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ST1-1301	12 @ 50				
ST1-1302	15 @ 40				
ST1-1303	24 @ 25				
ST1-1304	28 @ 21				
ST1-1305	48 @ 13				
Dual Output					
ST2-1401	2 @ 60	5 @ 60			
ST2-1402	5 @ 60	5 @ 60			
ST2-1403	5 @ 60	12 @ 33			
ST2-1404	12 @ 33	12 @ 33			
ST2-1405	15 @ 26	15 @ 26			
Triple Output					
ST3-1401	5 @ 60	12 @ 16	12 @ 16		
ST3-1402	5 @ 60	15 @ 13	15 @ 13		
ST3-1501	5 @ 90	12 @ 8	12 @ 8		
Quad Output					
ST4-1401	5 @ 30	12 @ 16	12 @ 16	5 @ 30	
ST4-1402	5 @ 30	15 @ 13	15 @ 13	5 @ 30	
ST4-1403	5 @ 30	12 @ 16	12 @ 16	24 @ 8	
ST4-1501	5 @ 30	15 @ 13	15 @ 13	24 @ 8	
ST4-1502	5 @ 60	12 @ 16	12 @ 8	5 @ 15	
ST4-1503	5 @ 60	15 @ 13	15 @ 7	5 @ 15	
ST4-1504	5 @ 60	12 @ 16	12 @ 8	24 @ 4	
ST4-1505	5 @ 60	15 @ 13	15 @ 7	24 @ 4	
Five Output					
ST5-1501	5 @ 30	12 @ 16	12 @ 16	5 @ 15	24 @ 4
ST5-1502	5 @ 30	15 @ 13	15 @ 13	5 @ 15	24 @ 4

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Debugging guidelines facilitate software development

Although software debugging can be something of a black art, some general rules do apply. Consider the various debugging options that are available at different stages of software design and integration.

Andy Lantz, *Intermetrics Inc*

Programmers, unfortunately, are not free from the human trait of fallibility. During every software project, engineers stare at listings and screens and wonder why their programs don't work. Although bugs, like human fallibility, are here to stay, finding them is easier than it used to be. Improved debugging tools help, as does experience. Collective experience yields some general guidelines that can help make debugging less of an art and more of a science. These guidelines include holding design meetings and code walkthroughs; using modular design; and taking full advantage of simulators, emulators, and ROM monitors.

One of the best ways to simplify software debugging is to use structured design methods. The design and coding phases of a project are not often thought of as steps in the debugging process, but the work done during these phases can have the most significant impact on the amount of time spent later in debugging. Top-down design, a rigorous review process, and adherence to strict coding standards and other principles of structured software development can make life much easier during a project's debugging phase.

Design reviews and a code walkthrough are crucial to the schedule of any significant software project. At the very least, your project should have a top-level design review, a detailed design review, and a code walkthrough. All can be instrumental in uncovering problems.

The top-level design review is an opportunity to find bugs at the conceptual level of a project's design. A program's designers should produce a top-level-design document detailing each of the program's functional units and the relationships and data flow between those units. This document should be distributed to a group of reviewers—experienced software developers not directly involved with the application's development—before the design review meeting. At the meeting, the reviewers should play devil's advocate and try to poke holes in the design.

The detailed design review and the code walkthrough should use the same forum as the top-level review. At the detailed review, reviewers examine the detailed design document, which contains pseudocode for every function that will be in the program; at the code walkthrough, reviewers examine the final code implementation.

A top-level design specifies ideas, functions, and concepts. At some point, you define what modules you will create to implement these concepts, then you design the modules. Modular design is not just good software engineering practice—it can also prevent some kinds of bugs from occurring in your code. Suppose you see the same sequence of statements appearing in multiple places in your program. If you incorporate that block of code into its own function or macro, you accomplish two objectives. First, you eliminate the possibility that the code is correct in some places and not in others. Second, if you need to change this common code, you have to change only one instance of it, thereby reducing the chance of clerical error.

C is efficient for building pointers and generating pointer bugs of the worst magnitude.

The way you use C—the high-level language of choice for coding embedded-systems applications—also greatly affects later debugging. C offers programmers many ways to get around cumbersome type restrictions found in stricter languages such as Pascal and Ada, but this flexibility can be a double-edged sword. Just as you can write C code that rivals assembly language's efficiency in handling pointers, you can also quickly and efficiently create insidious stray-pointer bugs of the worst magnitude. Fortunately, you can use several techniques to stringently check C code at compile time.

The *lint* program is probably the single most useful compile-time aid for preventing C bugs. Originally supplied as a utility program with Unix but now available elsewhere, *lint* accepts a C program as input and warns of unreachable statements, loops not entered at the top, automatic variables declared and not used, and logical expressions whose values are constant. The program also finds functions that return values in some places and not in others, functions called with varying numbers of arguments, and functions whose values are not used.

Lint sounds great, yet many people categorically refuse to use it, complaining that it forces them to wade through countless pages of warnings that aren't helpful or appropriate. These people may not have experimented with the various switches lint offers to disable checking that is irrelevant or redundant.

Even if *lint* isn't available on your system, there are other ways to get compile-time warnings of potential bugs. One way is to use a compiler that warns of situations such as possible infinite loops or local variables that your code never references. Another way to get compile-time warnings is to use a compiler that supports ANSI C's function prototype feature **(Fig 1)**.

Function prototypes were added to the ANSI standard for C so that programmers could make compilers perform stronger type checking on statements that declare, define, or call functions. A function prototype is a variant form of a function declaration; the difference is that a function declaration only names the function and its return type, but a function prototype includes information on the number and types of parameters the function requires. If a programmer uses a function prototype instead of a function declaration, the compiler will check to see if the corresponding function definition and any calls to the function have the proper number and types of parameters.

Other good coding habits can also help you avoid common C pitfalls. If you're comparing strings, for example, it's much safer to define a preprocessor macro called STRING_EQ than to risk forgetting that the *!* in *!(strcmp(x,y))* is required to test for equality between string x and string y.

In general, using preprocessor macros makes for good design practice. Don't use numeric literals throughout your program; there are too many opportunities for typos. Instead, define preprocessor names for them (for example, "#define MAXLEN 256"). If you type a numeric literal incorrectly, it may cause problems that you won't detect until the program mysteriously fails at runtime. If you type a macro name incorrectly, however, the compiler will tell you right away that you're referencing an unknown name.

Whenever you have a test for equality between a constant and an expression, get into the habit of putting the constant first: *if (7 == x)*. This practice makes it impossible for you to commit one of the most common and subtle C programming errors: using = when you mean to use == for a comparison. The compiler will not accept *if (7 = x)*, but it will accept *if (x = 7)* with no complaints. If you're trying to compare x with 7, the latter expression will not evaluate the way you want it to.

Print statements provide flexibility

Perhaps the most common debugging technique used at the coding stage of native applications (applications in which the code compiles and runs on the same system) is inserting *printf()* calls into a program. At runtime, these statements cause the program to display values of important variables and structures. Using this technique for embedded systems is complicated because the system might not have an obvious destination for standard output (*stdout*). Even if your system doesn't have standard I/O, you have other options, such as complex breakpoints and simulated I/O, for displaying diagnostic messages.

If you can use *printf()* calls for diagnostics, you'll benefit from enclosing the debugging code in conditional compilation directives. For example, define a preprocessor variable called DEBUG, which you can turn on or off at compile time. Then, you can isolate your debugging code as in the following:

```
#if DEBUG
printf("value of index is %d\n", index);
.
.
#endif
```

```
/* non-prototype function declaration for f() */
double f();

/* non-prototype function definition for f() */
        double
f(a,b,c)
        char a;
        int b;
        double c;
{
        return (a + b + c);
}
```
(a)

```
/* function prototype declaration for f() */
double f(char a, int b, double c);

/* function prototype definition for f() */
        double
f(char a, int b, double c)
{
        return (a + b + c);
}
```
(b)

```
Compiling the following  code...

/* function prototype declaration for f() */
double f(char a, int b, double c);

/* incorrect function definition for f() */
        double
f(char a, double b, int c)
{
        return (a + b + c);
}

...results in the following error messages

:FE:badproto.c:6:       f: Symbol redefined
:FE:badproto.c:6:       First declared type assumed for function
```
(c)

```
Compiling the following  code...

/* function prototype declaration for f() */
double f(char a, int b, double c);

/* function definition for f() */
        double
f(char a, int b, double c)
{
        return (a + b + c);
}

main()
{
        double  g;

        g = f('a', 3.14159);
}


...results in the following error message:


:FE:badproto2.c:15:    Mismatch between # of args at call and function
prototype
```
(d)

Fig 1—Function prototypes help avoid some C bugs by causing stronger type checking at compile time. The code shown in (a) contains a function declaration and a corresponding function definition; the code in (b) is the same function, using function prototypes for the declaration and the definition. If you use function prototypes instead of ordinary function declarations, your compiler will check for the correct number and types of function arguments. For example, (c) shows a compiler error message resulting from a type mismatch between a function prototype declaration and the corresponding function declaration. The code in (d) shows the compiler error message resulting from an incorrect call to a prototype function.

Develop programs top-down; debug them bottom-up.

Obvious locations for these kinds of messages are at the beginnings and ends of functions and inside loops.

The listings your compiler and linker produce can be a big help both before and after you start debugging. Many compilers can produce a listing that shows the user's original C code interleaved with the assembly language that corresponds to the generated machine instructions (**Fig 2**). These listings can alert you to bugs in your program.

Suppose, for example, that you've written a block of code that an optimizing compiler determines to be unreachable. The conspicuous lack of generated instructions for that source code is readily apparent during a casual glance through an interleaved listing. You can use a global symbol map to find similar anomalies in your program. A segment showing a length of zero can be an indication that the program has been written or linked incorrectly.

Decide where to run your code

After you've written most or all of your software, you still have to decide where it will run when you debug it. Your choice will depend on the readiness of your hardware and on your budget. Simulators let you debug software before the hardware is ready; emulators and ROM monitors let you integrate and test your hardware in conjunction with the software.

If the software engineers are ahead of the hardware engineers and your target board isn't yet ready for testing, you'll probably want to begin debugging your software by determining whether it is algorithmically correct. The best way to make this determination is with simulation. The principle behind simulation is that in the preliminary phases of debugging an embedded system, some aspects of the software can be tested independently of the target hardware.

A choice of simulators

You can choose either a software instruction-set simulator or a hardware simulation board. An instruction-set simulator is software that runs on the development host and mimics the target microprocessor. A hardware simulation board is a single-board computer that has a microprocessor, ROM containing a simple control program, and some RAM into which to download the application program. The simulation board usually connects to the host via a serial connection or, if the host is an IBM PC or compatible computer, via the AT bus.

Many simulators can be controlled by a source-level debugger, which lets you debug your code at the source-code level rather than at the assembly-language level. For the C programmer, source-level debugging is a requirement for maximum productivity.

Once you have an execution environment for your program, the next step is to organize your debugging strategy. Your first tendency might be to try running the program in its entirety. Very likely, you will encounter problems. At the discovery of the first bug, programmers often employ some kind of binary search, using breakpoints to iteratively narrow down the bug's location. Although this approach is popular, by itself it is not always as efficient as the more structured techniques of bottom-up debugging.

The best way to debug software is the opposite of the way you developed it. Develop programs starting at the highest level of organization and add detail during subsequent stages of development. Use bottom-up debugging to ensure that low-level functions are working correctly before you examine the behavior of your program as a whole. Observing the behavior of an individual function in the context of bottom-up debugging is known as unit testing.

```
A -->   * Variable i is in the D5 Register
        * Variable j is in the D4 Register
        * Variable k is in the D3 Register
                  .
                  .
                  .
        *5           for (i = 1; i < 10; ++i) {

                  MOVEQ.L #1,D5
B -->   *(code hoisted from following statement)
                  MOVE    D3,D2
                  MULS    D4,D2

        L20001
        *6                f(i + j * k);
                  MOVE    D5,D1
                  ADD     D2,D1
                  MOVE    D1,-(A7)
                  JSR     _f

C -->   *(see line 5)
                  ADDQ.L  #2,A7
                  ADDQ    #1,D5
                  CMPI    #10,D5
                  BLT.S   L20001
                  .
                  .
                  .
```

Fig 2—An interleaved listing can be helpful in debugging, showing how a compiler generates assembly-language code from lines of C code. The listing here shows how the compiler allocates local variable in registers (a), how the compiler generates code for a loop-invariant expression before the code for the body of the loop (b), and how the code for the increment-test-and-branch part of the loop is separated from the beginning of the loop (c).

There are a couple of ways to perform unit testing. The oldest method is to write a driver program for a routine. A driver is a routine that does little else than call a single function. Debugging a program consisting solely of a single function and its driver would be ideal, but isolating a single function in this way is often difficult: There are just too many interdependencies to avoid linking in a number of other functions. A much easier way of doing unit testing is to have a source-level debugger do the work for you. If your debugger can evaluate C expressions containing function calls, you can test a single function by passing all kinds of hypothetical parameters to it.

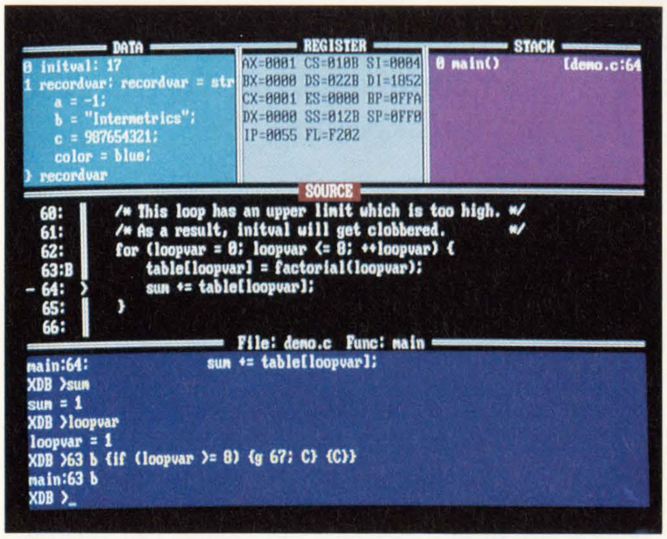
Emulator or ROM monitor?

Once your target hardware is available, you'll have more choices for where your code runs during debugging. Both in-circuit emulators and ROM-based monitors let you test your software along with the hardware. No matter what combination of hardware you choose to assist your debugging, you should try to exploit your investment as fully as possible. Learn as much as you can about the advanced features of your debugger's command language.

One of the most useful features of an in-circuit emulator is, of course, its ability to set breakpoints that impose no penalty in real-time execution speed. A code breakpoint instructs the emulator to halt execution when an instruction at a particular address executes. Code breakpoints are one of the mainstays of day-to-day debugging practice.

But programmers often overlook data breakpoints, which cause a program to halt whenever it reads from or writes to a specified memory address. Suppose you have a variable that is getting clobbered at some unknown line in your program. Rather than trying to discover the offending line by setting code breakpoints and inspecting the variable's value at various statements, use a data breakpoint to check for write operations to the variable's address.

Sometimes your requirements are more specific: You want your program to halt only if one particular value is being written to a certain memory location. Some emulators answer this need by offering data breakpoints with an additional capability: You can specify not only the breakpoint address, but also the one write-data value that you want to result in an actual stopping of the program. This capability can help you track down errors that occur at boundary conditions for input-data values. Data breakpoints can even operate over ranges of addresses. When applied over a range, they can help determine where a program attempts to write to ROM.



```
DATA
0 initval: 17
1 recordvar: recordvar = str
    a = -1;
    b = "Intermetrics";
    c = 987654321;
    color = blue;
} recordvar

REGISTER
AX=0001 CS=010B SI=0004
BX=0000 DS=022B DI=1852
CX=0001 ES=0000 BP=0FFA
DX=0000 SS=012B SP=0FF0
IP=0055 FL=F202

STACK
0 main()              [demo.c:64

SOURCE
  60:  |    /* This loop has an upper limit which is too high. */
  61:  |    /* As a result, initval will get clobbered.         */
  62:  |    for (loopvar = 0; loopvar <= 8; ++loopvar) {
  63:B |        table[loopvar] = factorial(loopvar);
- 64:  >        sum += table[loopvar];
  65:  |    }
  66:  |

File: demo.c  Func: main
main:64:                sum += table[loopvar];
XDB >sum
sum = 1
XDB >loopvar
loopvar = 1
XDB >63 b {if (loopvar >= 8) {g 67; C} {C}}
main:63 b
XDB >_
```

Fig 3—Complex breakpoints, which are supported by some debuggers, let you test fixes to your program before you change the source code. This example on the XDB debugger from Intermetrics (Cambridge, MA) shows a simulated patch. The user has set a breakpoint at line 63, which causes the program to exit the *for* loop (using the commands "g 67" to go to line 67 and "C" to continue execution) when the value of the variable ***loopvar*** becomes greater than or equal to 8. This patch temporarily fixes a bug caused by an incorrect upper limit in the comparison part of the loop.

Source-level debuggers offer one very obvious advantage over other debuggers. You can set a breakpoint by referring to a source-level statement's line number or by referring to a variable name; you don't have to refer to hexadecimal memory addresses. But few people make the best use of their source-level debugger's other features. They rely on three or four basic commands, forgetting that they can attack some of their problems more effectively with others.

For example, some source-level debuggers allow conditional breakpoints. These debuggers will stop your program at such a breakpoint and then check a simple condition to determine if the program will continue or remain at the breakpoint.

Other source-level debuggers provide complex breakpoints—breakpoints with attached command lists (**Fig 3**). The commands, which can be debugger instructions or C expressions, are performed when the breakpoint is hit. You can exploit this feature in a variety of ways. In the simplest case, you can use commands to display the value of a variable or an expression every time your program reaches a particular line of code.

Use complex breakpoints for patches

One powerful use of complex breakpoints is for simulating code patches. In the simplest case, suppose you need to add a missing statement to your code. You can set a complex breakpoint on the statement after the missing statement, append the missing statement to the breakpoint, and follow it with a command to continue execution.

Complex breakpoints let you attach lists of debugger commands or C instructions to ordinary breakpoints.

Deleting a line of code using complex breakpoints is a little more risky. You set a breakpoint on the statement to be deleted and then append a list of commands to the breakpoint. One of the commands changes the value of the program counter register to the address of the statement after the one to be deleted; another is a command to continue.

There are several reasons you should use this approach with caution. First, you can inadvertently cause condition codes to have the wrong values because a deleted line of code no longer executes and therefore doesn't set the codes. If program control later passes to a part of the program that evaluates such condition codes, then the result will be unpredictable. Also, deleting instructions might disrupt the stack pointer. Nevertheless, this kind of patching is valuable because it lets you test the logic of potential fixes without recompiling your code.

The debugging technique of placing *printf()* statements throughout your code is a long-used method of getting diagnostic information about the values of variables at runtime. But with embedded systems, as opposed to native application programs, the output—if the system has any output at all—does not necessarily go to a screen. Sometimes all that happens is that values in certain memory addresses change. One solution to this problem involves using a debugger's simulated I/O capability. With simulated I/O, you don't have to use peripheral hardware for input and output; you can use the resources of the host computer, such as disk files, the keyboard, or the screen. Many debugger packages offering simulated I/O include alternate versions of the compiler's standard I/O library routines.

In the course of tracking down an especially elusive bug, it is not uncommon for several engineers to work in shifts. By using the debugger to record into a disk file all the debugging commands and results during a particular shift, you can ensure that the next shift sees what has transpired. The next user simply uses the debugger to read in the file from the previous debugging session.

Many source-level debuggers also offer on-screen windows for monitoring variables and data expressions, automatically displaying the values whenever execution stops. Remembering to use this feature can save you from typing a command to display these values at each breakpoint. If you find yourself repeatedly asking the debugger to display the value of a particular expression after single steps or breakpoints, you should monitor the expression's value in a window.

Even with a source-level debugger's powerful arsenal of commands for high-level debugging, at times you'll need access to the low-level features of your emulator's own command set (**Fig 4**). These low-level features let you observe bus activity, establish trigger conditions for tracing, and set any type of emulator-specific breakpoints that is not available in the debugger itself. Debugging at the integration and testing phases of a project should include a balance of high-and low-level debugging. Most source-level debuggers let you "drop down" to the emulator's interface during a debugging session and then return to the high level.

Sometimes, however, an in-circuit emulator isn't the best choice for debugging, or an emulator might not be available for a chip. One debugging approach circumvents this problem and is rapidly growing in popularity. In the technique sometimes called remote debugging, a source-level debugger communicates directly with a monitor program burned into PROMs on the user's actual target board.

Like emulators, some ROM monitors can accumulate a trace buffer of a program's execution history in RAM. Because one CPU runs both the ROM monitor and the user's application code, ROM monitors can't save trace information without stopping execution before each machine instruction. ROM monitors make up for this sacrifice of real-time tracing by providing extended information in their trace buffers. Suppliers of ROM monitors reason that if a monitor has to run a program in step mode to get trace information, it might as well record more information than just the addresses of executed instructions.

With some ROM monitors, you have the option of saving only the program counter values in the trace buffer or saving both those values and the values of each instruction's operands before and after instruction execution. This trace with full data movement can pinpoint the precise instruction that causes a data value—even in a register—to go bad. Because this kind of trace also shows the effective addresses computed for instructions, you can use it to detect errors in assembly-language code.

Another difference between emulators and ROM monitors involves the ability to set breakpoints on data accesses. Because emulators watch external buses to detect accesses to particular memory locations, they can detect these kinds of breakpoints in real time. A ROM monitor can't detect an access to a memory location; it can, however, check the contents of a memory address before each instruction to see if the value has changed. A ROM monitor may let you set up a breakpoint that compares the contents of a register with some mask or value before each instruction and halts when a particular condition is met. Because an emulator cannot interrogate the values of internal registers while the processor is running, it cannot use its hardware to set breakpoints on register accesses or changes. As with an execution trace, a ROM monitor—resigned to running in trace mode—tries to compensate for not being able to set breakpoints by providing additional information not available to an emulator.

ROM monitors can also be useful for troubleshooting finished, but malfunctioning, products. If you may have occasion to debug your product after it has been sold, leaving a ROM monitor in the final version of your board gives you the opportunity to debug in the field. Keeping the monitor on the board adds to the cost and ROM requirements of your product, but the benefits may far outweigh the costs.

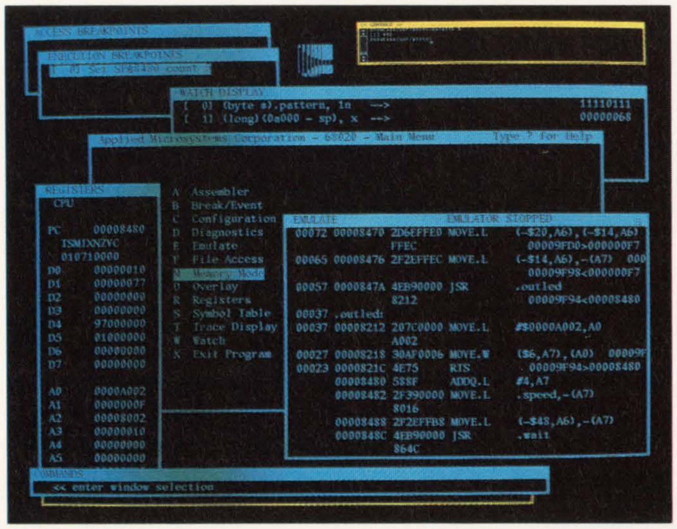
Embedded systems, extra problems

Native applications, of course, tend to be easier to debug than embedded systems. Developers of native applications programs don't have to know exactly where their code will reside in memory, for example. They also tend to have few worries about interrupts and external I/O devices. Embedded-systems programmers are not so fortunate.

Unlike native-system programs, which the host's operating system loads into available system memory, an embedded-system program must go into explicitly specified target-hardware addresses. One of the most troublesome problems that can result from the incorrect location of your program is the allocation of too small a region in target memory for the runtime stack. To further complicate matters, the symptoms of this problem are subtle. The program may mysteriously crash only after several iterations of a recursive routine or in a deep nesting of other function calls. Checking the value of your program's stack pointer at strategic places in your code and comparing its value with addresses in your global symbol map is a good practice.

Linking your program with a runtime library that is in some way inappropriate for your application may also result in bugs that are extremely hard to track down. Take great care when you build your program to link only with runtime libraries that have been proven correct and that match your compiler's calling conventions.

Debugging interrupt-driven code is one of the chal-



```
ACCESS BREAKPOINTS

EXECUTION BREAKPOINTS
[  0] Set SP@8480 count

WATCH DISPLAY
[  0] (byte s).pattern, in    -->                              11110111
[  1] (long)(0a000 - sp), x   -->                              00000068

Applied Microsystems Corporation - 68020 - Main Menu     Type ? For Help

REGISTERS
 CPU

PC       00008480
  ISMIXNZVC
  010710000
D0       00000010
D1       00000077
D2       00000000
D3       00000000
D4       97000000
D5       01000000
D6       00000080
D7       00000000

A0       0000A002
A1       0000000F
A2       00008002
A3       00000010
A4       00000000
A5       00000000

A  Assembler
B  Break/Event
C  Configuration
D  Diagnostics
E  Emulate
F  File Access
M  Memory Mode
O  Overlay
R  Registers
S  Symbol Table
T  Trace Display
W  Watch
X  Exit Program

EMULATE                          EMULATOR STOPPED
00072 00008470 2D6EFFE0 MOVE.L   (-$20,A6),(-$14,A6)
               FFEC                00009FD0>000000F7
00065 00008476 2F2EFFEC MOVE.L   (-$14,A6),-(A7)  000
                                   00009F98<000000F7
00057 0000847A 4EB90000 JSR      .outled
               8212                00009F94<00008480
00037 .outled:
00037 00008212 207C0000 MOVE.L   #$0000A002,A0
               A002
00027 00008218 30AF0006 MOVE.W   ($6,A7),(A0)  00009F
00023 0000821C 4E75     RTS        00009F94>00008480
      00008480 588F     ADDQ.L   #4,A7
      00008482 2F390000 MOVE.L   .speed,-(A7)
               8016
      00008488 2F2EFFB8 MOVE.L   (-$48,A6),-(A7)
      0000848C 4EB90000 JSR      .wait
               864C

COMMANDS
<< enter window selection
```

Fig 4—An emulator's user interface allows in-depth low-level debugging. This display from the interface to Applied Microsystems' (Redmond, WA) EL 3200 emulator shows windows for registers, breakpoints, the instruction trace, and monitored data.

lenges that embedded-systems applications present. A trace buffer for an interrupt-driven program frequently contains interrupt-handler code interspersed with code from the nonhandler routines. Looking at the complete asynchronous trace may be useful in some instances, but a more limited, qualified trace can also be helpful. You should make the best use of any trace-qualifying mechanisms you can.

Many emulators let you specify trigger conditions that determine when executed instructions will be recorded in the trace buffer. Some ROM monitors let you use conditional breakpoints to enable and disable tracing. If you're trying to debug an individual interrupt handler, you may want to give the appropriate debugger commands so that tracing is initiated at the beginning of the handler and disabled upon exit. Conversely, once a particular handler is known to work properly, you can arrange for the trace to be disabled on entry to the handler and enabled on exit. EDN

Author's biography

Andy Lantz has been debugging software for a variety of applications for more than eight years. He is a senior applications engineer at Intermetrics Inc (Cambridge, MA) where he provides technical support and training to software engineers who design embedded systems. Andy holds a bachelor's degree in computer science from Brown University.

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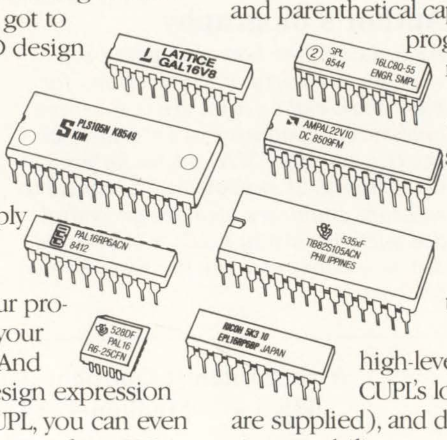

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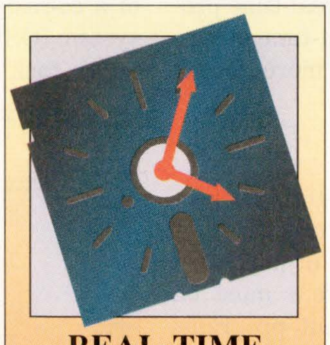
CIRCLE NO. 16

The nature of real time

As real-time programming has matured, a body of knowledge has developed about the special problems of real-time devices and the techniques required to handle these problems. This series of articles will present some of that knowledge in the context of a specific operating system (MTOS-UX) and will demonstrate how to write good, robust real-time programs. Part 1 introduces some basic concepts including real-time programming, multitasking, task attributes, operating systems, and operating-system services.

David L Ripps, *Industrial Programming Inc*

This series is about real-time programming—about programs that run telephone switches, control robot arms, or pilot airplanes. It is not about programs that generate last month's telephone bill, prepare parts lists for items made by a robot, or do cost accounting for an airline. Before you plunge into the technical issues, you should understand exactly why the first is a group of real-time programs and the second is not.



A fundamental property of a real-time program is that some or all of its input arrives from the outside world *asynchronously* with respect to any work that the program is already doing. The program must be able to interrupt its current activity immediately and then execute some predefined code to capture or respond to that input, which is often a fleeting, transient signal. The capture of new data, in turn, may trigger the running of one or more other urgent programs that were waiting for input. Finally, the computer is able to resume its original activity.

Consider a telephone switch that is capable of servicing a rotary dial. Dialing, say, a 5 produces five narrow pulses that must be detected immediately as they fly by. Meanwhile, other parts of the dial processing program must cancel the transaction if the caller hangs up; must time-out the call if there is too long an interval between digits; must start finding a special path if the leading digit is a 1, or an area code, or 800, or 911; and so on. Simultaneously, still other parts of the overall switch program are working on calls that have already been placed: searching for a connection path, generating ring or busy signals, recording billing information, and monitoring hangups, among other activities. This is real time because the timing of the input is completely imposed on the program by unpredictable outside agents (you and me).

In contrast, generating a telephone bill does not have that kind of frantic timing constraint. When the program needs input, it makes a disk access and then waits for the data. (In a multiuser system the billing program may be swapped out during the wait, but that is irrelevant.) If the program takes a long time to compute a bill, there's no catastrophe; the next customer's data will always be there when the program gets around to reading it.

In these two cases the strong difference between real-time and nonreal-time programs arises from the nature of the program specifications—from what the programs have to do. Sometimes the difference arises just from the relative time scales involved. For example, consider a program to control the speed of a rotating shaft. The shaft has a wheel on which are engraved a series of lines that reflect light onto a detector. Shaft speed is computed by counting the number of blips coming from the detector per unit of time or, equivalently, by measuring the

From the book, An Implementation Guide to Real-time Programming, by David L Ripps, ©1989. Excerpted by permission of Prentice-Hall Inc, Englewood Cliffs, NJ.

time interval between blips. (Assume that there is a high-resolution clock available to the program.) The program enters the raw speed measurements into an averaging filter, compares the result with the desired speed, and then computes the power to be sent to the drive motor.

Real-time applications must be written as a series of separate component programs that can execute concurrently.

On the one hand, if the shaft is rotating very quickly or there are many lines on the wheel, the blips arrive faster than the time needed to compute the motor power. The power calculation based on the last period's blip count would have to be interrupted now and then to count the blips for the next period. This is clearly real time. On the other hand, if the speed is low and there are few lines, the program might easily complete the calculation of the motor power in the interval between blips, and then wait to input the next blip. Now, the program has lost its real-time flavor. Thus, the same program requirements can be either real time or not depending upon the time scale of the input in relation to all the work that must be done by the system.

Real-time programs are organized to survive in the face of disturbances that would upset nonreal-time programs. Thus, if there is doubt as to the real-time nature of an application, it is safer to use the more robust real-time organization.

Organization of a real-time program

The need to interrupt one part of a real-time application spontaneously to perform data capture or other more urgent functions forces a particular organization upon such programs. Real-time applications must be written as a series of separate component programs that can execute concurrently. The components are called *tasks* or *processes*; the organization is called *multitasking* or *multiprocessing*. This series will use the terms tasks and multitasking. (The adjective "multiprocessing" is too easily confused with "multiprocessor," which describes a computer system having more than one CPU.)

Each task is a complete program that is capable of independent execution. Each task has a segment of code that it executes. Each task has its own private stack and its own local data areas. These are dedicated memory segments in which the task can keep procedure call parameters, return addresses, temporary data, and similar variables that are not shared with other tasks. Furthermore, each task has its own set of values for the program counter and stack pointer, plus any other general, special, and coprocessor registers that the hardware provides. The hardware register set is known as the execution context, or simply the *context*. (Some tasks may share some or all of their code segment with other tasks. Normally, every task will have the same value for certain special registers, such as those that determine the response to external interrupts. Neither type of overlap lessens the completeness of each task as an executable program.)

Because each task is itself a viable program, each can be started, suspended, resumed, and terminated separately. When an interrupt requires the current task, **C**, to suspend execution in deference to another task, **I, C** stops running, its context is saved, **I**'s context is installed in the hardware, and **I** starts running. Later, **C**'s context is reinstalled in the hardware, and **C** resumes as though there had been no break in its execution (**Fig 1**).

Often, a real-time application has several different kinds of spontaneous input. Some kinds are more important than others; some engender more important responses than others. As a result, task **I** may itself be preempted by yet another task, **I2**.

The real-time operating system

The discontinuous execution of a task is invisible to the task. Real-time programs operate under the control of a co-resident piece of code known as the operating system (OS). The OS is the master program; it decides which task executes on a processor and performs the

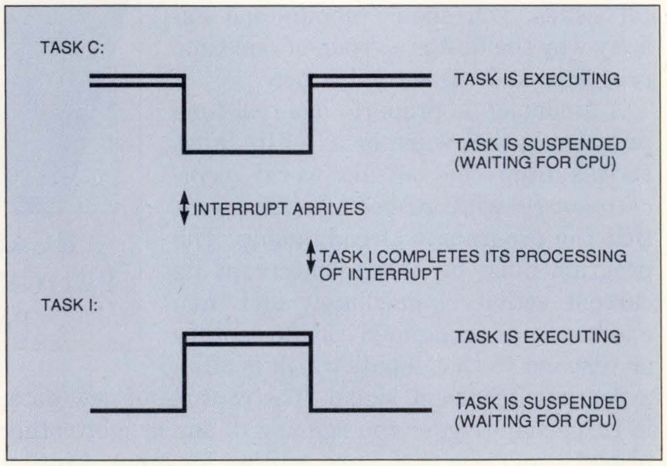

TASK C:
TASK IS EXECUTING
TASK IS SUSPENDED (WAITING FOR CPU)
INTERRUPT ARRIVES
TASK I COMPLETES ITS PROCESSING OF INTERRUPT
TASK I:
TASK IS EXECUTING
TASK IS SUSPENDED (WAITING FOR CPU)

Fig 1—Individual tasks can be started, resumed, and terminated separately. In this example, an interrupt causes task C to be suspended and task I to run. Later, when I must wait for another interrupt, it is suspended, and C resumes running.

Real-time operating systems, revisited

One premise of this series is that real-time services are to be supplied by an operating system or kernel. An operating system is often depicted as layers or concentric circles around the hardware. The innermost layer (the one closest to the hardware) is called the kernel. Thus, in this scheme, a file system is part of the OS proper. The peripheral I/O services that the file system calls are part of the kernel.

Furthermore, we assume that the OS is separate from the application code and is essentially independent of the application. More exactly, the real-time OS can be applied to a wide variety of applications. Alternate approaches are possible.

In the early history of real-time programming, the operating system was not always cleanly separated from the application. A typical real-time program consisted of a series of procedures that performed some function of the application. One procedure might input a certain kind of data by polling at a fixed rate. Another procedure might perform a calculation on the data after polling to determine that the data were available. Tying all this together was a "main program." It served as a crude OS; it called each functional procedure in a preset order. Generally, the main program would permit each procedure to complete before calling the next one.

This cyclic-scheduler approach to real-time programming has fallen into disfavor because it had many problems. First, the cycle times had to be determined by elaborate experiment and tuning. Every time one of the functions was revised, the dynamics of the program changed and the system had to be retuned. As a result, the programs were a nightmare to maintain and expand.

Equally annoying was the fact that the ad hoc approach to scheduling and service delivery required a new main program for each application. There was too much application-specific code inside the "operating system." Furthermore, there was little hope of making the execution efficient by performing actions in parallel. Instead of interrupts and preemption there was polling and serial execution. Thus, when a message had to be output to a console, the entire program waited while each character went out.

There is yet another approach to real-time programming that is not so easily dismissed. Time may even show that it is the right way to proceed. The idea is to build real-time facilities directly into the task language. Concurrent Pascal, Modula, and Ada incorporate this technique.

The chief advantages of having real-time features within the tasking language are increased portability and possibly enhanced error checking. In principle, the compiler can do extensive checking for misuse of real-time facilities and potentially dangerous practices.

The chief disadvantage of the linguistic approach is that the real-time primitives may not be adequate or appropriate for your application. Ada provides only one mechanism for coordination and communication among tasks—the rendezvous. But the rendezvous has some very unfortunate semantic properties that were not fully appreciated until after the language had been frozen. For example, the First International Workshop on Real-Time Ada Issues reported that a low-priority task can delay a high-priority task for an unlimited amount of time because the rendezvous has first-come, first-served queuing. These problems are likely to be corrected in the next version of Ada—Ada-9X—which won't be introduced until well into the 1990s.

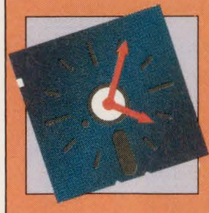
Ada restricted the number of real-time features to minimize other problems: compiler size and complexity. The more features you have in a language, the longer the compilation takes. At present, relying upon an independent OS for real-time facilities seems to be a good practical approach to real-time programming.

This series presents each aspect of real-time programming purely from the application (task) side; it does not explain how to write the operating system that supplies the required services. Robust real-time operating systems are commercially available. It is far more economical in money and project time to buy an OS than to plan, write, debug, test, and maintain one of your own. There is no more reason to develop a private OS than to develop a private editor, compiler, assembler, or linker. If you still doubt that point, see "No Silver Bullets—Essence and Accidents of Software Engineering," in particular, the section headed "Buy vs Build" (**Ref 1**).

The real-time OS selected for this series is MTOS-UX, a product of Industrial Programming Inc (Jericho, NY). MTOS-UX is available for several families of processors, such as the Motorola 680xx and 88x00, Intel 80x86, and National Semiconductor 32x32.

required context switches. It also handles the hardware interrupts that normally announce the availability of fresh input and determines when the response task is to be activated. In short, the OS schedules all processor work.

Thus, a real-time program consists of a set of tasks—separate programs that compete for access to the CPU—and the OS—a master program that schedules CPU access. The work done by the OS in scheduling and context switching is pure overhead; it decreases the time available for task work. Nevertheless, this small loss is easily repaid. The OS makes sure that the CPU is kept busy as long as there is any task work to do.



The operating system decides which task executes on a processor and performs the required context switches.

Consider the alternatives. Suppose that task **I** were executing and reached a point at which it had to have input to continue. If there were no OS, **I** would have to sit in a polling loop, repeating the question: Has the input arrived yet? This is a terrible waste of CPU time. Instead, the OS gives the CPU to task **C**. Task **C** can accomplish productive work until the interrupt arrives. At that point (with slight additional overhead), the CPU can be turned over to **I** to process the input.

Because of its role as central authority over all tasks and interrupts, the OS is also in the best position to provide centralized services and to control access to hardware and software facilities that are shared by the tasks. Thus, timekeeping, peripheral I/O, and allocation of memory are all in the domain of the OS.

Handling such chores as peripheral I/O within the OS yields considerable space efficiency over duplicating the code in each task that needs the function. Furthermore, the individual tasks rarely have the application-wide information required to resolve the conflicts that arise when allocating shared resources. Centralizing also shortens development time for real-time applications. A debugged general OS can usually be applied immediately to a new project.

In real-time work it is common to have dozens of concurrent tasks. Some have been suspended by the arrival of input that merited immediate attention. Others have been blocked because they requested a service of the OS and that service is not yet complete. (Incomplete services might involve a requested disk access that is still in progress, or some requested memory that cannot yet be allocated.)

Task states

To help track the activities of various tasks, OSs commonly maintain the state of each task. One scheme is to classify a task as Running if it is currently executing on a processor, as Ready if it can execute as soon as a processor becomes available, as Blocked if a requested service is not yet complete or there is some other impediment that prevents its execution, and as Dormant if it has terminated after it finished executing or it has not yet been requested to execute. This is the scheme used in this series of articles. The possible

Language issues

Although this series concentrates on the concepts of real-time programming, these concepts can become fuzzy until you see specific examples coded in real language for a real operating system. The MTOS-UX was chosen as the OS. The language chosen was C, based mainly on its popularity among real-time programmers and its ease of use. Furthermore, if one resists the urge to be overly terse, C can be as clear as any other high-level language. Those who are unfamiliar with C might want to read at least the early chapters of Kernighan and Ritchie **(Ref 2).**

Tasks need not be written in C; all MTOS-UX services can be invoked from assembly language as well as from Fortran, Pascal, or other high-level languages. As Part 2 of this series will discuss, a programmer requests an OS service by calling a procedure, such as *pause* (10+MS) to pause for 10 msec. All high-level languages that are likely to be used in real-time applications provide some mechanism to call procedures with arguments. In fact, many compilers have the option of generating calls that are compatible with C. Thus, as far as the OS services are concerned, it doesn't matter if the program is expressed in C or in any other language with a compatible interface.

Nevertheless, C, Fortran, and Pascal do share a property that sets them aside from a new group of languages typified by Ada. Ada has tasking and other real-time facilities built directly into the language; C, Fortran, and Pascal do not.

transitions between these four states of a task are shown in **Fig 2**. (It is not necessary to make such a strong distinction between Ready, Dormant, and Blocked states. A Ready task can be considered blocked waiting for a CPU to become available. Similarly, a Dormant task is just waiting to be restarted. In this view, every task is either Running or is Blocked, waiting for something.)

Different operating systems employ different strategies to choose which task to run next when there is more than one Ready task. The simplest rules are first-come, first-served and equal-execution-time-slice-for-all-tasks. However, at a given moment within a real-time application, each activity has a discernible level of importance or priority with respect to other ongoing activities. Consequently, the tasks that perform the activities carry a corresponding level of priority. A good real-time OS maintains not only the state of each task but the current priority as well. If there is more than one Ready task, the highest priority (most urgent) one gets the processor. Among tasks of equal priority, it can be first-come, first-served.

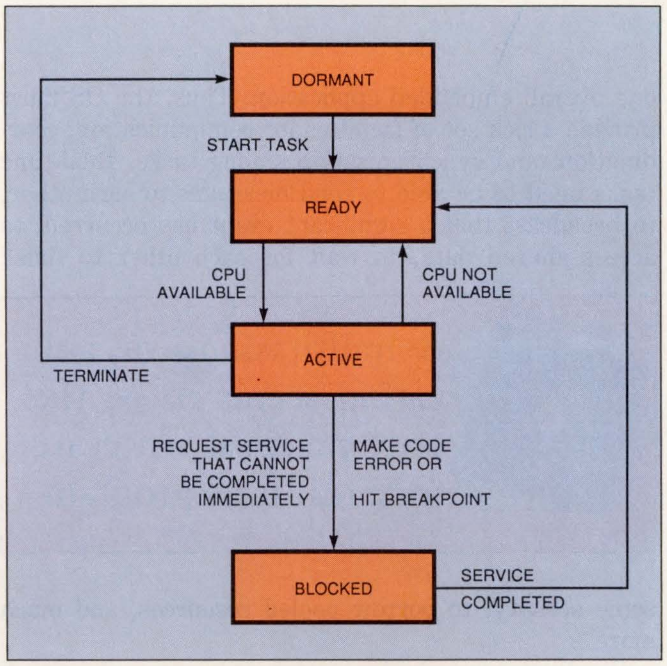


Fig 2—An operating system maintains the state of each task. A task is Running if it is currently executing on a processor; Ready if it can execute as soon as a processor becomes available; Blocked if a requested service is not yet complete or there is some other impediment that prevents its execution; and Dormant if it has terminated after it finished executing or it has not yet been requested to execute.

Further criteria for a real-time program

A multitasking organization seems to be the only practical structure for a real-time program. However, programs that have neither spontaneous data nor other aspects of real time to cope with may also employ multitasking. For example, Unix, VAX VMS, and OS/370 all use multitasking, even though these operating systems were not designed to support real-time work. Besides the presence of asynchronous input, two further properties seem to complete the definition of a real-time application: a high degree of interdependence among the component tasks and a need to have very rapid response to interrupts.

In a nonreal-time environment, there is little or no relation among the tasks that are running concurrently; they are a collection of independent programs that happen to have been submitted by the various independent users of the hardware. Thus, the OS need not and does not provide strong facilities to coordinate the tasks. Quite the contrary, for security reasons, the OS tries to make it difficult for one task to interfere with another.

In contrast, in a typical real-time program all of the tasks are highly interrelated: They are all aspects of

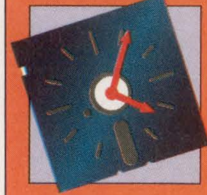
Companion disk offer

All of the C examples in this series, plus applications of your own, can be run on a personal computer with a set of demonstration disks available from Industrial Programming Inc. The disks contain a full version of MTOS-UX for an IBM PC/AT or compatible. An application program is edited, compiled, linked, and loaded under MS-DOS. The MTOS-UX then takes over the hardware to execute the program in real time. At any time, you can enter an alt/dlt command from the console to return control to MS-DOS.

The demonstrator requires an IBM PC/AT with at least 512k bytes of RAM and a hard disk with 2M bytes available for MTOS libraries and scratch storage. Program preparation requires the Microsoft C compiler/linker, version 5.0 or later. Microsoft tools are not included with the MTOS-UX demonstrator.

The demonstration version has all of the features and facilities of standard MTOS-UX. However, there is a limit of six of each type (six tasks, six mailboxes, six semaphores, and so forth). The disk set costs $25; unlimited versions are also available. For more details, call the IPI sales department at (800) 365-6867.

one overall embedded application. Thus, the OS must provide a rich set of facilities for communication, coordination, and synchronization among tasks. Real-time tasks need to be able to send messages to each other, to broadcast that a significant event has occurred, to access shared data, to wait for each other to finish



A multitasking organization seems to be the only practical structure for a real-time program.

some activity, to borrow pooled resources, and much more.

Finally, very rapid response to external stimuli seems to be inherent in the real-time world. The maximum time to recognize that an external interrupt is pending (latency) plus the time needed to suspend the current task and switch to an interrupt handler (context switch time) is commonly on the order of microseconds. Unix, and similar nonreal-time operating systems, were not designed to react so quickly.

This series will continue in regular issues of EDN, beginning with the October 1st issue. Part 2 will further explore the nature of real-time programming and describe how the operating system handles the special concerns imposed by working in real time. **EDN**

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1. Brooks, Jr, Frederick P, "No Silver Bullets—Essence and Accidents of Software Engineering," *Unix Review*, November 1987.

2. Kernighan, B and D Ritchie, *The C Programming Language*, Prentice Hall, Englewood Cliffs, NJ, 1978.

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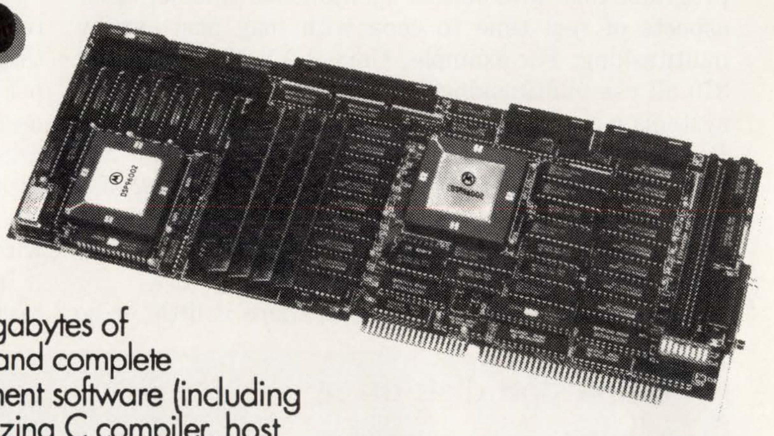

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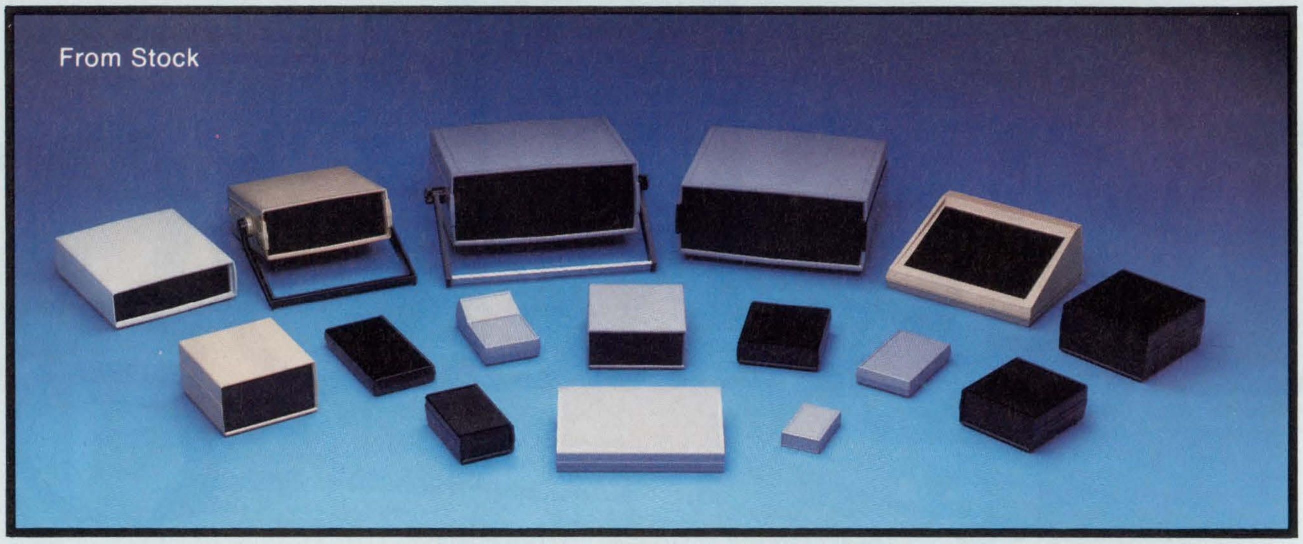

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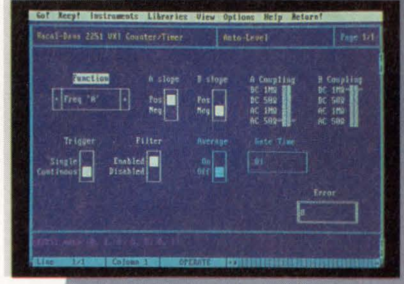

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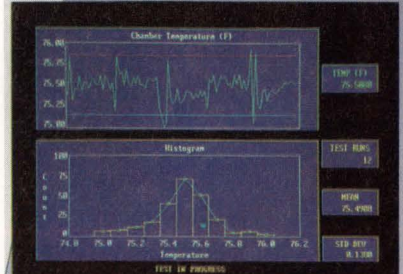

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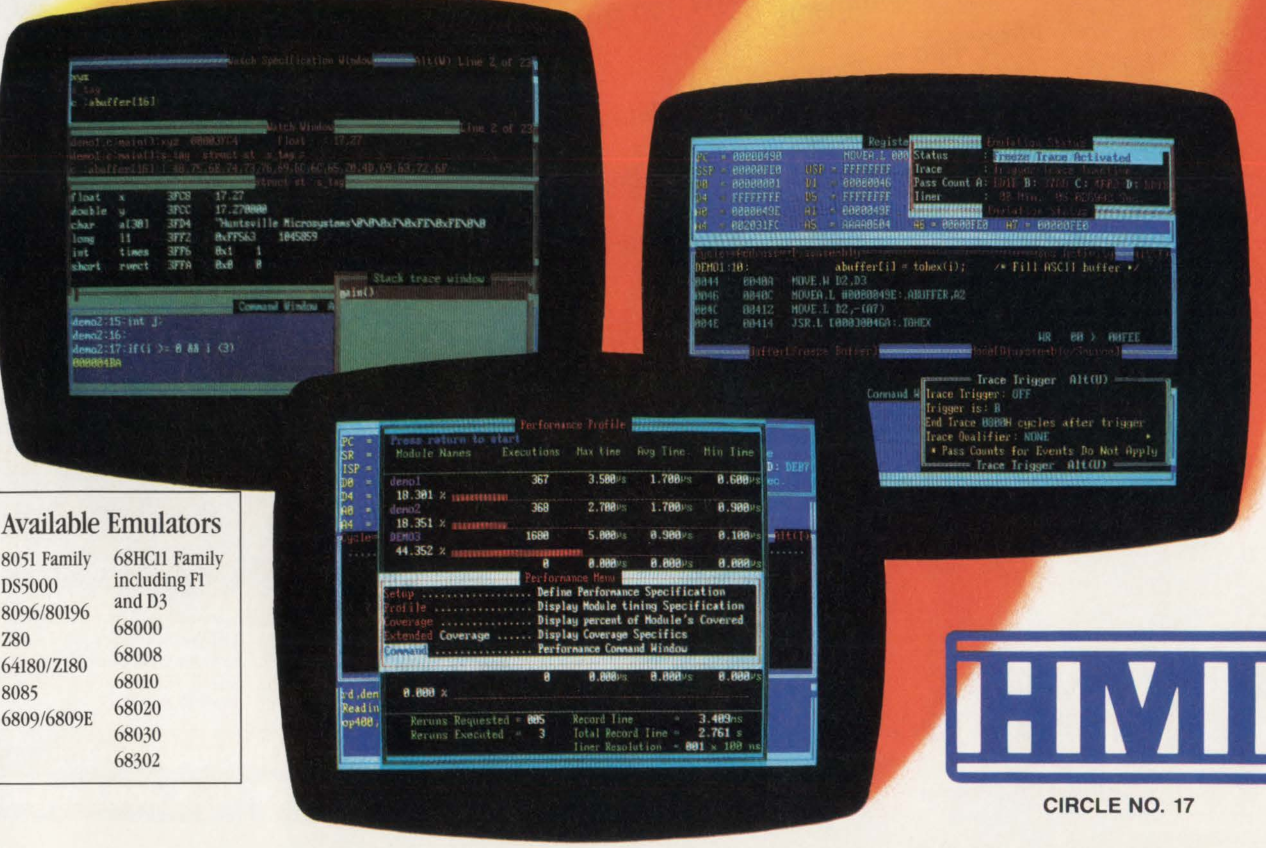

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Watch Specification Window      Alt(W) Line 2 of 23
xyz
s_tag
c :abuffer[16]
                Watch Window                Line 2 of 23
demo1.c:main():xyz  00003FC4      float   : 17.27
demo1.c:main():s_tag  struct st  s_tag :
c :abuffer[16] : 30,75,6E,74,73,76,69,6C,6C,65,20,4D,69,63,72,6F
                struct st  s_tag
float   x      3FC8   17.27
double  y      3FCC   17.270000
char    a[30]  3FD4   "Huntsville Microsystems\0\0\0xF\0xFE\0xFE\0\0
long    l1     3FF2   0xFF563   1045859
int     times  3FF6   0x1    1
short   rvect  3FFA   0x0    0
                                        Stack trace window
                                        main()
                 Command Window
demo2:15:int j;
demo2:16:
demo2:17:if(i >= 0 && i <3)
000004BA
```

```
                  Registe          Emulation Status
PC  = 00000490         MOVEA.L 000 Status      : Freeze Trace Activated
SSP = 00000FE0  USP = FFFFFFFF     Trace       : Trigger Trace Inactive
D0  = 00000001  D1  = 00000046     Pass Count A: [illegible] B: [illegible] C: [illegible] D: [illegible]
D4  = FFFFFFFF  D5  = FFFFFFFF     Timer       : 00 Min. 05.025945 Sec.
A0  = 0000049E  A1  = 0000049F            Emulation Status
A4  = 002031FC  A5  = AAAA0604    A6 = 00000FE0   A7 = 00000FE0
Cycle=Addressed[Disassembly]
DEMO1:10:              abuffer[i] = tohex(i);     /* Fill ASCII buffer */
0044    0040A   MOVE.W D2,D3
0046    0040C   MOVEA.L #0000049E:.ABUFFER,A2
004C    00412   MOVE.L D2,-(A7)
004E    00414   JSR.L [000]0046A:.TOHEX
                                              WR   00 >  ABFEE
     Buffer[Freeze Buffer]          Mode[Disassembly/Source]

                   Trace Trigger  Alt(U)
Command W Trace Trigger: OFF
          Trigger is: B
          End Trace 0000H cycles after trigger
          Trace Qualifier: NONE                      *
          * Pass Counts for Events Do Not Apply
                   Trace Trigger  Alt(U)
```

```
                    Performance Profile
PC  =  Press return to start
SR  =   Module Names      Executions   Max time   Avg Time   Min Time
ISP =
D0  =  demo1                  367      3.500μs    1.700μs    0.600μs
D4  =   10.301 %
A0  =  demo2                  368      2.700μs    1.700μs    0.900μs
A4  =   10.351 %
Cycle= DEMO3                 1680      5.000μs    0.900μs    0.100μs
        44.352 %
                                0      0.000μs    0.000μs    0.000μs
                    Performance Menu
Setup .................... Define Performance Specification
Profile .................. Display Module timing Specification
Coverage ................. Display percent of Module's Covered
Extended Coverage ........ Display Coverage Specifics
Command .................. Performance Command Window
                                0      0.000μs    0.000μs    0.000μs
rd,den  0.000 %
Readin
op400,   Reruns Requested = 005    Record Time        =  3.403ns
         Reruns Executed  =   3    Total Record Time =   2.761 s
                                   Timer Resolution  = 001 x 100 ns
```

Available Emulators

8051 Family	68HC11 Family including F1 and D3
DS5000	68000
8096/80196	68008
Z80	68010
64180/Z180	68020
8085	68030
6809/6809E	68302

HMI

CIRCLE NO. 17

Mix C and assembly language for fast real-time control

Flow-control code compiled in C often executes too slowly for real-time applications. But if you replace switch statements with an assembly-language driver, your program will run almost twice as fast as a pure C program.

Rick Brown, *Desert Research Institute, University of Nevada*

Programming in C gives you close control over hardware, and code that's easy to write, debug, and understand, but its compiler-generated code for program-flow control runs too slowly to suit high-speed real-time or control applications. Also, C provides no standard interrupt-processing capabilities. Assembly language, on the other hand, generates code that both executes faster than compiled C and can process interrupts, but the code is tedious to write and difficult to understand.

A method of combining the two languages preserves the clarity of the C language while minimizing its time penalties. Using C language makes designing the system logic easy; including an assembly-language driver, which controls a chain of small C functions, speeds up the transfer of control from one C function to another. This combination technique can speed up a system by 25 to 100%. When considering potential uses for an assembly-language driver, your first question will naturally be "What is the code really doing?" You'll find that, essentially, the code substitutes a simple address calculation for a C switch statement and its multiple tests to find a specific case.

A controller in an industrial laundry-folding machine illustrates this programming method. The folding-machine controller requires servicing of software routines at precise time intervals as well as moderately high-speed operation.

The folding machine processes material at a rate of 150 ft per minute. This rate requires that sensors and actuators be serviced about every five milliseconds in order to achieve the required ¼-in. resolution. The machine optically detects the leading and trailing edges of sheets of material to be folded, and it times the control functions from these edges. The five folding stations in the machine allow as many as five pieces of material to be in the machine at any one time. Thus, only about one millisecond out of five can be budgeted to track the progress of a single piece of material through the machine.

For the machine to use a Z80180 microprocessor running at 4.6 MHz, a control program written entirely in C is not fast enough. The time required for processing a C switch statement is too long. For example, a 7-case switch requires 175 to 257 μsec, depending on whether it detects the first or last case. In this case, one control statement uses more than 25% of the time budget. Assembly-language code, some of which is necessary anyway for interrupt processing in the controller, can provide a faster method of selecting a function, and thus speed up the system.

An interrupt-driven assembly-language driver can link together C functions and minimize control overhead in real-time applications.

The combination programming method uses numerous small C functions, which a segment of the assembly-language portion of the code (the "function driver") activates. Tracking a "control sequence" (the events and actions that constitute the processing of a single piece of material through the machine) requires about 20 C functions. This article refers only to the portions of the application code activated at 5-msec intervals by an interrupt request from the Z80180's counter timer. (Operator communication and other tasks that are not time critical are controlled by function-pointer stacks (**Ref 1**).)

Each C function controls a single part of the folding process. At each 5-msec timer interrupt, the function driver activates one or more of the C functions. For example, the first function continually checks to see if a new piece of material is entering the machine. As soon as a piece enters, the system activates a second (control) function, which waits for a predetermined time and then closes the first actuator. The function driver then transfers control to a third function, which looks for the tail end of the material at the machine entrance. Control continues to pass from function to function until the piece of material exits the machine.

Control flow is determined by the values that the C functions return. The return value is an index into a table that contains pointers to all of the possible C functions. Each time a function is called, it returns the index of the next function in the control sequence if it has completed its operation, or it returns its own index if its operation is incomplete. **Fig 1** is a control-flow diagram for the first five C functions.

In addition to performing some I/O services, the function driver maintains a control array containing the table indices and the working variables returned by the C functions. At each interrupt, the function driver transfers control in turn to each of the functions whose function-pointer-table indices are currently in the control array. After all entries in the control array have been satisfied, the machine idles or performs tasks that are not time critical until the next time interrupt.

Control-array structure

The control array consists of a FIFO circular buffer. Each entry in the buffer contains the index of a function to be activated, a time word, and a temporary storage word that active control sequences can use. The function driver maintains pointers to the bottom (oldest) and top (youngest) locations of the FIFO buffer. The youngest entry in the buffer is always the sensing function that waits for a new piece of material to enter the folding machine. It continually returns its own index until new material arrives; then it returns the index of the first control function. The function driver detects that occurrence, increments the buffer-top pointer, and places a new copy of the index of the "material-entering" function at the new buffer-top location. The function driver also monitors the value returned by the oldest control sequence in the buffer; when the function driver finds a 0 (a "process-complete" flag), it increments the buffer-bottom pointer, thereby removing that control sequence from the buffer.

Code directs function sequence

Listing 1 (see pg 46) presents a sample of the C source code that controls the first five functions of the folding machine. Lines 1 to 14 define function 0 (fa_start), which waits for new material at the entrance of the machine. This function is the first entry in the function-pointer table, so its index is 0.

The parameter *time* is the address of the time word for the current control sequence in the FIFO buffer. The function driver increments the contents of the time word for each control sequence at each timer interrupt. The C language routines may use or alter the contents of the time word as necessary; for example, at line 10 the contents are set to 0. If the machine is stopped, as determined by the nontime-critical portion of the machine code, the fa_start routine exits at line 5.

The function driver maintains the variable FA_PDREG; the contents of this variable are bits that reflect the state of the photosensors that detect the presence of material at each folding station. B1PD is the bit position in FA_PDREG of the photosensor at the machine entrance. The global variable fa_pd1clear lets the system detect the end of one piece of material and the beginning of a new piece. If the previous piece has not moved clear of the machine entrance, the routine exits at line 7. Otherwise, the routine waits for the entry of a new piece and counts it at line 9. The routine exits at line 11 and returns the index of the next routine. If no material is present at the machine entrance, then the routine sets the fa_pd1clear variable to reflect that condition and exits at line 13. No code (such as a timeout) exists to handle the possibility that the head of piece B will overlap the tail of piece A; defensive programming would call for an error-handling routine to cover this condition. In

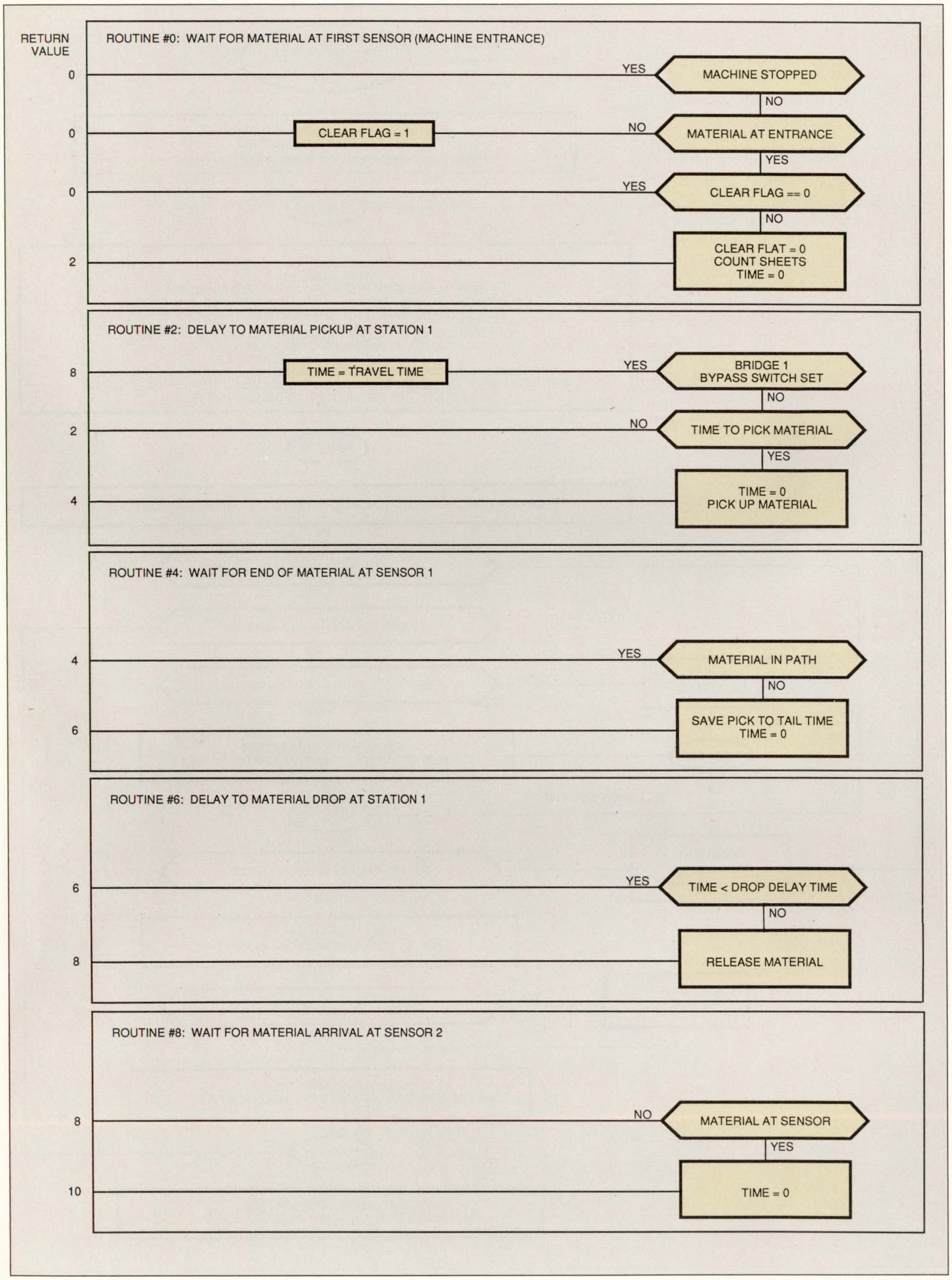


Fig 1—A C function implements each part of the control process. When an operation completes, the function returns the index of the next function in the control sequence.

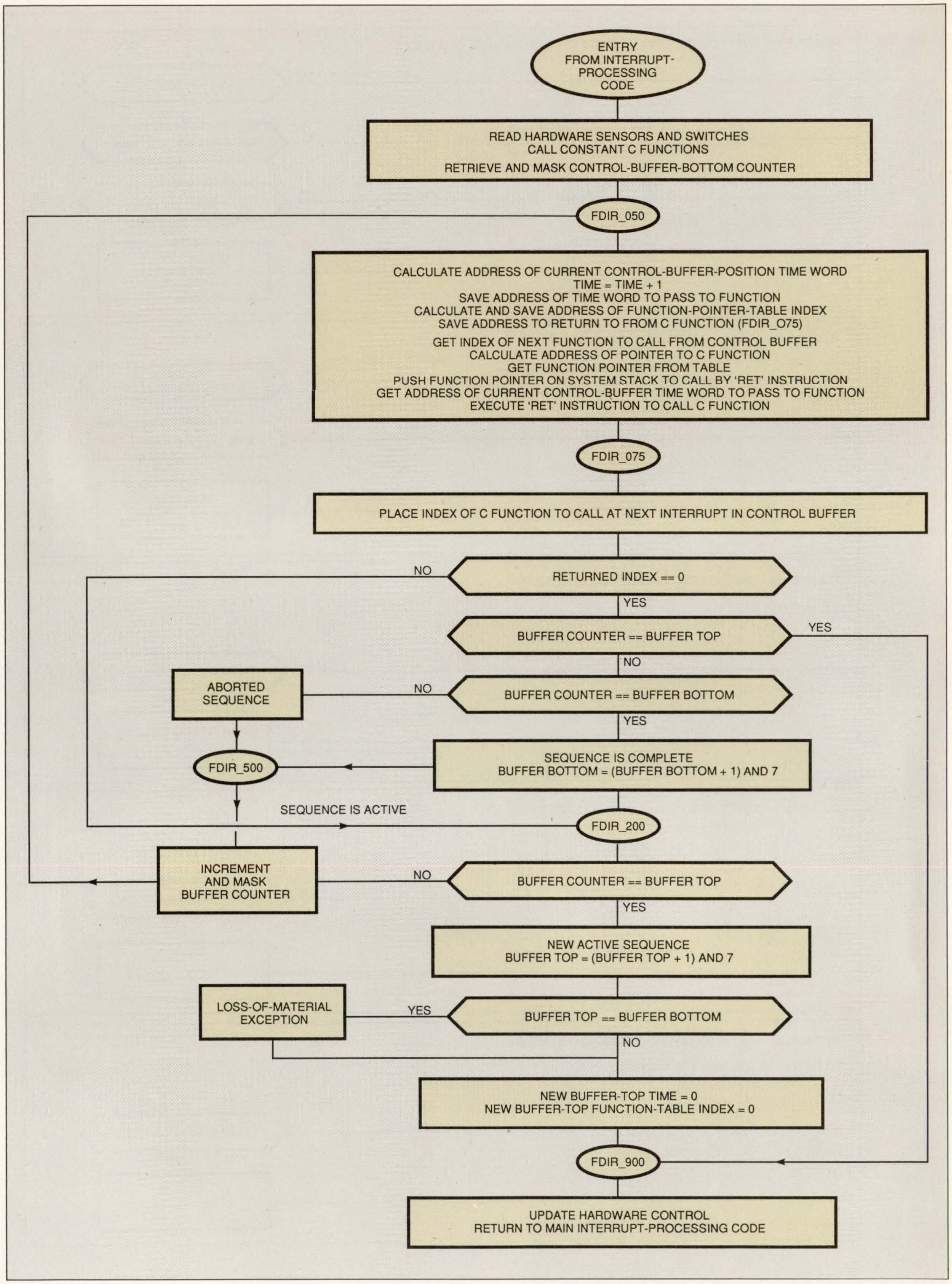

ENTRY FROM INTERRUPT-PROCESSING CODE
READ HARDWARE SENSORS AND SWITCHES
CALL CONSTANT C FUNCTIONS
RETRIEVE AND MASK CONTROL-BUFFER-BOTTOM COUNTER
FDIR_050
CALCULATE ADDRESS OF CURRENT CONTROL-BUFFER-POSITION TIME WORD
TIME = TIME + 1
SAVE ADDRESS OF TIME WORD TO PASS TO FUNCTION
CALCULATE AND SAVE ADDRESS OF FUNCTION-POINTER-TABLE INDEX
SAVE ADDRESS TO RETURN TO FROM C FUNCTION (FDIR_O75)
GET INDEX OF NEXT FUNCTION TO CALL FROM CONTROL BUFFER
CALCULATE ADDRESS OF POINTER TO C FUNCTION
GET FUNCTION POINTER FROM TABLE
PUSH FUNCTION POINTER ON SYSTEM STACK TO CALL BY 'RET' INSTRUCTION
GET ADDRESS OF CURRENT CONTROL-BUFFER TIME WORD TO PASS TO FUNCTION
EXECUTE 'RET' INSTRUCTION TO CALL C FUNCTION
FDIR_075
PLACE INDEX OF C FUNCTION TO CALL AT NEXT INTERRUPT IN CONTROL BUFFER
NO
RETURNED INDEX == 0
YES
BUFFER COUNTER == BUFFER TOP
YES
NO
ABORTED SEQUENCE
NO
BUFFER COUNTER == BUFFER BOTTOM
YES
FDIR_500
SEQUENCE IS COMPLETE
BUFFER BOTTOM = (BUFFER BOTTOM + 1) AND 7
SEQUENCE IS ACTIVE
FDIR_200
INCREMENT AND MASK BUFFER COUNTER
NO
BUFFER COUNTER == BUFFER TOP
YES
NEW ACTIVE SEQUENCE
BUFFER TOP = (BUFFER TOP + 1) AND 7
LOSS-OF-MATERIAL EXCEPTION
YES
BUFFER TOP == BUFFER BOTTOM
NO
NEW BUFFER-TOP TIME = 0
NEW BUFFER-TOP FUNCTION-TABLE INDEX = 0
FDIR_900
UPDATE HARDWARE CONTROL
RETURN TO MAIN INTERRUPT-PROCESSING CODE

Fig 2—The assembly-language function driver makes decisions based on the values returned by each C function. The driver also maintains the table of function pointers and a control buffer.

High-speed applications always need some assembly-language code for time-critical tasks; you can use that code as a means to improve overall system speed.

practice, however, the material enters the machine so fast that it's impossible for the operator to move quickly enough to cause an overlap.

Lines 15 to 26 define function 2 (fa_b1pick), which controls the first actuator. (The routine numbers (indices) increase by two because routine addresses are 2-byte numbers in the function-pointer table.) The function driver maintains the FA_SENSE variable, which contains the state of the operator switches. If the operator presses a control button to bypass the first actuator (for example, because the material is too small to need two folds), then the content of FA_SENSE causes the function to exit immediately at line 21, transferring control to routine 8. Otherwise, the routine monitors time at line 22 until it's time to operate the first actuator; then (at line 25) it transfers control to routine 4, which energizes the actuator.

The variable FA_CTLRG contains a bit position for each actuator. The C functions control the actuators by setting or resetting bit positions in this variable (line 24). The function driver passes the contents of FA_CTLRG to the hardware interface for use in selecting and energizing one or more actuators.

Other points to note in the C code are line 20, where the time word is preset for control of subsequent routines, and line 32, where the routine uses a temporary-storage location in the circular buffer to store an intermediate result. Also, in line 41, routine 6 modifies FA_CTLRG to turn off the actuator that was turned on at line 24. When a piece of material finally exits the machine, the last function executes a *return(0)* statement that terminates the control sequence. Remember that several control sequences may be active at any one time.

Fig 2 is the control-flow diagram of the assembly-language function driver, which receives the calls at every 5-msec timer interrupt and links the C functions into their control chain. **Listing 2** (see pg 47) presents the corresponding Z80 assembly-language source code. At lines 9 through 14, the driver reads the hardware photosensors and operator switches, and saves their states in global variables. Line 15 is a call to a C function that is activated unconditionally at every timer interrupt. Lines 16 through 19 set the buffer counter to the oldest buffer entry.

The loop that processes each buffer entry begins at line 21 and ends at line 125. For each control sequence, lines 21 through 39 calculate the buffer address and increment the time word. Lines 40 through 62 make the address of the control-sequence time word accessible to the C function and also retrieve the address of the pointer to a C function from the function-pointer table. Line 63 transfers control to the C function.

In lines 65 to 82, the driver makes its decisions about the activity of the C function on the basis of the returned index and current buffer counter. It is possible that the processing of a piece of material may be aborted during a control sequence. Should that occur, lines 83 to 85 cause the control sequence to idle until it becomes the oldest (bottom position) in the buffer. Lines 87 to 125 control the buffer-top and -bottom counters and the execution path through the control loop.

In lines 127 through 132, the driver sends the results of control decisions to the hardware. At line 133, the driver returns control to the interrupt-processing system, which can then work on the nontime-critical portion of the code.

```
int  (*fp_table[32])();         /*function pointer table*/
int  func_1(), func_2(), ...;   /*subject functions*/
int  index;
{
 ...
fp_table[0]=func_1;             /*initialize function*/
fp_table[1]=func_2;             /*pointer table*/
index=0;                        /*and function pointer index*/
...                             /*main program loop*/
index=fp_table[ index ]();      /*do appropriate function*/
...
}
```

Fig 3—You can speed up even pure C programs by replacing switch/case statements with a table of pointers to the control functions.

Transferring control by means of a table of function pointers is twice as fast as using C switch/case statements.

The remaining lines of code define the table of C function pointers (lines 143 through 174); some global variables (lines 176 through 183); and the control buffer (lines 184 through 188).

The time required for the folding-machine controller to process the single function from the entry of the processing loop at FDIR_050 (**Listing 2,** line 21) to the exit of the loop at FDIR_900 (line 127) is 216 μsec. Processing seven functions requires about 1250 μsec, depending on which functions are active. In contrast, seven executions of a single switch statement require 1750 μsec plus about 1 msec for housekeeping and actual function execution. It is apparent that the function-pointer method is at least twice as fast as the switch/case method.

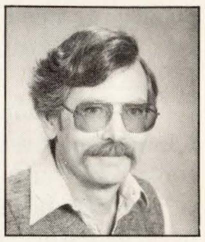
In a strictly C environment you might rewrite a switch statement and its associated code as indexed function-pointer addresses (**Fig 3**), since you would expect to see some speed improvement whenever you replace switch statements with indexed function-pointer addresses. Indeed, comparing the speed of the two methods on a personal computer shows that function-pointer control requires only 50 to 75% of the time required by switch/case control.

Programs written entirely or partly in C will probably never be as fast as an equivalent program written entirely in assembly language. However, to achieve an incremental speed increase without abandoning C, using indexed function pointers for program-flow control is a generic technique that you can adapt to many applications. EDN

Reference

1. Brown, Rick, 'C function pointers let you build generic control systems,' *EDN*, April 26, 1990, pg 215.

Author's biography



Rick Brown is an associate research engineer at the Desert Research Institute of the University of Nevada (Reno, NV), where he has worked for 18 years. Rick's prime responsibility is the development of instruments and instrumentation systems. He holds a BSEE from the University of Florida (Gainsville, FL) and is a member of the IEEE. He also runs a consulting service specializing in the design of embedded-processor systems. In his spare time he enjoys mountain climbing, skiing, and backcountry travel.

Article Interest Quotient (Circle One)
High 470 Medium 471 Low 472

Listing 1—Sample of C routines for folding-machine controller

```
/* wait for material arrival at sensor 1 */
fa_start( time )          /****** routine 0 ******/
int *time;
{
if( fa_stopped ) return(0);        /*no auto action when stop*/
if( !(FA_PDREG & B1PD) )
 {if( !fa_pd1clear ) return(0);    /*wait for sheet to leave*/
  fa_pd1clear=0;                   /*sheet in path*/
  sheet_count++;                   /*count arrivals*/
  *time=0;
  return(2);}                      /*to wait for pick up*/
fa_pd1clear=1;                     /*path is clear*/
return(0);
}
/* delay to pick up at station 1 */
fa_b1pick( time )        /****** routine 2 ******/
int *time;
{
```

Listing 1—Sample of C routines for folding-machine controller *(continued)*

```
if( !(FA_SENSE & B1BYPASS) )          /*low is true*/
 {*time = -b1b2_travel;
  return(8);}                         /*wait for arrival at b2*/
if( *time < b1apt ) return(2);        /*not yet*/
*time=0;
FA_CTLRG |= B1ACT;                    /*pick up*/
return(4);                            /*to wait for tail*/
}
/* wait for material tail at sensor 1 */
fa_b1tail( time )       /****** routine 4 ******/
int *time;
{
if( !(FA_PDREG & B1PD) ) return(4);       /*still in path*/
*(time+1) = *time;                    /*pick to tail*/
*time=0;
return(6);                            /*wait to drop*/
}
/* delay to drop at station 1 */
fa_b1drop( time )       /****** routine 6 ******/
int *time;
{
if( *time < b1btime ) return(6);      /*not time yet*/
FA_CTLRG &= ~B1ACT;
return(8);                            /*wait for arrival at b2*/
}
/* wait for material at sensor 2 */
fa_b2wait( time )       /****** routine 8 ******/
int *time;
{
if( FA_PDREG & B2PD ) return(8);      /*not there yet*/
*time=0
return(10);                           /*wait to pick*/
}
```

Listing 2—Assembly-language function driver for folding-machine controller

```
;
;           registers transferred to/from hardware
;
        PUBLIC  FA_CTLRG,FA_MOTRG,FA_SENSE,FA_PDREG
;
        NAME    FOLD_DIR
        CSEG
;
FOLD_DIR:       LD      BC,1001H        ;READ PHOTO DETECTORS
                IN      A,(C)
                LD      (FA_PDREG),A
                LD      C,5             ;READ SWITCHES
                IN      A,(C)
                LD      (FA_SENSE),A
                CALL    IRON_SPD        ;MONITOR IRONER SPEED
                LD      A,(FN_SKBOT)    ;CONTROL BUFFR BOTTOM
                AND     7               ;CIRCULAR 8 POSNS LONG
                LD      C,A             ;BUFFR COUNTER IN BC
                LD      B,0
                                       ;ALWAYS RUN BOTTOM BUFFR POSN
FDIR_050:       PUSH    BC              ;CURRENT BUFFR COUNTER
```

Listing continued

Listing 2—Assembly-language function driver for folding-machine controller ***(continued)***

```
            LD      HL,FN_BUFFR     ;CIRCULAR BUFFR BASE ADDR
            LD      A,C             ;+ 5*CONTROL BUFFR CTR
            ADD     A,C             ;TO PROCESS BUFFR FROM
            ADD     A,C             ;BOTTOM TO TOP
            ADD     A,C
            ADD     A,C
            LD      C,A
            ADD     HL,BC           ;POINTS TO CURRENT ENTRY
            PUSH    HL              ;IN CIRCULAR BUFFR
            LD      E,(HL)          ;(TIME)
            INC     HL
            LD      D,(HL)
            INC     DE              ;INCREMENT TIME
            POP     HL
            PUSH    HL
            LD      (HL),E          ;REPLACE TIME
            INC     HL
            LD      (HL),D
            POP     HL              ;ADDRESS OF TIME IN BUFFR
            LD      B,H             ;SAVE TO PASS TO ROUTINE
            LD      C,L
            INC     HL
            INC     HL
            INC     HL
            INC     HL              ;POINT TO INDEX CONTROL
            PUSH    HL              ;SAVE TO REPLACE INDEX
            LD      DE,FDIR_075     ;RETURN ADDRESS
            PUSH    DE              ;SAVE FOR 'RET' INSTR
            LD      D,0
            LD      A,(HL)          ;GET ROUTINE INDEX
            AND     3EH             ;MASK TO 32 X 2 ARRAY
            LD      E,A
            EX      DE,HL           ;IN HL
            LD      DE,FN_VECT      ;FUNCTION PTR TABLE ADDR
            ADD     HL,DE           ;ADDRESS OF FUNCTION PTR
            LD      E,(HL)          ;C FUNCTION ADDRESS
            INC     HL              ;TO CALL BY 'RET'
            LD      D,(HL)
            PUSH    DE              ;ON BUFFR TO EXECUTE
            LD      H,B             ;PASS CONTROL BUFFR ADDR
            LD      L,C             ;TO FUNCTION
            RET                     ;GO TO FUNCTION
;
FDIR_075:   LD      A,L             ;INDEX RETURNED
            POP     HL              ;ADDRESS OF INDEX
            LD      (HL),A          ;REPLACE INDEX
            POP     BC              ;CURRENT BUFFR COUNTER
            CP      0               ;TEST INDEX FOR INACTIVE
            JR      NZ,FDIR_200     ;IS ACTIVE
                                    ;IS INACTIVE
            LD      A,(FN_SKTOP)    ;IF CURRENT=TOP
            CP      C               ;WAITING FOR NEW MATERIAL
            JP      Z,FDIR_900      ;AND TEST IS COMPLETE
;
            LD      A,(FN_SKBOT)    ;IF CURRENT=BOTTOM THEN
            CP      C               ;MATERIAL COMPLETE
            JR      NZ,FDIR_080     ;IF NOT THEN SEQ ABORTED
            INC     A               ;SO MOVE UP BOTTOM
```

Listing 2—Assembly-language function driver for folding-machine controller *(continued)*

```
                AND     7                ;CIRCULAR 8 POSNS LONG
                LD      (FN_SKBOT),A     ;NEW BUFFR BOTTOM
                JR      FDIR_500         ;CONTINUE
FDIR_080:       LD      A,62             ;CALL FOR POSITION CLEAR
                LD      (HL),A           ;UNTIL AT BUFFR BOTTOM
                JR      FDIR_500         ;AND CONTINUE
                                         ;INDEX .NE. 0
FDIR_200:       LD      A,(FN_SKTOP)     ;TEST FOR NEW
                CP      C                ;BY CURRENT == TOP
                JR      NZ,FDIR_500      ;NOT NEW..CONTINUE
                INC     A                ;IS NEW..INCREASE BFR TOP
                AND     7                ;CIRCULAR BUFFR
                LD      (FN_SKTOP),A     ;NEW BUFFR TOP
                                         ;
                LD      C,A
                LD      A,(FN_SKBOT)     ;TEST FOR BOTTOM
                CP      C                ;OVER WRITTEN
                JR      NZ,FDIR_250
                CALL    EXCEPTION        ;BUFFER OVERFLOW
;
FDIR_250:       LD      A,(FN_SKTOP)     ;NEW CONTROL SEQUENCE
                AND     7                ;BY PLACING ENTRY MONITOR
                LD      C,A              ;ROUTINE AT BUFFR TOP
                LD      B,0
                ADD     A,C              ;BRIDGE 1 PD
                ADD     A,C              ;INDEX MUST BE 0
                ADD     A,C              ;POINT TO CONTROL TABLE
                ADD     A,C              ;LOCATION 0
                LD      C,A              ;THEN CALCULATE ADDRESS
                LD      HL,FN_BUFFR      ;OF TIME WORD
                ADD     HL,BC
                LD      (HL),0           ;TIME = 0
                INC     HL
                LD      (HL),0
                INC     HL
                INC     HL
                INC     HL               ;ADDRESS OF INDEX
                LD      (HL),0           ;INDEX = 0
                JP      FDIR_900         ;END OF INTERRUPT
FDIR_500:                       ;CONTINUE ON TO END OF BUFFR
                INC     C                ;UPDATE CURRENT
                LD      A,7              ;BUFFR COUNTER
                AND     C                ;MASK TO CIRCULAR
                LD      C,A
                LD      B,0
                JP      FDIR_050         ;DO NEXT BUFFR LOCATION
;
FDIR_900:       LD      BC,1004H         ;OUT TO MOTORS
                LD      A,(FA_MOTRG)
                OUT     (C),A
                LD      C,6              ;OUT TO CONTROL
                LD      A,(FA_CTLRG)
                OUT     (C),A
                RET                      ;TO INTERRUPT PROCESSOR
;
;  ROUTINE TO CLEAR BUFFR POSITION
;
```

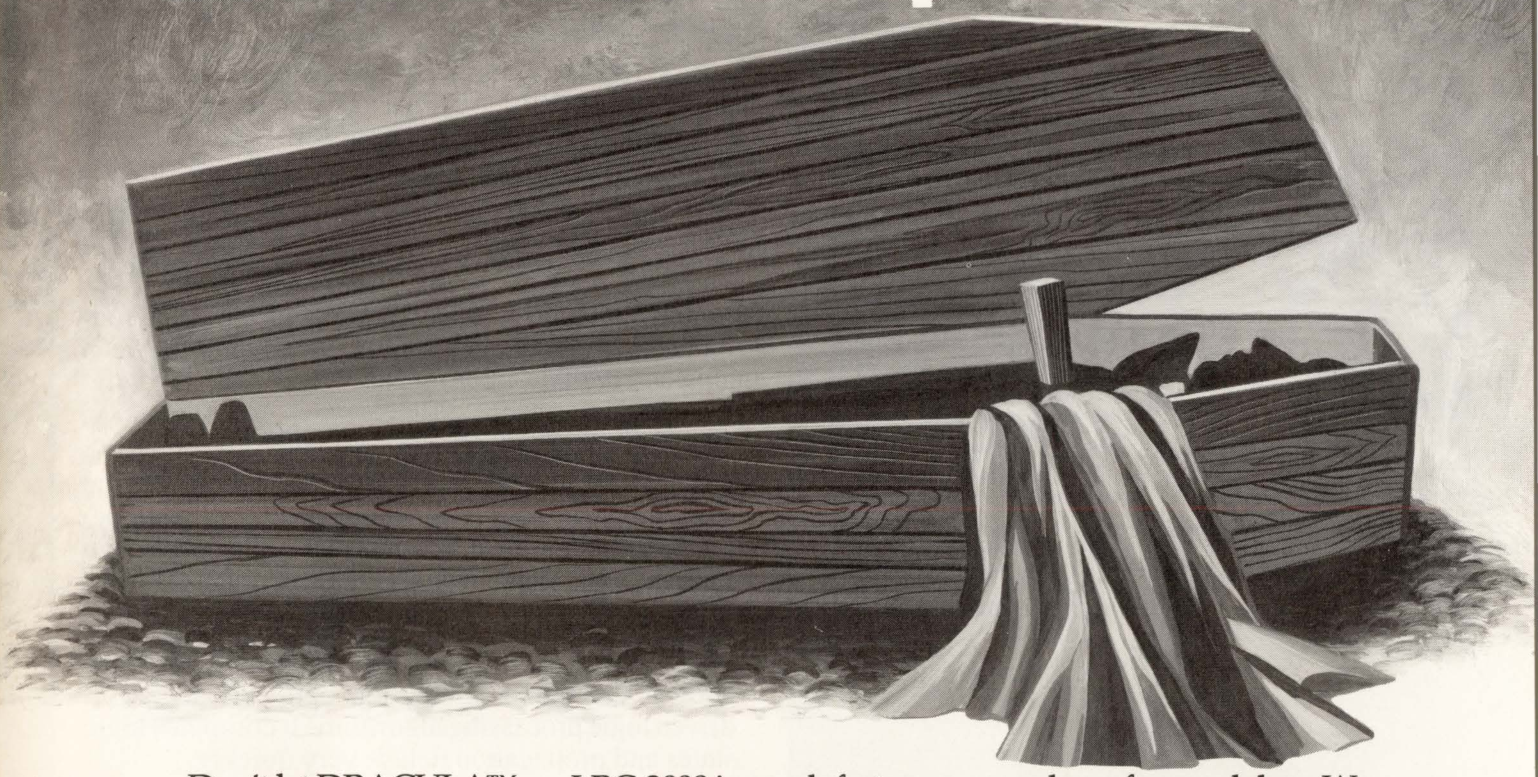
Listing continued

Listing 2—Assembly-language function driver for folding-machine controller *(continued)*

```
FA_CLEAR:       LD      HL,0
                RET
;
;
; FUNCTION POINTER TABLE.  POINTED TO BY INDEX
;
FN_VECT:        DW      FA_START        ; 0 TEST FOR START
                DW      FA_B1PICK       ; 2 WAIT FOR B1 PICK UP
                DW      FA_B1TAIL       ; 4 WAIT FOR B1 TAIL
                DW      FA_B1DROP       ; 6 WAIT TO DROP
                DW      FA_B2WAIT       ;WAIT FOR ARRIVAL AT B2
                DW      FA_B2PICK       ;B2 PICK UP
                DW      FA_B2TAIL       ;12
                DW      FA_B2DROP       ;B2 DROP
                DW      FA_C1WAIT       ;WAIT FOR ARRIVAL AT C1
                DW      FA_C1BREAK      ;BREAK MOTOR STOP
                DW      FA_C1AON        ;20 START AIR BLAST
                DW      FA_C1AOF        ;22 STOP AIR BLAST
                DW      FA_C2WAIT       ;WAIT FOR ARRIVAL AT C2
                DW      FA_C2PICK       ;C2 PICK UP
                DW      FA_C2TAIL       ;28
                DW      FA_C2DROP       ;C2 DROP
                DW      FA_C3WAIT       ;WAIT FOR ARRIVAL AT C3
                DW      FA_C3PICK       ;C3 PICK UP
                DW      FA_C3TAIL       ;36
                DW      FA_C3DROP       ;C3 DROP
                DW      FA_BYCROSS      ;BYPASS CROSS FOLDS
                DW      FA_B2BYTAIL     ;TAIL AT B2
                DW      FA_B2CLOSE      ;CLOSE BYPASS CHUTE
                DW      FA_BUZZER       ;SOUND THE HORN
                DW      FA_TANGLE       ;STOP FOR POSSIBLE TANGLE
                DW      FA_CLEAR        ;50 DUMMY LOCATION
                DW      FA_CLEAR        ;DUMMY LOCATION
                DW      FA_CLEAR        ;DUMMY LOCATION
                DW      FA_CLEAR        ;DUMMY LOCATION
                DW      FA_CLEAR        ;DUMMY LOCATION
                DW      FA_CLEAR        ;DUMMY LOCATION
                DW      FA_CLEAR        ;62 DUMMY LOCATION
;
        DSEG
;
FA_CTLRG:       DB      1               ;CONTROL SIGNALS
FA_MOTRG:       DB      1               ;MOTOR CONTROL
FA_SENSE:       DW      1               ;
FA_PDREG:       DW      1               ;PHOTO DETECTORS
FN_SKBOT:       DB      1               ;BOTTOM OF BUFFR POINTER
FN_SKTOP:       DB      1               ;TOP OF BUFFR POINTER
;                            PARAMETER BUFFER FOLLOWS
FN_BUFFR:       DW      1               ;TIME WORD
                DW      1               ;AUX TIME WORD
                DB      1               ;ENT BYTE
                DB      35              ;REST OF BUFFER
                END

XXXXXX
22 hours
XXXXXX
```

ISS. We've driven a stake through the DRC vampire



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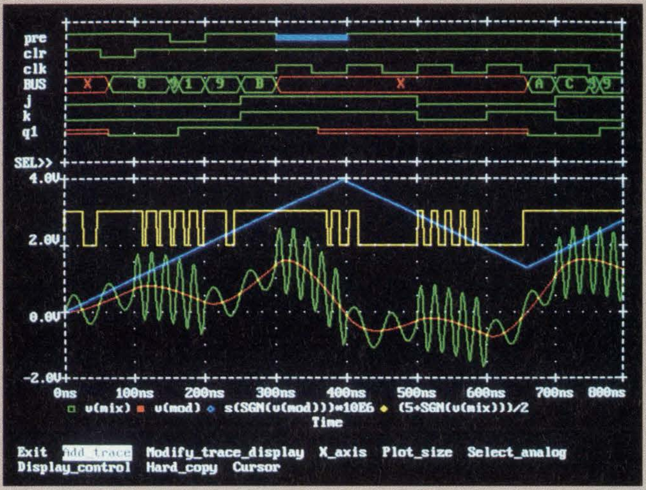

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Comprehensive features ease ports from Unix to OS/2

Porting an application from one operating system to another is rarely a simple procedure. Differences in system features and operating limits complicate the port. However, in the case of porting Unix applications to OS/2, your task is simpler because OS/2 has features similar or superior to Unix.

Joseph Gnocato, *MPR Teltech Ltd*

The problems peculiar to porting a Unix application to OS/2 stem from the substantial differences between the architectures of the two operating systems. The differences have a profound effect on how you write your code, how you structure your programs, and how you use your compiler.

A standard Unix application has difficulty processing the message-based "events" of OS/2. Under OS/2's graphical user interface, Presentation Manager (PM), all user-input events send messages to the active application via a queue. The user-input events first arrive at a System Message Queue, which subsequently sends them to the active application. The active application must always be ready to respond to any of its messages at any time.

For example, if an OS/2 PM application expects some keyboard input from the user, among other inputs, it cannot merely call the C function *getchar*. The *getchar* function call would "block" the application and wait for the user's input. If the user does not type a character, but instead tries to resize the window, the application cannot handle the window-resize message because the program is blocked waiting for user input.

Although the message-based architecture of PM seems to create a problem for software engineers who want to use functions like *getchar*, OS/2 provides a powerful solution. It allows a "process," or "task," to have more than one "thread" of execution. Threads can execute different parts of a single program concurrently. This concurrency means that one thread can manage window-manipulation tasks while another executes blocking functions like *getchar*.

In contrast, Unix-based applications generally do not operate in a message-based environment. Porting graphical Unix applications to PM is not simply a matter of blindly converting the graphics and file-system routines to equivalent PM routines. You must carefully consider how the Unix application's existing user-event handler will interact with OS/2 PM. Usually, your user-event handling will require some modification.

Handler acquires semaphores

Unix applications may require several fundamental changes to handle events under PM. You must employ semaphores to control different threads and to serialize specific actions. For example, an application that must periodically recalculate a large spreadsheet must still respond to the user during recalculation.

As a simple example, consider a program that begins a time-consuming operation whenever the user presses

The existence of virtual memory on the target computer is usually a prerequisite for successfully porting any large application.

Listing 2—MTDEMO definitions file

```
NAME            MTDEMO  WINDOWAPI

DESCRIPTION     'MTDEMO Program, (c) Joe Gnocato, 1990'
PROTMODE
HEAPSIZE        1024
STACKSIZE       8192
EXPORTS         ClientWndProc
```

the second mouse button. Now, assume that a user first presses the second mouse button and then decides to resize the program's window. In a single-threaded PM program, the window resizing would not occur until after the time-consuming operation was completed. Alternatively, a multithreaded program performs the time-consuming operation and the window resizing concurrently.

Listing 1 (see pg 59) contains a complete multithreaded, semaphore-controlled program for OS/2 PM called MTDEMO. **Listings 2** and 3 show the module-definition file and the make file, respectively, for the MTDEMO program. MTDEMO demonstrates how threads and semaphores combine to provide effective system response to the user.

In the PM code, the *main* procedure initializes the program's environment and creates a Frame and Client window on the PM Desktop (Presentation Manager's metaphor for its screen displays). Before entering the event-processing loop, *main* creates a second thread of execution with the *_beginthread* function.

The *main* procedure then starts processing events by repeatedly calling the *WinGetMsg* and *WinDispatchMsg* functions. When the user closes the program's window, *WinGetMsg* returns FALSE, and the *main* program terminates.

Simultaneously, the *_beginthread* function begins executing the second thread with the *SecondThreadFct* procedure. This procedure is an infinite loop that sets the *hsemPauseThread2* semaphore and waits for it to be cleared. When *hsemPauseThread2* clears, a beep sounds and the time-consuming operation begins (in this case a *sleep* operation). When it ends, a beep sounds again. The second thread sets the semaphore, and then waits for it to clear again.

The function *ClientWndProc* clears the *hsemPauseThread2* semaphore upon receiving the *WM_BUTTON2DOWN* message. This message occurs whenever the user presses the second mouse button.

Assume that a user invokes MTDEMO, presses the second mouse button, moves to the window border, and then resizes the window. **Fig 1** shows a timing diagram for a single-threaded version of MTDEMO. Notice that all processing occurs serially. Compare these results with **Fig 2**, which shows the timing diagram for the two-threaded version of MTDEMO.

A single-threaded implementation of MTDEMO would not create a second thread; it would invoke the time-consuming operation directly from *ClientWndProc* upon receiving the *WM_BUTTON2DOWN* message. Thus you can use multiple threads to handle several events in a seemingly simultaneous manner. Imagine an application that waits for user input, resizes its window, redraws the graphics area, and loads a data file—all simultaneously. OS/2's threads make this concurrency possible. Applications using threads will become even more powerful on architectures that have multiple CPUs, where each CPU will have one or more threads.

OS/2 supports a "DOS-style" file system that re-

Listing 3—MTDEMO make file

```
mtdemo.obj : mtdemo.c
     cl -c -AH -G2sw mtdemo.c

mtdemo.exe : mtdemo.obj mtdemo.def
     link mtdemo.obj, /align:16, NUL, /NOD llibcmt os2, mtdemo.def
```

stricts file names to an 8-character name followed by a period separator ("dot") and a 3-character extension. Unix users often find the DOS-style naming convention restrictive. When porting from Unix to OS/2, you must ensure that each application conforms to the DOS-style file-naming conventions.

With the introduction of OS/2 version 1.2, OS/2 began supporting multiple, installable file systems. The High Performance File System (HPFS) is the new OS/2 file system that removes the DOS-style file naming restrictions. HPFS file names may be very long strings composed of any combination of legal characters. This new file system removes many of the naming incompatibilities present between the Unix and DOS-style file systems.

Accommodating the differences between Unix and OS/2 often comes down to compiler considerations. For example, software engineers developing Unix applications never worry about which memory model to use during application development—Unix implicitly assumes a "flat" memory architecture. In contrast, because of the peculiarities of the 80X86 family's architecture, OS/2 PM developers face the task of first choosing an appropriate memory model for their programs.

Standardizing on the *HUGE* memory model eliminates many of the precautions needed when mixing and matching object files and library programs compiled with different memory models. Using the *HUGE* memory model also means that the code does not require the *FAR* and *NEAR* keywords (available in the Microsoft C compiler). In addition, the *HUGE* memory model provides a flat memory model that most closely resembles that of Unix.

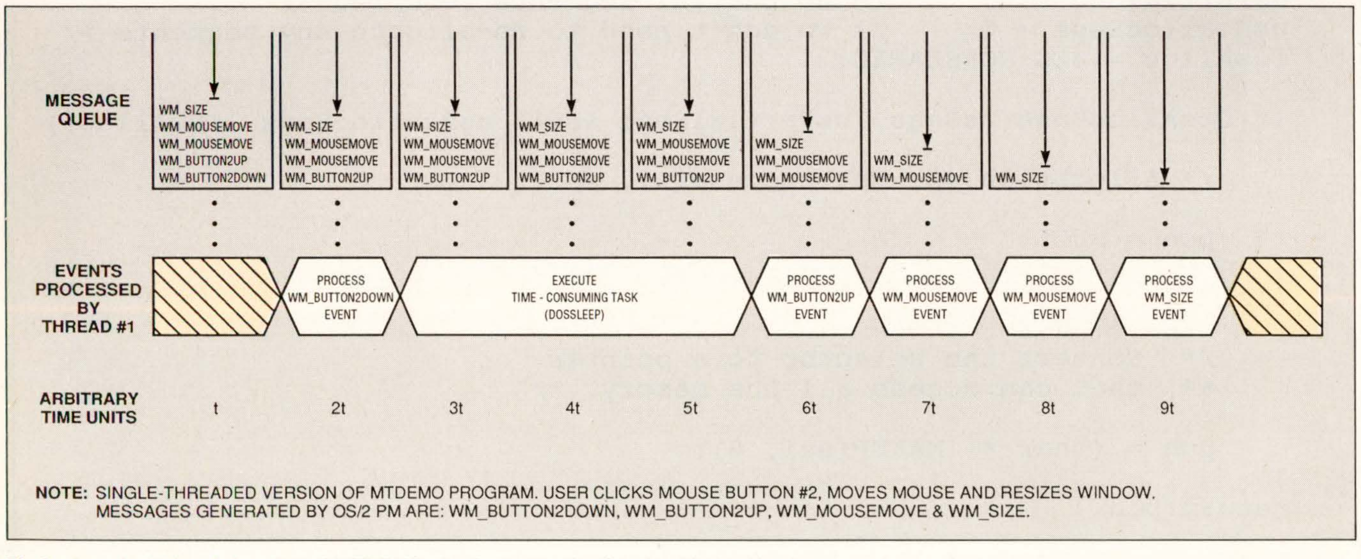
The existence of virtual memory on the target computer is usually a prerequisite for successfully porting any large application. OS/2's virtual memory handles all requests for dynamic memory and performs code or data swapping automatically. Program overlays, common in large DOS applications, are unnecessary under OS/2.

OS/2's virtual memory easily handles requests for large pieces of dynamically allocated memory. However, you will that the *halloc* function, in Microsoft's C runtime library V5.10, will not grant requests of more than 4M bytes per call. The *DosAllocHuge* function circumvents this restriction. **Listing 4** provides a source-code fragment that allocates 5M bytes of memory.

The *swapper.dat* file (usually \OS2\SYSTEM\SWAPPER.DAT) is OS/2's virtual-memory file on the hard disk. As requests for memory exceed the machine's RAM, the *swapper.dat* file grows dynamically as the RAM and hard disk swap data.

Unfortunately, the *swapper.dat* file does not dynamically shrink as an application frees memory. Users may see a sharp decrease in available hard-disk space when an application allocates large pieces of memory. The *swapper.dat* file only returns to its default size when users reboot their systems.

As with all ports, pay particular attention to indiscriminate mixing, or casting, of variables. Also pay attention to compiler-dependent "clever" programming. For example, in some C compilers for particular


MESSAGE QUEUE
WM_SIZE
WM_MOUSEMOVE
WM_MOUSEMOVE
WM_BUTTON2UP
WM_BUTTON2DOWN
WM_SIZE
WM_MOUSEMOVE
WM_MOUSEMOVE
WM_BUTTON2UP
WM_SIZE
WM_MOUSEMOVE
WM_MOUSEMOVE
WM_BUTTON2UP
WM_SIZE
WM_MOUSEMOVE
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WM_MOUSEMOVE
WM_MOUSEMOVE
WM_BUTTON2UP
WM_SIZE
WM_MOUSEMOVE
WM_MOUSEMOVE
WM_SIZE
WM_MOUSEMOVE
WM_SIZE
EVENTS PROCESSED BY THREAD #1
PROCESS WM_BUTTON2DOWN EVENT
EXECUTE TIME - CONSUMING TASK (DOSSLEEP)
PROCESS WM_BUTTON2UP EVENT
PROCESS WM_MOUSEMOVE EVENT
PROCESS WM_MOUSEMOVE EVENT
PROCESS WM_SIZE EVENT
ARBITRARY TIME UNITS
t
2t
3t
4t
5t
6t
7t
8t
9t
NOTE: SINGLE-THREADED VERSION OF MTDEMO PROGRAM. USER CLICKS MOUSE BUTTON #2, MOVES MOUSE AND RESIZES WINDOW. MESSAGES GENERATED BY OS/2 PM ARE: WM_BUTTON2DOWN, WM_BUTTON2UP, WM_MOUSEMOVE & WM_SIZE.

Fig 1—In a single-threaded version of MTDEMO, the time-consuming function blocks other input-event processing.

Accommodating the differences between Unix and OS/2 often comes down to compiler considerations.

processors, an *int* may be the same size as a pointer. Code that implicitly makes this assumption could be difficult to port to other processors with different underlying architectures.

Useless C runtime functions

Under Presentation Manager, several standard C runtime I/O functions (such as *printf* and *getchar*) are no longer useful because the application must receive user input from the message queue. For each character the user types, the application will receive a message providing the key's code and the status of other keys. The application must process these messages and concatenate the key events to produce a string. You can use PM's Dialog Boxes to perform this task automatically.

The C function *printf* prints to *stdout*, but in a graphical PM program, *stdout* is not linked to the graphics window. Therefore, *printf* will not produce any visible result on a graphical program's PM screen. PM programs usually accomplish text output through PM's *Gpi* or *Vio* routines.

Therefore, instead of using the standard *printf* function throughout your application's source code, you should instead use a system-independent function, perhaps *MyPrintFunction*. The actual code for *MyPrintFunction* will change from system to system, but the function isolates the application from these changes.

Listing 4—OS/2 megabyte allocator

```
char * GiveMeFiveMB()
{
   /*  This function tries to allocate 5 MB of memory. It returns a
   **   pointer to the memory if successful, otherwise NULL.
   **
   **  You must compile this function with the LARGE or HUGE
   **  memory model options. */

   USHORT  usSegs, usPartialSeg;
   USHORT  usReallocSegs, fusAlloc;
   SEL     sel;
   CHAR    *pch;

   usSegs = 80;            /* 80 segments of 64KB = 5 MB */
   usPartialSeg = 0;       /* no partial segments required */
   usReallocSegs = 0;      /* we don't need to re-allocte any segments */
   fusAlloc = SEG_NONSHARED;

   if(DosAllocHuge(usSegs, usPartialSeg, &sel, usReallocSegs, fusAlloc))
   {
       /* Allocation was not successful. */

       pch = NULL;
   }
   else
   {
       /*  Convert the selector to a pointer
       **  that can access all the memory. */

       pch = (char *) MAKEP(sel, 0);
   }
   return(pch);
}
```

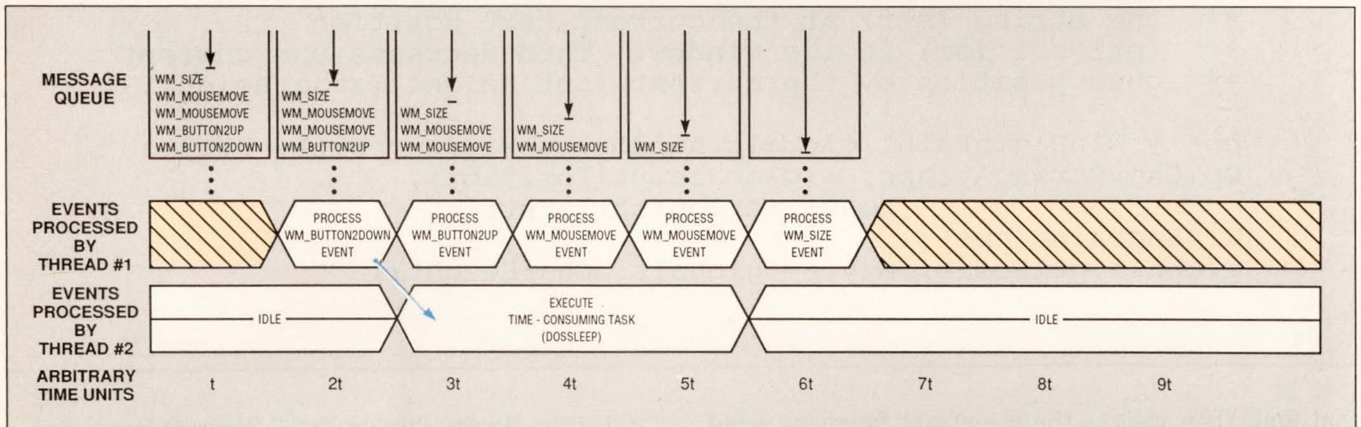
Listings 5a and **5b** show examples of Unix and OS/2 versions, respectively, of the actual code for *MyPrintFunction.*

Because of *MyPrintFunction*, the application is unaware of the actual mechanism for writing to the screen. Isolating the application from system dependencies minimizes the work required to port the application. In addition, environments that permit multiple fonts or colors can provide these features without making an impact on the application.

For multithreaded programs, where more than one thread makes use of the C runtime functions, you must use a special version of the Microsoft C runtime library. For example, suppose that one thread is in the middle of a *printf* call and the OS/2 scheduler suspends its execution. Now a second thread begins executing and it also makes a call to *printf.* With the regular (nonreentrant) function, the second thread's call to *printf* could corrupt the function's static data.

The Microsoft C compiler includes a large-model library that you should link to multithreaded programs where more than one thread executes C runtime functions. Applications do not require the multithreaded C runtime library when only one thread accesses the runtime library, or if the library accesses are done serially.

Note that some of the C runtime functions in the nonmultithreaded libraries are re-entrant. Programs



NOTE: TWO-THREADED VERSION OF MTDEMO PROGRAM.
SAME MESSAGES AS FIGURE #1 ARE QUEUED BY USER ACTIONS. HOWEVER, PROGRAM HANDLES THEM IN A DIFFERENT MANNER.
SECOND THREAD WORKS ON THE 'TIME-CONSUMING' TASK WHILE FIRST THREAD CAN IMMEDIATELY RESPOND TO USER'S 'RESIZE' REQUEST.

Fig 2—The two-threaded version of MTDEMO can simultaneously execute both the time-consuming task and service the user's mouse events.

Points to ponder when porting programs

As OS/2 continues to mature, more software engineers will port Unix applications to Presentation Manager and OS/2. These software engineers should consider the following points:

- You will need to tailor your Unix application's user-event handler for operation under OS/2 and Presentation Manager (PM).
- You will need multiple threads in the OS/2 PM application especially if the application uses blocking functions.
- A system-independent alternative for *printf* is a necessity.
- Applications with multiple threads, calling the C runtime library, require special multithreaded versions of the C runtime library programs.
- The possible incompatibilities in the file-naming conventions between the Unix file system and OS/2's DOS-style file system are often troublesome. However, OS/2's new High Performance File System (HPFS) eliminates most of these concerns.
- OS/2's virtual memory provides elegant memory management and is transparent to the user.
- Prototyping menus, dialog boxes, and icons under OS/2 PM is very quick and easy.

Unix users often find the DOS-style naming convention restrictive.

Listing 5—Unix and OS/2 versions of a system-independent printing function

```
void MyPrintFunction(str)
char    *str;
{
    printf("%s\n", str);
}
```

(a)

```
void MyPrintFunction(str)
char    *str;
{
    HPS        hps;

    /*  Obtain a Presentation Space handle (hps) and print
    **  the string (str) at the current text position
    **  (ptlPosition) in the window.  Then decrease the current
    **  text position by the current font height (sCharHeightY). */

    hps = WinBeginPaint(globals.hwndOutputWindow, NULL, NULL);
    GpiCharStringAt(hps, &(globals.ptlPosition),
                    (LONG) strlen(str), str);
    WinEndPaint(hps);
    globals.ptlPosition.y -= globals.sCharHeightY;
}
```

(b)

that limit their calls to the re-entrant functions could, therefore, use the regular functions. However, in practice, worrying about which functions can or cannot be used for multithreaded programs is too troublesome. Standardizing on the multithreaded libraries eliminates the need to check all code for calls to nonre-entrant C functions.

The OS/2 utilities for developing menus, dialog boxes, and icons are very useful and allow rapid prototyping of several aspects of your user interface.

Using the PM's Resource-Description Language, you can describe user menus and dialog boxes with text. The resource compiler compiles your descriptions into binary files that "bind" with your executable program. Alternatively, you can interactively construct dialog boxes with the *DlgBox* utility provided in the Software Developers' Kit. EDN

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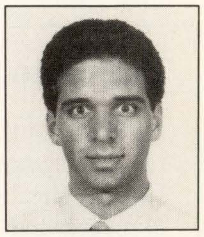
2. Letwin, Gordon, "Inside OS/2." Microsoft Press, Redmond, WA, 1988. ISBN 1-55615-117-9.

Author's biography



Joseph Gnocato is a systems development engineer with MPR Teltech Ltd in Burnaby, British Columbia, Canada. He's been with the company for four years. He develops CAD/CAE applications and user interfaces under Unix and OS/2. Joseph earned a BASC in electrical engineering from the University of British Columbia. Joseph, a member of the IEEE, enjoys traveling and river rafting.

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Listing 1—Multithreaded demonstration program

```
/*  PROGRAM: mtdemo (mutliple thread demo)
**
**  PURPOSE: This OS/2 PM program demonstrates:
**             1) executing multiple threads
**             2) semaphores controlling threads */

#define INCL_WIN
#define INCL_DOS
#include <os2.h>
#include <mt\process.h>       /* multi-threaded 'process.h' header file */
#include <mt\stdlib.h>        /* multi-threaded 'stdlib.h' header file */

#define STACKSIZE             4096        /* stack size for 2nd thread */
#define SLEEP_DURATION        5000        /* 5000 milliseconds */
#define BEEP_DURATION         150         /* 150 milliseconds */
#define HI_FREQ_BEEP          4000        /* 4000 Hz */
#define LO_FREQ_BEEP          100         /* 100 Hz */

void                main(void);
void                SecondThreadFct(void);
MRESULT EXPENTRY    ClientWndProc(HWND, USHORT, MPARAM, MPARAM);

HSEM    hsemPauseThread2;         /* control semaphore for thread#2 */

void main(void)
{

   /*  This sample program waits for the user to press the second
   **  mouse button.  When the user presses the button, a low-frequency
   **  beep sounds and a 'time-consuming' task begins in a
   **  second thread.  When this task completes, a high-frequency
   **  beep sounds.  While the 'time-consuming' task executes,
   **  the first thread still responds to the user's mouse and
   **  keyboard inputs.
   **
   **  The routine 'main' initializes the PM environment and
   **  launches the second thread of execution with the
   **  '_beginthread' function.  The 'hsemPauseThread2' semaphore controls
   **  the second thread's execution.
   **
   **  The 'WinDispatchMsg' function dispatches Message-based events
   **  arriving at the window's queue. The 'ClientWndProc' function
   **  processes messages. */

   HAB           hab;
   HMQ           hmq;
   QMSG          qmsg;
   HWND          hwndFrame, hwndClient;
   ULONG         FrameFlags;
   static CHAR   szClientClass[] = "DemoProg";
   static CHAR   ThreadStack[STACKSIZE];
   static TID    Thread2ID;
```

Listing continued

Threads can execute different parts of a single program concurrently.

Listing 1—Multithreaded demonstration program *(continued)*

```
    /* Initialize PM and create a message queue for the events. */

    hab = WinInitialize(0);
    hmq = WinCreateMsgQueue(hab, 0);

    /*  Register the window class and create a standard
    **  frame window and client window. */

    WinRegisterClass(hab,                  /* anchor block handle */
                     szClientClass,        /* window class name */
                     ClientWndProc,        /* window procedure */
                     CS_SIZEREDRAW,        /* window-style flags */
                     0);                   /* amount of reserved data */

    FrameFlags = FCF_TITLEBAR | FCF_SYSMENU | FCF_SIZEBORDER |
                 FCF_MINMAX | FCF_SHELLPOSITION;

    hwndFrame = WinCreateStdWindow(HWND_DESKTOP,   /* parent window handle */
                                   WS_VISIBLE,     /* frame window style */
                                   &FrameFlags,    /* frame creation flags */
                                   szClientClass,  /* client class name */
                                   " Demo",        /* title-bar text */
                                   0L,             /* client window style */
                                   NULL,           /* resource module handle */
                                   NULL,           /* frame resource id */
                                   &hwndClient);   /* client window handle */

    /* Before beginning the event processing, start a second thread
    **  of execution. The second thread will execute the function
    **  called 'SecondThreadFct'. */

    Thread2ID = _beginthread(SecondThreadFct,      /* thread2 startup function */
                  (void *) ThreadStack,            /* thread2 stack space */
                  STACKSIZE,                       /* stack size for thread2 */
                  NULL);                           /* thread2 parameters */

    /* Loop through the user events until program halts. */

    while(WinGetMsg(hab, &qmsg, NULL, 0, 0))
    {
        WinDispatchMsg(hab, &qmsg);
    }

    /* Program has terminated, so clean up windows and queues. */

    WinDestroyWindow(hwndFrame);
    WinDestroyMsgQueue(hmq);
    WinTerminate(hab);
}

/*-----------------------------------------------------------------------*/

MRESULT EXPENTRY ClientWndProc(hwnd, msg, mp1, mp2)
HWND hwnd;
USHORT msg;
```

Listing 1—Multithreaded demonstration program *(continued)*

```
MPARAM mp1;
MPARAM mp2;
{
  /*  This function processes all Client window event messages.
  **  We are only interested in the message generated when
  **  the user presses the second mouse button. Let the system
  **  handle all other messages in the default manner. */

  switch(msg)
  {
    case WM_BUTTON2DOWN:

        /* Clear the semaphore to wake up the second thread.
        **  Then continue to process user events normally. */

        DosSemClear(&hsemPauseThread2);
        break;
  }
  return(WinDefWindowProc(hwnd, msg, mp1, mp2));
}

/*------------------------------------------------------------------------------*/

void SecondThreadFct(void)
{
  /*  Only the second thread executes this function.
  **  The 'hsemPauseThread2' semaphore controls execution.
  **
  **  This routine will SET the 'hsemPauseThread2' semaphore and
  **  then wait indefinitely until the semaphore clears.  When the user
  **  clears 'hsemPauseThread2' by pressing the second
  **  mouse button the routine wakes up and makes a low-freq beep.
  **
  **  The routine then simulates a 'time-consuming' task by sleeping
  **  for SLEEP_DURATION milliseconds.  The 'time-consuming' task would
  **  typically be the recalculation of a large spreadsheet or waiting
  **  for user input.
  **
  **  After the 'time-consuming' task has completed, the routine makes
  **  a high-freq beep and reenters a dormant state by setting the
  **  'hsemPauseThread2' semaphore and then waiting for it to clear. */

  while(TRUE)
  {
    /*  Set the semaphore and wait for it to clear.  Pressing the
    **  second mouse button will clear the semaphore, (see the
    **  'ClientWndProc' procedure). */

    DosSemSet(&hsemPauseThread2);
    DosSemWait(&hsemPauseThread2, SEM_INDEFINITE_WAIT);

    DosBeep(LO_FREQ_BEEP, BEEP_DURATION);
    DosSleep((ULONG) SLEEP_DURATION);   /* perform time-consuming task */
    DosBeep(HI_FREQ_BEEP, BEEP_DURATION);
  }
}
```

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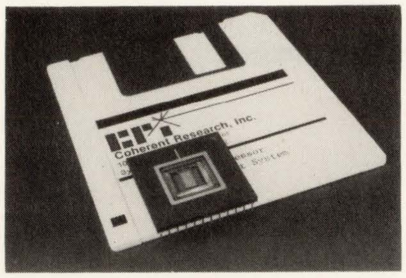

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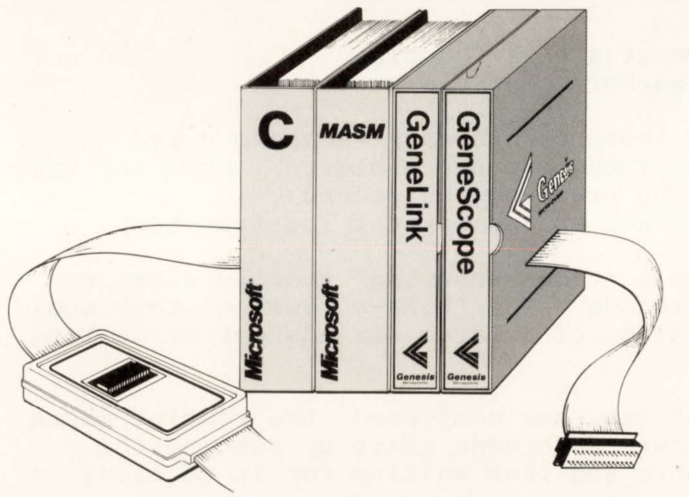

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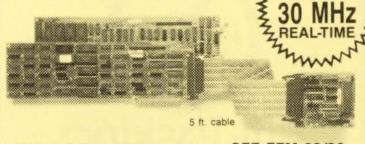

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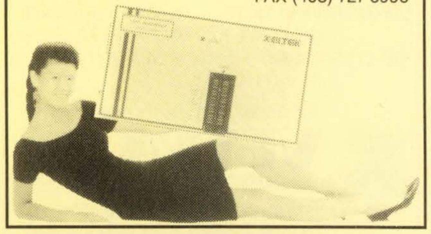

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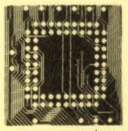

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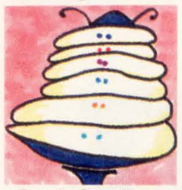

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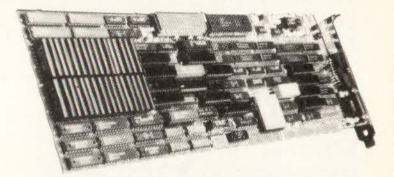

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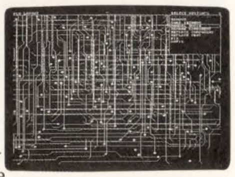

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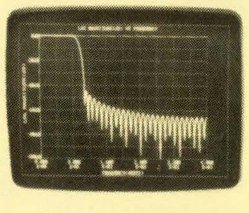

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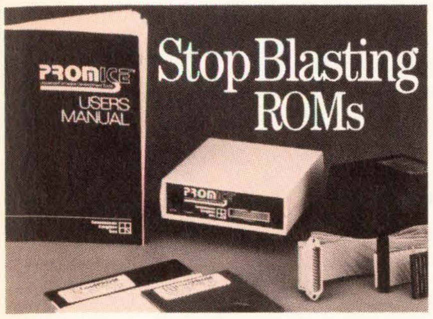

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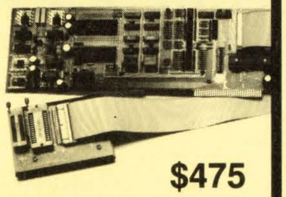

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```
#include <stdio.h>

typedef struct {
   int foo;
   double bar;
   char baz[36];
} quux;

/***     foobar - inspect baz in a quux
*/

static quux * foobar(bar, quuxptr)
   int bar;
   quux * quuxptr;
{
   int i;

   for (i = bar; quuxptr->baz[i]; i++)
      if (quuxptr->baz[i] == '\n')
         return (quuxptr);

   return (NULL);
}
-- More --_
```

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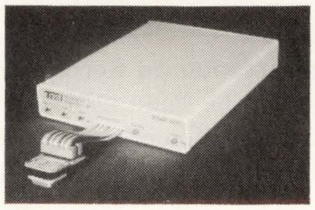

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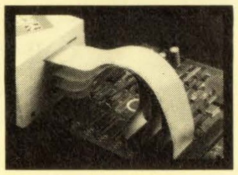

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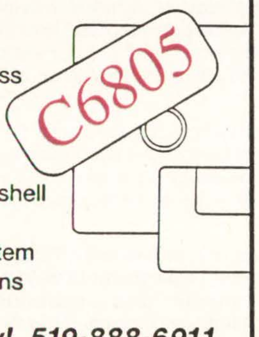

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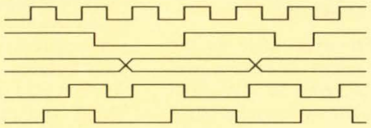

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Magazine Edition	Oct. 11	Sept. 20	Analog ICs, Computer-Aided Engineering, DSP IC Directory, Displays, International Technology Update
News Edition	Oct. 18	Sept. 28	CAE/Hardware, Datacom, Regional Profile: Idaho, Colorado, Utah
Magazine Edition	Oct. 25	Oct. 4	Test & Measurement Special Issue—Digital Instruments, Computers & Peripherals, ICs & Semiconductors, System Software
Magazine Edition	Nov. 8	Oct. 18	Signal Processing, Computer-Aided Engineering, Computers & Peripherals, Software, Wescon Show Issue
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CIRCLE NO. 30

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- Analyze technical problems and implement effective solutions
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- Proficiency in "C" and related languages

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(Dept. USE)

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(Dept. CSSE)

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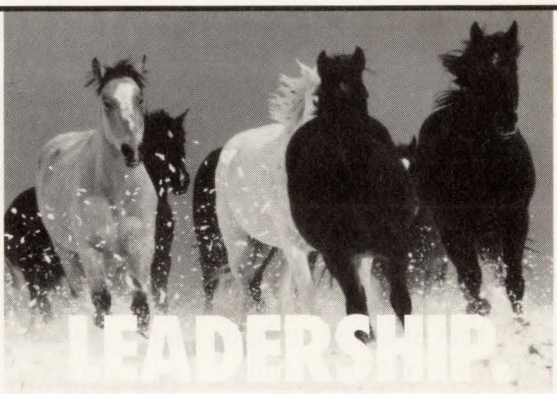

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Please submit resume to: **Motorola Semiconductor Products Sector, Dept. ATX-185, 505 Barton Springs Rd., One Texas Center, Suite 400, Austin, TX 78704. 24 hour FAX (512) 322-8811.** An Equal Opportunity/Affirmative Action Employer.

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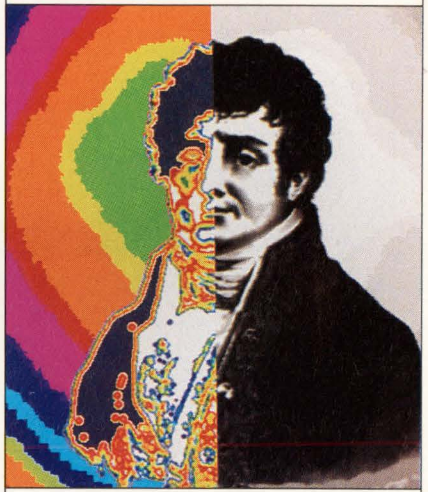
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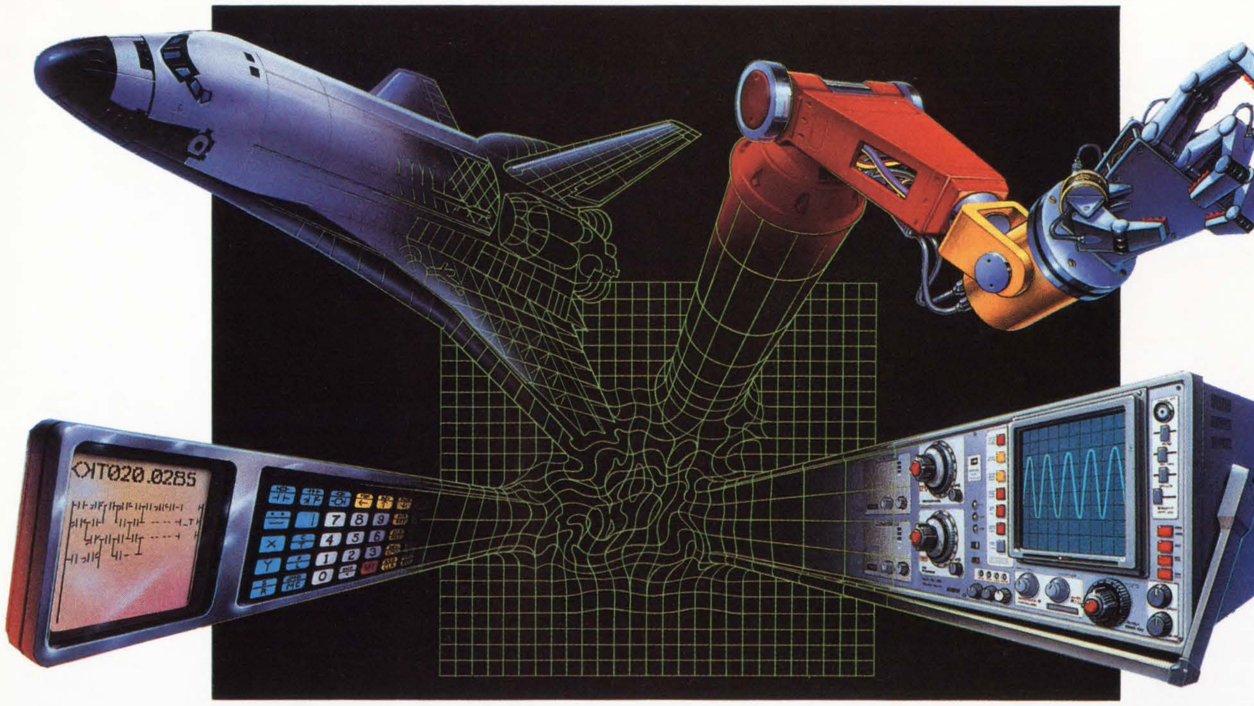

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