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MIPSpro™ Fortran 77 Programmer's Guide

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Introduction

This manual provides information on implementing FORTRAN 77 programs using the MIPSpro Fortran 77 compiler on the IRIX Operating System, Version 6.2 and above. This implementation of FORTRAN 77 contains full American National Standards Institute (ANSI) Programming Language Fortran (X3.9–1978) (in June, 1997, ANSI no longer supported this standard). Extensions provide full VMS Fortran compatibility to the extent possible without the VMS operating system or VAX data representation. This implementation of FORTRAN 77 also contains extensions that provide partial compatibility with programs written in SVS Fortran.

Organization

This manual contains the following chapters and appendix:

- Chapter 1, “Compiling, Linking, and Running Programs,” provides an overview of components of the compiler system, and describes how to compile, link, and execute a Fortran program. It also describes special considerations for programs running on IRIX systems, such as file format and error handling.
- Chapter 2, “Storage Mapping,” describes how the Fortran compiler implements size and value ranges for various data types and how they are mapped to storage. It also describes how to access misaligned data.
- Chapter 3, “Fortran Program Interfaces,” provides reference and guide information on writing programs in Fortran and C that can communicate with each other. It also describes the process of generating wrappers for C routines called by Fortran.
- Chapter 4, “System Functions and Subroutines,” describes functions and subroutines that can be used with a program to communicate with the IRIX operating system.
- Chapter 5, “OpenMP Multiprocessing Directives,” describes the OpenMP directives used for running Fortran programs in multiprocessor mode.

- Chapter 6, “Parallel Programming on Origin2000,” describes the support provided for writing parallel programs on Origin2000 and how to improve program performance.
- Chapter 7, “Compiling and Debugging Parallel Fortran,” describes and illustrates compilation and debugging techniques for running Fortran programs in a multiprocessor mode.
- Appendix A, “Run-Time Error Messages,” lists the error messages that can be generated during program execution.
- Appendix B, “Multiprocessing Directives (Outmoded),” describes outmoded programming directives for running Fortran programs in a multiprocessor mode.

Additional Reading

The *MIPSpro Fortran 77 Language Reference Manual* provides a description of the FORTRAN 77 language as implemented on Silicon Graphics systems.

The *MIPSpro Compiling and Performance Tuning Guide* provides information about the following topics:

- an overview of the compiler system
- improving program performance by using the optimization facilities of the compiler system
- general discussion of performance tuning
- the dump utilities, archiver, debugger, and tools used to maintain Fortran programs

The *MIPSpro Porting and Transition Guide* provides information about:

- overview of the 64-bit compiler system and language implementation differences
- porting source code to the 64-bit system
- compilation and run-time issues

For information about Fortran 90, see the *MIPSpro 7 Fortran 90 Commands and Directives Reference Manual* and the *Fortran Language Reference Manual*.

For information about interfaces to programs written in assembly language, refer to the *MIPSpro Assembly Language Programmer’s Guide*.

For information about automatic parallelization for Fortran, C, and C++, see the *MIPSpro Automatic Parallelizer Programmer's Guide*.

See the *Developer Magic: WorkShop Pro MPF User's Guide* for information about using WorkShop Pro MPF.

Typographical Conventions

The following conventions and symbols are used in the text to describe the form of Fortran statements:

Links	Links to other sections and chapters in this guide appear in blue. For example, Chapter 1 describes how to compile, link, and run programs. Links to applications, files, and reference pages appear in red. For example, for details on the *f77* command, see the f77(1) reference page.
Bold	Indicates literal command line option, keywords, and functions.
Italics	Represents user-defined values. Replace the item in italics with a valid value. Italics are also used for command names, path and file names, and manual titles.
`Courier`	Indicates command syntax, program listings, computer output, and error messages.
`Courier bold`	Indicates user input.
[ ]	Enclose optional command arguments.
()	Surround arguments or are empty if the function has no arguments following function/subroutine names. Surround manual page section in which the command is described following IRIX commands.
{}	Enclose two or more items from which you must specify exactly one.
|	Separates two or more optional items.
...	Indicates that the preceding optional items can appear more than once in succession.
#	IRIX shell prompt for the superuser.
%	IRIX shell prompt for users other than the superuser.

In the following example, the Fortran keyword **DIMENSION** must be written as shown, that the user-defined entity *a*(*d*) is required, and that one or more of *a*(*d*) can be optionally specified. The pair of parentheses ( ) enclosing *d* is required.

```
DIMENSION a(d) [,a(d)] ...
```

In this example, either the **STATIC** or **AUTOMATIC** keyword must be used, the user-defined entity *v* is required, and one or more of *v* items can be optionally specified.

```
{STATIC | AUTOMATIC} v [,v] ...
```

Chapter 1

Compiling, Linking, and Running Programs

This chapter contains the following major sections:

- "Compiling and Linking" on page 2 describes the compilation environment and how to compile and link Fortran programs. This section also contains examples that show how to create separate linkable objects written in Fortran, C, or other languages supported by the compiler system and how to link them into an executable object program.
- "Driver Options" on page 7 gives an overview of debugging, profiling, optimizing, and other options provided with the Fortran *f77* driver.
- "Specifying the Buffer Size for Direct Unformatted I/O" on page 16 describes the environment variable you can use to specify buffer size.
- "Object File Tools" on page 16 briefly summarizes the capabilities of the *elfdump*, *dis*, *nm*, *file*, *size* and *strip* programs that provide listing and other information on object files.
- "Archiver" on page 17 summarizes the functions of the *ar* program that maintains archive libraries.
- "Run-Time Considerations" on page 17 describes how to invoke a Fortran program, how the operating system treats files, and how to handle run-time errors.

Also refer to the *Fortran Release Notes* for a list of compiler enhancements, possible compiler errors, and instructions on how to circumvent them.

Compiling and Linking

This section covers compiling and linking, and discusses:

Drivers

Programs called *drivers* invoke the major components of the compiler system: the Fortran compiler, the optimizing code generator, and the linker. The *f77* command invokes the driver that causes your programs to be compiled, optimized, assembled, and linked.

The format of the *f77* driver command is as follows:

`f77` [*option*] ... *filename* [*option*]

For this format:

f77	invokes the various processing phases that compile, optimize, assemble, and link the program.
option	represents the driver options through which you provide instructions to the processing phases. They can be placed anywhere in the command line. These options are discussed later in this chapter and on the f77(1) reference page.
filename	is the name of the file that contains the Fortran source statements. The filename must always have the suffix **.f**, **.F**, **.for**, **.FOR**, or **.i**. For example, **myprog.f**.

Compilation

The driver command *f77* can both compile and link a source module. Figure 1-1 shows the primary drivers phases. It also shows their principal inputs and outputs for the source modules **more.f**.

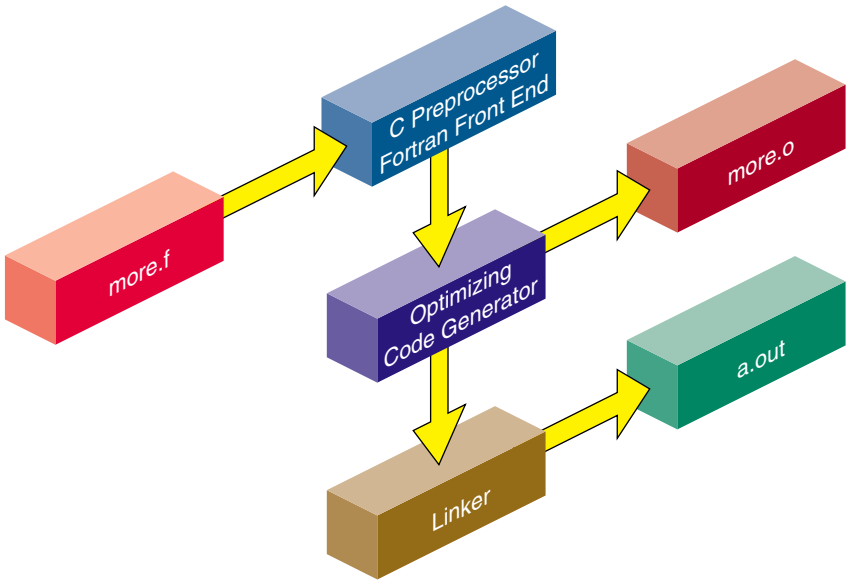


Figure 1-1 Compilation Process

Note the following:

- The source file ends with the required suffixes **.f**, **.F**, **.for**, **.FOR**, or **.i**.
- The Fortran front end has an integrated C preprocessor that provides full *cpp* capabilities.
- The driver produces a linkable object file when you specify the **–c** driver option. This file has the same name as the source file, except with the suffix **.o**. For example, the command line

  ```
  % f77 more.f -c
  ```

  produces the **more.o** file in the above example.
- The default name of the executable object file is **a.out**. For example, the command line

  ```
  % f77 myprog.f
  ```

  produces the executable object **a.out**.

- You can specify a name other than **a.out** for the executable object by using the **–o** *name* option, where *name* is the name of the executable object. For example, the command line

  ```
  % f77 myprog.o -o myprog
  ```

  links the object module **myprog.o** and produces an executable object named **myprog**.

- The command line

  ```
  % f77 myprog.f -o myprog
  ```

  compiles and links the source module **myprog.f** and produces an executable object named **myprog**.

Compiling Multilanguage Programs

The compiler system provides drivers for other languages, including C and C++. If one of these drivers is installed in your system, you can compile and link your Fortran programs to the language supported by the driver. See the *MIPSpro Compiling and Performance Tuning Guide* for a list of available drivers and the commands that invoke them. Refer to Chapter 3, "Fortran Program Interfaces," in this manual for conventions you must follow when writing Fortran program interfaces to C programs.

When your application has two or more source programs written in different languages, you should compile each program module separately with the appropriate driver and then link them in a separate step. Create objects suitable for linking by specifying the **–c** option, which stops the driver immediately after the assembler phase. For example,

```
% cc -c main.c
% f77 -c rest.f
```

The two command lines shown above produce linkable objects named **main.o** and **rest.o**, as illustrated in Figure 1-2.

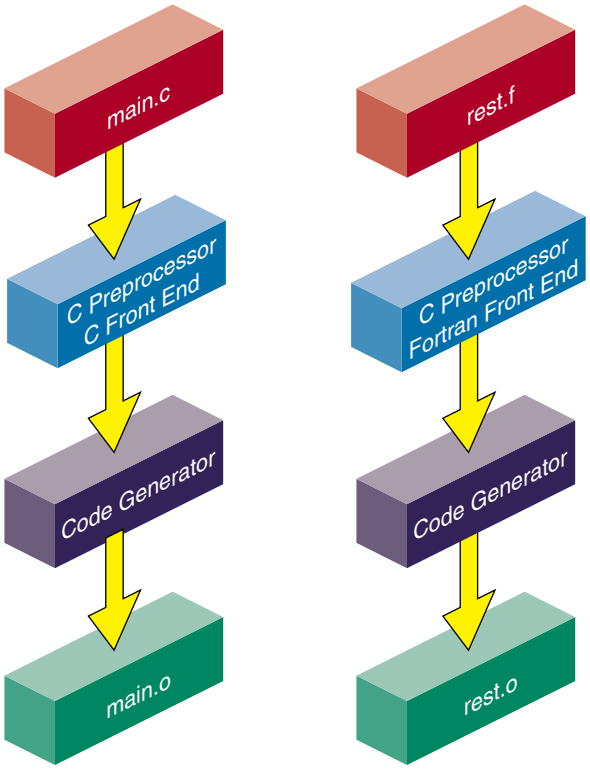


Figure 1-2 Compiling Multilanguage Programs

Linking Objects

You can use the *f77* driver command to link separate objects into one executable program when any one of the objects is compiled from a Fortran source. The driver recognizes the **.o** suffix as the name of a file containing object code suitable for linking and immediately invokes the linker. The following command links the object created in the last example:

```
% f77 -o myprog main.o rest.o
```

You can also use the *cc* driver command, as shown below:

```
% cc -o myprog main.o rest.o -lftn -lm
```

Figure 1-3 shows the flow of control for this link.

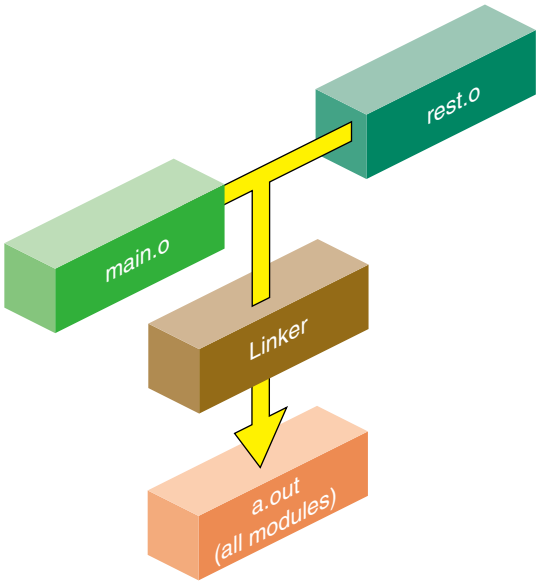


Figure 1-3 Linking

Both *f77* and *cc* use the C link library by default. However, the *cc* command does not know the names of the link libraries required by the Fortran objects; therefore, you must specify them explicitly to the linker using the **–l** option as shown in the example. The characters following **–l** are shorthand for link library files, as shown in Table 1-1.

Table 1-1 Link Libraries

–l	Link Library	Contents
ftn	/usr/lib*/nonshared/libftn.a	Intrinsic function, I/O, multiprocessing, IRIX interface, and indexed sequential access method library for nonshared linking and compiling
ftn	/usr/lib*/libftn.so	Same as above, except for shared linking and compiling (this is the default library)
m	/usr/lib*/libm.so	Mathematics library

See the FILES section of the f77(1) reference page for a complete list of the files used by the Fortran driver. Also refer to the ld(1) reference page for information on specifying the **–l** option.

Specifying Link Libraries

You may need to specify libraries when you use IRIX system packages that are not part of a particular language. Most of the reference pages for these packages list the required libraries. For example, the *getwd*(3B) subroutine requires the BSD compatibility library *libbsd.a*. Specify this library as follows:

```
% f77 main.o more.o rest.o -lbsd
```

To specify a library created with the archiver, type in the pathname of the library as shown below.

```
% f77 main.o more.o rest.o libfft.a
```

Note: The linker searches libraries in the order you specify. Therefore, if you have a library (for example, *libfft.a*) that uses data or procedures from **–lm**, you *must* specify *libfft.a* first.

Driver Options

This section contains an overview of the Fortran–specific driver options:

The f77(1) reference page has a complete description of the compiler options. This discussion only covers the relationships between some of the options, so as to help you make sense of the many options in the reference page. For more information you can review:

- The *MIPSpro Compiling and Performance Tuning Guide* for a discussion of the compiler options that are common to all MIPSpro compilers.
- The pfa(1) reference page for options related to the parallel optimizer.
- The ld(1) reference page for a description of the linker options.

Tip: The command *f77 -help* lists all compiler options for quick reference. Use the **-show** option to have the compiler document each phase of execution, showing the exact default and nondefault options passed to each.

Compiling Simple Programs

You need only a very few compiler options when you are compiling a simple program. Examples of simple programs include the following:

- Test cases used to explore algorithms or Fortran language features
- Programs that are principally interactive
- Programs whose performance is limited by disk I/O
- Programs you will execute under a debugger

In these cases you need only specify **-g** for debugging, the target machine architecture, and the word-length. For example, to compile a single source file to execute under *dbx* on a POWER CHALLENGE XL, you could use the following commands.

```
f77 -g -mips4 -n32 -o testcase testcase.f
dbx testcase
```

However, a program compiled in this way will take little advantage of the performance features of the machine. In particular, its speed when doing heavy floating-point calculations will be far slower than the machine capacity. For simple programs, that is not important.

Specifying Source File Format

The options shown in Table 1-2 tell the compiler how to treat the program source file.

Table 1-2 Compile Options for Source File Format

Options	Purpose
-ansi	Report any nonstandard usages.
-backslash	Treat \ in character literals as a character, not as the start of an escape sequence.
-col72, **-col120**, **-extend_source**, **-noextend_source**	Specify margin columns of source lines.
-d_lines	Compile lines with D in column 1.
-D*name*, **-D***name=def*, **-U***name*	Define, undefine names to the integrated C preprocessor.

Specifying Compiler Input and Output Files

The options summarized in Table 1-3 tell the compiler what output files to generate.

Table 1-3 Compile Options that Select Files

Options	Purpose
-c	Generate a single object file for each input file; do not link.
-E	Run only the macro preprocessor and write its output to standard output.
-I, **-I***dir*, **-nostdinc**	Specify location of include files.
-listing	Request a listing file.
-MDupdate	Request Makefile dependency output data.
-o	Specify name of output file.
-S	Specify only assembly-language source output.

Using a Defaults Specification File

You can set the Application Binary Interface (ABI), instruction set architecture (ISA), and processor type without explicitly specifying them. Just set the environment variable COMPILER_DEFAULTS_PATH to a colon separated list of paths designating where the compiler is to look for a *compiler.defaults* file. If no *compiler.defaults* file is found or if the environment variable is not set, the compiler looks for */etc/compiler.defaults*. If this file is not found, the compiler resorts to the built-in defaults.

The *compiler.defaults* file contains a **–DEFAULT:** *option* group specifier that specifies the default ABI, ISA, and processor. The compiler issues a warning if you specify anything other than **–DEFAULT:** *option* in the *compiler.defaults* file.

The format of the **–DEFAULT:** *option* group specifier is as follows:

```
–DEFAULT:[abi={o32|n32|64}] [:isa=mipsn] [:proc={r4k|r5k|r8k|r10k}] [:opt={0-3}]
[:arith={1-3}]
```

See the f77(1) reference page for an explanation of the *option* group.

Specifying Target Machine Features

The options summarized in Table 1-4 are used to specify the characteristics of the machine where the compiled program will be used.

Table 1-4 Compile Options for Target Machine Features

Options	Purpose
-64, **-n32**, **-o32**	Whether target machine runs 64-bit mode, "new" 32-bit mode available with IRIX 6.1 and above, or old 32-bit mode. The **-64** option is allowed only with the **-mips3** and **-mips4** architecture options.
-mips3, **-mips4**	The instruction architecture available in the target machine: use **-mips3** for MIPS R4000 and R4400® machines; use **-mips4** for MIPS R8000 and R10000™ machines.
-TARG:*option*,...	Specify certain details of the target CPU. Most of these options have correct default values based on the preceding options.
-TENV:*option*,...	Specify certain details of the software environment in which the source module will execute. Most of these options have correct default values based on other, more general values.

Specifying Memory Allocation and Alignment

The options summarized in Table 1-5 tell the compiler how to allocate memory and how to align variables in it. These options can have a strong effect on both program size and program speed.

Table 1-5 Compile Options for Memory Allocation and Alignment

Options	Purpose
-align8, **-align16**, **-align32**, **-align64**	Align all variables size *n* on *n*-byte address boundaries.
-d8, **-d16**	Specify the size of DOUBLE and DOUBLE COMPLEX variables.
-i2, **-i4**, **-i8**	Specify the size of INTEGER and LOGICAL variables.
-r4, **-r8**	Specify the size of REAL and COMPLEX variables.
-static	Allocate all local variables statically, not dynamically on the stack.
-G*size*, **-xgot**	Specify use of the global option table.

Specifying Debugging and Profiling

The options summarized in Table 1-6 direct the compiler to include more or less extra information in the object file for debugging or profiling.

Table 1-6 Compile Options for Debugging and Profiling

Options	Purpose
-**g0**, **-g2**, **-g3**, **-g**	Leave more or less symbol-table information in the object file for use with *dbx* or Workshop Pro *cvd*.
-p	Cause profiling to be enabled when the program is loaded.

For more information on debugging and profiling, see the manuals listed in the preface.

Specifying Optimization Levels

The optimization options, summarized in Table 1-7, are used to communicate to the different optimization phases. The optimizations that are common to all MIPSpro compilers are discussed in the *MIPSpro Compiling and Performance Tuning Guide.*

Table 1-7 Compile Options for Optimization Control

Options	Purpose
-O, **-O0**, **-O1**, **-O2**, **-O3**	Select basic level of optimization, setting defaults for all optimization phases.
-GCM:*option*,...	Specify details of global code motion performed by the back-end optimizer.
-INLINE:*option*,...	Standalone inliner option group to control application of intra-file subprogram inlining when interprocedural analysis is not enabled (see **-IPA** below). See the ipa(5) reference page for more information
-IPA:*option*,...	Specify Inter-Procedural Analyzer option group to control application of inter-procedural analysis and optimization, including inlining, common block array padding, constant propagation, dead function elimination, alias analysis and others.
-LNO:*option*,...	Loop nest optimizer (LNO) option control group to control optimizations and transformations performed by LNO. See the LNO(5) referece page for more information.
-OPT:*option*,...	Specify miscellaneous details of optimization. See the OPT(5) reference page for more information.
-SWP:*option*,...	Specify details of pipelining done by back-end optimizer.
-pfa	Request execution of the parallel source-to-source optimizer. The details of the optional product are in the pfa(1) reference page.
-WK,*option*,...	Pass options to parallel source-to-source optimizer of MIPSpro Power Fortran 77.

When you use *-O* to specify the optimization level, the compiler assumes default options for the accelerator phases. These defaults are listed in Table 1-8. To see all options that are passed to a compiler phase, use the *-show* option.

Table 1-8 Power Fortran Defaults for Optimization Levels

Optimization Level	Power Fortran Defaults Passed
-O0	–WK,–roundoff=0,–scalaropt=0,–optimize=0
-O1	–WK,–roundoff=0,–scalaropt=0,–optimize=0
-O2	–WK,–roundoff=0,–scalaropt=0,–optimize=0
-O3	–WK,–roundoff=2,–scalaropt=3,–optimize=5

In addition to optimizing options, the compiler system provides other options that can improve the performance of your programs:

- Two linker options**, –G** and **–bestG**, control the size of the global data area, which can produce significant performance improvements. See Chapter 2 of the *MIPSpro Compiling and Performance Tuning Guide* and the ld(1) reference page for more information.
- The **–jmpopt** option permits the linker to fill certain instruction delay slots not filled by the compiler front end. This option can improve the performance of smaller programs not requiring extremely large blocks of virtual memory. See the ld(1) reference page for more information.

Enabling Multiprocessing

The *f77* compiler recognizes several options related to multiprocessing. However, the associated programs and files are not present unless you install Power Fortran 77.

Table 1-9 lists the options. For more information about multiprocessing, see Chapter 5, "OpenMP Multiprocessing Directives," and Chapter 6, "Parallel Programming on Origin2000."

Table 1-9 Multiprocessing Options

Option	Description
-MP:*options*	Multiprocessing options group to enable or disable multiprocessing features. All of the features are enabled by default under **-mp**. The individual controls in this group are: **dsm=**(ON | OFF). Enable or disable data distribution. ON by default. **clone=**(ON | OFF). The compiler automatically clones procedures that are called with reshaped arrays as parameters for the incoming distribution. However, if you explicitly specify the distribution on all relevant formal parameters, then you can disable auto-cloning with **-MP:clone=off**. The consistency checking of the distribution between actual and formal parameters is not affected by this flag, and is always enabled. Enable or disable auto-cloning. ON by default. **check_reshape=**(ON | OFF). Enable or disable e generation of the runtime consistency checks across procedure boundaries when passing reshaped arrays (or portions thereof) as parameters. OFF by default.
-mp	Enable the multiprocessing and DSM directives. Use this option with either the **-mp** or the **-pfa** option. The saved file name has the form: $TMPDIR/P<user_subroutine_name><machine_name><pid>. If the TMPDIR environment variable is not set, then the file is in */tmp*.
-mp_keep	Keep the compiler generated temporary file and generate correct line numbers for debugging multiprocessed DO loops.
-pfa	Run the *pfa*(1) preprocessor to automatically discover parallelism in the source code. This also enables the multiprocessing directives. This is an optional software product.

Note: Under **-mp** compilation, the compiler silently generates some bookkeeping information under the *rii_files* directory. This information is used to implement data distribution directives, as well as perform consistency checks of these directives across multiple source files. To disable the processing of the data distribution directives and not generate the *rii_files*, compile your program with the **-MP:dsm=off** option.

Specifying Recursion

You can enable recursion support by using **-LANG:recursive** [= (**ON** | **OFF**)]

In either mode, the compiler supports a recursive stack-based calling sequence. The difference is in the optimization of statically allocated local variables. Table 1-10 defines this option.

Table 1-10 Recursive Option

Recursive Option	Purpose
-LANG:recursive=on	A statically allocated local variable can be referenced or modified by a recursive procedure call. The statically allocated local variable must be stored in memory before making a call and reloaded afterward.
-LANG:recursive=off	The default. The compiler can safely assume a statically allocated local variable will not be referenced or modified by a procedure call and can optimize more aggressively.

Controlling Compiler Execution

The options summarized in Table 1-11 control the execution of the compiler phases.

Table 1-11 Compile Options for Compiler Phase Control

Options	Purpose
-E, **-P**	Execute only the integrated C preprocessor.
-fe	Stop compilation immediately after the front-end (syntax analysis) runs.
-M	Run only the macro preprocessor.
-Y*c,path*	Load the compiler phase specified by *c* from the specified *path*.
-W*c,option,...*	Pass the specified list of options to the compiler phase specified by *c*.

Specifying the Buffer Size for Direct Unformatted I/O

You can use the environment variable, FORTRAN_BUFFER_SIZE, to change the buffer size for direct unformatted I/O. Once it is set to 128K (4-byte) words or greater, the I/O on direct unformatted file does not go though the system buffer. No upper limit exists on the number to which you can set FORTRAN_BUFFER_SIZE. However, when it exceeds the system maximum I/O limit, then the Fortran I/O library automatically resets it to the system limit.

You can find additional information about environment variables on the pe_environ(5) reference page.

Object File Tools

The following tools provide information on object files as indicated:

elfdump	Lists headers, tables, and other selected parts of an ELF-format object or archive file.
dis	Disassembles object files into machine instructions.
nm	Prints symbol table information for object and archive files.
file	Lists the properties of program source, text, object, and other files. This tool often erroneously recognizes command files as C programs. It does not recognize Pascal or LISP programs.
size	Prints information about the text, rdata, data, sdata, bss, and sbss sections of the specified object or archive files. See the a.out(4) reference page for a description of the contents and format of section data.
strip	Removes symbol table and relocation bits.

For more information about these tools, see the *MIPSpro Compiling and Performance Tuning Guide* and the dis(1), elfdump(1), file(1), nm(1), size(1), and strip(1) reference pages.

Archiver

An archive library is a file that contains one or more routines in object (**.o**) file format. The term *object* refers to an **.o** file that is part of an archive library file. When a program calls an object not explicitly included in the program, the link editor, *ld*, looks for that object in an archive library. The link editor then loads only that object (not the whole library) and links it with the calling program.

The archiver (*ar*) creates and maintains archive libraries and has the following main functions:

- copying new objects into the library
- replacing existing objects in the library
- moving objects about the library
- copying individual objects from the library into individual object files

See the *MIPSpro Compiling and Performance Tuning Guide* and the ar(1) reference page for additional information on the archiver.

Run-Time Considerations

This section describes the following run-time considerations:

Invoking a Program

To run a Fortran program, invoke the executable object module produced by the *f77* command by entering the name of the module as a command. By default, the name of the executable module is **a.out**. If you included the **–o** *filename* option on the *ld* (or *f77*) command line, the executable object module has the name that you specified.

Maximum Memory Allocations

The total memory allocation for a program, and individual arrays, can exceed 2 gigabytes (2 GB, or 2,048 MB).

Previous implementations of Fortran 77 limited the total program size, as well as the size of any single array, to 2 GB. The current release allows the total memory in use by the program to exceed this. For details about the memory use of individual scalar values, see "Alignment, Size, and Value Ranges" on page 25.

Arrays Larger Than 2 Gigabytes

The compiler supports arrays that are larger than 2 gigabytes for programs compiled under the –64 ABI. The arrays can be local, global, and dynamically created as the following example demonstrates. (Note: Initializers are not provided for these arrays.) Large array support is limited to FORTRAN 77, C, and C++.

For example:

```
$cat a2.c

#include <stdlib.h>

int i[0x100000008];

void foo()
{
int k[0x100000008];
 k[0x100000007] = 9;
 printf("%d \n", k[0x100000007]);
}
```

```
main()
{
char *j;
j = malloc(0x100000008);
 i[0x100000007] = 7;
 j[0x100000007] = 8;
 printf("%d \n", i[0x100000007]);
 printf("%d \n", j[0x100000007]);
 foo();
}
```

You must run this program on a 64-bit operating system with IRIX version 6.2 (or higher). You can verify the system type by using the **`uname -a`** command. You must have enough swap space to support the working set size and you must have your shell limit datasize, stacksize, and vmemoryuse variables set to values large enough to support the sizes of the arrays (see the sh(1) reference page).

The following example compiles and runs the above code after setting the stacksize to a correct value:

```
$uname -a
IRIX64 cydrome 6.2 03131016 IP19
$cc -64 -mips3 a2.c
$limit
cputime         unlimited
filesize        unlimited
datasize        unlimited
stacksize       65536 kbytesn
coredumpsize    unlimited
memoryuse
descriptors     200
vmemoryuse      unlimited
$limit stacksize unlimited
$limit
cputime         unlimited
filesize        unlimited
datasize        unlimited
stacksize       unlimited
coredumpsize    unlimited
memoryuse       754544 kbytes
descriptors     200
vmemoryuse      unlimited
$a.out
7
8
9
```

Local Variable (Stack Frame) Sizes

Arrays that are allocated on the process stack must not exceed 2 GB, but the total of all stack variables can exceed that limit. For example,

```
parameter (ndim = 16380)
integer*8 xmat(ndim,ndim), ymat(ndim,ndim), &
    zmat(ndim,ndim)
integer k(1073741824)
integer l(33554432, 256)
```

However, when an array is passed as an argument, it is not limited in size.

```
subroutine abc(k)
integer k(8589934592_8)
```

Static and Common Sizes

When compiling with the **-static** flag, global data is allocated as part of the compiled object (*.o*) file. The total size of any *.o* file may not exceed 2 GB. However, the total size of a program linked from multiple *.o* files may exceed 2 GB.

An individual common block may not exceed 2 GB. However, you can declare multiple common blocks, each having that size.

Pointer-based Memory

There is no limit on the size of a pointer-based array. For example,

```
integer *8 ndim
parameter (ndim = 20001)
pointer (xptr, xmat), (yptr, ymat), (zptr, zmat), &
    (aptr, amat)
xptr = malloc(ndim*ndim*8)
yptr = malloc(ndim*ndim*8)
zptr = malloc(ndim*ndim*8)
aptr = malloc(ndim*ndim*8)
```

It is important to make sure that malloc is called with an INTEGER*8 value. A count greater than 2 GB would be truncated if assigned to an INTEGER*4.

File Formats

Fortran supports five kinds of external files:

- sequential formatted
- sequential unformatted
- direct formatted
- direct unformatted
- key indexed file

The operating system implements other files as ordinary files and makes no assumptions about their internal structure.

Fortran I/O is based on records. When a program opens a direct file or key indexed file, the length of the records must be given. The Fortran I/O system uses the length to make the file appear to be made up of records of the given length. When the record length of a direct unformatted file is 1 byte, the system treats the file as ordinary system files (as byte strings, in which each byte is addressable). A **READ** or **WRITE** request on such files consumes bytes until satisfied, rather than restricting itself to a single record.

Because of special requirements, sequential unformatted files will probably be read or written only by Fortran I/O statements. Each record is preceded and followed by an integer containing the length of the record in bytes.

During a **READ**, Fortran I/O breaks sequential formatted files into records by using each new line indicator as a record separator. The FORTRAN 77 standard does not define the required result after reading past the end of a record; the I/O system treats the record as being extended by blanks. On output, the I/O system writes a new line indicator at the end of each record. If a user program also writes a new line indicator, the I/O system treats it as a separate record.

Preconnected Files

Table 1-12 shows the standard preconnected files at program start.

Table 1-12 Preconnected Files

Unit #	Unit	Alternate Unit #
5	Standard input	* (in READ)
6	Standard output	* (in WRITE)
0	Standard error	** (in WRITE)

All other units are also preconnected when execution begins. Unit *n* is connected to a file named **fort.***n*. These files need not exist, nor will they be created unless their units are used without first executing an open. The default connection is for sequentially formatted I/O.

File Positions

The FORTRAN 77 standard does not specify where **OPEN** should initially position a file explicitly opened for sequential I/O. The I/O system positions the file to start of file for both input and output. The execution of an **OPEN** statement followed by a **WRITE** on an existing file causes the file to be overwritten, erasing any data in the file. In a program called from a parent process, units 0, 5, and 6 remain where they were positioned by the parent process.

Unknown File Status

When the parameter **STATUS="UNKNOWN"** is specified in an **OPEN** statement, the following occurs:

- If the file does not exist, it is created and positioned at start of file.
- If the file exists, it is opened and positioned at the beginning of the file.

Quad-Precision Operations

When running programs that contain quad-precision operations, you must run the compiler in round-to-nearest mode. Because this mode is the default, you usually do not have to set it. You usually need to set this mode when writing programs that call your own assembly routines. Refer to the swapRM reference page for details.

Run-Time Error Handling

When the Fortran run-time system detects an error, the following actions takes place:

- A message describing the error is written to the standard error unit (unit 0). See Appendix A, "Run-Time Error Messages," for a list of the error messages.
- A core file is produced if the **f77_dump_flag** environment variable is set, as described in Appendix A, "Run-Time Error Messages." You can use *dbx* to inspect this file and determine the state of the program at termination. For more information, see the *dbx User's Guide*.

  To invoke *dbx* using the core file, enter the following:

  ```
  % dbx binary-file core
  ```

  where *binary-file* is the name of the object file output (the default is **a.out**). For more information about *dbx*, see the *dbx User's Guide*.

Floating Point Exceptions

The *libfpe* library provides two methods for handling floating point exceptions.

The library provides the subroutine **handle_sigfpes** and the environment variable TRAP_FPE. Both methods provide mechanisms for handling and classifying floating point exceptions, and for substituting new values. They also provide mechanisms to count, trace, exit, or abort on enabled exceptions. The **–TENV:check_div** compile option inserts checks for divide by zero or overflow. See the handle_sigfpes(3F) reference page for more information.

Chapter 2

Storage Mapping

This chapter contains two sections:

- "Alignment, Size, and Value Ranges" describes how the Fortran compiler implements size and value ranges for various data types as well as how data alignment occurs under normal conditions.
- "Access of Misaligned Data" describes two methods of accessing misaligned data.

Alignment, Size, and Value Ranges

Table 2-1 contains information about various Fortran scalar data types. For details on the maximum sizes of arrays, see "Maximum Memory Allocations" on page 18.

Table 2-1 Size, Alignment, and Value Ranges of Data Types

Type	Synonym	Size	Alignment	Value Range
BYTE	INTEGER*1	8 bits	Byte	–128…127
INTEGER*2		16 bits	Half word[a]	–32,768…32,767
INTEGER	INTEGER*4[b]	32 bits	Word[c]	$-2^{31}\ldots2^{31}-1$
INTEGER*8		64 bits	Double word	$-2^{63}\ldots2^{63}-1$
LOGICAL*1		8 bits	Byte	0…1
LOGICAL*2		16 bits	Half word[a]	0…1
LOGICAL	LOGICAL*4[d]	32 bits	Word[c]	0…1
LOGICAL*8		64 bits	Double word	0...1
REAL	REAL*4[e]	32 bits	Word[c]	See Table 2-2
DOUBLE PRECISION	REAL*8[f]	64 bits	Double word[g]	See Table 2-2

Table 2-1 (continued) Size, Alignment, and Value Ranges of Data Types

Type	Synonym	Size	Alignment	Value Range
REAL*16		128 bits	Double word	See Table 2-3
COMPLEX	COMPLEX*8[h]	64 bits	Double word[c]	See the fourth bullet item below
DOUBLE COMPLEX	COMPLEX*16[i]	128 bits	Double word[g]	See the fourth bullet item below
COMPLEX*32		256 bits	Double word	See the fourth bullet item below
CHARACTER		8 bits	Byte	–128…127

a. Byte boundary divisible by two.

b. When the –i2 option is used, type INTEGER is equivalent to INTEGER*2; when the –i8 option is used, INTEGER is equivalent to INTEGER*8.

c. Byte boundary divisible by four.

d. When the –i2 option is used, type LOGICAL is equivalent to LOGICAL*2; when the –i8 option is used, type LOGICAL is equivalent to LOGICAL*8.

e. When the –r8 option is used, type REAL is equivalent to REAL*8.

f. When the –d16 option is used, type DOUBLE PRECISION is equivalent to REAL*16.

g. Byte boundary divisible by eight.

h. When the –r8 option is used, type COMPLEX is equivalent to COMPLEX*16.

i. When the –d16 option is used, type DOUBLE COMPLEX is equivalent to COMPLEX*32.

The following notes provide details on some of the items in Table 2-1.

- Table 2-2 lists the approximate valid ranges for REAL*4 and REAL*8.

Table 2-2 Valid Ranges for REAL*4 and REAL*8 Data Types

Range	REAL*4	REAL*8
Maximum	$3.40282356 * 10^{38}$	$1.7976931348623158 * 10^{308}$
Minimum normalized	$1.17549424 * 10^{-38}$	$2.2250738585072012 * 10^{-308}$
Minimum denormalized	$1.40129846 * 10^{-46}$	$1.1125369292536006 * 10^{-308}$

- REAL*16 constants have the same form as DOUBLE PRECISION constants, except the exponent indicator is **Q** instead of **D**. Table 2-3 lists the approximate valid range

for REAL*16. REAL*16 values have an 11-bit exponent and a 107-bit mantissa; they are represented internally as the sum or difference of two doubles. Therefore, for REAL*16, "normal" means that both high and low parts are normals.

Table 2-3 Valid Ranges for REAL*16 Data Type

Range	Precise Exception Mode w/FS Bit Clear	Fast Mode or Precise Exception Mode w/FS Bit Set
Maximum	$1.7976931348623158079372897140530 23 * 10^{308}$	$1.7976931348623158079372897140530 23 * 10^{308}$
Minimum normalized	$2.0041683600089730005034939020703004 * 10^{-292}$	$2.0041683600089730005034939020703004 * 10^{-292}$
Minimum denormalized	$4.9406564584124654417656879286822 14 * 10^{-324}$	$2.2250738585072013830902327173324 04 * 10^{-308}$

- Table 2-1 indicates that REAL*8 (that is, DOUBLE PRECISION) variables always align on a double-word boundary. However, Fortran permits these variables to align on a word boundary if a **COMMON** statement or equivalencing requires it.
- Forcing INTEGER, LOGICAL, REAL, and COMPLEX variables to align on a halfword boundary is not allowed, except as permitted by the **–align8**, **–align16**, and **–align32** command line options. See Chapter 1, "Compiling, Linking, and Running Programs."
- A COMPLEX data item is an ordered pair of REAL*4 numbers; a DOUBLE COMPLEX data item is an ordered pair of REAL*8 numbers; a COMPLEX*32 data item is an ordered pair of REAL*16 numbers. In each case, the first number represents the real part and the second represents the imaginary part. Therefore, refer to Table 2-2 and Table 2-3 for valid ranges.
- LOGICAL data items denote only the logical values TRUE and FALSE (written as **.TRUE.** or **.FALSE.**). However, to provide VMS compatibility, LOGICAL variables can be assigned all integral values of the same size.
- You must explicitly declare an array in a **DIMENSION** declaration or in a data type declaration. To support **DIMENSION**, the compiler:
  - allows up to seven dimensions
  - assigns a default of 1 to the lower bound if a lower bound is not explicitly declared in the **DIMENSION** statement
  - creates an array the size of its element type times the number of elements
  - stores arrays in column-major mode

- The following rules apply to shared blocks of data set up by **COMMON** statements:
  - The compiler assigns data items in the same sequence as they appear in the common statements defining the block. Data items are padded according to the alignment compiler options or the compiler defaults. See "Access of Misaligned Data" on page 28 for more information.
  - You can allocate both character and noncharacter data in the same common block.
  - When a common block appears in multiple program units, the compiler allocates the same size for that block in each unit, even though the size required may differ (due to varying element names, types, and ordering sequences) from unit to unit. The allocated size corresponds to the maximum size required by the block among all the program units except when a common block is defined by using **DATA** statements, which initialize one or more of the common block variables. In this case the common block is allocated the same size as when it is defined.

Access of Misaligned Data

The Fortran compiler allows misalignment of data if specified by special options.

The architecture of the IRIS 4D series assumes a particular alignment of data. ANSI standard FORTRAN 77 cannot violate the rules governing this alignment. Opportunities for misalignment can arise when using common extensions. This is particularly true for small integer types, which have the following characteristics:

- allow intermixing of character and non-character data in **COMMON** and **EQUIVALENCE** statements
- allow mismatching the types of formal and actual parameters across a subroutine interface
- provide many opportunities for misalignment to occur

Code that use extensions that compile and execute correctly on other systems with less stringent alignment requirements may fail during compilation or execution on the IRIS 4D. This section describes a set of options to the Fortran compilation system that allow the compilation and execution of programs whose data may be misaligned. Note that the execution of programs that use these options is significantly slower than the execution of a program with aligned data.

This section describes the two methods that can be used to create an executable object file that accesses misaligned data.

Accessing Small Amounts of Misaligned Data

Use this method if the number of instances of misaligned data access is small or to provide information on the occurrence of such accesses so that misalignment problems can be corrected at the source level.

This method catches and corrects bus errors due to misaligned accesses. This ties the extent of program degradation to the frequency of these accesses. This method also includes capabilities for producing a report of these accesses to enable their correction.

To use this method, keep the Fortran front end from padding data to force alignment by compiling your program with one of following two options to *f77*:

- Use **–align8** if you do not anticipate that your program will have restrictions on alignment.
- Use **–align16** if your program must be run on a machine that requires half-word alignment.

You must also use the misalignment trap handler. This requires minor source code changes to initialize the handler and the addition of the handler binary to the link step (see the fixade(3f) reference page).

Accessing Misaligned Data Without Modifying Source

Use this second method for programs with widespread misalignment or whose source may not be modified.

In this method, a set of special instructions is substituted by the IRIS 4D assembler for data accesses whose alignment cannot be guaranteed. You can choose to have each source file independently substituted.

You can invoke this method by specifying one of the **-align** alignment options (**–align8**, **–align16**) to *f77* when compiling any source file that references misaligned data (see the f77(1) reference page for details). If your program passes misaligned data to system libraries, you may also have to link it with the trap handler. See the fixade(3f) reference page for more information.

Chapter 3

Fortran Program Interfaces

Sometimes it is necessary to create a program that combines modules written in Fortran and another language. For example,

- In a Fortran program, you need access to a facility that is only available as a C function, such as a member of a graphics library.
- In a program in another language, you need access to a computation that has been implemented as a Fortran subprogram, for example one of the many well-tested, efficient routines in the BLAS library.

Tip: Fortran subroutines and functions that give access to the IRIX system functions and other IRIX facilities already exist, and are documented in Chapter 4 of this manual.

This chapter focuses on the interface between Fortran and the most common other language, C. However other language can be called, for example C++.

Note: You should be aware that all compilers for a given version of IRIX use identical standard conventions for passing parameters in generated code. These conventions are documented at the machine instruction level in the *MIPSpro Assembly Language Programmer's Guide*, which also details the differences in the conventions used in different releases.

How Fortran Treats Subprogram Names

The Fortran compiler normally changes the names of subprograms and named common blocks while it translates the source file. When these names appear in the object file for reference by other modules, they are normally changed in two ways:

- Converted to all lowercase letters
- Extended with a final underscore (_) character

The following declarations usually produce the **matrix_**, **mixedcase_,** and **cblk_** identifiers (all in lowercase with appended underscores) in the generated object file:

```
SUBROUTINE MATRIX
function MixedCase()
COMMON /CBLK/a,b,c
```

Note: Fortran intrinsic functions are not named according to these rules. The external names of intrinsic functions as defined in the Fortran library are not directly related to the intrinsic function names as they are written in a program. The use of intrinsic function names is discussed in the *MIPSpro Fortran 77 Language Reference Manual*.

Working with Mixed-Case Names

You cannot make the Fortran compiler generate an external name containing uppercase letters. If you are porting a program that depends on the ability to call such a name, you must write a C function that takes the same arguments but which has a name composed of lowercase letters only. This C function can then call the function whose name contains mixed-case letters.

Note: Previous versions of the Fortran 77 compiler for 32-bit systems supported the **-U** compiler option, telling the compiler to not force all uppercase input to lowercase. As a result, uppercase letters could be preserved in external names in the object file. As now implemented, this option does not affect the case of external names in the object file.

Preventing a Suffix Underscore with $

You can prevent the compiler from appending an underscore to a name by writing the name with a terminal currency symbol ($). The '$' is not reproduced in the object file. It is dropped, but it prevents the compiler from appending an underscore. The following declaration produces the name **nounder** (lowercase, but with no trailing underscore) in the object file:

```
EXTERNAL NOUNDER$
```

Note: This meaning of '$' in names applies only to subprogram names. If you end the name of a COMMON block with '$,' the name in the object file includes the '$' and ends with an underscore.

Naming Fortran Subprograms from C

In order to call a Fortran subprogram from a C module you must spell the name the way the Fortran compiler spells it—normally, using all lowercase letters and a trailing underscore. A Fortran subprogram declared as follows:

```
SUBROUTINE HYPOT()
```

would typically be declared in this C function (lowercase with trailing underscore):

```
extern int hypot_()
```

You must know if a subprogram is declared with a trailing '$' to suppress the underscore.

Naming C Functions from Fortran

The C compiler does not modify the names of C functions. C functions can have uppercase or mixed-case names, and they have terminal underscores only when written to have terminal underscores.

In order to call a C function from a Fortran program you must ensure that the Fortran compiler spells the name correctly. When you control the name of the C function, the simplest solution is to give it a name that consists of lowercase letters with a terminal underscore. For example, the following C function:

```
int fromfort_() {...}
```

could be declared in a Fortran program as follows:

```
EXTERNAL FROMFORT
```

When you do not control the name of a C function, you must direct the Fortran compiler to generate the correct name in the object file. Write the C function name using a terminal '$' character to suppress the terminal underscore. (You cannot cause the compiler to generate an external name with uppercase letters in it.)

Testing Name Spelling Using *nm*

You can verify the spelling of names in an object file using the *nm* command (or with the *elfdump* command with the **-t** or **-Dt** options). To see the subroutine and common names generated by the compiler, use *nm* with the generated *.o* (object) or executable file.

Correspondence of Fortran and C Data Types

When you exchange data values between Fortran and C, either as parameters, as function results, or as elements of common blocks, you must make sure that the two languages agree on the size, alignment, and subscript of each data value.

Corresponding Scalar Types

The correspondence between Fortran and C scalar data types is shown in Table 3-1. This table assumes the default precisions. Using compiler options such as **-i2** or **-r8** affects the meaning of the words LOGICAL, INTEGER, and REAL.

Table 3-1 Corresponding Fortran and C Data Types

Fortran Data Type	Corresponding C type
BYTE, INTEGER*1, LOGICAL*1	signed char
CHARACTER*1	unsigned char
INTEGER*2, LOGICAL*2	short
INTEGER[a], INTEGER*4, LOGICAL[a], LOGICAL*4	int or long
INTEGER*8, LOGICAL*8	long long
REAL[a], REAL*4	float
DOUBLE PRECISION, REAL*8	double
REAL*16	long double
COMPLEX[a], COMPLEX*8	typedef struct{float real, imag; } cpx8;
DOUBLE COMPLEX, COMPLEX*16	typedef struct{ double real, imag; } cpx16;
COMPLEX*32	typedef struct{long double real, imag;} cpx32;
CHARACTER*n (n>1)	typedef char fstr_n[n];

a. Assuming default precision

The rules governing alignment of variables within common blocks are discussed in "Alignment, Size, and Value Ranges" on page 25.

Corresponding Character Types

The Fortran CHARACTER*1 data type corresponds to the C type unsigned char. However, the two languages differ in the treatment of strings of characters.

A Fortran CHARACTER*n (n>1) variable contains exactly n characters at all times. When a shorter character expression is assigned to it, it is padded on the right with spaces to reach n characters.

A C vector of characters is normally sized 1 greater than the longest string assigned to it. It may contain fewer meaningful characters than its size allows, and the end of meaningful data is marked by a null byte. There is no null byte at the end of a Fortran string. You can create a null byte using the Hollerith constant '\0' but it is not usually done.

Because there is no terminal null byte, most of the string library functions familiar to C programmers (**strcpy()**, **strcat()**, **strcmp()**, and so on) cannot be used with Fortran string values. The **strncpy()**, **strncmp()**, **bcopy()**, and **bcmp()** functions can be used because they depend on a count rather than a delimiter.

Corresponding Array Elements

Fortran and C use different arrangements for the elements of an array in memory. Fortran uses column-major order (when iterating sequentially through memory, the leftmost subscript varies fastest), whereas C uses row-major order (the rightmost subscript varies fastest to generate sequential storage locations). In addition, Fortran array indices are normally origin-1, while C indices are origin-0.

To use a Fortran array in C, you must:

- Reverse the order of dimension limits when declaring the array.
- Reverse the sequence of subscript variables in a subscript expression.
- Adjust the subscripts to origin-0 (usually, decrement by 1).

The correspondence between Fortran and C subscript values is depicted in Figure 3-1. You can derive the C subscripts for a given element by decrementing the Fortran subscripts and using them in reverse order; for example, Fortran (99,9) corresponds to C [8][98].

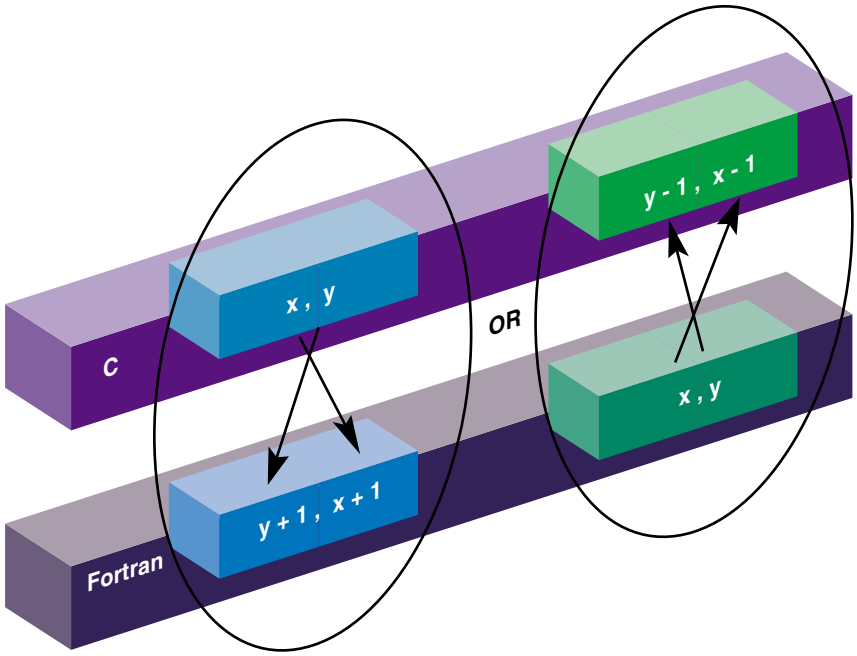


Figure 3-1 Correspondence Between Fortran and C Array Subscripts

For a coding example, see "Using Fortran Arrays in C Code" on page 45.

Note: A Fortran array can be declared with some other lower bound than the default of 1. If the Fortran subscript is origin-0, no adjustment is needed. If the Fortran lower bound is greater than 1, the C subscript is adjusted by that amount.

How Fortran Passes Subprogram Parameters

The Fortran compiler generates code to pass parameters according to simple, uniform rules and it generates subprogram code that expects parameters to be passed according to these rules. When calling non-Fortran functions, you must know how parameters will be passed; and when calling Fortran subprograms from other languages you must cause the other language to pass parameters correctly.

Normal Treatment of Parameters

Every parameter passed to a subprogram, regardless of its data type, is passed as the address of the actual parameter value in memory. This rule is extended for two cases:

- The length of each CHARACTER*n parameter (when n>1) is passed as an additional, INTEGER value, following the explicit parameters.
- When a function returns type CHARACTER*n parameter (n>1), the address of the space to receive the result is passed as the first parameter to the function and the length of the result space is passed as the second parameter, preceding all explicit parameters.

Example 3-1 Example Subroutine Call

```
COMPLEX*8 cp8
CHARACTER*16 creal, cimag
CALL CPXASC(creal,cimag,cp8)
```

Code generated from the **CALL** in Example 3-1 prepares these 5 argument values:

1. The address of *creal*
2. The address of *cimag*
3. The address of *cp8*
4. The length of *creal*, an integer value of 16
5. The length of *cimag*, an integer value of 16

Example 3-2 Example Function Call

```
CHARACTER*8 symbl,picksym
CHARACTER*100 sentence
INTEGER nsym
symbl = picksym(sentence,nsym)
```

Code generated from the function call in Example 3-2 prepares these 5 argument values:

1. The address of variable *symbl*, the function result space
2. The length of *symbl*, an integer value of 8
3. The address of *sentence*, the first explicit parameter
4. The address of *nsym*, the second explicit parameter
5. The length of *sentence*, an integer value of 100

You can force changes in these conventions using %VAL and %LOC; this is discussed in "Calls to C Using LOC%, REF% and VAL%" on page 46.

Calling Fortran from C

There are two types of callable Fortran subprograms: subroutines and functions (these units are documented in the *MIPSpro Fortran 77 Language Reference Manual*). In C terminology, both types of subprogram are external functions. The difference is the use of the function return value from each.

Calling Fortran Subroutines from C

From the standpoint of a C module, a Fortran subroutine is an external function returning int. The integer return value is normally ignored by a C caller (its meaning is discussed in "Alternate Subroutine Returns" on page 40).

The following two examples show a simple Fortran subroutine and a sketch of a call to it.

Example 3-3 Example Fortran Subroutine with COMPLEX Parameters

```
SUBROUTINE ADDC32(Z,A,B,N)
COMPLEX*32 Z(1),A(1),B(1)
INTEGER N,I
DO 10 I = 1,N
    Z(I) = A(I) + B(I)
10 CONTINUE
RETURN
END
```

Example 3-4 C Declaration and Call with COMPLEX Parameters

```
typedef struct{long double real, imag;} cpx32;
extern int
  addc32_(cpx32*pz,cpx32*pa,cpx32*pb,int*pn);
cpx32 z[MAXARRAY], a[MAXARRAY], b[MAXARRAY];
...
    int n = MAXARRAY;
    (void)addc32_(&z, &a, &b, &n);
```

The Fortran subroutine in Example 3-3 is named in Example 3-4 using lowercase letters and a terminal underscore. It is declared as returning an integer. For clarity, the actual call is cast to (void) to show that the return value is intentionally ignored.

The trivial subroutine in the following example takes adjustable-length character parameters.

Example 3-5 Example Fortran Subroutine with String Parameters

```
SUBROUTINE PRT(BEF,VAL,AFT)
CHARACTER*(*)BEF,AFT
REAL VAL
PRINT *,BEF,VAL,AFT
RETURN
END
```

Example 3-6 C Program that Passes String Parameters

```
typedef char fstr_16[16];
extern int
   prt_(fstr_16*pbef, float*pval, fstr_16*paft,
                int lbef, int laft);
main()
{
    float val = 2.1828e0;
    fstr_16 bef,aft;
    strncpy(bef,"Before..........",sizeof(bef));
    strncpy(aft,"...........After",sizeof(aft));
    (void)prt_(bef,&val,aft,sizeof(bef),sizeof(aft));
}
```

The C program in Example 3-6 prepares CHARACTER*16 values and passes them to the subroutine in Example 3-5. Note that the subroutine call requires 5 parameters, including the lengths of the two string parameters. In Example 3-6, the string length parameters are generated using **sizeof()**, derived from the typedef *fstr_16*.

Example 3-7 C Program that Passes Different String Lengths

```
extern int
prt_(char*pbef, float*pval, char*paft, int lbef, int laft);
main()
{
    float val = 2.1828e0;
    char *bef = "Start:";
    char *aft = ":End";
    (void)prt_(bef,&val,aft,strlen(bef),strlen(aft));
}
```

When the Fortran code does not require a specific length of string, the C code that calls it can pass an ordinary C character vector, as shown in Example 3-7. In Example 3-7, the string length parameter length values are calculated dynamically using **strlen()**.

Alternate Subroutine Returns

In Fortran, a subroutine can be defined with one or more asterisks (*) in the position of dummy parameters. When such a subroutine is called, the places of these parameters in the **CALL** statement are supposed to be filled with statement numbers or statement labels. The subroutine returns an integer which selects among the statement numbers, so that the subroutine call acts as both a call and a computed **GOTO** (for more details, see the discussions of the **CALL** and **RETURN** statements in the *MIPSpro Fortran 77 Language Reference Manual*).

Fortran does not generate code to pass statement numbers or labels to a subroutine. No actual parameters are passed to correspond to dummy parameters given as asterisks. When you code a C prototype for such a subroutine, ignore these parameter positions. A **CALL** statement such as the following:

```
CALL NRET (*1,*2,*3)
```

is treated exactly as if it were the computed GOTO written as

```
GOTO (1,2,3), NRET()
```

The value returned by a Fortran subroutine is the value specified on the **RETURN** statement, and will vary between 0 and the number of asterisk dummy parameters in the subroutine definition.

Calling Fortran Functions from C

A Fortran function returns a scalar value as its explicit result. This corresponds to the C concept of a function with an explicit return value. When the Fortran function returns any type shown in Table 3-1 other than CHARACTER*n (n>1), you can call the function from C and handle its return value exactly as if it were a C function returning that data type.

Example 3-8 Fortran Function Returning COMPLEX*16

```
COMPLEX*16 FUNCTION FSUB16(INP)
COMPLEX*16 INP
FSUB16 = INP
END
```

The function shown in Example 3-8 accepts and returns COMPLEX*16 values. Although a COMPLEX value is declared as a structure in C, it can be used as the return type of a function.

Example 3-9 C Program that Receives COMPLEX Return Value

```
typedef  struct{ double real, imag; } cpx16;
extern cpx16 fsub16_( cpx16 * inp );
main()
{
    cpx16 inp = { -3.333, -5.555 };
    cpx16 oup = { 0.0, 0.0 };
    printf("testing fsub16...");
    oup = fsub16_( &inp );
    if ( inp.real == oup.real && inp.imag == oup.imag )
        printf("Ok\n");
    else
        printf("Nope\n");
}
```

The C program in Example 3-9 shows how the function in Example 3-8 is declared and called. Note that the parameters to a function, like the parameters to a subroutine, are passed as pointers, but the value returned is a value, not a pointer to a value.

Note: In IRIX 5.3 and earlier, you *cannot* call a Fortran function that returns COMPLEX (although you can call one that returns any other arithmetic type). The register conventions used by compilers prior to IRIX 6.0 do not permit returning a structure value from a Fortran function to a C caller.

Example 3-10 Fortran Function Returning CHARACTER*16

```
CHARACTER*16 FUNCTION FS16(J,K,S)
CHARACTER*16 S
INTEGER J,K
FS16 = S(J:K)
RETURN
END
```

The function in Example 3-10 has a CHARACTER*16 return value. When the Fortran function returns a CHARACTER*n (n>1) value, the returned value is not the explicit result of the function. Instead, you must pass the address and length of the result area as the first two parameters of the function.

Example 3-11 C Program that Receives CHARACTER*16 Return

```
typedef char fstr_16[16];
extern void
fs16_ (fstr_16 *pz,int lz,int *pj,int *pk,fstr_16*ps,int ls);
main()
{
    char work[64];
    fstr_16 inp,oup;
    int j=7;
    int k=11;
    strncpy(inp,"0123456789abcdef",sizeof(inp));
    fs16_ ( oup, sizeof(oup), &j, &k, inp, sizeof(inp) );
    strncpy(work,oup,sizeof(oup));
    work[sizeof(oup)] = '\0';
    printf("FS16 returns <%s>\n",work);
}
```

The C program in Example 3-11 calls the function in Example 3-10. The address and length of the function result are the first two parameters of the function. (Because type *fstr_16* is an array, its name, *oup*, evaluates to the address of its first element.) The next three parameters are the addresses of the three named parameters; and the final parameter is the length of the string parameter.

Calling C from Fortran

In general, you can call units of C code from Fortran as if they were written in Fortran, provided the C modules follow the Fortran conventions for passing parameters (see "How Fortran Passes Subprogram Parameters" on page 36). When the C program expects parameters passed using other conventions, you can either write special forms of **CALL**, or you can build a "wrapper" for the C functions using the *mkf2c* command.

Normal Calls to C Functions

The C function in this section is written to use the Fortran conventions for its name (lowercase with final underscore) and for parameter passing.

Example 3-12 C Function Written to be Called from Fortran

```
/*
|| C functions to export the facilities of strtoll()
|| to Fortran 77 programs.  Effective Fortran declaration:
||
|| INTEGER*8 FUNCTION ISCAN(S,J)
|| CHARACTER*(*) S
|| INTEGER J
||
|| String S(J:) is scanned for the next signed long value
|| as specified by strtoll(3c) for a "base" argument of 0
|| (meaning that octal and hex literals are accepted).
||
|| The converted long long is the function value, and J is
|| updated to the nonspace character following the last
|| converted character, or to 1+LEN(S).
||
|| Note: if this routine is called when S(J:J) is neither
|| whitespace nor the initial of a valid numeric literal,
|| it returns 0 and does not advance J.
*/
#include <ctype.h> /* for isspace() */
long long iscan_(char *ps, int *pj, int ls)
{
   int  scanPos, scanLen;
   long long ret = 0;
   char wrk[1024];
   char *endpt;
   /* when J>LEN(S), do nothing, return 0 */
```

```
   if (ls >= *pj)
   {
      /* convert J to origin-0, permit J=0 */
      scanPos = (0 < *pj)? *pj-1 : 0 ;

      /* calculate effective length of S(J:) */
      scanLen = ls - scanPos;

      /* copy S(J:) and append a null for strtoll() */
      strncpy(wrk,(ps+scanPos),scanLen);
      wrk[scanLen] = '\0';

      /* scan for the integer */
      ret = strtoll(wrk, &endpt, 0);

      /*
      || Advance over any whitespace following the number.
      || Trailing spaces are common at the end of Fortran
      || fixed-length char vars.
      */
      while(isspace(*endpt)) { ++endpt; }
      *pj = (endpt - wrk)+scanPos+1;
   }
   return ret;
}
```

The following program demonstrates a call to the function in Example 3-12.

```
EXTERNAL ISCAN
INTEGER*8 ISCAN
INTEGER*8 RET
INTEGER J,K
CHARACTER*50 INP
INP = '1  -99   3141592  0xfff  033 '
J = 0
DO 10 WHILE (J .LT. LEN(INP))
    K = J
    RET = ISCAN(INP,J)
    PRINT *, K,': ',RET,' -->',J
10  CONTINUE
END
```

Using Fortran COMMON in C Code

A C function can refer to the contents of a COMMON block defined in a Fortran program. The name of the block as given in the **COMMON** statement is altered as described in "How Fortran Treats Subprogram Names" on page 31 (that is, forced to lowercase and extended with an underscore). The name of the "blank common" is _BLNK_ _ (one leading, two final, underscores).

Follow these steps to refer to the contents of a COMMON block:

- Declare a structure whose fields have the appropriate data types to match the successive elements of the Fortran common block. (See Table 3-1 for corresponding data types.)
- Declare the common block name as an external structure of that type.

An example is shown below.

Example 3-13 Common Block Usage in Fortran and C

```
      INTEGER STKTOP,STKLEN,STACK(100)
      COMMON /WITHC/STKTOP,STKLEN,STACK

struct fstack {
    int stktop, stklen;
    int stack[100];
}
extern fstack withc_;
int peektop_()
{
    if (withc_.stktop) /* stack not empty */
        return withc_.stack[withc_.stktop-1];
    else...
}
```

Using Fortran Arrays in C Code

As described under "Corresponding Array Elements" on page 35, a C program must take special steps to access arrays created in Fortran.

Example 3-14 Fortran Program Sharing an Array in Common with C

```
INTEGER IMAT(10,100),R,C
COMMON /WITHC/IMAT
R = 74
C = 6
CALL CSUB(C,R,746)
PRINT *,IMAT(6,74)
END
```

The Fortran fragment in Example 3-14 prepares a matrix in a common block, then calls a C subroutine to modify the array.

Example 3-15 C Subroutine to Modify a Common Array

```
extern struct { int imat[100][10]; } withc_;
int csub_(int *pc, int *pr, int *pval)
{
    withc_.imat[*pr-1][*pc-1] = *pval;
    return 0; /* all Fortran subrtns return int */
}
```

The C function in Example 3-15 stores its third argument in the common array using the subscripts passed in the first two arguments. In the C function, the order of the dimensions of the array are reversed. The subscript values are reversed to match, and decremented by 1 to match the C assumption of 0-origin indexing.

Calls to C Using LOC%, REF% and VAL%

Using the special intrinsic functions %VAL, %REF, and %LOC you can pass parameters in ways other than the standard Fortran conventions described under ‘“How Fortran Passes Subprogram Parameters” on page 36. These intrinsic functions are documented in the *MIPSpro Fortran 77 Language Reference Manual*.

Using %VAL

%VAL is used in parameter lists to cause parameters to be passed by value rather than by reference. Examine the following function prototype (from the random(3b) reference page).

```
char *initstate(unsigned int seed, char *state, int n);
```

This function takes an integer value as its first parameter. Fortran would normally pass the address of an integer value, but %VAL can be used to make it pass the integer itself. Example 3-16 demonstrates a call to function **initstate()** and the other functions of the **random()** group.

Example 3-16 Fortran Function Calls Using %VAL

```
C declare the external functions in random(3b)
C random() returns i*4, the others return char*
      EXTERNAL RANDOM$, INITSTATE$, SETSTATE$
      INTEGER*4 RANDOM$
      INTEGER*8 INITSTATE$,SETSTATE$
C We use "states" of 128 bytes, see random(3b)
C Note: An undocumented assumption of random() is that
C a "state" is dword-aligned!  Hence, use a common.
      CHARACTER*128 STATE1, STATE2
      COMMON /RANSTATES/STATE1,STATE2
C working storage for state pointers
      INTEGER*8 PSTATE0, PSTATE1, PSTATE2
C initialize two states to the same value
      PSTATE0 = INITSTATE$(%VAL(8191),STATE1)
      PSTATE1 = INITSTATE$(%VAL(8191),STATE2)
      PSTATE2 = SETSTATE$(%VAL(PSTATE1))
C pull 8 numbers from state 1, print
      DO 10 I=1,8
         PRINT *,RANDOM$()
10    CONTINUE
C set the other state, pull 8 numbers & print
      PSTATE1 = SETSTATE$(%VAL(PSTATE2))
      DO 20 I=1,8
         PRINT *,RANDOM$()
20    CONTINUE
      END
```

The use of %VAL(8191) or %VAL(PSTATE1) causes that value to be passed, rather than an address of that value.

Using %REF

%REF is used in parameter lists to cause parameters to be passed by reference, that is, to pass the address of a value rather than the value itself.

Parameters passed by reference is the normal behavior of Silicon Graphics Fortran 77 compilers; therefore, no effective difference exists between writing %REF(*parm*) and writing *parm* alone in a parameter list for non-character parameters. Using %REF(*parm*) for character parameters causes the character string length not to be added to the end of the parameter list as in the normal case. Thus, using the %REF(*parm*) guarantees that only the address of the parameter is parsed.

When calling a C function that expects the address of a value rather than the value itself, you can write %REF(*parm*). Examine this C prototype (see the gmatch(3G) reference page).

```
int gmatch (const char *str, const char *pattern);
```

This function **gmatch()** could be declared and called from Fortran.

Example 3-17 Fortran Call to *gmatch()* Using %REF

```
LOGICAL GMATCH$
CHARACTER*8 FNAME,FPATTERN
FNAME = 'foo.f\0'
FPATTERN = '*.f\0'
IF ( GMATCH$(%REF(FNAME),%REF(FPATTERN)) )...
```

The use of %REF() in Example 3-17 illustrates the fact that *gmatch()* expects addresses of character strings.

Using %LOC

%LOC returns the address of its argument. It can be used in any expression (not only within parameter lists), and is often used to set POINTER variables.

Making C Wrappers with *mkf2c*

The program *mkf2c* provides an alternate interface for C routines called by Fortran. See the mkf2c(1) reference page for more details.

The *mkf2c* program reads a file of C function prototype declarations and generates an assembly language module. This module contains one callable entry point for each C function. The entry point, or "wrapper," accepts parameters in the Fortran calling convention, and passes the same values to the C function using the C conventions.

A simple case of using a function as input to *mkf2c* is the following:

```
simplefunc (int a, double df)
{ /* function body ignored */ }
```

For this function, *mkf2c* (with no options) generates a wrapper function named **simplefunc_** (with an underscore appended). The wrapper function expects two parameters, an integer and a REAL*8, passed according to Fortran conventions; that is, by reference. The code of the wrapper loads the values of the parameters into registers using C conventions for passing parameters by value, and calls **simplefunc()**.

Parameter Assumptions by *mkf2c*

Because *mkf2c* processes only the C source, not the Fortran source, it treats the Fortran parameters based on the data types specified in the C function header. These treatments are summarized in Table 3-2.

Note: Through compiler release 6.0.2, *mkf2c* does not recognize the C data types "long long" and "long double" (INTEGER*8 and REAL*16). It treats arguments of this type as "long" and "double" respectively.

Table 3-2 How *mkf2c* treats Function Arguments

Data Type in C Prototype	Treatment by Generated Wrapper Code
unsigned char	Load CHARACTER*1 from memory to register, no sign extension
char	Load CHARACTER*1 from memory to register; sign extension only when *-signed* is specified
unsigned short, unsigned int	Load INTEGER*2 or INTEGER*4 from memory to register, no sign extension
short	Load INTEGER*2 from memory to register with sign extension
int, long	Load INTEGER*4 from memory to register with sign extension
long long	(Not supported through 6.0.2)
float	Load REAL*4 from memory to register, extending to double unless *-f* is specified
double	Load REAL*8 from memory to register
long double	(Not supported through 6.0.2)

Table 3-2 (continued) How *mkf2c* treats Function Arguments

Data Type in C Prototype	Treatment by Generated Wrapper Code
char *name*[], *name*[*n*]	Pass address of CHARACTER**n* and pass length as integer parameter as Fortran does
char *	Copy CHARACTER**n* value into allocated space, append null byte, pass address of copy

Character String Treatment by *mkf2c*

In Table 3-2, notice the different treatments for an argument declared as a character array and one declared as a character address (even though these two declarations are semantically the same in C).

When the C function expects a character address, *mkf2c* generates the code to dynamically allocate memory and to copy the Fortran character value, for its specified length, to the allocated memory. This creates a null-terminated string. In this case,

- The address passed to C points to the allocated memory
- The length of the value is not passed as an implicit argument
- There is a terminating null byte in the value
- Changes in the string are *not* reflected back to Fortran

A character array specified in the C function is processed by *mkf2c* just like a Fortran CHARACTER**n* value. In this case,

- The address prepared by Fortran is passed to the C function
- The length of the value is passed as an implicit argument (see "Normal Treatment of Parameters" on page 37)
- The character array contains no terminating null byte (unless the Fortran programmer supplies one)
- Changes in the array by the C function are visible to Fortran

Because the C function cannot declare the extra string-length parameter (if it declared the parameter, *mkf2c* would process it as an explicit argument) the C programmer has a choice of ways to access the string length. When the Fortran program always passes character values of the same size, the length parameter can simply be ignored. If its value is needed, the **varargs** macro can be used to retrieve it.

For example, if the C function prototype is specified as follows

```
void func1 (char carr1[],int i, char *str, char carr2[]);
```

mkf2c passes a total of six parameters to C. The fifth parameter is the length of the Fortran value corresponding to *carr1*. The sixth is the length of *carr2.* The C function can use the **varargs** macros to retrieve these hidden parameters. *mkf2c* ignores the *varargs* macro *va_alist* appearing at the end of the parameter name list.

When *func1* is changed to use *varargs*, the C source file is as follows.

Example 3-18 C Function Using *varargs*

```
#include "varargs.h"
void
func1 (char carr1[],int i,char *str,char carr2[],va_alist);
{}
```

The C routine would retrieve the lengths of *carr1* and *carr2,* placing them in the local variables *carr1_len* and *carr2_len* using code like the following fragment:

Example 3-19 C Code to Retrieve Hidden Parameters

```
va_list ap;
int carr1_len, carr2_len;
va_start(ap);
carr1_len = va_arg (ap, int)
carr2_len = va_arg (ap, int)
```

Restrictions of *mkf2c*

When it does not recognize the data type specified in the C function, *mkf2c* issues a warning message and generates code to simply pass the pointer passed by Fortran. It does this in the following cases:

- Any nonstandard data type name, for example a data type that might be declared using typedef or a data type defined as a macro
- Any structure argument
- Any argument with multiple indirection (two or more asterisks, for example *char***)

Because *mkf2c* does not support structure-valued arguments, it does not support passing COMPLEX**n* values.

Using *mkf2c* and *extcentry*

mkf2c understands only a limited subset of the C grammar. This subset includes common C syntax for function entry point, C-style comments, and function bodies. However, it does not include constructs such as typedefs, external function declarations, or C preprocessor directives.

To ensure that only the constructs understood by *mkf2c* are included in wrapper input, place special comments around each function for which Fortran-to-C wrappers are to be generated (see the example below).

The special comments **/* CENTRY */** and **/* ENDCENTRY */** surround the section that is to be made Fortran-callable. After these special comments are placed around the code, use the program *excentry*(1) before *mkf2c* to generate the input file for *mkf2c*.

Example 3-20 Source File for Use with *extcentry*

```
typedef unsigned short grunt [4];
struct {
   long 1,11;
   char *str;
} bar;
main ()
{
   int kappa =7;
   foo (kappa,bar.str);
}
/* CENTRY */
foo (integer, cstring)
int integer;
char *cstring;
{
   if (integer==1) printf("%s",cstring);
} /* ENDCENTRY */
```

Example 3-20 illustrates the use of *extcentry*. It shows the C file *foo.c* containing the function **foo**, which is to be made Fortran-callable.

To generate the assembly language wrapper *foowrp.s* from the above file *foo.c*, use the following set of commands:

```
% extcentry foo.c foowrp.fc
% mkf2c foowrp.fc foowrp.s
```

The programs *mkf2c* and *extcentry* are stored in the directory */usr/bin*.

Makefile Considerations

make(1) contains default rules to help automate the control of wrapper generation. The following example of a makefile illustrates the use of these rules. In the example, an executable object file is created from the files *main.f* (a Fortran main program) and *callc.c*:

```
test:  main.o callc.o
   f77 -o test main.o callc.o
callc.o: callc.fc
clean:
   rm -f *.o test *.fc
```

In this program, *main* calls a C routine in *callc.c*. The extension *.fc* has been adopted for Fortran-to-call-C wrapper source files. The wrappers created from *callc.fc* will be assembled and combined with the binary created from *callc.c*. Also, the dependency of *callc.o* on *callc.fc* will cause *callc.fc* to be recreated from *callc.c* whenever the C source file changes. The programmer is responsible for placing the special comments for *extcentry* in the C source as required.

Note: Options to *mkf2c* can be specified when *make* is invoked by setting the *make* variable *F2CFLAGS*. Also, do not create a *.fc* file for the modules that need wrappers created. These files are both created and removed by *make* in response to the *file.o:file.fc* dependency.

The *makefile* above controls the generation of wrappers and Fortran objects. You can add modules to the executable object file in one of the following ways:

- If the file is a native C file whose routines are not to be called from Fortran using a wrapper interface, or if it is a native Fortran file, add the *.o* specification of the final make target and dependencies.
- If the file is a C file containing routines to be called from Fortran using a wrapper interface, the comments for *extcentry* must be placed in the C source, and the *.o* file placed in the target list. In addition, the dependency of the *.o* file on the *.fc* file must be placed in the makefile. This dependency is illustrated in the example makefile above where *callf.o* depends on *callf.fc*.

Chapter 4

System Functions and Subroutines

This chapter describes extensions to FORTRAN 77 that are related to the IRIX compiler and operating system.

- "Library Functions" summarizes the Fortran run-time library functions.
- "Extended Intrinsic Subroutines" describes the extensions to the Fortran intrinsic subroutines.
- "Extended Intrinsic Functions" describes the extensions to the Fortran functions.

Library Functions

The Fortran library functions provide an interface from Fortran programs to the IRIX system functions. System functions are facilities that are provided by the IRIX system kernel directly, as opposed to functions that are supplied by library code linked with your program. System functions are documented in volume 2 of the reference pages, with an overview in the intro(2) reference page.

Table 4-1 summarizes the functions in the Fortran run-time library. In general, the name of the interface routine is the same as the name of the system function that would be called from a C program. For details on a system interface routine use the following command:

`man 2` *name_of_function*

Note: You must declare the **time** function as EXTERNAL; if you do not, the compiler will assume you mean the VMS-compatible intrinsic **time** function rather than the IRIX system function. It is a usually a good idea to declare any library function in an EXTERNAL statement as documentation.

Table 4-1 Summary of System Interface Library Routines

Function	Purpose
abort(3F)	abnormal termination
access	determine accessibility of a file
acct	enable/disable process accounting
alarm(3F)	execute a subroutine after a specified time
barrier(3P)	perform barrier operations
blockproc(2)	block processes
brk(2)	change data segment space allocation
chdir	change default directory
chmod(3F)	change mode of a file
chown(2)	change owner
chroot	change root directory for a command
close	close a file descriptor
creat	create or rewrite a file
ctime(3F)	return system time
dtime(3F)	return elapsed execution time
dup	duplicate an open file descriptor
etime(3F)	return elapsed execution time
exit(2)	terminate process with status
fcntl(2)	file control
fdate(3F)	return date and time in an ASCII string
fgetc(3F)	get a character from a logical unit

Table 4-1 (continued) Summary of System Interface Library Routines

Function	Purpose
fork(2)	create a copy of this process
fputc(3F)	write a character to a Fortran logical unit
free_barrier(3P)	free barrier
fseek(3F)	reposition a file on a logical unit
fseek64(3F)	reposition a file on a logical unit for 64-bit architecture
fstat(2)	get file status
ftell(3F)	reposition a file on a logical unit
ftell64(3F)	reposition a file on a logical unit for 64-bit architecture
gerror(3F)	get system error messages
getarg(3F)	return command line arguments
getc(3F)	get a character from a logical unit
getcwd	get pathname of current working directory
getdents(2)	read directory entries
getegid(2)	get effective group ID
gethostid(2)	get unique identifier of current host
getenv(3F)	get value of environment variables
geteuid(2)	get effective user ID
getgid(2)	get user or group ID of the caller
gethostname(2)	get current host ID
getlog(3F)	get user's login name
getpgrp	get process group ID
getpid	get process ID
getppid	get parent process ID
getsockopt(2)	get options on sockets

Table 4-1 (continued) Summary of System Interface Library Routines

Function	Purpose
getuid(2)	get user or group ID of caller
gmtime(3F)	return system time
iargc(3F)	return command line arguments
idate(3F)	return date or time in numerical form
ierrno(3F)	get system error messages
ioctl(2)	control device
isatty(3F)	determine if unit is associated with tty
itime(3F)	return date or time in numerical form
kill(2)	send a signal to a process
link(2)	make a link to an existing file
loc(3F)	return the address of an object
lseek(2)	move read/write file pointer
lseek64(2)	move read/write file pointer for 64-bit architecture
lstat(2)	get file status
ltime(3F)	return system time
m_fork(3P)	create parallel processes
m_get_myid(3P)	get task ID
m_get_numprocs(3P)	get number of subtasks
m_kill_procs(3P)	kill process
m_lock(3P)	set global lock
m_next(3P)	return value of counter
m_park_procs(3P)	suspend child processes
m_rele_procs(3P)	resume child processes
m_set_procs(3P)	set number of subtasks

Table 4-1 (continued) Summary of System Interface Library Routines

Function	Purpose
m_sync(3P)	synchronize all threads
m_unlock(3P)	unset a global lock
mkdir(2)	make a directory
mknod(2)	make a directory/file
mount(2)	mount a filesystem
new_barrier(3P)	initialize a barrier structure
nice	lower priority of a process
open(2)	open a file
oserror(3F)	get/set system error
pause(2)	suspend process until signal
perror(3F)	get system error messages
pipe(2)	create an interprocess channel
plock(2)	lock process, test, or data in memory
prctl(2)	control processes
profil(2)	execution-time profile
ptrace	process trace
putc(3F)	write a character to a Fortran logical unit
putenv(3F)	set environment variable
qsort(3F)	quick sort
read	read from a file descriptor
readlink	read value of symbolic link
rename(3F)	change the name of a file
rmdir(2)	remove a directory
sbrk(2)	change data segment space allocation

Table 4-1 (continued) Summary of System Interface Library Routines

Function	Purpose
schedctl(2)	call to scheduler control
send(2)	send a message to a socket
setblockproccnt(2)	set semaphore count
setgid	set group ID
sethostid(2)	set current host ID
setoserror(3F)	set system error
setpgrp(2)	set process group ID
setsockopt(2)	set options on sockets
setuid	set user ID
sginap(2)	put process to sleep
sginap64(2)	put process to sleep in 64-bit environment
shmat(2)	attach shared memory
shmdt(2)	detach shared memory
sighold(2)	raise priority and hold signal
sigignore(2)	ignore signal
signal(2)	change the action for a signal
sigpause(2)	suspend until receive signal
sigrelse(2)	release signal and lower priority
sigset(2)	specify system signal handling
sleep(3F)	suspend execution for an interval
socket(2)	create an endpoint for communication TCP
sproc(2)	create a new share group process
stat(2)	get file status
stime(2)	set time

Table 4-1 (continued) Summary of System Interface Library Routines

Function	Purpose
symlink(2)	make symbolic link
sync	update superblock
sysmp(2)	control multiprocessing
sysmp64(2)	control multiprocessing in 64-bit environment
system(3F)	issue a shell command
taskblock(3P)	block tasks
taskcreate(3P)	create a new task
taskctl(3P)	control task
taskdestroy(3P)	kill task
tasksetblockcnt(3P)	set task semaphore count
taskunblock(3P)	unblock task
time(3F)	return system time (must be declared EXTERNAL)
ttynam(3F)	find name of terminal port
uadmin	administrative control
ulimit(2)	get and set user limits
ulimit64(2)	get and set user limits in 64-bit architecture
umask	get and set file creation mask
umount(2)	dismount a file system
unblockproc(2)	unblock processes
unlink(2)	remove a directory entry
uscalloc(3P)	shared memory allocator
uscalloc64(3P)	shared memory allocator in 64-bit environment
uscas(3P)	compare and swap operator
usclosepollsema(3P)	detach file descriptor from a pollable semaphore

Table 4-1 (continued) Summary of System Interface Library Routines

Function	Purpose
usconfig(3P)	semaphore and lock configuration operations
uscpsema(3P)	acquire a semaphore
uscsetlock(3P)	unconditionally set lock
usctlsema(3P)	semaphore control operations
usdumplock(3P)	dump lock information
usdumpsema(3P)	dump semaphore information
usfree(3P)	user shared memory allocation
usfreelock(3P)	free a lock
usfreepollsema(3P)	free a pollable semaphore
usfreesema(3P)	free a semaphore
usgetinfo(3P)	exchange information through an arena
usinit(3P)	semaphore and lock initialize routine
usinitlock(3P)	initialize a lock
usinitsema(3P)	initialize a semaphore
usmalloc(3P)	allocate shared memory
usmalloc64(3P)	allocate shared memory in 64-bit environment
usmallopt(3P)	control allocation algorithm
usnewlock(3P)	allocate and initialize a lock
usnewpollsema(3P)	allocate and initialize a pollable semaphore
usnewsema(3P)	allocate and initialize a semaphore
usopenpollsema(3P)	attach a file descriptor to a pollable semaphore
uspsema(3P)	acquire a semaphore
usputinfo(3P)	exchange information through an arena
usrealloc(3P)	user share memory allocation

Table 4-1 (continued) Summary of System Interface Library Routines

Function	Purpose
usrealloc64(3P)	user share memory allocation in 64-bit environment
ussetlock(3P)	set lock
ustestlock(3P)	test lock
ustestsema(3P)	return value of semaphore
usunsetlock(3P)	unset lock
usvsema(3P)	free a resource to a semaphore
uswsetlock(3P)	set lock
wait(2)	wait for a process to terminate
write	write to a file

You can use the **datapool** statement to cause Fortran interprocess data sharing. However, this is a nonstandard statement. The **datapool** statement is a way that different processes can use to access the same pool of common symbols. Any processes can access the shared datapool by linking with the datapool DSO. For more information see the datapool(5) reference page.

Extended Intrinsic Subroutines

This section describes the intrinsic subroutines that are extensions to FORTRAN 77. The intrinsic *functions* that are standard to FORTRAN 77 are documented in Appendix A of the *MIPSpro Fortran 77 Language Reference Manual*. The rules for using the names of intrinsic subroutines are also discussed in that appendix.

Table 4-2 gives an overview of the intrinsic subroutines and their function; they are described in detail in the following sections.

Table 4-2 Overview of System Subroutines

Subroutine	Information Returned
DATE	Current date as nine-byte string in ASCII representation
IDATE	Current month, day, and year, each represented by a separate integer
ERRSNS	Description of the most recent error
EXIT	Terminates program execution
TIME	Current time in hours, minutes, and seconds as an eight-byte string in ASCII representation
MVBITS	Moves a bit field to a different storage location

DATE

The **DATE** routine returns the current date as set by the system; the format is as follows:

```
CALL DATE (buf)
```

The *buf* argument is a variable, array, array element, or character substring nine bytes long. After the call, *buf* contains an ASCII variable in the format *dd-mmm-yy*, where *dd* is the date in digits, *mmm* is the month in alphabetic characters, and *yy* is the year in digits.

IDATE

The **IDATE** routine returns the current date as three integer values representing the month, date, and year; the format is as follows:

```
CALL IDATE (m, d, y)
```

The *m*, *d*, and *y* arguments are either INTEGER*4 or INTEGER*2 values representing the current month, day and year. For example, the values of *m*, *d*, and *y* on August 10, 1989, are

```
m = 8
d = 10
y = 89
```

ERRSNS

The **ERRSNS** routine returns information about the most recent program error; the format is as follows:

```
CALL ERRSNS (arg1, arg2, arg3, arg4, arg5)
```

The arguments (*arg1, arg2*, and so on) can be either INTEGER*4 or INTEGER*2 variables. On return from **ERRSNS**, the arguments contain the information shown in Table 4-3.

Table 4-3 Information Returned by ERRSNS

Argument	Contents
arg1	IRIX global variable *errno*, which is then reset to zero after the call
arg2	Zero
arg3	Zero
arg4	Logical unit number of the file that was being processed when the error occurred
arg5	Zero

Although only *arg1* and *arg4* return relevant information, *arg2, arg3,* and *arg5* are always required.

EXIT

The **EXIT** routine causes normal program termination and optionally returns an exit-status code; the format is as follows:

```
CALL EXIT (status)
```

The *status* argument is an INTEGER*4 or INTEGER*2 argument containing a status code.

TIME

The **TIME** routine returns the current time in hours, minutes, and seconds; the format is as follows:

```
CALL TIME (clock)
```

The *clock* argument is a variable, array, array element, or character substring; it must be eight bytes long. After execution, *clock* contains the time in the format *hh:mm:ss*, where *hh*, *mm*, and *ss* are numerical values representing the hour, the minute, and the second.

MVBITS

The **MVBITS** routine transfers a bit field from one storage location to another; the format is as follows:

```
CALL MVBITS (source , sbit , length , destination , dbit)
```

Table 4-4 defines the arguments. Arguments can be declared as INTEGER*2, INTEGER*4, or INTEGER*8.

Table 4-4 Arguments to MVBITS

Argument	Type	Contents
source	Integer variable or array element	Source location of bit field to be transferred.
sbit	Integer expression	First bit position in the field to be transferred from *source.*
length	Integer expression	Length of the field to be transferred from *source.*
destination	Integer variable or array element	Destination location of the bit field
dbit	Integer expression	First bit in *destination* to which the field is transferred.

Extended Intrinsic Functions

Table 4-5 gives an overview of the intrinsic functions added as extensions of FORTRAN 77.

Table 4-5 Function Extensions

Function	Information Returned
SECNDS	Elapsed time as a floating point value in seconds. This is an intrinsic routine.
RAN	The next number from a sequence of pseudo-random numbers. This is not an intrinsic routine.

These functions are described in detail in the following sections.

SECNDS

SECNDS is an intrinsic routine that returns the number of seconds since midnight, minus the value of the passed argument; the format is as follows:

```
s = SECNDS(n)
```

After execution, *s* contains the number of seconds past midnight less the value specified by *n.* Both *s* and *n* are single-precision, floating point values.

RAN

RAN generates a pseudo-random number. The format is as follows:

```
v = RAN(s)
```

The argument *s* is an INTEGER*4 variable or array element. This variable serves as a seed in determining the next random number. It should initially be set to a large, odd integer value. You can compute multiple random number series by supplying different variables or array elements as the seed argument to different calls of **RAN**.

Caution: Because **RAN** modifies the *s* argument, calling the function with a constant can cause a core dump.

The algorithm used in **RAN** is the linear congruential method. The code is similar to the following fragment:

```
S = S * 1103515245L + 12345
RAN = FLOAT(IAND(RSHIFT(S,16),32767))/32768.0
```

RAN is supplied for compatibility with VMS. For demanding applications, use the functions described on the random(3b) reference page. These can all be called using techniques described under “Using %VAL” on page 46.

Chapter 5

OpenMP Multiprocessing Directives

This chapter describes the multiprocessing directives suported by the MIPSpro Fortran 77 compiler. These directives are based on the OpenMP Fortran API standard. Programs that use these directives are portable and can be compiled by other compilers that support the OpenMP standard.

Directives enable, disable, or modify a feature of the compiler. Essentially, directives are command line options specified within the input file instead of on the command line. Unlike command line options, directives have no default setting. To invoke a directive, you must either toggle it on or set a desired value for its level.

In addition to directives, the OpenMP Fortran API describes several library routines and environment variables. Information on the library routines can be found on the omp_lock(3), omp_nested(3), and omp_threads(3) man pages. Information about the environment variables can be found on the pe_environ(5) man page.

This chapter discusses the following directives:

- **OMP PARALLELL** and **END PARALLEL** in "Defining Parallel Regions" on page 72
- **OMP DO** and **END DO** in "DO Directive" on page 75
- **OMP SECTIONS** and **END SECTIONS** in "SECTIONS Directive" on page 77
- **OMP SINGLE** and **END END SINGLE** in "SINGLE Directive" on page 78
- **OMP PARALLEL DO** and **END PARALLEL DO** in "PARALLEL DO Directive" on page 79
- **OMP PARALLELL SECTIONS** and **END PARALLEL SECTIONS** in "PARALLEL SECTIONS Directive" on page 80
- **OMP MASTER** and **END MASTER** in "MASTER Directive" on page 81
- **OMP CRITICAL** and **END CRITICAL** in "CRITICAL Directive" on page 81
- **OMP BARRIER** in "BARRIER Directive" on page 82
- **OMP ATOMIC** in "ATOMIC Directive" on page 82

- **OMP FLUSH** in "FLUSH Directive" on page 83
- **OMP ORDERED** in "ORDERED Directive" on page 84
- **OMP THREADPRIVATE** in "THREADPRIVATE Directive" on page 85

In addition, clauses to control scope attributes are discusssed in "Defining Parallel Regions" on page 72.

A data environment is associated with each process; this environment provides a context for execution. A data environment is initiated at the start of a program. New environments are constructed for new processes created during program execution. The objects comprising a data environment can have a **SHARED**, **PRIVATE**, or **REDUCTION** attribute. All of these attributes are discussed later in this chapter.

Using Directives

OpenMP directives are ignored by default. To enable both the newer OpenMP directives and the older multiprocessing directives, use the *f77 -mp* command. To disable either type of directive, use one of the following commands:.

```
f77 -mp -MP:open_mp=off
f77 -mp -MP:old_mp=off
```

Directives placed on the first line of the input file are called *global directives*. The compiler interprets them as if they appeared at the top of each program unit in the file. Directives that appear elsewhere in the file apply only until the end of the current program unit. The compiler resets the value of the directive to the global value at the start of the next program unit. You can set the global value using a command line option or a global directive.

Some command line options override directives and many directives have corresponding command line options. If you specify conflicting settings in the command line and in a directive, the compiler chooses the most restrictive setting. For Boolean options, if either the directive or the command line has the option turned off, it is considered off. For options that require a numeric value, the compiler uses the minimum of the command line setting and the directive setting.

The compiler directives look like Fortran comments: they begin with a **C** in column one. If multiprocessing is not turned on, the statements are treated as comments. This allows the identical source to be compiled with a single-processing compiler or by the compiler without the multiprocessing option.

All multiprocessing directives are case-insensitive and are of the following form:

prefix directive [*clause*[[,] *clause*]...]

The **C$OMP** and ***$OMP** prefixes can be used.

Prefixes must start in column one and appear as a single word with no intervening white space. Fortran fixed form line length, case sensitivity, white space, continuation, and column rules apply to the directive line.

The *clause* indicates one or more directive clauses. Clauses can appear in any order after the directive name and can be repeated as needed, subject to the restrictions listed in the description of each clause.

Directives cannot be embedded within continued statements, and statements cannot be embedded within directives. Comments cannot appear on the same line as a directive.

The following formats for specifying directives are equivalent (the first line represents the position of the first 9 columns):

```
C23456789
C$OMP PARALLEL DO
C$OMP+SHARED(A,B,C)
C$OMP PARALLELDOSHARED(A,B,C)
```

In order to simplify the presentation, the remainder of this chapter uses the **C$OMP** prefix in all syntax descriptions and examples.

Initial directive lines must have a space or zero in column six, and continuation directive lines must have a character other than a space or a zero in column six.

Conditional Compilation

Conditional compilation can be used to comment out sections of code. When using conditional compilation, the code is commented out if the **-mp** compile option is not used.

Fortran statements can be compiled conditionally as long as they are preceded by one of the following conditional compilation prefixes:, **C$**, or ***$**. The prefix must be followed by a legal Fortran statement on the same line. During compilation, the prefix is replaced by two spaces, and the rest of the line is treated as a normal Fortran statement.

The prefixes must start in column one and appear as a single word with no intervening white space. Fortran fixed form line length, case sensitivity, white space, continuation, and column rules apply to the line. Initial lines must have a space or zero in column six, and continuation lines must have a character other than a space or zero in column six.

Example. The following forms for specifying conditional compilation are equivalent:

```
C23456789
C$ 10 IAM = OMP_GET_THREAD_NUM() +
C$   &           INDEX

#ifdef _OPENMP
   10 IAM = OMP_GET_THREAD_NUM() +
     &           INDEX
#endif
```

In addition to the Fortran conditional compilation prefixes, a preprocessor macro, **_OPENMP**, can be used for conditional compilation.

Defining Parallel Regions

The **PARALLEL** and **ENDPARALLEL** directives define a parallel region. A parallel region is a block of code that is to be executed by multiple threads in parallel. This is the fundamental OpenMP parallel construct that starts parallel execution. These directives have the following format:

```
C$OMP PARALLEL [clause [[,] clause]...]
block
C$OMP END PARALLEL
```

The *clause* can be one or more of the following:

- **PRIVATE(***var***[,** *var***] ...)**
- **SHARED(***var***[,** *var* **]...)**
- **DEFAULT(PRIVATE | SHARED | NONE)**
- **FIRSTPRIVATE(***var***,[** *var***] ...)**
- **REDUCTION ({***operator* **|** *intrinsic***}:***var***[,** *var***]...)**
- **IF(***scalar_logical_expression***)**
- **COPYIN(***var***[,** *var***] ...)**

The **PRIVATE**, **SHARED**, **DEFAULT**, **FIRSTPRIVATE**, **REDUCTION**, and **COPYIN** clauses are described in "Defining Parallel Regions" on page 72.

The *block* denotes a structured block of Fortran statements. You cannot branch into or out of the block. The code contained within the dynamic extent of the parallel region is executed on each thread, and the code path can be different for different threads.

The **ENDPARALLEL** directive denotes the end of the parallel region. There is an implied barrier at this point. Only the master thread of the team continues execution at the end of a parallel region.

When a thread encounters a parallel region, it creates a team of threads, and it becomes the master of the team. The master thread is a member of the team and it has a thread number of 0 within the team. The number of threads in the team is controlled by environment variables and/or library calls.

The number of physical processors actually hosting the threads at any given time is implementation dependent. Once created, the number of threads in the team remains constant for the duration of that parallel region, but it can be changed either explicitly by the user or automatically by the run-time system from one parallel region to another. The **OMP_SET_DYNAMIC** library routine and the **OMP_DYNAMIC** environment variable can be used to enable and disable the automatic adjustment of the number of threads. For more information about environment variables that affect OpenMP directives, see the pe_environ(5) man page.

Note: The OpenMP Fortran API does not specify the number of physical processors that can host the threads at any given time.

If a thread in a team executing a parallel region encounters another parallel region, it creates a new team, and it becomes the master of that new team. By default, nested parallel regions are serialized; that is, they are executed by a team composed of one thread. This default behavior can be changed by using either the **OMP_SET_NESTED** library routine or the **OMP_NESTED** environment variable. For more information on environment variables that affect OpenMP directives, see the pe_environ(5) man page.

If an **IF** clause is present, the enclosed code region is executed in parallel only if the scalar_logical_expression evaluates to .TRUE.. Otherwise, the parallel region is serialized. The expression must be a scalar Fortran logical expression.

The following restrictions apply to parallel regions:

- The **PARALLEL/ENDPARALLEL** directive pair must appear in the same routine in the executable section of the code.
- The code contained by these two directives must be a structured block. You cannot branch into or out of a parallel region.
- Only a single **IF** clause can appear on the directive.

Work-sharing Constructs

A work-sharing construct divides the execution of the enclosed code region among the members of the team that encounter it. A work-sharing construct must be enclosed within a parallel region in order for the directive to execute in parallel. The work-sharing directives do not launch new threads, and there is no implied barrier on entry to a work-sharing construct.

The following restrictions apply to the work-sharing directives:

- Work-sharing constructs and **BARRIER** directives must be encountered by all threads in a team or by none at all.
- Work-sharing constructs and **BARRIER** directives must be encountered in the same order by all threads in a team.

The following sections describe the work-sharing constructs.

DO Directive

The **DO** directive specifies that the iterations of the immediately following **DO** loop will be divided among the parallel threads. The loop that follows a **DO** directive cannot be a **DOWHILE** or a **DO** loop without loop control. The iterations of the **DO** loop are distributed across threads that already exist.

The format of this directive is as follows:

```
C$OMP DO [clause[[, ]clause]...]
do_loop
[C$OMP END DO [NOWAIT]]
```

The *clause* can be one of the following:

- **PRIVATE(***var***[,** *var***] ...)**
- **FIRSTPRIVATE(***var***[,** *var***] ...)**
- **LASTPRIVATE(***var***[,** *var***] ...)**
- **REDUCTION({***operator* **|** *intrinsic***}:***var***[,** *var***]...)**
- **SCHEDULE(***type***[,***chunk***])**
- **ORDERED**

See “Defining Parallel Regions” on page 72 for information about these *clause*s.

If ordered sections are contained in the dynamic extent of the **DO** directive, the **ORDERED** clause must be present. The code enclosed within an ordered section is executed in the order in which iterations would be executed in a sequential execution of the loop.

The **SCHEDULE** clause specifies how iterations of the **DO** loop are divided among the threads of the team. Within the **SCHEDULE(***type***,***chunk***)** clause syntax, *type* can be one of the following:

type	**Effect**
STATIC	When **SCHEDULE(STATIC,** *chunk***)** is specified, iterations are divided into pieces of a size specified by *chunk*. The pieces are statically assigned to threads in the team in a round-robin fashion in the order of the thread number. *chunk* must be a scalar integer expression. When no *chunk* is specified, the iterations are divided among threads in contiguous pieces, and one piece is assigned to each thread.

DYNAMIC When **SCHEDULE(DYNAMIC,***chunk***)** is specified, the iterations are broken into pieces of a size specified by *chunk*. As each thread finishes its iterations, it dynamically obtains the next set of iterations. When no *chunk* is specified, it defaults to 1.

GUIDED When **SCHEDULE(GUIDED,***chunk***)** is specified, the *chunk* size is reduced in an exponentially decreasing manner with each dispatched piece of the iteration space. *chunk* specifies the minimum number of iterations to dispatch each time, except when there are less than *chunk* number of iterations, at which point the rest are dispatched. When no *chunk* is specified, the default is 1.

RUNTIME When **SCHEDULE(RUNTIME)** is specified, the decision regarding scheduling is deferred until run time and you cannot specify a *chunk*.

The schedule *type* and *chunk* size can be chosen at run time by setting the **OMP_SCHEDULE** environment variable. If not set, the default is **STATIC**.

For more information about the **OMP_SCHEDULE** environment variable, see the pe_environ(5) man page.

Note: The OpenMP Fortran API does not define a default scheduling mechanism. You should not rely on a particular implementation of a schedule type for correct execution because it is possible to have variations in the implementations of the same schedule type across different compilers.

If an **ENDDO** directive is not specified, it is assumed at the end of the **DO** loop. If **NOWAIT** is specified on the **ENDDO** directive, threads do not synchronize at the end of the parallel loop. Threads that finish early proceed straight to the instructions following the loop without waiting for the other members of the team to finish the **DO** directive.

Parallel **DO** loop control variables are block-level entities within the **DO** loop. If the loop control variable also appears in the **LASTPRIVATE** variable list of the parallel **DO**, it is copied out to a variable of the same name in the enclosing **PARALLEL** region. The variable in the enclosing **PARALLEL** region must be **SHARED** if it is specified on the **LASTPRIVATE** variable list of a **DO** directive.

The following restrictions apply to the **DO** directives:

- You cannot branch out of a **DO** loop associated with a **DO** directive.
- The values of the loop control parameters of the **DO** loop associated with a **DO** directive must be the same for all the threads in the team.

- The **DO** loop iteration variable must be of type integer.
- If used, the **ENDDO** directive must appear immediately after the end of the loop.
- Only a single **SCHEDULE** clause can appear on a **DO** directive.
- Only a single **ORDERED** clause can appear on a **DO** directive.

SECTIONS Directive

The **SECTIONS** directive specifies that the enclosed sections of code are to be divided among threads in the team. It is a non-iterative work-sharing construct. Each section is executed once by a thread in the team.

The format of this directive is as follows:

```
C$OMP SECTIONS [clause[[,] clause]...]
C$OMP SECTION
block
[C$OMP SECTION
block]
. . .
C$OMP END SECTIONS [NOWAIT]
```

The *clause* can be one of the following:

- **PRIVATE(***var***[,** *var* **]...)**
- **FIRSTPRIVATE(***var***[,** *var***] ...)**
- **LASTPRIVATE(***var***[,** *var***] ...)**
- **REDUCTION({** *operator* **|** *intrinsic***}:***var***[,** *var***]...)**

The **PRIVATE**, **FIRSTPRIVATE**, **LASTPRIVATE**, and **REDUCTION** clauses are described in “Defining Parallel Regions” on page 72.

The *block* denotes a structured block of Fortran statements. You cannot branch into or out of the block.

Each section must be preceded by a **SECTION** directive, though the **SECTION** directive is optional for the first section. The **SECTION** directives must appear within the lexical extent of the **SECTIONS**/**ENDSECTIONS** directive pair. The last section ends at the **ENDSECTIONS** directive. Threads that complete execution of their sections wait at a barrier at the **ENDSECTIONS** directive unless a **NOWAIT** is specified.

The following restrictions apply to the **SECTIONS** directive:

- The code enclosed in a **SECTIONS**/**ENDSECTIONS** directive pair must be a structured block. In addition, each constituent section must also be a structured block. You cannot branch into or out of the constituent section blocks.
- You cannot have a **SECTION** directive outside the lexical extent of the **SECTIONS**/**ENDSECTIONS** directive pair.

SINGLE Directive

The **SINGLE** directive specifies that the enclosed code is to be executed by only one thread in the team. Threads in the team that are not executing the **SINGLE** directive wait at the **ENDSINGLE** directive unless **NOWAIT** is specified.

The format of this directive is as follows:

```
C$OMP SINGLE [clause[,] clause]...]
 block
C$OMP END SINGLE [NOWAIT]
```

The *clause* can be one of the following:

- **PRIVATE(***var***[,** *var***] ...)**
- **FIRSTPRIVATE(***var***[,** *var***] ...)**

The **PRIVATE** and **FIRSTPRIVATE** clauses are described in "Defining Parallel Regions" on page 72.

The *block* denotes a structured block of Fortran statements. You cannot branch into or out of the block.

Combined Parallel Work-sharing Constructs

The combined parallel work-sharing constructs are shortcuts for specifying a parallel region that contains only one work-sharing construct. The semantics of these directives are identical to that of explicitly specifying a **PARALLEL** directive followed by a single work-sharing construct.

The following sections describe the combined parallel work-sharing directives.

PARALLEL DO Directive

The **PARALLEL DO** directive provides a shortcut form for specifying a parallel region that contains a single **DO** directive.

The format of this directive is as follows:

```
C$OMP PARALLEL DO [clause[[,] clause...]
do_loop
[C$OMP END PARALLEL DO]
```

The *clause* can be one or more of the clauses accepted by the **PARALLEL** directive or the **DO** directive, as follows:

- **PRIVATE(***var***[,** *var***] ...)**
- **FIRSTPRIVATE(***var***[,** *var***] ...)**
- **LASTPRIVATE(***var***[,** *var***] ...)**
- **REDUCTION({***operator* **|** *intrinsic***}:***var***[,** *var***] ...)**
- **SCHEDULE(***type***[,***chunk***])**
- **ORDERED**
- **SHARED(***var***[,** *var***] ...)**
- **DEFAULT(PRIVATE | SHARED | NONE)**
- **IF(***scalar_logical_expression***)**
- **COPYIN(***var***[,** *var***] ...)**

See “Defining Parallel Regions” on page 72 for details about these *clause*s.

If the **END PARALLEL DO** directive is not specified, the **PARALLEL DO** is assumed to end with the **DO** loop that immediately follows the **PARALLEL DO** directive. If used, the **END PARALLEL DO** directive must appear immediately after the end of the **DO** loop.

The semantics are identical to explicitly specifying a **PARALLEL** directive immediately followed by a **DO** directive.

PARALLEL SECTIONS Directive

The **PARALLEL SECTIONS** directive provides a shortcut form for specifying a parallel region that contains a single **SECTIONS** directive. The semantics are identical to explicitly specifying a **PARALLEL** directive immediately followed by a **SECTIONS** directive.

The format of this directive is as follows:

```
C$OMP PARALLEL SECTIONS [clause[[,] clause]...]
[C$OMP SECTION]
block
[C$OMP SECTION
block]
. . .
C$OMP END PARALLEL SECTIONS
```

The *clause* can be one or more of the clauses accepted by the **PARALLEL** directive or the **SECTIONS** directive. These clauses are as follows:

- **PRIVATE(***var***[,** *var***] ...)**
- **FIRSTPRIVATE(***var***[,** *var***] ...)**
- **LASTPRIVATE(***var***[,** *var***] ...)**
- **REDUCTION({** *operator* **|** *intrinsic***}:***var***[,***var***]...)**
- **SHARED(***var***[,** *var***] ...)**
- **DEFAULT(PRIVATE | SHARED | NONE)**
- **IF(***scalar_logical_expression***)**
- **COPYIN(***var***[,** *var***] ...)**

See "Defining Parallel Regions" on page 72 for details about these *clause*s.

The *block* denotes a structured block of Fortran statements. You cannot branch into or out of the block.

The last section ends at the **END PARALLEL SECTIONS** directive.

Synchronization Constructs

The following synchronization constructs are discussed in this section:

- **MASTER** and **ENDMASTER** directives in “MASTER Directive”.
- **CRITICAL** and **END CRITICAL** directives in “CRITICAL Directive” on page 81
- **BARRIER** directive in “BARRIER Directive” on page 82.
- **ATOMIC** directive in “ATOMIC Directive” on page 82.
- **FLUSH** directive in “FLUSH Directive” on page 83.
- **ORDERED** and **END ORDERED in** directives “ORDERED Directive” on page 84.

MASTER Directive

The code enclosed within **MASTER** and **ENDMASTER** directives is executed by the master thread.

These directives have the following format:

```
C$OMP MASTER
block
C$OMP END MASTER
```

The *block* denotes a structured block of Fortran statements. You cannot branch into or out of the block. The other threads in the team skip the enclosed section of code and continue execution. There is no implied barrier either on entry to or exit from the master section.

CRITICAL Directive

The **CRITICAL** and **END CRITICAL** directives restrict access to the enclosed code to one thread at a time.

These directives have the following format:

```
C$OMP CRITICAL [(name)]
block
C$OMP END CRITICAL [(name)]
```

The *name* identifies the critical section. If a *name* is specified on a **CRITICAL** directive, the same *name* must also be specified on the **END CRITICAL** directive. If no name appears on the **CRITICAL** directive, no name can appear on the **END CRITICAL** directive.

The *block* denotes a structured block of Fortran statements. You cannot branch into or out of the block.

A thread waits at the beginning of a critical section until no other thread in the team is executing a critical section with the same name. All unnamed **CRITICAL** directives map to the same name. Critical section names are global entities of the program. If a name conflicts with any other entity, the behavior of the program is undefined.

BARRIER Directive

The **BARRIER** directive synchronizes all the threads in a team. When it encounters a barrier, a thread waits until all other threads have reached the same point.

This directive has the following format:

```
C$OMP BARRIER
```

ATOMIC Directive

The **ATOMIC** directive ensures that a specific memory location is updated atomically, rather than exposing it to the possibility of multiple, simultaneous writing threads.

This directive has the following format:

```
C$OMP ATOMIC
```

This directive applies only to the immediately following statement, which must have one of the following forms:

- *x = x operator expr*
- *x = expr operator x*
- *x = intrinsic (x, expr)*
- *x = intrinsic (expr, x)*

In the preceding statements:

- *x* is a scalar variable of intrinsic type. All references to storage location *x* must have the same type and type parameters.
- *expr* is a scalar expression that does not reference x.
- *intrinsic* is one of **MAX**, **MIN**, **IAND**, **IOR**, or **IEOR**.
- *operator* is one of **+**, *****, **-**, **/**, **.AND.**, **.OR.**, **.EQV.**, or **.NEQV.** .

Only the load and store of *x* are atomic; the evaluation of *expr* is not atomic. To avoid race conditions, all updates of the location in parallel must be protected with the **ATOMIC** directive, except those that are known to be free of race conditions. The following is an example:

```
C$OMP ATOMIC
      Y(INDEX(I)) = Y(INDEX(I)) + B
```

FLUSH Directive

The **FLUSH** directive identifies synchronization points at which thread-visible variables are written back to memory. This directive must appear at the precise point in the code at which the synchronization is required.

Thread-visible variables include the following data items:

- Globally visible variables (common blocks).
- Local variables that do not have the **SAVE** attribute but have had their address taken and saved or have had their address passed to another subprogram.
- Local variables that do not have the **SAVE** attribute that are declared shared in a parallel region within the subprogram.
- Dummy arguments.
- All pointer dereferences.

This directive has the following format:

```
C$OMP FLUSH [(var[, var] ...)]
```

The *var* argument indicates the variables to be flushed.

An implicit **FLUSH** directive is assumed for the following directives:

- **BARRIER**
- **CRITICAL** and **END CRITICAL**
- **END DO**
- **END PARALLEL**
- **END SECTIONS**
- **END SINGLE**
- **ORDERED** and **END ORDERED**

The directive is not implied if a **NOWAIT** clause is present.

ORDERED Directive

The code enclosed within **ORDERED** and **END ORDERED** directives is executed in the order in which iterations would be executed in a sequential execution of the loop.

These directives have the following format:

```
C$OMP ORDERED
block
C$OMP END ORDERED
```

The *block* denotes a structured block of Fortran statements. You cannot branch into or out of the block.

An **ORDERED** directive can appear only in the dynamic extent of a **DO** or **PARALLEL DO** directive. The closest enclosing **DO** directive must have the **ORDERED** clause specified.

One thread is allowed in an ordered section at a time. Threads are allowed to enter in the order of the loop iterations. No thread can enter an ordered section until it is guaranteed that all previous iterations have completed or will never execute an ordered section. This sequentializes and orders code within ordered sections while allowing code outside the section to run in parallel. **ORDERED** sections that bind to different **DO** directives are independent of each other.

The following restrictions apply to the **ORDERED** directive:

- An **ORDERED** directive cannot bind to a **DO** directive that does not have the **ORDERED** clause specified.
- An iteration of a loop with a **DO** directive must not execute the same **ORDERED** directive more than once, and it must not execute more than one **ORDERED** directive.

Data Environment Constructs

This section discusses constructs for controlling the data environment during the execution of parallel constructs.

THREADPRIVATE Directive

The **THREADPRIVATE** directive makes named common blocks private to a thread but global within the thread. In other words, each thread executing a **THREADPRIVATE** directive receives its own private copy of the named common blocks, which are then available to it in any routine within the scope of an application.

This directive must appear in the declaration section of the routine after the declaration of the listed common blocks. Each thread gets its own copy of the common block, so data written to the common block by one thread is not directly visible to other threads. During serial portions and **MASTER** sections of the program, accesses are to the master thread's copy of the common block.

On entry to the first parallel region, data in the **THREADPRIVATE** common blocks should be assumed to be undefined unless a **COPYIN** clause is specified on the **PARALLEL** directive (the **COPYIN** clause is discussed in "COPYIN Clause" on page 91).

When a common block that is initialized using **DATA** statements appears in a **THREADPRIVATE** directive, each thread's copy is initialized once prior to its first use. For subsequent parallel regions, the data in the **THREADPRIVATE** common blocks are guaranteed to persist only if the dynamic threads mechanism has been disabled and if the number of threads are the same for all the parallel regions.

For more information about dynamic threads, see the **OMP_SET_DYNAMIC** library routine and the **OMP_DYNAMIC** environment variable on the pe_environ(5) man page.

The format of this directive is as follows:

```
C$OMP THREADPRIVATE(/cb/[,/cb/]...)
```

The *cb* argument is the name of the common block to be made private to a thread. Only named common blocks can be made thread private.

The following restrictions apply to the **THREADPRIVATE** directive:

- The **THREADPRIVATE** directive must appear after every declaration of a thread private common block.
- You cannot use a **THREADPRIVATE** common block or its constituent variables in any clause other than a **COPYIN** clause. As a result, they are not permitted in a **PRIVATE**, **FIRSTPRIVATE**, **LASTPRIVATE**, **SHARED**, or **REDUCTION** clause. They are not affected by the **DEFAULT** clause.

Data Scope Attribute Clauses

Several directives accept clauses that allow a user to control the scope attributes of variables for the duration of the construct. Not all of the clauses in this section are allowed on all directives, but the clauses that are valid on a particular directive are included with the description of the directive. Usually, if no data scope clauses are specified for a directive, the default scope for variables affected by the directive is **SHARED**.

The following clauses to control scope attributes are discusssed in this section:

- **PRIVATE**
- **SHARED**
- **DEFAULT**
- **FIRSTPRIVATE**
- **LASTPRIVATE**
- **REDUCTION**
- **COPYIN**

PRIVATE Clause

The **PRIVATE** clause declares variables to be private to each thread in a team.

This clause has the following format:

```
PRIVATE(var[, var]...)
```

The *var* argument is a named variable or named common block that is accessible in the scoping unit. Subobjects cannot be specified. If a named common block is specified, its name must appear between slashes.

The behavior of a variable declared in a **PRIVATE** clause is as follows:

- A new object of the same type is declared once for each thread in the team. The new object is no longer storage-associated with the storage location of the original object.
- All references to the original object in the lexical extent of the directive construct are replaced with references to the private object.
- Variables defined as **PRIVATE** are undefined for each thread on entering the construct and the corresponding shared variable is undefined on exit from a parallel construct.
- Contents, allocation state, and association status of variables defined as **PRIVATE** are undefined when they are referenced outside the lexical extent (but inside the dynamic extent) of the construct, unless they are passed as actual arguments to called routines.

SHARED Clause

The **SHARED** clause makes variables shared among all the threads in a team. All threads within a team access the same storage area for **SHARED** data.

This clause has the following format:

```
SHARED(var[, var] ...)
```

The *var* argument is a named variable or named common block that is accessible in the scoping unit. Subobjects cannot be specified. If a named common block is specified, its name must appear between slashes.

DEFAULT Clause

The **DEFAULT** clause allows the user to specify a **PRIVATE**, **SHARED**, or **NONE** default scope attribute for all variables in the lexical extent of any parallel region. Variables in **THREADPRIVATE** common blocks are not affected by this clause.

This clause has the following format:

```
DEFAULT(PRIVATE | SHARED | NONE)
```

The **PRIVATE**, **SHARED**, and **NONE** specifications have the following effects:

- Specifying **DEFAULT(PRIVATE)** makes all named objects in the lexical extent of the parallel region, including common block variables but excluding **THREADPRIVATE** variables, private to a thread as if each variable were listed explicitly in a **PRIVATE** clause.
- Specifying **DEFAULT(SHARED)** makes all named objects in the lexical extent of the parallel region shared among the threads in a team, as if each variable were listed explicitly in a **SHARED** clause. In the absence of an explicit **DEFAULT** clause, the default behavior is the same as if **DEFAULT(SHARED)** were specified.
- Specifying **DEFAULT(NONE)** declares that there is no implicit default as to whether variables are **PRIVATE** or **SHARED**. In this case, the **PRIVATE**, **SHARED**, **FIRSTPRIVATE**, **LASTPRIVATE**, or **REDUCTION** attribute of each variable used in the lexical extent of the parallel region must be specified.

Only one **DEFAULT** clause can be specified on a **PARALLEL** directive.

Variables can be exempted from a defined default using the **PRIVATE**, **SHARED**, **FIRSTPRIVATE**, **LASTPRIVATE**, and **REDUCTION** clauses. As a result, the following example is valid:

```
C$OMP PARALLEL DO DEFAULT(PRIVATE), FIRSTPRIVATE(I),SHARED(X),
C$OMP& SHARED(R) LASTPRIVATE(I)
```

FIRSTPRIVATE Clause

The **FIRSTPRIVATE** clause provides a superset of the functionality provided by the **PRIVATE** clause.

This clause has the following format:

```
FIRSTPRIVATE(var[, var] ...)
```

The *var* argument is a named variable or named common block that is accessible in the scoping unit. Subobjects cannot be specified. If a named common block is specified, its name must appear between slashes.

Variables specified are subject to **PRIVATE** clause semantics as described previously. In addition, private copies of the variables are initialized from the original object existing before the construct.

LASTPRIVATE Clause

The **LASTPRIVATE** clause provides a superset of the functionality provided by the **PRIVATE** clause.

When the **LASTPRIVATE** clause appears on a **DO** directive, the thread that executes the sequentially last iteration updates the version of the object it had before the construct. When the **LASTPRIVATE** clause appears in a **SECTIONS** directive, the thread that executes the lexically last **SECTION** updates the version of the object it had before the construct. Subobjects that are not assigned a value by the last iteration of the **DO** or the lexically last **SECTION** of the **SECTIONS** directive are undefined after the construct.

This clause has the following format:

`LASTPRIVATE(`*var*`[, var] ...)`

The *var* argument is a named variable or named common block that is accessible in the scoping unit. Subobjects cannot be specified. If a named common block is specified, its name must appear between slashes.

Each *var* is subject to the **PRIVATE** clause semantics described previously.

REDUCTION Clause

This clause performs a reduction on the variables specified, with the operator or the intrinsic specified. These can only be used on scalar variables of **INTRINSIC** type.

This clause has the following format:

`REDUCTION({`*operator*`|`*intrinsic*`}:`*var*`[, var] ...)`

Specify one of the following for *operator*: **+**, *****, **-**, **.AND.**, **.OR.**, **.EQV.**, or .**NEQV. .**

Specify one of the following for *intrinsic*: **MAX**, **MIN**, **IAND**, **IOR**, or **IEOR**.

The *var* argument is a named variable or named common block that is accessible in the scoping unit. Subobjects cannot be specified. Each *var* must be a named scalar variable of intrinsic type.

Variables that appear in a **REDUCTION** clause must be **SHARED** in the enclosing context. A private copy of each var is created for each thread as if the **PRIVATE** clause had been used. The private copy is initialized according to the operator. If a named common block is specified, its name must appear between slashes.

At the end of the **REDUCTION**, the shared variable is updated to reflect the result of combining the original value of the (shared) reduction variable with the final value of each of the private copies using the operator specified. The reduction operators are all associative (except for subtraction), and the compiler can freely reassociate the computation of the final value (the partial results of a subtraction reduction are added to form the final value).

The value of the shared variable becomes undefined when the first thread reaches the containing clause, and it remains so until the reduction computation is complete. Normally, the computation is complete at the end of the **REDUCTION** construct; however, if the **REDUCTION** clause is used on a construct to which **NOWAIT** is also applied, the shared variable remains undefined until a barrier synchronization has been performed to ensure that all the threads have completed the **REDUCTION** clause.

The **REDUCTION** clause is intended to be used on a region or work-sharing construct in which the reduction variable is used only in reduction statements with one of the following forms:

- *x = x operator expr*
- *x = expr operator x* (except for subtraction)
- *x = intrinsic (x,expr)*
- *x = intrinsic (expr, x)*

Some reductions can be expressed in other forms. For instance, a **MAX** reduction might be expressed as follows:

```
IF (x .LT. expr) x = expr
```

Alternatively, the reduction might be hidden inside a subroutine call. The user should be careful that the operator specified in the **REDUCTION** clause matches the reduction operation.

The following table lists the operators and intrinsics that are valid and their canonical initialization values. The actual initialization value will be consistent with the data type of the reduction variable.

Operator	Initialization
+	0
*	1
_	0
.AND.	.TRUE.
.OR.	.FALSE.
.EQV.	.TRUE.
.**NEQV**.	.FALSE.
MAX	Smallest representable number
MIN	Largest representable number
IAND	All bits on
IOR	0
IEOR	0

Any number of reduction clauses can be specified on the directive, but a variable can appear only once in a **REDUCTION** clause for that directive. The following is an example:

```
C$OMP DO REDUCTION(+: A, Y) REDUCTION(.OR.: AM)
```

COPYIN Clause

The **COPYIN** clause applies only to common blocks that are declared **THREADPRIVATE (**discussed in"THREADPRIVATE Directive" on page 85). A **COPYIN** clause on a parallel region specifies that the data in the master thread of the team be copied to the thread private copies of the common block at the beginning of the parallel region.

This clause has the following format:

```
COPYIN(var[, var] ...)
```

The *var* argument is a named variable or named common block that is accessible in the scoping unit. Subobjects cannot be specified. If a named common block is specified, its name must appear between slashes. It is not necessary to specify a whole common block to be copied in.

Example. In the following example, the common blocks **BLK1** and **FIELDS** are specified as **THREADPRIVATE**, but only one of the variables in common block **FIELDS** is specified to be copied in:

```
      COMMON /BLK1/ SCRATCH
      COMMON /FIELDS/ XFIELD, YFIELD, ZFIELD
C$OMP THREADPRIVATE(/BLK1/, /FIELDS/)
C$OMP PARALLEL DEFAULT(PRIVATE) COPYIN(/BLK1/,ZFIELD)
```

Data Scope Rules and Restrictions

The following rules and restrictions apply with respect to data scope:

- Sequential **DO** loop control variables in the lexical extent of a **PARALLEL** region that would otherwise be **SHARED** based on default rules are automatically made private on the **PARALLEL** directive. Sequential **DO** loop control variables with no enclosing **PARALLEL** region are not classified automatically. It is the user's responsibility to guarantee that these indexes are private if the containing procedures are called from a **PARALLEL** region.

  All implied **DO** loop control variables are automatically made private at the enclosing implied **DO** construct.

- Variables that are made private in a parallel region cannot be made private again on an enclosed work-sharing directive. As a result, variables that appear in the **PRIVATE**, **FIRSTPRIVATE**, **LASTPRIVATE**, and **REDUCTION** clauses on a work-sharing directive have shared scope in the enclosing parallel region.

- A variable that appears in a **PRIVATE**, **FIRSTPRIVATE**, **LASTPRIVATE**, or **REDUCTION** clause must be definable.

- **PRIVATE** or **SHARED** attributes can be declared for a Cray pointer but not for the pointee. The scope attribute for the pointee is determined at the point of pointer definition. You cannot declare a scope attribute for a pointee. Cray pointers cannot be specified in **FIRSTPRIVATE** or **LASTPRIVATE** clauses.

- Scope clauses apply only to variables in the static extent of the directive on which the clause appears, with the exception of variables passed as actual arguments. Local variables in called routines that do not have the **SAVE** attribute are **PRIVATE**. Common blocks in called routines in the dynamic extent of a parallel region always have an implicit **SHARED** attribute, unless they are **THREADPRIVATE** common blocks.
- When a named common block is declared as **PRIVATE**, **FIRSTPRIVATE**, or **LASTPRIVATE**, none of its constituent elements may be declared in another scope attribute. When individual members of a common block are privatized, the storage of the specified variables is no longer associated with the storage of the common block itself.
- Variables that are not allowed in the **PRIVATE** and **SHARED** clauses are not affected by **DEFAULT(PRIVATE)** or **DEFAULT(SHARED)** clauses, respectively.
- Clauses can be repeated as needed, but each variable can appear explicitly in only one clause per directive; the exception is that a variable can be specified as both **FIRSTPRIVATE** and **LASTPRIVATE**.

Variables affected by the **DEFAULT** clause can be listed explicitly in a clause to override the default specification.

Directive Binding

Some directives are bound to other directives. A binding specifies the way in which one directive is related to another. For instance, a directive is bound to a second directive if it can appear **DEFAULT** in the dynamic extent of that second directive. The following rules apply with respect to the dynamic binding of directives:

- The **DO**, **SECTIONS**, **SINGLE**, **MASTER**, and **BARRIER** directives bind to the dynamically enclosing **PARALLEL** directive, if one exists.
- The **ORDERED** directive binds to the dynamically enclosing **DO** directive.
- The **ATOMIC** directive enforces exclusive access with respect to **ATOMIC** directives in all threads, not just the current team.
- The **CRITICAL** directive enforces exclusive access with respect to **CRITICAL** directives in all threads, not just the current team.
- A directive can never bind to any directive outside the closest enclosing **PARALLEL**.

Directive Nesting

The following rules apply to the dynamic nesting of directives:

- A **PARALLEL** directive dynamically inside another **PARALLEL** directive logically establishes a new team, which is composed of only the current thread.
- **DO**, **SECTIONS**, and **SINGLE** directives that bind to the same **PARALLEL** directive cannot be nested one inside the other.
- **DO**, **SECTIONS**, and **SINGLE** directives are not permitted in the dynamic extent of **CRITICAL** and **MASTER** directives.
- **BARRIER** directives are not permitted in the dynamic extent of **DO**, **SECTIONS**, **SINGLE**, **MASTER**, and **CRITICAL** directives.
- **MASTER** directives are not permitted in the dynamic extent of **DO**, **SECTIONS**, and **SINGLE** directives.
- **ORDERED** sections are not allowed in the dynamic extent of **CRITICAL** sections.
- Any directive set that is legal when executed dynamically inside a **PARALLEL** region is also legal when executed outside a parallel region. When executed dynamically outside a user-specified parallel region, the directive is executed with respect to a team composed of only the master thread.

Chapter 6

Parallel Programming on Origin2000

This chapter describes the support provided for writing parallel programs on Origin2000. It assumes that you are familiar with basic parallel constructs. For more information about parallel constructs, refer to Chapter 5, "OpenMP Multiprocessing Directives."

Topics covered in this chapter include:

A subset of the mechanisms described in this chapter are supported for C and C++, and are described in the *C Language Reference Manual*, Chapter 11. You can find additional information on parallel programming in "Models of Parallel Computation" in *Topics in IRIX Programming*.

Note: The multiprocessing features described in this chapter require support from the MP run-time library (*libmp*). IRIX operating system versions 6.3 (and above) are automatically shipped with this new library. If you wish to access these features on a machine running IRIX 6.2, contact your local Silicon Graphics service provider or SGI Customer Support (1-800-800-4744) for *libmp*.

Performance Tuning of Parallel Programs on Origin2000

Origin2000 provides cache-coherent, shared memory in the hardware. Memory is physically distributed across processors. Consequently, references to locations in the remote memory of another processor take substantially longer (by a factor of two or more) to complete than references to locations in local memory. This can severely affect the performance of programs that suffer from a large number of cache misses. Figure 6-1 shows a simplified version of the Origin2000 memory hierarchy.

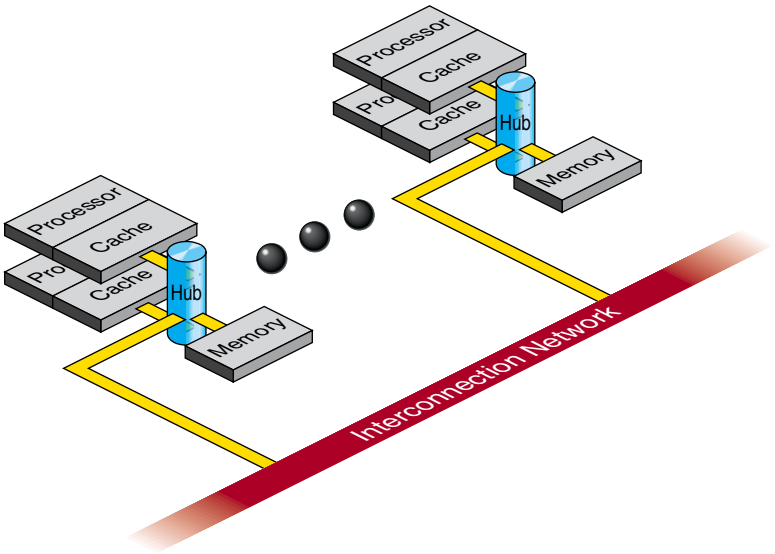


Figure 6-1 Origin2000 Memory Hierarchy

Improving Program Performance

To obtain good performance in such programs, it is important to schedule computation and distribute data across the underlying processors and memory modules, so that most cache misses are satisfied from local rather than remote memory. The primary goal of the programming support, therefore, is to enable user control over data placement and computation scheduling.

Cache behavior continues to be the largest single factor affecting performance, and programs with good cache behavior usually have little need for explicit data placement. In programs with high cache misses, if the misses correspond to true data communication between processors, then data placement is unlikely to help. In these cases, it may be necessary to redesign the algorithm to reduce inter-processor communication. Figure 6-2 shows this scenario.

If the misses are to data that is referenced primarily by a single processor, data placement may be able to convert remote references to local references, thereby reducing the latency of the miss. The possible options for data placement are automatic page migration or explicit data distribution, either regular or reshaped (both of these are described in "Regular Data Distribution" on page 108 and "Data Distribution With Reshaping" on page 108). The differences between these choices are shown in Figure 6-2.

Automatic page migration requires no user intervention and is based on the run-time cache miss behavior of the program. It can therefore adjust to dynamic changes in the reference patterns. However, the page migration heuristics are deliberately conservative, and may be slow to react to changes in the references patterns. They are also limited to performing page-level allocation of data.

Regular data distribution (performing just page-level placement of the array) is also limited to page-level allocation, but is useful when the page migration heuristics are slow and the desired distribution is known to the programmer.

Finally, reshaped data distribution changes the layout of the array thereby overcoming the page-level allocation constraints; however, it is useful only if a data structure has the same (static) distribution for the duration of the program. Given these differences, it may be necessary to use each of these options for different data structures in the same program.

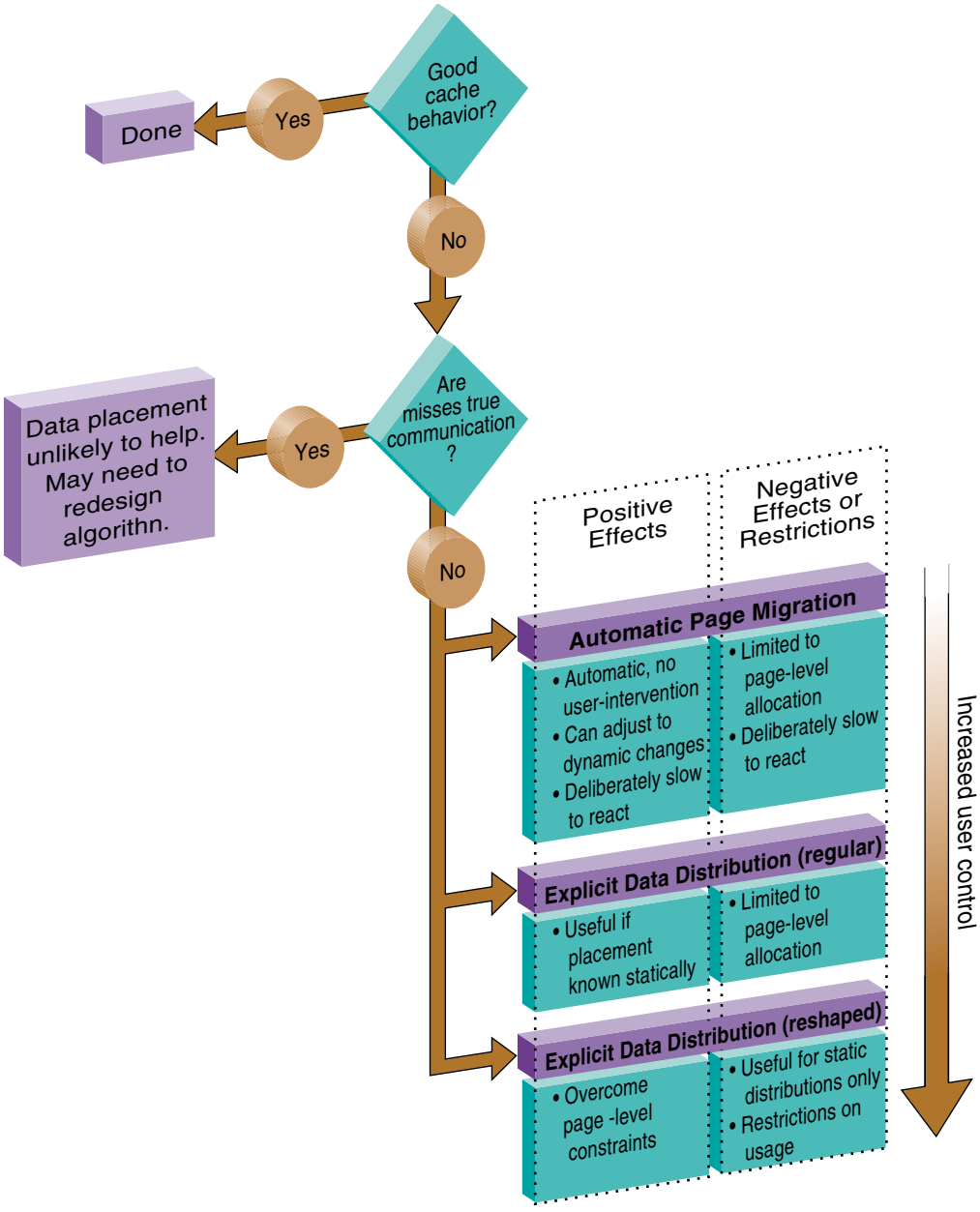


Figure 6-2 Cache Behavior and Solutions

Choosing Between Multiple Options

For a given data structure in the program, you can choose from the options described above based on the following criteria:

- If the program repeatedly references the data structure and benefits from reuse in the cache, then data placement is not needed.
- If the program incurs a large number of cache misses on the data structure, then you should identify the desired distribution in the array dimensions (such as BLOCK or CYCLIC, described in "Data Distribution Directives" on page 102) based on the desired parallelism in the program. For example, the code below suggests a distribution A(BLOCK, *):

  ```
  c$doacross
  do i=2,n
    do j=2,n
      A(i,j) = 3*i + 4*j + A(i, j-1)
    enddo
  enddo
  ```

  Whereas, the next code segment suggests a distribution of A(*, BLOCK):

  ```
  do i=2,n
  c$doacross
    do j=2,n
      A(i,j) = 3*i + 4*j + A(i-1, j)
    enddo
  enddo
  ```

- After identifying the desired distribution, you can select either regular and reshaped distribution based on the size of an individual processor's portion of the distributed array. Regular distribution is useful only if each processor's portion is substantially larger than the page-size in the underlying system (16KBytes on the Origin2000). Otherwise regular distribution is unlikely to be useful, and you should use **distribute_reshape**, where the compiler changes the layout of the array to overcome page-level constraints.

For example, consider the following code:

```
real*8 A(m, n)
c$distribute A(BLOCK, *)
```

In this example, the size of each processor's portion is approximately m/P elements (8*(m/P) bytes), where P is the number of processors. If m is 1000,000 then each processor's portion is likely to exceed a page and regular distribution is sufficient. If instead m is 10,000 then distribute_reshape is required to obtain the desired distribution.

In contrast, consider the following distribution:

```
c$distribute A(*, BLOCK)
```

In this example, the size of each processor's portion is approximately (m*n)/P elements (8*(m*n)/P bytes). So if n is 100 (for instance), regular distribution may be sufficient even if m is only 10,000.

As this example illustrates, distributing the outer dimensions of an array increases the size of an individual processor's portion (favoring regular distribution), whereas distributing the inner dimensions is more likely to require reshaped distribution.

Finally, the IRIX operating system on Origin2000 follows a default "first-touch" page-allocation policy; that is, each page is allocated from the local memory of the processor that incurs a page-fault on that page. Therefore, in programs where the array is initialized (and consequently first referenced) in parallel, even a regular distribution directive may not be necessary, since the underlying pages are allocated from the desired memory location automatically due to the first-touch policy.

New Directives for Performance Tuning on Origin2000

The programming support consists of extensions to the existing Power Fortran/C directives/pragmas. Table 6-1 summarizes the new directives. Like the other Power Fortran/C directives, these new directives are ignored except under multiprocessor compilation.

Table 6-1 Summary of New Directives

Directive	Description
c$distribute A (<*dist*>, <*dist*>, • • •) [a]	Data distribution
c$redistribute A(<*dist*>, <*dist*>)	Dynamic data redistribution
c$dynamic A	Redistributable annotation
c$distribute_reshape B(<*dist*>)	Data distribution with reshaping
c*$*fill_symbol, c*$*align_symbol	Pad and align variables within pages of memory and cachelines (see the *MIPSpro Compiling and Performance Tuning Guide*.
c$page_place (<*addr*>, <*sz*>, <*thread*>)	Explicit placement of data
c$doacross affinity (i) = data (A(i))	Data-affinity scheduling
c$doacross affinity (i) = thread (<*expr*>)	Thread-affinity scheduling
c$doacross nest (i,j)	Nested doacross

a. <*dist*> can be one of BLOCK, CYCLIC, CYCLIC(<*expr*>), or "*". CYCLIC by itself implies a chunk size of 1. For performance reasons, CYCLIC(3) and CYCLIC(*k*) (where *k* has a run-time value of 3), may be incompatible when passing a reshaped array as a parameter to another routine.

The data distribution directives and **doacross** nest directive have an optional **ONTO** clause (described in "Specifying Processor Topology With the ONTO Clause" on page 107) to control the partitioning of processors across multiple dimensions.

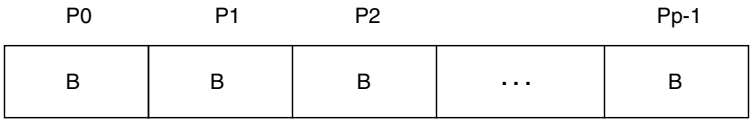
Data Distribution Directives

The data distribution directives allow you to specify High Performance Fortran-like distributions for array data structures. For irregular data structures, directives are provided to explicitly place data directly on a specific processor.

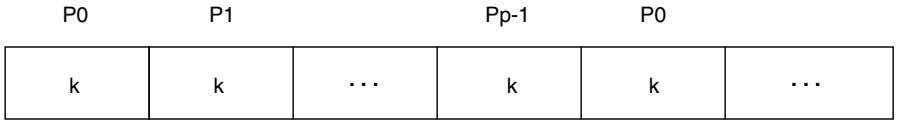
The **distribute**, **dynamic**, and **distribute_reshape** directives are declarations that must be specified in the declaration part of the program, along with the array declaration. The **redistribute** directive is an executable statement and can appear in any executable portion of the program.

You can specify a data distribution directive for any local, global, or common-block array. Each dimension of a multi-dimensional array can be independently distributed. The possible distribution types for an array dimension are BLOCK, CYCLIC (<*expr*>), and * (asterisk not distributed). (A CYCLIC distribution with a chunk size that is either greater than 1 or is determined at runtime is sometimes also called BLOCK-CYCLIC.)

A BLOCK distribution partitions the elements of the dimension of size *N* into *P* blocks (one per processor), with each block of size B = ceiling (*N*/*P*).



A CYCLIC(*k*) distribution partitions the elements of the dimension into pieces of size *k* each, and distributes them sequentially across the processors.



A distributed array is distributed across all of the processors being used in that particular execution of the program, as determined by the environment variable **MP_SET_NUMTHREADS**. If a distributed array is distributed in more than one dimension, then by default the processors are apportioned as equally as possible across each distributed dimension. For instance, if an array has two distributed dimensions, then an execution with 16 processors assigns 4 processors to each dimension (4 x 4=16), whereas an execution with 8 processors assigns 4 processors to the first dimension and 2 processors to the second dimension. You can override this default and explicitly control the number of processors in each dimension using the ONTO clause along with a data distribution directive.

Nested Doacross Directive

The nested **doacross** directive allows you to exploit nested concurrency in a limited manner. Although true nested parallelism is not supported, you can exploit parallelism across iterations of a perfectly nested loop-nest. For example:

```
c$doacross nest(i, j)
do i = 1, n
   do j = 1, m
      A(i,j) = 0
   enddo
enddo
```

This directive specifies that the entire set of iterations across the `(i, j)` loops can be executed concurrently. The restriction is that the `do-i` and `do-j` loops must be *perfectly nested*, that is, no code is allowed between either the `do-i` and `do-j` statements or the `enddo-i` and `enddo-j` statements. You can also supply the nest clause with the PCF **pdo** directive.

The existing clauses such as LOCAL and SHARED behave as before. You can combine a nested **doacross** with an affinity clause (as shown below), or with a schedtype of simple or interleaved (**dynamic** and **gss** are not currently supported). The default is simple scheduling, except when accessing reshaped arrays (see "Affinity Scheduling" on page 104).

```
c$doacross nest(i, j) affinity(i,j) = data(A(i,j))
do i = 2, n-1
   do j = 2, m-1
      A(i,j) = A(i,j) + i*j
   enddo
enddo
```

Affinity Scheduling

The goal of affinity scheduling is to control the mapping of iterations of a parallel loop for execution onto the underlying threads. Specify affinity scheduling with an additional clause to a **doacross** directive. An affinity clause, if supplied, overrides the SCHEDTYPE clause. This section describes the following topics:

- "Data Affinity" on page 104
- "Thread Affinity" on page 106

Data Affinity

The following code shows an example of data affinity:

```
c$distribute A(block)
c$doacross affinity(i) = data(A(a*i+b))
do i = 1, n
   A(a*i+b) = 0
enddo
```

The multiplier for the loop index variable (`a`) and the constant term (`b`) must both be literal constants, with `a` greater than zero.

The effect of this clause is to distribute the iterations of the parallel loop to match the data distribution specified for the array `A`, such that iteration `i` is executed on the processor that owns element `A(a*i+b)` based on the distribution for `A`. The iterations are scheduled based on the specified distribution, and are not affected by the actual underlying data-distribution (which may differ at page boundaries, for example).

In case of a multi-dimensional array, affinity is provided for the dimension that contains the loop-index variable. The loop-index variable cannot appear in more than one dimension in an affinity directive. For example:

```
c$distribute A (block, cyclic(1))
c$doacross affinity (i) = data (A(i+3, j))
do i = 1,n
  do j = 1,n
    A(i+3, j) = A(i+3,j-1)
  enddo
enddo
```

In this example, the loop is scheduled based on the block-distribution of the first dimension. Information on **doacross** is in "Nested Doacross Directive" on page 103. The affinity clause is also available with the PCF **pdo** directive.

The default schedtype for parallel loops is SIMPLE. However, under **–O3** compilation, loops that reference reshaped arrays default to data-affinity scheduling for the most frequently accessed reshaped array in the loop (chosen heuristically by the compiler). To obtain SIMPLE scheduling even at **–O3**, you can explicitly specify the schedtype on the parallel loop.

Data affinity for loops with non-unit stride can sometimes result in non-linear affinity expressions. In such situations the compiler issues a warning, ignores the affinity clause, and defaults to simple scheduling.

Data Affinity for Redistributed Arrays

By default, the compiler assumes that a distributed array is not dynamically redistributed, and directly schedules a parallel loop for the specified data affinity. In contrast, a redistributed array can have multiple possible distributions, and data affinity for a redistributed array must be implemented in the run-time system based on the particular distribution.

However, the compiler does not know whether or not an array is redistributed, since the array may be redistributed in another function (possibly even in another file). Therefore, you must explicitly specify the **c$dynamic** declaration for redistributed arrays. This directive is required only in those functions that contain a **doacross** loop with data affinity for that array (see "Nested Doacross Directive" on page 103 for additional information). This informs the compiler that the array can be dynamically redistributed. Data affinity for such arrays is implemented through a run-time lookup.

Implementing data affinity through a run-time lookup incurs some extra overhead compared to a direct compile-time implementation. You can avoid this overhead when a subroutine contains data affinity for a redistributed array and the distribution of the array for the entire duration of that subroutine is known. In this situation, you can supply the **c$distribute** directive with the particular distribution and omit the **c$dynamic** directive.

By default, the compiler assumes that a distributed array is **not** redistributed at runtime. As a result, the distribution is known at compile time, and data affinity for the array can be implemented directly by the compiler. In contrast, since a redistributed array can have multiple possible distributions at runtime, data affinity for a redistributed array is implemented in the run-time system based on the distribution at runtime, incurring extra run-time overhead.

If an array is redistributed in the program, then you can explicitly specify a **c$dynamic** directive for that array. The only effect of the **c$dynamic** directive is to implement data affinity for that array at runtime rather than at compile time. If you know an array has a specified distribution throughout the duration of a subroutine, then you do not have to supply the **c$dynamic** directive. The result is more efficient compile time affinity scheduling.

Since reshaped arrays cannot be dynamically redistributed, this is an issue only for regular data distribution.

Data Affinity for a Formal Parameter

You can supply a **c$distribute** directive on a formal parameter, thereby specifying the distribution on the incoming actual parameter. If different calls to the subroutine have parameters with different distributions, then you can omit the **c$distribute** directive on the formal parameter; data affinity loops in that subroutine are automatically implemented through a run-time lookup of the distribution. (This is permissible only for regular data distribution. For reshaped array parameters, the distribution must be fully specified on the formal parameter.)

Thread Affinity

Similar to data affinity, you can specify thread affinity as an additional clause on a **doacross** directive (refer to "Nested Doacross Directive" on page 103 for details). The syntax for thread affinity is as follows:

```
c$doacross affinity (i) = thread(<expr>)
```

The effect of this directive is to execute iteration `i` on the thread number given by the user-supplied expression (modulo the number of threads). Since the threads may need to evaluate this expression in each iteration of the loop, the variables used in the expression (other than the loop induction variable) must be declared shared and must not be modified during the execution of the loop. Violating these rules can lead to incorrect results.

If the expression does not depend on the loop induction variable, then all iterations will execute on the same thread and will not benefit from parallel execution.

Specifying Processor Topology With the ONTO Clause

This clause allows you to specify the processor topology when two (or more) dimensions of processors are required. For instance, if an array is distributed in two dimensions, then you can use the ONTO clause to specify how to partition the processors across the distributed dimensions. Or, in a nested **doacross** with two or more nested loops, use the ONTO clause to specify the partitioning of processors across the multiple parallel loops. The ONTO clause is also available with the PCF **pdo** directive.

For example:

```
C Assign processor in the ratio 1:2 to the two dimension
real*8 A (100, 200)
c$distribute A (block, block) onto (1, 2)

C Use 2 processors in the do-i loop, and the remaining in the do-j loop
c$doacross nest (i, j) onto (2, *)
do i = 1, n
  do j = 1, m
    • • •
  enddo
enddo
```

Types of Data Distribution

There are two types of data distribution: *regular* and *reshaped*. The following sections describe each of these distributions.

Regular Data Distribution

The regular data distribution directives try to achieve the desired distribution solely by influencing the mapping of virtual addresses to physical pages without affecting the layout of the data structure. Since the granularity of data allocation is a physical page (at least 16 Kbytes), the achieved distribution is limited by the underlying page-granularity. However, the advantages are that regular data distribution directives can be added to an existing program without any restrictions, and can be used for affinity scheduling (see "Data Affinity" on page 104).

Distributed arrays can be dynamically redistributed with the following redistribute statement:

```
c$redistribute A (block, cyclic(k))
```

The **redistribute** is an executable statement that changes the distribution "permanently" (or until another **redistribute** statement). It also affects subsequent affinity scheduling.

The **c$dynamic** directive specifies that the named array is redistributed in the program, and is useful in controlling affinity scheduling for dynamically redistributed arrays. It is discussed in "Data Affinity for Redistributed Arrays" on page 105.

Data Distribution With Reshaping

Similar to regular data distribution, the **reshape** directive specifies the desired distribution of an array. In addition, however, the **reshape** directive declares that the program makes no assumptions about the storage layout of that array. The compiler performs aggressive optimizations for reshaped arrays that violate standard Fortran-77 layout assumptions but guarantee the desired data distribution for that array.

The **reshape** directive accepts the same distributions as the regular data distribution directive, but uses a different keyword, as shown below:

```
c$distribute_reshape A(block, cyclic(1))
```

Restrictions on Reshaped Arrays

Since the **distribute_reshape** directive specifies that the program does not depend on the storage layout of the reshaped array, restrictions on the arrays that can be reshaped include the following:

- The distribution of a reshaped array cannot be changed dynamically (that is, there is no **redistribute_reshape** directive).
- Initialized data cannot be reshaped.
- Arrays that are explicitly allocated through **alloca/malloc** and accessed through pointers cannot be reshaped.
- An array that is equivalenced to another array cannot be reshaped.
- I/O for a reshaped array cannot be mixed with namelist I/O or a function call in the same I/O statement.
- A COMMON block containing a reshaped array cannot be linked **–Xlocal**.

  Caution: This user error is **not** caught by the compiler/linker.

If a reshaped array is passed as an actual parameter to a subroutine, two possible scenarios exist:

- The array is passed in its entirety (`call func(A)` passes the entire array `A`, whereas `call func(A(i,j))` passes a portion of `A`). The compiler automatically clones a copy of the called subroutine and compiles it for the incoming distribution. The actual and formal parameters must match in the number of dimensions, and the size of each dimension.

  You can restrict a subroutine to accept a particular reshaped distribution on a parameter by specifying a **distribute_reshape** directive on the formal parameter within the subroutine. All calls to this subroutine with a mismatched distribution will lead to compile- or link-time errors.
- A portion of the array can be passed as a parameter, but the callee must access only a single processor's portion. If the callee exceeds a single processor's portion, then the results are undefined. You can use intrinsics to access details about the array distribution (described in "Query Intrinsics for Distributed Arrays" on page 110).

Error-Detection Support

Most errors in accessing reshaped arrays are caught either at compile time or at link time. These include:

- Inconsistencies in reshaped arrays across COMMON blocks (including across files)
- Declaring a reshaped array EQUIVALENCED to another array
- Inconsistencies in reshaped distributions on actual and formal parameters
- Other errors such as disallowed I/O statements involving reshaped arrays, reshaping initialized data, or reshaping dynamically allocated data

Errors such as matching the declared size of an array dimension typically are caught only at runtime. The compiler option, **–MP:check_reshape=on**, generates code to perform these tests at runtime. These run-time checks are not generated by default, since they incur overhead, but are useful during program development.

The run-time checks include:

- Inconsistencies in array-bound declarations on each actual and formal parameter
- Inconsistencies in declared bounds of a formal parameter that corresponds to a portion of a reshaped actual parameter.

Query Intrinsics for Distributed Arrays

You can use the following set of intrinsics to obtain information about an individual dimension of a distributed array. Fortran array dimensions are numbered starting at 1. All routines work with 64-bit integers as shown below, and return -1 in case of an error (except **dsm_this_startingindex** where -1 may be a legal return value).

```
extern INT64 dsm_numthreads (void* array, INT64 dim)
```
Called with a distributed array and a dimension number. Returns the number of threads in that dimension.

```
extern INT64 dsm_chunksize (void* array, INT64 dim)
```
Returns the chunk size (ignoring partial chunks) in the given dimension for each of block, cyclic(..), and star distributions.

`extern INT64 dsm_this_chunksize (void* array,INT64 dim,INT64 index)`
Returns the chunk size for the chunk containing the given index value for each of block, cyclic(..), and star. This value may be different from `dsm_chunksize` due to edge effects that may lead to a partial chunk.

`extern INT64 dsm_rem_chunksize (void* array,INT64 dim,INT64 index)`
Returns the *remaining* chunk size from `index` to the end of the current chunk, inclusive of each end point. Essentially it is the distance from `index` to the end of that contiguous block, inclusive.

`extern INT64 dsm_this_startingindex (void* array,INT64 dim,INT64 index)`
Returns the starting index value of the chunk containing the supplied index.

`extern INT64 dsm_numchunks (void* array, INT64 dim)`
Returns the number of chunks (including partial chunks) in given `dim` for each of block, cyclic(..), and star distributions.

`extern INT64 dsm_this_threadnum(void* array,INT64 dim,INT64 index)`
Returns the thread number for the chunk containing the given index value for each of block, cyclic(..), and star distributions.

```
extern INT64 dsm_distribution_block  (void* array, INT64 dim)
extern INT64 dsm_distribution_cyclic (void* array, INT64 dim)
```

`extern INT64 dsm_distribution_star   (void* array, INT64 dim)`
Boolean routines to query the distribution of a given dimension.

`extern INT64 dsm_isreshaped (void* array)`
Boolean routine to query whether reshaped or not.

`extern INT64 dsm_isdistributed (void* array)`
Boolean routine to query whether distributed (regular or reshaped) or not.

Implementation of Reshaped Arrays

The compiler transforms a reshaped array into a pointer to a "processor array." The processor array has one element per processor, with the element pointing to the portion of the array local to the corresponding processor.

Figure 6-3 shows the effect of the **distribute_reshape** directive with a BLOCK distribution on a 1-dimensional array. *N* is the size of the array dimension, *P* is the number of processors, and *B* is the block-size on each processor, ceiling = (*N*/*P*).

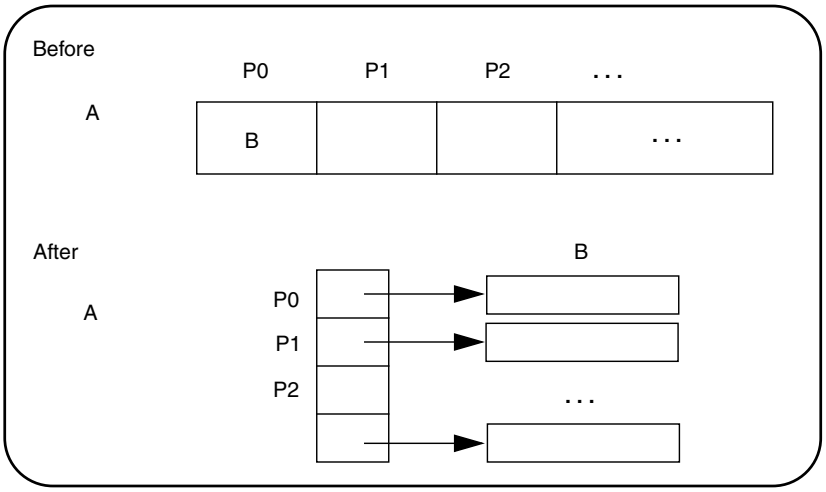


Figure 6-3 Implementation of BLOCK Distribution

With this implementation, an array reference **A(i)** is transformed into a two-dimensional reference **A[i/B] [i%B]** (in C syntax with C dimension order), where *B* is the size of each block, and given by ceiling (*N*/*P*). Thus **A[i/B]** points to a processor's local portion of the array, and **A[i/B][i%B]** refers to a specific element within the local processor's portion.

A CYCLIC distribution with a chunk size of 1 is implemented as shown in Figure 6-4.

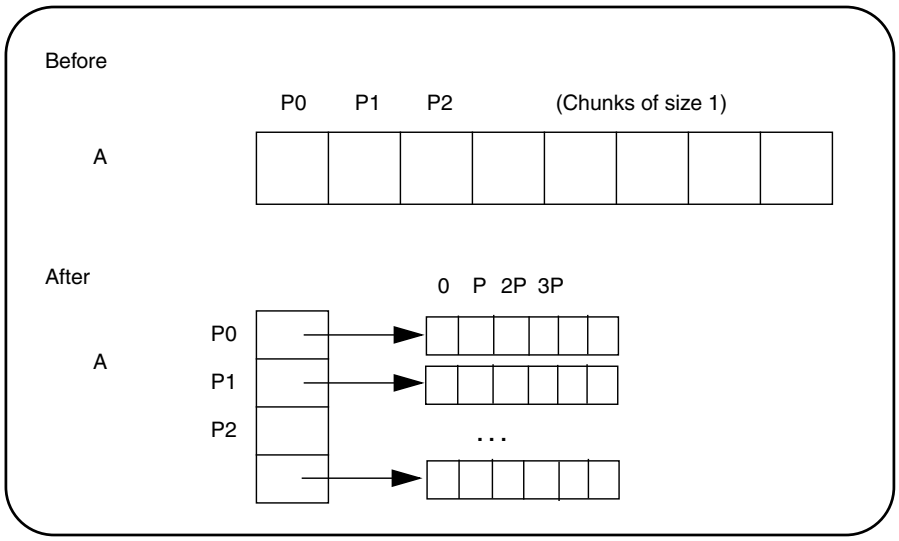


Figure 6-4 Implementation of CYCLIC(1) Distribution

An array reference, **A(i)**, is transformed to **A[i%P] [i/P]** where *P* is the number of threads in that distributed dimension.

Finally, a CYCLIC distribution with a chunk size that is either a constant greater than 1 or a run-time value (also called BLOCK-CYCLIC) is implemented as Figure 6-5 shows.

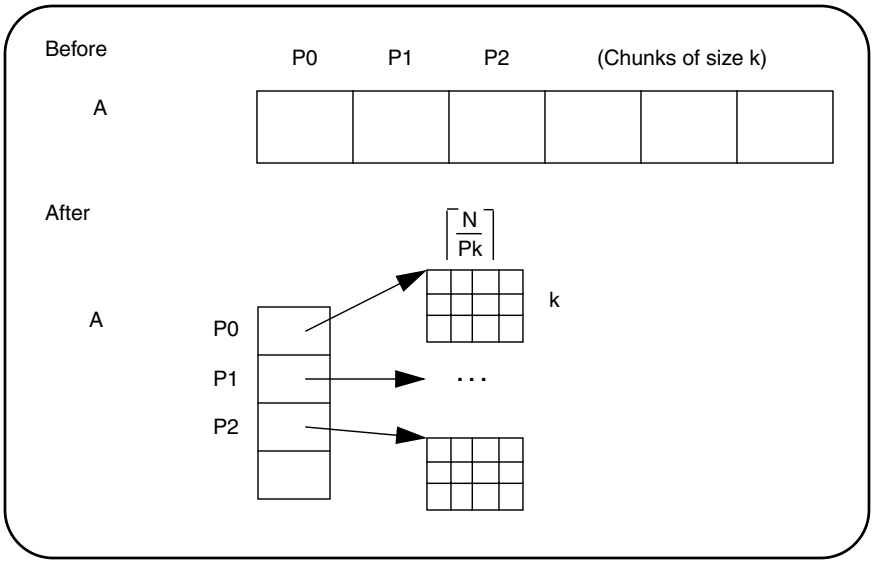


Figure 6-5 Implementation of BLOCK-CYCLIC Distribution

An array reference, **A(i)**, is transformed to the three-dimensional reference **A[(i/k)%P] [i/(Pk)] [i%k]**, where *P* is the total number of threads in that dimension, and *k* is the chunk size.

The compiler tries to optimize these divide/modulo operations out of inner loops through aggressive loop transformations such as blocking and peeling.

Regular vs. Reshaped Data Distribution

In summary, consider the differences between regular and reshaped data distribution. The advantage of regular distributions is that they do not impose any restrictions on the distributed arrays and can be freely applied in existing codes. Furthermore, they work well for distributions where page granularity is not a problem. For example, consider a BLOCK distribution of the columns of a two-dimensional Fortran array of size A(r, c) (column-major layout) and distribution (*, BLOCK). If the size of each processor's portion, ceiling = $(c/P)*r*element\_size$ is significantly greater than the page size (16KB on Origin2000), then regular data distribution should be effective in placing the data in the desired fashion.

However, regular data distribution is limited by page-granularity considerations. For instance, consider a (BLOCK, BLOCK) distribution of a two-dimensional array where the size of a column is much smaller than a page. Each physical page is likely to contain data belonging to multiple processors, making the data-distribution quite ineffective. (Data distribution may still be desirable from affinity-scheduling considerations, described in "Affinity Scheduling" on page 104.)

Reshaped data distribution addresses the problems of regular distributions by changing the layout of the array in memory so as to guarantee the desired distribution. However, since the array no longer conforms to standard Fortran-77 storage layout, there are restrictions on the usage of reshaped arrays.

Given both types of data distribution, you can choose between the two based on the characteristics of the particular array in an application.

Explicit Placement of Data

For irregular data structures, you can explicitly place data in the physical memory of a particular processor using the following directive:

```
c$page_place (<obj>, <size>, <threadnum>)
```

where <*obj*> is the object, <*size*> is the size of the object in bytes, and <*threadnum*> is the number of the destination processor.

This directive causes all the pages spanned by the virtual address range [<*address of the object*> ••• <*address of the object*>+<*size*>] to be allocated from the local memory of processor number <*threadnum*>. It is an executable statement; therefore, you can use it to place either statically or dynamically allocated data.

An example of this directive is as follows:

```
real*8 a(100)
c$page_place (a, 800, 3)
```

For information on directives you can use to facilitate padding and alignment of variables within cachelines and pages of memory, see the *MIPSpro Compiling and Performance Tuning Guide*.

Optional Environment Variables and Compile-Time Options

You can control various run-time features through the following optional environment variables and options. This section describes:

Multiprocessing Environment Variables

Environment variables are listed below.

_DSM_OFF Disables non-uniform memory access (NUMA) specific calls (for example, to allocate pages from a particular memory).

_DSM_VERBOSE
Prints messages about parameters being used during execution.

_DSM_BARRIER
Controls the barrier implementation within the MP runtime. The accepted values are as follows:

- FOP (to use the uncached operations available on the Origin platforms)

  Note: Requires kernel patch #1856. On Origin systems FOP achieves the best performance.

- SHM (to use regular shared memory). The default.
- LLSC (to use LL/SC (load-linked store-conditional) operations on shared memory).

_DSM_PPM Specifies the number of processors to use for each memory module. Must be set to an integer value; to use only one processor per memory module, set this variable to 1.

_DSM_PLACEMENT
Can be set to the following for all stack, data, and text segments:

- FIRST_TOUCH (to request first-touch data placement). The default.
- ROUND_ROBIN (to request round-robin data allocation across memories).

_DSM_MIGRATION
Automatic page migration is OFF by default. This variable, if set, it must be set to one of the following:

OFF disables migration. The default.
ON enables migration except for explicitly placed data (using **page_place** or a data distribution directive).
ALL_ON enables migration for ALL data.

_DSM_MIGRATION_LEVEL
Controls the aggressiveness level of automatic page migration. Must be an integer value between 0 (most conservative, effectively disabled) and 100 (most aggressive). The default value is 100.

_DSM_WAIT Sets the wait at a synchronization point to one of the following:

- SPIN (for pure spin-waiting).
- YIELD (for periodically yielding the underlying processor to another runnable job, if any). The default.

MP_SIMPLE_SCHED
Controls simple scheduling of parallel loops. This variable can be set to one of the following:

- EQUAL (to distribute iterations as equally as possible across the processors).
- BLOCK (to distribute iterations in a BLOCK distribution)

The default is EQUAL, unless you are using distributed arrays, in which case the default is BLOCK. The critical path (that is, the largest piece of the iteration space) is the same in either case.

MP_SUGNUMTHD
If set, this variable enables the use of *dynamic threads* in the multiprocessor (MP) runtime. With dynamic threads the MP runtime automatically adjusts the number of threads used for a parallel loop at runtime based on the overall system load. This feature improves the overall throughput of the system. Furthermore, by avoiding excessive concurrency, this feature can reduce delays at synchronization points within a single application.

PAGESIZE_STACK, PAGESIZE_DATA, PAGESIZE_TEXT
Specifies the desired page size in kilobytes. Must be set to an integer value.

You can find information about other environment variables on the pe_environ(5) reference page and "Specifying the Buffer Size for Direct Unformatted I/O" on page 16.

Compile-Time Options

Useful compile-time options include:

–MP:dsm={on, off} (default on)
All the data-distribution and scheduling features described in this chapter are enabled by default under **–mp** compilation. To disable all the DSM-specific directives (for example, distribution and affinity scheduling), compile with **–MP:dsm=off**.

Note: Under **-mp** compilation, the compiler silently generates some book-keeping information under the directory *rii_files*. This information is used to implement data distribution directives, as well as perform consistency checks of these directives across multiple source files. To disable the processing of the data distribution directives and not generate the *rii_files*, compile with the **-MP:dsm=off** option.

–MP:clone={on, off} (default on)
The compiler automatically clones procedures that are called with reshaped arrays as parameters for the incoming distribution. However, if you have explicitly specified the distribution on all relevant formal parameters, then you can disable auto-cloning with **–MP:clone=off**. The consistency checking of the distribution between actual and formal parameters is *not* affected by this flag, and is always enabled.

–MP:check_reshape={on, off} (default off)
Enables generation of the run-time consistency checks across procedure boundaries when passing reshaped arrays (or portions thereof) as parameters.

Examples

The examples in this section include the following:

Distributing Columns of a Matrix

The example below distributes sequentially the columns of a matrix. Such a distribution places data effectively only if the size of an individual column exceeds that of a page.

```
real*8 A(n, n)
C Distribute columns in cyclic fashion
c$distribute A (*, CYCLIC(1))

C Perform Gaussian elimination across columns
C The affinity clause distributes the loop iterations based
C on the column distribution of A
do i = 1, n
c$doacross affinity(j) = data(A(i,j))
   do j = i+1, n
      ... reduce column j by column i ...
     enddo
enddo
```

If the columns are smaller than a page, then it may be beneficial to reshape the array. This is easily specified by changing the keyword from **distribute** to **distribute_reshape**.

In addition to overcoming size constraints as shown above, the **distribute_reshape** directive is useful when the desired distribution is *contrary* to the layout of the array. For instance, suppose you want to distribute the *rows* of a two-dimensional matrix. In the following example, the **distribute_reshape** directive overcomes the storage layout constraints to provide the desired distribution.

```
real*8 A(n, n)
C Distribute rows in block fashion
c$distribute_reshape A (BLOCK, *)
real*8 sum(n)
c$distribute sum(BLOCK)

C Perform sum-reduction on the elements of each row
c$doacross local(j) affinity(i) = data(A(i,j))
do i = 1,n
   do j = 1,n
      sum(i) = sum(i) + A(i,j)
   enddo
enddo
```

Using Data Distribution and Data Affinity Scheduling

This example demonstrates regular data distribution and data affinity. This example, run on a 4-processor Origin2000 server, uses simple block scheduling. Processor 0 will calculate the results of the first 25,000 elements of A, processor 1 will calculate the second 25,000 elements of A, and so on. Arrays B and C are initialized using one processor; hence all of the memory pages are touched by the master processor (processor 0) and are placed in processor 0's local memory.

Using data distribution changes the placement of memory pages for arrays A, B, and C to match the data reference pattern. Thus, the code runs 33% faster on a 4-processor Origin2000 (than it would run using SMP directives without data distribution).

Without Data Distribution

```
   real*8 a(1000000), b(1000000)
   real*8 c(1000000)
   integer i

c$par parallel shared(a, b, c) local(i)
c$par pdo
    do i = 1, 100000
       a(i) = b(i) + c(i)
    enddo
c$par end parallel
```

With Data Distribution

```
   real*8 a(1000000), b(1000000)
   real*8 c(1000000)
   integer i
c$distribute a(block),b(block),c(block)

c$par parallel shared(a, b, c) local(i)
c$par pdo affinity( i ) = data( a(i) )
    do i = 1, 100000
       a(i) = b(i) + c(i)
    enddo
c$par end parallel
```

Parameter Passing

A distributed array can be passed as a parameter to a subroutine that has a matching declaration on the formal parameter:

```
real*8 A (m, n)
c$distribute_reshape A (block, *)
call foo (A, m, n)
end

subroutine foo (A, p, q)
real*8 A (p, q)
c$distribute_reshape A (block, *)
c$doacross affinity (i) = data (A(i, j))
  do i = 1, P
  enddo
end
```

Since the array is reshaped, it is *required* that the **distribute_reshape** directive in the caller and the callee match exactly. Furthermore, all calls to subroutine `foo()` must pass in an array with the exact same distribution.

If the array was only distributed (that is, not reshaped) in the above example, then the subroutine `foo()` can be called from different places with different incoming distributions. In this case, you can omit the distribution directive on the formal parameter, thereby ensuring that any data affinity within the loop is based on the distribution (at runtime) of the incoming actual parameter.

```
real*8 A(m, n), B (p, q)
real*8 A (block, *)
real*8 B (cyclic(1), *)
call foo (A, m, n)
call foo (B, p, q)
-------------------------------------------------------
subroutine foo (X, s, t)
real*8 X (s, t)

c$doacross affinity (i) = data (X(i+2, j))
do i = • • •
enddo
```

Redistributed Arrays

This example shows how an array is redistributed at runtime:

```
subroutine bar (X, n)
real*8 X(n, n)
...
c$redistribute X (*, cyclic(<expr>))
...
end
-------------------------------------------------------
subroutine foo
real*8 LocalArray (1000, 1000)
c$distribute LocalArray (*, BLOCK)
C the call to bar() may redistribute LocalArray
c$dynamic LocalArray
...
call bar (LocalArray, 100)
```

```
C The distribution for the following doacross
C is not known statically
c$doacross affinity (i) = data (A(i, j))
end
```

The next example illustrates a situation where the **c$dynamic** directive can be optimized away. The main routine contains a local array `A` that is both distributed and dynamically redistributed. This array is passed as a parameter to `foo()` before being redistributed, and to `bar()` after being (possibly) redistributed. The incoming distribution for `foo()` is statically known; you can specify a **c$distribute** directive on the formal parameter, thereby obtaining more efficient static scheduling for the affinity **doacross**. The subroutine `bar()`, however, can be called with multiple distributions, requiring run-time scheduling of the affinity **doacross**.

```
program main
c$distribute A (block, *)
c$dynamic A
call foo (A)
if (x.ne.17) then
   c$redistribute A (cyclic(x), *)
endif
call bar (A)
end

subroutine foo (A)
C Incoming distribution is known to the user
c$distribute A(block, *)
c$doacross affinity (i) = data (A(i, j))
   ...
end

subroutine bar (A)
C Incoming distribution is not known statically
c$dynamic A
c$doacross affinity (i) = data (A(i, j))
   ...
end
```

Irregular Distributions and Thread Affinity

The example below consists of a large array that is conceptually partitioned into unequal portions, one for each processor. This array is indexed through an index array `idx`, which stores the starting index value and the size of each processor's portion.

```
real*8 A(N)
C idx ---> index array containing start index into A (idx(p, 0))
C and size (idx(p, 1)) for each processor
real*4 idx (P, 2)
c$page_place (A(idx(0, 0)), idx(0, 1)*8, 0)
c$page_place (A(idx(1, 0)), idx(1, 1)*8, 1)
c$page_place (A(idx(2, 0)), idx(2, 1)*8, 2)
...
c$doacross affinity (i) = thread(i)
do i = 0, P-1
   ... process elements on processor i •••
   ... A(idx(i, 0)) to A(idx(i,0)+idx(i,1)) •••
enddo
```

Chapter 7

Compiling and Debugging Parallel Fortran

This chapter gives instructions on how to compile and debug a parallel Fortran program. It contains the following sections:

- "Compiling and Running Parallel Fortran" on page 125 explains how to compile and run a parallel Fortran program.
- "Profiling a Parallel Fortran Program" on page 127 describes how to use the system profiler, *prof*, to examine execution profiles.
- "Debugging Parallel Fortran" on page 127 presents some standard techniques for debugging a parallel Fortran program.

Compiling and Running Parallel Fortran

After you have written a program for parallel processing, you should debug your program in a single-processor environment by using the Fortran compiler with the *f77* command. You can also debug your program using the WorkShop Pro MPF debugger, which is sold as a separate product. After your program has executed successfully on a single processor, you can compile it for multiprocessing.

To enable multiprocessing, add **–mp** to the *f77* command line. This option causes the Fortran compiler to generate multiprocessing code for the files being compiled. When linking, you can specify both object files produced with the **–mp** option and object files produced without it. If any or all of the files are compiled with **–mp**, the executable must be linked with **–mp** so that the correct libraries are used.

Using the –static Option

Multiprocessing implementation demands some use of the stack to allow multiple threads of execution to execute the same code simultaneously. Therefore, the parallel **DO** loops themselves are compiled with the **–automatic** option, even if the routine enclosing them is compiled with **–static**.

This means that **SHARE** variables in a parallel loop behave correctly according to the **–static** semantics but that **LOCAL** variables in a parallel loop do not (see "Debugging Parallel Fortran" on page 127 for a description of **SHARE** and **LOCAL** variables).

Finally, if the parallel loop calls an external routine, that external routine cannot be compiled with **–static**. You can mix static and multiprocessed object files in the same executable; the restriction is that a static routine cannot be called from within a parallel loop.

Examples of Compiling

This section steps you through a few examples of compiling code using **–mp**.

The following command line compiles and links the Fortran program ***foo.f*** into a multiprocessor executable:

```
% f77 -mp foo.f
```

In the following example, the Fortran routines in the file ***snark.f*** are compiled with multiprocess code generation enabled:

```
% f77 -c -mp -O2 snark.f
```

The optimizer is also used. A standard ***snark.o*** binary file is produced, which must be linked:

```
% f77 -mp -o boojum snark.o bellman.o
```

Here, the **–mp** option signals the linker to use the Fortran multiprocessing library. The file ***bellman.o*** did not have to be compiled with the **–mp** option, although it could be.

After linking, the resulting executable can be run like any standard executable. Creating multiple execution threads, running and synchronizing them, and task termination are all handled automatically.

When an executable has been linked with **–mp**, the Fortran initialization routines determine how many parallel threads of execution to create. This determination occurs each time the task starts; the number of threads is not compiled into the code. The default is to use whichever is less: 4 or the number of processors that are on the machine (the value returned by the system call **sysmp(MP_NAPROCS)**; see the sysmp(2) reference page). You can override the default by setting the shell environment variable **MP_SET_NUMTHREADS**. If it is set, Fortran tasks use the specified number of execution threads regardless of the number of processors physically present on the machine. **MP_SET_NUMTHREADS** can be a value from 1 to 64.

Profiling a Parallel Fortran Program

After converting a program, you need to examine execution profiles to judge the effectiveness of the transformation. Good execution profiles of the program are crucial to help you focus on the loops that consume the most time.

IRIX provides profiling tools that can be used on Fortran parallel programs. Both pixie(1) and pc-sample profiling can be used (pc-sampling can help show the system overhead). On jobs that use multiple threads, both these methods will create multiple profile data files, one for each thread. You can use the standard profile analyzer prof(1) to examine this output. Also, timex(1) indicates whether or not the parallelized versions performed better overall than the serial version.

The profile of a Fortran parallel job is different from a standard profile. To produce a parallel program, the compiler pulls the parallel **DO** loops out into separate subroutines, one routine for each loop. Each of these loops is shown as a separate procedure in the profile. Comparing the amount of time spent in each loop by the various threads shows how well the workload is balanced.

In addition to the loops, the profile shows the special routines that actually do the multiprocessing. The **__mp_parallel_do** routine is the synchronizer and controller. Slave threads wait for work in the routine **__mp_slave_wait_for_work**. The less time they wait, the more time they work. This gives a rough estimate of a program's parallelization.

Debugging Parallel Fortran

This section presents some standard techniques to assist in debugging a parallel program. Topics include:

- "General Debugging Hints"
- "EQUIVALENCE Statements and Storage of Local Variables"

General Debugging Hints

- Debugging a multiprocessed program is much more difficult than debugging a single-processor program. Therefore you should do as much debugging as possible on the single-processor version.
- Try to isolate the problem as much as possible. Ideally, try to reduce the problem to a single **C$DOACROSS** loop.
- Before debugging a multiprocessed program, change the order of the iterations on the parallel **DO** loop on a single-processor version. If the loop can be multiprocessed, then the iterations can execute in any order and produce the same answer. If the loop cannot be multiprocessed, changing the order frequently causes the single-processor version to fail, and standard single-process debugging techniques can be used to find the problem.
- When debugging a program using *dbx*, use the **`ignore TERM`** command. When debugging a program using *cvd*, select *Views/Signal Panel*, then select *disable SIGTERM*. Debugging is possible without these commands, but the program may not terminate gracefully after execution is complete.

Example: Erroneous C$DOACROSS

In this example, the two references to **a** have the indexes in reverse order, causing a bug. If the indexes were in the same order (if both were **a(i,j)** or both were **a(j,i)**), the loop could be multiprocessed. As written, there is a data dependency, so the **C$DOACROSS** is a mistake.

```
c$doacross local(i,j)
      do i = 1, n
         do j = 1, n
            a(i,j) = a(j,i) + x*b(i)
         end do
      end do
```

Because a (correct) multiprocessed loop can execute its iterations in any order, you could rewrite this as:

```
c$doacross local(i,j)
      do i = n, 1, -1
         do j = 1, n
            a(i,j) = a(j,i) + x*b(i)
         end do
      end do
```

This loop no longer gives the same answer as the original even when compiled without the **–mp** option. This reduces the problem to a normal debugging problem. When a multiprocessed loop is giving the wrong answer, perform the following checks:

- Check the **LOCAL** variables when the code runs correctly as a single process but fails when multiprocessed. Carefully check any scalar variables that appear in the left-hand side of an assignment statement in the loop to be sure they are all declared **LOCAL**. Be sure to include the index of any loop nested inside the parallel loop.

  A related problem occurs when you need the final value of a variable but the variable is declared **LOCAL** rather than **LASTLOCAL**. If the use of the final value happens several hundred lines farther down in the code, or if the variable is in a **COMMON** block and the final value is used in a completely separate routine, a variable can look as if it is **LOCAL** when in fact it should be **LASTLOCAL**. To fix this problem, declare all the **LOCAL** variables **LASTLOCAL** when debugging a loop.

- Check for arrays with complicated subscripts. If the array subscripts are simply the index variables of a **DO** loop, the analysis is probably correct. If the subscripts are more involved, they are a good choice to examine first.

- Check for **EQUIVALENCE** problems. Two variables of different names may in fact refer to the same storage location if they are associated through an **EQUIVALENCE**.

- Check for the use of uninitialized variables. Some programs assume uninitialized variables have a value of 0. This works with the **–static** option, but without it, uninitialized values assume the value that is left on the stack. When compiling with **–mp**, the program executes differently and the stack contents are different. You should suspect this type of problem when a program compiled with **–mp** and run on a single processor gives a different result than when it is compiled without **–mp**. One way to check a problem of this type is to compile suspected routines with **–static**. If an uninitialized variable is the problem, it should be fixed by initializing the variable rather than by continuing to compile with **–static**.

- Try compiling with the **–C** option for range checking on array references. If arrays are indexed out of bounds, a memory location may be referenced in unexpected ways. This is particularly true of adjacent arrays in a **COMMON** block.

- If the analysis of the loop was incorrect, one or more arrays that are **SHARE** may have data dependencies. This sort of error is seen only when running multiprocessed code. When stepping through the code in the debugger, the program executes correctly. This sort of error is usually seen only intermittently; the program works correctly most of the time.
- As a final solution, print out all the values of all the subscripts on each iteration through the loop. Then use uniq(1) to look for duplicates. If duplicates are found, there is a data dependency.

EQUIVALENCE Statements and Storage of Local Variables

EQUIVALENCE statements affect storage of local variables and can cause data dependencies when parallelizing code. **EQUIVALENCE** statements with local variables cause the storage location to be statically allocated (initialized to zero and saved between calls to the subroutine).

In particular, if a loop without equivalenced variables calls a subroutine that appears in an **ASSERT CONNCURENT CALL** that does have equivalenced local variables, a data dependency occurs. This is because the equivalenced storage locations are statically allocated.

Appendix A

Run-Time Error Messages

Table A-1 lists possible Fortran run-time I/O errors. Other errors given by the operating system may also occur (refer to the intro(2) and perror(3F) reference pages for details).

Each error is listed on the screen alone or with one of these phrases appended to it:

- apparent state: unit *num* named *user filename*
- last format: *string*
- lately (reading, writing) (sequential, direct, indexed)
- formatted, unformatted (external, internal) IO

When the Fortran run-time system detects an error, the following actions take place:

- A message describing the error is written to the standard error unit (Unit 0).
- A core file, which can be used with *dbx* (the debugger) to inspect the state of the program at termination, is produced if the **f77_dump_flag** environment variable is defined and set to **y**.

When a run-time error occurs, the program terminates with one of the error messages shown in Table A-1. The errors are output in the format *user filename* : *message*.

Table A-1 Run-Time Error Messages

Number	Message/Cause
100	`error in format` Illegal characters are encountered in FORMAT statement.
101	`out of space for I/O unit table` Out of virtual space that can be allocated for the I/O unit table.
102	`formatted io not allowed` Cannot do formatted I/O on logical units opened for unformatted I/O.

Table A-1 (continued) Run-Time Error Messages

Number	Message/Cause
103	`unformatted io not allowed` Cannot do unformatted I/O on logical units opened for formatted I/O.
104	`direct io not allowed` Cannot do direct I/O on sequential file.
106	`can't backspace file` Cannot perform BACKSPACE/REWIND on file.
107	`null file name` Filename specification in OPEN statement is null.
108	`can't stat file` The directory information for the file is not accessible.
109	`file already connected` The specified filename has already been opened as a different logical unit.
110	`off end of record` Attempt to do I/O beyond the end of the record.
112	`incomprehensible list input` `Input` data for list-directed read contains invalid character for its data type.
113	`out of free space` Cannot allocate virtual memory space on the system.
114	`unit not connected` `Attempt` to do I/O on unit that has not been opened or cannot be opened.
115	`read unexpected character` Unexpected character encountered in formatted or directed read.
116	`blank logical input field` Invalid character encountered for logical value.
117	`bad variable type` Specified type for the namelist element is invalid. This error is most likely caused by incompatible versions of the front end and the run-time I/O library.

Table A-1 (continued) Run-Time Error Messages

Number	Message/Cause
118	`bad namelist name` The specified namelist name cannot be found in the input data file.
119	`variable not in namelist` The namelist variable name in the input data file does not belong to the specified namelist.
120	`no end record` $END is not found at the end of the namelist input data file.
121	`namelist subscript out of range` `The` array subscript of the character substring value in the input data file exceeds the range for that array or character string.
122	`negative repeat count` The repeat count in the input data file is less than or equal to zero.
123	`illegal operation for unit` You cannot set your own buffer on direct unformatted files.
124	`off beginning of record` `Format` edit descriptor causes positioning to go off the beginning of the record.
125	`no * after repeat count` `An` asterisk (*) is expected after an integer repeat count.
126	`'new' file exists` The file is opened as new but already exists.
127	`can't find 'old' file` The file is opened as old but does not exist.
128	`unknown system error` An unexpected error was returned by IRIX.
129	`requires seek ability` The file is on a device that cannot do direct access.
130	`illegal argument` Invalid value in the I/O control list.

Table A-1 (continued) Run-Time Error Messages

Number	Message/Cause
131	`duplicate key value on write` Cannot write a key that already exists.
132	`indexed file not open` Cannot perform indexed I/O on an unopened file.
133	`bad isam argument` The indexed I/O library function receives a bad argument because of a corrupted index file or bad run-time I/O libraries.
134	`bad key description` The key description is invalid.
135	`too many open indexed files` Cannot have more than 32 open indexed files.
136	`corrupted isam file` The indexed file format is not recognizable. This error is usually caused by a corrupted file.
137	`isam file not opened for exclusive access` Cannot obtain lock on the indexed file.
138	`record locked` The record has already been locked by another process.
138	`key already exists` The key specification in the OPEN statement has already been specified.
140	`cannot delete primary key` DELETE cannot be executed on a primary key.
141	`beginning or end of file reached` The index for the specified key points beyond the length of the indexed data file. This error is probably because of corrupted ISAM files or a bad indexed I/O run-time library.
142	`cannot find request record` The requested key for indexed READ does not exist.

Table A-1 (continued) Run-Time Error Messages

Number	Message/Cause
143	`current record not defined` Cannot execute REWRITE, UNLOCK, or DELETE before doing a READ to define the current record.
144	`isam file is exclusively locked` The indexed file has been exclusively locked by another process.
145	`filename too long` The indexed filename exceeds 128 characters.
148	`key structure does not match file structure` Mismatch between the key specifications in the OPEN statement and the indexed file.
149	`direct access on an indexed file not allowed` Cannot have direct-access I/O on an indexed file.
150	`keyed access on a sequential file not allowed` Cannot specify keyed access together with sequential organization.
151	`keyed access on a relative file not allowed` Cannot specify keyed access together with relative organization.
152	`append access on an indexed file not allowed` Cannot specify append access together with indexed organization.
153	`must specify record length` A record length specification is required when opening a direct or keyed access file.
154	`key field value type does not match key type` The type of the given key value does not match the type specified in the OPEN statement for that key.
155	`character key field value length too long` The length of the character key value exceeds the length specification for that key.
156	`fixed record on sequential file not allowed` RECORDTYPE='fixed' cannot be used with a sequential file.
157	`variable records allowed only on unformatted sequential file` RECORDTYPE='variable' can only be used with an unformatted sequential file.

Table A-1 (continued) Run-Time Error Messages

Number	Message/Cause
158	`stream records allowed only on formatted sequential file` RECORDTYPE='stream_lf' can only be used with a formatted sequential file.
159	`maximum number of records in direct access file exceeded` The specified record is bigger than the MAXREC= value used in the OPEN statement.
160	`attempt to create or write to a read-only file` User does not have write permission on the file.
161	`must specify key descriptions` Must specify all the keys when opening an indexed file.
162	`carriage control not allowed for unformatted units` CARRIAGECONTROL specifier can be used only on a formatted file.
163	`indexed files only` Indexed I/O can be done only on logical units that have been opened for indexed (keyed) access.
164	`cannot use on indexed file` Illegal I/O operation on an indexed (keyed) file.
165	`cannot use on indexed or append file` Illegal I/O operation on an indexed (keyed) or append file.
167	`invalid code in format specification` Unknown code is encountered in format specification.
168	`invalid record number in direct access file` The specified record number is less than 1.
169	`cannot have endfile record on non-sequential file` Cannot have an endfile on a direct- or keyed-access file.
170	`cannot position within current file` Cannot perform fseek() on a file opened for sequential unformatted I/O.
171	`cannot have sequential records on direct access file` Cannot do sequential formatted I/O on a file opened for direct access.

Table A-1 (continued) Run-Time Error Messages

Number	Message/Cause
173	`cannot read from stdout` Attempt to read from stdout.
174	`cannot write to stdin` Attempt to write to stdin.
175	`stat call failed in f77inode` The directory information for the file is unreadable.
176	`illegal specifier` The I/O control list contains an invalid value for one of the I/O specifiers. For example, ACCESS='INDEXED'.
180	`attempt to read from a writeonly file` User does not have read permission on the file.
181	`direct unformatted io not allowed` Direct unformatted file cannot be used with this I/O operation.
182	`cannot open a directory` The name specified in FILE= must be the name of a file, not a directory.
183	`subscript out of bounds` The exit status returned when a program compiled with the –C option has an array subscript that is out of range.
184	`function not declared as varargs` Variable argument routines called in subroutines that have not been declared in a $VARARGS directive.
185	`internal error` Internal run-time library error.
186	`Illegal input character in formatted read.` The numeric input field in a formatted file contains non-blank characters beyond the maximum usable field width of 83 characters.
187	`Position specifier is allowed on sequential files only` Cannot have a position specifier in a format statement for a non-sequential file.

Table A-1 (continued) Run-Time Error Messages

Number	Message/Cause
188	`Position specifier has an illegal value` The position specifier has a value that does not make sense.
189	`Out of memory` The system is out of memory for allocation. Try to allocate more swap space.
195	`Cannot keep a file opened as a scratch file.` If a file is opened as a scratch file, it cannot be kept when closed, and is automatically deleted.

Appendix B

Multiprocessing Directives (Outmoded)

The directives which are described in this appendix are outmoded. They are supported for older codes that require this functionality. Silicon Graphics encourages you to write new codes using the OpenMP directives described in Chapter 5.

This chapter contains these sections:

- "Overview" on page 140 provides an overview of this chapter.
- "Parallel Loops" on page 140 discusses the concept of parallel **DO** loops.
- "Writing Parallel Fortran" on page 141 explains how to use compiler directives to generate code that can be run in parallel.
- "Analyzing Data Dependencies for Multiprocessing" on page 149 describes how to analyze **DO** loops to determine whether they can be parallelized.
- "Breaking Data Dependencies" on page 154 explains how to rewrite **DO** loops that contain data dependencies so that some or all of the loop can be run in parallel.
- "Work Quantum" on page 159 describes how to determine whether the work performed in a loop is greater than the overhead associated with multiprocessing the loop.
- "Cache Effects" on page 161 explains how to write loops that account for the effect of the cache.
- "Advanced Features" on page 166 describes features that override multiprocessing defaults and customize parallelism.
- "DOACROSS Implementation" on page 174 discusses how multiprocessing is implemented in a **DOACROSS** routine.
- "PCF Directives" on page 176 describes how PCF implements a general model of parallelism.
- "Communicating Between Threads Through Thread Local Data" on page 189 explains how to use **mp_shmem** to explicitly communicate between threads of a MP Fortran program.
- "Synchronization Intrinsics" on page 191 describes synchronization operations.

Overview

The MIPSpro Fortran 77 compiler allows you to apply the capabilities of a Silicon Graphics multiprocessor workstation to the execution of a single job. By coding a few simple directives, the compiler splits the job into concurrently executing pieces, thereby decreasing the wall-clock run time of the job. This chapter discusses techniques for analyzing your program and converting it to multiprocessing operations. Chapter 6, "Parallel Programming on Origin2000," describes the support provided for writing parallel programs on Origin2000. Chapter 7, "Compiling and Debugging Parallel Fortran," gives compilation and debugging instructions for parallel processing.

Note: You can automatically parallelize Fortran programs by using the optional program **-pfa**. For information about this software, contact Silicon Graphics customer support.

Parallel Loops

The model of parallelism used focuses on the Fortran **DO** loop. The compiler executes different iterations of the **DO** loop in parallel on multiple processors. For example, suppose a **DO** loop consisting of 200 iterations will run on a machine with four processors using the **SIMPLE** scheduling method (described in"CHUNK, MP_SCHEDTYPE" on page 144). The first 50 iterations run on one processor, the next 50 on another, and so on.

The multiprocessing code adjusts itself at run time to the number of processors actually present on the machine. By default, the multiprocessing code does not use more than 8 processors. If you want to use more processors, set the environment variable MP_SET_NUMTHREADS (see "Environment Variables for Origin Systems" on page 169 for more information). If the above 200-iteration loop was moved to a machine with only two processors, it would be divided into two blocks of 100 iterations each, without any need to recompile or relink. In fact, multiprocessing code can be run on single-processor machines. So the above loop is divided into one block of 200 iterations. This allows code to be developed on a single-processor Silicon Graphics workstation, and later run on an IRIS POWER Series™ multiprocessor.

The processes that participate in the parallel execution of a task are arranged in a master/slave organization. The original process is the master. It creates zero or more slaves to assist. When a parallel **DO** loop is encountered, the master asks the slaves for help. When the loop is complete, the slaves wait on the master, and the master resumes normal execution. The master process and each of the slave processes are called a *thread of execution* or simply a *thread*. By default, the number of threads is set to the number of

processors on the machine or 8, whichever is smaller. If you want, you can override the default and explicitly control the number of threads of execution used by a parallel job.

For multiprocessing to work correctly, the iterations of the loop must not depend on each other; each iteration must stand alone and produce the same answer regardless of when any other iteration of the loop is executed. Not all **DO** loops have this property, and loops without it cannot be correctly executed in parallel. However, many of the loops encountered in practice fit this model. Further, many loops that cannot be run in parallel in their original form can be rewritten to run wholly or partially in parallel.

To provide compatibility for existing parallel programs, Silicon Graphics has adopted the syntax for parallelism used by Sequent Computer Corporation. This syntax takes the form of compiler directives embedded in comments. These fairly high-level directives provide a convenient method for you to describe a parallel loop, while leaving the details to the Fortran compiler. For advanced users the proposed Parallel Computing Forum (PCF) standard (ANSI-X3H5 91-0023-B Fortran language binding) is available (refer to "PCF Directives" on page 176). Additionally, a number of special routines exist that permit more direct control over the parallel execution (refer to "Advanced Features" on page 166 for more information.)

Writing Parallel Fortran

The compiler accepts directives that cause it to generate code that can be run in parallel. The compiler directives look like Fortran comments: they begin with a **C** in column one. If multiprocessing is not turned on, these statements are treated as comments. This allows the identical source to be compiled with a single-processing compiler or by Fortran without the multiprocessing option. The directives are distinguished by having a **$** as the second character. There are six directives that are supported: **C$DOACROSS**, **C$&**, **C$**, **C$MP_SCHEDTYPE**, **C$CHUNK**, and **C$COPYIN**. The **C$COPYIN** directive is described in "Local COMMON Blocks" on page 172. This section describes the others.

C$DOACROSS

The essential compiler directive for multiprocessing is **C$DOACROSS**. This directive directs the compiler to generate special code to run iterations of a **DO** loop in parallel. The **C$DOACROSS** directive applies only to the next statement (which must be a **DO** loop). The **C$DOACROSS** directive has the form

```
C$DOACROSS [clause [ [,] clause ...]
```

where valid values for the optional *clause* are

```
[IF (logical_expression)]
[{LOCAL | PRIVATE} (item[,item ...])]
[{SHARE | SHARED} (item[,item ...])]
[{LASTLOCAL | LAST LOCAL} (item[,item ...])]
[REDUCTION (item[,item ...])]
[MP_SCHEDTYPE=mode ]
[CHUNK=integer_expression]
```

The preferred form of the directive (as generated by WorkShop Pro MPF) uses the optional commas between clauses. This section discusses the meaning of each clause.

IF

The **IF** clause determines whether the loop is actually executed in parallel. If the logical expression is TRUE, the loop is executed in parallel. If the expression is FALSE, the loop is executed serially. Typically, the expression tests the number of times the loop will execute to be sure that there is enough work in the loop to amortize the overhead of parallel execution. Currently, the break-even point is about 4000 CPU clocks of work, which normally translates to about 1000 floating point operations.

LOCAL, SHARE, LASTLOCAL

The **LOCAL**, **SHARE**, and **LASTLOCAL** clauses specify lists of variables used within parallel loops. A variable can appear in only one of these lists. To make the task of writing these lists easier, there are several defaults. The loop-iteration variable is **LASTLOCAL** by default. All other variables are **SHARE** by default.

LOCAL Specifies variables that are local to each process. If a variable is declared as **LOCAL**, each iteration of the loop is given its own uninitialized copy of the variable. You can declare a variable as **LOCAL** if its value does not depend on any other iteration of the loop and if its value is used only within a single iteration. In effect the **LOCAL** variable is just temporary; a new copy can be created in each loop iteration without changing the final answer. The name **LOCAL** is preferred over **PRIVATE**.

SHARE Specifies variables that are shared across all processes. If a variable is declared as **SHARE**, all iterations of the loop use the same copy of the variable. You can declare a variable as **SHARE** if it is only read (not written) within the loop or if it is an array where each iteration of the loop uses a different element of the array. The name **SHARE** is preferred over **SHARED**.

LASTLOCAL Specifies variables that are local to each process.Unlike with the **LOCAL** clause, the compiler saves only the value of the logically last iteration of the loop when it exits. The name **LASTLOCAL** is preferred over **LAST LOCAL**.

LOCAL is a little faster than **LASTLOCAL**, so if you do not need the final value, it is good practice to put the **DO** loop index variable into the **LOCAL** list, although this is not required.

Only variables can appear in these lists. In particular, **COMMON** blocks cannot appear in a **LOCAL** list (but see the discussion of local **COMMON** blocks in "Advanced Features" on page 166). The **SHARE**, **LOCAL**, and **LASTLOCAL** lists give only the names of the variables. If any member of the list is an array, it is listed without any subscripts.

REDUCTION

The **REDUCTION** clause specifies variables involved in a reduction operation. In a reduction operation, the compiler keeps local copies of the variables and combines them when it exits the loop. For an example and details see Example B-17 in "Breaking Data Dependencies." An element of the **REDUCTION** list must be an individual variable (also called a scalar variable) and cannot be an array. However, it can be an individual element of an array. In a **REDUCTION** clause, it would appear in the list with the proper subscripts.

One element of an array can be used in a reduction operation, while other elements of the array are used in other ways. To allow for this, if an element of an array appears in the **REDUCTION** list, the entire array can also appear in the **SHARE** list.

The four types of reductions supported are **sum**(+), **product**(*), **min**(), and **max**(). Note that **min**(**max**) reductions must use the **min**(**max**) intrinsic functions to be recognized correctly.

The compiler confirms that the reduction expression is legal by making some simple checks. The compiler does not, however, check all statements in the **DO** loop for illegal reductions. You must ensure that the reduction variable is used correctly in a reduction operation.

CHUNK, MP_SCHEDTYPE

The **CHUNK** and **MP_SCHEDTYPE** clauses affect the way the compiler schedules work among the participating tasks in a loop. These clauses do not affect the correctness of the loop. They are useful for tuning the performance of critical loops. See "Load Balancing" on page 163 for more details.

For the **MP_SCHEDTYPE=***mode* clause, *mode* can be one of the following:

```
[SIMPLE | STATIC]
[DYNAMIC]
[INTERLEAVE INTERLEAVED]
[GUIDED GSS]
[RUNTIME]
```

You can use any or all of these modes in a single program. The **CHUNK** clause is valid only with the **DYNAMIC** and **INTERLEAVE** modes. **SIMPLE**, **DYNAMIC**, **INTERLEAVE**, **GSS**, and **RUNTIME** are the preferred names for each mode.

The simple method (**MP_SCHEDTYPE=SIMPLE**) divides the iterations among processes by dividing them into contiguous pieces and assigning one piece to each process.

In dynamic scheduling (**MP_SCHEDTYPE=DYNAMIC**) the iterations are broken into pieces the size of which is specified with the **CHUNK** clause. As each process finishes a piece, it enters a critical section to grab the next available piece. This gives good load balancing at the price of higher overhead.

The interleave method (**MP_SCHEDTYPE=INTERLEAVE**) breaks the iterations into pieces of the size specified by the **CHUNK** option, and execution of those pieces is interleaved among the processes. For example, if there are four processes and **CHUNK=2**, then the first process will execute iterations 1–2, 9–10, 17–18, …; the second process will execute iterations 3–4, 11–12, 19–20,…; and so on. Although this is more complex than the simple method, it is still a fixed schedule with only a single scheduling decision.

The fourth method is a variation of the guided self-scheduling algorithm (**MP_SCHEDTYPE=GSS**). Here, the piece size is varied depending on the number of iterations remaining. By parceling out relatively large pieces to start with and relatively small pieces toward the end, the system can achieve good load balancing while reducing the number of entries into the critical section.

In addition to these four methods, you can specify the scheduling method at run time (**MP_SCHEDTYPE=RUNTIME**). Here, the scheduling routine examines values in your run-time environment and uses that information to select one of the other four methods. See "Advanced Features" on page 166 for more details.

If both the **MP_SCHEDTYPE** and **CHUNK** clauses are omitted, **SIMPLE** scheduling is assumed. If **MP_SCHEDTYPE** is set to **INTERLEAVE** or **DYNAMIC** and the **CHUNK** clause are omitted, **CHUNK=1** is assumed. If **MP_SCHEDTYPE** is set to one of the other values, **CHUNK** is ignored. If the **MP_SCHEDTYPE** clause is omitted, but **CHUNK** is set, then **MP_SCHEDTYPE=DYNAMIC** is assumed.

Example B-1 Simple DOACROSS

The code fragment

```
   DO 10 I = 1, 100
      A(I) = B(I)
10 CONTINUE
```

could be multiprocessed with the directive:

```
C$DOACROSS LOCAL(I), SHARE(A, B)
   DO 10 I = 1, 100
      A(I) = B(I)
10 CONTINUE
```

Here, the defaults are sufficient, provided **A** and **B** are mentioned in a nonparallel region or in another **SHARE** list. The following then works:

```
C$DOACROSS
   DO 10 I = 1, 100
      A(I) = B(I)
10 CONTINUE
```

Example B-2 DOACROSS LOCAL

Consider the following code fragment:

```
   DO 10 I = 1, N
      X = SQRT(A(I))
      B(I) = X*C(I) + X*D(I)
10 CONTINUE
```

You can be fully explicit, as shown below:

```
C$DOACROSS LOCAL(I, X), share(A, B, C, D, N)
   DO 10 I = 1, N
      X = SQRT(A(I))
      B(I) = X*C(I) + X*D(I)
10 CONTINUE
```

You can also use the defaults:

```
C$DOACROSS LOCAL(X)
   DO 10 I = 1, N
      X = SQRT(A(I))
      B(I) = X*C(I) + X*D(I)
10 CONTINUE
```

See Example B-8 in "Analyzing Data Dependencies for Multiprocessing" on page 149 for more information on this example.

Example B-3 DOACROSS LAST LOCAL

Consider the following code fragment:

```
   DO 10 I = M, K, N
      X = D(I)**2
      Y = X + X
      DO 20 J = I, MAX
         A(I,J) = A(I,J) + B(I,J) * C(I,J) * X + Y
20 CONTINUE
10 CONTINUE
   PRINT*, I, X
```

Here, the final values of **I** and **X** are needed after the loop completes. A correct directive is shown below:

```
C$DOACROSS LOCAL(Y,J), LASTLOCAL(I,X),
C$& SHARE(M,K,N,ITOP,A,B,C,D)
   DO 10 I = M, K, N
       X = D(I)**2
       Y = X + X
       DO 20 J = I, ITOP
           A(I,J) = A(I,J) + B(I,J) * C(I,J) *X + Y
20 CONTINUE
10 CONTINUE
   PRINT*, I, X
```

You can also use the defaults:

```
C$DOACROSS LOCAL(Y,J), LASTLOCAL(X)
   DO 10 I = M, K, N
       X = D(I)**2
       Y = X + X
       DO 20 J = I, MAX
           A(I,J) = A(I,J) + B(I,J) * C(I,J) *X + Y
20 CONTINUE
10 CONTINUE
   PRINT*, I, X
```

I is a loop index variable for the **C$DOACROSS** loop, so it is **LASTLOCAL** by default. However, even though **J** is a loop index variable, it is not the loop index of the loop being multiprocessed and has no special status. If it is not declared, it is assigned the default value of **SHARE**, which produces an incorrect answer.

C$&

Occasionally, the clauses in the **C$DOACROSS** directive are longer than one line. Use the **C$&** directive to continue the directive onto multiple lines. For example:

```
C$DOACROSS share(ALPHA, BETA, GAMMA, DELTA,
C$&  EPSILON, OMEGA), LASTLOCAL(I, J, K, L, M, N),
C$&  LOCAL(XXX1, XXX2, XXX3, XXX4, XXX5, XXX6, XXX7,
C$&  XXX8, XXX9)
```

C$

The **C$** directive is considered a comment line except when multiprocessing. A line beginning with **C$** is treated as a conditionally compiled Fortran statement. The rest of the line contains a standard Fortran statement. The statement is compiled only if multiprocessing is turned on. In this case, the **C** and **$** are treated as if they are blanks. They can be used to insert debugging statements, or an experienced user can use them to insert arbitrary code into the multiprocessed version.

The following code demonstrates the use of the **C$** directive:

```
C$    PRINT 10
C$ 10 FORMAT('BEGIN MULTIPROCESSED LOOP')
C$DOACROSS LOCAL(I), SHARE(A,B)
      DO I = 1, 100
         CALL COMPUTE(A, B, I)
      END DO
```

C$MP_SCHEDTYPE and C$CHUNK

The **C$MP_SCHEDTYPE=***mode* directive acts as an implicit **MP_SCHEDTYPE** clause for all **C$DOACROSS** directives in scope. *mode* is any of the modes listed in the section called "CHUNK, MP_SCHEDTYPE" on page 144. A **C$DOACROSS** directive that does not have an explicit **MP_SCHEDTYPE** clause is given the value specified in the last directive prior to the look, rather than the normal default. If the **C$DOACROSS** does have an explicit clause, then the explicit value is used.

The **C$CHUNK=***integer_expression* directive affects the **CHUNK** clause of a **C$DOACROSS** in the same way that the **C$MP_SCHEDTYPE** directive affects the **MP_SCHEDTYPE** clause for all **C$DOACROSS** directives in scope. Both directives are in effect from the place they occur in the source until another corresponding directive is encountered or the end of the procedure is reached.

Nesting C$DOACROSS

The Fortran compiler does not support direct nesting of **C$DOACROSS** loops.

For example, the following is illegal and generates a compilation error:

```
C$DOACROSS LOCAL(I)
      DO I = 1, N
C$DOACROSS LOCAL(J)
         DO J = 1, N
            A(I,J) = B(I,J)
         END DO
      END DO
```

However, to simplify separate compilation, a different form of nesting is allowed. A routine that uses **C$DOACROSS** can be called from within a multiprocessed region. This can be useful if a single routine is called from several different places: sometimes from within a multiprocessed region, sometimes not. Nesting does not increase the parallelism. When the first **C$DOACROSS** loop is encountered, that loop is run in parallel. If while in the parallel loop a call is made to a routine that itself has a **C$DOACROSS**, this subsequent loop is executed serially.

Analyzing Data Dependencies for Multiprocessing

The essential condition required to parallelize a loop correctly is that each iteration of the loop must be independent of all other iterations. If a loop meets this condition, then the order in which the iterations of the loop execute is not important. They can be executed backward or at the same time, and the answer is still the same. This property is captured by the notion of *data independence*. For a loop to be data-independent, no iterations of the loop can write a value into a memory location that is read or written by any other iteration of that loop. It is all right if the same iteration reads and/or writes a memory location repeatedly as long as no others do; it is all right if many iterations read the same location, as long as none of them write to it. In a Fortran program, memory locations are represented by variable names. So, to determine if a particular loop can be run in parallel, examine the way variables are used in the loop. Because data dependence occurs only when memory locations are modified, pay particular attention to variables that appear on the left-hand side of assignment statements. If a variable is not modified or if it is passed to a function or subroutine, there is no data dependence associated with it.

The Fortran compiler supports four kinds of variable usage within a parallel loop: **SHARE**, **LOCAL**, **LASTLOCAL**, and **REDUCTION**. If a variable is declared as **SHARE**, all iterations of the loop use the same copy. If a variable is declared as **LOCAL**, each iteration is given its own uninitialized copy. A variable is declared **SHARE** if it is only read (not written) within the loop or if it is an array where each iteration of the loop uses a different element of the array. A variable can be **LOCAL** if its value does not depend on any other iteration and if its value is used only within a single iteration. In effect the **LOCAL** variable is just temporary; a new copy can be created in each loop iteration without changing the final answer. As a special case, if only the very last value of a variable computed on the very last iteration is used outside the loop (but would otherwise qualify as a **LOCAL** variable), the loop can be multiprocessed by declaring the variable to be **LASTLOCAL**. “REDUCTION” on page 143 describes the use of **REDUCTION** variables.

It is often difficult to analyze loops for data dependence information. Each use of each variable must be examined to determine if it fulfills the criteria for **LOCAL**, **LASTLOCAL**, **SHARE**, or **REDUCTION**. If all of the variables’ uses conform, the loop can be parallelized. If not, the loop cannot be parallelized as it stands, but possibly can be rewritten into an equivalent parallel form. (See “Breaking Data Dependencies” on page 154 for information on rewriting code in parallel form.)

An alternative to analyzing variable usage by hand is to use Power Fortran. This optional software package is a Fortran preprocessor that analyzes loops for data dependence. If Power Fortran determines that a loop is data-independent, it automatically inserts the

required compiler directives (see "Writing Parallel Fortran" on page 141). If Power Fortran cannot determine whether the loop is independent, it produces a listing file detailing where the problems lie. You can use Power Fortran in conjunction with WorkShop Pro MPF to visualize these dependencies and make it easier to understand the obstacles to parallelization.

The rest of this section is devoted to analyzing sample loops, some parallel and some not parallel.

Example B-4 Simple Independence

```
      DO 10 I = 1,N
10    A(I) = X + B(I)*C(I)
```

In this example, each iteration writes to a different location in **A**, and none of the variables appearing on the right-hand side is ever written to, only read from. This loop can be correctly run in parallel. All the variables are **SHARE** except for **I**, which is either **LOCAL** or **LASTLOCAL**, depending on whether the last value of **I** is used later in the code.

Example B-5 Data Dependence

```
       DO 20 I = 2,N
20     A(I) = B(I) - A(I-1)
```

This fragment contains **A(I)** on the left-hand side and **A(I-1)** on the right. This means that one iteration of the loop writes to a location in **A** and the next iteration reads from that same location. Because different iterations of the loop read and write the same memory location, this loop cannot be run in parallel.

Example B-6 Stride Not 1

```
       DO 20 I = 2,N,2
20     A(I) = B(I) - A(I-1)
```

This example looks like the previous example. The difference is that the stride of the **DO** loop is now two rather than one. Now **A(I)** references every other element of **A**, and **A(I-1)** references exactly those elements of **A** that are not referenced by **A(I)**. None of the data locations on the right-hand side is ever the same as any of the data locations written to on the left-hand side. The data are disjoint, so there is no dependence. The loop can be run in parallel. Arrays **A** and **B** can be declared **SHARE**, while variable **I** should be declared **LOCAL** or **LASTLOCAL**.

Example B-7 Local Variable

```
DO I = 1, N
   X = A(I)*A(I) + B(I)
   B(I) = X + B(I)*X
END DO
```

In this loop, each iteration of the loop reads and writes the variable **X**. However, no loop iteration ever needs the value of **X** from any other iteration. **X** is used as a temporary variable; its value does not survive from one iteration to the next. This loop can be parallelized by declaring **X** to be a **LOCAL** variable within the loop. Note that **B(I)** is both read and written by the loop. This is not a problem because each iteration has a different value for **I**, so each iteration uses a different **B(I)**. The same **B(I)** is allowed to be read and written as long as it is done by the same iteration of the loop. The loop can be run in parallel. Arrays **A** and **B** can be declared **SHARE**, while variable **I** should be declared **LOCAL** or **LASTLOCAL**.

Example B-8 Function Call

```
   DO 10 I = 1, N
      X = SQRT(A(I))
      B(I) = X*C(I) + X*D(I)
10 CONTINUE
```

The value of **X** in any iteration of the loop is independent of the value of **X** in any other iteration, so **X** can be made a **LOCAL** variable. The loop can be run in parallel. Arrays **A**, **B**, **C**, and **D** can be declared **SHARE**, while variable **I** should be declared **LOCAL** or **LASTLOCAL**.

The interesting feature of this loop is that it invokes an external routine, **SQRT**. It is possible to use functions and/or subroutines (intrinsic or user defined) within a parallel loop. However, make sure that the various parallel invocations of the routine do not interfere with one another. In particular, **SQRT** returns a value that depends only on its input argument, does not modify global data, and does not use static storage. We say that **SQRT** has no *side effects*.

All the Fortran intrinsic functions listed in Appendix A of the *MIPSpro Fortran 77 Language Reference Manual* have no side effects and can safely be part of a parallel loop. For the most part, the Fortran library functions and VMS intrinsic subroutine extensions (listed in Chapter 4, "System Functions and Subroutines,") cannot safely be included in a parallel loop. In particular, **rand** is not safe for multiprocessing. For user-written routines, it is the user's responsibility to ensure that the routines can be correctly multiprocessed.

Caution: Do not use the **–static** option when compiling routines called within a parallel loop.

Example B-9 Rewritable Data Dependence

```
INDX = 0
DO I = 1, N
   INDX = INDX + I
   A(I) = B(I) + C(INDX)
END DO
```

Here, the value of **INDX** survives the loop iteration and is carried into the next iteration. This loop cannot be parallelized as it is written. Making **INDX** a **LOCAL** variable does not work; you need the value of **INDX** computed in the previous iteration. It is possible to rewrite this loop to make it parallel (see Example B-14 in "Breaking Data Dependencies" on page 154).

Example B-10 Exit Branch

```
     DO I = 1, N
        IF (A(I) .LT. EPSILON) GOTO 320
        A(I) = A(I) * B(I)
     END DO
 320 CONTINUE
```

This loop contains an exit branch; that is, under certain conditions the flow of control suddenly exits the loop. The Fortran compiler cannot parallelize loops containing exit branches.

Example B-11 Complicated Independence

```
DO I = K+1, 2*K
   W(I) = W(I) + B(I,K) * W(I-K)
END DO
```

At first glance, this loop looks like it cannot be run in parallel because it uses both **W(I)** and **W(I-K)**. Closer inspection reveals that because the value of **I** varies between **K**+1 and 2***K**, then **I-K** goes from 1 to **K**. This means that the **W(I-K)** term varies from **W(1)** up to **W**(**K**), while the **W**(**I**) term varies from **W(K+1)** up to **W(2*K)**. So **W(I-K)** in any iteration of the loop is never the same memory location as **W(I)** in any other iterations. Because there is no data overlap, there are no data dependencies. This loop can be run in parallel. Elements **W**, **B**, and **K** can be declared **SHARE**, while variable **I** should be declared **LOCAL** or **LASTLOCAL**.

This example points out a general rule: the more complex the expression used to index an array, the harder it is to analyze. If the arrays in a loop are indexed only by the loop index variable, the analysis is usually straightforward though tedious. Fortunately, in practice most array indexing expressions are simple.

Example B-12 Inconsequential Data Dependence

```
INDEX = SELECT(N)
DO I = 1, N
   A(I) = A(INDEX)
END DO
```

There is a data dependence in this loop because it is possible that at some point **I** will be the same as **INDEX**, so there will be a data location that is being read and written by different iterations of the loop. In this special case, you can simply ignore it. You know that when **I** and **INDEX** are equal, the value written into **A(I)** is exactly the same as the value that is already there. The fact that some iterations of the loop read the value before it is written and some after it is written is not important because they all get the same value. Therefore, this loop can be parallelized. Array **A** can be declared **SHARE**, while variable **I** should be declared **LOCAL** or **LASTLOCAL**.

Example B-13 Local Array

```
DO I = 1, N
   D(1) = A(I,1) - A(J,1)
   D(2) = A(I,2) - A(J,2)
   D(3) = A(I,3) - A(J,3)
   TOTAL_DISTANCE(I,J) = SQRT(D(1)**2 + D(2)**2 + D(3)**2)
END DO
```

In this fragment, each iteration of the loop uses the same locations in the **D** array. However, closer inspection reveals that the entire **D** array is being used as a temporary. This can be multiprocessed by declaring **D** to be **LOCAL**. The Fortran compiler allows arrays (even multidimensional arrays) to be **LOCAL** variables with one restriction: the size of the array must be known at compile time. The dimension bounds must be constants; the **LOCAL** array cannot have been declared using a variable or the asterisk syntax.

Therefore, this loop can be parallelized. Arrays **TOTAL_DISTANCE** and **A** can be declared **SHARE**, while array **D** and variable **I** should be declared **LOCAL** or **LASTLOCAL**.

Breaking Data Dependencies

Many loops that have data dependencies can be rewritten so that some or all of the loop can be run in parallel. The essential idea is to locate the statement(s) in the loop that cannot be made parallel and try to find another way to express it that does not depend on any other iteration of the loop. If this fails, try to pull the statements out of the loop and into a separate loop, allowing the remainder of the original loop to be run in parallel.

The first step is to analyze the loop to discover the data dependencies (see "Writing Parallel Fortran" on page 141). You can use WorkShop Pro MPF with MIPSpro Power Fortran 77 to identify the problem areas. Once you have identified these areas, you can use various techniques to rewrite the code to break the dependence. Sometimes the dependencies in a loop cannot be broken, and you must either accept the serial execution rate or try to discover a new parallel method of solving the problem. The rest of this section is devoted to a series of "cookbook" examples on how to deal with commonly occurring situations. These are by no means exhaustive but cover many situations that happen in practice.

Example B-14 Loop Carried Value

```
INDX = 0
DO I = 1, N
    INDX = INDX + I
    A(I) = B(I) + C(INDX)
END DO
```

This code segment is the same as in "Rewritable Data Dependence" on page 152. **INDX** has its value carried from iteration to iteration. However, you can compute the appropriate value for **INDX** without making reference to any previous value.

For example, consider the following code:

```
C$DOACROSS LOCAL (I, INDX)
  DO I  = 1, N
     INDX = (I*(I+1))/2
     A(I) = B(I) + C(INDX)
  END DO
```

In this loop, the value of **INDX** is computed without using any values computed on any other iteration. **INDX** can correctly be made a **LOCAL** variable, and the loop can now be multiprocessed.

Example B-15 Indirect Indexing

```
   DO 100 I = 1, N
      IX = INDEXX(I)
      IY = INDEXY(I)
      XFORCE(I) = XFORCE(I) + NEWXFORCE(IX)
      YFORCE(I) = YFORCE(I) + NEWYFORCE(IY)
      IXX = IXOFFSET(IX)
      IYY = IYOFFSET(IY)
      TOTAL(IXX, IYY) = TOTAL(IXX, IYY) + EPSILON
100 CONTINUE
```

It is the final statement that causes problems. The indexes **IXX** and **IYY** are computed in a complex way and depend on the values from the **IXOFFSET** and **IYOFFSET** arrays. We do not know if **TOTAL (IXX,IYY)** in one iteration of the loop will always be different from **TOTAL (IXX,IYY)** in every other iteration of the loop.

We can pull the statement out into its own separate loop by expanding **IXX** and **IYY** into arrays to hold intermediate values:

```
C$DOACROSS LOCAL(IX, IY, I)
    DO I  = 1, N
       IX = INDEXX(I)
       IY = INDEXY(I)
       XFORCE(I) = XFORCE(I) + NEWXFORCE(IX)
       YFORCE(I) = YFORCE(I) + NEWYFORCE(IY)
       IXX(I) = IXOFFSET(IX)
       IYY(I) = IYOFFSET(IY)
    END DO

    DO 100 I = 1, N
       TOTAL(IXX(I),IYY(I)) = TOTAL(IXX(I), IYY(I)) + EPSILON
100 CONTINUE
```

Here, **IXX** and **IYY** have been turned into arrays to hold all the values computed by the first loop. The first loop (containing most of the work) can now be run in parallel. Only the second loop must still be run serially. This will be true if **IXOFFSET** or **IYOFFSET** are permutation vectors.

Before we leave this example, note that if we were certain that the value for **IXX** was always different in every iteration of the loop, then the original loop could be run in parallel. It could also be run in parallel if **IYY** was always different. If **IXX** (or **IYY**) is always different in every iteration, then **TOTAL(IXX,IYY)** is never the same location in any iteration of the loop, and so there is no data conflict.

This sort of knowledge is, of course, program-specific and should always be used with great care. It may be true for a particular data set, but to run the original code in parallel as it stands, you need to be sure it will always be true for all possible input data sets.

Example B-16 Recurrence

```
DO I = 1,N
   X(I) = X(I-1) + Y(I)
END DO
```

This is an example of *recurrence*, which exists when a value computed in one iteration is immediately used by another iteration. There is no good way of running this loop in parallel. If this type of construct appears in a critical loop, try pulling the statement(s) out of the loop as in the previous example. Sometimes another loop encloses the recurrence; in that case, try to parallelize the outer loop.

Example B-17 Sum Reduction

```
SUM  = 0.0
DO I = 1,N
   SUM = SUM + A(I)
END DO
```

This operation is known as a *reduction*. Reductions occur when an array of values is combined and reduced into a single value. This example is a sum reduction because the combining operation is addition. Here, the value of **SUM** is carried from one loop iteration to the next, so this loop cannot be multiprocessed. However, because this loop simply sums the elements of **A(I)**, we can rewrite the loop to accumulate multiple, independent subtotals.

Then we can do much of the work in parallel:

```
   NUM_THREADS = MP_NUMTHREADS()
C
C  IPIECE_SIZE = N/NUM_THREADS ROUNDED UP
C
   IPIECE_SIZE = (N + (NUM_THREADS -1)) / NUM_THREADS
   DO K = 1, NUM_THREADS
      PARTIAL_SUM(K) = 0.0
C
C  THE FIRST THREAD DOES 1 THROUGH IPIECE_SIZE, THE
C  SECOND DOES IPIECE_SIZE + 1 THROUGH 2*IPIECE_SIZE,
C  ETC. IF N IS NOT EVENLY DIVISIBLE BY NUM_THREADS,
C  THE LAST PIECE NEEDS TO TAKE THIS INTO ACCOUNT,
C  HENCE THE "MIN" EXPRESSION.
```

```
C
   DO I =K*IPIECE_SIZE -IPIECE_SIZE +1, MIN(K*IPIECE_SIZE,N)
      PARTIAL_SUM(K) = PARTIAL_SUM(K) + A(I)
   END DO
   END DO
C
C  NOW ADD UP THE PARTIAL SUMS
   SUM = 0.0
   DO I = 1, NUM_THREADS
      SUM = SUM + PARTIAL_SUM(I)
   END DO
```

The outer **K** loop can be run in parallel. In this method, the array pieces for the partial sums are contiguous, resulting in good cache utilization and performance.

This is an important and common transformation, and so automatic support is provided by the **REDUCTION** clause:

```
   SUM = 0.0
C$DOACROSS LOCAL (I), REDUCTION (SUM)
   DO 10 I = 1, N
      SUM = SUM + A(I)
10 CONTINUE
```

The previous code has essentially the same meaning as the much longer and more confusing code above. It is an important example to study because the idea of adding an extra dimension to an array to permit parallel computation, and then combining the partial results, is an important technique for trying to break data dependencies. This idea occurs over and over in various contexts and disguises.

Note that reduction transformations such as this do not produce the same results as the original code. Because computer arithmetic has limited precision, when you sum the values together in a different order, as was done here, the round-off errors accumulate slightly differently. It is likely that the final answer will be slightly different from the original loop. Both answers are equally “correct.” Most of the time the difference is irrelevant, but sometimes it can be significant, so some caution is in order. If the difference is significant, neither answer is really trustworthy.

This example is a *sum* reduction because the operator is plus (+). The Fortran compiler supports three other types of reduction operations:

1. sum: p = p+a(i)
2. product: p = p*a(i)
3. min: m = min(m,a(i))
4. max: m = max(m,a(i))

For example,

```
C$DOACROSS LOCAL(I),REDUCTION(BG_SUM,BG_PROD,BG_MIN,BG_MAX)
        DO I = 1,N
           BG_SUM  = BG_SUM + A(I)
           BG_PROD = BG_PROD * A(I)
           BG_MIN  = MIN(BG_MIN, A(I))
           BG_MAX  = MAX(BG_MAX, A(I)
        END DO
```

One further example of a reduction transformation is noteworthy. Consider this code:

```
      DO I = 1, N
         TOTAL = 0.0
         DO J = 1, M
            TOTAL = TOTAL + A(J)
         END DO
         B(I) = C(I) * TOTAL
      END DO
```

Initially, it might look as if the inner loop should be parallelized with a **REDUCTION** clause. However, look at the outer **I** loop. Although **TOTAL** cannot be made a **LOCAL** variable in the inner loop, it fulfills the criteria for a **LOCAL** variable in the outer loop: the value of **TOTAL** in each iteration of the outer loop does not depend on the value of **TOTAL** in any other iteration of the outer loop. Thus, you do not have to rewrite the loop; you can parallelize this reduction on the outer **I** loop, making **TOTAL** and **J** local variables.

Work Quantum

A certain amount of overhead is associated with multiprocessing a loop. If the work occurring in the loop is small, the loop can actually run slower by multiprocessing than by single processing. To avoid this, make the amount of work inside the multiprocessed region as large as possible.

Example B-18 Loop Interchange

```
DO K = 1, N
   DO I = 1, N
      DO J = 1, N
         A(I,J) = A(I,J) + B(I,K) * C(K,J)
      END DO
   END DO
END DO
```

Here you have several choices: parallelize the **J** loop or the **I** loop. You cannot parallelize the **K** loop because different iterations of the **K** loop will all try to read and write the same values of **A(I,J)**. Try to parallelize the outermost **DO** loop possible, because it encloses the most work. In this example, that is the **I** loop. For this example, use the technique called *loop interchange*. Although the parallelizable loops are not the outermost ones, you can reorder the loops to make one of them outermost.

Thus, loop interchange would produce

```
C$DOACROSS LOCAL(I, J, K)
      DO I = 1, N
         DO K = 1, N
            DO J = 1, N
               A(I,J) = A(I,J) + B(I,K) * C(K,J)
            END DO
         END DO
      END DO
```

Now the parallelizable loop encloses more work and shows better performance. In practice, relatively few loops can be reordered in this way. However, it does occasionally happen that several loops in a nest of loops are candidates for parallelization. In such a case, it is usually best to parallelize the outermost one.

Occasionally, the only loop available to be parallelized has a fairly small amount of work. It may be worthwhile to force certain loops to run without parallelism or to select between a parallel version and a serial version, on the basis of the length of the loop.

Example B-19 Conditional Parallelism

```
J = (N/4) * 4
DO I = J+1, N
   A(I) = A(I) + X*B(I)
END DO
DO I = 1, J, 4
   A(I) = A(I) + X*B(I)
   A(I+1) = A(I+1) + X*B(I+1)
   A(I+2) = A(I+2) + X*B(I+2)
   A(I+3) = A(I+3) + X*B(I+3)
END DO
```

Here you are using loop unrolling of order four to improve speed. For the first loop, the number of iterations is always fewer than four, so this loop does not do enough work to justify running it in parallel. The second loop is worthwhile to parallelize if **N** is big enough. To overcome the parallel loop overhead, **N** needs to be around 500.

An optimized version would use the **IF** clause on the **DOACROSS** directive:

```
J = (N/4) * 4
DO I = J+1, N
   A(I) = A(I) + X*B(I)
END DO
C$DOACROSS IF (J.GE.500), LOCAL(I)
      DO I = 1, J, 4
         A(I) = A(I) + X*B(I)
         A(I+1) = A(I+1) + X*B(I+1)
         A(I+2) = A(I+2) + X*B(I+2)
         A(I+3) = A(I+3) + X*B(I+3)
      END DO
   ENDIF
```

Cache Effects

It is good policy to write loops that take the effect of the cache into account, with or without parallelism. The technique for the best cache performance is also quite simple: make the loop step through the array in the same way that the array is laid out in memory. For Fortran, this means stepping through the array without any gaps and with the leftmost subscript varying the fastest. Note that this does not depend on multiprocessing, nor is it required in order for multiprocessing to work correctly. However, multiprocessing can affect how the cache is used, so it is worthwhile to understand.

Topics covered in this section include:

Performing a Matrix Multiply

Consider the following code segment:

```
DO I = 1, N
   DO K = 1, N
      DO J = 1, N
         A(I,J) = A(I,J) + B(I,K) * C(K,J)
      END DO
   END DO
END DO
```

This is the same as Example B-18 in "Work Quantum" on page 159 (after interchange). To get the best cache performance, the **I** loop should be innermost. At the same time, to get the best multiprocessing performance, the outermost loop should be parallelized.

For this example, you can interchange the **I** and **J** loops, and get the best of both optimizations:

```
C$DOACROSS LOCAL(I, J, K)
      DO J = 1, N
         DO K = 1, N
            DO I = 1, N
               A(I,J) = A(I,J) + B(I,K) * C(K,J)
            END DO
         END DO
      END DO
```

Understanding Trade-Offs

Sometimes you must choose between the possible optimizations and their costs. Look at the following code segment:

```
DO J = 1, N
   DO I = 1, M
      A(I) = A(I) + B(J)*C(I,J)
   END DO
END DO
```

This loop can be parallelized on **I** but not on **J**. You could interchange the loops to put **I** on the outside, thus getting a bigger work quantum.

```
C$DOACROSS LOCAL(I,J)
   DO I = 1, M
      DO J = 1, N
         A(I) = A(I) + B(J)*C(I,J)
      END DO
   END DO
```

However, putting **J** on the inside means that you will step through the **C** array in the wrong direction; the leftmost subscript should be the one that varies the fastest. It is possible to parallelize the **I** loop where it stands:

```
   DO J = 1, N
C$DOACROSS LOCAL(I)
      DO I = 1, M
         A(I) = A(I) + B(J)*C(I,J)
      END DO
   END DO
```

However, **M** needs to be large for the work quantum to show any improvement. In this example, **A(I)** is used to do a sum reduction, and it is possible to use the reduction techniques shown in Example B-17 of "Breaking Data Dependencies" on page 154 to rewrite this in a parallel form. (Recall that there is no support for an entire array as a member of the **REDUCTION** clause on a **DOACROSS**.) However, that involves converting array **A** from a one-dimensional array to a two-dimensional array to hold the partial sums; this is analogous to the way we converted the scalar summation variable into an array of partial sums.

If **A** is large, however, the conversion can take more memory than you can spare. It can also take extra time to initialize the expanded array and increase the memory bandwidth requirements.

```
   NUM = MP_NUMTHREADS()
   IPIECE = (N + (NUM-1)) / NUM
C$DOACROSS LOCAL(K,J,I)
   DO K = 1, NUM
      DO J = K*IPIECE - IPIECE + 1, MIN(N, K*IPIECE)
         DO I = 1, M
            PARTIAL_A(I,K) = PARTIAL_A(I,K) + B(J)*C(I,J)
         END DO
      END DO
   END DO
C$DOACROSS LOCAL (I,K)
   DO I = 1, M
      DO K = 1, NUM
         A(I) = A(I) + PARTIAL_A(I,K)
      END DO
   END DO
```

You must trade off the various possible optimizations to find the combination that is right for the particular job.

Load Balancing

When the Fortran compiler divides a loop into pieces, by default it uses the simple method of separating the iterations into contiguous blocks of equal size for each process. It can happen that some iterations take significantly longer to complete than other iterations. At the end of a parallel region, the program waits for all processes to complete their tasks. If the work is not divided evenly, time is wasted waiting for the slowest process to finish.

Example B-20 Load Balancing

```
DO I = 1, N
   DO J = 1, I
      A(J, I) = A(J, I) + B(J)*C(I)
   END DO
END DO
```

The previous code segment can be parallelized on the **I** loop. Because the inner loop goes from 1 to **I**, the first block of iterations of the outer loop will end long before the last block of iterations of the outer loop.

In this example, this is easy to see and predictable, so you can change the program:

```
   NUM_THREADS = MP_NUMTHREADS()
C$DOACROSS LOCAL(I, J, K)
   DO K = 1, NUM_THREADS
      DO I = K, N, NUM_THREADS
         DO J = 1, I
            A(J, I) = A(J, I) + B(J)*C(I)
         END DO
      END DO
   END DO
```

In this rewritten version, instead of breaking up the **I** loop into contiguous blocks, break it into interleaved blocks. Thus, each execution thread receives some small values of **I** and some large values of **I**, giving a better balance of work between the threads. Interleaving usually, but not always, cures a load balancing problem.

You can use the **MP_SCHEDTYPE** clause to automatically perform this desirable transformation.

```
C$DOACROSS LOCAL (I,J), MP_SCHEDTYPE=INTERLEAVE
       DO 20 I = 1, N
          DO 10 J = 1, I
          A (J,I) = A(J,I) + B(J)*C(J)
 10    CONTINUE
 20    CONTINUE
```

The previous code has the same meaning as the rewritten form above.

Note that interleaving can cause poor cache performance because the array is no longer stepped through at stride 1. You can improve performance somewhat by adding a **CHUNK**=*integer_expression* clause. Usually 4 or 8 is a good value for *integer_expression*. Each small chunk will have stride 1 to improve cache performance, while the chunks are interleaved to improve load balancing.

The way that iterations are assigned to processes is known as *scheduling*. Interleaving is one possible schedule. Both interleaving and the "simple" scheduling methods are examples of *fixed* schedules; the iterations are assigned to processes by a single decision made when the loop is entered. For more complex loops, it may be desirable to use **DYNAMIC** or **GSS** schedules.

Comparing the output from pixie(1) or from pc sampling allows you to see how well the load is being balanced so you can compare the different methods of dividing the load. Refer to the discussion of the **MP_SCHEDTYPE** clause in "C$DOACROSS" on page 141 for more information.

Even when the load is perfectly balanced, iterations may still take varying amounts of time to finish because of random factors. One process may take a page fault, another may be interrupted to let a different program run, and so on. Because of these unpredictable events, the time spent waiting for all processes to complete can be several hundred cycles, even with near perfect balance.

Reorganizing Common Blocks To Improve Cache Behavior

You can use the **–OPT:reorg_common** option, which reorganizes common blocks to improve the cache behavior of accesses to members of the common block. This option produces consistent results as long as the code follows the standard and array references are made within the bounds of the array. It produces unexpected results if you violate the standard, for example, if you access an array out of its declared bounds.

The option is enabled by default at **–O3** only if all files referencing the common block are compiled at that optimization level. It is disabled if any file with the common block is compiled at either **–O2** and below, **–OPT:reorg_common=OFF**, or **–Wl,–noivpad**.

Advanced Features

A number of features are provided so that sophisticated users can override the multiprocessing defaults and customize the parallelism to their particular applications. This section provides a brief explanation of the following features:

mp_block and mp_unblock

mp_block puts the slave threads into a blocked state using the system call **blockproc**. The slave threads stay blocked until a call is made to **mp_unblock**. These routines are useful if the job has bursts of parallelism separated by long stretches of single processing, as with an interactive program. You can block the slave processes so they consume CPU cycles only as needed, thus freeing the machine for other users. The Fortran system automatically unblocks the slaves on entering a parallel region if you neglect to do so.

mp_setup, mp_create, and mp_destroy

The **mp_setup**, **mp_create**, and **mp_destroy** subroutine calls create and destroy threads of execution. This can be useful if the job has only one parallel portion or if the parallel parts are widely scattered. When you destroy the extra execution threads, they cannot consume system resources; they must be re-created when needed. Use of these routines is discouraged because they degrade performance; use the **mp_block** and **mp_unblock** routines in almost all cases.

mp_setup takes no arguments. It creates the default number of processes as defined by previous calls to **mp_set_numthreads**, by the **MP_SET_NUMTHREADS** environment variable (described in "Environment Variables for Origin Systems" on page 169), or by the number of CPUs on the current hardware platform. **mp_setup** is called automatically when the first parallel loop is entered to initialize the slave threads.

mp_create takes a single integer argument, the total number of execution threads desired. Note that the total number of threads includes the master thread. Thus, **mp_create(***n***)** creates one thread less than the value of its argument. **mp_destroy** takes no arguments; it destroys all the slave execution threads, leaving the master untouched.

When the slave threads die, they generate a **SIGCLD** signal. If your program has changed the signal handler to catch **SIGCLD**, it must be prepared to deal with this signal when **mp_destroy** is executed. This signal also occurs when the program exits; **mp_destroy** is called as part of normal cleanup when a parallel Fortran job terminates.

mp_blocktime

The Fortran slave threads spin wait until there is work to do. This makes them immediately available when a parallel region is reached. However, this consumes CPU resources. After enough wait time has passed, the slaves block themselves through **blockproc**. Once the slaves are blocked, it requires a system call to **unblockproc** to activate the slaves again (refer to the unblockproc(2) reference page for details). This makes the response time much longer when starting up a parallel region.

This trade-off between response time and CPU usage can be adjusted with the **mp_blocktime** call. **mp_blocktime** takes a single integer argument that specifies the number of times to spin before blocking. By default, it is set to 10,000,000; this takes roughly one second. If called with an argument of 0, the slave threads will not block themselves no matter how much time has passed. Explicit calls to **mp_block**, however, will still block the threads.

This automatic blocking is transparent to the user's program; blocked threads are automatically unblocked when a parallel region is reached.

mp_numthreads, mp_set_numthreads

Occasionally, you may want to know how many execution threads are available. **mp_numthreads** is a zero-argument integer function that returns the total number of execution threads for this job. The count includes the master thread.

In addition, this routine has the side-effect of freezing (for eternity) the number of threads to the returned value, so use this routine sparingly. To determine the number of threads without this freeze property, see the description of **mp_suggested_numthreads** below.

mp_set_numthreads takes a single-integer argument. It changes the default number of threads to the specified value. A subsequent call to **mp_setup** will use the specified value rather than the original defaults. If the slave threads have already been created, this call will not change their number. It only has an effect when **mp_setup** is called.

mp_suggested_numthreads

The **mp_suggested_numthreads**(integer*4) uses the supplied value as a hint about how many threads to use in subsequent parallel regions, and returns the previous value of the number of threads to be employed in parallel regions. It does not affect currently executing parallel regions, if any. The implementation may ignore this hint depending on factors such as overall system load. This routine returns the previous value of the number of threads being employed at parallel regions. Therefore, to simply query the number of threads, call it with the value 0.

The **mp_suggested_numthreads** interface is available whether or not dynamic threads is turned on (see "Using Dynamic Threads" on page 170).

mp_my_threadnum

mp_my_threadnum is a zero-argument function that allows a thread to differentiate itself while in a parallel region. If there are n execution threads, the function call returns a value between zero and $n - 1$. The master thread is always thread zero. This function can be useful when parallelizing certain kinds of loops. Most of the time the loop index variable can be used for the same purpose. Occasionally, the loop index may not be accessible, as, for example, when an external routine is called from within the parallel loop. This routine provides a mechanism for those cases.

mp_setlock, mp_unsetlock, mp_barrier

mp_setlock, **mp_unsetlock**, and **mp_barrier** are zero-argument subroutines that provide convenient (although limited) access to the locking and barrier functions provided by **ussetlock**, **usunsetlock**, and **barrier**. These subroutines are convenient because you do not need to initialize them; calls such as **usconfig** and **usinit** are done automatically. The limitation is that there is only one lock and one barrier. For most programs, this amount is sufficient. If your program requires more complex or flexible locking facilities, use the **ussetlock** family of subroutines directly.

Environment Variables for Origin Systems

The environment variables are described in these subsections:

You can find information about other environment variables in "Multiprocessing Environment Variables" on page 116 and "Specifying the Buffer Size for Direct Unformatted I/O" on page 16.

Using the Environment Variables MP_SET_NUMTHREADS, MP_BLOCKTIME, MP_SETUP

The **MP_SET_NUMTHREADS**, **MP_BLOCKTIME**, and **MP_SETUP** environment variables act as an implicit call to the corresponding routine(s) of the same name at program start-up time.

For example, the *csh* command

```
% setenv MP_SET_NUMTHREADS 2
```

causes the program to create two threads regardless of the number of CPUs actually on the machine, just like the source statement

```
CALL MP_SET_NUMTHREADS (2)
```

Similarly, the *sh* commands

```
% set MP_BLOCKTIME 0
% export MP_BLOCKTIME
```

prevent the slave threads from autoblocking, just like the source statement

```
call mp_blocktime (0)
```

For compatibility with older releases, the environment variable **NUM_THREADS** is supported as a synonym for **MP_SET_NUMTHREADS**.

To help support networks with multiple multiprocessors and multiple CPUs, the environment variable **MP_SET_NUMTHREADS** also accepts an expression involving integers **+**, **–**, *min*, *max*, and the special symbol **all**, which stands for "the number of CPUs on the current machine." For example, the following command selects the number of threads to be two fewer than the total number of CPUs (but always at least one):

```
% setenv MP_SET_NUMTHREADS max(1,all-2)
```

Setting the Environment Variable _DSM_WAIT

This variable controls how a thread waits for a synchronization event, such as a lock or a barrier. If this variable is set to YIELD, a waiting thread spins for a while and then invokes **sginap(0)**, surrendering the CPU to another waiting process (if any). If set to SPIN, a waiting thread simply busy-waits in a loop until the synchronization event succeeds. The default value is YIELD.

Using Dynamic Threads

In an environment with long running jobs and varying workloads, you may want to vary the number of threads during execution of some jobs.

Setting MP_SUGNUMTHD causes the run-time library to create an additional, asynchronous process that periodically wakes up and monitors the system load. When idle processors exist, this process increases the number of threads, up to a maximum of MP_SET_NUMTHREADS. When the system load increases, it decreases the number of threads, possibly to as few as 1. When MP_SUGNUMTHD has no value, this feature is disabled and multithreading works as before.

Note: The number of threads being used is adjusted only at the START of a parallel region (for example, a *doacross*), and not within a parallel region.

In the past, the number of threads utilized during execution of a multiprocessor job was generally constant, set for example, using MP_SET_NUMTHREADS.

The environment variables MP_SUGNUMTHD_MIN and MP_SUGNUMTHD_MAX are used to limit this feature as desired. When MP_SUGNUMTHD_MIN is set to an integer value between 1 and MP_SET_NUMTHREADS, the process will not decrease the number of threads below that value.

When MP_SUGNUMTHD_MAX is set to an integer value between the minimum number of threads and MP_SET_NUMTHREADS, the process will not increase the number of threads above that value.

If you set any value in the environment variable MP_SUGNUMTHD_VERBOSE, informational messages are written to *stderr* whenever the process changes the number of threads in use.

Calls to **mp_numthreads** and **mp_set_numthreads** are taken as a sign that the application depends on the number of threads in use. The number in use is frozen upon either of these calls; and if MP_SUGNUMTHD_VERBOSE is set, a message to that effect is written to *stderr*.

Controlling the Stacksize of Slave Processes

Use the environment variable, MP_STACK_SLAVESIZE, to control the stacksize of slave processes. Set this variable to the desired stacksize in bytes. The default value is 16 MB (4 MB for greater than 64 threads). Note that slave processes only allocate their local data onto their stack; shared data (even if allocated on the master's stack) is not counted.

Specifying Page Sizes for Stack, Data, and Text

Use the environment variables, PAGESIZE_STACK, PAGESIZE_DATA, and PAGESIZE_TEXT, to specify the desired page size (in KB) for each of stack, data, and text segments.

Specifying Run-Time Scheduling

These environment variables specify the type of scheduling to use on **DOACROSS** loops that have their scheduling type set to **RUNTIME**. For example, the following *csh* commands cause loops with the **RUNTIME** scheduling type to be executed as interleaved loops with a chunk size of 4:

```
% setenv MP_SCHEDTYPE INTERLEAVE
% setenv CHUNK 4
```

The defaults are the same as on the **DOACROSS** directive; if neither variable is set, **SIMPLE** scheduling is assumed. If **MP_SCHEDTYPE** is set, but **CHUNK** is not set, a **CHUNK** of 1 is assumed. If **CHUNK** is set, but **MP_SCHEDTYPE** is not, **DYNAMIC** scheduling is assumed.

Specifying Gang Scheduling

Set **MPC_GANG** to ON specify gang scheduling. Set to OFF to disable gang scheduling.

Local COMMON Blocks

A special *ld* option allows named **COMMON** blocks to be local to a process. Each process in the parallel job gets its own private copy of the common block. This can be helpful in converting certain types of Fortran programs into a parallel form.

The common block must be a named **COMMON** (blank **COMMON** may not be made local), and it must not be initialized by **DATA** statements.

To create a local **COMMON** block, give the special loader directive **–Wl,–Xlocal** followed by a list of **COMMON** block names. Note that the external name of a **COMMON** block known to the loader has a trailing underscore and is not surrounded by slashes. For example, the command

```
% f77 -mp a.o -Wl,-Xlocal,foo_
```

makes the **COMMON** block **/foo/** a local **COMMON** block in the resulting **a.out** file. You can specify multiple **–Wl,–Xlocal** options if necessary.

It is occasionally desirable to be able to copy values from the master thread's version of the **COMMON** block into the slave thread's version. The special directive **C$COPYIN** allows this. It has the form

```
C$COPYIN item [, item ...]
```

Each *item* must be a member of a local **COMMON** block. It can be a variable, an array, an individual element of an array, or the entire **COMMON** block.

Note: The **C$COPYIN** directive cannot be executed from inside a parallel region.

For example,

```
C$COPYIN x,y, /foo/, a(i)
```

propagates the values for **x** and **y**, all the values in the **COMMON** block **foo**, and the **i**th element of array **a**. All these items must be members of local **COMMON** blocks. Note that this directive is translated into executable code, so in this example **i** is evaluated at the time this statement is executed.

Compatibility With sproc

The parallelism used in Fortran is implemented using the standard system call **sproc**. It is recommended that programs not attempt to use both **C$DOACROSS** loops and **sproc** calls. It is possible, but there are several restrictions:

- Any threads you create may not execute **$DOACROSS** loops; only the original thread is allowed to do this.
- The calls to routines like **mp_block** and **mp_destroy** apply only to the threads created by **mp_create** or to those automatically created when the Fortran job starts; they have no effect on any user-defined threads.
- Calls to routines such as **m_get_numprocs** do not apply to the threads created by the Fortran routines. However, the Fortran threads are ordinary subprocesses; using the routine **kill** with the arguments **0** and **sig** (for example, **kill**(0,**sig**)) to signal all members of the process group might kill threads used to execute **C$DOACROSS**. If you choose to intercept the **SIGCLD** signal, you must be prepared to receive this signal when the threads used for the **C$DOACROSS** loops exit; this occurs when **mp_destroy** is called or at program termination.
- Note in particular that **m_fork** is implemented using **sproc**, so it is not legal to **m_fork** a family of processes that each subsequently executes **C$DOACROSS** loops. Only the original thread can execute **C$DOACROSS** loops.

DOACROSS Implementation

This section discusses how multiprocessing is implemented in a **DOACROSS** routine. This information is useful when you use a debugger or interpret the results of an execution profile.

Loop Transformation

When the Fortran compiler encounters a **C$DOACROSS** directive, it spools the body of the corresponding **DO** loop into a separate subroutine and replaces the loop with a call to a special library routine **__mp_parallel_do**.

The newly created routine is named by appending **.pregion** to the name of the original routine, followed by the number of the parallel loop in the routine (where 0 is the first loop). For example, the first parallel loop in a routine named **foo** is named **foo.pregion0**, the second parallel loop is **foo.pregion1**, and so on.

If a loop occurs in the **main** routine and if that routine has not been given a name by the **PROGRAM** statement, its name is assumed to be **main**. Any variables declared to be **LOCAL** in the original **C$DOACROSS** statement are declared as local variables in the spooled routine. References to **SHARE** variables are resolved by referring back to the original routine.

Because the spooled routine is now just a **DO** loop, the routine uses subroutine arguments to specify which part of the loop a particular process is to execute. The spooled routine has three arguments: the starting value for the index, the number of times to execute the loop, and a special flag word. As an example, the following routine that appears on line 1000:

```
   SUBROUTINE EXAMPLE(A, B, C, N)
   REAL A(*), B(*), C(*)
C$DOACROSS LOCAL(I,X)
   DO I = 1, N
      X = A(I)*B(I)
      C(I) = X + X**2
   END DO
   C(N) = A(1) + B(2)
   RETURN
   END
```

produces this spooled routine to represent the loop:

```
   SUBROUTINE EXAMPLE.pregion
X ( _LOCAL_START, _LOCAL_NTRIP, _THREADINFO)
   INTEGER*4 _LOCAL_START
   INTEGER*4 _LOCAL_NTRIP
   INTEGER*4 _THREADINFO
   INTEGER*4 I
   REAL X
   INTEGER*4 _DUMMY

   I = _LOCAL_START
   DO _DUMMY = 1,_LOCAL_NTRIP
       X = A(I)*B(I)
       C(I) = X + X**2
   I = I + 1
   END DO

   END
```

Executing Spooled Routines

The set of processes that cooperate to execute the parallel Fortran job are members of a process share group created by the system call **sproc**. The process share group is created by special Fortran start-up routines that are used only when the executable is linked with the **–mp** option, which enables multiprocessing.

The first process is the master process. It executes all the nonparallel portions of the code. The other processes are slave processes; they are controlled by the routine **mp_slave_control**. When they are inactive, they wait in the special routine **__mp_slave_wait_for_work**.

The **__mp_parallel_do** routine divides the work and signals the slaves. The master process then calls the spooled routine to do its share of the work. When a slave is signaled, it wakes up from the wait loop, calculates which iterations of the spooled **DO** loop it is to execute, and then calls the spooled routine with the appropriate arguments. When a slave completes its execution of the spooled routine, it reports that it has finished and returns to **__mp_slave_wait_for_work**.

When the master completes its execution of its portion of the spooled routine, it waits in the special routine **mp_wait_for_loop_completion** until all the slaves have completed processing. The master then returns to the main routine and continues execution.

PCF Directives

In addition to the simple loop-level parallelism offered by the **C$DOACROSS** directive (described in "Parallel Loops" on page 140), the compiler supports a more general model of parallelism. This model is based on the work done by the Parallel Computing Forum (PCF), which itself formed the basis for the proposed ANSI-X3H5 standard. The compiler supports this model through compiler directives, rather than extensions to the source language.

The main concept in this model is the *parallel region*, which can be any arbitrary section of code (not just a **DO** loop). Within the parallel region, there are special *work-sharing constructs* that can be used to divide the work among separate processes or threads. The parallel region can also contain a *critical section* construct, where exactly one process executes at a time.

The master thread executes the user program until it reaches a parallel region. It then spawns one or more slave threads that begin executing code at the beginning of a parallel region. Each thread executes all the code in the region until a work sharing construct is encountered. Each thread then executes some portion of the work sharing construct, and then resumes executing the parallel region code. At the end of the parallel region, all the threads synchronize, and the master thread continues execution of the user program.

The PCF directives, summarized in Table B-1, implement the general model of parallelism. They look like Fortran comments, with a **C** in column one. The compiler recognizes these directives when multiprocessing is enabled with either the **–mp** option. (Multiprocessing is also enabled with the **–pfa** option if you have purchased MIPSpro Power Fortran 77.) If multiprocessing is not enabled, the compiler treats these statements as comments. Therefore, you can compile identical source with a single-processing compiler or by Fortran without the multiprocessing option. The PCF directives start with the characters **C$PAR**.

Table B-1 Summary of PCF Directives

Directive	Description
C$PAR BARRIER	Ensures that each process waits until all processes reach the barrier before proceeding.
C$PAR [END] CRITICAL SECTION	Ensures that the enclosed block of code is executed by only one process at a time by using a global lock.

Table B-1 (continued) Summary of PCF Directives

Directive	Description
C$PAR [END] PARALLEL	Encloses a parallel region, which includes work-sharing constructs and critical sections.
C$PAR PARALLEL DO	Precedes a single DO loop for which separate iterations are executed by different processes. This directive is equivalent to the C$DOACROSS directive.
C$PAR [END] PDO	Separate iterations of the enclosed loop are executed by different processes. This directive must be inside a parallel region.
C$PAR [END] PSECTION[S]	Parcels out each block of code in turn to a process.
C$PAR SECTION	Signifies a starting line for an individual section within a parallel section.
C$PAR [END] SINGLE PROCESS	Ensures that the enclosed block of code is executed by exactly one process.
C$PAR &	Continues a PCF directive onto multiple lines.

Parallel Region

A parallel region encloses any number of PCF constructs (described in "PCF Constructs" on page 178). It signifies the boundary within which slave threads execute. A user program can contain any number of parallel regions. The syntax of the parallel region is

```
C$PAR PARALLEL [clause [[,] clause]...]
           code
C$PAR END PARALLEL
```

where valid clauses are

```
[IF ( logical_expression )]
[{LOCAL | PRIVATE}(item [,item ...])]
[{SHARE | SHARED}(item [,item ...])]
```

The **IF**, **LOCAL**, and **SHARED** clauses have the same meaning as in the **C$DOACROSS** directive (refer to "Writing Parallel Fortran" on page 141).

The preferred form of the directive has no commas between the clauses. The **SHARED** clause is preferred over **SHARE** and **LOCAL** is preferred over **PRIVATE**.

In the following code, all threads enter the parallel region and call the routine **foo**:

```
        subroutine ex1(index)
        integer i
C$PAR PARALLEL LOCAL(i)
        i = mp_my_threadnum()
        call foo(i)
C$PAR END PARALLEL
        end
```

PCF Constructs

The three types of PCF constructs are work-sharing constructs, critical sections, and barriers. All master and slave threads synchronize at the bottom of a work-sharing construct. None of the threads continue past the end of the construct until they all have completed execution within that construct.

The four work-sharing constructs are

- parallel **DO**
- PDO
- parallel sections
- single process

If specified, the PDO, parallel section, and single process constructs must appear inside of a parallel region; the parallel **DO** construct cannot. Specifying a parallel **DO** construct inside of a parallel region produces a syntax error.

The critical section construct protects a block of code with a lock so that it is executed by only one thread at a time. Threads do not synchronize at the bottom of a critical section.

The barrier construct ensures that each process that is executing waits until all others reach the barrier before proceeding.

Parallel DO

The parallel **DO** construct is the same as the **C$DOACROSS** directive (described in "C$DOACROSS" on page 141) and conceptually the same as a parallel region containing exactly one PDO construct and no other code. Each thread inside the enclosing parallel region executes separate iterations of the loop within the parallel **DO** construct. The syntax of the parallel **DO** construct is

```
C$PAR PARALLEL DO [clause [[,] clause]...]
```

"C$DOACROSS" on page 141 describes valid values for *clause* with the exception of the **MP_SCHEDTYPE=***mode* clause. For the **C$PAR PARALLEL DO** directive, **MP_SCHEDTYPE=** is optional; you can just specify *mode*.

PDO

Each thread inside the enclosing parallel region executes a separate iteration of the loop within the PDO construct. The syntax of the PDO construct, which can only be specified within a parallel region, is

```
C$PAR PDO [clause [[,] clause]...]
    code
[C$PAR END PDO [NOWAIT]]
```

The valid values for *clause* are

```
[{LOCAL | PRIVATE} (item[,item ...])]
[{LASTLOCAL | LAST LOCAL} (item[,item ...])]
[(ORDERED)]
[ sched ]
[ chunk ]
```

LOCAL, **LASTLOCAL**, s*ched*, and *chunk* have the same meaning as in the **C$DOACROSS** directive (refer to "Writing Parallel Fortran" on page 141). Note in particular that it is legal to declare a data item as **LOCAL** in a PDO even if it was declared as **SHARED** in the enclosing parallel region. The **(ORDERED)** clause is equivalent to a *sched* clause of **DYNAMIC** and a *chunk* clause of **1**. The parenthesis are required.

LASTLOCAL is preferred over **LAST LOCAL** and **LOCAL** is preferred over **PRIVATE**.

The **END PDO** directive is optional. If specified, this directive must appear immediately after the end of the **DO** loop. The optional **NOWAIT** clause specifies that each process should proceed directly to the code immediately following the directive. If you do not specify **NOWAIT**, the processes will wait until all have reached the directive before proceeding.

As an example of the PDO construct, consider the following code:

```
        subroutine ex2(a,n)
        real a(n)
C$PAR PARALLEL local(i) shared(a)
C$PAR PDO
        do i = 1, n
          a(i) = a(i) + 1.0
        enddo
C$PAR END PARALLEL
        end
```

This sample code is the same as a **C$DOACROSS** loop. In fact, the compiler recognizes this as a special case and generates the same (more efficient) code as for a **C$DOACROSS** directive.

Parallel Sections

The parallel sections construct is a parallel version of the Fortran 90 **SELECT** statement. Each block of code is parcelled out in turn to a separate thread. The syntax of the parallel sections construct is

```
C$PAR PSECTION[S] [clause [[,]clause ]...
   code
[C$PAR SECTION
  code] ...
C$PAR END PSECTION[S] [NOWAIT]
```

where the only valid value for *clause* is

```
[{LOCAL | PRIVATE} (item [,item]) ]
```

LOCAL is preferred over **PRIVATE** and has the same meaning as for the **C$DOACROSS** directive (refer to "C$DOACROSS" on page 141). Note in particular that it is legal to declare a data item as **LOCAL** in a parallel sections construct even if it was declared as **SHARED** in the enclosing parallel region.

The optional **NOWAIT** clause specifies that each process should proceed directly to the code immediately following the directive. If you do not specify **NOWAIT**, the processes will wait until all have reached the **END PSECTION** directive before proceeding.

Parallel sections must appear within a parallel region. They can contain critical section constructs (described in "Critical Section" on page 185) but cannot contain any of the following types of constructs:

- PDO
- parallel **DO** or **C$DOACROSS**
- single process

Each code block is executed in parallel (depending on the number of processes available). The code blocks are assigned to threads one at a time, in the order specified. Each code block is executed by only one thread.

For example, consider the following code:

```
        subroutine ex3(a,n1,b,n2,c,n3)
        real a(n1), b(n2), c(n3)

C$PAR PARALLEL local(i) shared(a,b,c)

C$PAR PSECTIONS
C$PAR SECTION
        do i = 1, n1
          a(i) = 0.0
        enddo
C$PAR SECTION
        do i = 1, n2
          b(i) = 0.5
        enddo
C$PAR SECTION
        call normalize(c,n3)
        do i = 1, n3
          c(i) = c(i) + 1.0
        enddo
C$PAR END PSECTION

C$PAR END PARALLEL

        end
```

The first thread to enter the parallel sections construct executes the first block, the second thread executes the second block, and so on. This example has only three sections, so if

more than three threads are in the parallel region, the fourth and higher threads wait at the **C$PAR END PSECTION** directive until all threads are finished. If the parallel region is being executed by only two threads, whichever thread finishes its block first continues and executes the remaining block.

This example uses **DO** loops, but a parallel section can be any arbitrary block of code. Be aware of the significant overhead of a parallel construct. Make sure the amount of work performed is enough to outweigh the extra overhead.

The sections within a parallel sections construct are assigned to threads one at a time, from the top down. There is no other implied ordering to the operations within the sections. In particular, a later section cannot depend on the results of an earlier section, unless some form of explicit synchronization is used. If there is such explicit synchronization, you must be sure that the lexical ordering of the blocks is a legal order of execution.

Single Process

The single process construct, which can only be specified within a parallel region, ensures that a block of code is executed by exactly one process. The syntax of the single process construct is

```
C$PAR SINGLE PROCESS [clause [[,] clause]...]
     code
C$PAR END SINGLE PROCESS [NOWAIT]
```

where the only valid value for clause is

```
[{LOCAL | PRIVATE} (item [,item]) ]
```

LOCAL is preferred over **PRIVATE** and has the same meaning as for the **C$DOACROSS** directive (refer to "C$DOACROSS" on page 141). Note in particular that it is legal to declare a data item as **LOCAL** in a single process construct even if it was declared as **SHARED** in the enclosing parallel region.

The optional **NOWAIT** clause specifies that each process should proceed directly to the code immediately following the directive. If you do not specify **NOWAIT**, the processes will wait until all have reached the directive before proceeding.

This construct is semantically equivalent to a parallel sections construct with only one section. The single process construct provides a more descriptive syntax. For example, consider the following code:

```
        real function ex4(a,n, big_max, bmax_x, bmax_y)
        real a(n,n), big_max
        integer bmax_x, bmax_y

C$ volatile big_max, bmax_x, bmax_y
C$ volatile cur_max, index_x, index_y

        index_x = 0
        index_y = 0
        cur_max = 0.0

C$PAR PARALLEL local(i,j)
C$PAR& shared(a,n,index_x,index_y,cur_max,
C$PAR& big_max,bmax_x,bmax_y)

C$PAR PDO
        do j = 1, n
          do i = 1, n
            if (a(i,j) .gt. cur_max) then
C$PAR CRITICAL SECTION
              if (a(i,j) .gt. cur_max) then
                index_x = i
                index_y = j
                cur_max = a(i,j)
              endif
C$PAR END CRITICAL SECTION
            endif
          enddo
        enddo

C$PAR SINGLE PROCESS
        if (cur_max .gt. big_max) then
          big_max = (big_max + cur_max) / 2.0
          bmax_x = index_x
          bmax_y = index_y
        endif
C$PAR END SINGLE PROCESS

C$PAR PDO
        do j = 1, n
          do i = 1, n
            a(i,j) = a(i,j)/big_max
          enddo
        enddo

C$PAR END PARALLEL

        ex4 = cur_max

        end
```

The first thread to reach the single process section executes the code in that block. All other threads wait at the end of the block until the code has been executed.

This example contains a number of interesting points to be examined. First, note the use of the **VOLATILE** declaration. Any data item that might be written by one thread and then read by a different thread must be marked as **VOLATILE**. Making a variable **VOLATILE** can reduce opportunities for optimization, so the declarations are prefixed by **C$** to prevent the single-processor version of the code from being penalized. Refer to the *MIPSpro Fortran 77 Language Reference Manual* for more information about the **VOLATILE** statement. Also see "Synchronization Intrinsics" on page 191.

Second, note the use of the odd looking repetition of the **IF** test in the first parallel loop:

```
           if (a(i,j) .gt. cur_max) then
C$PAR CRITICAL SECTION
             if (a(i,j) .gt. cur_max) then
```

This practice is usually called *test&test&set*. It is a multi-processing optimization. Note that the following straight forward code segment is incorrect:

```
        do i = 1, n
          if (a(i,j) .gt. cur_max) then
C$PAR CRITICAL SECTION
                index_x = i
                index_y = j
                cur_max = a(i,j)
C$PAR END CRITICAL SECTION
          endif
        enddo
```

Because many threads execute the loop in parallel, there is no guarantee that once inside the critical section, **cur_max** still has the same value it did in the **IF** test outside the critical section (some other thread may have updated it). In particular, **cur_max** may now have a value that is larger than **a(i,j)**. Therefore, the critical section must be locked before testing the value of **cur_max**. Changing the previous code into the equally straightforward

```
          do i = 1, n
C$PAR CRITICAL SECTION
              if (a(i,j) .gt. cur_max) then
                index_x = i
                index_y = j
                cur_max = a(i,j)
              endif
C$PAR END CRITICAL SECTION
       enddo
```

works correctly, but suffers from a serious performance penalty: the critical section lock must be acquired and released (an expensive operation) for each element of the array. Because the values are rarely updated, this process involves a lot of wasted effort. It is almost certainly slower than just executing the loop serially.

Combining the two methods, as in the original example, produces code that is both fast and correct. If the **IF** test outside of the critical section fails, you can be certain that the values will not be updated, and can proceed. You can expect that the outside **IF** test will account for the majority of cases. If the outer **IF** test passes, then the values *might* be updated, but you cannot always be certain. To ensure correctness, you must perform the test again after acquiring the critical section lock.

You can prefix one of the two identical **IF** tests with **C$** to reduce overhead in the non-multiprocessed case.

Lastly, note the difference between the single process and critical section constructs. If several processes arrive at a critical section construct, they execute the code one at a time. However, they will *all* execute the code. If several processes arrive at a single process construct, only one process executes the code. The other processes bypass the code and wait at the end of the construct for the chosen process to finish.

Critical Section

The critical section construct restricts execution of a block of code so that only one process can execute it at a time. Another process attempting to gain entry to the critical section must wait until the previous process has exited.

The critical section construct can appear anywhere in a program, including inside and outside a parallel region and within a **C$DOACROSS** loop. The syntax of the critical section construct is

```
C$PAR CRITICAL SECTION [ ( lock_variable ) ]
    code
C$PAR END CRITICAL SECTION
```

The *lock_variable* is an optional integer variable that must be initialized to zero. The parenthesis are required. If you do not specify *lock_variable*, the compiler automatically supplies a global lock. Multiple critical section constructs inside the same parallel region are considered to be independent of each other unless they use the same explicit *lock_variable*.

Consider the following code:

```
        integer function num_exceptions(a,n,biggest_allowed)
        double precision a(n,n,n), biggest_allowed

        integer count
        integer lock_var

        volatile count

        count = 0
        lock_var = 0

C$PAR PARALLEL  local(i,j,k) shared(count,lock_var)

C$PAR PDO
        do 10 k = 1,n
          do 10 j = 1,n
            do 10 i = 1,n
              if (a(i,j,k) .gt. biggest_allowed) then


C$PAR CRITICAL SECTION (lock_var)
                count = count + 1
C$PAR END CRITICAL SECTION (lock_var)

              else
                call transform(a(i,j,k))
                if (a(i,j,k) .gt. biggest_allowed) then

C$PAR CRITICAL SECTION (lock_var)
                  count = count + 1
C$PAR END CRITICAL SECTION (lock_var)

                endif
              endif
 10    continue

C$PAR END PARALLEL

       num_exceptions = count

       return
       end
```

This example demonstrates the use of the lock variable (**lock_var**). A **C$PAR CRITICAL SECTION** directive ensures that no more than one process executes the enclosed block of code at a time. However, if there are multiple critical sections, different processes can be in different critical sections at the same time. This example does not allow different processes to be in different critical sections at the same time because both critical sections control access to the same variable (**count**). Specifying the same lock variable for both

critical sections ensures that no more than one process is executing either of the critical sections that use that lock variable. Note that the **lock_var** must be **SHARED** (so that all processes use the same lock), and that **count** must be **volatile** (because other processes might change its value). Refer to "Synchronization Intrinsics" on page 191.

Barrier Constructs

A barrier construct ensures that each process waits until all processes reach the barrier before proceeding. The syntax of the barrier construct is

```
C$PAR BARRIER
```

C$PAR &

Occasionally, the clauses in PCF directives are longer than one line. You can use the **C$PAR &** directive to continue a directive onto multiple lines.

For example,

```
C$PAR PARALLEL local(i,j)
C$PAR& shared(a,n,index_x,index_y,cur_max,
C$PAR& big_max,bmax_x,bmax_y)
```

Restrictions

The three work-sharing constructs, **PDO**, **PSECTION**, and **SINGLE PROCESS**, must be executed by all the threads executing in the parallel region (or none of the threads). The following is illegal:

```
        .
        .
        .
C$PAR PARALLEL
         if (mp_my_threadnum() .gt. 5) then
C$PAR SINGLE PROCESS
              many_processes = .true.
C$PAR END SINGLE PROCESS
         endif
          .
          .
          .
```

This code will hang forever when run with enough processes. One or more process will be stuck at the **C$PAR END SINGLE PROCESS** directive waiting for all the threads to arrive. Because some of the threads never took the appropriate branch, they will never encounter the construct. However, the following kind of simple looping is supported:

```
      code
C$PAR PARALLEL local(i,j) shared(a)
        do i= 1,n
C$PAR PDO
          do j = 2,n
      code
```

The distinction here is that all of the threads encounter the work-sharing construct, they all complete it, and they all loop around and encounter it again.

Note that this restriction does not apply to the critical section construct, which operates on one thread at a time without regard to any other threads.

Parallel regions cannot be lexically nested inside of other parallel regions, nor can work-sharing constructs be nested. However, as an aid to writing library code, you can call an external routine that contains a parallel region even from within a parallel region. In this case, only the first region is actually run in parallel. Therefore, you can create a parallelized routine without accounting for whether it will be called from within an already parallelized routine.

A Few Words About Efficiency

The more general PCF constructs are typically slower than the special case parallelism offered by the **C$DOACROSS** directive. They are slower because of the extra synchronization required. When a **C$DOACROSS** loop executes, there is a synchronization point at entry and another at exit. When a parallel region executes, there is a synchronization point at entry to the region, another at each entry to a work-sharing construct, another at each exit from a work-sharing construct, and one at exit from the region. Thus, several separate **C$DOACROSS** loops typically execute faster than a single parallel region with several PDO constructs. Limit your use of the parallel region construct to those few cases that actually need it.

Communicating Between Threads Through Thread Local Data

The routines described below allow you to perform explicit communication between threads within their MP Fortran program. These communication mechanisms are similar to message-passing, one-sided-communication, or **shmem**, and may be desirable for reasons of performance and/or style.

The operations allow a thread to fetch from (get) or send to (put) data belonging to other threads. Therefore these operations can be performed only on data that has been declared to be **–Xlocal** (that is, each thread has its own private copy of that data; see the ld(1) reference page for details on **Xlocal**), the equivalent of the Cray TASKCOMMON directive. A "get" operation requires that source point to Xlocal data, while a "put" operation requires that target point to Xlocal data.

The routines are similar to the original **shmem** routines (see the shmem reference page), but are prefixed by **mp_**.

Routines are listed below.

```
mp_shmem_get32  (integer*4 target,
                integer*4 source,
                integer*4 length,
                integer*4 source_thread)

mp_shmem_put32  (integer*4 target,
                integer*4 source,
                integer*4 length,
                integer*4 target_thread)

mp_shmem_iget32 (integer*4 target,
                integer*4 source,
                integer*4 target_inc,
                integer*4 source_inc,
                integer*4 length,
                integer*4 source_thread)

mp_shmem_iput32 (integer*4 target,
                integer*4 source,
                integer*4 target_inc,
                integer*4 source_inc,
                integer*4 length,
                integer*4 target_thread)
```

```
mp_shmem_get64  (integer*8 target,
                 integer*8 source,
                 integer*4 length,
                 integer*4 source_thread)

mp_shmem_put64  (integer*8 target,
                 integer*8 source,
                 integer*4 length,
                 integer*4 target_thread)

mp_shmem_iget64 (integer*8 target,
                 integer*8 source,
                 integer*4 target_inc,
                 integer*4 source_inc,
                 integer*4 length,
                 integer*4 source_thread)

mp_shmem_iput64 (integer*8 target,
                 integer*8 source,
                 integer*4 target_inc,
                 integer*4 source_inc,
                 integer*4 length,
                 integer*4 target_thread)
```

For the routines listed above:

- Both source and target are pointers to 32-bit quantities for the 32-bit versions, and to 64-bit quantities for the 64-bit versions of the calls. The actual type of the data is not important, since the routines perform a bit-wise copy.
- For a put operation, the target must be Xlocal. For a get operation, the source must be Xlocal.
- Length specifies the number of elements to be copied, in units of 32/64-bit elements, as appropriate.
- *Source_thread/target_thread* specify the thread-number of the remote PE.
- A “get” copies FROM the remote PE, and “put” copies TO the remote PE.
- *Target_inc/source_inc* are specified for the strided iget/iput operations. They specify the “increment” (in units of 32/64 bit elements) along each of source and target when performing the data transfer. The number of elements copied during a strided put/get operation is still determined by “length.”

Call these routines only after the threads have been created (typically, the first doacross/parallel region). Performing these operations while the program is still serial leads to a run-time error since each thread's copy has not yet been created.

In the example below, compiling with **–Wl,–Xlocal,mycommon_** ensures that each thread has a private copy of `x` and `y`.

```
integer x
real*8 y(100)
common /mycommon/ x, y
```

The following example copies the value of `x` on thread 3 into the private copy of `x` for the current thread.

```
call mp_shmem_get32 (x, x, 1, 3)
```

The next example copies the value of `localvar` into the thread-5 copy of `x`.

```
call mp_shmem_put32 (x, localvar, 1, 5)
```

The example below fetches values from the thread-7 copy of array `y` into `localarray`.

```
call mp_shmem_get64 (localarray, y, 100, 7)
```

The next example copies the value of every other element of `localarray` into the thread-9 copy of `y`.

```
call mp_shmem_iput64 (y, localarray, 2, 2, 50, 9)
```

Synchronization Intrinsics

The intrinsics described in this section provide a variety of primitive synchronization operations. Besides performing the particular synchronization operation, each of these intrinsics has two key properties:

- The function performed is guaranteed to be atomic (typically achieved by implementing the operation using a sequence of load-linked and/or store-conditional instructions in a loop).
- Associated with each instrinsic are certain *memory barrier* properties that restrict the movement of memory references to *visible data* across the intrinsic operation (by either the compiler or the processor).

A *visible memory reference* is a reference to a data object potentially accessible by another thread executing in the same shared address space. A visible data object can be one of the following types:

- Fortran COMMON data
- data declared extern
- volatile data
- static data (either file-scope or function-scope)
- data accessible via function parameters
- automatic data (local-scope) that has had its address taken and assigned to some object that is visible (recursively)

The memory barrier semantics of an intrinsic can be one of the following types:

- *acquire barrier*, which disallows the movement of memory references to visible data from after the intrinsic (in program order) to before the intrinsic (this behavior is desirable at lock-acquire operations)
- *release barrier*, which disallows the movement of memory references to visible data from before the intrinsic (in program order) to after the intrinsic (this behavior is desirable at lock-release operations)
- *full barrier*, which disallows the movement of memory references to visible data past the intrinsic (in either direction), and is thus both an acquire and a release barrier. A barrier only restricts the movement of memory references to visible data across the intrinsic operation: between synchronization operations (or in their absence), memory references to visible data may be freely reordered subject to the usual data-dependence constraints.

Caution: Conditional execution of a synchronization intrinsic (such as within an **if** or a **while** statement) does not prevent the movement of memory references to visible data past the overall **if** or **while** construct.

Synopsis

```
integer*4 i4, j4, k4, jj4
integer*8 i8, j8, k8, jj8
logical*4 l4
logical*8 l8
```

Atomic fetch-and-op Operations

```
i4 = fetch_and_add (j4, k4)
i8 = fetch_and_add (j8, k8)
i4 = fetch_and_sub (j4, k4)
i8 = fetch_and_sub (j8, k8)
i4 = fetch_and_or (j4, k4)
i8 = fetch_and_or (j8, k8)
i4 = fetch_and_and (j4, k4)
i8 = fetch_and_and (j8, k8)
i4 = fetch_and_xor (j4, k4)
i8 = fetch_and_xor (j8, k8)
i4 = fetch_and_nand (j4, k4)
i8 = fetch_and_nand (j8, k8)
```

Behavior:

1. Atomically performs the specified operation with the given value on `j4`, and returns the old value of `j4`.

   ```
   { tmp = j4;
   j4 = j4 <op> k4;
   return tmp;
   }
   ```

2. Full barrier.

Atomic op-and-fetch Operations

```
i4 = add_and_fetch (j4, k4)
i8 = add_and_fetch (j8, k8)
i4 = sub_and_fetch (j4, k4)
i8 = sub_and_fetch (j8, k8)
i4 = or_and_fetch (j4, k4)
i8 = or_and_fetch (j8, k8)
i4 = and_and_fetch (j4, k4)
i8 = and_and_fetch (j8, k8)
i4 = xor_and_fetch (j4, k4)
i8 = xor_and_fetch (j8, k8)
i4 = nand_and_fetch (j4, k4)
i8 = nand_and_fetch (j8, k8)
```

Behavior:

1. Atomically performs the specified operation with the given value on `j4`, and returns the new value of `j4`.

```
{ j4 op = k4;
return j4;
}
```

2. Full barrier.

Atomic BOOL Operation

```
l4 = compare_and_swap( j4, k4, jj4)
l8 = compare_and_swap( j8, k8, jj8)
```

Behavior:

1. Atomically do the following: compare `j4` to old value. If equal, store the new value and return 1, otherwise return 0.

```
if (j4 .ne. oldvalue) return 0;
else {
    j4 = newvalue
    return 1;
}
```

2. Full barrier.

Atomic synchronize Operation

```
call synchronize
```

Behavior:

1. Full barrier.

Atomic lock and unlock Operations

```
i4 = lock_test_and_set (j4 , k4)
i8 = lock_test_and_set (j8 , k8)
```

Behavior:

1. Atomically store the supplied value in `j4` and return the old value of `j4`.

```
{ tmp = j4;
j4 = k4;
return tmp;
}
```

2. Acquire barrier.

```
call lock_release(i4)
call lock_release(i8)
```

Behavior:

1. Set j4 to 0.

```
{ j4 = 0 }
```

2. Release barrier.

Example of Implementing a Pure Spin-Wait Lock

The following example shows implementation of a spin-wait lock.

```
integer*4 lockvar
lockvar = 0
DO WHILE (lock_test_and_set (lockvar, 1) .ne. 0) /* acquire lock */
end do
    ... read and update shared variables ...
call lock_release (lockvar)                  /* release lock */
```

The memory barrier semantics of the intrinsics guarantee that no memory reference to visible data is moved out of the above critical section, either before of the lock-acquire or after the lock-release.

Note: Pure spin-wait locks can perform poorly under heavy contention.

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