Parallel Programming Guide for HP-UX Systems

Fifth Edition

Manufacturing Part Number: B3909-90011
Document Number: B3909-90011
August 2003

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Revision History

Fifth Edition.	Document Number:
	August 2003. Document updates
Fourth Edition.	Document Number: B3909-90008
	September 2001. Full OpenMP chapter
Third Edition.	Document Number: B3909-90006
	June 2001. Document updates
Second Edition.	Document Number: B3909-90003
	March 2000. OpenMP appendix
Initial release.	Document Number: B6056-96006
	June 1998

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Preface

This guide describes efficient methods for shared-memory programming using the following HP-UX compilers: HP Fortran, HP aC++ (ANSI C++), and HP C.

The *Parallel Programming Guide for HP-UX Systems* is intended for use by experienced Fortran, C, and C++ programmers. This guide describes the enhanced features of HP-UX 11.0 compilers on single-node multiprocessor HP technical servers. These enhancements include new loop optimizations and constructs for creating programs to run concurrently on multiple processors.

You need not be familiar with the HP parallel architecture, programming models, or optimization concepts to understand the concepts introduced in this book.

Scope

This guide covers programming methods for the following HP compilers on V2200 and V2250 and K-Class machines running HP-UX 11.0 and higher:

- HP Fortran Version 2.0 (and higher)
- HP aC++ Version 3.0 (and higher)
- HP C Version 1.2.3 (and higher)

The HP compilers now support an extensive shared-memory programming model. HP-UX 11.0 and higher includes the required assembler, linker, and libraries.

This guide describes how to produce programs that efficiently exploit the features of HP parallel architecture concepts and the HP compiler set. Producing efficient programs requires the use of efficient algorithms and implementation. The techniques of writing an efficient algorithm are beyond the scope of this guide. It is assumed that you have chosen the best possible algorithm for your problem. This manual should help you obtain the best possible performance from that algorithm.

Notational conventions

This section discusses notational conventions used in this book.

Table 1

`bold monospace`	In command examples, **`bold monospace`** identifies input that must be typed exactly as shown.
`monospace`	In paragraph text, `monospace` identifies command names, system calls, and data structures and types. In command examples, `monospace` identifies command output, including error messages.
`italic`	In paragraph text, *`italic`* identifies titles of documents. In command syntax diagrams, *`italic`* identifies variables that you must provide. The following command example uses brackets to indicate that the variable *`output_file`* is optional: `command` *`input_file`* [*`output_file`*]
Brackets ([ ])	In command examples, square brackets designate optional entries.
Curly brackets ({}), Pipe (|)	In command syntax diagrams, text surrounded by curly brackets indicates a choice. The choices available are shown inside the curly brackets and separated by the pipe sign (|). The following command example indicates that you can enter either `a` or `b`: `command {a | b}`
Horizontal ellipses (...)	In command examples, horizontal ellipses show repetition of the preceding items.

Table 1 **(Continued)**

Vertical ellipses	Vertical ellipses show that lines of code have been left out of an example.
Keycap	**Keycap** indicates the keyboard keys you must press to execute the command example.

The directives and pragmas described in this book can be used with the Fortran and C compilers, unless otherwise noted. The aC++ compiler does not support the pragmas, but does support the memory classes. In general discussion, these directives and pragmas are presented in lowercase type, but each compiler recognizes them regardless of their case.

References to man pages appear in the form mnpgname(1), where "mnpgname" is the name of the man page and is followed by its section number enclosed in parentheses. To view this man page, type:

```
% man 1 mnpgname
```

NOTE A Note highlights important supplemental information.

Command syntax

Consider this example:

COMMAND *input_file* [...] {a | b} [*output_file*]

COMMAND must be typed as it appears.

input_file indicates a file name that must be supplied by the user.

The horizontal ellipsis in brackets indicates that additional, optional input file names may be supplied.

Either a or b must be supplied.

[*output_file*] indicates an optional file name.

Associated documents

The following documents are listed as additional resources to help you use the compilers and associated tools:

- *HP Fortran Programmer's Guide*—Provides extensive usage information (including how to compile and link), suggestions and tools for migrating to HP Fortran, and how to call C and HP-UX routines for HP Fortran 90.
- *HP Fortran Programmer's Reference*—Presents complete Fortran 90 language reference information. It also covers compiler options, compiler directives, and library information.
- *HP aC++ Online Programmer's Guide*—Presents reference and tutorial information on aC++. This manual is only available in html format.
- *HP MPI User's Guide*—Discusses message-passing programming using Hewlett-Packard's Message-Passing Interface library.
- *Programming with Threads on HP-UX*—Discusses programming with POSIX threads.
- *HP C/HP-UX Reference Manual*—Presents reference information on the C programming language, as implemented by HP.
- *HP C/HP-UX Programmer's Guide*—Contains detailed discussions of selected C topics.
- *HP-UX Linker and Libraries User's Guide*—Describes how to develop software on HP-UX, using the HP compilers, assemblers, linker, libraries, and object files.
- *Managing Systems and Workgroups*—Describes how to perform various system administration tasks.
- *Threadtime* by Scott J. Norton and Mark D. DiPasquale—Provides detailed guidelines on the basics of thread management, including POSIX thread structure; thread management functions; and the creation, termination and synchronization of threads.
- *HP MLIB User's Guide VECLIB and LAPACK*—Provides usage information about mathematical software and computational kernels for engineering and scientific applications.

1 Introduction

Hewlett-Packard compilers generate efficient parallel code with little user intervention. However, you can increase this efficiency by using the techniques discussed in this book.

This chapter contains a discussion of the following topics:

- HP SMP architectures
- Parallel programming model
- Overview of HP optimizations

HP SMP architectures

Hewlett-Packard offers single-processor and symmetric multiprocessor (SMP) systems. This book focuses on SMP systems, specifically, those that utilize different bus configurations for memory access. These are briefly described in the following sections, and in more detail in the “Architecture overview” section.

Bus-based systems

The K-Class servers are midrange servers with a bus-based architecture. It contains one set of processors and physical memory. Memory is shared among all the processors, with a bus serving as the interconnect. The shared-memory architecture has a uniform access time from each processor.

Hyperplane Interconnect systems

The V-Class servers configurations range from one to 16 processors on the V-Class single-node system. These systems have the following characteristics:

- Processors communicate with each other through memory and by using I/O devices through a Hyperplane Interconnect nonblocking crossbar.
- Scalable physical memory. The current V-Class server supports up to 16 Gbytes of memory.
- Each process on an HP system can access a 16-terabyte (Tbyte) virtual address space.

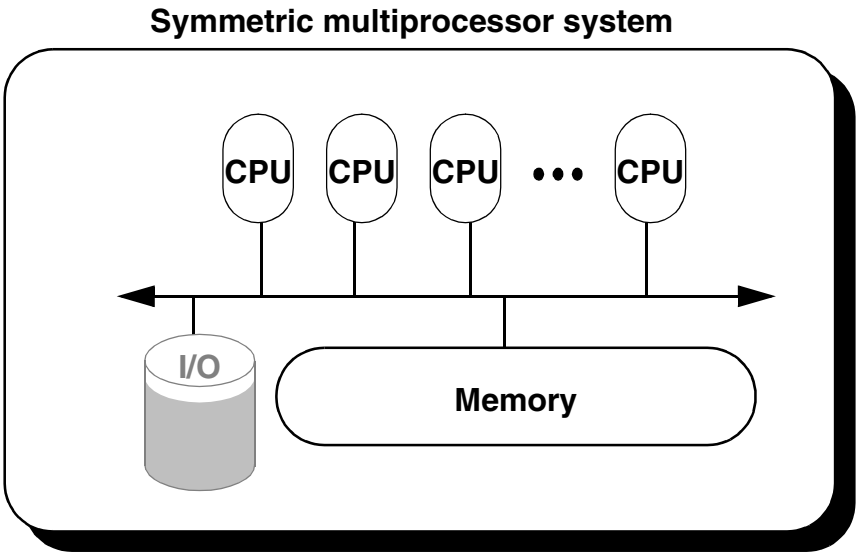
Parallel programming model

Parallel programming models provide perspectives from which you can write—or adapt—code to run on a high-end HP system. You can perform both shared-memory programming and message-passing programming on an SMP. This book focuses on using the shared-memory paradigm, but includes reference material and pointers to other manuals about message passing.

The shared-memory paradigm

In the shared-memory paradigm, compilers handle optimizations, and, if requested, parallelization. Numerous compiler directives and pragmas are available to further increase optimization opportunities. Parallelization can also be specified using POSIX threads (Pthreads). Figure 1-1 shows the SMP model for the shared-memory paradigm.

Figure 1-1 Symmetric multiprocessor system



The directives and pragmas associated with the shared-memory programming model are discussed in the chapter titled “Parallel Programming Techniques,” “Memory classes,” and “Parallel synchronization.”

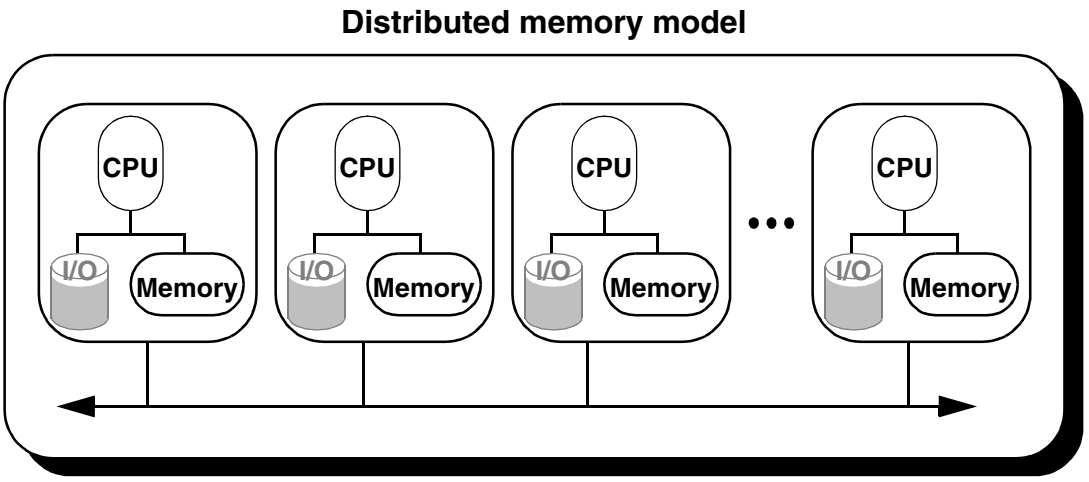
The message-passing paradigm

HP has implemented a version of the message-passing interface (MPI) standard known as HP MPI. This implementation is finely tuned for HP technical servers.

In message-passing, a parallel application consists of a number of processes that run concurrently. Each process has its own local memory. It communicates with other processes by sending and receiving messages. When data is passed in a message, both processes must work to transfer the data from the local memory of one to the local memory of the other.

Under the message-passing paradigm, functions allow you to explicitly spawn parallel processes, communicate data among them, and coordinate their activities. Unlike the previous model, there is no shared-memory. Each process has its own private 16-terabyte (Tbyte) address space, and any data that must be shared must be explicitly passed between processes. Figure 1-2 shows a layout of the message-passing paradigm.

Figure 1-2 Message-passing programming model



Support of message passing allows programs written under this paradigm for distributed memory to be easily ported to HP servers. Programs that require more per-process memory than possible using shared-memory benefit from the manually-tuned message-passing style.

For more information about HP MPI, see the *HP MPI User's Guide* and the `MPI Reference`.

Overview of HP optimizations

HP compilers perform a range of user-selectable optimizations. These new and standard optimizations, specified using compiler command-line options, are briefly introduced here. A more thorough discussion, including the features associated with each, is provided in “Optimization levels,” on page 25.

Basic scalar optimizations

Basic scalar optimizations improve performance at the basic block and program unit level.

A basic block is a sequence of statements that has a single entry point and a single exit. Branches do not exist within the body of a basic block. A program unit is a subroutine, function, or `main` program in Fortran or a function (including `main`) in C and C++. Program units are also generically referred to as procedures. Basic blocks are contained within program units. Optimizations at the program unit level span basic blocks.

To improve performance, basic optimizations perform the following activities:

- Exploit the processor’s functional units and registers
- Reduce the number of times memory is accessed
- Simplify expressions
- Eliminate redundant operations
- Replace variables with constants
- Replace slow operations with faster equivalents

Advanced scalar optimizations

Advanced scalar optimizations are primarily intended to maximize data cache usage. This is referred to as data localization. Concentrating on loops, these optimizations strive to encache the data most frequently used by the loop and keep it encached so as to avoid costly memory accesses.

Advanced scalar optimizations include several loop transformations. Many of these optimizations either facilitate more efficient strip mining or are performed on strip-mined loops to optimize processor data cache usage. All of these optimizations are covered in "Controlling optimization," on page 119.

Advanced scalar optimizations implicitly include all basic scalar optimizations.

Parallelization

HP compilers automatically locate and exploit loop-level parallelism in most programs. Using the techniques described in "Parallel programming techniques," on page 181, you can help the compilers find even more parallelism in your programs.

Loops that have been data-localized are prime candidates for parallelization. Individual iterations of loops that contain strips of localizable data are parcelled out among several processors and run simultaneously. For example, the maximum number of processors that can be used is limited by the number of iterations of the loop and by processor availability.

While most parallelization is done on nested, data-localized loops, other code can also be parallelized. For example, through the use of manually inserted compiler directives, sections of code outside of loops can also be parallelized.

Parallelization optimizations implicitly include both basic and advanced scalar optimizations.

2 Architecture overview

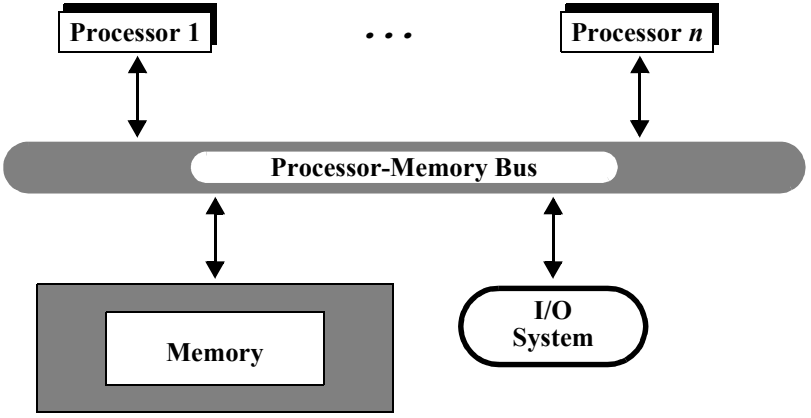
This chapter provides an overview of Hewlett-Packard's shared memory K-Class and V-Class architectures. The information in this chapter focuses on this architecture as it relates to parallel programming.

This chapter describes architectural features of HP's K-Class and V-Class. For more information on the family of V-Class servers, see the *V-Class Architecture* manual.

System architectures

PA-RISC processors communicate with each other, with memory, and with peripherals through various bus configuration. The difference between the K-Class and V-Class servers are presented by the manner in which they access memory. The K-Class maintains a bus-based configuration, shown in Figure 2-1.

Figure 2-1 K-Class bus configuration

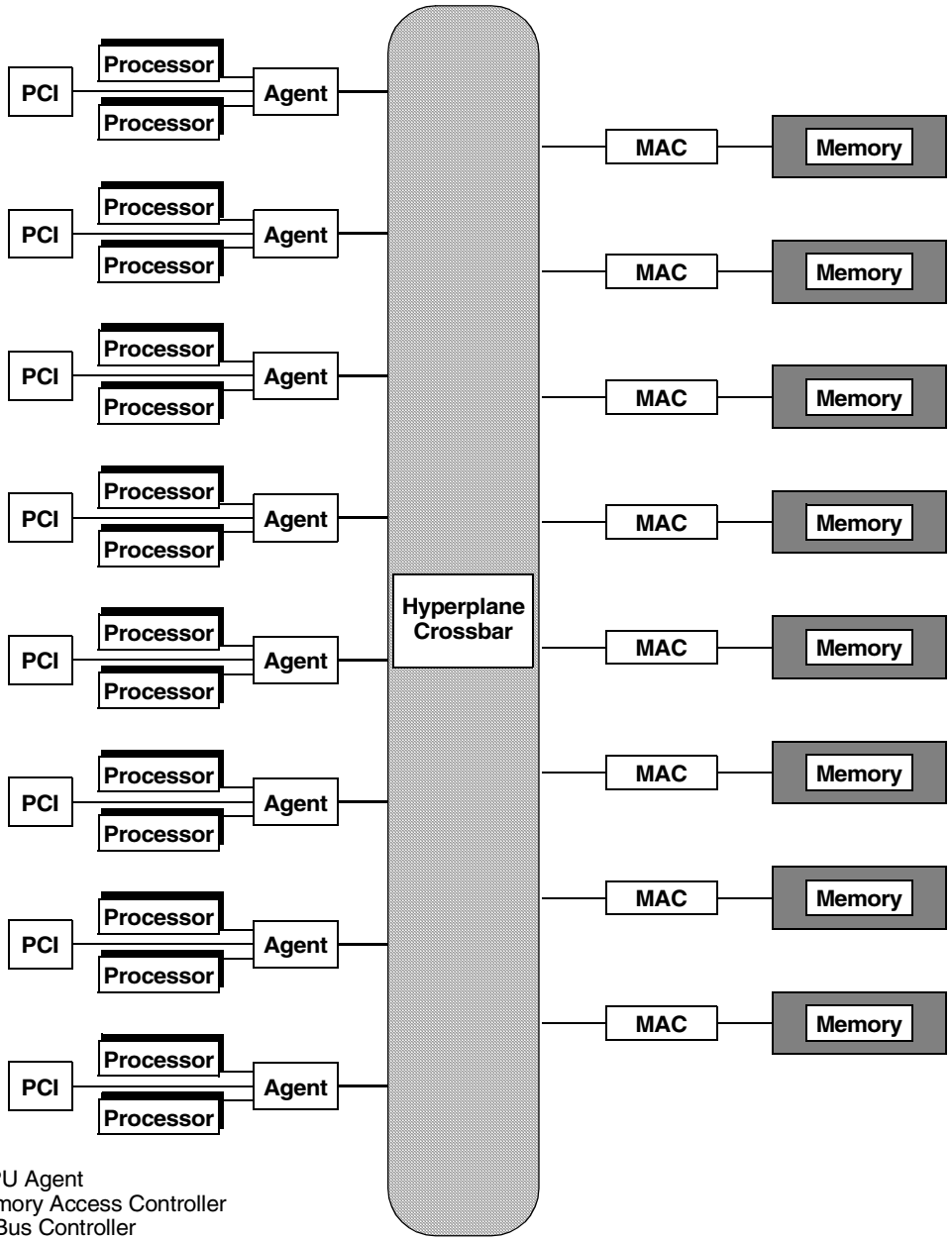


On a V-Class, processors communicate with each other, memory, and peripherals through a nonblocking crossbar. The V-Class implementation is achieved through the Hyperplane Interconnect, shown in Figure 2-2.

The HP V2250 server has one to 16 PA-8200 processors and 256 Mbytes to 16 Gbytes of physical memory. Two CPUs and a PCI bus share a single CPU agent. The CPUs communicate with the rest of the machine through the CPU agent. The Memory Access Controllers (MACs) provide the interface between the memory banks and the rest of the machine.

CPUs communicate directly with their own instruction and data caches, which are accessed by the processor in one clock (assuming a full pipeline). V2250 servers use 2-Mbyte off-chip instruction caches and data caches.

Figure 2-2 V2250 Hyperplane Interconnect view



Agent: CPU Agent
MAC: Memory Access Controller
PCI: PCI Bus Controller

Data caches

HP systems use cache to enhance performance. Cache sizes, as well as cache line sizes, vary with the processor used. Data is moved between the cache and memory using cache lines. A cache line describes the size of a chunk of contiguous data that must be copied into or out of a cache in one operation.

When a processor experiences a cache miss—requests data that is not already encached—the cache line containing the address of the requested data is moved to the cache. This cache line also contains a number of other data objects that were not specifically requested.

One reason cache lines are employed is to allow for data reuse. Data in a cache line is subject to reuse if, while the line is encached, any of the data elements contained in the line besides the originally requested element are referenced by the program, or if the originally requested element is referenced more than once.

Because data can only be moved to and from memory as part of a cache line, both load and store operations cause their operands to be encached. Cache-coherency hardware, as found on a V2250, invalidates cache lines in other processors when they are stored to by a particular processor. This indicates to other processors that they must load the cache line from memory the next time they reference its data.

Data alignment

Aligning data addresses on cache line boundaries allows for efficient data reuse in loops (refer to “Data reuse” on page 74). The linker automatically aligns data objects larger than 32 bytes in size on a 32-byte boundary. It also aligns data greater than a page size on a 64-byte boundary.

Only the first item in a list of data objects appearing in any of these statements is aligned on a cache line boundary. To make the most efficient use of available memory, the total size, in bytes, of any array appearing in one of these statements should be an integral multiple of 32.

Sizing your arrays this way prevents data following the first array from becoming misaligned. Scalar variables should be listed after arrays and ordered from longest data type to shortest. For example, `REAL*8` scalars should precede `REAL*4` scalars.

You can align data on 64-byte boundaries by doing the following. These apply only to parallel executables:

- Using Fortran `ALLOCATE` statements
- Using the C functions `malloc` or `memory_class_malloc`

NOTE Aliases can inhibit data alignment. Be careful when equivalencing arrays in Fortran.

Cache thrashing

Cache thrashing occurs when two or more data items that are frequently needed by the program both map to the same cache address. Each time one of the items is encached, it overwrites another needed item, causing cache misses and impairing data reuse. This section explains how thrashing happens on the V-Class.

A type of thrashing known as false cache line sharing is discussed in the section “False cache line sharing” on page 296.

Example 2-1 Cache thrashing

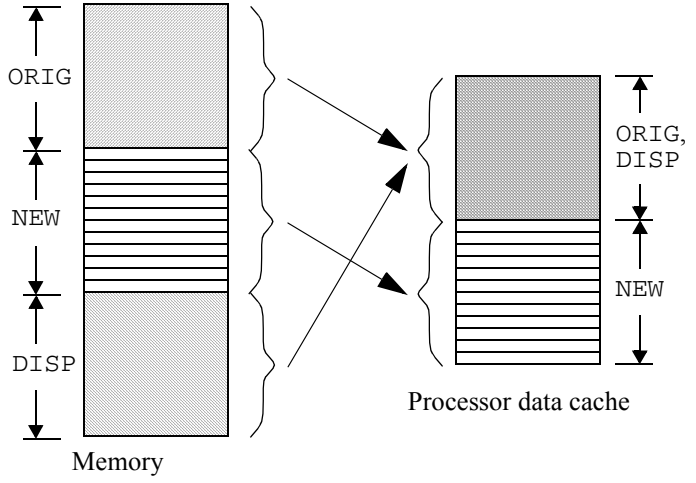
The following Fortran example provides an example of cache thrashing:

```
REAL*8 ORIG(131072), NEW(131072), DISP(131072)
COMMON /BLK1/ ORIG, NEW, DISP
.
.
.
DO I = 1, N
  NEW(I) = ORIG(I) + DISP(I)
ENDDO
```

In this example, the arrays `ORIG` and `DISP` overwrite each other in a 2-Mbyte cache. Because the arrays are in a `COMMON` block, they are allocated in contiguous memory in the order shown. Each array element occupies 8 bytes, so each array occupies one Mbyte ($8 \times 131072 = 1048576$ bytes). Therefore, arrays `ORIG` and `DISP` are exactly 2-Mbytes apart in

memory, and all their elements have identical cache addresses. The layout of the arrays in memory and in the data cache is shown in Figure 2-3.

Figure 2-3 Array layouts—cache-thrashing



When the addition in the body of the loop executes, the current elements of both ORIG and DISP must be fetched from memory into the cache. Because these elements have identical cache addresses, whichever is fetched last overwrites the first. Processor cache data is fetched 32 bytes at a time.

To efficiently execute a loop such as this, the unused elements in the fetched cache line (three extra REAL*8 elements are fetched in this case) must remain encached until they are used in subsequent iterations of the loop. Because ORIG and DISP thrash each other, this reuse is never possible. Every cache line of ORIG that is fetched is overwritten by the cache line of DISP that is subsequently fetched, and vice versa. The cache line is overwritten on every iteration. Typically, in a loop like this, it would not be overwritten until all of its elements were used.

Memory accesses take substantially longer than cache accesses, which severely degrades performance. Even if the overwriting involved the NEW array, which is stored rather than loaded on each iteration, thrashing would occur, because stores overwrite entire cache lines the same way loads do.

The problem is easily fixed by increasing the distance between the arrays. You can accomplish this by either increasing the array sizes or inserting a padding array.

Example 2-2 Cache padding

The following Fortran example illustrates cache padding:

```
REAL*8 ORIG(131072), NEW(131072), P(4),DISP(131072)
COMMON /BLK1/ ORIG, NEW, P, DISP
.
.
.
```

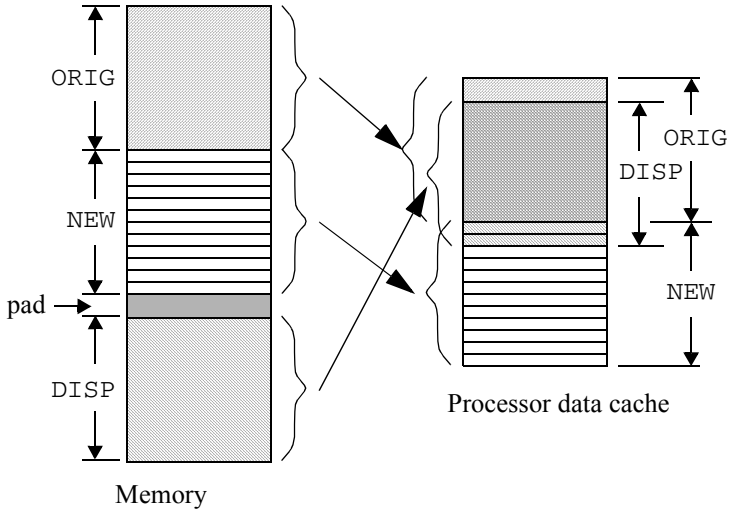
In this example, the array `P(4)` moves `DISP` 32 bytes further from `ORIG` in memory. No two elements of the same index share a cache address. This postpones cache overwriting for the given loop until the entire current cache line is completely exploited.

The alternate approach involves increasing the size of `ORIG` or `NEW` by 4 elements (32 bytes), as shown in the following example:

```
REAL*8 ORIG(131072), NEW(131080), DISP(131072)
COMMON /BLK1/ ORIG, NEW, DISP
.
.
.
```

Here, NEW has been increased by 4 elements, providing the padding necessary to prevent ORIG from sharing cache addresses with DISP. Figure 2-4 shows how both solutions prevent thrashing.

Figure 2-4 Array layouts—non-thrashing



It is important to note that this is a highly simplified, worst-case example.

Loop blocking optimization (described in "Loop blocking" on page 73) eliminates thrashing from certain nested loops, but not from all loops. Declaring arrays with dimensions that are not powers of two can help, but it does not completely eliminate the problem.

Using COMMON blocks in Fortran can also help because it allows you to accurately measure distances between data items, making thrashing problems easier to spot before they happen.

Memory Systems

HP's K-Class and V-Class servers maintain a single level of memory latency. Memory functions and interleaving work similarly on both servers, as described in the following sections.

Physical memory

Multiple, independently accessible memory banks are available on both the K-Class and V-Class servers. In 16-processor V2250 servers, for example, each node consists of up to 32 memory banks. This memory is typically partitioned (by the system administrator) into system-global and buffer cache. It is also interleaved as described in "Interleaving" on page 19. The K-Class architecture supports up to four memory banks.

System-global memory is accessible by all processors in a given system. The buffer cache is a file system cache and is used to encache items that have been read from disk and items that are to be written to disk.

Memory interleaving is used to improve performance. For an explanation, see the section "Interleaving" on page 19.

Virtual memory

Each process running on a V-Class or K-Class server under HP-UX accesses its own 16-Tbyte virtual address space. Almost all of this space is available to hold program text, data, and the stack. The space used by the operating system is negligible.

The memory stack size is configurable. Refer to the section "Setting thread default stack size" on page 211 for more information.

Both servers share data among all threads unless a variable is declared to be thread private. Memory class definitions describing data disposition across hypernodes have been retained for the V-Class. This is primarily for potential use when porting to multinode machines.

```
thread_private
```

This memory is private to each thread of a process. A `thread_private` data object has a unique virtual address for each thread. These addresses map to unique physical addresses in hypernode-local physical memory.

`node_private`

This memory is shared among the threads of a process running on a single node. Since the V-Class and K-Class servers are single-node machines, `node_private` actually serves as one common shared memory class.

Memory classes are discussed more fully in Chapter 12, “Memory classes,” on page 245.

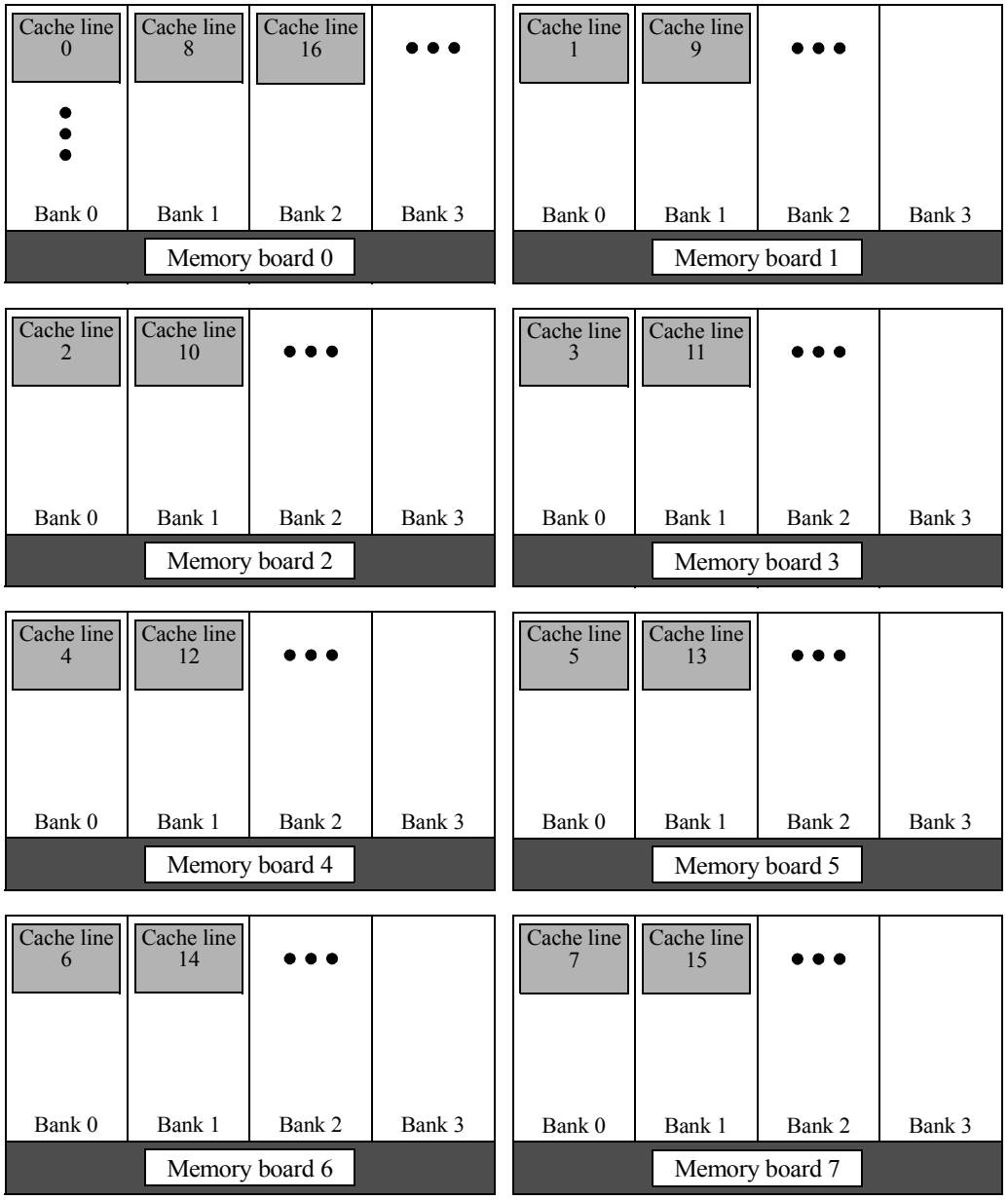
Processes cannot access each other’s virtual address spaces. This virtual memory maps to the physical memory of the system on which the process is running.

Interleaving

Physical pages are interleaved across the memory banks on a cache-line basis. There are up to 32 banks in the V2250 servers; there are up to four on a K-Class. Contiguous cache lines are assigned in round-robin fashion, first to the even banks, then to the odd.

Interleaving speeds memory accesses by allowing several processors to access contiguous data simultaneously. It also eliminates busy bank and board waits for unit stride accesses. This is beneficial when a loop that manipulates arrays is split among many processors. In the best case, threads access data in patterns with no bank contention. Even in the worst case, in which each thread initially needs the same data from the same bank, after the initial contention delay, the accesses are spread out among the banks.

Figure 2-5 V2250 interleaving



Example 2-3 Interleaving

The following Fortran example illustrates a nested loop that accesses memory with very little contention. This example is greatly simplified for illustrative purposes, but the concepts apply to arrays of any size.

```
REAL*8 A(12,12), B(12,12)
...
DO J = 1, N
  DO I = 1, N
    A(I,J) = B(I,J)
  ENDDO
ENDDO
```

Assume that arrays `A` and `B` are stored contiguously in memory, with `A` starting in bank 0, processor cache line 0 for V2250 servers, as shown in Figure on page 23.

You may assume that the HP Fortran compiler parallelizes the `J` loop to run on as many processors as are available in the system (up to `N`). Assuming `N=12` and there are four processors available when the program is run, the `J` loop could be divided into four new loops, each with 3 iterations. Each new loop would run to completion on a separate processor. These four processors are identified as CPU0 through CPU3.

NOTE This example is designed to simplify illustration. In reality, the dynamic selection optimization (discussed in "Dynamic selection" on page 108) would, given the iteration count and available number of processors described, cause this loop to run serially. The overhead of going parallel would outweigh the benefits.

In order to execute the body of the `I` loop, `A` and `B` must be fetched from memory and encached. Each of the four processors running the `J` loop attempt to simultaneously fetch its portion of the arrays.

This means CPU0 will attempt to read arrays `A` and `B` starting at elements `(1,1)`, CPU1 will attempt to start at elements `(1,4)` and so on.

Because of the number of memory banks in the V2250 architecture, interleaving removes the contention from the beginning of the loop from the example, as shown in Figure .

- CPU0 needs `A(1:12,1:3)` and `B(1:12,1:3)`

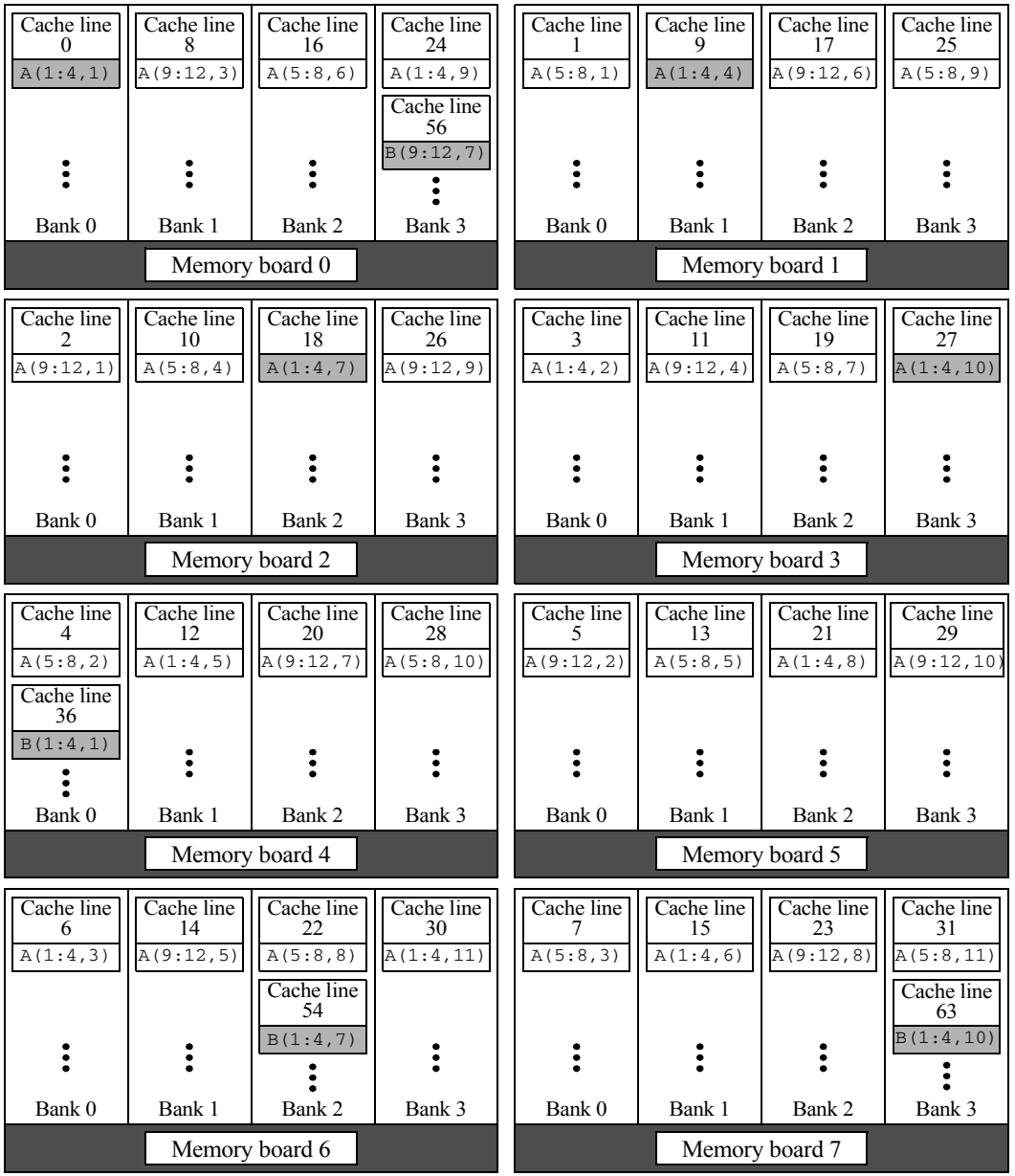
- CPU1 needs `A(1:12,4:6)` and `B(1:12,4:6)`
- CPU2 needs `A(1:12,7:9)` and `B(1:12,7:9)`
- CPU3 needs `A(1:12,10:12)` and `B(1:12,10:12)`

The data from the V2250 example above is spread out on different memory banks as described below:

- `A(1,1)`, the first element of the chunk needed by CPU0, is on cache line 0 in bank 0 on board 0
- `A(1,4)`, the first element needed by CPU1, is on cache line 9 in bank 1 on board 1
- `A(1,7)`, the first element needed by CPU2, is on cache line 18 in bank 2 on board 2
- `A(1,10)` the first element needed by CPU3, is on cache line 27 in bank 3 on board 3

Because of interleaving, no contention exists between the processors when trying to read their respective portions of the arrays. Contention may surface occasionally as the processors make their way through the data, but the resulting delays are minimal compared to what could be expected without interleaving.

Figure 2-6 V2250 interleaving of arrays A and B



Variable-sized pages on HP-UX

Variable-sized pages are used to reduce Translation Lookaside Buffer (TLB) misses, improving performance. A TLB is a hardware entity used to hold a virtual to physical address translation. With variable-sized pages, each TLB entry used can map a larger portion of an application's virtual address space. Thus, applications with large data sets are mapped using fewer TLB entries, resulting in fewer TLB misses.

Using a different page size does not help if an application is not experiencing performance degradation due to TLB misses. Additionally, if an application uses too large a page size, fewer pages are available to other applications on the system. This potentially results in increased paging activity and performance degradation.

Valid page sizes on the PA-8200 processors are 4K, 16K, 64K, 256K, 1 Mbyte, 4 Mbytes, 16 Mbytes, 64 Mbytes, and 256 Mbytes. The default configurable page size is 4K. Methods for specifying a page size are described below. Note that the user-specified page size only requests a specific size. The operating system takes various factors into account when selecting the page size.

Specifying a page size

The following `chatr` utility command options allow you to specify information regarding page sizes.

- `+pi` affects the page size for the application's text segment
- `+pd` affects the page size for the application's data segment

The following configurable kernel parameters allow you to specify information regarding page sizes.

- `vps_pagesize` represents the default or minimum page size (in kilobytes) if the user has not used `chatr` to specify a value. The default is 4Kbytes.
- `vps_ceiling` represents the maximum page size (in kilobytes) if the user has not used chatr to specify a value. The default is 16Kbytes.
- `vps_chatr_ceiling` places a restriction on the largest value (in kilobytes) a user can specify using chatr. The default is 64 Mbytes.

For more information on the `chatr` utility, see the `chatr(1)` man page.

3 Optimization levels

This chapter discusses various optimization levels available with the HP compilers, including:

- HP optimization levels and features

- Using the Optimizer

The locations of the compilers discussed in this manual are provided in Table 3-1.

Table 3-1 Locations of HP compilers

Compiler	Description	Location
f90	HP Fortran	`/opt/fortran90/bin/f90`
cc	ANSI C	`/opt/ansic/bin/c89`
aC++	ANSI C++	`/opt/aCC/bin/aCC`

For detailed information about optimization command-line options, and pragmas and directives, see “Controlling optimization,” on page 119.

HP optimization levels and features

This section provides an overview of optimization features which can be through either the command-line optimization options or manual specification using pragmas or directives.

Five optimization levels are available for use with the HP compiler: +O0 (the default), +O1, +O2, +O3, and +O4. These options have identical names and perform identical optimizations, regardless of which compiler you are using. They can also be specified on the compiler command line in conjunction with other options you may want to use. HP compiler optimization levels are described in Table 3-2.

Table 3-2 Optimization levels and features

Optimization Levels	Features	Benefits
+O0 (the default)	Occurs at the machine-instruction level Constant folding Data alignment on natural boundaries Partial evaluation of test conditions Registers (simple allocation)	Compiles fastest.
+O1 includes all of +O0	Occurs at the block level Branch optimization Dead code elimination Instruction scheduler Peephole optimizations Registers (faster allocation)	Produces faster programs than +O0, and compiles faster than level +O2.

Table 3-2 Optimization levels and features (Continued)

Optimization Levels	Features	Benefits
+O2 (-O) includes all of +O0, +O1	Occurs at the routine level Common subexpression elimination Constant folding (advanced) and propagation Loop-invariant code motion Loop unrolling Registers (global allocation) Register reassociation Software pipelining Store/copy optimization Strength reduction of induction variables and constants Unused definition elimination	Can produce faster run-time code than +O1 if loops are used extensively. Run-times for loop-oriented floating-point intensive applications may be reduced up to 90 per cent. Operating system and interactive applications that use the optimized system libraries may achieve 30 per cent to 50 per cent additional improvement.
+O3 includes all of +O0,+O1,+O2	Occurs at the file level Cloning within a single source file Data localization Automatic and directive-specified loop parallelization Directive-specified region parallelization Directive-specified task parallelization	Can produce faster run-time code than +O2 on code that frequently calls small functions, or if loops are extensively used. Links faster than +O4.

Table 3-2 Optimization levels and features (Continued)

Optimization Levels	Features	Benefits
	Inlining within a single source file Loop blocking Loop distribution Loop fusion Loop interchange Loop reordering - preventing Loop unroll and jam Parallelization Parallelization, preventing Reductions Test promotion All of the directives and pragmas of the HP parallel programming model are available in the Fortranand C compilers. `prefer_parallel` requests parallelization of the following loop `loop_parallel` forces parallelization on the last loop `parallel`, `end_parallel` parallelizes a single code region to run on multiple threads. `begin_tasks, next_task, end_tasks` forces parallelization of following code section	

Table 3-2 Optimization levels and features (Continued)

Optimization Levels	Features	Benefits
+O4 includes all of +O0, +O1, +O2, +O3 Not available in Fortran	Occurs at the cross-module level and performed at link time Cloning across multiple source files Global/static variable optimizations Inlining across multiple source files	Produces faster run-time code than when +O3 global variables are used or when procedure calls are inlined across modules.

Cumulative Options

The optimization options that control an optimization level are cumulative so that each option retains the optimizations of the previous option. For example, entering the following command line compiles the Fortran program foo.f with all +O2, +O1, and +O0 optimizations shown in Table 3-2:

```
% f90 +O2 foo.f
```

In addition to these options, the +Oparallel option is available for use at +O3 and above; +Onoparallel is the default, When the +Oparallel option is specified, the compiler:

- Looks for opportunities for parallel execution in loops
- Honors the parallelism-related directives and pragmas of the HP parallel programming model.

The +Onoautopar (no automatic parallelization) option is available for use with +Oparallel at +O3 and above. +Oautopar is the default. +Onoautopar causes the compiler to parallelize only those loops that are immediately preceded by loop_parallel or prefer_parallel directives or pragmas. For more information, refer to "Parallel programming techniques," on page 181.

Using the Optimizer

Before exploring the various optimizations that are performed, it is important to review the coding guidelines used to assist the optimizer. This section is broken down into the following subsections:

- General guidelines
- C and C++ guidelines
- Fortran guidelines

General guidelines

The coding guidelines presented in this section help the optimizer to optimize your program, regardless of the language in which the program is written.

- Use local variables to help the optimizer promote variables to registers.
- Do not use local variables before they are initialized. When you request `+O2`, `+O3`, or `+O4` optimizations, the compiler tries to detect and indicate violations of this rule. See "`+O[no]initcheck`" on page 129 for related information.
- Use constants instead of variables in arithmetic expressions such as shift, multiplication, division, or remainder operations.
- Position the loop inside the procedure or use a directive to call the loop in parallel, when a loop contains a procedure call.
- Construct loops so the induction variable increases or decreases toward zero where possible. The code generated for a loop termination test is more efficient with a test against zero than with a test against some other value.
- Do not reference outside the bounds of an array. Fortran provides the `-C` option to check whether your program references outside array bounds.
- Do not pass an incorrect number of arguments to a function.

C and C++ guidelines

The coding guidelines presented in this section help the optimizer to optimize your C and C++ programs.

- Use `do` loops and `for` loops in place of `while` loops. `do` loops and `for` loops are more efficient because opportunities for removing loop-invariant code are greater.
- Use `register` variables where possible.
- Use unsigned variables rather than signed, when using `short` or `char` variables or bit-fields. This is more efficient because a signed variable causes an extra instruction to be generated.
- Pass and return pointers to large structs instead of passing and returning large structs by value, where possible.
- Use type-checking tools like `lint` to help eliminate semantic errors.
- Use local variables for the upper bounds (stop values) of loops. Using local variables may enable the compiler to optimize the loop.

During optimization, the compiler gathers information about the use of variables and passes this information to the optimizer. The optimizer uses this information to ensure that every code transformation maintains the correctness of the program, at least to the extent that the original unoptimized program is correct.

When gathering this information, the compiler assumes that while inside a function, the only variables that are accessed indirectly through a pointer or by another function call are:

- Global variables (all variables with file scope)
- Local variables that have had their addresses taken either explicitly by the `&` operator, or implicitly by the automatic conversion of array references to pointers.

In general, the preceding assumption should not pose a problem. Standard-compliant C and C++ programs do not violate this assumption. However, if you have code that does violate this assumption, the optimizer can change the behavior of the program in an undesirable way. In particular, you should follow the coding practices to ensure correct program execution for optimized code:

- Avoid using variables that are accessed by external processes. Unless a variable is declared with the `volatile` attribute, the compiler assumes that a program's data is accessed only by that program. Using the `volatile` attribute may significantly slow down a program.
- Avoid accessing an array other than the one being subscripted. For example, the construct `a[b-a]`, where `a` and `b` are the same type of array, actually references the array `b`, because it is equivalent to `*(a+(b-a))`, which is equivalent to `*b`. Using this construct might yield unexpected optimization results.
- Avoid referencing outside the bounds of the objects a pointer is pointing to. All references of the form `*(p+i)` are assumed to remain within the bounds of the variable or variables that `p` was assigned to point to.
- Do not rely on the memory layout scheme when manipulating pointers, as incorrect optimizations may result. For example, if `p` is pointing to the first member of a structure, do not assume that `p+1` points to the second member of the structure. Additionally, if `p` is pointing to the first in a list of declared variables, `p+1` is not necessarily pointing to the second variable in the list.

For more information regarding coding guidelines, see "General guidelines" on page 31.

Fortran guidelines

The coding guidelines presented in this section help the optimizer to optimize Fortran programs.

As part of the optimization process, the compiler gathers information about the use of variables and passes this information to the optimizer. The optimizer uses this information to ensure that every code transformation maintains the correctness of the program, at least to the extent that the original unoptimized program is correct.

When gathering this information, the compiler assumes that inside a routine (either a function or a subroutine) the only variables that are accessed (directly or indirectly) are:

- `COMMON` variables declared in the routine
- Local variables
- Parameters to this routine

Local variables include all static and nonstatic variables.

In general, you do not need to be concerned about the preceding assumption. However, if you have code that violates it, the optimizer can adversely affect the behavior of the program.

Avoid using variables that are accessed by a process other than the program. The compiler assumes that the program is the only process accessing its data. The only exception is the shared `COMMON` variable in Fortran.

Also avoid using extensive equivalencing and memory-mapping schemes, where possible.

See the section “General guidelines” on page 31 for additional guidelines.

4 Standard optimization features

This chapter discusses the standard optimization features available with the HP-UX compilers, including those inherent in optimization levels

+O0 through +O2. This includes a discussion of the following topics:

- Constant folding
- Partial evaluation of test conditions
- Simple register assignment
- Data alignment on natural boundaries
- Branch optimization
- Dead code elimination
- Faster register allocation
- Instruction scheduling
- Peephole optimizations
- Advanced constant folding and propagation
- Common subexpression elimination
- Global register allocation (GRA)
- Loop-invariant code motion, and unrolling
- Register reassociation
- Software pipelining
- Strength reduction of induction variables and constants
- Store and copy optimization
- Unused definition elimination

For more information as to specific command-line options, pragmas and directives for optimization, please see “Controlling optimization” on page 119.

Machine instruction level optimizations (+O0)

At optimization level +O0, the compiler performs optimizations that span only a single source statement. This is the default. The +O0 machine instruction level optimizations include:

- Constant folding
- Partial evaluation of test conditions
- Simple register assignment
- Data alignment on natural boundaries

Constant folding

Constant folding is the replacement of operations on constants with the result of the operation. For example, Y=5+7 is replaced with Y=12.

More advanced constant folding is performed at optimization level +O2. See the section “Advanced constant folding and propagation” on page 43 for more information.

Partial evaluation of test conditions

Where possible, the compiler determines the truth value of a logical expression without evaluating all the operands. This is known as short-circuiting. The Fortran example below describes this:

```
IF ((I .EQ. J) .OR. (I .EQ. K)) GOTO 100
```

If (I .EQ. J) is true, control immediately goes to 100; otherwise, (I .EQ. K) must be evaluated before control can go to 100 or the following statement.

Do not rely upon partial evaluation if you use function calls in the logical expression because:

- There is no guarantee on the order of evaluation.
- A procedure or function call can have side effects on variable values that may or may not be partially evaluated correctly.

Simple register assignment

The compiler may place frequently used variables in registers to avoid more costly accesses to memory.

A more advanced register assignment algorithm is used at optimization level +O2. See the section “Global register allocation (GRA)” on page 44 for more information.

Data alignment on natural boundaries

The compiler automatically aligns data objects to their natural boundaries in memory, providing more efficient access to data. This means that a data object’s address is integrally divisible by the length of its data type; for example, REAL*8 objects have addresses integrally divisible by 8 bytes.

NOTE Aliases can inhibit data alignment. Be especially careful when equivalencing arrays in Fortran.

Declare scalar variables in order from longest to shortest data length to ensure the efficient layout of such aligned data in memory. This minimizes the amount of padding the compiler has to do to get the data onto its natural boundary.

Example 4-1 Data alignment on natural boundaries

The following Fortran example describes the alignment of data objects to their natural boundaries:

```
C     CAUTION: POORLY ORDERED DATA FOLLOWS:
      LOGICAL*2 BOOL
      INTEGER*8 A, B
      REAL*4 C
      REAL*8 D
```

Here, the compiler must insert 6 unused bytes after BOOL in order to correctly align A, and it must insert 4 unused bytes after C to correctly align D.

The same data is more efficiently ordered as shown in the following example:

```
C     PROPERLY ORDERED DATA FOLLOWS:
      INTEGER*8 A, B
      REAL*8 D
      REAL*4 C
      LOGICAL*2 BOOL
```

Natural boundary alignment is performed on all data. This is not to be confused with cache line boundary alignment.

Block level optimizations (+O1)

At optimization level +O1, the compiler performs optimizations on a block level. The compiler continues to run the +O0 optimizations, with the following additions:

- Branch optimization
- Dead code elimination
- Faster register allocation
- Instruction scheduling
- Peephole optimizations

Branch optimization

Branch optimization involves traversing the procedure and transforming branch instruction sequences into more efficient sequences where possible. Examples of possible transformations are:

- Deleting branches whose target is the fall-through instruction (the target is two instructions away)
- Changing the target of the first branch to be the target of the second (unconditional) branch when the target of a branch is an unconditional branch
- Transforming an unconditional branch at the bottom of a loop that branches to a conditional branch at the top of the loop into a conditional branch at the bottom of the loop
- Changing an unconditional branch to the exit of a procedure into an exit sequence where possible
- Changing conditional or unconditional branch instructions that branch over a single instruction into a conditional nullification in the following instruction
- Looking for conditional branches over unconditional branches, where the sense of the first branch could be inverted and the second branch deleted. These result from null THEN clauses and from THEN clauses that only contain GOTO statements.

Example 4-2 Conditional/unconditional branches

The following Fortran example provides a transformation from a branch instruction to a more efficient sequence:

```
      IF (L) THEN
        A=A*2
      ELSE
        GOTO 100
      ENDIF
      B=A+1
100   C=A*10
```

becomes:

```
      IF (.NOT. L) GOTO 100
      A=A*2
      B=A+1
100   C=A*10
```

Dead code elimination

Dead code elimination removes unreachable code that is never executed.

For example, in C:

```
if(0)
  a = 1;
else
  a = 2;
```

becomes:

```
  a = 2;
```

Faster register allocation

Faster register allocation involves:

- Inserting entry and exit code
- Generating code for operations such as multiplication and division
- Eliminating unnecessary copy instructions
- Allocating actual registers to the dummy registers in instructions

Faster register allocation, when used at `+O0` or `+O1`, analyzes register use faster than the global register allocation performed at `+O2`.

Instruction scheduling

The instruction scheduler optimization performs the following tasks:

- Reorders the instructions in a basic block to improve memory pipelining. For example, where possible, a load instruction is separated from the use of the loaded register.
- Follows a branch instruction with an instruction that is executed as the branch occurs, where possible.
- Schedules floating-point instructions.

Peephole optimizations

A peephole optimization is a machine-dependent optimization that makes a pass through low-level assembly-like instruction sequences of the program. It applies patterns to a small window (peephole) of code looking for optimization opportunities. It performs the following optimizations:

- Changes the addressing mode of instructions so they use shorter sequences
- Replaces low-level assembly-like instruction sequences with faster (usually shorter) sequences and removes redundant register loads and stores

Routine level optimizations (+O2)

At optimization level +O2, the compiler performs optimizations on a routine level. The compiler continues to perform the optimizations performed at +O1, with the following additions:

- Advanced constant folding and propagation
- Common subexpression elimination
- Global register allocation (GRA)
- Loop-invariant code motion
- Loop unrolling
- Register reassociation
- Software pipelining
- Strength reduction of induction variables and constants
- Store and copy optimization
- Unused definition elimination

Advanced constant folding and propagation

Constant folding computes the value of a constant expression at compile time. Constant propagation is the automatic compile-time replacement of variable references with a constant value previously assigned to that variable.

Example 4-3 Advanced constant folding and propagation

The following C/C++ code example describes an advanced constant folding and propagation:

```
a = 10;
b = a + 5;
c = 4 * b;
```

Once a is assigned, its value is propagated to the statement where b is assigned so that the assignment reads:

```
b = 10 + 5;
```

The expression `10 + 5` can then be folded. Now that `b` has been assigned a constant, the value of `b` is propagated to the statement where `c` is assigned. After all the folding and propagation, the original code is replaced by:

```
a = 10;
b = 15;
c = 60;
```

Common subexpression elimination

Common subexpression elimination optimization identifies expressions that appear more than once and have the same result. It then computes the result and substitutes the result for each occurrence of the expression. Subexpression types include instructions that load values from memory, as well as arithmetic evaluation.

Example 4-4 Common subexpression elimination

In Fortran, for example, the code first looks like this:

```
A = X + Y + Z
B = X + Y + W
```

After this form of optimization, it becomes:

```
T1 = X + Y
A = T1 + Z
B = T1 + W
```

Global register allocation (GRA)

Scalar variables can often be stored in registers, eliminating the need for costly memory accesses. Global register allocation (GRA) attempts to store commonly referenced scalar variables in registers throughout the code in which they are most frequently accessed.

The compiler automatically determines which scalar variables are the best candidates for GRA and allocates registers accordingly.

GRA can sometimes cause problems when parallel threads attempt to update a shared variable that has been allocated a register. In this case, each parallel thread allocates a register for the shared variable; it is then unlikely that the copy in memory is updated correctly as each thread executes.

Parallel assignments to the same shared variables from multiple threads make sense only if the assignments are contained inside critical or ordered sections, or are executed conditionally based on the thread ID. GRA does not allocate registers for shared variables that are assigned within critical or ordered sections, as long as the sections are implemented using compiler directives or `sync_routine`-defined functions (refer to "Parallel synchronization," on page 255 for a discussion of `sync_routine`). However, for conditional assignments based on the thread ID, GRA may allocate registers that may cause wrong answers when stored.

In such cases, GRA is disabled only for shared variables that are visible to multiple threads by specifying `+Onosharedgra`. A description of this option is located in See "+O[no]sharedgra" on page 142.

In procedures with large numbers of loops, GRA can contribute to long compile times. Therefore, GRA is only performed if the number of loops in the procedure is below a predetermined limit. You can remove this limit (and possibly increase compile time) by specifying `+O[no]limit`. A description of this option is located on page 132.

This optimization is also known as coloring register allocation because of the similarity to map-coloring algorithms in graph theory.

Register allocation in C and C++

In C and C++, you can help the optimizer understand when certain variables are heavily used within a function by declaring these variables with the `register` qualifier.

GRA may override your choices and promote a variable not declared `register` to a register over a variable that is declared `register`, based on estimated speed improvements.

Loop-invariant code motion

The loop-invariant code motion optimization recognizes instructions inside a loop whose results do not change and then moves the instructions outside the loop. This optimization ensures that the invariant code is only executed once.

Example 4-5 Loop-invariant code motion

This example begins with following C/C++ code:

```
x = z;
for(i=0; i<10; i++)
  a[i] = 4 * x + i;
```

After loop-invariant code motion, it becomes:

```
x = z;
t1 = 4 * x;
for(i=0; i<10; i++)
  a[i] = t1 + i;
```

Loop unrolling

Loop unrolling increases a loop's step value and replicates the loop body. Each replication is appropriately offset from the induction variable so that all iterations are performed, given the new step.

Unrolling is total or partial. Total unrolling involves eliminating the loop structure completely by replicating the loop body a number of times equal to the iteration count and replacing the iteration variable with constants. This makes sense only for loops with small iteration counts.

Loop unrolling and the unroll factor are controlled using the `+O[no]loop_unroll[=unroll factor]`. This option is described on page 133.

Some loop transformations cause loops to be fully or partially replicated. Because unlimited loop replication can significantly increase compile times, loop replication is limited by default. You can increase this limit (and possibly increase your program's compile time and code size) by specifying the `+Onosize` and `+Onolimit` compiler options.

Example 4-6 Loop unrolling

Consider the following Fortran example:

```
SUBROUTINE FOO(A,B)
REAL A(10,10), B(10,10)
DO J=1, 4
  DO I=1, 4
    A(I,J) = B(I,J)
  ENDDO
ENDDO
END
```

The loop nest is completely unrolled as shown below:

```
A(1,1) = B(1,1)
A(2,1) = B(2,1)
A(3,1) = B(3,1)
A(4,1) = B(4,1)

A(1,2) = B(1,2)
A(2,2) = B(2,2)
A(3,2) = B(3,2)
A(4,2) = B(4,2)

A(1,3) = B(1,3)
A(2,3) = B(2,3)
A(3,3) = B(3,3)
A(4,3) = B(4,3)

A(1,4) = B(1,4)
A(2,4) = B(2,4)
A(3,4) = B(3,4)
A(4,4) = B(4,4)
```

Partial unrolling is performed on loops with larger or unknown iteration counts. This form of unrolling retains the loop structure, but replicates the body a number of times equal to the unroll factor and adjusts references to the iteration variable accordingly.

Example 4-7 Loop unrolling

This example begins with the following Fortran example:

```
DO I = 1, 100
  A(I) = B(I) + C(I)
ENDDO
```

It is unrolled to a depth of four as shown below:

```
DO I = 1, 100, 4
  A(I) = B(I) + C(I)
  A(I+1) = B(I+1) + C(I+1)
  A(I+2) = B(I+2) + C(I+2)
  A(I+3) = B(I+3) + C(I+3)
ENDDO
```

Each iteration of the loop now computes four values of `A` instead of one value. The compiler also generates ‘clean-up’ code for the case where the range is not evenly divisible by the unroll factor.

Register reassociation

Array references often require one or more instructions to compute the virtual memory address of the array element specified by the subscript expression. The register reassociation optimization implemented in PA-RISC compilers tries to reduce the cost of computing the virtual memory address expression for array references found in loops.

Within loops, the virtual memory address expression is rearranged and separated into a loop-variant term and a loop-invariant term.

- Loop-variant terms are those items whose values may change from one iteration of the loop to another.
- Loop-invariant terms are those items whose values are constant throughout all iterations of the loop. The loop-variant term corresponds to the difference in the virtual memory address associated with a particular array reference from one iteration of the loop to the next.

The register reassociation optimization dedicates a register to track the value of the virtual memory address expression for one or more array references in a loop and updates the register appropriately in each iteration of a loop.

The register is initialized outside the loop to the loop-invariant portion of the virtual memory address expression. The register is incremented or decremented within the loop by the loop-variant portion of the virtual memory address expression. The net result is that array references in loops are converted into equivalent, but more efficient, pointer dereferences.

Register reassociation can often enable another loop optimization. After performing the register reassociation optimization, the loop variable may be needed only to control the iteration count of the loop. If this is the case, the original loop variable is eliminated altogether by using the PA-RISC `ADDIB` and `ADDB` machine instructions to control the loop iteration count.

You can enable or disable register reassociation using the `+O[no]regreassoc` command-line option at `+O2` and above. The default is `+Oregreassoc`. See ”`+O[no]regreassoc`” on page 141 for more information.

Example 4-8 Register allocation

This example begins with the following C/C++ code:

```
int a[10][20][30];

void example (void)
{
    int i, j, k;

    for (k = 0; k < 10; k++)
      for (j = 0; j < 10;j++)
        for (i = 0; i < 10; i++)
           a[i][j][k] = 1;
}
```

After register reassociation is applied, the innermost loop becomes:

```
int a[10][20][30];

void example (void)
{
    int i, j, k;
    register int (*p)[20][30];

    for (k = 0; k < 10; k++)
      for (j = 0; j < 10; j++)
        for (p = (int (*)[20][30]) &a[0][j][k], i = 0; i < 10; i++)
            *(p++[0][0]) = 1;
}
```

As you can see, the compiler-generated temporary register variable, `p`, strides through the array `a` in the innermost loop. This register pointer variable is initialized outside the innermost loop and auto-incremented within the innermost loop as a side-effect of the pointer dereference.

Software pipelining

Software pipelining transforms code in order to optimize program loops. It achieves this by rearranging the order in which instructions are executed in a loop. Software pipelining generates code that overlaps operations from different loop iterations. It is particularly useful for loops that contain arithmetic operations on `REAL*4` and `REAL*8` data in Fortran or on `float` and `double` data in C or C++.

The goal of this optimization is to avoid processor stalls due to memory or hardware pipeline latencies. The software pipelining transformation partially unrolls a loop and adds code before and after the loop to achieve a high degree of optimization within the loop.

You can enable or disable software pipelining using the +O[no]pipeline command-line option at +O2 and above. The default is +Opipeline. Use +Onopipeline if a smaller program size and faster compile time are more important than faster execution speed. See "+O[no]pipeline" on page 136 for more information.

Prerequisites of pipelining

Software pipelining is attempted on a loop that meets the following criteria:

- It is the innermost loop
- There are no branches or function calls within the loop
- The loop is of moderate size

This optimization produces slightly larger program files and increases compile time. It is most beneficial in programs containing loops that are executed many times.

Example 4-9 Software pipelining

The following C/C++ example shows a loop before and after the software pipelining optimization:

```
#define SIZ 10000
float x[SIZ], y[SIZ];
int i;
init();
for (i = 0;i<= SIZ;i++)
    x[i] = x[i] / y[i] + 4.00;
```

Four significant things happen in this example:

- A portion of the first iteration of the loop is performed before the loop.
- A portion of the last iteration of the loop is performed after the loop.
- The loop is unrolled twice.
- Operations from different loop iterations are interleaved with each other.

When this loop is compiled with software pipelining, the optimization is expressed as follows:

```
R1 = 0;                    Initialize array index
```

`R2 = 4.00;`	Load constant value
`R3 = X[0];`	Load first X value
`R4 = Y[0];`	Load first Y value
`R5 = R3 / R4;`	Perform division on first element: `n = X[0]/Y[0]`
`do {`	Begin loop
`R6 = R1;`	Save current array index
`R1++;`	Increment array index
`R7 = X[R1];`	Load current X value
`R8 = Y[R1];`	Load current Y value
`R9 = R5 + R2;`	Perform addition on prior row: `X[i] = n + 4.00`
`R10 = R7 / R8;`	Perform division on current row: `m = X[i+1]/Y[i+1]`
`X[R6] = R9;`	Save result of operations on prior row
`R6 = R1;`	Save current array index
`R1++;`	Increment array index
`R3 = X[R1];`	Load next X value
`R4 = Y[R1];`	Load next Y value
`R11 = R10 + R2;`	Perform addition on current row: `X[i+1] = m + 4.00`
`R5 = R3 / R4;`	Perform division on next row: `n = X[i+2]/Y[i+2]`
`X[R6] = R11;`	Save result of operations on current row
`} while (R1 <= 100);`	End loop
`R9 = R5 + R2;`	Perform addition on last row: `X[i+2] = n + 4.00`

`X[R6] = R9;`	Save result of operations on last row

This transformation stores intermediate results of the division instructions in unique registers (noted as `n` and `m`). These registers are not referenced until several instructions after the division operations. This decreases the possibility that the long latency period of the division instructions will stall the instruction pipeline and cause processing delays.

Strength reduction of induction variables and constants

This optimization removes expressions that are linear functions of a loop counter and replaces each of them with a variable that contains the value of the function. Variables of the same linear function are computed only once. This optimization also replaces multiplication instructions with addition instructions wherever possible.

Example 4-10 Strength reduction of induction variables and constants

This example begins with the following C/C++ code:

```
for (i=0; i<25; i++) {
  r[i] = i * k;
}
```

After this optimization, it looks like this:

```
t1 = 0;
for (i=0; i<25; i++) {
  r[i] = t1;
  t1 += k;
}
```

Store and copy optimization

Where possible, the store and copy optimization substitutes registers for memory locations, by replacing store instructions with copy instructions and deleting load instructions.

Unused definition elimination

The unused definition elimination optimization removes unused memory location and register definitions. These definitions are often a result of transformations made by other optimizations.

Example 4-11 Unused definition elimination

This example begins with the following C/C++ code:

```
f(int x){
  int a,b,c;

  a = 1;
  b = 2;
  c = x * b;
  return c;
}
```

After unused definition elimination, it looks like this:

```
f(int x) {
  int a,b,c;

  c = x * 2;
  return c;
}
```

The assignment `a = 1` is removed because `a` is not used after it is defined. Due to another `+O2` optimization (constant propagation), the `c = x * b` statement becomes `c = x * 2`. The assignment `b = 2` is then removed as well.

5 Loop and cross-module optimization features

This chapter discusses loop optimization features available with the HP-UX compilers, including those inherent in optimization level +O3.

This includes a discussion of the following topics:

- Strip mining
- Inlining within a single source file
- Cloning within a single source file
- Data localization
- Loop blocking
- Loop distribution
- Loop fusion
- Loop interchange
- Loop unroll and jam
- Preventing loop reordering
- Test promotion
- Cross-module cloning

For more information as to specific loop optimization command-line options, as well as related pragmas and directives for optimization, please see “Controlling optimization” on page 119.

Strip mining

Strip mining is a fundamental +O3 transformation. Used by itself, strip mining is not profitable. However, it is used by loop blocking, loop unroll and jam, and, in a sense, by parallelization.

Strip mining involves splitting a single loop into a nested loop. The resulting inner loop iterates over a section or strip of the original loop, and the new outer loop runs the inner loop enough times to cover all the strips, achieving the necessary total number of iterations. The number of iterations of the inner loop is known as the loop's strip length.

Example 5-1 Strip mining

This example begins with the Fortran code below:

```
DO I = 1, 10000
  A(I) = A(I) * B(I)
ENDDO
```

Strip mining this loop using a strip length of 1000 yields the following loop nest:

```
DO IOUTER = 1, 10000, 1000
  DO ISTRIP = IOUTER, IOUTER+999
    A(ISTRIP) = A(ISTRIP) * B(ISTRIP)
  ENDDO
ENDDO
```

In this loop, the strip length integrally divides the number of iterations, so the loop is evenly split up. If the iteration count was not an integral multiple of the strip length—if I went from 1 to 10500 rather than 1 to 10000, for example—the final iteration of the strip loop would execute 500 iterations instead of 1000.

Inlining within a single source file

Inlining substitutes selected function calls with copies of the function's object code. Only functions that meet the optimizer's criteria are inlined. Inlining may result in slightly larger executable files. However, this increase in size is offset by the elimination of time-consuming procedure calls and procedure returns.

At +O3, inlining is performed within a file; at +O4, it is performed across files. Inlining is affected by the +O[no]inline[=*namelist*] and +Oinline_budget=*n* command-line options. See "Controlling optimization" on page 119 for more information.

Example 5-2 Inlining within single source file

The following is an example of inlining at the source code level. Before inlining, the C source file looks like this:

```
/* Return the greatest common divisor of two positive integers,*/
/* int1 and int2, computed using Euclid's algorithm. (Return 0 */
/* if either is not positive.) */

int gcd(int int1,int int2)
{
  int inttemp;

  if ( (int1 <= 0) || (int2 <= 0) ) {
    return(0);
  }
  do {
      if (int1 < int2) {
        inttemp = int1;
        int1    = int2;
        int2    = inttemp;
      }
      int1 = int1 - int2;
  } while (int1 > 0);
  return(int2);
}main()
{
  int xval,yval,gcdxy;
  .
  .       /* statements before call to gcd */
  .
  gcdxy = gcd(xval,yval);
  .
```

```
  .       /* statements after call to gcd */
  .
}
```

After inlining, `main` looks like this:

```
main()
{
  int xval,yval,gcdxy;
  .
  .       /* statements before inlined version of gcd */
  .
  {
    int int1;
    int int2;      int1 = xval;
      int2 = yval;
      {
        int inttemp;        if ( (int1 <= 0) || (int2 <= 0) ){
           gcdxy = (0);
           goto AA003;
        }
        do {
            if (int1 < int2){
              inttemp = int1;
              int1    = int2;
              int2    = inttemp;
            }
            int1 = int1 - int2;
        } while (int1 > 0);
        gcdxy = (int2);
      }
  }
AA003 : ;
  .
  .       /* statements after inlined version of gcd */
  .
}
```

Cloning within a single source file

Cloning replaces a call to a routine by calling a clone of that routine. The clone is optimized differently than the original routine.

Cloning can expose additional opportunities for interprocedural optimization. At `+O3`, cloning is performed within a file, and at `+O4`, cloning is performed across files. Cloning is enabled by default, and is disabled by specifying the `+Onoinline` command-line option.

Data localization

Data localization occurs as a result of various loop transformations that occur at optimization levels +O2 or +O3. Because optimizations are cumulative, specifying +O3 or +O4 takes advantage of the transformations that happen at +O2.

Table 5-1 Loop transformations affecting data localization

Loop transformation	Options required for behavior to occur
Loop unrolling	+O2 +Oloop_unroll (+Oloop_unroll is on by default at +O2 and above)
Loop distribution	+O3 +Oloop_transform (+Oloop_transform is on by default at +O3 and above)
Loop interchange	+O3 +Oloop_transform (+Oloop_transform is on by default at +O3 and above)
Loop blocking	+O3 +Oloop_transform +Oloop_block (+Oloop_transform is on by default at +O3 and above) (+Oloop_block is off by default)
Loop fusion	+O3 +Oloop_transform (+Oloop_transform is on by default at +O3 and above)
Loop unroll and jam	+O3 +Oloop_transform +Oloop_unroll_jam (+Oloop_transform is on by default at +O3 and above) (+Oloop_unroll_jam is off by default at +O3 and above)

Data localization keeps frequently used data in the processor data cache, eliminating the need for more costly memory accesses.

Loops that manipulate arrays are the main candidates for localization optimizations. Most of these loops are eligible for the various transformations that the compiler performs at `+O3`. These transformations are explained in detail in this section.

Some loop transformations cause loops to be fully or partially replicated. Because unlimited loop replication can significantly increase compile times, loop replication is limited by default. You can increase this limit (and possibly increase your program's compile time and code size) by specifying the `+Onosize` and `+Onolimit` compiler options.

NOTE Most of the following code examples demonstrate optimization by showing the original code first and optimized code second. The optimized code is shown in the same language as the original code for illustrative purposes only.

Conditions that inhibit data localization

Any of the following conditions can inhibit or prevent data localization:

- Loop-carried dependences (LCDs)
- Other loop fusion dependences
- Aliasing
- Computed or assigned GOTO statements in Fortran
- return or exit statements in C or C++
- throw statements in C++
- Procedure calls

The following sections discuss these conditions and their effects on data localization.

Loop-carried dependences (LCDs)

A loop-carried dependence (LCD) exists when one iteration of a loop assigns a value to an address that is referenced or assigned on another iteration. In some cases, LCDs can inhibit loop interchange, thereby inhibiting localization. Typically, these cases involve array indexes that are offset in opposite directions.

To ignore LCDs, use the `no_loop_dependence` directive or pragma. The form of this directive and pragma is shown in Table 5-2.

NOTE This directive and pragmas should only be used if you are certain that there are no loop dependences. Otherwise, errors will result.

Table 5-2 Form of `no_loop_dependence` directive and pragma

Language	Form
Fortran	`C$DIR NO_LOOP_DEPENDENCE(`*`namelist`*`)`
C	`#pragma _CNX no_loop_dependence(`*`namelist`*`)`

where

namelist is a comma-separated list of variables or arrays that have no dependences for the immediately following loop.

Example 5-3 Loop-carried dependences

The Fortran loop below contains an LCD that inhibits interchange:

```
DO I = 2, M
  DO J = 2, N
    A(I,J) = A(I-1,J-1) + A(I-1,J+1)
  ENDDO
ENDDO
```

C and C++ loops can contain similar constructs, but to simplify illustration, only the Fortran example is discussed here.

As written, this loop uses `A(I-1,J-1)` and `A(I-1,J+1)` to compute `A(I,J)`. Table 5-3 shows the sequence in which values of `A` are computed for this loop.

Table 5-3 Computation sequence of `A(I,J)`: original loop

I	J	A(I,J)	A(I-1,J-1)	A(I-1,J+1)
2	2	A(2,2)	A(1,1)	A(1,3)
2	3	A(2,3)	A(1,2)	A(1,4)
2	4	A(2,4)	A(1,3)	A(1,5)
...	...	...	...	...
3	2	A(3,2)	A(2,1)	A(2,3)
3	3	A(3,3)	A(2,2)	A(2,4)
3	4	A(3,4)	A(2,3)	A(2,5)
...	...	...	...	...

As shown in Table 5-3, the original loop computes the elements of the current row of `A` using the elements of the previous row of `A`. For all rows except the first (which is never written), the values contained in the previous row must be written before the current row is computed. This dependence must be honored for the loop to yield its intended results. If a row element of `A` is computed before the previous row elements are computed, the result is incorrect.

Interchanging the `I` and `J` loops yields the following code:

```
DO J = 2, N
  DO I = 2, M
    A(I,J) = A(I-1,J+1) + A(I-1,J-1)
  ENDDO
ENDDO
```

After interchange, the loop computes values of `A` in the sequence shown in Table 5-4.

Table 5-4 Computation sequence of `A(I,J)`: interchanged loop

I	J	A(I,J)	A(I-1,J-1)	A(I-1,J+1)
2	2	A(2,2)	A(1,1)	A(1,3)

Table 5-4 Computation sequence of `A(I,J)`: interchanged loop

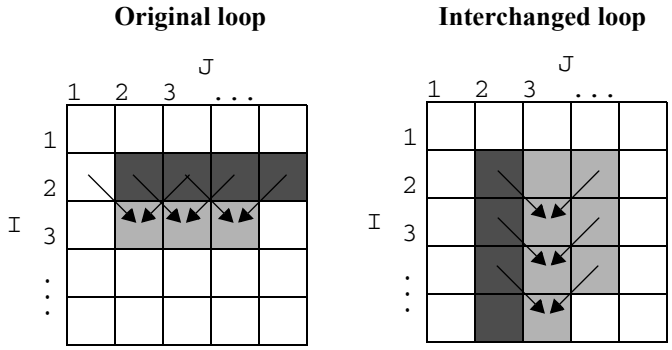
I	J	A(I,J)	A(I-1,J-1)	A(I-1,J+1)
3	2	A(3,2)	A(2,1)	A(2,3)
4	2	A(4,2)	A(3,1)	A(3,3)
...	...	...	...	...
2	3	A(2,3)	A(1,2)	A(1,4)
3	3	A(3,3)	A(2,2)	A(2,4)
4	3	A(4,3)	A(3,2)	A(3,4)
...	...	...	...	...

Here, the elements of the current column of `A` are computed using the elements of the previous column and the next column of `A`.

The problem here is that columns of `A` are being computed using elements from the next column, which have not been written yet. This computation violates the dependence illustrated in Table 5-3.

The element-to-element dependences in both the original and interchanged loop are illustrated in Figure 5-1.

Figure 5-1 LCDs in original and interchanged loops



The arrows in Figure 5-1 represent dependences from one element to another, pointing at elements that depend on the elements at the arrows' bases. Shaded elements indicate a typical row or column computed in the inner loop:

- Darkly shaded elements have already been computed.
- Lightly shaded elements have not yet been computed.

This figure helps to illustrate the sequence in which the array elements are cycled through by the respective loops: the original loop cycles across all the columns in a row, then moves on to the next row. The interchanged loop cycles down all the rows in a column first, then moves on to the next column.

Example 5-4 Avoid loop interchange

Interchange is inhibited only by loops that contain dependences that change when the loop is interchanged. Most LCDs do not fall into this category and thus do not inhibit loop interchange.

Occasionally, the compiler encounters an apparent LCD. If it cannot determine whether the LCD actually inhibits interchange, it conservatively avoids interchanging the loop.

The following Fortran example illustrates this situation:

```
DO I = 1, N
  DO J = 2, M
    A(I,J) = A(I+IADD,J+JADD) + B(I,J)
  ENDDO
ENDDO
```

In these example, if `IADD` and `JADD` are either both positive or both negative, the loop contains no interchange-inhibiting dependence. However, if one and only one of the variables is negative, interchange is inhibited. The compiler has no way of knowing the runtime values of `IADD` and `JADD`, so it avoids interchanging the loop.

If you are positive that the `IADD` and `JADD` are both negative or both positive, you can tell the compiler that the loop is free of dependences using the `no_loop_dependence` directive or pragma, described in this chapter Table NOTE on page 63.

The previous Fortran loop is interchanged when the `NO_LOOP_DEPENDENCE` directive is specified for `A` on the `J` loop as shown in the following code:

```
      DO I = 1, N
C$DIR   NO_LOOP_DEPENDENCE(A)
        DO J = 2, M
          A(I,J) = A(I+IADD,J+JADD) + B(I,J)
        ENDDO
      ENDDO
```

If IADD and JADD acquire opposite-signed values at runtime, these loops may result in incorrect answers.

Other loop fusion dependences

In some cases, loop fusion is also inhibited by simpler dependences than those that inhibit interchange. Consider the following Fortran example:

```
DO I = 1, N-1
  A(I) = B(I+1) + C(I)
ENDDO
DO J = 1, N-1
  D(J) = A(J+1) + E(J)
ENDDO
```

While it might appear that loop fusion would benefit the preceding example, it would actually yield the following incorrect code:

```
DO ITEMP = 1, N-1
  A(ITEMP) = B(ITEMP+1) + C(ITEMP)
  D(ITEMP) = A(ITEMP+1) + E(ITEMP)
ENDDO
```

This loop produces different answers than the original loops, because the reference to A(ITEMP+1) in the fused loop accesses a value that has not been assigned yet, while the analogous reference to A(J+1) in the original J loop accesses a value that was assigned in the original I loop.

Aliasing

An alias is an alternate name for an object. Aliasing occurs in a program when two or more names are attached to the same memory location. Aliasing is typically caused in Fortran by use of the EQUIVALENCE statement. The use of pointers normally causes the problem in C and C++. Passing identical actual arguments into different dummy arguments in a Fortran subprogram can also cause aliasing, as can passing the same address into different pointer arguments in a C or C++ function.

Example 5-5 Aliasing

Aliasing interferes with data localization because it can mask LCDs where arrays `A` and `B` have been equivalenced. This is shown in the following Fortran example:

```
INTEGER A(100,100), B(100,100), C(100,100)
EQUIVALENCE(A,B)
.
.
.
DO I = 1, N
  DO J = 2, M
    A(I,J) = B(I-1,J+1) + C(I,J)
  ENDDO
ENDDO
```

This loop has the same problem as the loop used to demonstrate LCDs in the previous section; because `A` and `B` refer to the same array, the loop contains an LCD on `A`, which prevents interchange and thus interferes with localization.

The C and C++ equivalent of this loop follows. Keep in mind that C and C++ store arrays in row-major order, which requires different subscripting to access the same elements.

```
int a[100][100], c[100][100], i, j;
int (*b)[100];
b = a;
.
.
.
for(i=1;i<n;i++){
  for(j=0;j<m;j++){
    a[j][i] = b[j+1][i-1] + c[j][i];
  }
}
```

Fortran's `EQUIVALENCE` statement is imitated in C and C++; through the use of pointers, arrays are effectively equivalenced, as shown.

Passing the same address into different dummy procedure arguments can yield the same result. Fortran passes arguments by reference while C and C++ pass them by value. However, pass-by-reference is simulated in C and C++ by passing the argument's address into a pointer in the receiving procedure or in C++ by using references.

Example 5-6 Aliasing

The following Fortran code exhibits the same aliasing problem as the previous example, but the alias is created by passing the same actual argument into different dummy arguments.

NOTE The sample code below violates the Fortran standard.

```
.
.
.
CALL ALI(A,A,C)
.
.
.
SUBROUTINE ALI(A,B,C)
INTEGER A(100,100), B(100,100), C(100,100)
DO J = 1, N
  DO I = 2, M
    A(I,J) = B(I-1,J+1) + C(I,J)
  ENDDO
ENDDO
.
.
.
```

The following (legal ANSI C) code shows the same argument-passing problem in C:

```
.
.
.
ali(&a,&a,&c);
.
.
.
void ali(a,b,c)
int a[100][100], b[100][100], c[100][100];
{
  int i,j;
  for(j=0;j<n;j++){
    for(i=1;i<m;i++){
      a[j][i] = b[j+1][i-1] + c[j][i];
    }
  }
}
```

Computed or assigned GOTO statements in Fortran

When the Fortran compiler encounters a computed or assigned GOTO statement in an otherwise interchangeable loop, it cannot always determine whether the branch destination is within the loop. Because an out-of-loop destination would be a loop exit, these statements often prevent loop interchange and therefore data localization.

I/O statements

The order in which values are read into or written from a loop may change if the loop is interchanged. For this reason, I/O statements inhibit interchange and, consequently, data localization.

Example 5-7 **I/O statements**

The following Fortran code is the basis for this example:

```
DO I = 1, 4
  DO J = 1, 4
    READ *, IA(I,J)
  ENDDO
ENDDO
```

Given a data stream consisting of alternating zeros and ones (0,1,0,1,0,1...), the contents for A(I,J) for both the original loop and the interchanged loop are shown in Figure 5-2.

Figure 5-2 **Values read into array A**

Original loop

I \ J	1	2	3	4
1	0	1	0	1
2	0	1	0	1
3	0	1	0	1
4	0	1	0	1

Interchanged loop

I \ J	1	2	3	4
1	1	1	1	1
2	0	0	0	0
3	1	1	1	1
4	0	0	0	0

Multiple loop entries or exits

Loops that contain multiple entries or exits inhibit data localization because they cannot safely be interchanged. Extra loop entries are usually created when a loop contains a branch destination. Extra exits are more common, however. These are often created in C and C++ using the `break` statement, and in Fortran using the `GOTO` statement.

As noted before, the order of computation changes if the loops are interchanged.

Example 5-8 **Multiple loop entries or exits**

This example begins with the following C code:

```
for(j=0;j<n;j++){
  for(i=0;i<m;i++){
    a[i][j] = b[i][j] + c[i][j];
    if(a[i][j] == 0) break;
    .
    .
    .
  }
}
```

Interchanging this loop would change the order in which the values of `a` are computed. The original loop computes `a` column-by-column, whereas the interchanged loop would compute it row-by-row. This means that the interchanged loop may hit the `break` statement and exit after computing a different set of elements than the original loop computes. Interchange therefore may cause the results of the loop to differ and must be avoided.

`RETURN` or `STOP` statements in Fortran

Like loops with multiple exits, `RETURN` and `STOP` statements in Fortran inhibit localization because they inhibit interchange. If a loop containing a `RETURN` or `STOP` is interchanged, its order of computation may change, giving wrong answers.

`return` or `exit` statements in C or C++

Similar to Fortran's `RETURN` and `STOP` statements (discussed in the previous section), `return` and `exit` statements in C and C++ inhibit localization because they inhibit interchange.

`throw` statements in C++

In C++, `throw` statements, like loops containing multiple exits, inhibit localization because they inhibit interchange.

Procedure calls

HP compilers are unaware of the side effects of most procedures, and therefore cannot determine whether or not they might interfere with loop interchange. Consequently, the compilers do not perform loop interchange in an embedded procedure call. These side effects may include data dependences involving loop arrays, aliasing (as described in the section “Aliasing” on page 67), and processor data cache that use conflicts with the loop’s cache. This renders useless any data localization optimizations performed on the loop.

NOTE The compiler can loop parallel on a loop with a procedure call if it can verify that the procedure will not cause any side effects.

Loop blocking

Loop blocking is a combination of strip mining and interchange that maximizes data localization. It is provided primarily to deal with nested loops that manipulate arrays that are too large to fit into the cache. Under certain circumstances, loop blocking allows reuse of these arrays by transforming the loops that manipulate them so that they manipulate strips of the arrays that fit into the cache. Effectively, a blocked loop accesses array elements in sections that are optimally sized to fit in the cache.

The loop-blocking optimization is only available at `+O3` (and above) in the HP compilers; it is disabled by default. To enable loop blocking, use the `+Oloop_block` option. Specifying `+Onoloop_block` (the default) disables both automatic and directive-specified loop blocking. Specifying `+Onoloop_transform` also disables loop blocking, as well as loop distribution, loop interchange, loop fusion, loop unroll, and loop unroll and jam.Loop blocking can also be enabled for specific loops using the `block_loop` directive and pragma. The `block_loop` and `no_block_loop` directives and pragmas affect the immediately following loop. You can also instruct the compiler to use a specific block factor using `block_loop`. The `no_block_loop` directive and pragma disables loop blocking for a particular loop.

The forms of these directives and pragmas is shown in Table 5-5.

Table 5-5 Forms of `block_loop`, `no_block_loop` directives and pragmas

Language	Form
Fortran	`C$DIR BLOCK_LOOP[(BLOCK_FACTOR = n)]` `C$DIR NO_BLOCK_LOOP`
C	`#pragma _CNX block_loop[(block_factor = n)]` `#pragma _CNX no_block_loop`

where

n is the requested block factor, which must be a compile-time integer constant. The compiler uses this value as stated. For the best performance, the block factor multiplied by the data type size of the data in the loop should be an integral multiple of the cache line size.

In the absence of the `block_factor` argument, this directive is useful for indicating which loop in a nest to block. In this case, the compiler uses a heuristic to determine the block factor.

Data reuse

Data reuse is important to understand when discussing blocking. There are two types of data reuse associated with loop blocking:

- Spatial reuse
- Temporal reuse

Spatial reuse

Spatial reuse uses data that was encached as a result of fetching another piece of data from memory; data is fetched by cache lines. 32 bytes of data is encached on every fetch on V2250 servers. Cache line sizes may be different on other HP SMPs.

On the initial fetch of array data from memory within a stride-one loop, the requested item is located anywhere in the 32 bytes. The exception is if array is aligned on cache line boundaries. Refer to “Standard optimization features” on page 35, for a description of data alignment.

Starting with the cache-aligned memory fetch, the requested data is located at the beginning of the cache line, and the rest of the cache line contains subsequent array elements. For a `REAL*4` array, this means the requested element and the seven following elements are encached on each fetch after the first.

If any of these seven elements could then be used on any subsequent iterations of the loop, the loop would be exploiting spatial reuse. For loops with strides greater than one, spatial reuse can still occur. However, the cache lines contain fewer usable elements.

Temporal reuse

Temporal reuse uses the same data item on more than one iteration of the loop. An array element whose subscript does not change as a function of the iterations of a surrounding loop exhibits temporal reuse in the context of the loop.

Loops that stride through arrays are candidates for blocking when there is also an outermost loop carrying spatial or temporal reuse. Blocking the innermost loop allows data referenced by the outermore loop to remain in the cache across multiple iterations. Blocking exploits spatial reuse by ensuring that once fetched, cache lines are not overwritten until their spatial reuse is exhausted. Temporal reuse is similarly exploited.

Example 5-9 **Simple loop blocking**

In order to exploit reuse in more realistic examples that manipulate arrays that do not all fit in the cache, the compiler can apply a blocking transformation.

The following Fortran example demonstrates this:

```
REAL*8 A(1000,1000),B(1000,1000)
REAL*8 C(1000),D(1000)
COMMON /BLK2/ A, B, C
.
.
.
DO J = 1, 1000
  DO I = 1, 1000
    A(I,J) = B(J,I) + C(I) + D(J)
  ENDDO
ENDDO
```

Here the array elements occupy nearly 16 Mbytes of memory. Thus, blocking becomes profitable.

First the compiler strip mines the `I` loop:

```
DO J = 1, 1000
  DO IOUT = 1, 1000, IBLOCK
    DO I = IOUT, IOUT+IBLOCK-1
      A(I,J) = B(J,I) + C(I) + D(J)
    ENDDO
  ENDDO
ENDDO
```

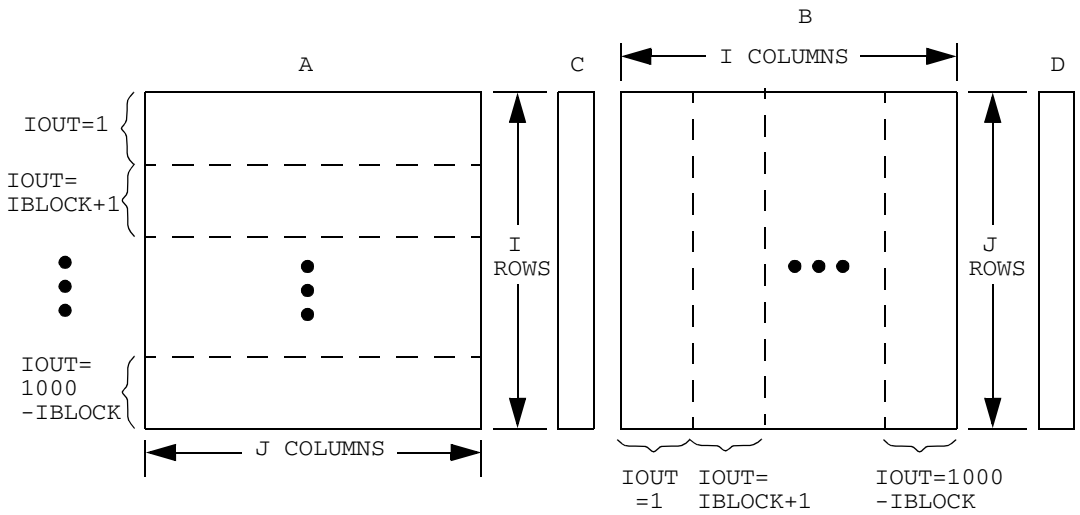
`IBLOCK` is the block factor (also referred to as the strip mine length) the compiler chooses based on the size of the arrays and size of the cache. Note that this example assumes the chosen `IBLOCK` divides 1000 evenly.

Next, the compiler moves the outer strip loop (IOUT) outward as far as possible.

```
DO IOUT = 1, 1000, IBLOCK
  DO J = 1, 1000
    DO I = IOUT, IOUT+IBLOCK-1
      A(I,J) = B(J,I) + C(I) + D(J)
    ENDDO
  ENDDO
ENDDO
```

This new nest accesses IBLOCK rows of A and IBLOCK columns of B for every iteration of J. At every iteration of IOUT, the nest accesses 1000 IBLOCK-length columns of A (or an IBLOCK ¥ 1000 chunk of A) and 1000 IBLOCK-width rows of B are accessed. This is illustrated in Figure 5-3.

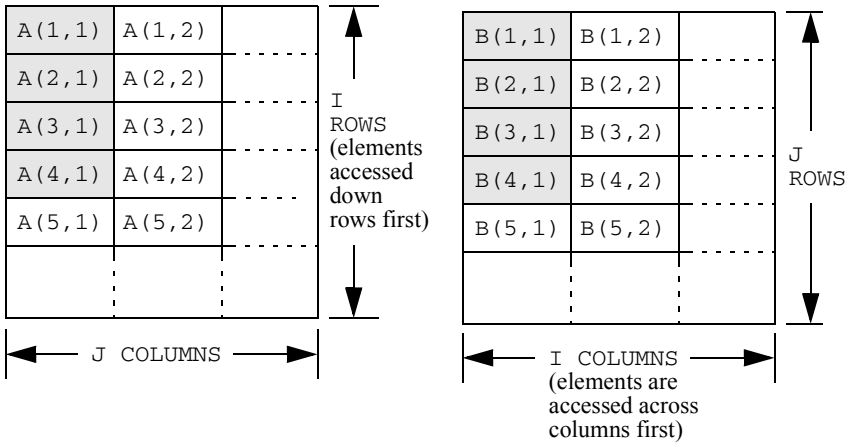
Figure 5-3 Blocked array access



Fetches of A encache the needed element and the three elements that are used in the three subsequent iterations, giving spatial reuse on A. Because the I loop traverses columns of B, fetches of B encache extra elements that are not spatially reused until J increments. IBLOCK is chosen by the compiler to efficiently exploit spatial reuse of both A and B.

Figure 5-4 illustrates how cache lines of each array are fetched. A and B both start on cache line boundaries because they are in COMMON. The shaded area represents the initial cache line fetched.

Figure 5-4 Spatial reuse of A and B



- When A(1,1) is accessed, A(1:4,1) is fetched; A(2:4,1) is used on subsequent iterations 2,3 and 4 of I.
- B(1:4,1) is fetched when I=1, but B(2:4,1) is not be used until J increments to 2, 3, 4. B(1:4,2) is fetched when I=2.

Typically, IBLOCK elements of C remain in the cache for several iterations of J before being overwritten, giving temporal reuse on C for those iterations. By the time any of the arrays are overwritten, all spatial reuse has been exhausted. The load of D is removed from the I loop so that it remains in a register for all iterations of I.

Example 5-10 Matrix multiply blocking

The more complicated matrix multiply algorithm, which follows, is a prime candidate for blocking:

```
REAL*8 A(1000,1000),B(1000,1000),C(1000,1000)
COMMON /BLK3/ A, B, C
.
.
.
DO I = 1, 1000
  DO J = 1, 1000
```

```
    DO K = 1, 1000
      C(I,J) = C(I,J) + A(I,K) * B(K,J)
    ENDDO
  ENDDO
ENDDO
```

This loop is blocked as shown below:

```
DO IOUT = 1, 1000, IBLOCK
  DO KOUT = 1, 1000, KBLOCK
    DO J = 1, 1000
      DO I = IOUT, IOUT+IBLOCK-1
        DO K = KOUT, KOUT+KBLOCK-1
          C(I,J) = C(I,J) + A(I,K) * B(K,J)
        ENDDO
      ENDDO
    ENDDO
  ENDDO
ENDDO
```

As a result, the following occurs:

- Spatial reuse of `B` with respect to the `K` loop
- Temporal reuse of `B` with respect to the `I` loop
- Spatial reuse of `A` with respect to the `I` loop
- Temporal reuse of `A` with respect to the `J` loop
- Spatial reuse of `C` with respect to the `I` loop
- Temporal reuse of `C` with respect to the `K` loop

An analogous C and C++ example follows with a different resulting interchange:

```
static double a[1000][1000], b[1000][1000];
static double c[1000][1000];
.
.
.
for(i=0;i<1000;i++)
    for(j=0;j<1000;j++)
      for(k=0;k<1000;k++)
        c[i][j] = c[i][j] + a[i][k] * b[k][j];
```

The HP C and aC++ compilers interchange and block the loop in this example to provide optimal access efficiency for the row-major C and C++ arrays. The blocked loop is shown below:

```
for(jout=0;jout<1000;jout+=jblk)
  for(kout=0;kout<1000;kout+=kblk)
    for(i=0;i<1000;i++)
      for(j=jout;j<jout+jblk;j++)
        for(k=kout;k<kout+kblk;k++)
          c[i][j]=c[i][j]+a[i][k]*b[k][j];
```

As you can see, the interchange was done differently because of C and C++'s different array storage strategies. This code yields:

- Spatial reuse of `b` with respect to the `j` loop
- Temporal reuse of `b` with respect to the `i` loop
- Spatial reuse of `a` with respect to the `k` loop
- Temporal reuse of `a` with respect to the `j` loop
- Spatial reuse on `c` with respect to the `j` loop
- Temporal reuse on `c` with respect to the `k` loop

Blocking is inhibited when loop interchange is inhibited. If a candidate loop nest contains loops that cannot be interchanged, blocking is not performed.

Example 5-11 Loop blocking

The following example shows the affect of the `block_loop` directive on the code shown earlier in "Matrix multiply blocking" on page 77:

```
      REAL*8 A(1000,1000),B(1000,1000)
      REAL*8 C(1000,1000)
      COMMON /BLK3/ A, B, C
      .
      .
      .
      DO I = 1,1000
        DO J = 1, 1000
C$DIR     BLOCK_LOOP(BLOCK_FACTOR = 112)
          DO K = 1,1000
            C(I,J) = C(I,J) + A(I,K)*B(K,J)
          ENDDO
        ENDDO
      ENDDO
```

The original example involving this code showed that the compiler blocks the `I` and `K` loops. In this example, the `BLOCK_LOOP` directive instructs the compiler to use a block factor of 112 for the `K` loop. This is an efficient blocking factor for this example because 112 × 8 bytes = 896 bytes,

and 896/32 bytes (the cache line size) = 28, which is an integer, so partial cache lines are not necessary. The compiler-chosen value is still used on the `I` loop.

Loop distribution

Loop distribution is another fundamental +O3 transformation necessary for more advanced transformations. These advanced transformations require that all calculations in a nested loop be performed inside the innermost loop. To facilitate this, loop distribution transforms complicated nested loops into several simple loops that contain all computations inside the body of the innermost loop.

Loop distribution takes place at +O3 and above and is enabled by default. Specifying +Onoloop_transform disables loop distribution, as well as loop interchange, loop blocking, loop fusion, loop unroll, and loop unroll and jam.

Loop distribution is disabled for specific loops by specifying the no_distribute directive or pragma immediately before the loop.

The form of this directive and pragma is shown in Table 5-6.

Table 5-6 Form of `no_distribute` directive and pragma

Language	Form
Fortran	C$DIR NO_DISTRIBUTE
C	#pragma _CNX no_distribute

Example 5-12 Loop distribution

This example begins with the following Fortran code:

```
DO I = 1, N
  C(I) = 0
  DO J = 1, M
    A(I,J) = A(I,J) + B(I,J) * C(I)
  ENDDO
ENDDO
```

Loop distribution creates two copies of the I loop, separating the nested J loop from the assignments to array C. In this way, all assignments are moved to innermost loops. Interchange is then performed on the I and J loops.

The distribution and interchange is shown in the following transformed code:

```
DO I = 1, N
  C(I) = 0
ENDDO
DO J = 1, M
  DO I = 1, N
    A(I,J) = A(I,J) + B(I,J) * C(I)
  ENDDO
ENDDO
```

Distribution can improve efficiency by reducing the number of memory references per loop iteration and the amount of cache thrashing. It also creates more opportunities for interchange.

Loop fusion

Loop fusion involves creating one loop out of two or more neighboring loops that have identical loop bounds and trip counts. This reduces loop overhead, memory accesses, and increases register usage. It can also lead to other optimizations. By potentially reducing the number of parallelizable loops in a program and increasing the amount of work in each of those loops, loop fusion can greatly reduce parallelization overhead. Because fewer spawns and joins are necessary.

Loop fusion takes place at `+O3` and above and is enabled by default. Specifying `+Onoloop_transform` disables loop fusion, as well as loop distribution, loop interchange, loop blocking, loop unroll, and loop unroll and jam.

Occasionally, loops that do not appear to be fusible become fusible as a result of compiler transformations that precede fusion. For instance, interchanging a loop may make it suitable for fusing with another loop.

Loop fusion is especially beneficial when applied to Fortran array assignments. The compiler translates these statements into loops; when such loops do not contain code that inhibit fusion, they are fused.

Example 5-13 Loop fusion

This example begins with the following Fortran code:

```
DO I = 1, N
  A(I) = B(I) + C(I)
ENDDO
DO J = 1, N
  IF(A(J) .LT. 0) A(J) = B(J)*B(J)
ENDDO
```

The two loops shown above are fused into the following loop using loop fusion:

```
DO I = 1, N
  A(I) = B(I) + C(I)
  IF(A(I) .LT. 0) A(I) = B(I)*B(I)
ENDDO
```

Example 5-14 Loop fusion

This example begins with the following Fortran code:

```
REAL A(100,100), B(100,100), C(100,100)
.
.
.
C = 2.0 * B
A = A + B
```

The compiler first transforms these Fortran array assignments into loops, generating code similar to that shown below.

```
DO TEMP1 = 1, 100
  DO TEMP2 = 1, 100
    C(TEMP2, TEMP1) = 2.0 * B(TEMP2, TEMP1)
  ENDDO
ENDDO
DO TEMP3 = 1, 100
  DO TEMP4 = 1, 100
    A(TEMP4,TEMP3)=A(TEMP4,TEMP3)+B(TEMP4,TEMP3)
  ENDDO
ENDDO
```

These two loops would then be fused as shown in the following loop nest:

```
DO TEMP1 = 1, 100
  DO TEMP2 = 1, 100
    C(TEMP2,TEMP1) = 2.0 * B(TEMP2, TEMP1)
    A(TEMP2,TEMP1)=A(TEMP2,TEMP1)+B(TEMP2,TEMP1)
  ENDDO
ENDDO
```

Further optimizations could be applied to this new nest as appropriate.

Example 5-15 Loop peeling

When trip counts of adjacent loops differ by only a single iteration (+1 or -1), the compiler may peel an iteration from one of the two loops so that the loops may then be fused. The peeled iteration is performed separately from the original loop.

The following Fortran example shows how this is implemented:

```
DO I = 1, N-1
  A(I) = I
ENDDO

DO J = 1, N
  A(J) = A(J) + 1
ENDDO
```

As you can see, the `N`th iteration of the `J` loop is peeled, resulting in a trip count of `N - 1`. The `N`th iteration is performed outside the `J` loop. As a result, the code is changed to the following:

```
DO I = 1, N-1
  A(I) = I
ENDDO

DO J = 1, N-1
  A(J) = A(J) + 1
ENDDO

A(N) = A(N) + 1
```

The `I` and `J` loops now have the same trip count and are fused, as shown below:

```
DO I = 1, N-1
  A(I) = I
  A(I) = A(I) + 1
ENDDO

A(N) = A(N) + 1
```

Loop interchange

The compiler may interchange (or reorder) nested loops for the following reasons:

- To facilitate other transformations
- To relocate the loop that is the most profitable to parallelize so that it is outermost
- To optimize inner-loop memory accesses

Loop interchange takes place at `+O3` and above and is enabled by default. Specifying `+Onoloop_transform` disables loop interchange, as well as loop distribution, loop blocking, loop fusion, loop unroll, and loop unroll and jam.

Example 5-16 Loop interchange

This example begins with the Fortran matrix addition algorithm below:

```
DO I = 1, N
  DO J = 1, M
    A(I, J) = B(I, J) + C(I, J)
  ENDDO
ENDDO
```

The loop accesses the arrays `A`, `B` and `C` row by row, which, in Fortran, is very inefficient. Interchanging the `I` and `J` loops, as shown in the following example, facilitates column by column access.

```
DO J = 1, M
  DO I = 1, N
    A(I, J) = B(I, J) + C(I, J)
  ENDDO
ENDDO
```

Unlike Fortran, C and C++ access arrays in row-major order. An analogous example in C and C++, then, employs an opposite nest ordering, as shown below.

```
for(j=0;j<m;j++)
  for(i=0;i<n;i++)
    a[i][j] = b[i][j] + c[i][j];
```

Interchange facilitates row-by-row access. The interchanged loop is shown below.

```
for(i=0;i<n;i++)
  for(j=0;j<m;j++)
    a[i][j] = b[i][j] + c[i][j];
```

Loop unroll and jam

The loop unroll and jam transformation is primarily intended to increase register exploitation and decrease memory loads and stores per operation within an iteration of a nested loop. Improved register usage decreases the need for main memory accesses and allows better exploitation of certain machine instructions.

Unroll and jam involves partially unrolling one or more loops higher in the nest than the innermost loop, and fusing ("jamming") the resulting loops back together. For unroll and jam to be effective, a loop must be nested and must contain data references that are temporally reused with respect to some loop other than the innermost (temporal reuse is described in "Data reuse" on page 74). The unroll and jam optimization is automatically applied only to those loops that consist strictly of a basic block.

Loop unroll and jam takes place at `+O3` and above and is not enabled by default in the HP compilers. To enable loop unroll and jam on the command line, use the `+Oloop_unroll_jam` option. This allows both automatic and directive-specified unroll and jam. Specifying `+Onoloop_transform` disables loop unroll and jam, loop distribution, loop interchange, loop blocking, loop fusion, and loop unroll.

The `unroll_and_jam` directive and pragma also enables this transformation. The `no_unroll_and_jam` directive and pragma is used to disable loop unroll and jam for an individual loop.

The forms of these directives and pragmas are shown in Table 5-7.

Table 5-7 Forms of `unroll_and_jam`, `no_unroll_and_jam` directives and pragmas

Language	Form

Fortran	`C$DIR UNROLL_AND_JAM[(UNROLL_FACTOR=`*n*`)]`
	
	`C$DIR NO_UNROLL_AND_JAM`

Table 5-7 Forms of `unroll_and_jam`, `no_unroll_and_jam` directives and pragmas (Continued)

Language	Form

C	`#pragma _CNX unroll_and_jam[(unroll_factor=`*n*`)]`
	
	`#pragma _CNX no_unroll_and_jam`

where

`unroll_factor=`*n* allows you to specify an unroll factor for the loop in question.

NOTE Because unroll and jam is only performed on nested loops, you must ensure that the directive or pragma is specified on a loop that, after any compiler-initiated interchanges, is not the innermost loop. You can determine which loops in a nest are innermost by compiling the nest without any directives and examining the Optimization Report, described in “Optimization Report” on page 155.

Example 5-17 Unroll and jam

Consider the following matrix multiply loop:

```
DO I = 1, N
  DO J = 1, N
    DO K = 1, N
      A(I,J) = A(I,J) + B(I,K) * C(K,J)
    ENDDO
  ENDDO
ENDDO
```

Here, the compiler can exploit a maximum of 3 registers: one for `A(I,J)`, one for `B(I,K)`, and one for `C(K,J)`.

Register exploitation is vastly increased on this loop by unrolling and jamming the `I` and `J` loops. First, the compiler unrolls the `I` loop. To simplify the illustration, an unrolling factor of 2 for `I` is used. This is the number of times the contents of the loop are replicated.

The following Fortran example shows this replication:

```
DO I = 1, N, 2
  DO J = 1, N
    DO K = 1, N
      A(I,J) = A(I,J) + B(I,K) * C(K,J)
    ENDDO
  ENDDO
  DO J = 1, N
    DO K = 1, N
      A(I+1,J) = A(I+1,J) + B(I+1,K) * C(K,J)
    ENDDO
  ENDDO
ENDDO
```

The “jam” part of unroll and jam occurs when the loops are fused back together, to create the following:

```
DO I = 1, N, 2
  DO J = 1, N
    DO K = 1, N
      A(I,J) = A(I,J) + B(I,K) * C(K,J)
      A(I+1,J) = A(I+1,J) + B(I+1,K) * C(K,J)
    ENDDO
  ENDDO
ENDDO
```

This new loop can exploit registers for two additional references: `A(I,J)` and `A(I+1,J)`. However, the compiler still has the `J` loop to unroll and jam. An unroll factor of 4 for the `J` loop is used, in which case unrolling gives the following:

```
DO I = 1, N, 2
  DO J = 1, N, 4
    DO K = 1, N
      A(I,J) = A(I,J) + B(I,K) * C(K,J)
      A(I+1,J) = A(I+1,J) + B(I+1,K) * C(K,J)
    ENDDO
    DO K = 1, N
      A(I,J+1) = A(I,J+1) + B(I,K) * C(K,J+1)
      A(I+1,J+1) = A(I+1,J+1) + B(I+1,K) * C(K,J+1)
    ENDDO
    DO K = 1, N
      A(I,J+2) = A(I,J+2) + B(I,K) * C(K,J+2)
      A(I+1,J+2) = A(I+1,J+2) + B(I+1,K) * C(K,J+2)
    ENDDO
    DO K = 1, N
      A(I,J+3) = A(I,J+3) + B(I,K) * C(K,J+3)
      A(I+1,J+3) = A(I+1,J+3) + B(I+1,K) * C(K,J+3)
    ENDDO
  ENDDO
ENDDO
```

Fusing (jamming) the unrolled loop results in the following:

```
DO I = 1, N, 2
  DO J = 1, N, 4
    DO K = 1, N
      A(I,J) = A(I,J) + B(I,K) * C(K,J)
      A(I+1,J) = A(I+1,J) + B(I+1,K) * C(K,J)
      A(I,J+1) = A(I,J+1) + B(I,K) * C(K,J+1)
      A(I+1,J+1) = A(I+1,J+1) + B(I+1,K) * C(K,J+1)
      A(I,J+2) = A(I,J+2) + B(I,K) * C(K,J+2)
      A(I+1,J+2) = A(I+1,J+2) + B(I+1,K) * C(K,J+2)
      A(I,J+3) = A(I,J+3) + B(I,K) * C(K,J+3)
      A(I+1,J+3) = A(I+1,J+3) + B(I+1,K) * C(K,J+3)
    ENDDO
  ENDDO
ENDDO
```

This new loop exploits more registers and requires fewer loads and stores than the original. Recall that the original loop could use no more than 3 registers. This unrolled-and-jammed loop can use 14, one for each of the following references:

`A(I,J)`	`B(I,K)`	`C(K,J)`	`A(I+1,J)`
`B(I+1,K)`	`A(I,J+1)`	`C(K,J+1)`	`A(I+1,J+1)`
`A(I,J+2)`	`C(K,J+2)`	`A(I,J+3)`	`A(I+1,J+2)`
`A(I+1,J+3)`	`C(K,J+3)`		

Fewer loads and stores per operation are required because all of the registers containing these elements are referenced at least twice. This particular example can also benefit from the PA-RISC `FMPYFADD` instruction, which is available with PA-8*x*00 processors. This instruction doubles the speed of the operations in the body of the loop by simultaneously performing related adds and multiplies.

This is a very simplified example. In reality, the compiler attempts to exploit as many of the PA-RISC processor's registers as possible. For the matrix multiply algorithm used here, the compiler would select a larger unrolling factor, creating a much larger `K` loop body. This would result in increased register exploitation and fewer loads and stores per operation.

NOTE Excessive unrolling may introduce extra register spills if the unrolled and jammed loop body becomes too large. Each cache line has a 32-bit register value; register spills

occur when this value is exceeded. This most often occurs as a result of continuous loop unrolling. Register spills may have negative effects on performance.

You should attempt to select unroll factor values that align data references in the innermost loop on cache boundaries. As a result, references to the consecutive memory regions in the innermost loop can have very high cache hit ratios. Unroll factors of 5 or 7 may not be good choices because most array element sizes are either 4 bytes or 8 bytes and the cache line size is 32 bytes. Therefore, an unroll factor of 2 or 4 is more likely to effectively exploit cache line reuse for the references that access consecutive memory regions.

As with all optimizations that replicate code, the number of new loops created when the compiler performs the unroll and jam optimization is limited by default to ensure reasonable compile times. To increase the replication limit and possibly increase your compile time and code size, specify the `+Onosize` and `+Onolimit` compiler options.

Preventing loop reordering

The `no_loop_transform` directive or pragma allows you to prevent all loop-reordering transformations on the immediately following loop. The form of this directive and pragma are shown in Table 5-8.

Table 5-8 Form of `no_loop_transform` directive and pragma

Language	Form
Fortran	`C$DIR NO_LOOP_TRANSFORM`
C	`#pragma _CNX no_loop_transform`

Use the command-line option `+Onoloop_transform` (at `+O3` and above) to disable loop distribution, loop blocking, loop fusion, loop interchange, loop unroll, and loop unroll and jam at the file level.

Test promotion

Test promotion involves promoting a test out of the loop that encloses it by replicating the containing loop for each branch of the test. The replicated loops contain fewer tests than the originals, or no tests at all, so the loops execute much faster. Multiple tests are promoted, and copies of the loop are made for each test.

Example 5-18 Test promotion

Consider the following Fortran loop:

```
DO I=1, 100
  DO J=1, 100
    IF(FOO .EQ. BAR) THEN
      A(I,J) = I + J
    ELSE
      A(I,J) = 0
    ENDIF
  ENDDO
ENDDO
```

Test promotion (and loop interchange) produces the following code:

```
IF(FOO .EQ. BAR) THEN
  DO J=1, 100
    DO I=1, 100
      A(I,J) = I + J
    ENDDO
  ENDDO
ELSE
  DO J=1, 100
    DO I=1, 100
      A(I,J) = 0
    ENDDO
  ENDDO
ENDIF
```

For loops containing large numbers of tests, loop replication can greatly increase the size of the code.

Each `DO` loop in Fortran and `for` loop in C and C++ whose bounds are not known at compile-time is implicitly tested to check that the loop iterates at least once. This test may be promoted, with the promotion noted in the Optimization Report. If you see unexpected promotions in the report, this implicit testing may be the cause. For more information on the Optimization Report, see “Optimization Report” on page 155.

Cross-module cloning

Cloning is the replacement of a call to a routine by a call to a clone of that routine. The clone is optimized differently than the original routine. Cloning can expose additional opportunities for optimization across multiple source files.

Cloning at `+O4` is performed across all procedures within the program, and is disabled by specifying the `+Onoinline` command-line option. This option is described on page 130.

Global and static variable optimizations

Global and static variable optimizations look for ways to reduce the number of instructions required for accessing global and static variables (`COMMON` and `SAVE` variables in Fortran, and `extern` and `static` variables in C and C++).

The compiler normally generates two machine instructions when referencing global variables. Depending on the locality of the global variables, single machine instructions may sometimes be used to access these variables. The linker rearranges the storage location of global and static data to increase the number of variables that are referenced by single instructions.

Global variable optimization coding standards

Because this optimization rearranges the location and data alignment of global variables, follow the programming practices given below:

- Do not make assumptions about the relative storage location of variables, such as generating a pointer by adding an offset to the address of another variable.
- Do not rely on pointer or address comparisons between two different variables.
- Do not make assumptions about the alignment of variables, such as assuming that a `short` integer is aligned the same as an integer.

Inlining across multiple source files

Inlining substitutes function calls with copies of the function's object code. Only functions that meet the optimizer's criteria are inlined. This may result in slightly larger executable files. However, this increase in size is offset by the elimination of time-consuming procedure calls and procedure returns. See the section "Inlining within a single source file" on page 58 for an example of inlining.

Inlining at `+O4` is performed across all procedures within the program. Inlining at `+O3` is done within one file.

Inlining is affected by the `+O[no]inline[=`*`namelist`*`]` and `+Oinline_budget=`*`n`* command-line options. See "Controlling optimization" on page 119 for more information on these options.

6 Parallel optimization features

This chapter discusses parallel optimization features available with the HP-UX compilers, including those inherent in optimization levels +O3

`and +O4`. This includes a discussion of the following topics:

- Levels of parallelism
- Threads
- Idle thread states
- Parallel optimizations
- Inhibiting parallelization
- Reductions
- Preventing parallelization
- Parallelism in the aC++ compiler
- Cloning across multiple source files

For more information as to specific parallel command-line options, as well as pragmas and directives, please see “Controlling optimization” on page 119.

Levels of parallelism

In the HP compilers, parallelism exists at the loop level, task level, and region level, as described in Chapter 9, “Parallel programming techniques,” on page 181. These are briefly described as follows.

- HP compilers automatically exploit loop-level parallelism. This type of parallelism involves dividing a loop into several smaller iteration spaces and scheduling these to run simultaneously on the available processors. For more information, see “Parallelizing loops” on page 187.

  Using the `+Oparallel` option at `+O3` and above allows the compiler to automatically parallelize loops that are profitable to parallelize.

NOTE Only loops with iteration counts that can be determined prior to loop invocation at runtime are candidates for parallelization. Loops with iteration counts that depend on values or conditions calculated within the loop cannot be parallelized by any means.

- Specify task-level parallelism using the `begin_tasks`, `next_task` and `end_tasks` directives and pragmas, as discussed in the section “Parallelizing tasks” on page 201.
- Specify parallel regions using the `parallel` and `end_parallel` directives and pragmas, as discussed in the section “Parallelizing regions” on page 206. These directives and pragmas allow the compiler to run identified sections of code in parallel.

Loop-level parallelism

HP compilers locate parallelism at the loop level, generating parallel code that is automatically run on as many processors as are available at runtime. Normally, these are all the processors on the same system where your program is running. You can specify a smaller number of processors using any of the following:

- `loop_parallel(max_threads=`*m*`)` directive and pragma—available in Fortran and C
- `prefer_parallel(max_threads=`*m*`)` directive and pragma—available in Fortran and C

  For more information on the `loop_parallel` and `prefer_parallel` directives and pragmas see Chapter 9.
- `MP_NUMBER_OF_THREADS` environment variable—This variable is read at runtime by your program. If this variable is set to some positive integer *n*, your program executes on *n* processors. *n* must be less than or equal to the number of processors in the system where the program is executing.

Automatic parallelization

Automatic parallelization is useful for programs containing loops. You can use compiler directives or pragmas to improve on the automatic optimizations and to assist the compiler in locating additional opportunities for parallelization.

If you are writing your program entirely under the message-passing paradigm, you must explicitly handle parallelism as discussed in the *HP MPI User's Guide*.

Example 6-1 Loop-level parallelism

This example begins with the following Fortran code:

```
PROGRAM PARAXPL
.
.
.
DO I = 1, 1024
  A(I) = B(I) + C(I)
  .
  .
  .
ENDDO
```

Assuming that the `I` loop does not contain any parallelization-inhibiting code, this program can be parallelized to run on eight processors by running 128 iterations per processor (1024 iterations divided by 8 processors = 128 iterations each). One processor would run the loop for `I` = 1 to 128. The next processor would run `I` = 129 to 256, and so on. The loop could similarly be parallelized to run on any number of processors, with each one taking its appropriate share of iterations.

At a certain point, however, adding more processors does not improve performance. The compiler generates code that runs on as many processors as are available, but the dynamic selection optimization (described in the section “Dynamic selection” on page 108) ensures that parallel code is executed only if it is profitable to do so. If the number of available processors does not evenly divide the number of iterations, some processors perform fewer iterations than others.

Threads

Parallelization divides a program into threads. A thread is a single flow of control within a process. It can be a unique flow of control that performs a specific function, or one of several instances of a flow of control, each of which is operating on a unique data set.

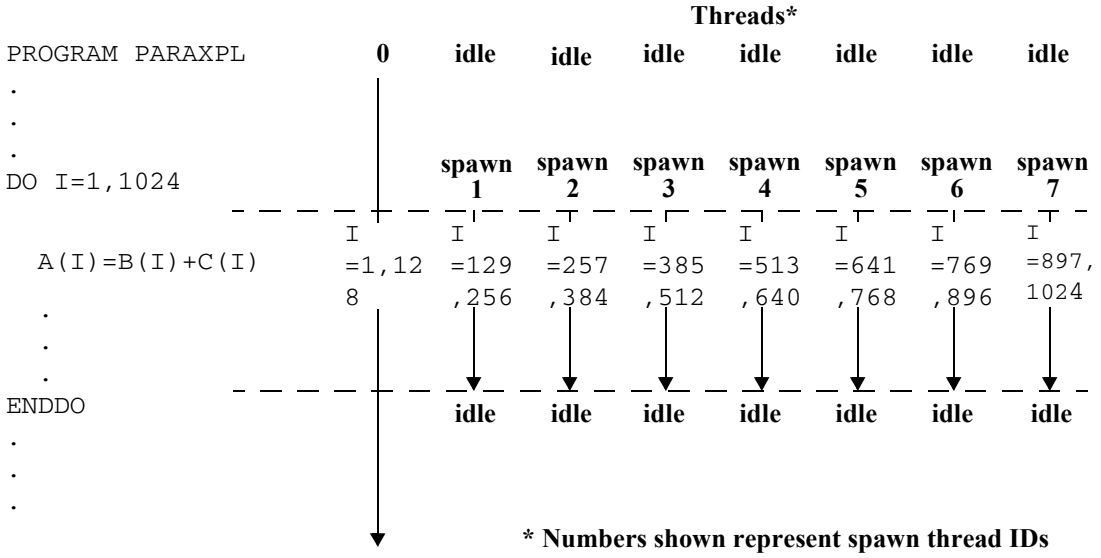
On a V-Class server, parallel shared-memory programs run as a collection of threads on multiple processors. When a program starts, a separate execution thread is created on each system processor on which the program is running. All but one of these threads is then idle. The nonidle thread is known as thread 1, and this thread runs all of the serial code in the program.

Spawn thread IDs are assigned only to nonidle threads when they are spawned. This occurs when thread 1 encounters parallelism and "wakes up" other idle threads to execute the parallel code. Spawn thread IDs are consecutive, ranging from 0 to *N*-1, where *N* is the number of threads spawned as a result of the spawn operation. This operation defines the current spawn context. The spawn context is the loop, task list, or region that initiates the spawning of the threads. Spawn thread IDs are valid only within a given spawn context.

This means that the idle threads are not assigned spawn thread IDs at the time of their creation. When thread 1 encounters a parallel loop, task, or region, it spawns the other threads, signaling them to begin execution. The threads then become active, acquire spawn thread IDs, run until their portion of the parallel code is finished, and go idle once again, as shown in Figure 6-1.

NOTE Machine loading does not affect the number of threads spawned, but it may affect the order in which the threads in a given spawn context complete.

Figure 6-1 One-dimensional parallelism in threads



Loop transformations

Figure 6-1 above shows that various loop transformations can affect the manner in which a loop is parallelized.

To implement this, the compiler transforms the loop in a manner similar to strip mining. However, unlike in strip mining, the outer loop is conceptual. Because the strips execute on different processors, there is no processor to run an outer loop like the one created in traditional strip mining.

Instead, the loop is transformed. The starting and stopping iteration values are variables that are determined at runtime based on how many threads are available and which thread is running the strip in question.

Example 6-2 Loop transformations

Consider the previous Fortran example written for an unspecified number of iterations:

```
DO I = 1, N
  A(I) = B(I) + C(I)
ENDDO
```

The code shown in Figure 6-2 is a conceptual representation of the transformation the compiler performs on this example when it is compiled for parallelization, assuming that `N >= NumThreads`. For `N < NumThreads`, the compiler uses `N` threads, assuming there is enough work in the loop to justify the overhead of parallelizing it. If `NumThreads` is not an integral divisor of `N`, some threads perform fewer iterations than others.

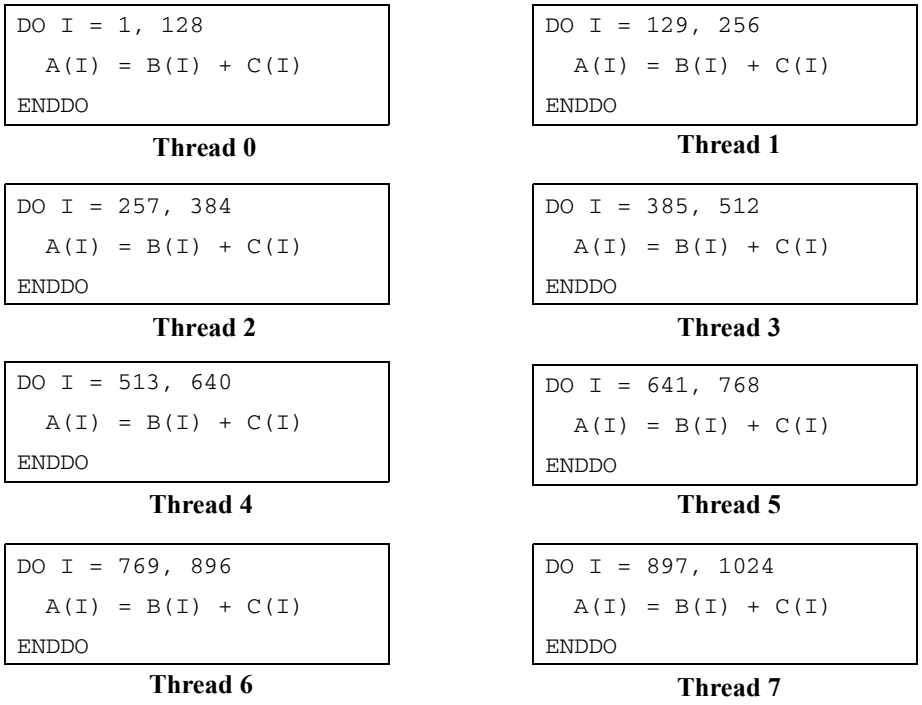
Figure 6-2 Conceptual strip mine for parallelization

```
For each available thread do:
  DO I = ThrdID*(N/NumThreads)+1,ThrdID*(N/NumThreads)+N/NumThreads
    A(I) = B(I) + C(I)
  ENDDO
```

`NumThreads` is the number of available threads. `ThrdID` is the ID number of the thread this particular loop runs on, which is between 0 and `NumThreads-1`. A unique `ThrdID` is assigned to each thread, and the

ThrdIDs are consecutive. So, for NumThreads = 8, as in Figure 6-1, 8 loops would be spawned, with ThrdIDs = 0 through 7. These 8 loops are illustrated in Figure 6-3.

Figure 6-3 Parallelized loop



NOTE The strip-based parallelism described here is the default. Stride-based parallelism is possible through use of the prefer_parallel and loop_parallel compiler directives and pragmas.

In these examples, the data being manipulated within the loop is disjoint so that no two threads attempt to write the same data item. If two parallel threads attempt to update the same storage location, their actions must be synchronized. This is discussed further in “Parallel synchronization” on page 255.

Idle thread states

Idle threads can be suspended or spin-waiting. Suspended threads release control of the processor while spin-waiting threads repeatedly check an encached global semaphore that indicates whether or not they have code to execute. This obviously prevents any other process from gaining control of the CPU and can severely degrade multiprocess performance.

Alternately, waking a suspended thread takes substantially longer than activating a spin-waiting thread. By default, idle threads spin-wait briefly after creation or a join, then suspend themselves if no work is received.

When threads are suspended, HP-UX may schedule threads of another process on their processors in order to balance machine load. However, threads have an affinity for their original processors. HP-UX tries to schedule unsuspended threads to their original processors in order to exploit the presence of any data encached during the thread's last timeslice. This occurs only if the original processor is available. Otherwise, the thread is assigned to the first processor to become available.

Determining idle thread states

Use the `MP_IDLE_THREADS_WAIT` environment variable to determine how threads wait. The form of the `MP_IDLE_THREADS_WAIT` environment variable is shown in Table 6-1.

Table 6-1 Form of `MP_IDLE_THREADS_WAIT` environment variable

Language	Form
Fortran, C	`setenv MP_IDLE_THREADS_WAIT=`*n*

where

n is the integer value, represented in milliseconds, that the threads spin-wait. These have values as described below:

- For *n* less than 0, the threads spin-wait.

- For *n* equal to or greater than 0, the threads spin-wait for *n* milliseconds before being suspended.

By default, idle threads spin-wait briefly after creation or a join. They then suspend themselves if no work is received.

Parallel optimizations

Simple loops can be parallelized without the need for extensive transformations. However, most loop transformations do enhance optimum parallelization. For instance, loop interchange orders loops so that the innermost loop best exploits the processor data cache, and the outermost loop is the most efficient loop to parallelize.

Loop blocking similarly aids parallelization by maximizing cache data reuse on each of the processors that the loop runs on. It also ensures that each processor is working on nonoverlapping array data.

Dynamic selection

The compiler has no way of determining how many processors are available to run compiled code. Therefore, it sometimes generates both serial and parallel code for loops that are parallelized. Replicating the loop in this manner is called cloning, and the resulting versions of the loop are called clones. Cloning is also performed when the loop-iteration count is unknown at compile-time.

It is not always profitable, however, to run the parallel clone when multiple processors are available. Some overhead is involved in executing parallel code. This overhead includes the time it takes to spawn parallel threads, to privatize any variables used in the loop that must be privatized, and to join the parallel threads when they complete their work.

Workload-based dynamic selection

HP compilers use a powerful form of dynamic selection known as workload-based dynamic selection. When a loop's iteration count is available at compile time, workload-based dynamic selection determines the profitability of parallelizing the loop. It only writes a parallel version to the executable if it is profitable to do so.

If the parallel version will not be needed, the compiler can omit it from the executable to further enhance performance. This eliminates the runtime decision as to which version to use.

The power of dynamic selection becomes more apparent when the loop's iteration count is unknown at compile time. In this case, the compiler generates code that, at runtime, compares the amount of work performed

in the loop nest (given the actual iteration counts) to the parallelization overhead for the available number of processors. It then runs the parallel version of the loop only if it is profitable to do so.

When specified with `+Oparallel` at `+O3`, workload-based dynamic selection is enabled by default. The compiler only generates a parallel version of the loop when `+Onodynsel` is selected, thereby disabling dynamic selection. When dynamic selection is disabled, the compiler assumes that it is profitable to parallelize all parallelizable loops and generates both serial and parallel clones for them. In this case the parallel version is run if there are multiple processors at runtime, regardless of the profitability of doing so.

`dynsel, no_dynsel`

The `dynsel` and `no_dynsel` directives are used to specify dynamic selection for specific loops in programs compiled using the `+Onodynsel` option or to provide trip count information for specific loops in programs compiled with dynamic selection enabled.

To disable dynamic selection for selected loops by using the `no_dynsel` compiler directive or pragma. This directive or pragma is used to disable dynamic selection on specific loops in programs compiled with dynamic selection enabled.

The form of these directives and pragmas are shown in Table 6-2.

Table 6-2 Form of `dynsel` directive and pragma

Language	Form

Fortran	`C$DIR DYNSEL [(THREAD_TRIP_COUNT = n)]`
	
	`C$DIR NO_DYNSEL`

C	`#pragma _CNX dynsel [(thread_trip_count = n )]`
	
	`#pragma _CNX no_dynsel`

where

`thread_trip_count`

is an optional attribute used to specify threshold iteration counts.

When `thread_trip_count = n` is specified, the serial version of the loop is run if the iteration count is less than *n*. Otherwise, the thread-parallel version is run.

If a trip count is not specified for a `dynsel` directive or pragma, the compiler uses a heuristic to estimate the actual execution costs. This estimate is then used to determine if it is profitable to execute the loop in parallel.

As with all optimizations that replicate loops, the number of new loops created when the compiler performs dynamic selection is limited by default to ensure reasonable code sizes. To increase the replication limit (and possibly increase your compile time and code size), specify the `+Onosize` `+Onolimit` compiler options. These are described in “Controlling optimization” on page 119.

Inhibiting parallelization

Certain constructs, such as loop-carried dependences, inhibit parallelization. Other types of constructs, such as procedure calls and I/O statements, inhibit parallelism for the same reason they inhibit localization. An exception to this is that more categories of loop-carried dependences can inhibit parallelization than data localization. This is described in the following sections.

Loop-carried dependences (LCDs)

The specific loop-carried dependences (LCDs) that inhibit data localization represent a very small portion of all loop-carried dependences. A much broader set of LCDs inhibits parallelization. Examples of various parallel-inhibiting LCDs follows.

Example 6-3 Parallel-inhibiting LCDs

One type of LCD exists when one iteration references a variable whose value is assigned on a later iteration. The Fortran loop below contains this type of LCD on the array `A`.

```
DO I = 1, N - 1
  A(I) = A(I + 1) + B(I)
ENDDO
```

In this example, the first iteration assigns a value to `A(1)` and references `A(2)`. The second iteration assigns a value to `A(2)` and references `A(3)`. The reference to `A(I)` depends on the fact that the `I`+1th iteration, which assigns a new value to `A(I)`, has not yet executed.

Forward LCDs inhibit parallelization because if the loop is broken up to run on several processors, when `I` reaches its terminal value on one processor, `A(I+1)` has usually already been computed by another processor. It is, in fact, the first value computed by another processor. Because the calculation depends on `A(I+1)` not being computed yet, this would produce wrong answers.

Example 6-4 Parallel-inhibiting LCDs

Another type of LCD exists when one iteration references a variable whose value was assigned on an earlier iteration.The Fortran loop below contains a backward LCD on the array

A.

```
DO I = 2, N
  A(I) = A(I-1) + B(I)
ENDDO
```

Here, each iteration assigns a value to A based on the value assigned to A in the previous iteration. If A(I-1) has not been computed before A(I) is assigned, wrong answers result.

Backward LCDs inhibit parallelism because if the loop is broken up to run on several processors, A(I-1) are not computed for the first iteration of the loop on every processor except the processor running the chunk of the loop containing I = 1.

Example 6-5 Output LCDs

An output LCD exists when the same memory location is assigned values on two or more iterations. A potential output LCD exists when the compiler cannot determine whether an array subscript contains the same values between loop iterations.

The Fortran loop below contains a potential output LCD on the array A:

```
DO I = 1, N
  A(J(I)) = B(I)
ENDDO
```

Here, if any referenced elements of J contain the same value, the same element of A is assigned several different elements of B. In this case, as this loop is written, any A elements that are assigned more than once should contain the final assignment at the end of the loop. This cannot be guaranteed if the loop is run in parallel.

Example 6-6 Apparent LCDs

The compiler chooses to not parallelize loops containing apparent LCDs rather than risk wrong answers by doing so.

If you are sure that a loop with an apparent LCD is safe to parallelize, you can indicate this to the compiler using the no_loop_dependence directive or pragma, which is explained in the section “Loop-carried dependences (LCDs)” on page 63.

The following Fortran example illustrates a NO_LOOP_DEPENDENCE directive being used on the output LCD example presented previously:

```
C$DIR NO_LOOP_DEPENDENCE(A)
      DO I = 1, N
        A(J(I)) = B(I)
      ENDDO
```

This effectively tells the compiler that no two elements of J are identical, so there is no output LCD and the loop is safe to parallelize. If any of the J values are identical, wrong answers could result.

Reductions

In many cases, the compiler can recognize and parallelize loops containing a special class of dependence known as a reduction. In general, a reduction has the form:

`X = X` *`operator`* `Y`

where

`X` is a variable not assigned or used elsewhere in the loop, `Y` is a loop constant expression not involving `X`, and *operator* is `+`, `*`, `.AND.`, `.OR.`, or `.XOR.`

The compiler also recognizes reductions of the form:

`X =` *`function`*`(X,Y)`

where

`X` is a variable not assigned or referenced elsewhere in the loop, `Y` is a loop constant expression not involving `X`, and *function* is the intrinsic `MAX` function or intrinsic `MIN` function.

Generally, the compiler automatically recognizes reductions in a loop and is able to parallelize the loop. If the loop is under the influence of the `prefer_parallel` directive or pragma, the compiler still recognizes reductions.

However, in a loop being manipulated by the `loop_parallel` directive or pragma, reduction analysis is not performed. Consequently, the loop may not be correctly parallelized unless the reduction is enforced using the `reduction` directive or pragma.

The form of this directive and pragma is shown in Table 6-3.

Table 6-3 Form of `reduction` directive and pragma

Language	Form
Fortran	`C$DIR REDUCTION`
C	`#pragma _CNX reduction`

Example 6-7 Reduction

Reductions commonly appear in the form of sum operations, as shown in the following Fortran example:

```
DO I = 1, N
  A(I) = B(I) + C(I)
  .
  .
  .
  ASUM = ASUM + A(I)
ENDDO
```

Assuming this loop does not contain any parallelization-inhibiting code, the compiler would automatically parallelize it. The code generated to accomplish this creates temporary, thread-specific copies of `ASUM` for each thread that runs the loop. When each parallel thread completes its portion of the loop, thread 0 for the current spawn context accumulates the thread-specific values into the global `ASUM`.

The following Fortran example shows the use of the `reduction` directive on the above code. `loop_parallel` is described on page 188. `loop_private` is described on page 233.

```
C$DIR LOOP_PARALLEL, LOOP_PRIVATE(FUNCTEMP), REDUCTION(SUM)
      DO I = 1, N
        .
        .
        .
        FUNCTEMP = FUNC(X(I))
        SUM = SUM + FUNCTEMP
        .
        .
        .
      ENDDO
```

Preventing parallelization

You can prevent parallelization on a loop-by-loop basis using the `no_parallel` directive or pragma. The form of this directive and pragma is shown in Table 6-4.

Table 6-4 Form of `no_parallel` directive and pragma

Language	Form
Fortran	`C$DIR NO_PARALLEL`
C	`#pragma _CNX no_parallel`

Use these directives to prevent parallelization of the loop that immediately follows them. Only parallelization is inhibited; all other loop optimizations are still applied.

Example 6-8 no_parallel

The following Fortran example illustrates the use of `no_parallel`:

```
      DO I = 1, 1000
C$DIR   NO_PARALLEL
        DO J = 1, 1000
          A(I,J) = B(I,J)
        ENDDO
      ENDDO
```

In this example, parallelization of the `J` loop is prevented. The `I` loop can still be parallelized.

The `+Onoautopar` compiler option is available to disable automatic parallelization but allows parallelization of directive-specified loops. Refer to “Controlling optimization” on page 119, and “Parallel programming techniques” on page 181, for more information on `+Onoautopar`.

Parallelism in the aC++ compiler

Parallelism in the aC++ compiler is available through the use of the following command-line options or libraries:

- `+O3 +Oparallel` or `+O4 +Oparallel` optimization options—Automatic parallelization is available from the compiler; see the section “Levels of parallelism” on page 99 for more information.
- HP MPI—HP’s implementation of the message-passing interface; see the *HP MPI User’s Guide* for more information.
- Pthreads (POSIX threads)— See the pthread(3t) man page or the manual *Programming with Threads on HP-UX* for more information.

None of the pragmas described in this book are currently available in the HP aC++ compiler. However, aC++ does support the memory classes briefly explained in “Controlling optimization” on page 119, and more specifically in “Memory classes” on page 245. These classes are implemented through the storage class specifiers `node_private` and `thread_private`.

Cloning across multiple source files

Cloning is the replacement of a call to a routine by a call to a clone of that routine. The clone is optimized differently than the original routine. Cloning can expose additional opportunities for interprocedural optimization.

Cloning at `+O4` is performed across all procedures within the program. Cloning at `+O3` is done within one file. Cloning is enabled by default. It is disabled by specifying the `+Onoinline` command-line option.

7 Controlling optimization

The HP-UX compiler set includes a group of optimization controls that are used to improve code performance. These controls can be invoked from either the command line or from within a program using certain directives and pragmas.

This chapter includes a discussion of the following topics:

- Command-line optimization options
- Invoking command-line options
- C aliasing options
- Optimization directives and pragmas

Refer to Chapter 3, “Optimization levels,” on page 25 for information on coding guidelines that assist the optimizer. See the f90(1), cc(1), and aCC(1) man pages for information on compiler options in general.

NOTE The HP aC++ compiler does not support the pragmas described in this chapter.

Command-line optimization options

This section lists the command-line optimization options available for use with the HP C, C++, and Fortran compilers. Table 7-1 describes the options and the optimization levels at which they are used.

Table 7-1 Command-line optimization options

Optimization options	Valid optimization levels
Command-line options	
`+O[no]aggressive`	`+O2, +O3, +O4`
`+O[no]all`	all
`+O[no]autopar` (must be used with the `+Oparallel` option at `+O3` or above)	`+O3, +O4`
`+O[no]conservative`	`+O2, +O3, +O4`
`+O[no]dataprefetch`	`+O2, +O3, +O4`
`+O[no]dynsel` (must be used with the `+Oparallel` option at `+O3` or above)	`+O3, +O4`
`+O[no]entrysched`	`+O1, +O2,+O3, +O4`
`+O[no]fail_safe`	`+O1, +O2,+O3, +O4`
`+O[no]fastaccess`	all
`+O[no]fltacc`	`+O2, +O3, +O4`
`+O[no]global_ptrs_unique[=namelist]` (C only)	`+O2, +O3, +O4`
`+O[no]info`	all

Table 7-1 Command-line optimization options (Continued)

Optimization options	Valid optimization levels
+O[no]initcheck	+O2, +O3, +O4
+O[no]inline[=namelist]	+O3, +O4
+Oinline_budget=n	+O3, +O4
+O[no]libcalls	all
+O[no]limit	+O2, +O3, +O4
+O[no]loop_block	+O3, +O4
+O[no]loop_transform	+O3, +O4
+O[no]loop_unroll[=unroll_factor]	+O2, +O3, +O4
+O[no]loop_unroll_jam	+O3, +O4
+O[no]moveflops	+O2, +O3, +O4
+O[no]multiprocessor	+O2, +O3, +O4
+O[no]parallel	+O3, +O4
+O[no]parmsoverlap	+O2, +O3, +O4
+O[no]pipeline	+O2, +O3, +O4
+O[no]procelim	all
+O[no]ptrs_ansi	+O2, +O3, +O4
+O[no]ptrs_strongly_typed	+O2, +O3, +O4
+O[no]ptrs_to_globals[=namelist] (C only)	+O2, +O3, +O4
+O[no]regreassoc	+O2, +O3, +O4
+O[no]report[=report_type]	+O3, +O4
+O[no]sharedgra	+O2, +O3, +O4

Table 7-1 Command-line optimization options (Continued)

Optimization options	Valid optimization levels
+O[no]signedpointers (C/C++ only)	+O2, +O3, +O4
+O[no]size	+O2, +O3, +O4
+O[no]static_prediction	all
+O[no]vectorize	+O3, +O4
+O[no]volatile	+O1, +O2, +O3, +O4
+O[no]whole_program_mode	+O4

Invoking command-line options

At each optimization level, you can turn specific optimizations on or off using the +O[no]*optimization* option. The *optimization* parameter is the name of a specific optimization. The optional prefix [no] disables the specified optimization.

The following sections describe the optimizations that are turned on or off, their defaults, and the optimization levels at which they may be used. In syntax descriptions, *namelist* represents a comma-separated list of names.

+O[no]aggressive

Optimization level: +O2, +O3, +O4

Default: +Onoaggressive

+O[no]aggressive enables or disables optimizations that can result in significant performance improvement, and can change a program's behavior. This includes the optimizations invoked by the following advanced options (these are discussed separately in this chapter):

- +Osignedpointers (C and C++)
- +Oentrysched
- +Onofltacc
- +Olibcalls
- +Onoinitcheck
- +Ovectorize

+O[no]all

Optimization level: all

Default: +Onoall

Equivalent option: +Oall option is equivalent to specifying +O4 +Oaggressive +Onolimit

+Oall performs maximum optimization, including aggressive optimizations and optimizations that can significantly increase compile time and memory usage.

+O[no]autopar

Optimization level: +O3, +O4 (+Oparallel must also be specified)

Default: +Oautopar

When used with +Oparallel option, +Oautopar causes the compiler to automatically parallelize loops that are safe to parallelize. A loop is considered safe to parallelize if its iteration count can be determined at runtime before loop invocation. It must also contain no loop-carried dependences, procedure calls, or I/O operations.

A loop-carried dependence exists when one iteration of a loop assigns a value to an address that is referenced or assigned on another iteration.

When used with +Oparallel, the +Onoautopar option causes the compiler to parallelize only those loops marked by the loop_parallel or prefer_parallel directives or pragmas. Because the compiler does not automatically find parallel tasks or regions, user-specified task and region parallelization is not affected by this option.

C pragmas and Fortran directives are used to improve the effect of automatic optimizations and to assist the compiler in locating additional opportunities for parallelization. See “Optimization directives and pragmas” on page 150 for more information.

+O[no]conservative

Optimization level: +O2, +O3, +O4

Default: +Onoconservative

Equivalent option: +Oconservative is equivalent to +Onoaggressive

+O[no]conservative causes the optimizer to make or not make conservative assumptions about the code when optimizing. +Oconservative is useful in assuming a particular program’s coding style, such as whether it is standard-compliant. Specifying +Onoconservative disables any optimizations that assume standard-compliant code.

+O[no]dataprefetch

Optimization level: +O2, +O3, +O4

Default: +Onodataprefetch

When +Odataprefetch is used, the optimizer inserts instructions within innermost loops to explicitly prefetch data from memory into the data cache. For cache lines containing data to be written, +Odataprefetch prefetches the cache lines so that they are valid for both read and write access. Data prefetch instructions are inserted only for data referenced within innermost loops using simple loop-varying addresses in a simple arithmetic progression. It is only available for PA-RISC 2.0 targets.

The math library libm contains special prefetching versions of vector routines. If you have a PA-RISC 2.0 application containing operations on arrays larger than one megabyte in size, using +Ovectorize in conjunction with +Odataprefetch may substantially improve performance.

You can also use the +Odataprefetch option for applications that have high data cache miss overhead.

+O[no]dynsel

Optimization level: +O3, +O4 (+Oparallel must also be specified)

Default: +Odynsel

When specified with +Oparallel, +Odynsel enables workload-based dynamic selection. For parallelizable loops whose iteration counts are known at compile time, +Odynsel causes the compiler to generate either a parallel or a serial version of the loop—depending on which is more profitable.

This optimization also causes the compiler to generate both parallel and serial versions of parallelizable loops whose iteration counts are unknown at compile time. At runtime, the loop's workload is compared to parallelization overhead, and the parallel version is run only if it is profitable to do so.

The +Onodynsel option disables dynamic selection and tells the compiler that it is profitable to parallelize all parallelizable loops. The dynsel directive and pragma are used to enable dynamic selection for specific loops, when +Onodynsel is in effect. See the section “Dynamic selection” on page 108 for additional information.

+O[no]entrysched

Optimization level: +O1, +O2, +O3, +O4

Default: +Onoentrysched

+Oentrysched optimizes instruction scheduling on a procedure’s entry and exit sequences by unwinding in the entry and exit regions. Subsequently, this option is used to increase the speed of an application.

+O[no]entrysched can also change the behavior of programs performing exception-handling or that handle asynchronous interrupts. The behavior of setjmp() and longjmp() is not affected.

+O[no]fail_safe

Optimization level: +O1, +O2, +O3, +O4

Default: +Ofail_safe

+Ofail_safe allows your compilations to continue when internal optimization errors are detected. When an error is encountered, this option issues a warning message and restarts the compilation at +O0. The +Ofail_safe option is disabled when you specify +Oparallel with +O3 or +O4 to compile with parallelization.

Using +Onofail_safe aborts your compilation when internal optimization errors are detected.

+O[no]fastaccess

Optimization level: +O0, +O1, +O2, +O3, +O4

Default: +Onofastaccess at +O0, +O1, +O2 and +O3; +Ofastaccess at +O4

+Ofastaccess performs optimization for fast access to global data items. Use +Ofastaccess to improve execution speed at the expense of longer compile times.

+O[no]fltacc

Optimization level: +O2, +O3, +O4

Default: none (See Table 7-2.)

+O[no]fltacc enables or disables optimizations that cause imprecise floating-point results.

+Ofltacc disables optimizations that cause imprecise floating-point results. Specifying +Ofltacc disables the generation of Fused Multiply-Add (FMA) instructions, as well as other floating-point optimizations. Use +Ofltacc if it is important that the compiler evaluates floating-point expressions according to the order specified by the language standard.

+Onofltacc improves execution speed at the expense of floating-point precision. The +Onofltacc option allows the compiler to perform floating-point optimizations that are algebraically correct, but may result in numerical differences. These differences are generally insignificant. The +Onofltacc option also enables the optimizer to generate FMA instructions.

If you optimize code at +O2 or higher, and do not specify +Onofltacc or +Ofltacc, the optimizer uses FMA instructions. However, it does not perform floating-point optimizations that involve expression reordering. FMA is implemented by the PA-8*x*00 instructions FMPYFADD and FMPYNFADD and improves performance. Occasionally, these instructions may produce results that may differ in accuracy from results produced by code without FMA. In general, the differences are slight.

Table 7-2 presents a summary of the preceding information.

Table 7-2 +O[no]fltacc and floating-point optimizations

Option specified[a]	FMA optimizations	Other floating-point optimizations
+Ofltacc	Disabled	Disabled
+Onofltacc	Enabled	Enabled
neither option is specified	Enabled	Disabled

a. +O[no]fltacc is only available at +O2 and above.

+O[no]global_ptrs_unique[=namelist]

Optimization level: +O2, +O3, +O4

Default: +Onoglobal_ptrs_unique

NOTE This option is not available in Fortran or C++.

Using this C compiler option identifies unique global pointers so that the optimizer can generate more efficient code in the presence of unique pointers, such as using copy propagation and common subexpression elimination. A global pointer is unique if it does not alias with any variable in the entire program.

This option supports a comma-separated list of unique global pointer variable names, represented by *namelist* in +O[no]global_ptrs_unique[=*namelist*]. If *namelist* is not specified, using +O[no]global_ptrs_unique informs the compiler that all [no] global pointers are unique.

The example below states that no global pointers are unique, except a and b:

```
+Oglobal_ptrs_unique=a,b
```

The next example says that all global pointers are unique except a and b:

```
+Onoglobal_ptrs_unique=a,b
```

+O[no]info

Optimization level: +O0, +O1, +O2, +O3, +O4

Default: +Onoinfo

+Oinfo displays informational messages about the optimization process. This option is used at all optimization levels, but is most useful at +O3 and +O4. For more information about this option, see Chapter 14 page 289.

+O[no]initcheck

Optimization level: +O2, +O3, +O4

Default: unspecified

`+O[no]initcheck` performs an initialization check for the optimizer. The optimizer has three possible states that check for initialization: on, off, or unspecified.

- When on (`+Oinitcheck`), the optimizer initializes to zero any local, scalar, and nonstatic variables that are uninitialized with respect to at least one path leading to a use of the variable.
- When off (`+Onoinitcheck`), the optimizer issues warning messages when it discovers definitely uninitialized variables, but does not initialize them.
- When unspecified, the optimizer initializes to zero any local, scalar, nonstatic variables that are definitely uninitialized with respect to all paths leading to a use of the variable.

`+O[no]inline[=`*namelist*`]`

Optimization level: `+O3`, `+O4`

Default: `+Oinline`

When `+Oinline` is specified without a name list, any function can be inlined. For successful inlining, follow the prototype definitions for function calls in the appropriate header files.

When specified with a name list, the named functions are important candidates for inlining. For example, the following statement indicates that inlining be strongly considered for `foo` and `bar`:

```
+Oinline=foo,bar +Onoinline
```

All other routines are not considered for inlining because `+Onoinline` is given.

NOTE The Fortran and aC++ compilers accept only `+O[no]inline`. No *namelist* values are accepted.

Use the +Onoinline[=namelist] option to exercise precise control over which subprograms are inlined. Use of this option is guided by knowledge of the frequency with which certain routines are called and may be warranted by code size concerns.

When this option is disabled with a name list, the compiler does not consider the specified routines as candidates for inlining. For example, the following statement indicates that inlining should not be considered for `baz` and `x`:

```
+Onoinline=baz,x
```

All other routines are considered for inlining because `+Oinline` is the default.

+Oinline_budget=*n*

Optimization level: `+O3`, `+O4`

Default: `+Oinline_budget=100`

In `+Oinline_budget=`*n*, *n* is an integer in the range 1 to 1000000 that specifies the level of aggressiveness, as follows:

n = 100	Default level of inlining
n > 100	More aggressive inlining
	The optimizer is less restricted by compilation time and code size when searching for eligible routines to inline
n = 1	Only inline if it reduces code size

The `+Onolimit` and `+Osize` options also affect inlining. Specifying the `+Onolimit` option implies specifying `+Oinline_budget=200`. The `+Osize` option implies `+Oinline_budget=1`. However, `+Oinline_budget` takes precedence over both of these options. This means that you can override the effects on inlining of the `+Onolimit` and `+Osize` options, by specifying the `+Oinline_budget` option on the same command line.

+O[no]libcalls

Optimization level: `+O0`, `+O1`, `+O2`, `+O3`, `+O4`

Default: `+Onolibcalls` at `+O0` and `+O1`;
`+Olibcalls` at `+O2`, `+O3`, and `+O4`

`+Olibcalls` increases the runtime performance of code that calls standard library routines in simple contexts. The `+Olibcalls` option expands the following library calls inline:

- `strcpy()`

- `sqrt()`
- `fabs()`
- `alloca()`

Inlining takes place only if the function call follows the prototype definition in the appropriate header file. A single call to `printf()` may be replaced by a series of calls to `putchar()`. Calls to `sprintf()` and `strlen()` may be optimized more effectively, including elimination of some calls producing unused results. Calls to `setjmp()` and `longjmp()` may be replaced by their equivalents `_setjmp()` and `_longjmp()`, which do not manipulate the process's signal mask.

Using the `+Olibcalls` option invokes millicode versions of frequently called math functions. Currently, there are millicode versions for the following functions:

acos	asin	atan	atan2
cos	exp	log	log10
pow	sin	tan	

See the *HP-UX Floating-Point Guide* for the most up-to-date listing of the math library functions.

`+Olibcalls` also improves the performance of selected library routines (when you are not performing error checking for these routines). The calling code must not expect to access `ERRNO` after the function's return.

Using `+Olibcalls` with `+Ofltacc` gives different floating-point calculation results than those given using `+Olibcalls` without `+Ofltacc`.

+O[no]limit

Optimization level: `+O2`, `+O3`, `+O4`

Default: `+Olimit`

The `+Olimit` option suppresses optimizations that significantly increase compile-time or that can consume a considerable amount of memory.

The +Onolimit option allows optimizations to be performed, regardless of their effects on compile-time and memory usage. Specifying the +Onolimit option implies specifying +Oinline_budget=200. See the section ““+Oinline_budget=n” on page 131+Oinline_budget=*n*” page 131 for more information.

+O[no]loop_block

Optimization level: +O3, +O4

Default: +Onoloop_block

+O[no]loop_block enables or disables blocking of eligible loops for improved cache performance. The +Onoloop_block option disables both automatic and directive-specified loop blocking. For more information on loop blocking, see the section “Loop blocking” on page 73.

+O[no]loop_transform

Optimization level: +O3, +O4

Default: +Oloop_transform

+O[no]loop_transform enables or disables transformation of eligible loops for improved cache performance. The most important transformation is the interchange of nested loops to make the inner loop unit stride, resulting in fewer cache misses.

The other transformations affected by +O[no]loop_transform are loop distribution, loop blocking, loop fusion, loop unroll, and loop unroll and jam. See “Optimization levels” on page 25 for information on loop transformations.

If you experience any problem while using +Oparallel, +Onoloop_transform may be a helpful option.

+O[no]loop_unroll[=*unroll factor*]

Optimization level: +O2, +O3, +O4

Default: +Oloop_unroll=4

+Oloop_unroll enables loop unrolling. When you use +Oloop_unroll, you can also suggest the unroll factor to control the code expansion. The default unroll factor is four, meaning that the loop body is replicated four

times. By experimenting with different factors, you may improve the performance of your program. In some cases, the compiler uses its own unroll factor.

The `+Onoloop_unroll` option disables partial and complete unrolling. Loop unrolling improves efficiency by eliminating loop overhead, and can create opportunities for other optimizations, such as improved register use and more efficient scheduling. See the section “Loop unrolling” on page 46 for more information on unrolling.

+O[no]loop_unroll_jam

Optimization level: `+O3`, `+O4`

Default: `+Onoloop_unroll_jam`

The `+O[no]loop_unroll_jam` option enables or disables loop unrolling and jamming. The `+Onoloop_unroll_jam` option (the default) disables both automatic and directive-specified unroll and jam. Loop unrolling and jamming increases register exploitation. For more information on the unroll and jam optimization, see the section “Loop unroll and jam” on page 88.

+O[no]moveflops

Optimization level: `+O2`, `+O3`, `+O4`

Default: `+Omoveflops`

`+O[no]moveflops` allows or disallows moving conditional floating-point instructions out of loops. The behavior of floating-point exception handling may be altered by this option.

Use +Onomoveflops if floating-point traps are enabled and you do not want the behavior of floating-point exceptions to be altered by the relocation of floating-point instructions.

+O[no]multiprocessor

Optimization level: `+O2, +O3`, `+O4`

Default: `+Onomultiprocesssor`

Specifying the +Omultiprocessor option at +O2 and above tells the compiler to appropriately optimize several different processes on multiprocessor machines. The optimizations are those appropriate for executables and shared libraries.

Enabling this option incorrectly (such as on a uniprocessor machine) may cause performance problems.

Specifying +Onomultiprocessor (the default) disables the optimization of more than one process running on multiprocessor machines.

+O[no]parallel

Optimization level: +O3, +O4

Default: +Onoparallel

The +Onoparallel option is the default for all optimization levels. This option disables automatic and directive-specified parallelization.

If you compile one or more files in an application using +Oparallel, then the application must be linked (using the compiler driver) with the +Oparallel option to link in the proper start-up files and runtime support.

The +Oparallel option causes the compiler to:

- Recognize the directives and pragmas that involve parallelism, such as begin_tasks, loop_parallel, and prefer_parallel
- Look for opportunities for parallel execution in loops

The following methods are used to specify the number of processors used in executing your parallel programs:

- loop_parallel(max_threads=*m*) directive and pragma
- prefer_parallel(max_threads=*m*) directive and pragma

  For a description of these directives and pragmas, see “Parallel programming techniques” on page 181 and “Parallel synchronization” on page 255. These pragmas are not available in the HP aC++ compiler.

- MP_NUMBER_OF_THREADS environment variable, which is read at runtime by your program. If this variable is set to some positive integer *n*, your program executes on *n* processors. *n* must be less than or equal to the number of processors in the system where the program is executing.

The +Oparallel option is valid only at optimization level +O3 and above. For information on parallelization, see the section "Levels of parallelism" on page 99.

Using the +Oparallel option disables +Ofail_safe, which is enabled by default. See the section "+O[no]fail_safe" on page 127 for more information.

+O[no]parmsoverlap

Optimization level: +O2, +O3, +O4

Default (Fortran): +Onoparmsoverlap

Default (C/C++): +Oparmsoverlap

+Oparmsoverlap causes the optimizer to assume that the actual arguments of function calls overlap in memory.

+O[no]pipeline

Optimization level: +O2, +O3, +O4

Default: +Opipeline

+O[no]pipeline enables or disables software pipelining. If program size is more important than execution speed, use +Onopipeline.

Software pipelining is particularly useful for loops containing arithmetic operations on REAL or REAL*8 variables in Fortran or on float or double variables in C and C++.

+O[no]procelim

Optimization level: +O0, +O1, +O2, +O3, +O4

Default: +Onoprocelim at +O0, +01, +O2, +O3;
+Oprocelim at +O4

When +Oprocelim is specified, procedures not referenced by the application are eliminated from the output executable file. The +Oprocelim option reduces the size of the executable file, especially when optimizing at +O3 and +O4, at which inlining may have removed all of the calls to some routines.

When +Onoprocelim is specified, procedures not referenced by the application are not eliminated from the output executable file.

If the +Oall option is enabled, the +Oprocelim option is enabled.

+O[no]ptrs_ansi

Optimization level: +O2, +O3, +O4

Default: +Onoptrs_ansi

The +Optrs_ansi option makes the following two assumptions, which the more aggressive +Optrs_strongly_typed does not:

- int *p is assumed to point to an int field of a struct or union.
- char * is assumed to point to any type of object.

NOTE This option is not available in C++.

When both +Optrs_ansi and +Optrs_strongly_typed are specified, +Optrs_ansi takes precedence.

+O[no]ptrs_strongly_typed

Optimization level: +O2, +O3, +O4

Default: +Onoptrs_strongly_typed

Use the C compiler option +Optrs_strongly_typed when pointers are type-safe. The optimizer can use this information to generate more efficient code.

NOTE This option is not available in C++.

Type-safe (strongly-typed) pointers point to a specific type that, in turn, only point to objects of that type. For example, a pointer declared as a pointer to an `int` is considered type-safe if that pointer points to an object of type `int` only.

Based on the type-safe concept, a set of groups are built based on object types. A given group includes all the objects of the same type.

In type-inferred aliasing, any pointer of a type in a given group (of objects of the same type) can only point to any object from the same group. It cannot point to a typed object from any other group.

Type casting to a different type violates type-inferring aliasing rules. Dynamic casting is, however, allowed, as shown in Example 41.

Example 7-1 Data type interaction

The optimizer generally spills all global data from registers to memory before any modification to global variables or any loads through pointers. However, the optimizer can generate more efficient code if it knows how various data types interact.

Consider the following example (line numbers are provided for reference):

```
1  int *p;
2  float *q;
3  int a,b,c;
4  float d,e,f;
5  foo()
6  {
7    for (i=1;i<10;i++) {
8              d=e;
9             *p=...;
10             e=d+f;
11             f=*q;
12   }
13 }
```

With `+Onoptrs_strongly_typed` turned on, the pointers `p` and `q` are assumed to be disjoint because the types they point to are different types. Without type-inferred aliasing, `*p` is assumed to invalidate all the definitions. So, the use of `d` and `f` on line 10 have to be loaded from memory. With type-inferred aliasing, the optimizer can propagate the copy of `d` and `f`, thus avoiding two loads and two stores.

This option is used for any application involving the use of pointers, where those pointers are type safe. To specify when a subset of types are type-safe, use the `ptrs_strongly_typed` pragma. The compiler issues warnings for any incompatible pointer assignments that may violate the type-inferred aliasing rules discussed in the section “C aliasing options” on page 147.

Example 7-2 Unsafe type cast

Any type cast to a different type violates type-inferred aliasing rules. Do not use `+Optrs_strongly_typed` with code that has these “unsafe” type casts. Use the `no_ptrs_strongly_typed` pragma to prevent the application of type-inferred aliasing to the unsafe type casts.

```
struct foo{
        int a;
        int b;
      } *P;     struct bar {
        float a;
        int b;
        float c;
      } *q;     P = (struct foo *) q;
        /* Incompatible pointer assignment
      through type cast */
```

Generally applying type aliasing

Dynamic casting is allowed with `+Optrs_strongly_typed` or `+Optrs_ansi`. A pointer dereference is called a dynamic cast if a cast is applied on the pointer to a different type.

In the example below, type-inferred aliasing is generally applied on `P`, not just to the particular dereference. Type-aliasing is applied to any other dereferences of `P`.

```
     struct s {
        short int a;
        short int b;
        int c;
      } *P
      * (int *)P = 0;
```

For more information about type aliasing, see the section “C aliasing options” on page 147.

+O[no]ptrs_to_globals[=*namelist*]

Optimization level: `+O2`, `+O3`, `+O4`

Default: `+Optrs_to_globals`

By default, global variables are conservatively assumed to be modified anywhere in the program. Use the C compiler option `+Onoptrs_to_globals` to specify which global variables are not modified through pointers. This allows the optimizer to make the program run more efficiently by incorporating copy propagation and common subexpression elimination.

NOTE This option is not available in C++.

This option is used to specify all global variables that are not modified using pointers, or to specify a comma-separated list of global variables that are not modified using pointers.

The on state for this option disables some optimizations, such as aggressive optimizations on the program's global symbols.

For example, use the command-line option `+Onoptrs_to_globals=a,b,c` to specify global variables `a`, `b`, and `c` to not be accessible through pointers. The result (shown below) is that no pointer can access these global variables. The optimizer performs copy propagation and constant folding because storing to `*p` does not modify `a` or `b`.

```
int a, b, c;
      float *p;
      foo()
      {
         a = 10;
         b = 20;
        *p = 1.0;
         c = a + b;
      }
```

If all global variables are unique, use the `+Onoptrs_to_globals` option without listing the global variables (that is, without using *`namelist`*).

In the example below, the address of `b` is taken. This means `b` is accessed indirectly through the pointer. You can still use `+Onoptrs_to_globals` as:

```
+Onoptrs_to_globals +Optrs_to_globals=b.
int b,c;
int *p
p=&b;
foo()
```

For more information about type aliasing, see the section “C aliasing options” on page 147.

+O[no]regreassoc

Optimization level: `+O2`, `+O3`, `+O4`

Default: `+Oregreassoc`

`+O[no]regreassoc` enables or disables register reassociation. This is a technique for folding and eliminating integer arithmetic operations within loops, especially those used for array address computations.

This optimization provides a code-improving transformation supplementing loop-invariant code motion and strength reduction. Additionally, when performed in conjunction with software pipelining, register reassociation can also yield significant performance improvement.

+O[no]report[=*report_type*]

Optimization level: `+O3`, `+O4`

Default: `+Onoreport`

`+Oreport[=`*report_type*`]` specifies the contents of the Optimization Report. Values of *report_type* and the Optimization Reports they produce are shown in Table 7-3.

Table 7-3 Optimization Report contents

***report_type* value**	**Report contents**
`all`	Loop Report and Privatization Table
`loop`	Loop Report
`private`	Loop Report and Privatization Table
report_type not given (default)	Loop Report

The Loop Report gives information on optimizations performed on loops and calls. Using +Oreport (without =*report_type*) also produces the Loop Report.

The Privatization Table provides information on loop variables that are privatized by the compiler.

+Oreport[=*report_type*] is active only at +O3 and above.
The +Onoreport option does not accept any of the *report_type* values. For more information about the Optimization Report, see "Optimization Report" on page 155.

+Oinfo also displays information on the various optimizations being performed by the compilers. +Oinfo is used at any optimization level, but is most useful at +O3 and above. The default at all optimization levels is +Onoinfo.

+O[no]sharedgra

Optimization level: +O2, +O3, +O4

Default: +Osharedgra

The +Onosharedgra option disables global register allocation for shared-memory variables that are visible to multiple threads. This option may help if a variable shared among parallel threads is causing wrong answers. See the section "Global register allocation (GRA)" on page 44 for more information.

Global register allocation (+Osharedgra) is enabled by default at optimization level +O2 and higher.

+O[no]signedpointers

Optimization level: +O2, +O3, +O4

Default: +Onosignedpointers

NOTE This option is not available in the HP Fortran compiler.

The C and C++ option +O[no]signedpointers requests that the compiler perform or not perform optimizations related to treating pointers as signed quantities. This helps improve application runtime

speed. Applications that allocate shared memory and that compare a pointer to shared memory with a pointer to private memory may run incorrectly if this optimization is enabled.

+O[no]size

Optimization level: +O2, +O3, +O4

Default: +Onosize

The +Osize option suppresses optimizations that significantly increase code size. Specifying +Osize implies specifying +Oinline_budget=1. See the section "+Oinline_budget=n" on page 131"+Oinline_budget=*n*" page 131 for additional information.

The +Onosize option does not prevent optimizations that can increase code size.

+O[no]static_prediction

Optimization level: +O0, +O1, +O2, +O3, +O4

Default: +Onostatic_prediction

+Ostatic_prediction turns on static branch prediction for PA-RISC 2.0 targets. Use +Ostatic_prediction to better optimize large programs with poor instruction locality, such as operating system and database code.

PA-RISC 2.0 predicts the direction conditional branches go in one of two ways:

- Dynamic branch prediction uses a hardware history mechanism to predict future executions of a branch from its last three executions. It is transparent and quite effective, unless the hardware buffers involved are overwhelmed by a large program with poor locality.
- Static branch prediction, when enabled, predicts each branch based on implicit hints encoded in the branch instruction itself. The static branch prediction is responsible for handling large codes with poor locality for which the small dynamic hardware facility proves inadequate.

+O[no]vectorize

Optimization level: +O3, +O4

Default: `+Onovectorize`

`+Ovectorize` allows the compiler to replace certain loops with calls to vector routines. Use `+Ovectorize` to increase the execution speed of loops.

NOTE This option is not available in the HP aC++ compiler.

When `+Onovectorize` is specified, loops are not replaced with calls to vector routines.

Because the `+Ovectorize` option may change the order of floating-point operations in an application, it may also change the results of those operations slightly. See the *HP-UX Floating-Point Guide* for more information.

The math library contains special prefetching versions of vector routines. If you have a PA2.0 application containing operations on large arrays (larger than 1 Megabyte in size), using `+Ovectorize` in conjunction with `+Odataprefetch` may improve performance.

`+Ovectorize` is also included as part of the `+Oaggressive` and `+Oall` options.

+O[no]volatile

Optimization level: `+O1`, `+O2`, `+O3`, `+O4`

Default: `+Onovolatile`

NOTE This option is not available in the HP Fortran compiler.

The C and C++ option `+Ovolatile` implies that memory references to global variables cannot be removed during optimization.

The `+Onovolatile` option indicates that all globals are not of volatile class. This means that references to global variables are removed during optimization.

Use this option to control the volatile semantics for all global variables.

+O[no]whole_program_mode

Optimization level: +O4

Default: +Onowhole_program_mode

Use +Owhole_program_mode to increase performance speed. This should be used only when you are certain that only the files compiled with +Owhole_program_mode directly access any globals that are defined in these files.

NOTE This option is not available in the HP Fortran or aC++ compilers.

+Owhole_program_mode enables the assertion that only the files that are compiled with this option directly reference any global variables and procedures that are defined in these files. In other words, this option asserts that there are no unseen accesses to the globals.

When this assertion is in effect, the optimizer can hold global variables in registers longer and delete inlined or cloned global procedures.

All files compiled with +Owhole_program_mode must also be compiled with +O4. If any of the files were compiled with +O4, but were not compiled with +Owhole_program_mode, the linker disables the assertion for all files in the program.

The default, +Onowhole_program_mode, disables the assertion noted above.

+tm *target*

Optimization level: +O0, +O1, +O2, +O3, +O4

Default *target* value: corresponds to the machine on which you invoke the compiler.

This option specifies the target machine architecture for which compilation is to be performed. Using this option causes the compiler to perform architecture-specific optimizations.

target takes one of the following values:

- K8000 to specify K-Class servers using PA-8000 processors

- `V2000` to specify V2000 servers
- `V2200` to specify V2200 servers
- `V2250` to specify V2250 servers

This option is valid at all optimization levels. The default *target* value corresponds to the machine on which you invoke the compiler.

Using the `+tm` *`target`* option implies `+DA` and `+DS` settings as described in Table 7-4. `+DA`*`architecture`* causes the compiler to generate code for the architecture specified by *`architecture`*. `+DS`*`model`* causes the compiler to use the instruction scheduler tuned to *`model`*. See the f90(1) man page, aCC(1) page, or the cc(1) man page for more information describing the `+DA` and `+DS` options.

Table 7-4 `+tm` *`target`* and `+DA`/`+DS`

target **value specified**	**`+DA`*`architecture`* implied**	**`+DS`*`model`* implied**
K8000	2.0	2.0
V2000	2.0	2.0
V2200	2.0	2.0
V2250	2.0	2.0

If you specify `+DA` or `+DS` on the compiler command line, your setting takes precedence over the setting implied by `+tm` *`target`*.

C aliasing options

The optimizer makes a conservative assumption that a pointer can point to any object in the entire application. Command-line options to the C compiler are available to inform the optimizer of an application's pointer usage. Using this information, the optimizer can generate more efficient code, due to the elimination of some false assumptions.

You can direct pointer behavior to the optimizer by using the following options:

- `+O[no]ptrs_strongly_typed`
- `+O[no]ptrs_to_globals[=`*`namelist`*`]`
- `+O[no]global_ptrs_unique[=`*`namelist`*`]`
- `+O[no]ptrs_ansi`

where

`namelist` is a comma-separated list of global variable names.

The following are type-inferred aliasing rules that apply when using these `+O` optimization options:

- Type-aliasing optimizations are based on the assumption that pointer dereferences obey their declared types.
- A C variable is considered address-exposed if and only if the address of that variable is assigned to another variable or passed to a function as an actual parameter. In general, address-exposed objects are collected into a separate group, based on their declared types. Global and static variables are considered address-exposed by default. Local variables and actual parameters are considered address-exposed only if their addresses have been computed using the address operator `&`.
- Dereferences of pointers to a certain type are assumed to only alias with the corresponding equivalent group. An equivalent group includes all the address-exposed objects of the same type. The dereferences of pointers are also assumed to alias with other pointer dereferences associated with the same group.

  For example, in the following line:

```
int *p, *q;
```

`*p` and `*q` are assumed to alias with any objects of type `int`. Also, `*p` and `*q` are assumed to alias with each other.

- Signed/unsigned type distinctions are ignored in grouping objects into an equivalent group. Likewise, `long` and `int` types are considered to map to the same equivalent group. However, the `volatile` type qualifier is considered significant in grouping objects into equivalent groups. For example, a pointer to `int` is not considered to alias with a `volatile int` object.
- If two type names reduce to the same type, they are considered synonymous.

  In the following example, both types `type_old` and `type_new` reduce to the same type, `struct foo`.

  ```
  typedef struct foo_st type_old;
  typedef type_old type_new;
  ```

- Each field of a structure type is placed in a separate equivalent group that is distinct from the equivalent group of the field's base type. The assumption here is that a pointer to `int` is not assigned the address of a structure field whose type is `int`. The actual type name of a structure type is not considered significant in constructing equivalent groups. For example, dereferences of a `struct foo` pointer and a `struct bar` pointer is assumed to alias with each other even if `struct foo` and `struct bar` have identical field declarations.
- All fields of a `union` type are placed in the same equivalent group, which is distinct from the equivalent group of any of the field's base types. This means that all dereferences of pointers to a particular `union` type are assumed to alias with each other, regardless of which union field is being accessed.
- Address-exposed array variables are grouped into the equivalent group of the array element type.
- Applying an explicit pointer typecast to an expression value causes any later use of the typecast expression value to be associated with the equivalent group of the typecast expression value.

  For example, an `int` pointer typecast into a `float` pointer and then dereferenced is assumed to potentially access objects in the `float` equivalent group—and not the `int` equivalent group.

However, type-incompatible assignments to pointer variables do not alter the aliasing assumptions on subsequent references of such pointer variables.

In general, type-incompatible assignments can potentially invalidate some of the type-safe assumptions. Such constructs may elicit compiler warning messages.

Optimization directives and pragmas

This section lists the directives, and pragmas available for use in optimization. Table 7-5 below describes the options and the optimization levels at which they are used. The pragmas are not supported by the aC++ compiler.

The `loop_parallel`, `parallel`, `prefer_parallel`, and `end_parallel` options are described in “Parallel programming techniques” on page 181.

Table 7-5 Directive-based optimization options

Directives and Pragmas	Valid Optimization levels
`block_loop [(block_factor=`*n*`)]`	+O3, +O4
`dynsel[(trip_count=n)]`	+O3, +O4
`no_block_loop`	+O3, +O4
`no_distribute`	+O3, +O4
`no_dynsel`	+O3, +O4
`no_loop_dependence(namelist)`	+O3, +O4
`no_loop_transform`	+O3, +O4
`no_parallel`	+O3, +O4
`no_side_effects`	+O3, +O4
`no_unroll_and_jam`	+O3, +O4
`reduction(namelist)`	+O3, +O4
`scalar`	+O3, +O4
`sync_routine(routinelist)`	+O3, +O4
`unroll_and_jam[(unroll_factor=n)]`	+O3, +O4

Rules for usage

The form of the optimization directives and pragmas is shown in Table 7-6.

NOTE The HP aC++ compiler does not support the optimization pragmas described in this section.

Table 7-6 Form of optimization directives and pragmas

Language	Form
Fortran	`C$DIR` *directive-list*
C	`#pragma _CNX` *directive-list*

where

directive-list

is a comma-separated list of one or more of the directives/pragmas described in this chapter.

- Directive names are presented here in lowercase, and they may be specified in either case in both languages. However, `#pragma` must always appear in lowercase in C.
- In the sections that follow, *namelist* represents a comma-separated list of names. These names can be variables, arrays, or `COMMON` blocks. In the case of a `COMMON` block, its name must be enclosed within slashes. The occurrence of a lowercase *n* or *m* is used to indicate an integer constant.
- Occurrences of *gate_var* are for variables that have been or are being defined as gates. Any parameters that appear within square brackets (`[ ]`) are optional.

block_loop[(block_factor=n)]

`block_loop[(block_factor=`*n*`)]` indicates a specific loop to block and, optionally, the block factor *n*. This block factor is used in the compiler's internal computation of loop nest-based data reuse; this is the number of times that the data reuse has resulted as a result of loop nesting. This

figure must be an integer constant greater than or equal to 2. If no `block_factor` is specified, the compiler uses a heuristic to determine the `block_factor`. For more information on loop blocking, refer to “Optimization levels” on page 25.

dynsel[(*trip_count=n*)]

`dynsel[(`*trip_count*`=`*n*`)]` enables workload-based dynamic selection for the immediately following loop. *trip_count* represents the `thread_trip_count` attribute, and *n* is an integer constant.

- When `thread_trip_count =` *n* is specified, the serial version of the loop is run if the iteration count is less than *n*. Otherwise, the thread-parallel version is run.
- For more information on dynamic selection, refer to the description of the optimization option ”`+O[no]dynsel`” on page 126.

no_block_loop

`no_block_loop` disables loop blocking on the immediately following loop. For more information on loop blocking, see the description of `block_loop[(block_factor=`*n*`)]` in this section, or refer to the description of the optimization option ”`+O[no]loop_block`” on page 133.

no_distribute

`no_distribute` disables loop distribution for the immediately following loop. For more information on loop distribution, refer to the description of the optimization option ”`+O[no]loop_transform`” on page 133.

no_dynsel

`no_dynsel` disables workload-based dynamic selection for the immediately following loop. For more information on dynamic selection, refer to the description of the optimization option ”`+O[no]dynsel`” on page 126.

no_loop_dependence(*namelist*)

`no_loop_dependence(`*`namelist`*`)` informs the compiler that the arrays in *`namelist`* do not have any dependences for iterations of the immediately following loop. Use `no_loop_dependence` for arrays only. Use `loop_private` to indicate dependence-free scalar variables.

This directive or pragma causes the compiler to ignore any dependences that it perceives to exist. This can enhance the compiler's ability to optimize the loop, including parallelization.

For more information on loop dependence, refer to "Loop-carried dependences" on page 310.

no_loop_transform

`no_loop_transform` prevents the compiler from performing reordering transformations on the following loop. The compiler does not distribute, fuse, block, interchange, unroll, or unroll and jam a loop on which this directive appears. For more information on `no_loop_transform`, refer to the optimization option "`+O[no]loop_transform`" on page 133.

no_parallel

`no_parallel` prevents the compiler from generating parallel code for the immediately following loop. For more information on `no_parallel`, refer to the optimization option "`+O[no]parallel`" on page 135.

no_side_effects(*funclist*)

`no_side_effects(`*`funclist`*`)` informs the compiler that the functions appearing in *`funclist`* have no side effects wherever they appear lexically following the directive. Side effects include modifying a function argument, modifying a Fortran `COMMON` variable, performing I/O, or calling another routine that does any of the above. The compiler can sometimes eliminate calls to procedures that have no side effects. The compiler may also be able to parallelize loops with calls when informed that the called routines do not have side effects.

unroll_and_jam[(unroll_factor=*n*)]

`unroll_and_jam[(unroll_factor=`*n*`)]` causes one or more noninnermost loops in the immediately following nest to be partially unrolled (to a depth of *n* if `unroll_factor` is specified), then fuses the resulting loops back together. It must be placed on a loop that ends up being noninnermost after any compiler-initiated interchanges. For more information on `unroll_and_jam`, refer to the description of "`+O[no]loop_unroll_jam` on page 134.

8 Optimization Report

The Optimization Report is produced by the HP Fortran, HP aC++, and HP C compilers. It is most useful at optimization levels +O3 and +O4. This chapter includes a discussion of the following topics:

- Optimization Report contents
- Loop Report

Optimization Report contents

When you compile a program with the `+Oreport[=report_type]` optimization option at the `+O3` and `+O4` levels, the compiler generates an Optimization Report for each program unit. The `+Oreport[=report_type]` option determines the report's contents based on the value of *report_type*, as shown in Table 8-1.

Table 8-1 Optimization Report contents

***report_type* values**	**Report contents**
`all`	Loop Report and Privatization Table
`loop`	Loop Report
`private`	Loop Report and Privatization Table
report_type not given (default)	Loop Report

The `+Onoreport` option does not accept any of the *report_type* values. Sample Optimization Reports are provided throughout this chapter.

Loop Report

The Loop Report lists the optimizations that are performed on loops and calls. If appropriate, the report gives reasons why a possible optimization was not performed. Loop nests are reported in the order in which they are encountered and separated by a blank line.

Below is a sample optimization report.

```
           Optimization ReportLine      Id    Var       Reordering        New
Optimizing / Special
Num.       Num.  Name       Transformation    Id Nums          Transformation
-------------------------------------------------------------------------------
    3         1  sub1      *Inlined call      (2-4)
    8         2  iloopi:1   Serial                        Fused
   11         3  jloopi:2   Serial                        Fused
   14         4  kloopi:3   Serial                        Fused
                            *Fused             (5)        (2 3 4) -> (5)
    8         5  iloopi:1   PARALLEL                     Footnoted   User
Var Name     Var Name
-------------------------------------------------------------------------------
iloopi:1     iloopindex
jloopi:2     jloopindex
kloopi:3     kloopindex
           Optimization for sub1Line      Id    Var       Reordering        New
Optimizing / Special
Num.       Num.  Name       Transformation    Id Nums    Transformation
-------------------------------------------------------------------------------
    8         1  iloopi:1   Serial                        Fused
   11         2  jloopi:2   Serial                        Fused
   14         3  kloopi:3   Serial                        Fused
                            *Fused             (4)        (1 2 3) -> (4)
    8         4  iloopi:1   PARALLEL                     Footnoted   User
Var Name     Var Name
-------------------------------------------------------------------------------
iloopi:1     iloopindex
jloopi:2     jloopindex
kloopi:3     kloopindex
```

A description of each column of the Loop Report is shown in Table 8-2.

Table 8-2 Loop Report column definitions

Column	Description
`Line Num.`	Specifies the source line of the beginning of the loop or of the loop from which it was derived. For cloned calls and inlined calls, the `Line Num.` column specifies the source line at which the call statement appears.
`Id Num.`	Specifies a unique ID number for every optimized loop and for every optimized call. This ID number can then be referenced by other parts of the report. Both loops appearing in the original program source and loops created by the compiler are given loop ID numbers. Loops created by the compiler are also shown in the `New Id Nums` column as described later. No distinction between compiler-generated loops and loops that existed in the original source is made in the `Id Num.` column. Loops are assigned unique, sequential numbers as they are encountered.
`Var Name`	Specifies the name of the iteration variable controlling the loop or the called procedure if the line represents a call. If the variable is compiler-generated, its name is listed as `*VAR*`. If it consists of a truncated variable name followed by a colon and a number, the number is a reference to the variable name footnote table, which appears after the Loop Report and Analysis Table in the Optimization Report.
`Reordering Transformation`	Indicates which reordering transformations were performed. Reordering transformations are performed on loops, calls, and loop nests, and typically involve reordering and/or duplicating sections of code to facilitate more efficient execution. This column has one of the values shown in *** 'The following values apply to the Reordering Transformation column described in Table 8-2 on page 159.' on page 160 *** .

Table 8-2 Loop Report column definitions (Continued)

Column	Description
`New Id Nums`	Specifies the ID number for loops or calls created by the compiler. These ID numbers are listed in the `Id Num.` column and is referenced in other parts of the report. However, the loops and calls they represent were not present in the original source code. In the case of loop fusion, the number in this column indicates the new loop created by merging all the fused loops. New ID numbers are also created for cloned calls, inlined calls, loop blocking, loop distribution, loop interchange, loop unroll and jam, dynamic selection, and test promotion.
`Optimizing / Special Transformation`	Indicates which, if any, optimizing transformations were performed. An optimizing transformation reduces the number of operations executed, or replaces operations with simpler operations. A special transformation allows the compiler to optimize code under special circumstances. When appropriate, this column has one of the values shown in Table 8-4 on page 162 .

The following values apply to the Reordering Transformation column described in Table 8-2 on page 159.

Table 8-3 Reordering transformation values in the Loop Report

Value	Description
`Block`	Loop blocking was performed. The new loop order is indicated under the `Optimizing/Special Transformation` column, as shown in Table 8-4.
`Cloned call`	A call to a subroutine was cloned.
`Dist`	Loop distribution was performed.
`DynSel`	Dynamic selection was performed. The numbers in the `New Id Nums` column correspond to the loops created. For parallel loops, these generally include a `PARALLEL` and a `Serial` version.

Table 8-3 Reordering transformation values in the Loop Report

Value	Description
`Fused`	The loops were fused into another loop and no longer exist. The original loops and the new loop is indicated under the `Optimizing/Special Transformation` column, as shown in Table 8-4.
`Inlined call`	A call to a subroutine was inlined.
`Interchange`	Loop interchange was performed. The new loop order is indicated under the `Optimizing/Special Transformation` column, as shown in Table 8-4.
`None`	No reordering transformation was performed on the call.
`PARALLEL`	The loop runs in thread-parallel mode.
`Peel`	The first or last iteration of the loop was peeled in order to fuse the loop with an adjacent loop.
`Promote`	Test promotion was performed.
`Serial`	No reordering transformation was performed on the loop.
`Unroll and Jam`	The loop was unrolled and the nested loops were jammed (fused).
`VECTOR`	The loop was fully or partially replaced with more efficient calls to one or more vector routines.
`*`	Appears at left of loop-producing transformation optimizations (distribution, dynamic selection, blocking, fusion, interchange, call cloning, call inlining, peeling, promotion, unroll and jam).

The following values apply to the `Optimizing/special transformations` column described in Table 8-2 on page 159.

Table 8-4 Optimizing/special transformations values in the Loop Report

Value	Explanation
`Fused`	The loop was fused into another loop and no longer exists.
`Reduction`	The compiler recognized a reduction in the loop.
`Removed`	The compiler removed the loop.
`Unrolled`	The loop was completely unrolled.
(*OrigOrder*) -> (*InterchangedOrder*)	This information appears when `Interchange` is reported under `Reordering Transformation`. *OrigOrder* indicates the order of loops in the original nest. *InterchangedOrder* indicates the new order that occurs due to interchange. *OrigOrder* and *InterchangedOrder* consist of user iteration variables presented in outermost to innermost order.
(*OrigLoops*)->(*NewLoop*)	This information appears when `Fused` is reported under `Reordering Transformation`. *OrigLoops* indicates the original loops that were fused by the compiler to form the loop indicated by *NewLoop*. *OrigLoops* and *NewLoop* refer to loops based on the values from the `Id Num.` and `New Id Nums` columns in the Loop Report.

Table 8-4 Optimizing/special transformations values in the Loop Report

Value	Explanation
(*OrigLoopNest*)->(*BlockedLoopNest*)	This information appears when `Block` is reported under `Reordering Transformation`. *OrigLoopNest* indicates the order of the original loop nest containing a loop that was blocked. *BlockedLoopNest* indicates the order of loops after blocking. *OrigLoopNest* and *BlockedLoopNest* refer to user iteration variables presented in outermost to innermost order.

Supplemental tables

The tables described in this section may be included in the Optimization Report to provide information supplemental to the Loop Report.

Analysis Table

If necessary, an Analysis Table is included in the Optimization Report to further elaborate on optimizations reported in the Loop Report.

A description of each column in the Analysis Table is shown in Table 8-5.

Table 8-5 Analysis Table column definitions

Column	Description
`Line Num.`	Specifies the source line of the beginning of the loop or call.
`Id Num.`	References the ID number assigned to the loop or call in the Loop Report.
`Var Name`	Specifies the name of the iteration variable controlling the loop, `*VAR*` (as discussed in the `Var Name` description in the section “Loop Report” on page 158).

Table 8-5 Analysis Table column definitions (Continued)

Column	Description
`Analysis`	Indicates why a transformation or optimization was not performed, or additional information on what was done.

Privatization Table

This table reports any user variables contained in a parallelized loop that are privatized by the compiler. Because the Privatization Table refers to loops, the Loop Report is automatically provided with it.

A description of each column in the Privatization Table is shown in Table 8-6.

Table 8-6 Privatization Table column definitions

Column	Definitions
`Line Num.`	Specifies the source line of the beginning of the loop.
`Id Num.`	References the ID number assigned to the loop in the loop table.
`Var Name`	Specifies the name of the iteration variable controlling the loop. `*VAR*` may also appear in this column, as discussed in the `Var Name` description in the section “Loop Report” on page 158.
`Priv Var`	Specifies the name of the privatized user variable. Compiler-generated variables that are privatized are not reported here.
`Privatization Information for Parallel Loops`	Provides more detail on the variable privatizations performed.

Variable Name Footnote Table

Variable names that are too long to fit in the `Var Name` columns of the other tables are truncated and followed by a colon and a footnote number. These footnotes are explained in the Variable Name Footnote Table.

A description of each column in the Variable Name Footnote Table is shown in Table 8-7.

Table 8-7 Variable Name Footnote Table column definitions

Column	Definition
`Footnoted Var Name`	Specifies the truncated variable name and its footnote number.
`User Var Name`	Specifies the full name of the variable as identified in the source code.

Example 8-1 Optimization Report

The following Fortran program is the basis for the Optimization Report shown in this example. Line numbers are provided for ease of reference.

```
1     PROGRAM EXAMPLE99
2     REAL A(100), B(100), C(100)
3     CALL SUB1(A,B,C)
4     END
5
6     SUBROUTINE SUB1(A,B,C)
7     REAL A(100), B(100), C(100)
8     DO ILOOPINDEX=1,100
9       A(ILOOPINDEX) = ILOOPINDEX
10    ENDDO
11    DO JLOOPINDEX=1,100
12      B(JLOOPINDEX) = A(JLOOPINDEX)**2
13    ENDDO
14    DO KLOOPINDEX=1, 100
15      C(KLOOPINDEX) = A(KLOOPINDEX) + B(KLOOPINDEX)
16    ENDDO
17    PRINT *, A(1), B(50), C(100)
18    END
```

The following Optimization Report is generated by compiling the program `EXAMPLE99` with the command-line options `+O3 +Oparallel +Oreport=all +Oinline=sub1`:

```
% f90 +O3 +Oparallel +Oreport=all +Oinline=sub1 EXAMPLE99.f
Optimization for EXAMPLE99Line      Id    Var       Reordering        New
Optimizing / Special
Num.       Num.  Name      Transformation    Id Nums   Transformation
-------------------------------------------------------------------------
    3        1  sub1     *Inlined call      (2-4)
    8        2  iloopi:1  Serial                       Fused
   11        3  jloopi:2  Serial                       Fused
   14        4  kloopi:3  Serial                       Fused
                         *Fused             (5)       (2 3 4) -> (5)
    8        5  iloopi:1  PARALLEL
Footnoted   User
Var Name    Var Name
-------------------------------------------------------------------------
iloopi:1    iloopindex
jloopi:2    jloopindex
kloopi:3    kloopindex
          Optimization for sub1Line     Id    Var      Reordering       New
Optimizing / Special
Num.       Num.  Name      Transformation    Id Nums   Transformation
-------------------------------------------------------------------------
    8        1  iloopi:1  Serial                       Fused
   11        2  jloopi:2  Serial                       Fused
   14        3  kloopi:3  Serial                       Fused
                         *Fused             (4)       (1 2 3) -> (4)
    8        4  iloopi:1  PARALLEL

Footnoted   User
Var Name    Var Name
-------------------------------------------------------------------------
iloopi:1    iloopindex
jloopi:2    jloopindex
kloopi:3    kloopindex
```

The Optimization Report for `EXAMPLE99` provides the following information:

- Call to sub1 is inlined
  The first line of the Loop Report shows that the call to `sub1` was inlined, as shown below:

```
3 1 sub1 *Inlined call (2-4)
```

- Three new loops produced
  The inlining produced three new loops in EXAMPLE99: Loop #2, Loop #3, and Loop #4. Internally, the EXAMPLE99 module that originally looked like:

```
1      PROGRAM EXAMPLE99
2      REAL A(100), B(100), C(100)
3      CALL SUB1(A,B,C)
4      END
```

now looks like this:

```
PROGRAM EXAMPLE99
REAL A(100), B(100), C(100)
DO ILOOPINDEX=1,100                    !Loop #2
  A(ILOOPINDEX) = ILOOPINDEX
ENDDO
DO JLOOPINDEX=1,100                    !Loop #3
  B(JLOOPINDEX) = A(JLOOPINDEX)**2
ENDDO
DO KLOOPINDEX=1, 100                   !Loop #4
  C(KLOOPINDEX) = A(KLOOPINDEX) + B(KLOOPINDEX)
ENDDO
PRINT *, A(1), B(50), C(100)
END
```

- New loops are fused
  These lines indicate that the new loops have been fused. The following line indicates that the three loops were fused into one new loop, Loop #5.

```
 8        2  iloopi:1  Serial                      Fused
11        3  jloopi:2  Serial                      Fused
14        4  kloopi:3  Serial                      Fused
                     *Fused             (5)       (2 3 4) (5)
```

After fusing, the code internally appears as the following:

```
PROGRAM EXAMPLE99
REAL A(100), B(100), C(100)
DO ILOOPINDEX=1,100                    !Loop #5
  A(ILOOPINDEX) = ILOOPINDEX
  B(ILOOPINDEX) = A(ILOOPINDEX)**2
  C(ILOOPINDEX) = A(ILOOPINDEX) + B(ILOOPINDEX)
ENDDO
PRINT *, A(1), B(50), C(100)
END
```

- New loop is parallelized
  In the following Loop Report line:

```
8 5 iloopi:1 PARALLEL
```

`Loop #5` uses `iloopi:1` as the iteration variable, referencing the Variable Name Footnote Table; `iloopi:1` corresponds to `iloopindex`. The same line in the report also indicates that the newly-created `Loop #5` was parallelized.

- Variable Name Footnote Table lists iteration variables
  According to the Variable Name Footnote Table (duplicated below), the original variable `iloopindex` is abbreviated by the compiler as `iloopi:1` so that it fits into the `Var Name` columns of other reports.

  `jloopindex` and `kloopindex` are abbreviated as `jloopi:2` and `kloopi:3`, respectively. These names are used throughout the report to refer to these iteration variables.

```
Footnoted   User
Var Name    Var Name
-----------------------
iloopi:1    iloopindex
jloopi:2    jloopindex
kloopi:3    kloopindex
```

Example 8-2 Optimization Report

The following Fortran code provides an example of other transformations the compiler performs. Line numbers are provided for ease of reference.

```
1      PROGRAM EXAMPLE100
2
3      INTEGER IA1(100), IA2(100), IA3(100)
4      INTEGER I1, I2
5
6      DO I = 1, 100
7        IA1(I) = I
8        IA2(I) = I * 2
9        IA3(I) = I * 3
10     ENDDO
11
12     I1 = 0
13     I2 = 100
14     CALL SUB1 (IA1, IA2, IA3, I1, I2)
15     END
```

```
16
17      SUBROUTINE SUB1(A, B, C, S, N)
18      INTEGER A(N), B(N), C(N), S, I, J
19        DO J = 1, N
20          DO I = 1, N
21            IF (I .EQ. 1) THEN
22              S = S + A(I)
23            ELSE IF (I .EQ. N) THEN
24              S = S + B(I)
25            ELSE
26              S = S + C(I)
27            ENDIF
28          ENDDO
29        ENDDO
30      END
```

The following Optimization Report is generated by compiling the program `EXAMPLE100` for parallelization:

```
% f90 +O3 +Oparallel +Oreport=all example100.f
```

```
           Optimization for SUB1

Line      Id    Var         Reordering          New        Optimizing / Special
Num.      Num.  Name        Transformation      Id Nums    Transformation
-------------------------------------------------------------------------------
   19        1  j          *Interchange        (2)        (j i) -> (i j)
   20        2  i          *DynSel             (3-4)
   20        3  i           PARALLEL                      Reduction
   19        5  j          *Promote            (6-7)
   19        6  j           Serial
   19        7  j           Serial

   20        4  i           Serial
   19        8  j          *Promote            (9-10)
   19        9  j           Serial
   19       10  j          *Promote            (11-12)
   19       11  j           Serial
   19       12  j           Serial

Line      Id    Var         Analysis
Num.      Num.  Name
-------------------------------------------------------------------------------
   19        5  j          Test on line 21 promoted out of loop
   19        8  j          Test on line 21 promoted out of loop
   19       10  j          Test on line 23 promoted out of loop
```

```
            Optimization for clone 1 of SUB1 (6_e70_cl_sub1)

Line      Id    Var         Reordering         New        Optimizing / Special
Num.      Num.  Name        Transformation     Id Nums    Transformation
-------------------------------------------------------------------------------
   19       1   j          *Interchange        (2)        (j i) -> (i j)
   20       2   i           PARALLEL                      Reduction
   19       3   j          *Promote            (4-5)
   19       4   j           Serial
   19       5   j          *Promote            (6-7)
   19       6   j           Serial
   19       7   j           Serial

Line      Id    Var        Analysis
Num.      Num.  Name
-------------------------------------------------------------------------------
   19       3   j          Test on line 21 promoted out of loop
   19       5   j          Test on line 23 promoted out of loop

            Optimization for example100

Line      Id    Var         Reordering         New        Optimizing / Special
Num.      Num.  Name        Transformation     Id Nums    Transformation
-------------------------------------------------------------------------------
    6       1   i           Serial

   14       2   sub1       *Cloned call        (3)
   14       3   sub1        None

Line      Id    Var        Analysis
Num.      Num.  Name
-------------------------------------------------------------------------------
   14       2   sub1       Call target changed to clone 1 of SUB1 (6_e70_cl_sub1)
```

The Optimization Report for EXAMPLE100 shows Optimization Reports for the subroutine and its clone, followed by the optimizations to the subroutine. It includes the following information:

- Original subroutine contents
  Originally, the subroutine appeared as shown below:

```
17    SUBROUTINE SUB1(A, B, C, S, N)
18    INTEGER A(N), B(N), C(N), S, I, J
19      DO J = 1, N
20        DO I = 1, N
21          IF (I .EQ. 1) THEN
22            S = S + A(I)
```

```
23          ELSE IF (I .EQ. N) THEN
24            S = S + B(I)
25          ELSE
26            S = S + C(I)
27          ENDIF
28        ENDDO
29      ENDDO
30    END
```

- Loop interchange performed first
  The compiler first performs loop interchange (listed as `Interchange` in the report) to maximize cache performance:

```
19        1  j        *Interchange       (2)       (j i) -> (i j)
```

- The subroutine then becomes the following

```
17    SUBROUTINE SUB1(A, B, C, S, N)
18    INTEGER A(N), B(N), C(N), S, I, J
19      DO I = 1, N                          ! Loop #2
20        DO J = 1, N                        ! Loop #1
21          IF (I .EQ. 1) THEN
22            S = S + A(I)
23          ELSE IF (I .EQ. N) THEN
24            S = S + B(I)
25          ELSE
26            S = S + C(I)
27          ENDIF
28        ENDDO
29      ENDDO
30    END
```

- The program is optimized for parallelization
  The compiler would like to parallelize the outermost loop in the nest, which is now the `I` loop. However because the value of `N` is not known, the compiler does not know how many times the `I` loop needs to be executed. To ensure that the loop is executed as efficiently as possible at runtime, the compiler replaces the `I` loop nest with two new copies of the `I` loop nest, one to be run in parallel, the other to be run serially.

- Dynamic selection is executed
  An `IF` is then inserted to select the more efficient version of the loop to execute at runtime. This method of making one copy for parallel execution and one copy for serial execution is known as dynamic selection, which is enabled by default when

+O3 +Oparallel is specified (see "Dynamic selection" on page 108 for more information). This optimization is reported in the Loop Report in the line:

```
20        2  i        *DynSel            (3-4)
```

- Loop#2 creates two loops
  According to the report, Loop #2 was used to create the new loops, Loop #3 and Loop #4. Internally, the code now is represented as follows:

```
SUBROUTINE SUB1(A, B, C, S, N)
INTEGER A(N), B(N), C(N), S, I, J

             IF (N .GT. some_threshold) THEN

  DO (parallel) I = 1, N              ! Loop #3
    DO J = 1, N                       ! Loop #5
      IF (I .EQ. 1) THEN
        S = S + A(I)
      ELSE IF (I .EQ. N) THEN
        S = S + B(I)
      ELSE
        S = S + C(I)
      ENDIF
    ENDDO
  ENDDO
ELSE
  DO I = 1, N                         ! Loop #4
    DO J = 1, N                       ! Loop #8
      IF (I .EQ. 1) THEN
        S = S + A(I)
      ELSE IF (I .EQ. N) THEN
        S = S + B(I)
      ELSE
        S = S + C(I)
      ENDIF
    ENDDO
  ENDDO
ENDIF
END
```

- Loop#3 contains reductions
  Loop #3 (which was parallelized) also contained one or more reductions. The Reordering Transformation column indicates that the IF statements were promoted out of Loop #5, Loop #8, and Loop #10.

- Analysis Table lists new loops
  The line numbers of the promoted `IF` statements are listed. The first test in `Loop #5` was promoted, creating two new loops, `Loop #6` and `Loop #7`. Similarly, `Loop #8` has a test promoted, creating `Loop #9` and `Loop #10`. The test remaining in `Loop #10` is then promoted, thereby creating two additional loops. A promoted test is an `IF` statement that is hoisted out of a loop. See the section "Test promotion" on page 94 for more information. The Analysis Table contents are shown below:

```
19      5   j      Test on line 21 promoted out of loop
19      8   j      Test on line 21 promoted out of loop
19      10   j      Test on line 23 promoted out of loop
```

- DO loop is not reordered
  The following `DO` loop does not undergo any reordering transformation:

```
6      DO I = 1, 100
7        IA1(I) = I
8        IA2(I) = I * 2
9        IA3(I) = I * 3
10     ENDDO
```

This fact is reported by the line

```
6         1  i          Serial
```

- `sub1` is cloned
  The call to the subroutine `sub1` is cloned. As indicated by the asterisk (`*`), the compiler produced a new call. The new call is given the ID (3) listed in the `New Id Nums` column. The new call is then listed, with `None` indicating that no reordering transformation was performed on the call to the new subroutine.

```
14         2  sub1      *Cloned call       (3)
14         3  sub1       None
```

- `Cloned call` is transformed
  The call to the subroutine is then appended to the Loop Report to elaborate on the `Cloned call` transformation. This line shows that the clone was called in place of the original subroutine.

```
14    2  sub1  Call target changed to clone 1 of SUB1 (6_e70_cl_sub1)
```

Example 8-3 Optimization Report

The following Fortran code shows loop blocking, loop peeling, loop distribution, and loop unroll and jam. Line numbers are listed for ease of reference.

```
1     PROGRAM EXAMPLE200
2
3     REAL*8 A(1000,1000), B(1000,1000), C(1000)
4     REAL*8 D(1000), E(1000)
5     INTEGER M, N
6
7     N = 1000
8     M = 1000
9
10    DO I = 1, N
11      C(I) = 0
12      DO J = 1, M
13        A(I,J) = A(I,J) + B(I,J) * C(I)
14      ENDDO
15    ENDDO
16
17    DO I = 1, N-1
18      D(I) = I
19    ENDDO
20
21    DO J = 1, N
22      E(J) = D(J) + 1
23    ENDDO
24
25    PRINT *, A(103,103), B(517, 517), D(11), E(29)
26
27    END
```

The following Optimization Report is generated by compiling program EXAMPLE200 as follows:

```
% f90 +O3 +Oreport +Oloop_block example200.f
```

```
            Optimization for example3

Line      Id    Var         Reordering         New       Optimizing / Special
Num.      Num.  Name        Transformation     Id Nums   Transformation
-------------------------------------------------------------------------------
   10       1   i:1        *Dist              (2-3)
   10       2   i:1         Serial

   10       3   i:1        *Interchange       (4)       (i:1 j:1) -> (j:1 i:1)
```

```
   12        4  j:1        *Block              (5)        (j:1 i:1) -> (i:1 j:1 i:1)
   10        5  i:1        *Promote            (6-7)
   10        6  i:1         Serial                        Removed
   10        7  i:1         Serial
   12        8  j:1        *Unroll And Jam     (9)
   12        9  j:1        *Promote            (10-11)
   12       10  j:1         Serial                        Removed
   12       11  j:1         Serial
   10       12  i:1         Serial

   17       13  i:2         Serial                        Fused
   21       14  j:2        *Peel               (15)
   21       15  j:2         Serial                        Fused
                           *Fused              (16)       (13 15) -> (16)
   17       16  i:2         Serial

Line      Id    Var        Analysis
Num.      Num.  Name
-------------------------------------------------------------------------------
   10        5  i:1        Loop blocked by 56 iterations
   10        5  i:1        Test on line 12 promoted out of loop
   10        6  i:1        Loop blocked by 56 iterations
   10        7  i:1        Loop blocked by 56 iterations
   12        8  j:1        Loop unrolled by 8 iterations and jammed into the
innermost loop
   12        9  j:1        Test on line 10 promoted out of loop
   21       14  j:2        Peeled last iteration of loop
```

The Optimization Report for `EXAMPLE200` provides the following results:

```
    10        1  i:1        *Dist               (2-3)
```

- Several occurrences of variables noted
  In this report, the `Var Name` column has entries such as `i:1`, `j:1`, `i:2`, and `j:2`. This type of entry appears when a variable is used more than once. In `EXAMPLE200`, `I` is used as an iteration variable twice. Consequently, `i:1` refers to the first occurrence, and `i:2` refers to the second occurrence.

- `Loop #1` creates new loops
  The first line of the report shows that `Loop #1`, shown on line 10, is distributed to create `Loop #2` and `Loop #3`:

Initially, `Loop #1` appears as shown.

```
      DO I = 1, N                              ! Loop #1
        C(I) = 0
        DO J = 1, M
          A(I,J) = A(I,J) + B(I,J) * C(I)
        ENDDO
      ENDDO
```

It is then distributed as follows:

```
      DO I = 1, N                              ! Loop #2
        C(I) = 0
      ENDDO

      DO I = 1, N                              ! Loop #3
        DO J = 1, M
          A(I,J) = A(I,J) + B(I,J) * C(I)
        ENDDO
      ENDDO
```

- `Loop #3` is interchanged to create `Loop#4`
  The third line indicates this:

```
10       3  i:1       *Interchange       (4)       (i:1 j:1) ->
  (j:1 i:1)
```

Now, the loop looks like the following code:

```
      DO J = 1, M                              ! Loop #4
        DO I = 1, N
          A(I,J) = A(I,J) + B(I,J) * C(I)
        ENDDO
      ENDDO
```

- Nested loop is blocked
  The next line of the Optimization Report indicates that the nest rooted at `Loop #4` is blocked:

```
12       4  j:1       *Block             (5)       (j:1 i:1) ->
  (i:1 j:1 i:1)
```

- The blocked nest internally appears as follows:

```
      DO IOUT = 1, N, 56                       ! Loop #5
        DO J = 1, M
          DO I = IOUT, IOUT + 55
            A(I,J) = A(I,J) + B(I,J) * C(I)
          ENDDO
        ENDDO
      ENDDO
```

- `Loop #5` noted as blocked
  The loop with iteration variable `i:1` is the loop that was actually blocked. The report shows `*Block` on `Loop #4` (the `j:1` loop) because the entire nest rooted at `Loop #4` is replaced by the blocked nest.

- `IOUT` variable facilitates loop blocking
  The `IOUT` variable is introduced to facilitate the loop blocking. The compiler uses a step value of 56 for the `IOUT` loop as reported in the Analysis Table:

```
10       5  i:1        Loop blocked by 56 iterations
```

- Test promotion creates new loops
  The next three lines of the report show that a test was promoted out of `Loop #5`, creating `Loop #6` (which is removed) and `Loop #7` (which is run serially). This test—which does not appear in the source code—is an implicit test that the compiler inserts in the code to ensure that the loop iterates at least once.

```
10       5  i:1        *Promote          (6-7)
10       6  i:1         Serial                      Removed
10       7  i:1         Serial
```

- This test is referenced again in the following line from the Analysis Table:

```
10       5  i:1        Test on line 12 promoted out of loop
```

- Unroll and jam creates new loop
  The report indicates that the `J` is unrolled and jammed, creating `Loop #9`:

```
12       8  j:1        *Unroll And Jam    (9)
```

- `J` loop unrolled by 8 iterations
  This line also indicates that the `J` loop is unrolled by 8 iterations and fused:

```
12     8  j:1      Loop unrolled by 8 iterations and jammed
                   into the innermost loop
```

- The unrolled and jammed loop results in the following code:

```
DO IOUT = 1, N, 56                        ! Loop #5
  DO J = 1, M, 8                          ! Loop #8
    DO I = IOUT, IOUT + 55                ! Loop #9
      A(I,J) = A(I,J) + B(I,J) * C(I)
      A(I,J+1) = A(I,J+1) + B(I,J+1) * C(I)
```

```
          A(I,J+2) = A(I,J+2) + B(I,J+2) * C(I)
          A(I,J+3) = A(I,J+3) + B(I,J+3) * C(I)
          A(I,J+4) = A(I,J+4) + B(I,J+4) * C(I)
          A(I,J+5) = A(I,J+5) + B(I,J+5) * C(I)
          A(I,J+6) = A(I,J+6) + B(I,J+6) * C(I)
          A(I,J+7) = A(I,J+7) + B(I,J+7) * C(I)
        ENDDO
      ENDDO
    ENDDO
```

- Test promotion in `Loop #9` creates new loops
  The Optimization Report indicates that the compiler-inserted test in `Loop #9` is promoted out the loop, creating `Loop #10` and `Loop #11`.

```
12      9      j:1    *Promote      (10-11)
12      10     j:1     Serial                 Removed
12      11     j:1     Serial
```

- Loops are fused
  According to the report, the last two loops in the program are fused (once an iteration is peeled off the second loop), then the new loop is run serially.

```
17      13   i:2         Serial                    Fused
21      14   j:2        *Peel             (15)
21      15   j:2         Serial                    Fused
                        *Fused            (16)    (13 15) -> (16)
17      16   i:2         Serial
```

That information is combined with the following line from the Analysis Table:

```
21       14   j:2         Peeled last iteration of loop
```

- Loop peeling creates loop, enables fusion
  Initially, `Loop #14` has an iteration peeled to create `Loop #15`, as shown below. The loop peeling is performed to enable loop fusion.

```
DO I = 1, N-1                          ! Loop #13
  D(I) = I
ENDDO

DO J = 1, N-1                          ! Loop #15
  E(J) = D(J) + 1
ENDDO
```

- Loops are fused to create new loop
  `Loop #13` and `Loop #15` are then fused to produce `Loop #16`:

```
DO I = 1, N-1                          ! Loop #16
  D(I) = I
  E(I) = D(I) + 1
ENDDO
```

9 Parallel programming techniques

The HP compiler set provides programming techniques that allow you to increase code efficiency while achieving three-tier parallelism. This

chapter describes the following programming techniques and requirements for implementing low-overhead parallel programs:

- Parallelizing directives and pragmas
- Parallelizing loops
- Parallelizing tasks
- Parallelizing regions
- Reentrant compilation
- Setting thread default stack size
- Collecting parallel information

NOTE The HP aC++ compiler does not support the pragmas described in this chapter.

Parallelizing directives and pragmas

This section summarizes the directives and pragmas used to achieve parallelization in the HP compilers. The directives and pragmas are listed in the order of how they would typically be used within a given program.

Table 9-1 Parallel directives and pragmas

Pragma / Directive	Description	Level of parallelism
`prefer_parallel [(attribute_list)]`	Requests parallelization of the immediately following loop, accepting attribute combinations for thread-parallelism, strip-length adjustment, and maximum number of threads. The compiler handles data privatization and does not parallelize the loop if it is not safe to do so.	Loop
`loop_parallel [(attribute_list)]`	Forces parallelization of the immediately following loop. Accepts attributes for thread-parallelism, strip-length adjustment, maximum number of threads, and ordered execution. Requires you to manually privatize loop data and synchronize data dependences.	Loop

Table 9-1 Parallel directives and pragmas (Continued)

Pragma / Directive	Description	Level of parallelism
`parallel [(attribute_list)]`	Allow you to parallelize a single code region to run on multiple threads. Unlike the tasking directives, which run discrete sections of code in parallel, `parallel` and `end_parallel` run multiple copies of a single section. Accepts attribute combinations for thread-parallelism and maximum number of threads. Within a parallel region, loop directives (`prefer_parallel`, `loop_parallel`) and tasking directives (`begin_tasks`) may appear with the `dist` attribute.	Region
`end_parallel`	Signifies the end of a parallel region (see `parallel`).	Region
`begin_tasks (attribute_list)`	Defines the beginning of a series of tasks, allowing you to parallelize consecutive blocks of code. Accepts attribute combinations for thread-parallelism, ordered execution, maximum number of threads, and others.	Task

Table 9-1 Parallel directives and pragmas (Continued)

Pragma / Directive	Description	Level of parallelism
`next_task`	Starts a block of code following a `begin_tasks` block that will be executed as a parallel task.	Task
`end_tasks`	Terminates parallel tasks started by `begin_tasks` and `next_task`.	Task
`ordered_section (gate)`	Allows you to isolate dependences within a loop so that code contained within the ordered section executes in iteration order. Only useful when used with `loop_parallel(ordered)`.	Loop
`critical_section [(gate)]`	Allows you to isolate nonordered manipulations of a shared variable within a loop. Only one parallel thread can execute the code contained in the critical section at a time, eliminating possible contention.	Loop
`end_critical section`	Identifies the end of a critical section (see `critical_section`).	Loop
`reduction`	Forces reduction analysis on a loop being manipulated by the `loop_parallel` directive. See “Reductions” on page 114.	Loop

Table 9-1 Parallel directives and pragmas (Continued)

Pragma / Directive	Description	Level of parallelism
`sync_routine`	Must be used to identify synchronization functions that you call indirectly call in your own routines. See “sync_routine” on page 263.	Loop or Task

Parallelizing loops

The HP compilers automatically exploit loop parallelism in dependence-free loops. The `prefer_parallel`, `loop_parallel`, and `parallel` directives and pragmas allow you to increase parallelization opportunities and to manually control many aspects of parallelization using simple manual loop parallelization.

The `prefer_parallel` and `loop_parallel` directives and pragmas, apply to the immediately following loop. Data privatization is necessary when using `loop_parallel`; this is achieved by using the `loop_private` directive, discussed in “Data privatization” on page 229. Manual data privatization using memory classes is discussed in “Memory classes” on page 245 and “Parallel synchronization” on page 255.

The parallel directives and pragmas should only be used on Fortran `DO` and C `for` loops that have iteration counts that are determined prior to loop invocation at runtime.

prefer_parallel

The `prefer_parallel` directive and pragma causes the compiler to automatically parallelize the immediately following loop if it is free of dependences and other parallelization inhibitors. The compiler automatically privatizes any loop variables that must be privatized. `prefer_parallel` requires less manual intervention. However, it is less powerful than the `loop_parallel` directive and pragma.

See ”`prefer_parallel, loop_parallel attributes`” on page 190 for a description of attributes for this directive.

`prefer_parallel` can also be used to indicate the preferred loop in a nest to parallelize, as shown in the following Fortran code:

```
      DO J = 1, 100
C$DIR   PREFER_PARALLEL
        DO I = 1, 100
          .
          .
          .
        ENDDO
      ENDDO
```

This code indicates that PREFER_PARALLEL causes the compiler to choose the innermost loop for parallelization, provided it is free of dependences. PREFER_PARALLEL does not inhibit loop interchange.

The ordered attribute in a prefer_parallel directive is only useful if the loop contains synchronized dependences. The ordered attribute is most useful in the loop_parallel directive, described in the next section.

loop_parallel

The loop_parallel directive forces parallelization of the immediately following loop. The compiler does not check for data dependences, perform variable privatization, or perform parallelization analysis. You must synchronize any dependences manually and manually privatize loop data as necessary. loop_parallel defaults to thread parallelization.

See "prefer_parallel, loop_parallel attributes" on page 190 for a description of attributes for this directive.

loop_parallel(ordered) is useful for manually parallelizing loops that contain ordered dependences. This is described in "Parallel synchronization" on page 255.

Parallelizing loops with calls

loop_parallel is useful for manually parallelizing loops containing procedure calls.

This is shown in the following Fortran code:

```
C$DIR LOOP_PARALLEL
      DO I = 1, N
        X(I) = FUNC(I)
      ENDDO
```

The call to FUNC in this loop would normally prevent it from parallelizing. To verify that the FUNC has no side effects, review the following conditions. A function does not have side effects if:

- It does not modify its arguments.
- It does not modify the same memory location from one call to the next.
- It performs no I/O.

- It does not call any procedures that have side effects. If `FUNC` does have side effects or is not reentrant, this loop may yield wrong answers.

If you are sure that

`FUNC`

has no side effects and is compiled for reentrancy (the default), this loop can be safely parallelized.

NOTE In some cases, global register allocation can interfere with the routine being called. Refer to the “Global register allocation (GRA)” on page 44 for more information.

Unparallelizable loops

The compiler does not parallelize any loop that does not have a number of iterations that can be determined prior to loop invocation at execution time, even when `loop_parallel` is specified.

This is shown in the following Fortran code:

```
C$DIR LOOP_PARALLEL
      DO WHILE(A(I) .GT. 0)!WILL NOT PARALLELIZE
        .
        .
        A(I) = ...
        .
        .
      ENDDO
```

In general, there is no way the compiler can determine the loop’s iteration count prior to loop invocation here, so the loop cannot be parallelized.

`prefer_parallel`, `loop_parallel` attributes

The `prefer_parallel` and `loop_parallel` directives and pragmas maintain the same attributes. The forms of these directives and pragmas are shown in Table 9-2.

Table 9-2 Forms of `prefer_parallel` and `loop_parallel` directives and pragmas

Language	Form

Fortran	`C$DIR PREFER_PARALLEL[(`*attribute-list*`)]`
	
	`C$DIR LOOP_PARALLEL[(`*attribute-list*`)]`

C	`#pragma _CNX prefer_parallel[(`*attribute-list*`)]`
	
	`#pragma _CNX loop_parallel(ivar = `*indvar*`[,` *attribute-list*`])`

where

`ivar = `*indvar*

specifies that the primary loop induction variable is *indvar*. `ivar = `*indvar* is optional in Fortran, but required in C. Use only with `loop_parallel`.

attribute-list can contain one of the case-insensitive attributes noted in Table 9-3.

NOTE The values of *n* and *m* must be compile-time constants for the loop parallelization attributes in which they appear.

Table 9-3 Attributes for `loop_parallel`, `prefer_parallel`

Attribute	Description
`dist`	Causes the compiler to distribute the iterations of a loop across active threads instead of spawning new threads. This significantly reduces parallelization overhead. Must be used with `prefer_parallel` or `loop_parallel` inside a `parallel`/`end_parallel` region. Can be used with any `prefer_parallel` or `loop_parallel` attribute, except `threads`.
`ordered`	Causes the iterations of the loop to be initiated in iteration order across the processors. This is useful only in loops with manually-synchronized dependences, constructed using `loop_parallel`. To achieve ordered parallelism, dependences must be synchronized within ordered sections, constructed using the `ordered_section` and `end_ordered_section` directives.

Table 9-3 Attributes for `loop_parallel`, `prefer_parallel`

Attribute	Description
`max_threads = m`	Restricts execution of the specified loop to no more than *m* threads if specified alone. *m* must be an integer constant. `max_threads = m` is useful when you know the maximum number of threads your loop runs on efficiently. If specified with the `chunk_size = n` attribute, the chunks are parallelized across no more than *m* threads.
`chunk_size = n`	Divides the loop into chunks of *n* or fewer iterations by which to strip mine the loop for parallelization. *n* must be an integer constant. If `chunk_size = n` is present alone, *n* or fewer loop iterations are distributed round-robin to each available thread until there are no remaining iterations. This is shown in Table 9-5 and *** 'For chunk_size=n, with n > 1, the distribution is round-robin. However, it is not the same as specifying the ordered attribute. For example, using the same loop as above, specifying chunk_size=5 produces the distribution shown in Table 9-6.' on page 196 ***. If the number of threads does not evenly divide the number of iterations, some threads perform one less chunk than others.

Table 9-3 Attributes for `loop_parallel`, `prefer_parallel`

Attribute	Description
`dist, ordered`	Causes ordered invocation of each iteration across existing threads.
`dist, max_threads = m`	Causes thread-parallelism on no more than *m* existing threads.
`ordered, max_threads = m`	Causes ordered parallelism on no more than *m* threads.
`dist, chunk_size = n`	Causes thread-parallelism by chunks.
`dist, ordered, max_threads = m`	Causes ordered thread-parallelism on no more than *m* existing threads.
`chunk_size = n, max_threads = m`	Causes chunk parallelism on no more than *m* threads.
`dist, chunk_size = n, max_threads = m`	Causes thread-parallelism by chunks on no more than *m* existing threads.

Any loop under the influence of `loop_parallel(dist)` or `prefer_parallel(dist)` appears in the Optimization Report as serial. This is because it is already inside a parallel region. You can generate an Optimization Report by specifying the `+Oreport` option. For more information, see “Optimization Report” on page 155.

Combining the attributes

Table 9-3 shown above describes the acceptable combinations of `loop_parallel` and `prefer_parallel` attributes. In such combinations, the attributes are listed in any order.

The `loop_parallel` C pragma requires the `ivar =` *indvar* attribute, which specifies the primary loop induction variable. If this is not present, the compiler issues a warning and ignores the pragma. `ivar` should specify only the primary induction variable. Any other loop induction variables should be a function of this variable and should be declared `loop_private`.

In Fortran, ivar is optional for DO loops. If it is not provided, the compiler picks the primary induction variable for the loop. ivar is required for DO, WHILE and customized loops in Fortran.

NOTE prefer_parallel does not require ivar. The compiler issues an error if it encounters this combination.

Comparing prefer_parallel, loop_parallel

The prefer_parallel and loop_parallel directives and pragmas are used to parallelize loops. Table 9-4 provides an overview of the differences between the two pragmas/directives. See the sections "prefer_parallel" on page 187 and "loop_parallel" on page 188 for more information.

Table 9-4 Comparison of loop_parallel and prefer_parallel

	prefer_parallel	loop_parallel
Description	Requests compiler to perform parallelization analysis on the following loop then parallelize the loop if it is safe to do so. When used with the +Oautopar option (the default), it overrides the compiler heuristic for picking which loop in a loop nest to parallelize. When used with +Onoautopar, the compiler only performs directive-specified parallelization. No heuristic is used to pick the loop in a nest to parallelize. In such cases, prefer_parallel requests loop parallelization.	Forces the compiler to parallelize the following loop—assuming the iteration count can be determined prior to loop invocation.

Table 9-4 Comparison of `loop_parallel` and `prefer_parallel`

	`prefer_parallel`	`loop_parallel`
Advantages	Compiler automatically performs parallelization analysis and variable privatization.	Allows you to parallelize loops that the compiler is not able to automatically parallelize because it cannot determine dependences or side effects.
Disadvantages	Loop may or may not execute in parallel.	Requires you to: —Check for and synchronize any data dependences —Perform variable privatization

Stride-based parallelism

Stride-based parallelism differs from the default strip-based parallelism described in that:

- Strip-based parallelism divides the loop's iterations into a number of contiguous chunks equal to the number of available threads, and each thread computes one chunk.
- Stride-based parallelism, set by the `chunk_size=`*n* attribute, allows each thread to do several noncontiguous chunks.

  Specifying `chunk_size =` ((*number of iterations* - 1) / *number of threads*) + 1 is similar to default strip mining for parallelization.

Using `chunk_size = 1` distributes individual iterations cyclically across the processors. For example, if a loop has 1000 iterations to be distributed among 4 processors, specifying `chunk_size=1` causes the distribution shown in Table 9-5.

Table 9-5 Iteration distribution using `chunk_size = 1`

	CPU0	CPU1	CPU2	CPU3
Iterations	1	2	3	4
	5	6	7	. . .

For `chunk_size=`*n*, with *n* > 1, the distribution is round-robin. However, it is not the same as specifying the `ordered` attribute. For example, using the same loop as above, specifying `chunk_size=5` produces the distribution shown in Table 9-6.

Table 9-6 Iteration distribution using `chunk_size = 5`

	CPU0	CPU1	CPU2	CPU3
Iterations	1, 2, 3, 4, 5	6, 7, 8, 9, 10	11, 12, 13, 14, 15	16, 17, 18, 19, 20
	21, 22, 23, 24, 25	26, 27, 28, 29, 30	31, 32, 33, 34, 35,	. . .

For more information and examples on using the `chunk_size =` *n* attribute, see “Troubleshooting” on page 289.

Example 9-1 prefer_parallel, loop_parallel

The following Fortran example uses the

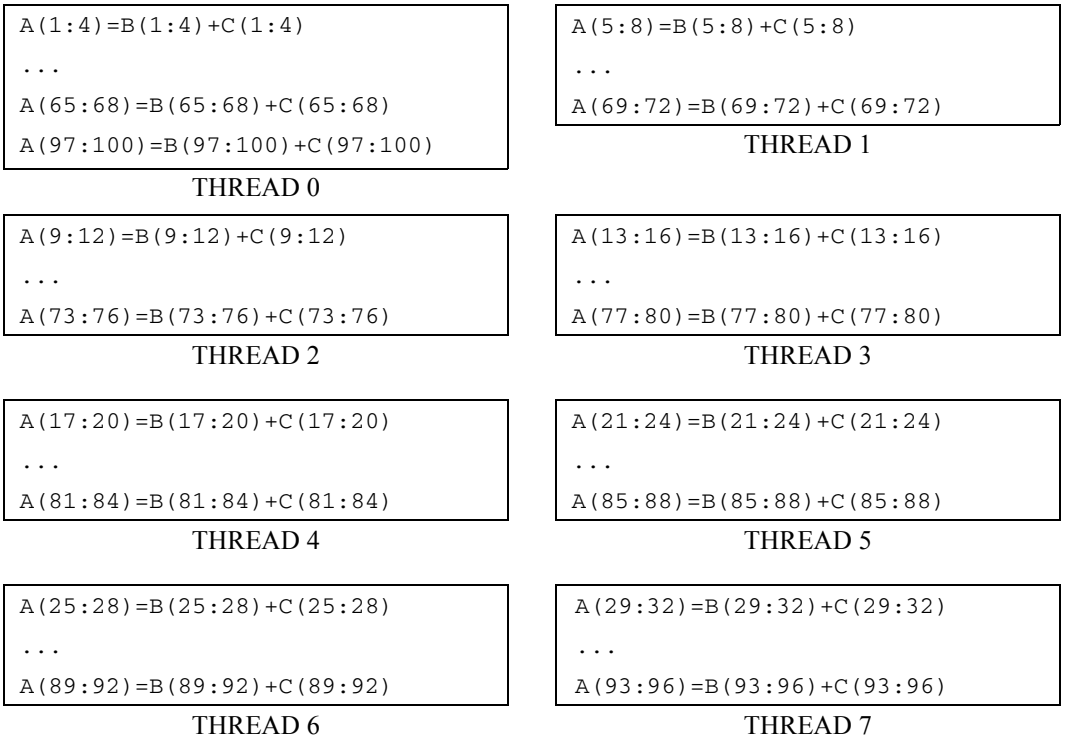
`PREFER_PARALLEL` directive, but applies to `LOOP_PARALLEL` as well:

```
C$DIR PREFER_PARALLEL(CHUNK_SIZE = 4)
      DO I = 1, 100
        A(I) = B(I) + C(I)
      ENDDO
```

In this example, the loop is parallelized by parcelling out chunks of four iterations to each available thread. Figure 9-1 uses Fortran array syntax to illustrate the iterations performed by each thread, assuming eight available threads.

Figure 9-1 shows that the 100 iterations of `I` are parcelled out in chunks of four iterations to each of the eight available threads. After the chunks are distributed evenly to all threads, there is one chunk left over (iterations 97:100), which executes on thread 0.

Figure 9-1 Stride-parallelized loop



Example 9-2 prefer_parallel, loop_parallel

The `chunk_size` = *n* attribute is most useful on loops in which the amount of work increases or decreases as a function of the iteration count. These loops are also known as triangular loops. The following Fortran example shows such a loop. As with the previous example, `PREFER_PARALLEL` is used here, but the concept also applies to `LOOP_PARALLEL`.

```
C$DIR PREFER_PARALLEL(CHUNK_SIZE = 4)
      DO J = 1,N
        DO I = J, N
          A(I,J) = ...
```

```
        .
        .
        .
      ENDDO
    ENDDO
```

Here, the work of the `I` loop decreases as `J` increases. By specifying a `chunk_size` for the `J` loop, the load is more evenly balanced across the threads executing the loop.

If this loop was strip-mined in the traditional manner, the amount of work contained in the strips would decrease with each successive strip. The threads performing early iterations of `J` would do substantially more work than those performing later iterations.

critical_section, end_critical_section

The `critical_section` and `end_critical_section` directives and pragmas allow you to specify sections of code in parallel loops or tasks that must be executed by only one thread at a time. These directives cannot be used for ordered synchronization within a `loop_parallel(ordered)` loop, but are suitable for simple synchronization in any other `loop_parallel` loops. Use the `ordered_section` and `end_ordered_section` directives or pragmas for ordered synchronization within a `loop_parallel(ordered)` loop.

A `critical_section` directive or pragma and its associated `end_critical_section` must appear in the same procedure and under the same control flow. They do not have to appear in the same procedure as the parallel construct in which they are used. For instance, the pair can appear in a procedure called from a parallel loop.

The forms of these directives and pragmas are shown in Table 9.

Table 9-7 Forms of critical_section/end_critical_section directives and pragmas

Language	Form

Fortran	`C$DIR CRITICAL_SECTION [(gate)]`
	
	`C$DIR END_CRITICAL_SECTION`

Table 9-7 Forms of critical_section/end_critical_section directives and pragmas (Continued)

Language	Form

C	`#pragma _CNX critical_section [(gate)]`
	
	`#pragma _CNX end_critical_section`

The `critical_section` directive/pragma can take an optional gate attribute that allows the declaration of multiple critical sections. This is described in "Using gates and barriers" on page 258. Only simple critical sections are discussed in this section.

Example 9-3 critical_section

Consider the following Fortran example:

```
C$DIR LOOP_PARALLEL, LOOP_PRIVATE(FUNCTEMP)
      DO I = 1, N  ! LOOP IS PARALLELIZABLE
         .
         .
         .
         FUNCTEMP = FUNC(X(I))
C$DIR    CRITICAL_SECTION
         SUM = SUM + FUNCTEMP
C$DIR    END_CRITICAL_SECTION
         .
         .
         .
      ENDDO
```

Because `FUNC` has no side effects and is called in parallel, the `I` loop is parallelized as long as the `SUM` variable is only updated by one thread at a time. The critical section created around `SUM` ensures this behavior.

The `LOOP_PARALLEL` directive and the critical section directive are required to parallelize this loop because the call to `FUNC` would normally inhibit parallelization. If this call were not present, and if the loop did not contain other parallelization inhibitors, the compiler would automatically parallelize the reduction of `SUM` as described in the section "Reductions" on page 114. However, the presence of the call necessitates the `LOOP_PARALLEL` directive, which prevents the compiler from automatically handling the reduction.

This, in turn, requires using either a critical section directive or the `reduction` directive. Placing the call to `FUNC` outside of the critical section allows `FUNC` to be called in parallel, decreasing the amount of serial work within the critical section.

In order to justify the cost of the compiler-generated synchronization code associated with the use of critical sections, loops that contain them must also contain a large amount of parallelizable (non-critical section) code. If you are unsure of the profitability of using a critical section to help parallelize a certain loop, time the loop with and without the critical section. This helps to determine if parallelization justifies the overhead of the critical section.

For this particular example, the `reduction` directive or pragma could have been used in place of the `critical_section`, `end_critical_section` combination. For more information, see the section “Reductions” on page 114.

Disabling automatic loop thread-parallelization

You can disable automatic loop thread-parallelization by specifying the `+Onoautopar` option on the compiler command line. `+Onoautopar` is only meaningful when specified with the `+Oparallel` option at `+O3` or `+O4`.

This option causes the compiler to parallelize only those loops that are immediately preceded by `prefer_parallel` or `loop_parallel`. Because the compiler does not automatically find parallel tasks or regions, user-specified task and region parallelization is not affected by this option.

Parallelizing tasks

The compiler does not automatically parallelize code outside a loop. However, you can use tasking directives and pragmas to instruct the compiler to parallelize this type of code.

- The `begin_tasks` directive and pragma tells the compiler to begin parallelizing a series of tasks.
- The `next_task` directive and pragma marks the end of a task and the start of the next task.
- The `end_tasks` directive and pragma marks the end of a series of tasks to be parallelized and prevents execution from continuing until all tasks have completed.

The sections of code delimited by these directives are referred to as a task list. Within a task list, the compiler does not check for data dependences, perform variable privatization, or perform parallelization analysis. You must manually synchronize any dependences between tasks and manually privatize data as necessary.

The forms of these directives and pragmas are shown in Table 9-8.

Table 9-8 Forms of task parallelization directives and pragmas

Language	Form

Fortran	`C$DIR BEGIN_TASKS[(`*attribute-list*`)]`
	
	`C$DIR NEXT_TASK`
	
	`C$DIR END_TASKS`

C	`#pragma _CNX begin_tasks[(`*attribute-list*`)]`
	
	`#pragma _CNX next_task`
	
	`#pragma _CNX end_tasks`

where

attribute-list can contain one of the case-insensitive attributes noted in Table 9-9.

The optional *attribute-list* can contain one of the following attribute combinations, with *m* being an integer constant.

Table 9-9 Attributes for task parallelization

Attribute	Description
`dist`	Instructs the compiler to distribute the tasks across the currently threads, instead of spawning new threads. Use with other valid attributes to `begin_tasks` inside a `parallel`/`end_parallel` region. `begin_tasks` and `parallel`/`end_parallel` must appear inside the same function.
`ordered`	Causes the tasks to be initiated in their lexical order. That is, the first task in the sequence begins to run on its respective thread before the second and so on. In the absence of the `ordered` argument, the starting order is indeterminate. While this argument ensures an ordered starting sequence, it does not provide any synchronization between tasks, and does not guarantee any particular ending order. You can manually synchronize the tasks, if necessary, as described in “Parallel synchronization” on page 255.

Table 9-9 Attributes for task parallelization (Continued)

Attribute	Description
`max_threads = m`	Restricts execution of the specified loop to no more than *m* threads if specified alone or with the `threads` attribute. *m* must be an integer constant. `max_threads = m` is useful when you know the maximum number of threads on which your task runs efficiently. Can include any combination of thread-parallel, ordered or unordered execution.
`dist, ordered`	Causes ordered invocation of each task across threads, as specified in the attribute list to the `parallel` directive.
`dist, max_threads = m`	Causes thread-parallelism on no more than *m* existing threads.
`ordered, max_threads = m`	Causes ordered parallelism on no more than *m* threads.
`dist, ordered, max_threads = m`	Causes ordered thread-parallelism on no more than *m* existing threads.

NOTE Do not use tasking directives or pragmas unless you have verified that dependences do not exist. You may insert your own synchronization code in the code delimited by the tasking directives or pragmas. The compiler will not performs dependence checking or synchronization on the code in these regions. Synchronization is discussed in “Parallel synchronization” on page 255.

Example 9-4 Parallelizing tasks

The following Fortran example shows how to insert tasking directives into a section of code containing three tasks that can be run in parallel:

```
C$DIR BEGIN_TASKS
            parallel task 1
C$DIR NEXT_TASK
            parallel task 2
C$DIR NEXT_TASK
            parallel task 3
C$DIR END_TASKS
```

The example above specifies thread-parallelism by default. The compiler transforms the code into a parallel loop and creates machine code equivalent to the following Fortran code:

```
C$DIR LOOP_PARALLEL
 DO 40 I = 1,3
 GOTO (10,20,30)I
10 parallel task 1
 GOTO 40
20 parallel task 2
 GOTO 40
30 parallel task 3
 GOTO 40
40 CONTINUE
```

If there are more tasks than available threads, some threads execute multiple tasks. If there are more threads than tasks, some threads do not execute tasks.

In this example, the `END_TASKS` directive and pragma acts as a barrier. All parallel tasks must complete before the code following `END_TASKS` can execute.

Example 9-5 Parallelizing tasks

The following C example illustrates how to use these directives to specify simple task-parallelization:

```
#pragma _CNX begin_tasks, task_private(i)
for(i=0;i<n-1;i++)
  a[i] = a[i+1] + b[i];
#pragma _CNX next_task
tsub(x,y);
#pragma _CNX next_task
for(i=0;i<500;i++)
  c[i*2] = d[i];
#pragma _CNX end_tasks
```

In this example, one thread executes the `for` loop, another thread executes the `tsub(x,y) function call`, and a third thread assigns the elements of the array d to every other element of `c`. These threads execute in parallel, but their starting and ending orders are indeterminate.

The tasks are thread-parallelized. This means that there is no room for nested parallelization within the individual parallel tasks of this example, so the forward LCD on the `for I` loop is inconsequential. There is no way for the loop to run but serially.

The loop induction variable `i` must be manually privatized here because it is used to control loops in two different tasks. If `i` were not private, both tasks would modify it, causing wrong answers. The `task_private` directive and pragma is described in detail in the section ”`task_private`” on page 240.

Task parallelism can become even more involved, as described in “Parallel synchronization” on page 255.

Parallelizing regions

A parallel region is a single block of code that is written to run replicated on several threads. Certain scalar code within the parallel region is run by each thread in preparation for work-sharing parallel constructs such as `prefer_parallel(dist)`, `loop_parallel(dist)`, or `begin_tasks(dist)`. The scalar code typically assigns data into `parallel_private` variables so that subsequent references to the data have a high cache hit rate. Within a parallel region, code execution can be restricted to subsets of threads by using conditional blocks that test the thread ID.

Region parallelization differs from task parallelization in that parallel tasks are separate, contiguous blocks of code. When parallelized using the tasking directives and pragmas, each block generally runs on a separate thread. This is in comparison to a single parallel region, which runs on several threads.

Specifying parallel tasks is also typically less time consuming because each thread's work is implicitly defined by the task boundaries. In region parallelization, you must manually modify the region to identify thread-specific code. However, region parallelism can reduce parallelization overhead as discussed in the section explaining the `dist` attribute.

The beginning of a parallel region is denoted by the `parallel` directive or pragma. The end is denoted by the `end_parallel` directive or pragma. `end_parallel` also prevents execution from continuing until all copies of the parallel region have completed.

Within a parallel region, the compiler does not check for data dependences, perform variable privatization, or perform parallelization analysis. You must manually synchronize any dependences between copies of the region and manually privatize data as necessary. In the absence of a `threads` attribute, `parallel` defaults to thread parallelization.

The forms of the regional parallelization directives and pragmas are shown in Table 9-10.

Table 9-10 Forms of region parallelization directives and pragmas

Language	Form

Fortran	`C$DIR PARALLEL[(`*`attribute-list`*`)]`
	
	`C$DIR END_PARALLEL`

C	`#pragma _CNX parallel(`*`attribute-list`*`)` #pragma _CNX end_parallel

The optional *`attribute-list`* can contain one of the following attributes (*`m`* is an integer constant).

Table 9-11 Attributes for region parallelization

Attribute	Description
`max_threads = `*`m`*	Restricts execution of the specified region to no more than *`m`* threads if specified alone or with the `threads` attribute. *`m`* must be an integer constant. Can include any combination of ordered, or unordered execution.

WARNING **Do not use the parallel region directives or pragmas unless you ensure that dependences do not exist or you insert your own synchronization code, if necessary, in the region. The compiler performs no dependence checking or synchronization on the**

code delimited by the parallel region directives and pragmas. Synchronization is discussed in “Parallel synchronization” on page 255.

Example 9-6 Region parallelization

The following Fortran example provides an implementation of region parallelization using the PARALLEL directive:

```
      REAL A(1000,8), B(1000,8), C(1000,8), RDONLY(1000), SUM(8)
      INTEGER MYTID
      .
      .
      .
C     FIRST INITIALIZATION OF RDONLY IN SERIAL CODE:
      CALL INIT1(RDONLY)
      IF(NUM_THREADS() .LT. 8) STOP "NOT ENOUGH THREADS; EXITING"
C$DIR PARALLEL(MAX_THREADS = 8), PARALLEL_PRIVATE(I, J, K, MYTID)
      MYTID = MY_THREAD() + 1 !ADD 1 FOR PROPER SUBSCRIPTING
      DO I = 1, 1000
        A(I, MYTID) = B(I, MYTID) * RDONLY(I)
      ENDDO
      IF(MYTID .EQ. 1) THEN ! ONLY THREAD 0 EXECUTES SECOND
        CALL INIT2(RDONLY)  ! INITIALIZATION
      ENDIF
      DO J = 1, 1000
        B(J, MYTID) = B(J, MYTID) * RDONLY(J)
        C(J, MYTID) = A(J, MYTID) * B(J, MYTID)
      ENDDO
      DO K = 1, 1000
        SUM(MYTID) = SUM(MYTID) + A(K,MYTID) + B(K,MYTID) + C(K,MYTID)
      ENDDO
C$DIR END_PARALLEL
```

In this example, all arrays written to in the parallel code have one dimension for each of the anticipated number of parallel threads. Each thread can work on disjoint data, there is no chance of two threads attempting to update the same element, and, therefore, there is no need for explicit synchronization. The RDONLY array is one-dimensional, but it is never written to by parallel threads. Before the parallel region, RDONLY is initialized in serial code.

The PARALLEL_PRIVATE directive is used to privatize the induction variables used in the parallel region. This must be done so that the various threads processing the region do not attempt to write to the same shared induction variables. PARALLEL_PRIVATE is covered in more detail in the section “parallel_private” on page 242.

At the beginning of the parallel region, the NUM_THREADS() intrinsic is called to ensure that the expected number of threads are available. Then the MY_THREAD() intrinsic, is called by each thread to determine its thread ID. All subsequent code in the region is executed based on this ID. In the I loop, each thread computes one row of A using RDONLY and the corresponding row of B.

RDONLY is reinitialized in a subroutine call that is only executed by thread 0 before it is used again in the computation of B in the J loop. In J, each thread computes a row again. The J loop similarly computes C.

Finally, the K loop sums each dimension of A, B, and C into the SUM array. No synchronization is necessary here because each thread is running the entire loop serially and assigning into a discrete element of SUM.

Reentrant compilation

By default, HP-UX parallel compilers compile for reentrancy in that the compiler itself does not introduce static or global references beyond what exist in the original code. Reentrant compilation causes procedures to store uninitialized local variables on the stack. No locals can carry values from one invocation of the procedure to the next, unless the variables appear in Fortran `COMMON` blocks or `DATA` or `SAVE` statements or in C/C++ `static` statements. This allows loops containing procedure calls to be manually parallelized, assuming no other inhibitors of parallelization exist.

When procedures are called in parallel, each thread receives a private stack on which to allocate local variables. This allows each parallel copy of the procedure to manipulate its local variables without interfering with any other copy's locals of the same name. When the procedure returns and the parallel threads join, all values on the stack are lost.

Setting thread default stack size

Thread 0's stack can grow to the size specified in the `maxssiz` configurable kernel parameter. Refer to the *Managing Systems and Workgroups* manual for more information on configurable kernel parameters.

Any threads your program spawns (as the result of `loop_parallel` or tasking directives or pragmas) receive a default stack size of 80 Mbytes. This means that if the following conditions exist, then you must modify the stack size of the spawned threads using the `CPS_STACK_SIZE` environment variable:

- A parallel construct declares more than 80 Mbytes of `loop_private`, `task_private`, or `parallel_private` data, or
- A subprogram with more than 80 Mbytes of local data is called in parallel, or
- The cumulative size of all local variables in a chain of subprograms called in parallel exceeds 80 Mbytes,

Modifying thread stack size

Under `csh`, you can modify the stack size of the spawned threads using the `CPS_STACK_SIZE` environment variable. The form of the `CPS_STACK_SIZE` environment variable is shown in Table 9-12.

Table 9-12 Forms of `CPS_STACK_SIZE` environment variable

Language	Form
Fortran, C	`setenv CPS_STACK_SIZE` *`size_in_kbytes`*

where

`size_in_kbytes` is the desired stack size in kbytes. This value is read at program start-up, and it cannot be changed during execution.

For example, the following command sets the thread stack size to 100 Mbytes:

```
setenv CPS_STACK_SIZE 102400
```

Collecting parallel information

Several intrinsics are available to provide information regarding the parallelism or potential parallelism of your program. These are all integer functions, available in both 4- and 8-byte variants. They can appear in executable statements anywhere an integer expression is allowed.

The 8-byte functions, which are suffixed with `_8`, are typically only used in Fortran programs in which the default data lengths have been changed using the `-I8` or similar compiler options. When default integer lengths are modified via compiler options in Fortran, the correct intrinsic is automatically chosen regardless of which is specified. These versions expect 8-byte input arguments and return 8-byte values.

NOTE All C/C++ code examples presented in this chapter assume that the line below appears above the C code presented. This header file contains the necessary type and function definitions.

```
#include <spp_prog_model.h>
```

Number of processors

Certain functions return the total number of processors on which the process has initiated threads. These threads are not necessarily active at the time of the call. The forms of these functions are shown in Table 9-13.

Table 9-13 Number of processors functions

Language	Form

Fortran	`INTEGER NUM_PROCS()`
	
	`INTEGER*8 NUM_PROCS_8()`

Table 9-13 Number of processors functions (Continued)

Language	Form

C/C++	`int num_procs(void);`
	
	`long long num_procs_8(void);`

`num_procs` is used to dimension automatic and adjustable arrays in Fortran. It may be used in Fortran, C, and C++ to dynamically specify array dimensions and allocate storage.

Number of threads

Certain functions return the total number of threads the process creates at initiation, regardless of how many are idle or active. The forms of these functions is shown in Table 9-14.

Table 9-14 Number of threads functions

Language	Form

Fortran	`INTEGER NUM_THREADS()`
	
	`INTEGER*8 NUM_THREADS_8()`

C/C++	`int num_threads(void);`
	
	`long long num_threads_8(void);`

The return value differs from `num_procs` only if threads are oversubscribed.

Thread ID

When called from parallel code these functions return the spawn thread ID of the calling thread, in the range 0..*N*-1, where *nst* is the number of threads in the current spawn context (the number of threads spawned by

the last parallel construct). Use them when you wish to direct specific tasks to specific threads inside parallel constructs. The forms of these functions is shown in Table 9-15.

Table 9-15 Thread ID functions

Language	Form

Fortran	`INTEGER MY_THREAD()`
	
	`INTEGER*8 MY_THREADS_8()`

C/C++	`int my_thread(void);`
	
	`long long my_thread_8(void);`

When called from serial code, these functions return 0.

Stack memory type

These functions return a value representing the memory class that the current thread stack is allocated from. The thread stack holds all the procedure-local arrays and variables not manually assigned a class. On a single-node system, the thread stack is created in `node_private` memory by default. The forms of these functions is shown in Table 9-16.

Table 9-16 Stack memory type functions

Language	Form
Fortran	`INTEGER MEMORY_TYPE_OF_STACK()` INTEGER*8 MEMORY_TYPE_OF_STACK_8()

C/C++	`int memory_type_of_stack(void);`
	
	long long memory_type_of_stack_8(void);

10 OpenMP Parallel Programming Model

This chapter discusses HP's implementation of the OpenMP v1.1 parallel programming model, including OpenMP directives and command line

options in the f90 front end and bridge. Topics covered include:

- What is OpenMP?
- HP's implementation of OpenMP
- Libraries
- Implementation-defined behavior
- From HP Programming Model (HPPM) to OpenMP
- Other resources for information

What is OpenMP?

OpenMP is a portable, scalable model that gives shared-memory parallel programmers a simple and flexible interface for developing parallel applications on platforms ranging from the desktop to the supercomputer. The OpenMP Application Program Interface (API) supports multi-platform shared-memory parallel programming in Fortran on all architectures, including UNIX and Windows NT.

HP's implementation of OpenMP

This section discusses HP's implementation of OpenMP.

Command-line option

HP OpenMP directives are only accepted if the command-line option `+Oopenmp` is given.

NOTE `+Oopenmp` implies `+Onodynsel`, `+Oparallel`, and `+Onoautopar`.

Default

The default command-line option is `+Onoopenmp`. If `+Oopenmp` is not given, all OpenMP directives (`c$omp`) are ignored.

Optimization levels and parallelism

`+Oopenmp` is accepted at all optimization levels. However, the following differences exist between Itanium®-based and PA-RISC architectures.

Itanium®-based architectures

OpenMP is accepted at all optimization levels on Itanium®-based architectures. Parallelization directives and worksharing directives can be compiled at any optimization level from `+O0` through `+O4`. Additionally, OpenMP will interoperate with `+objdebug`, `+noobjdebug`, and `-g`. Therefore, source-level debugging of parallelized applications is supported subject to the same restrictions of debugging at `+O2` or below.

PA-RISC architectures

The following limitations exist for OpenMP on PA-RISC architectures.

For parallel and work-shared directives (including the clauses for these directives), code is parallelized only at optimization levels +O3 or +O4. The parallel and work-shared directives are listed in Table 10-1 on page 219.

Optimization levels +O0 through +O2

When using optimization levels +O0 through +O2:

- All sync and run-time library directives are processed and honored.
- Parallel and work-shared directives (including the clauses for these directives) are only processed. While they will return right answers, you will not achieve parallel code. Each thread will run a serial version of the code.

Optimization levels +O3 through +O4

When using optimization levels +O3 and +O4:

- All sync and run-time library directives are processed and honored.
- Parallel and work-shared directives (including the clauses for these directives) are processed and honored. The compiler will generate the parallel and work-shared code required to go parallel.

Table 10-1 Parallel and work-shared directives

Parallel / work-shared directives	Opt level accepted	Opt level required to achieve parallelism
PARALLEL	+O0, +O1, +O2	+O3, +O4
PARALLEL DO	+O0, +O1, +O2	+O3, +O4
PARALLEL SECTIONS	+O0, +O1, +O2	+O3, +O4
DO	+O0, +O1, +O2	+O3, +O4
SECTION	+O0, +O1, +O2	+O3, +O4
SECTIONS	+O0, +O1, +O2	+O3, +O4

Parallelism

Nested parallelism is now supported dynamically, and with the use of the `NUM_THREADS` clause on the `Parallel` directive, finer-grained control of parallelism is possible. This also allows parallelized code to use parallel versions of MLIB.

Additionally, statically-nested parallelization is enabled.

Arrays

Arrays are allowed in reduction clauses as well as scalar variables.

Portable timing routines

There are two portable timing routines:

```
DOUBLE PRECISION OMP_GET_WTIME()
DOUBLE PRECISION OMP_GET_WTICK()
```

Nested lock routines

Nested lock routines are as follows:

```
SUBROUTINE OMP_INIT_NEST_LOCK (NLOCK)
SUBROUTINE OMP_DESTROY_NEST_LOCK (NLOCK)
SUBROUTINE OMP_SET_NEST_LOCK (NLOCK)
SUBROUTINE OMP_UNSET_NEST_LOCK (NLOCK)
INTEGER FUNCTION OMP_TEST_NEST_LOCK (NLOCK)
```

Additional features

- `Copyin` now allows non-threadprivate objects in a parallel region.
- Relaxed reprivatization rules now allow an inner directive to reprivatize a variable privatized in a containing directive.
- Privatization of module data is now allowed, as well as privatization of deferred and assumed shape objects.

New library

The OpenMP APIs are defined in the library `libomp`. These libraries are in patches PHSS_25028 (HP-UX 11.00) and PHSS_25029 (HP-UX 11.11).

Implementation-defined behavior

This following summarizes the behaviors that are described as *implementation dependent* in this API. Each behavior is cross-referenced back to its description in the OpenMP v2.0 main specification. HP, in conformance with the OpenMP v2.0 API, defines and documents the following behavior.

1. SCHEDULE(GUIDED,chunk): chunk specifies the size of the smallest piece, except possibly the last. The size of the initial piece is computed using the formula #iterations/(num_threads*2). (Table 1, page 17)
2. When SCHEDULE(RUNTIME) is specified, the decision regarding scheduling is deferred until run time. The schedule type and chunk size can be chosen at run time by setting the OMP_SCHEDULE environment variable. If this environment variable is not set, the resulting schedule defaults to STATIC scheduled with a chunk size of 1 (Table 1, page 17).
3. In the absence of the SCHEDULE clause, the default schedule is STATIC with chunksize computed as iterations / #threads (Section 2.3.1, page 15).
4. OMP_GET_NUM_THREADS: If the number of threads has not been explicitly set by the user, the default is the number of physical processors on the system (Section 3.1.2, page 48).
5. OMP_SET_DYNAMIC: The default for dynamic thread adjustment is FALSE (Section 3.1.7, page 51).
6. OMP_SET_NESTED: When nested parallelism is enabled, the number of threads used to execute nested parallel regions is determined at runtime by the underlying openmp parallel library implementation-dependent (Section 3.1.9, page 52).
7. OMP_SCHEDULE environment variable: The default value for this environment variable is STATIC (Section 4.1, page 59).
8. OMP_NUM_THREADS environment variable: The default value is the number of physical processors on the system (Section 4.2, page 60).

9. OMP_DYNAMIC environment variable: The default value is FALSE (Section 4.3, page 60).
10. An implementation can replace all ATOMIC directives by enclosing the statement in a critical section (Section 2.5.4, page 27). HP implements the ATOMIC clause using a slightly more efficient form of critical section roughly 60-70% faster than critical, although This is still a runtime call.
11. If the dynamic threads mechanism is enabled on entering a parallel region, the allocation status of an allocatable array that is not affected by a COPYIN clause that appears on the region will have an initial allocation status of not currently allocated (Section 2.6.1, page 32).
12. Due to resource constraints, it is not possible for an implementation to document the maximum number of threads that can be created successfully during a program's execution. This number is dependent upon the load on the system, the amount of memory allocated by the program, and the amount of implementation dependent stack space allocated to each thread. For a 32 bit process, the stack space for each thread is allocated from the heap. The heap defaults 1 gigabyte, and the default stacksize is 8 megabytes. See the linker option -N for increasing data area size to 2 gigabytes.
13. If the dynamic threads mechanism is disabled, requests for additional threads will result in no additional threads being created. Programs should not assume that a request will result in additional threads for all requests. If the dynamic threads mechanism is enabled, requests for more threads than an implementation can support are satisfied by creating additional pthreads which are then schedule the HP-UX scheduler using a smaller number of threads (Section 2.3.1, page 15).
14. If an OMP runtime library routine interface is defined to be generic by an implementation, use of arguments of kind other than those specified by the OMP_*_KIND constants will likely lead to incorrect program behavior due to incorrect argument passing for the runtime routine (Section D.3, page 111).

From HP Programming Model to OpenMP

This section discusses migration from the HP Programming Model (HPPM) to the OpenMP parallel programming model.

Syntax

The OpenMP parallel programming model is very similar to the HP Programming Model (HPPM). The general thread model is the same, the spawn (fork) mechanisms behave in a similar fashion, etc. However, the specific syntax to specify the underlying semantics has been changed significantly.

The following table shows the OpenMP directive or clause (relative to the directive) and the equivalent HPPM directive or clause that implements the same functionality. Certain clauses are valid on multiple directives, but are typically listed only once unless there is a distinction warranting further explanation.

Exceptions are defined immediately following the table.

Table 10-2 OpenMP and HPPM Directives/Clauses

HPPM	OpenMP

`!$dir parallel`
`  task_private(list)`
`  <'shared' is default>`
`  <None, see below>`
	`!$OMP parallel`
	`  private (list)`
	`  shared (list)`
	`  default (private|shared|none)`

`!$dir loop_parallel(dist)`
`  blocked(chunkconstant)`
`  ordered`
	`!$OMP do`
	`  schedule(static[,chunkconstant])`
	`  ordered`

`!$dir begin_tasks(dist)`	`!$OMP sections`
`!$dir next_task`	`!$OMP section`

Table 10-2 OpenMP and HPPM Directives/Clauses (Continued)

HPPM	OpenMP
!$dir loop_parallel <see parallel and loop_parallel(dist) clauses>	!$OMP parallel do <see parallel and do clauses>
!$dir begin_tasks <see parallel and begin_tasks(dist) clauses>	!$OMP parallel sections <see parallel and sections clauses>
!$dir critical_section[(name)]	!$OMP critical[(name)]
!$dir wait_barrier	!$OMP barrier
!$dir ordered_section	!$OMP ordered
<none>	!$OMP end parallel
!$dir end_tasks	!$OMP end sections
!$dir end_tasks	!$OMP end parallel sections
<none>	!$OMP end parallel do
!$dir end_critical_section	!$OMP end critical
!$dir end_ordered_section	!$OMP end ordered
<none>	!$OMP end do

Exceptions

- `private(list)` / `loop_private(list)`

  OpenMP allows the induction variable to be a member of the variable list. HPPM does not.

- `default(private|shared|none)`

The HPPM defaults to "shared" and allows the user to specify which variables should be private. The HP model does not provide "none"; therefore, undeclared variables will be treated as shared.

HP Programming Model directives

This section describes how the HP Programming Model (HPPM) directives are affected by the implementation of OpenMP.

Not Accepted with +Oopenmp

These HPPM directives will not be accepted when +Oopenmp is given.

- parallel
- end_parallel
- loop_parallel
- prefer_parallel
- begin_tasks
- next_task
- end_tasks
- critical_section
- end_critical_section
- ordered_section
- end_ordered_section
- loop_private
- parallel_private
- task_private
- save_last
- reduction
- dynsel
- barrier
- gate
- sync_routine

- thread_private
- node_private
- thread_private_pointer
- node_private_pointer
- near_shared
- far_shared
- block_shared
- near_shared_pointer
- far_shared_pointer

NOTE If +Oopenmp is given, the directives above are ignored.

Accepted with +Oopenmp

These HPPM directives will continue to be accepted when +Oopenmp is given.

- options
- no_dynsel
- no_unroll_and_jam
- no_parallel
- no_block_loop
- no_loop_transform
- no_distribute
- no_loop_dependence
- scalar
- unroll_and_jam
- block_loop

More information on OpenMP

For more information on OpenMP, see *www.openmp.org*.

11 Data privatization

Once HP shared memory classes are assigned, they are implemented throughout your entire program. Very efficient programs are written using these memory classes, as described in “Memory classes,” on page 245. However, these programs also require some manual

intervention. Any loops that manipulate variables that are explicitly assigned to a memory class must be manually parallelized. Once a variable is assigned a class, its class cannot change.

This chapter describes the workarounds provided by the HP Fortran and C compilers to support:

- Privatizing loop variables
- Privatizing task variables
- Privatizing region variables

Directives and pragmas for data privatization

This section describes the various directives and pragmas that are implemented to achieve data privatization. These directives and pragmas are discussed in Table 11-1.

Table 11-1 Data Privatization Directives and Pragmas

Directive / Pragma	Description	Level of parallelism
`loop_private (namelist)`	Declares a list of variables and/or arrays private to the following loop.	Loop
`parallel_private (namelist)`	Declares a list of variables and/or arrays private to the following parallel region.	Region
`save_last[(list)]`	Specifies that the variables in the comma-delimited list (also named in an associated `loop_private(namelist)` directive or pragma) must have their values saved into the shared variable of the same name at loop termination.	Loop
`task_private (namelist)`	Privatizes the variables and arrays specified in namelist for each task specified in the following `begin_tasks/end_tasks` block.	Task

These directives and pragmas allow you to easily and temporarily privatize parallel loop, task, or region data. When used with `prefer_parallel`, these directives and pragmas do not inhibit automatic compiler optimizations. This facilitates increased performance of your shared-memory program. It occurs with less work than is required when using the standard memory classes for manual parallelization and synchronization.

The data privatization directives and pragmas are used on local variables and arrays of any type, but they should not be used on data assigned to `thread_private`.

In some cases, data declared `loop_private`, `task_private`, or `parallel_private` is stored on the stacks of the spawned threads. Spawned thread stacks default to 80 Mbytes in size.

Privatizing loop variables

This section describes the following directives and pragmas associated with privatizing loop variables:

- `loop_private`
- `save_last`

loop_private

The `loop_private` directive and pragma declares a list of variables and/or arrays private to the immediately following Fortran `DO` or C `for` loop. `loop_private` array dimensions must be identifiable at compile-time.

The compiler assumes that data objects declared to be `loop_private` have no loop-carried dependences with respect to the parallel loops in which they are used. If dependences exist, they must be handled manually using the synchronization directives and techniques described in "Parallel synchronization," on page 255.

Each parallel thread of execution receives a private copy of the `loop_private` data object for the duration of the loop. No starting values are assumed for the data. Unless a `save_last` directive or pragma is specified, no ending value is assumed. If a `loop_private` data object is referenced within an iteration of the loop, it must be assigned a value previously on that same iteration.

The form of this directive and pragma is shown in Table 11-2.

Table 11-2 Form of `loop_private` directive and pragma

Language	Form
Fortran	`C$DIR LOOP_PRIVATE(`*namelist*`)`
C	`#pragma _CNX loop_private(`*namelist*`)`

where

namelist is a comma-separated list of variables and/or arrays that are to be private to the immediately following loop. *namelist* cannot contain structures, dynamic arrays, allocatable arrays, or automatic arrays.

Example 11-1 loop_private

The following is a Fortran example of `loop_private`:

```
C$DIR LOOP_PRIVATE(S)
      DO I = 1, N
C       S IS ONLY CORRECTLY PRIVATE IF AT LEAST
C       ONE IF TEST PASSES ON EACH ITERATION:
        IF(A(I) .GT. 0) S = A(I)
        IF(U(I) .LT. V(I)) S = V(I)
        IF(X(I) .LE. Y(I)) S = Z(I)
        B(I) = S * C(I) + D(I)
      ENDDO
```

A potential loop-carried dependence on `S` exists in this example. If none of the `IF` tests are true on a given iteration, the value of `S` must wrap around from the previous iteration. The `LOOP_PRIVATE(S)` directive indicates to the compiler that `S` does, in fact, get assigned on every iteration, and therefore it is safe to parallelize this loop.

If on any iteration none of the `IF` tests pass, an actual LCD exists and privatizing `S` results in wrong answers.

Example 11-2 Using loop_private with loop_parallel

Because the compiler does not automatically perform variable privatization in

`loop_parallel` loops, you must manually privatize loop data requiring privatization. This is easily done using the `loop_private` directive or pragma.

The following Fortran example shows how `loop_private` manually privatizes loop data:

```
      SUBROUTINE PRIV(X,Y,Z)
      REAL X(1000), Y(4,1000), Z(1000)
      REAL XMFIED(1000)
C$DIR LOOP_PARALLEL, LOOP_PRIVATE(XMFIED, J)
      DO I = 1, 4
C   INITIALIZE XMFIED; MFY MUST NOT WRITE TO X:
        CALL MFY(X, XMFIED)
        DO J = 1, 999
          IF (XMFIED(J) .GE. Y(I,J)) THEN
            Y(I,J) = XMFIED(J) * Z(J)
          ELSE
```

```
          XMFIED(J+1) = XMFIED(J)
        ENDIF
      ENDDO
    ENDDO
    END
```

Here, the LOOP_PARALLEL directive is required to parallelize the I loop because of the call to MFY. The X and Y arrays are in shared memory by default. X and Z are not written to, and the portions of Y written to in the J loop's IF statement are disjoint, so these shared arrays require no special attention. The local array XMFIED, however, is written to. But because XMFIED carries no values into or out of the I loop, it is privatized using LOOP_PRIVATE. This gives each thread running the I loop its own private copy of XMFIED, eliminating the expensive necessity of synchronized access to XMFIED.

Note that an LCD exists for XMFIED in the J loop, but because this loop runs serially on each processor, the dependence is safe.

Denoting induction variables in parallel loops

To safely parallelize a loop with the loop_parallel directive or pragma, the compiler must be able to correctly determine the loop's primary induction variable.

The compiler can find primary Fortran DO loop induction variables. It may, however, have trouble with DO WHILE or customized Fortran loops, and with all loop_parallel loops in C. Therefore, when you use the loop_parallel directive or pragma to manually parallelize a loop other than an explicit Fortran DO loop, you should indicate the loop's primary induction variable using the IVAR=*indvar* attribute to loop_parallel.

Example 11-3 Denoting induction variables in parallel loops

Consider the following Fortran example:

```
      I = 1
C$DIR LOOP_PARALLEL(IVAR = I)
10    A(I) = ...
      .
      .           ! ASSUME NO DEPENDENCES
      .
      I = I + 1
      IF(I .LE. N) GOTO 10
```

The above is a customized loop that uses I as its primary induction variable. To ensure parallelization, the LOOP_PARALLEL directive is placed immediately before the start of the loop, and the induction variable, I, is specified.

Example 11-4 Denoting induction variables in parallel loops

Primary induction variables in C loops are difficult for the compiler to find, so

`ivar` is required in all `loop_parallel` C loops. Its use is shown in the following example:

```
#pragma _CNX loop_parallel(ivar=i)
  for(i=0; i<n; i++) {
    a[i] = ...;
    .
    . /* assume no dependences */
    .
  }
}
```

Secondary induction variables

Secondary induction variables are variables used to track loop iterations, even though they do not appear in the Fortran `DO` statement. They cannot appear in addition to the primary induction variable in the C `for` statement.

Such variables *must* be a function of the primary loop induction variable, and they cannot be independent. Secondary induction variables must be assigned `loop_private`.

Example 11-5 Secondary induction variables

The following Fortran example contains an incorrectly incremented secondary induction variable:

```
C WARNING: INCORRECT EXAMPLE!!!!
      J = 1
C$DIR LOOP_PARALLEL
      DO I = 1, N
        J = J + 2 ! WRONG!!!
```

In this example, `J` does not produce expected values in each iteration because multiple threads are overwriting its value with no synchronization. The compiler cannot privatize `J` because it is a loop-carried dependence (LCD). This example is corrected by privatizing `J` and making it a function of `I`, as shown below.

```
C CORRECT EXAMPLE:
      J = 1
C$DIR LOOP_PARALLEL
C$DIR LOOP_PRIVATE(J) ! J IS PRIVATE
      DO I = 1, N
        J = (2*I)+1 ! J IS PRIVATE
```

As shown in the preceding example, `J` is assigned correct values on each iteration because it is a function of `I` and is safely privatized.

Example 11-6 Secondary induction variables

In C, secondary induction variables are sometimes included in

`for` statements, as shown in the following example:

```
/* warning: unparallelizable code follows */
#pragma _CNX loop_parallel(ivar=i)
  for(i=j=0; i<n;i++,j+=2) {
    a[i] = ...;
    .
    .
    .
  }
}
```

Because secondary induction variables must be private to the loop and must be a function of the primary induction variable, this example cannot be safely parallelized using `loop_parallel(ivar=i)`. In the presence of this directive, the secondary induction variable is not recognized.

To manually parallelize this loop, you must remove `j` from the `for` statement, privatize it, and make it a function of `i`.

The following example demonstrates how to restructure the loop so that `j` is a valid secondary induction variable:

```
#pragma _CNX loop_parallel(ivar=i)
#pragma _CNX loop_private(j)
  for(i=0; i<n; i++) {
    j = 2*i;
    a[i] = ...;
    .
    .
    .
  }
}
```

This method runs faster than placing `j` in a critical section because it requires no synchronization overhead, and the private copy of `j` used here can typically be more quickly accessed than a shared variable.

`save_last[(list)]`

A `save_last` directive or pragma causes the thread that executes the last iteration of the loop to write back the private (or local) copy of the variable into the global reference.

The save_last directive and pragma allows you to save the final value of loop_private data objects assigned in the last iteration of the immediately following loop.

- If *list* (the optional, comma-separated list of loop_private data objects) is specified, only the final values of those data objects in *list* are saved.
- If *list* is not specified, the final values of all loop_private data objects assigned in the last loop iteration are saved.

The values for this directive and pragma must be assigned in the last iteration. If the assignment is executed conditionally, it is your responsibility to ensure that the condition is met and the assignment executes. Inaccurate results may occur if the assignment does not execute on the last iteration. For loop_private arrays, only those elements of the array assigned on the last iteration are saved.

The form of this directive and pragma is shown in Table 11-3.

Table 11-3 Form of save_last directive and pragma

Language	Form
Fortran	C$DIR SAVE_LAST[(*list*)]
C	#pragma _CNX save_last[(*list*)]

save_last must appear immediately before or after the associated loop_private directive or pragma, or on the same line.

Example 11-7 save_last

The following is a C example of save_last:

```
#pragma _CNX loop_parallel(ivar=i)
#pragma _CNX loop_private(atemp, x, y)
#pragma _CNX save_last(atemp, x)
for(i=0;i<n;i++) {
  if(i==d[i]) atemp = a[i];
  if(i==e[i]) atemp = b[i];
  if(i==f[i]) atemp = c[i];
  a[i] = b[i] + c[i];
  b[i] = atemp;
  x = atemp * a[i];
  y = atemp * c[i];
}
.
.
```

```
.
if(atemp > amax) {
.
.
.
```

In this example, the `loop_private` variable `atemp` is conditionally assigned in the loop. In order for `atemp` to be truly private, you must be sure that at least one of the conditions is met so that `atemp` is assigned on every iteration.

When the loop terminates, the `save_last` pragma ensures that `atemp` and `X` contain the values they are assigned on the last iteration. These values can then be used later in the program. The value of `y`, however, is not available once the loop finishes because `y` is not specified as an argument to `save_last`.

Example 11-8 save_last

There are some loop contexts in which the

`save_last` directive and pragma is misleading.

The following Fortran code provides an example of this:

```
C$DIR LOOP_PARALLEL
C$DIR LOOP_PRIVATE(S)
C$DIR SAVE_LAST
      DO I = 1, N
        IF(G(I) .GT. 0) THEN
          S = G(I) * G(I)
        ENDIF
      ENDDO
```

While it may appear that the last value of `S` assigned is saved in this example, you must remember that the `SAVE_LAST` directive applies only to the last (`N`th) iteration, with no regard for any conditionals contained in the loop. For `SAVE_LAST` to be valid here, `G(N)` must be greater than 0 so that the assignment to `S` takes place on the final iteration.

Obviously, if this condition is predicted, the loop is more efficiently written to exclude the `IF` test, so the presence of a `SAVE_LAST` in such a loop is suspect.

Privatizing task variables

Task privatization is manually specified using the `task_private` directive and pragma. `task_private` declares a list of variables and/or arrays private to the immediately following tasks. It serves the same purpose for parallel tasks that `loop_private` serves for loops and `parallel_private` serves for regions.

`task_private`

The `task_private` directive must immediately precede, or appear on the same line as, its corresponding `begin_tasks` directive. The compiler assumes that data objects declared to be `task_private` have no dependences between the tasks in which they are used. If dependences exist, you must handle them manually using the synchronization directives and techniques described in "Parallel synchronization," on page 255.

Each parallel thread of execution receives a private copy of the `task_private` data object for the duration of the tasks. No starting or ending values are assumed for the data. If a `task_private` data object is referenced within a task, it must have been previously assigned a value in that task.

The form of this directive and pragma is shown in Table 11-4.

Table 11-4 Form of `task_private` directive and pragma

Language	Form
Fortran	`C$DIR TASK_PRIVATE(`*namelist*`)`
C	`#pragma _CNX task_private(`*namelist*`)`

where

namelist is a comma-separated list of variables and/or arrays that are to be private to the immediately following tasks. *namelist* cannot contain dynamic, allocatable, or automatic arrays.

Example 11-9 task_private

The following Fortran code provides an example of task privatization:

```
      REAL*8 A(1000), B(1000), WRK(1000)
      .
      .
      .
C$DIR BEGIN_TASKS, TASK_PRIVATE(WRK)
      DO I = 1, N
        WRK(I) = A(I)
      ENDDO
      DO I = 1, N
        A(I) = WRK(N+1-I)
        .
        .
        .
      ENDDO
C$DIR NEXT_TASK
      DO J = 1, M
        WRK(J) = B(J)
      ENDDO
      DO J = 1, M
        B(J) = WRK(M+1-J)
        .
        .
        .
      ENDDO
C$DIR END_TASKS
```

In this example, the `WRK` array is used in the first task to temporarily hold the `A` array so that its order is reversed. It serves the same purpose for the `B` array in the second task. `WRK` is assigned before it is used in each task.

Privatizing region variables

Regional privatization is manually specified using the `parallel_private` directive or pragma. `parallel_private` is provided to declare a list of variables and/or arrays private to the immediately following parallel region. It serves the same purpose for parallel regions as `task_private` does for tasks, and `loop_private` does for loops.

`parallel_private`

The `parallel_private` directive must immediately precede, or appear on the same line as, its corresponding `parallel` directive. Using `parallel_private` asserts that there are no dependences in the parallel region.

Do not use `parallel_private` if there are dependences.

Each parallel thread of execution receives a private copy of the `parallel_private` data object for the duration of the region. No starting or ending values are assumed for the data. If a `parallel_private` data object is referenced within a region, it must have been previously assigned a value in the region.

The form of this directive and pragma is shown in Table 11-5.

Table 11-5 Form of `parallel_private` directive and pragma

Language	Form
Fortran	`C$DIR PARALLEL_PRIVATE(`*namelist*`)`
C	`#pragma _CNX parallel_private(`*namelist*`)`

where

namelist is a comma-separated list of variables and/or arrays that are to be private to the immediately following parallel region. *namelist* cannot contain dynamic, allocatable, or automatic arrays.

Example 11-10 parallel_private

The following Fortran code shows how

parallel_private privatizes regions:

```
      REAL A(1000,8), B(1000,8), C(1000,8), AWORK(1000), SUM(8)
      INTEGER MYTID
      .
      .
      .
C$DIR PARALLEL(MAX_THREADS = 8)
C$DIR PARALLEL_PRIVATE(I,J,K,L,M,AWORK,MYTID)
      IF(NUM_THREADS() .LT. 8) STOP "NOT ENOUGH THREADS; EXITING"
      MYTID = MY_THREAD() + 1 !ADD 1 FOR PROPER SUBSCRIPTING
      DO I = 1, 1000
        AWORK(I) = A(I, MYTID)
      ENDDO
      DO J = 1, 1000
        A(J, MYTID) = AWORK(J) + B(J, MYTID)
      ENDDO
      DO K = 1, 1000
        B(K, MYTID) = B(K, MYTID) * AWORK(K)
        C(K, MYTID) = A(K, MYTID) * B(K, MYTID)
      ENDDO
      DO L = 1, 1000
        SUM(MYTID) = SUM(MYTID) + A(L,MYTID) + B(L,MYTID) +
C(L,MYTID)
      ENDDO
      DO M = 1, 1000
        A(M, MYTID) = AWORK(M)
      ENDDO
C$DIR END_PARALLEL
```

This example checks for a certain number of threads and divides up the work among those threads. The example additionally introduces the parallel_private variable AWORK.

Each thread initializes its private copy of AWORK to the values contained in a dimension of the array A at the beginning of the parallel region. This allows the threads to reference AWORK without regard to thread ID. This is because no thread can access any other thread's copy of AWORK. Because AWORK cannot carry values into or out of the region, it must be initialized within the region.

Induction variables in region privatization

All induction variables contained in a parallel region must be privatized. Code contained in the region runs on all available threads. Failing to privatize an induction variable would allow each thread to update the same shared variable, creating indeterminate loop counts on every thread.

In the previous example, in the J loop, after AWORK is initialized, AWORK is effectively used in a reduction on A; at this point its contents are identical to the MYTID dimension of A. After A is modified and used in the K and L loops, each thread restores a dimension of A's original values from its private copy of AWORK. This carries the appropriate dimension through the region unaltered.

12 Memory classes

The V-Class server implements only one partition of hypernode-local memory. This is accessed using the `thread_private` and `node_private` virtual memory classes. This chapter includes discussion of the following topics:

- Private versus shared memory
- Memory class assignments

The information in this chapter is provided for programmers who want to manually optimize their shared-memory programs on a single-node server. This is ultimately achieved by using compiler directives or pragmas to partition memory and otherwise control compiler optimizations. It can also be achieved using storage class specifiers in C and C++.

Porting multinode applications to single-node servers

Programs developed to run on multinode servers, such as the legacy X-Class server, can be run on K-Class or V-Class servers. The program runs as it would on one node of a multinode machine.

When a multinode application is executed on a single-node server:

- All `PARALLEL`, `LOOP_PARALLEL`, `PREFER_PARALLEL`, and `BEGIN_TASKS` directives containing `node` attributes are ignored.
- All variables, arrays and pointers that are declared to be `NEAR_SHARED`, `FAR_SHARED`, or `BLOCK_SHARED` are assigned to the `NODE_PRIVATE` class.
- The `THREAD_PRIVATE` and `NODE_PRIVATE` classes remain unchanged and function as usual.

See the *Exemplar Programming Guide for HP-UX Systems* for a complete description of how to program multinode applications using HP parallel directives.

Private versus shared memory

Private and shared data are differentiated by their accessibility and by the physical memory classes in which they are stored.

`thread_private` data is stored in node-local memory. Access to `thread_private` is restricted to the declaring thread.

When porting multinode applications to the HP single-node machine, all legacy shared memory classes (such as `near_shared`, `far_shared`, and `block_shared`) are automatically mapped to the `node_private` memory class. This is the default memory class on the K-Class and V-Class servers.

thread_private

`thread_private` data is private to each thread of a process. Each `thread_private` data object has its own unique virtual address within a hypernode. This virtual address maps to unique physical addresses in hypernode-local physical memory.

Any sharing of `thread_private` data items between threads (regardless of whether they are running on the same node) must be done by synchronized copying of the item into a shared variable, or by message passing.

NOTE `thread_private` data cannot be initialized in C, C++, or in Fortran `DATA` statements.

node_private

`node_private` data is shared among the threads of a process running on a given node. It is the default memory class on the V-Class single-node server, and does not need to be explicitly specified. `node_private` data items have one virtual address, and any thread on a node can access that node's `node_private` data using the same virtual address. This virtual address maps to a unique physical address in node-local memory.

Memory class assignments

In Fortran, compiler directives are used to assign memory classes to data items. In C and C++, memory classes are assigned through the use of syntax extensions, which are defined in the header file `/usr/include/spp_prog_model.h`. This file must be included in any C or C++ program that uses memory classes. In C++, you can also use operator `new` to assign memory classes.

- The Fortran memory class declarations must appear with other specification statements; they cannot appear within executable statements.
- In C and C++, parallel storage class extensions are used, so memory classes are assigned in variable declarations.

On a single-node system, HP compilers provide mechanisms for statically assigning memory classes. This chapter discusses these memory class assignments.

The form of the directives and pragmas associated with is shown in Table 12-1.

Table 12-1 Form of memory class directives and variable declarations

Language	Form
Fortran	`C$DIR` *memory_class_name* (*namelist*)
C/C++	`#include <spp_prog_model.h>` . . . [*storage_class_specifier*] *memory_class_name type_specifier namelist*

where (for Fortran)

memory_class_name can be `THREAD_PRIVATE`, or `NODE_PRIVATE`

namelist is a comma-separated list of variables, arrays, and/or `COMMON` block names to be assigned the class *memory_class_name*. `COMMON` block names must be

enclosed in slashes (/), and only entire COMMON blocks can be assigned a class. This means arrays and variables in *namelist* must not also appear in a COMMON block and must not be equivalenced to data objects in COMMON blocks.

where (for C)

storage_class_specifier specifies a nonautomatic storage class

memory_class_name is the desired memory class (thread_private, node_private)

type_specifier is a C or C++ data type (int, float, etc.)

namelist is a comma-separated list of variables and/or arrays of type *type_specifier*

C and C++ data objects

In C and C++, data objects that are assigned a memory class must have static storage duration. This means that if the object is declared within a function, it must have the storage class extern or static. If such an object is not given one of these storage classes, its storage class defaults to automatic and it is allocated on the stack. Stack-based objects cannot be assigned a memory class; attempting to do so results in a compile-time error.

Data objects declared at file scope and assigned a memory class need not specify a storage class.

All C and C++ code examples presented in this chapter assume that the following line appears above the code presented:

```
#include <spp_prog_model.h>
```

This header file maps user symbols to the implementation reserved space.

If operator new is used, it is also assumed that the line below appears above the code:

```
#include <new.h>
```

If you assign a memory class to a C or C++ structure, all structure members must be of the same class.

Once a data item is assigned a memory class, the class cannot be changed.

Static assignments

Static memory class assignments are physically located with variable type declarations in the source. Static memory classes are typically used with data objects that are accessed with equal frequency by all threads. These include objects of the `thread_private` and `node_private` classes. Static assignments for all classes are explained in the subsections that follow.

thread_private

Because `thread_private` variables are replicated for every thread, static declarations make the most sense for them.

Example 12-1 thread_private

In Fortran, the `thread_private` memory class is assigned using the `THREAD_PRIVATE` compiler directive, as shown in the following example:

```
      REAL*8 TPX(1000)
      REAL*8 TPY(1000)
      REAL*8 TPZ(1000), X, Y
      COMMON /BLK1/ TPZ, X, Y
C$DIR THREAD_PRIVATE(TPX, TPY, /BLK1/)
```

Each array declared here is 8000 bytes in size, and each scalar variable is 8 bytes, for a total of 24,016 bytes of data. The entire `COMMON` block `BLK1` is placed in `thread_private` memory along with `TPX` and `TPY`. All memory space is replicated for each thread in hypernode-local physical memory.

Example 12-2 thread_private

The following C/C++ example demonstrates several ways to declare `thread_private` storage. The data objects declared here are not scoped analogously to those declared in the Fortran example:

```
/* tpa is global: */
thread_private double tpa[1000];
func() {
  /* tpb is local to func: */
  static thread_private double tpb[1000];
  /* tpc, a and b are declared elsewhere: */
  extern thread_private double tpc[1000],a,b;
  .
  .
  .
```

The C/C++ `double` data type provides the same precision as Fortran's `REAL*8`. The `thread_private` data declared here occupies the same amount of memory as that declared in the Fortran example. `tpa` is available to all functions lexically following it in the file. `tpb` is local to `func` and inaccessible to other functions. `tpc`, `a`, and `b` are declared at filescope in another file that is linked with this one.

Assume a Fortran or C program containing the appropriate example is running on a 4-hypernode subcomplex with 16 processors per hypernode and the `thread_private` memory is allocated from `node_private` memory (see the mpa(1) man page). Each data item requires 16 virtual addresses, for a total of 384,256 bytes of virtual space. These virtual addresses map to 16 physical addresses per hypernode, or 64 total physical addresses per data item, requiring a total of 1,537,024 (64×24016) bytes of physical memory.

Example 12-3 thread_private COMMON blocks in parallel subroutines

Data local to a procedure that is called in parallel is effectively private because storage for it is allocated on the thread's private stack. However, if the data is in a Fortran `COMMON` block (or if it appears in a `DATA` or `SAVE` statement), it is not stored on the stack. Parallel accesses to such nonprivate data must be synchronized if it is assigned a shared class. Additionally, if the parallel copies of the procedure do not need to share the data, it can be assigned a private class.

Consider the following Fortran example:

```
      INTEGER A(1000,1000)
      .
      .
      .
C$DIR LOOP_PARALLEL(THREADS)
      DO I = 1, N
        CALL PARCOM(A(1,I))
        .
        .
        .
      ENDDO
      SUBROUTINE PARCOM(A)
      INTEGER A(*)
      INTEGER C(1000), D(1000)
      COMMON /BLK1/ C, D
C$DIR THREAD_PRIVATE(/BLK1/)
      INTEGER TEMP1, TEMP2
      D(1:1000) = ...
      .
      .
      .
      CALL PARCOM2(A, JTA)
```

```
      .
      .
      .
      END

      SUBROUTINE PARCOM2(B,JTA)
      INTEGER B(*), JTA
      INTEGER C(1000), D(1000)
      COMMON /BLK1/ C, D
C$DIR THREAD_PRIVATE(/BLK1/)
      DO J = 1, 1000
        C(J) = D(J) * B(J)
      ENDDO
      END
      .
      .
      .
```

In this example, COMMON block BLK1 is declared THREAD_PRIVATE, so every parallel instance of PARCOM gets its own copy of the arrays C and D.

Because this code is already thread-parallel when the COMMON block is defined, no further parallelism is possible, and BLK1 is therefore suitable for use anywhere in PARCOM. The local variables TEMP1 and TEMP2 are allocated on the stack, so each thread effectively has private copies of them.

node_private

Because the space for node_private variables is physically replicated, static declarations make the most sense for them.

In Fortran, the node_private memory class is assigned using the NODE_PRIVATE compiler directive, as shown in the following example:

```
      REAL*8 XNP(1000)
      REAL*8 YNP(1000)
      REAL*8 ZNP(1000), X, Y
      COMMON /BLK1/ ZNP, X, Y
C$DIR NODE_PRIVATE(XNP, YNP, /BLK1/)
```

Again, the data requires 24,016 bytes. The contents of BLK1 are placed in node_private memory along with XNP and YNP. Space for each data item is replicated once per hypernode in hypernode-local physical memory. The same virtual address is used by each thread to access its hypernode's copy of a data item.

node_private variables and arrays can be initialized in Fortran DATA statements.

Example 12-4 node_private

The following example shows several ways to declare

`node_private` data objects in C and C++:

```
/* npa is global: */
node_private double npa[1000];
func() {
  /* npb is local to func: */
  static node_private double npb[1000];
  /* npc, a and b are declared elsewhere: */
  extern node_private double npc[1000],a,b;
  .
  .
  .
```

The `node_private` data declared here occupies the same amount of memory as that declared in the Fortran example. Scoping rules for this data are similar to those given for the `thread_private` C/C++ example.

13 Parallel synchronization

Most of the manual parallelization techniques discussed in “Parallel programming techniques” on page 181, allow you to take advantage of the compilers’ automatic dependence checking and data privatization. The examples that used the `LOOP_PRIVATE` and `TASK_PRIVATE` directives

and pragmas in “Data privatization” on page 229, are exceptions to this. In these cases, manual privatization is required, but is performed on a loop-by-loop basis. Only the simplest data dependences are handled.

This chapter discusses manual parallelizations and that handle multiple and ordered data dependences. This includes a discussion of the following topics:

- Thread-parallelism
- Synchronization tools
- Synchronizing code

Thread-parallelism

Only one level of parallelism is supported: thread-parallelism. If you attempt to spawn thread-parallelism from within a thread-parallel, your directives on the inner thread-parallel construct are ignored.

Thread ID assignments

Programs are initiated as a collection of threads, one per available processor. All but thread 0 are idle until parallelism is encountered.

When a process begins, the threads created to run it have unique kernel thread IDs. Thread 0, which runs all the serial code in the program, has kernel thread ID 0. The rest of the threads have unique but unspecified kernel thread IDs at this point. The `num_threads()` intrinsic returns the number of threads created, regardless of how many are active when it is called.

When thread 0 encounters parallelism, it spawns some or all of the threads created at program start. This means it causes these threads to go from idle to active, at which point they begin working on their share of the parallel code. All available threads are spawned by default, but this is changed using various compiler directives.

If the parallel structure is thread-parallel, then `num_threads()` threads are spawned, subject to user-specified limits. At this point, kernel thread 0 becomes spawn thread 0, and the spawned threads are assigned spawn thread IDs ranging from 0..`num_threads()`-1. This range begins at what used to be kernel thread 0.

If you manually limit the number of spawned threads, these IDs range from 0 to one less than your limit.

Synchronization tools

The compiler cannot automatically parallelize loops containing complex dependences. However, a rich set of directives, pragmas, and data types is available to help you manually parallelize such loops by synchronizing and ordering access to the code containing the dependence.

These directives can also be used to synchronize dependences in parallel tasks. They allow you to efficiently exploit parallelism in structures that would otherwise be unparallelizable.

Using gates and barriers

Gates allow you to restrict execution of a block of code to a single thread. They are allocated, locked, unlocked, and deallocated using the functions described in “Synchronization functions” on page 259. They can also be used with the ordered or critical section directives, which automate the locking and unlocking functions.

Barriers block further execution until all executing threads reach the barrier and then thread 0 can proceed past the barrier.

Gates and barriers use dynamically allocatable variables, declared using compiler directives in Fortran and using data declarations in C and C++. They may be initialized and referenced only by passing them as arguments to the functions discussed in the following sections.

The forms of these variable declarations are shown in Table 13-1.

Table 13-1 Forms of gate and barriers variable declarations

Language	Form

Fortran	`C$DIR GATE(`*namelist*`)`
	
	`C$DIR BARRIER(`*namelist*`)`

C/C++	`gate_t` *namelist*`;`
	
	`barrier_t` *namelist*`;`

where

namelist is a comma-separated list of one or more gate or barrier names, as appropriate.

In C and C++

In C and C++, gates and barriers should appear only in definition and declaration statements, and as formal, and actual arguments. They declare default-size variables.

In Fortran

The Fortran `gate` and `barrier` variable declarations can only appear:

- In `COMMON` statements (statement must precede `GATE` directive/`BARRIER` directive)
- In `DIMENSION` statements (statement must precede `GATE` directive/`BARRIER` directive)
- In preceding type statements
- As dummy arguments
- As actual arguments

Gate and barrier types override other same-named types declared prior to the gate/barrier pragmas. Once a variable is defined as a gate or barrier, it cannot be redeclared as another type. Gates and barriers cannot be equivalenced.

If you place gates or barriers in `COMMON`, the `COMMON` block declaration must precede the `GATE` directive/`BARRIER` directive. The `COMMON` block should contain only gates or only barriers. Arrays of gates or barriers must be dimensioned using `DIMENSION` statements. The `DIMENSION` statement must precede the `GATE` directive/`BARRIER` directive.

Synchronization functions

The Fortran, C, and C++ allocation, deallocation, lock and unlock functions for use with gates and barriers are described in this section. The 4- and 8-byte versions are provided. The 8-byte Fortran functions are primarily for use with compiler options that change the default data size to 8 bytes (for example, `-I8`). You must be consistent in your choice of versions—memory allocated using an 8-byte function must be deallocated using an 8-byte function.

Examples of using these functions are presented and explained throughout this section.

Allocation functions

Allocation functions allocate memory for a gate or barrier. When first allocated, gate variables are unlocked. The forms of these allocation functions are shown in Table 13-2.

Table 13-2 Forms of allocation functions

Language	Form

Fortran	`INTEGER FUNCTION ALLOC_GATE(`*gate*`)`
	
	`INTEGER FUNCTION ALLOC_BARRIER(`*barrier*`)`

C/C++	`int alloc_gate(gate_t *`*gate_p*`);`
	
	`int alloc_barrier(barrier_t *`*barrier_p*`);`

where (in Fortran)

gate and *barrier* are gate or barrier variables.

where (in C/C++)

gate_p and *barrier_p* are pointers of the indicated type.

Deallocation functions

The deallocation functions free the memory assigned to the specified gate or barrier variable. The forms of these deallocation functions are shown in Table 13-3.

Table 13-3 Forms of deallocation functions

Language	Form

Fortran	`INTEGER FUNCTION FREE_GATE(`*gate*`)`
	
	`INTEGER FUNCTION FREE_BARRIER(`*barrier*`)`

Table 13-3 Forms of deallocation functions (Continued)

Language	Form

C/C++	`int free_gate(gate_t *gate_p);`
	
	`int free_barrier(barrier_t *barrier_p);`

where (in Fortran)

gate and *barrier* are gate or barrier variables previously declared in the gate and barrier allocation functions.

where (in C/C++)

gate_p and *barrier_p* are pointers of the indicated type.

NOTE Always free gates and barriers after using them.

Locking functions

The locking functions acquire a gate for exclusive access. If the gate cannot be immediately acquired, the calling thread waits for it. The conditional locking functions, which are prefixed with `COND_` or `cond_`, acquire a gate only if a wait is not required. If the gate is acquired, the functions return 0; if not, they return -1.

The forms of these locking functions are shown in Table 13-4.

Table 13-4 Forms of locking functions

Language	Form

Fortran	`INTEGER FUNCTION LOCK_GATE(`*gate*`)`
	
	`INTEGER FUNCTION COND_LOCK_GATE(`*gate*`)`

C/C++	`int lock_gate(gate_t *`*gate_p*`);`
	
	`int cond_lock_gate(gate_t *`*gate_p*`);`

where (in Fortran)

gate is a gate variable.

where (in C/C++)

gate_p is a pointer of the indicated type.

Unlocking functions

The unlocking functions release a gate from exclusive access. Gates are typically released by the thread that locks them, unless a gate was locked by thread 0 in serial code. In that case it might be unlocked by a single different thread in a parallel construct.

The form of these unlocking functions is shown in Table 13-5.

Table 13-5 Form of unlocking functions

Language	Form
Fortran	`INTEGER FUNCTION UNLOCK_GATE(`*gate*`)`
C/C++	`int unlock_gate(gate_t *`*gate_p*`);`

where (in Fortran)

gate is a gate variable.

where (in C/C++)

gate_p is a pointer of the indicated type.

Wait functions

The wait functions use a barrier to cause the calling thread to wait until the specified number of threads call the function. At this point all threads are released from the function simultaneously.

The form of the wait functions is shown in Table 13-6.

Table 13-6 Form of wait functions

Language	Form
Fortran	`INTEGER FUNCTION WAIT_BARRIER(`*barrier*`,`*nthr*`)`
C/C++	`int wait_barrier(barrier_t *`*barrier_p*`,const int *`*nthr*`);`

where (in Fortran)

barrier is a barrier variable of the indicated type and *nthr* is the number of threads calling the routine.

where (in C/C++)

barrier_p is a pointer of the indicated type and *nthr* is a pointer referencing the number of threads calling the routine.

You can use a barrier variable in multiple calls to the `wait` function, if you ensure that two such barriers are not simultaneously active. You must also verify that *nthr* reflects the correct number of threads.

sync_routine

Among the most basic optimizations performed by the HP compilers is code motion, which is described in Standard optimization features. This optimization moves code across routine calls. If the routine call is to a synchronization function that the compiler cannot identify as such, and the code moved must execute on a certain side of it, this movement may result in wrong answers.

The compiler is aware of all synchronization functions and does not move code across them when they appear directly in code. However, if the synchronization function is hidden in a user-defined routine, the compiler has no way of knowing about it and may move code across it.

Any time you call synchronization functions indirectly using your own routines, you must identify your routines with a `sync_routine` directive or pragma.

The form of sync_routine is shown in Table 13-7.

Table 13-7 Form of sync_routine directive and pragma

Language	Form
Fortran	C$DIR SYNC_ROUTINE (*routinelist*)
C	#pragma CNX sync_routine (*routinelist*)

where

routinelist is a comma-separated list of synchronization routines.

Example 13-1 sync_routine

sync_routine is effective only for the listed routines that lexically follow it in the same file where it appears. The following Fortran code example features the sync_routine directive:

```
      INTEGER MY_LOCK, MY_UNLOCK
C$DIR GATE(LOCK)
C$DIR SYNC_ROUTINE(MY_LOCK, MY_UNLOCK)
      .
      .
      .
      LCK = ALLOC_GATE(LOCK)
C$DIR LOOP_PARALLEL
      DO I = 1, N
        LCK = MY_LOCK(LOCK)
        .
        .
        .
        SUM = SUM + A(I)
        LCK = MY_UNLOCK(LOCK)
      ENDDO
      .
      .
      .
      INTEGER FUNCTION MY_LOCK(LOCK)
C$DIR GATE(LOCK)
      LCK = LOCK_GATE(LOCK)
      MY_LOCK = LCK
      RETURN
      END

      INTEGER FUNCTION MY_UNLOCK(LOCK)
C$DIR GATE(LOCK)
      LCK = UNLOCK_GATE(LOCK)
```

```
      MY_UNLOCK = LCK
      RETURN
      END
```

In this example, MY_LOCK and MY_UNLOCK are user functions that call the LOCK_GATE and UNLOCK_GATE intrinsics. The SYNC_ROUTINE directive prevents the compiler from moving code across the calls to MY_LOCK and MY_UNLOCK.

Programming techniques such as this are used to implement portable code across several parallel architectures that support critical sections. This would be done using different syntax. For example, MY_LOCK and MY_UNLOCK could simply be modified to call the correct locking and unlocking functions.

Example 13-2 sync_routine

The following C example achieves the same task as shown in the previous Fortran example:

```
#include <spp_prog_model.h>
main() {
  int i, n, lck, sum, a[1000];
  gate_t lock;
#pragma _CNX sync_routine(mylock, myunlock)
  .
  .
  .
  lck = alloc_gate(&lock);
#pragma _CNX loop_parallel(ivar=i)
  for(i=0; i<n; i++) {
    lck = mylock(&lock);
    .
    .
    .
    sum = sum+a[i];
    lck = myunlock(&lock);
  }
}

int mylock(gate_t *lock) {
  int lck;
  lck = lock_gate(lock);  return lck;
}
int myunlock(gate_t *lock) {
  int lck;
  lck = unlock_gate(lock);
  return lck;
}
```

loop_parallel(ordered)

The `loop_parallel(ordered)` directive and pragma is designed to be used with ordered sections to execute loops with ordered dependences in loop order. It accomplishes this by parallelizing the loop so that consecutive iterations are initiated on separate processors, in loop order.

While `loop_parallel(ordered)` guarantees starting order, it does not guarantee ending order, and it provides no automatic synchronization. To avoid wrong answers, you must manually synchronize dependences using the ordered section directives, pragmas, or the synchronization intrinsics (see “Critical sections” on page 267 of this chapter for more information).

Example 13-3 loop_parallel, ordered

The following Fortran code shows how

`loop_parallel(ordered) is structured`:

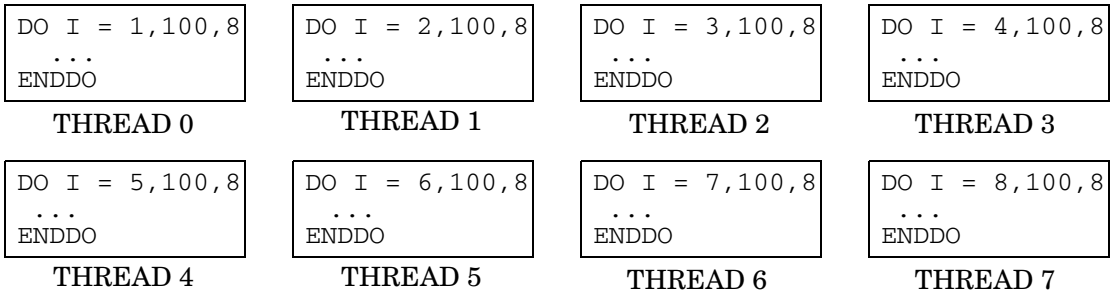
```
C$DIR LOOP_PARALLEL(ORDERED)
      DO I = 1, 100
        .
        . !CODE CONTAINING ORDERED SECTION
        .
      ENDDO
```

Assume that the body of this loop contains code that is parallelizable except for an ordered data dependence (otherwise there is no need to order the parallelization). Also assume that 8 threads, numbered 0..7, are available to run the loop in parallel. Each thread would then execute code equivalent to the following:

```
DO I = (my_thread()+1), 100, num_threads()
  ...
ENDDO
```

Figure 13-1 illustrates this assumption.

Figure 13-1 Ordered parallelization



Here, thread 0 executes first, followed by thread 1, and so on. Each thread starts its iteration after the preceding iteration has started. A manually defined ordered section prevents one thread from executing the code in the ordered section until the previous thread exits the section. This means that thread 0 cannot enter the section for iteration 9 until thread 7 exits it for iteration 8.

This is efficient only if the loop body contains enough code to keep a thread busy until all other threads start their consecutive iterations, thus taking advantage of parallelism.

You may find the `max_threads` attribute helpful when fine-tuning `loop_parallel(ordered)` loops to fully exploit their parallel code.

Examples of synchronizing `loop_parallel(ordered)` loops are shown in “Synchronizing code” on page 270.

Critical sections

Critical sections allow you to synchronize simple, nonordered dependences. You must use the `critical_section` directive or pragma to enter a critical section, and the `end_critical_section` directive or pragma to exit one.

Critical sections must not contain branches to outside the section. The two directives must appear in the same procedure, but they do not have to be in the same procedure as the parallel construct in which they are used. This means that the directives can exist in a procedure that is called in parallel.

The forms of these directives and pragmas are shown in Table 13-8.

Table 13-8 Forms of `critical_section`, `end_critical_section` directives and pragmas

Language	Form

Fortran	`C$DIR CRITICAL_SECTION[(`*gate*`)]`
	`...`
	`C$DIR END_CRITICAL_SECTION`

C	`#pragma _CNX critical_section[(`*gate*`)]` ...`#pragma _CNX end_critical_section`

where

gate is an optional gate variable used for access to the critical section. *gate* must be appropriately declared as described in the “Using gates and barriers” on page 258.

The gate variable is required when synchronizing access to a shared variable from multiple parallel tasks.

- When a gate variable is specified, it must be allocated (using the `alloc_gate` intrinsic) outside of parallel code prior to use
- If no gate is specified, the compiler creates a unique gate for the critical section
- When a gate is no longer needed, it should be deallocated using the `free_gate` function.

NOTE Critical sections add synchronization overhead to your program. They should only be used when the amount of parallel code is significantly larger than the amount of code containing the dependence.

Ordered sections

Ordered sections allow you to synchronize dependences that must execute in iteration order. The `ordered_section` and `end_ordered_section` directives and pragmas are used to specify critical sections within manually defined, ordered `loop_parallel` loops only.

The forms of these directives and pragmas are shown in Table 13-9.

Table 13-9 Forms of `ordered_section`, `end_ordered_section` directives and pragmas

Language	Form

Fortran	`C$DIR ORDERED_SECTION(`*gate*`)`
	`...`
	`C$DIR END_ORDERED_SECTION`

C	`#pragma _CNX`
	`ordered_section(`*gate*`)` `...#pragma _CNX`
	`end_ordered_section`

where

gate is a required gate variable that must be allocated and, if necessary, unlocked prior to invocation of the parallel loop containing the ordered section. *gate* must be appropriately declared as described in the "Using gates and barriers" section of this chapter.

Ordered sections must be entered through `ordered_section` and exited through `end_ordered_section`. They cannot contain branches to outside the section. Ordered sections are subject to the same control flow rules as critical sections.

NOTE As with critical sections, ordered sections should be used with care, as they add synchronization overhead to your program. They should only be used when the amount of parallel code is significantly larger than the amount of code containing the dependence.

Synchronizing code

Code containing dependences are parallelized by synchronizing the way the parallel tasks access the dependence. This is done manually using the gates, barriers and synchronization functions discussed earlier in this chapter, or semiautomatically using critical and ordered sections, described in the following sections.

Using critical sections

The `critical_section` example page 198 isolates a single critical section in a loop, so that the `critical_section` directive does not require a gate. In this case, the critical section directives automate allocation, locking, unlocking and deallocation of the needed gate. Multiple dependences and dependences in manually-defined parallel tasks are handled when user-defined gates are used with the directives.

Example 13-4 critical_section

The following Fortran example, however, uses the manual methods of code synchronization:

```
      REAL GLOBAL_SUM
C$DIR FAR_SHARED(GLOBAL_SUM)
C$DIR GATE(SUM_GATE)
      .
      .
      .
      LOCK = ALLOC_GATE(SUM_GATE)
C$DIR BEGIN_TASKS
      CONTRIB1 = 0.0
      DO J = 1, M
        CONTRIB1 = CONTRIB1 + FUNC1(J)
      ENDDO
      .
      .
      .
C$DIR CRITICAL_SECTION (SUM_GATE)
      GLOBAL_SUM = GLOBAL_SUM + CONTRIB1
C$DIR END_CRITICAL_SECTION
      .
      .
      .
```

```
C$DIR NEXT_TASK
      CONTRIB2 = 0.0
      DO I = 1, N
        CONTRIB2 = CONTRIB2 + FUNC2(J)
      ENDDO
      .
      .
      .
C$DIR CRITICAL_SECTION (SUM_GATE)
      GLOBAL_SUM = GLOBAL_SUM + CONTRIB2
C$DIR END_CRITICAL_SECTION
      .
      .
      .
C$DIR END_TASKS
      LOCK = FREE_GATE(SUM_GATE)
```

Here, both parallel tasks must access the shared GLOBAL_SUM variable. To ensure that GLOBAL_SUM is updated by only one task at a time, it is placed in a critical section. The critical sections both reference the SUM_GATE variable. This variable is unlocked on entry into the parallel code (gates are always unlocked when they are allocated).

When one task reaches the critical section, the CRITICAL_SECTION directive automatically locks SUM_GATE. The END_CRITICAL_SECTION directive unlocks SUM_GATE on exit from the section. Because access to both critical sections is controlled by a single gate, the sections must execute one at a time.

Example 13-5 Gated critical sections

Gated critical sections are also useful in loops containing multiple critical sections when there are dependences between the critical sections. If no dependences exist between the sections, gates are not needed. The compiler automatically supplies a unique gate for every critical section lacking a gate.

The C example below uses gates so that threads do not update at the same time, within a critical section:

```
static far_shared float absum;
static gate_t gate1;
int adjb[...];
.
.
.
lock = alloc_gate(&gate1);
```

```
#pragma _CNX loop_parallel(ivar=i)
for(i=0;i<n;i++) {
  a[i] = b[i] + c[i];
#pragma _CNX critical_section(gate1)
  absum = absum + a[i];
#pragma _CNX end_critical_section
  if(adjb[i]) {
    b[i] = c[i] + d[i];
#pragma _CNX critical_section(gate1)
    absum = absum + b[i];
#pragma _CNX end_critical_section
  }
  .
  .
  .
}
lock = free_gate(&gate1);
```

The shared variable `absum` must be updated after `a(I)` is assigned and again if `b(i)` is assigned. Access to `absum` must be guarded by the same gate to ensure that two threads do not attempt to update it at once. The critical sections protecting the assignment to `ABSUM` must explicitly name this gate, or the compiler chooses unique gates for each section, potentially resulting in incorrect answers.There must be a substantial amount of parallelizable code outside of these critical sections to make parallelizing this loop cost-effective.

Using ordered sections

Like critical sections, ordered sections lock and unlock a specified gate to isolate a section of code in a loop. However, they also ensure that the enclosed section of code executes in the same order as the iterations of the ordered parallel loop that contains it.

Once a given thread passes through an ordered section, it cannot enter again until all other threads have passed through in order. This ordering is difficult to implement without using the ordered section directives or pragmas.

You must use a `loop_parallel(ordered)` directive or pragma to parallelize any loop containing an ordered section. See ”`loop_parallel(ordered)`” on page 266 for a description of this.

Example 13-6 Ordered sections

The following Fortran example contains a backward loop-carried dependence on the array `A` that would normally inhibit parallelization.

```
DO I = 2, N
   . ! PARALLELIZABLE CODE...
   .
   .
  A(I) = A(I-1) + B(I)
   . ! MORE PARALLELIZABLE CODE...
   .
   .
ENDDO
```

Assuming that the dependence shown is the only one in the loop, and that a significant amount of parallel code exists elsewhere in the loop, the dependence is isolated. The loop is parallelized as shown below:

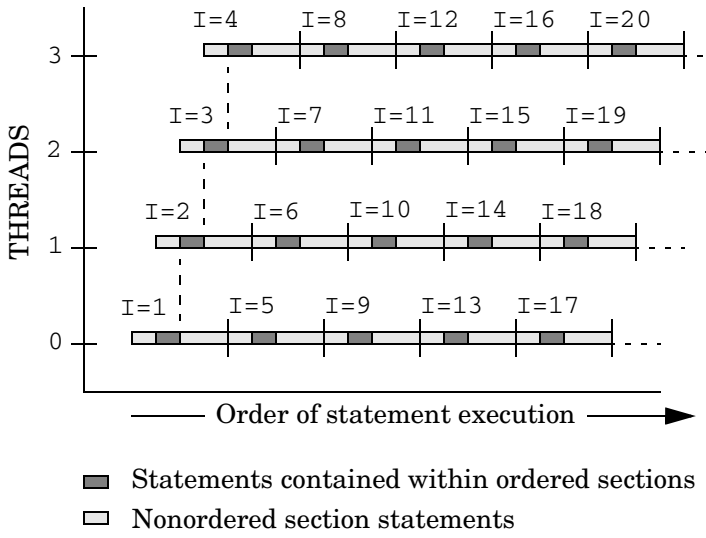
```
C$DIR GATE(LCD)
      LOCK = ALLOC_GATE(LCD)
      .
      .
      .
      LOCK = UNLOCK_GATE(LCD)
C$DIR LOOP_PARALLEL(ORDERED)
      DO I = 2, N
        . ! PARALLELIZABLE CODE...
        .
        .
C$DIR   ORDERED_SECTION(LCD)
        A(I) = A(I-1) + B(I)



C$DIR   END_ORDERED_SECTION
        . ! MORE PARALLELIZABLE CODE...
        .
        .
      ENDDO
      LOCK = FREE_GATE(LCD)
```

The ordered section containing the `A(I)` assignment executes in iteration order. This ensures that the value of `A(I-1)` used in the assignment is always valid. Assuming this loop runs on four threads, the synchronization of statement execution between threads is illustrated in Figure 13-2.

Figure 13-2 `LOOP_PARALLEL(ORDERED)` synchronization



As shown by the dashed lines between initial iterations for each thread, one ordered section must be completed before the next is allowed to begin execution. Once a thread exits an ordered section, it cannot reenter until all other threads have passed through in sequence.

Overlap of nonordered statements, represented as lightly shaded boxes, allows all threads to proceed fully loaded. Only brief idle periods occur on 1, 2, and 3 at the beginning of the loop, and on 0, 1, and 2 at the end.

Example 13-7 Ordered section limitations

Each thread in a parallel loop containing an ordered section must pass through the ordered section exactly once on every iteration of the loop. If you execute an ordered section conditionally, you must execute it in all possible branches of the condition. If the code contained in the section is not valid for some branches, you can insert a blank ordered section, as shown in the following Fortran example:

```
C$DIR GATE (LCD)
      .
      .
      .
      LOCK = ALLOC_GATE(LCD)
C$DIR LOOP_PARALLEL(ORDERED)
      DO I = 1, N
        .
        .
        .
        IF (Z(I) .GT. 0.0) THEN
C$DIR     ORDERED_SECTION(LCD)
C         HERE'S THE BACKWARD LCD:
          A(I) = A(I-1) + B(I)
C$DIR     END_ORDERED_SECTION
        ELSE
C         HERE IS THE BLANK ORDERED SECTION:
C$DIR     ORDERED_SECTION(LCD)
C$DIR     END_ORDERED_SECTION
        ENDIF
        .
        .
        .
      ENDDO
      LOCK = FREE_GATE(LCD)
```

No matter which path through the `IF` statement the loop takes, and though the `ELSE` section is empty, it must pass through the ordered section. This allows the compiler to properly synchronize the ordered loop. It is assumed that a substantial amount of parallel code exists outside the ordered sections, to offset the synchronization overhead.

Example 13-8 Ordered section limitations

Ordered sections within nested loops can create similar, but more difficult to recognize, problems. Consider the following Fortran example (gate manipulation is omitted for brevity):

```
C$DIR LOOP_PARALLEL(ORDERED)
      DO I = 1, 99
        DO J = 1,M
          .
          .
          .
```

```
C$DIR      ORDERED_SECTION(ORDGATE)
           A(I,J) = A(I+1,J)
C$DIR      END_ORDERED_SECTION
           .
           .
           .
         ENDDO
       ENDDO
```

Recall that once a given thread has passed through an ordered section, it cannot reenter it until all other threads have passed through in order. This is only possible in the given example if the number of available threads integrally divides 99 (the `I` loop limit). If not, deadlock results.

To better understand this:

- Assume 6 threads, numbered 0 through 5, are running the parallel `I` loop.
- For `I` = 1, `J` = 1, thread 0 passes through the ordered section and loops back through `J`, stopping when it reaches the ordered section again for `I` = 1, `J` = 2. It cannot enter until threads 1 through 5 (which are executing `I` = 2 through 6, `J` = 1 respectively) pass through in sequence. This is not a problem, and the loop proceeds through `I` = 96 in this fashion in parallel.
- For `I` > 96, all 6 threads are no longer needed. In a single loop nest this would not pose a problem as the leftover 3 iterations would be handled by threads 0 through 2. When thread 2 exited the ordered section it would hit the `ENDDO` and the `I` loop would terminate normally.
- But in this example, the `J` loop isolates the ordered section from the `I` loop, so thread 0 executes `J` = 1 for `I` = 97, loops through `J` and waits during `J` = 2 at the ordered section for thread 5, which has gone idle, to complete. Threads 1 and 2 similarly execute `J` = 1 for `I` = 98 and `I` = 99, and similarly wait after incrementing `J` to 2. The entire `J` loop must terminate before the `I` loop can terminate, but the `J` loop can never terminate because the idle threads 3, 4, and 5 never pass through the ordered section. As a result, deadlock occurs.

To handle this problem, you can expand the ordered section to include the entire `j` loop, as shown in the following C example:

```
#pragma _CNX loop_parallel(ordered,ivar=i)
for(i=0;i<99;i++) {
#pragma _CNX ordered_section(ordgate)
  for(j=0;j<m;j++) {
    .
    .
    .
    a[i][j] = a[i+1][j];
    .
    .
    .
  }
#pragma _CNX end_ordered_section
}
```

In this approach, each thread executes the entire `j` loop each time it enters the ordered section, allowing the `i` loop to terminate normally regardless of the number of threads available.

Another approach is to manually interchange the `i` and `j` loops, as shown in the following Fortran example:

```
      DO J = 1, M
        LOCK = UNLOCK_GATE(ORDGATE)
C$DIR   LOOP_PARALLEL(ORDERED)
        DO I = 1, 99
          .
          .
          .
C$DIR     ORDERED_SECTION(ORDGATE)
          A(I,J) = A(I+1,J)
C$DIR     END_ORDERED_SECTION
          .
          .
          .
        ENDDO
      ENDDO
```

Here, the `I` loop is parallelized on every iteration of the `J` loop. The ordered section is not isolated from its parent loop, so the loop can terminate normally. This example has added benefit; elements of `A` are accessed more efficiently.

Manual synchronization

Ordered and critical sections allow you to isolate dependences in a structured, semiautomatic manner. The same isolation is accomplished manually using the functions discussed in “Synchronization functions” on page 259.

Example 13-9 Critical sections and gates

Below is a simple critical section Fortran example using `loop_parallel`:

```
C$DIR LOOP_PARALLEL
      DO I = 1, N  ! LOOP IS PARALLELIZABLE
        .
        .
        .
C$DIR   CRITICAL_SECTION
        SUM = SUM + X(I)
C$DIR   END_CRITICAL_SECTION
        .
        .
        .
      ENDDO
```

As shown, this example is easily implemented using critical sections. It is manually implemented in Fortran, using gate functions, as shown below:

```
C$DIR GATE(CRITSEC)
      .
      .
      .
      LOCK = ALLOC_GATE(CRITSEC)
C$DIR LOOP_PARALLEL
      DO I = 1, N
        .
        .
        .
        LOCK = LOCK_GATE(CRITSEC)
        SUM = SUM + X(I)
        LOCK = UNLOCK_GATE(CRITSEC)
        .
        .
```

```
      .
      ENDDO
      LOCK = FREE_GATE(CRITSEC)
```

As shown, the manual implementation requires declaring, allocating, and deallocating a gate, which must be locked on entry into the critical section using the LOCK_GATE function and unlocked on exit using UNLOCK_GATE.

Example 13-10 Conditionally lock critical sections

Another advantage of manually defined critical sections is the ability to conditionally lock them. This allows the task that wishes to execute the section to proceed with other work if the lock cannot be acquired. This construct is useful, for example, in situations where one thread is performing I/O for several other parallel threads.

While a processing thread is reading from the input queue, the queue is locked, and the I/O thread can move on to do output. While a processing thread is writing to the output queue, the I/O thread can do input. This allows the I/O thread to keep as busy as possible while the parallel computational threads execute their (presumably large) computational code.

This situation is illustrated in the following Fortran example. Task 1 performs I/O for the 7 other tasks, which perform parallel computations by calling the THREAD_WRK subroutine:

```
      COMMON INGATE,OUTGATE,COMPBAR
C$DIR GATE (INGATE, OUTGATE)
C$DIR BARRIER (COMPBAR)
      REAL DIN(:), DOUT(:)       ! I/O BUFFERS FOR TASK 1
      ALLOCATABLE DIN, DOUT      ! THREAD 0 WILL ALLOCATE
      REAL QIN(1000,1000), QOUT(1000,1000) ! SHARED I/O
QUEUES
      INTEGER NIN/0/,NOUT/0/ ! QUEUE ENTRY COUNTERS
C     CIRCULAR BUFFER POINTERS:
      INTEGER
IN_QIN/1/,OUT_QIN/1/,IN_QOUT/1/,OUT_QOUT/1/
        COMMON /DONE/ DONEIN, DONECOMP
      LOGICAL DONECOMP, DONEIN
C                          SIGNALS FOR COMPUTATION DONE
AND INPUT DONE
      LOGICAL COMPDONE, INDONE
C                          FUNCTIONS TO RETURN DONECOMP
```

```
AND DONEIN
      LOGICAL INFLAG, OUTFLAG  ! INPUT READ AND OUTPUT
WRITE FLAGS
C$DIR THREAD_PRIVATE (INFLAG,OUTFLAG) ! ONLY NEEDED BY
TASK 1
C                                          (WHICH RUNS ON
THREAD 0)
        IF (NUM_THREADS() .LT. 8) STOP 1
        IN = 10
        OUT = 11
      LOCK = ALLOC_GATE(INGATE)
      LOCK = ALLOC_GATE(OUTGATE)
      IBAR = ALLOC_BARRIER(COMPBAR)
      DONECOMP = .FALSE.
C$DIR BEGIN_TASKS             ! TASK 1 STARTS HERE
      INFLAG = .TRUE.
      DONEIN = .FALSE.
      ALLOCATE(DIN(1000),DOUT(1000)) ! ALLOCATE LOCAL
BUFFERS
     DO WHILE(.NOT. INDONE() .OR. .NOT. COMPDONE() .OR.
NOUT .GT. 0)
C                       DO TILL EOF AND COMPUTATION DONE
AND OUTPUT DONE
       IF(NIN.LT.1000.AND.(.NOT.COMPDONE()) .AND.(.NOT.
INDONE())) THEN



C                         FILL QUEUE
          IF (INFLAG) THEN  ! FILL BUFFER FIRST:
            READ(IN, IOSTAT = IOS) DIN  ! READ A RECORD;
QUIT ON EOF
             IF(IOS .EQ. -1) THEN
               DONEIN = .TRUE. ! SIGNAL THAT INPUT IS DONE
                INFLAG = .TRUE.
             ELSE
               INFLAG = .FALSE.
             ENDIF
          ENDIF
C SYNCHRONOUSLY ENTER INTO INPUT QUEUE:
C         BLOCK QUEUE ACCESS WITH INGATE:
          IF (COND_LOCK_GATE(INGATE) .EQ. 0 .AND. .NOT.
```

```
INDONE()) THEN
             QIN(:,IN_QIN) = DIN(:)   ! COPY INPUT BUFFER
INTO QIN
             IN_QIN=1+MOD(IN_QIN,1000)   ! INCREMENT INPUT
BUFFER PTR
             NIN = NIN + 1   ! INCREMENT INPUT QUEUE ENTRY
COUNTER
              INFLAG = .TRUE.
              LOCK = UNLOCK_GATE(INGATE)   ! ALLOW INPUT
QUEUE ACCESS
            ENDIF
          ENDIF
C SYNCHRONOUSLY REMOVE FROM OUTPUT QUEUE:
C           BLOCK QUEUE ACCESS WITH OUTGATE:
            IF (COND_LOCK_GATE(OUTGATE) .EQ. 0) THEN
             IF (NOUT .GT. 0) THEN
              DOUT(:)=QOUT(:,OUT_QOUT)   ! COPY OUTPUT QUE
INTO BUFFR
              OUT_QOUT=1+MOD(OUT_QOUT,1000)
C                                          INCREMENT OUTPUT
BUFR PTR
              NOUT = NOUT - 1   ! DECREMENT OUTPUT QUEUE
ENTRY COUNTR
              OUTFLAG = .TRUE.
             ELSE
              OUTFLAG = .FALSE.
             ENDIF
              LOCK = UNLOCK_GATE(OUTGATE)
C                                 ALLOW OUTPUT QUEUE
ACCESS
            IF (OUTFLAG) WRITE(OUT) DOUT   ! WRITE A RECORD
            ENDIF
       ENDDO
C                                   TASK 1 ENDS HERE
C$DIR NEXT_TASK                  ! TASK 2:
       CALL
THREAD_WRK(NIN,NOUT,QIN,QOUT,IN_QIN,OUT_QIN,IN_QOUT,OUT_
QOUT)
       IBAR = WAIT_BARRIER(COMPBAR,7)
C$DIR NEXT_TASK                  ! TASK 3:
       CALL
THREAD_WRK(NIN,NOUT,QIN,QOUT,IN_QIN,OUT_QIN,IN_QOUT,OUT_
```

```
QOUT)
      IBAR = WAIT_BARRIER(COMPBAR,7)
C$DIR NEXT_TASK                ! TASK 4:
      CALL
THREAD_WRK(NIN,NOUT,QIN,QOUT,IN_QIN,OUT_QIN,IN_QOUT,OUT_
QOUT)
      IBAR = WAIT_BARRIER(COMPBAR,7)
C$DIR NEXT_TASK                ! TASK 5:
      CALL
THREAD_WRK(NIN,NOUT,QIN,QOUT,IN_QIN,OUT_QIN,IN_QOUT,OUT_
QOUT)
      IBAR = WAIT_BARRIER(COMPBAR,7)
C$DIR NEXT_TASK                ! TASK 6:
      CALL
THREAD_WRK(NIN,NOUT,QIN,QOUT,IN_QIN,OUT_QIN,IN_QOUT,OUT_
QOUT)
      IBAR = WAIT_BARRIER(COMPBAR,7)
C$DIR NEXT_TASK                ! TASK 7:
      CALL
THREAD_WRK(NIN,NOUT,QIN,QOUT,IN_QIN,OUT_QIN,IN_QOUT,OUT_
QOUT)
      IBAR = WAIT_BARRIER(COMPBAR,7)
C$DIR NEXT_TASK                ! TASK 8:
      CALL
THREAD_WRK(NIN,NOUT,QIN,QOUT,IN_QIN,OUT_QIN,IN_QOUT,OUT_
QOUT)
      IBAR = WAIT_BARRIER(COMPBAR,7)
      DONECOMP = .TRUE.
C$DIR END_TASKS
      END
```

Before looking at the `THREAD_WRK` subroutine it is necessary to examine these parallel tasks, particularly task 1, the I/O server. Task 1 performs all the I/O required by all the tasks:

- Conditionally locked gates control task 1's access to one section of code that fills the input queue and one that empties the output queue.
- Task 1 works by first filling an input buffer. The code that does this does not require gate protection because no other tasks attempt to access the input buffer array.

- The section of code where the input buffer is copied into the input queue, however, must be protected by gates to prevent any threads from trying to read the input queue while it is being filled.

The other seven tasks perform computational work, receiving their input from and sending their output to task 1's queues. If a task acquires a lock on the input queue, task 1 cannot fill it until the task is done reading from it.

- When task 1 cannot get a lock to access the input queue code, it tries to lock the output queue code.
- If it gets a lock here, it can copy the output queue into the output buffer array and relinquish the lock. It can then proceed to empty the output buffer.
- If another task is writing to the output queue, task 1 loops back and begins the entire process over again.
- When the end of the input file is reached, all computation is complete, and the output queue is empty: task 1 is finished.

NOTE The task loops on `DONEIN` (using `INDONE()`), which is initially false. When input is exhausted, `DONEIN` is set to true, signalling all tasks that there is no more input.

The `INDONE()` function references `DONEIN`, forcing a memory reference. If `DONEIN` were referenced directly, the compiler might optimize it into a register and consequently not detect a change in its value.

This means that task 1 has four main jobs to do:

1. Read input into input buffer—no other tasks access the input buffer. This is done in parallel regardless of what other tasks are doing, as long as the buffer needs filling.
2. Copy input buffer into input queue—the other tasks read their input from the input queue, therefore it can only be filled when no computational task is reading it. This section of code is protected by the `INGATE` gate. It can run in parallel with the computational portions of other tasks, but only one task can access the input queue at a time.

3. Copy output queue into output buffer—the output queue is where other tasks write their output. It can only be emptied when no computational task is writing to it. This section of code is protected by the OUTGATE gate. It can run in parallel with the computational portions of other tasks, but only one task can access the output queue at a time.
4. Write out output buffer—no other tasks access the output buffer. This is done in parallel regardless of what the other tasks are doing.

Next, it is important to look at the subroutine THREAD_WRK, which tasks 2-7 call to perform computations.

```
      SUBROUTINE
     >
THREAD_WRK(NIN,NOUT,QIN,QOUT,IN_QIN,OUT_QIN,IN_QOUT,OUT_
QOUT)
      INTEGER NIN,NOUT
      REAL QIN(1000,1000), QOUT(1000,1000) ! SHARED I/O
QUEUES
      INTEGER OUT_QIN, OUT_QOUT
      COMMON INGATE,OUTGATE,COMPBAR
C$DIR GATE(INGATE, OUTGATE)
      REAL WORK(1000)     ! LOCAL THREAD PRIVATE WORK
ARRAY
      LOGICAL OUTFLAG, INDONE
      OUTFLAG = .FALSE.
C$DIR THREAD_PRIVATE (WORK) ! EVERY THREAD WILL CREATE A
COPY

     DO WHILE(.NOT. INDONE() .OR. NIN.GT.0 .OR. OUTFLAG)
C                                WORK/QOUT EMPTYING LOOP
        IF (.NOT. OUTFLAG) THEN  ! IF NO PENDING OUTPUT
C$DIR CRITICAL_SECTION (INGATE)  ! BLOCK ACCESS TO INPUT
QUE
          IF (NIN .GT. 0) THEN  ! MORE WORK TO DO
            WORK(:) = QIN(:,OUT_QIN)
            OUT_QIN = 1 + MOD(OUT_QIN, 1000)
            NIN = NIN - 1
            OUTFLAG = .TRUE.
C                          INDICATE THAT INPUT DATA HAS
BEEN RECEIVED
          ENDIF
C$DIR END_CRITICAL_SECTION
```

```
          .
          .   ! SIGNIFICANT PARALLEL CODE HERE USING WORK
ARRAY
          .
         ENDIF
         IF (OUTFLAG) THEN  ! IF PENDING OUTPUT, MOVE TO
OUTPUT QUEUE
C AFTER INPUT QUEUE IS USED IN COMPUTATION, FILL OUTPUT
QUEUE:
C$DIR CRITICAL_SECTION (OUTGATE) ! BLOCK ACCESS TO
OUTPUT QUEUE
           IF(NOUT.LT.1000) THEN
C                               IF THERE IS ROOM IN THE
OUTPUT QUEUE
             QOUT(:,IN_QOUT) = WORK(:) ! COPY WORK INTO
OUTPUT QUEUE
             IN_QOUT =1+MOD(IN_QOUT,1000) ! INCREMENT
BUFFER PTR
           NOUT = NOUT + 1 ! INCREMENT OUTPUT QUEUE ENTRY
COUNTER
             OUTFLAG = .FALSE.  ! INDICATE NO OUTPUT
PENDING
           ENDIF
C$DIR END_CRITICAL_SECTION
         ENDIF
       ENDDO ! END WORK/QOUT EMPTYING LOOP
       END   ! END THREAD_WRK       LOGICAL FUNCTION
INDONE()
C THIS FUNCTION FORCES A MEMORY REFERENCE TO GET THE
DONEIN VALUE
       LOGICAL DONEIN
       COMMON /DONE/ DONEIN, DONECOMP
       INDONE = DONEIN
       END

       LOGICAL FUNCTION COMPDONE()

C THIS FUNCTION FORCES A MEMORY REFERENCE TO GET THE
DONECOMP VALUE
       LOGICAL DONECOMP
```

```
COMMON /DONE/ DONEIN, DONECOMP
COMPDONE= DONECOMP
END
```

Notice that the gates are accessed through `COMMON` blocks. Each thread that calls this subroutine allocates a `thread_private WORK` array.

This subroutine contains a loop that tests `INDONE()`.

- The loop copies the input queue into the local `WORK` array, then does a significant amount of computational work that has been omitted for simplicity.

NOTE The computational work is the main code that executes in parallel, if there is not a large amount of it, the overhead of setting up these parallel tasks and critical sections cannot be justified.

- The loop encompasses this computation, and also the section of code that copies the `WORK` array to the output queue.
- This construct allows final output to be written after all input has been used in computation.
- To avoid accessing the input queue while it is being filled or accessed by another thread, the section of code that copies it into the local `WORK` array is protected by a critical section.

NOTE This section must be unconditionally locked as the computational threads cannot do something else until they receive their input.

Once the input queue has been copied, `THREAD_WRK` can perform its large section of computational code in parallel with whatever the other tasks are doing. After the computational section is finished, another unconditional critical section must be entered so that the results are written to the output queue. This prevents two threads from accessing the output queue at once.

Problems like this require performance testing and tuning to achieve optimal parallel efficiency. Variables such as the number of computational threads and the size of the I/O queues are adjusted to yield the best processor utilization.

14 Troubleshooting

This chapter discusses common optimization problems that occasionally occur when developing programs for SMP servers. Possible solutions to these problems are offered where applicable.

Optimization can remove instructions, replace them, and change the order in which they execute. In some cases, improper optimizations can cause unexpected or incorrect results or code that slows down at higher optimization levels. In other cases, user error can cause similar problems in code that contains improperly used syntactically correct constructs or directives. If you encounter any of these problems, look for the following possible causes:

- Aliasing
- False cache line sharing
- Floating-point imprecision
- Invalid subscripts
- Misused directives and pragmas
- Triangular loops
- Compiler assumptions

NOTE Compilers perform optimizations assuming that the source code being compiled is valid. Optimizations done on source that violates certain ANSI standard rules can cause the compilers to generate incorrect code.

Aliasing

As described in the section “Inhibiting parallelization” on page 111, an alias is an alternate name for an object. Fortran `EQUIVALENCE` statements, C pointers, and procedure calls in both languages can potentially cause aliasing problems. Problems can and do occur at optimization levels `+O3` and above. However, code motion can also cause aliasing problems at optimization levels `+O1` and above.

Because they frequently use pointers, C programs are especially susceptible to aliasing problems. By default, the optimizer assumes that a pointer can point to any object in the entire application. Thus, any two pointers are potential aliases. The C compiler has two algorithms you can specify in place of the default: an ANSI-C aliasing algorithm and a type-safe algorithm.

The ANSI-C algorithm is enabled [disabled] through the `+O[no]ptrs_ansi` option.

The type-safe algorithm is enabled [disabled] by specifying the command-line option `+O[no]ptrs_strongly_typed`.

The defaults for these options are `+Onoptrs_ansi` and `+Onoptrs_strongly_typed`.

ANSI algorithm

ANSI C provides strict type-checking. Pointers and variables cannot alias with pointers or variables of a different base type. The ANSI C aliasing algorithm may not be safe if your program is not ANSI compliant.

Type-safe algorithm

The type-safe algorithm provides stricter type-checking. This allows the C compiler to use a stricter algorithm that eliminates many potential aliases found by the ANSI algorithm.

Specifying aliasing modes

To specify an aliasing mode, use one of the following options on the C compiler command line:

- `+Optrs_ansi`
- `+Optrs_strongly_typed`

Additional C aliasing options are discussed in “Controlling optimization” on page 119.

Iteration and stop values

Aliasing a variable in an array subscript can make it unsafe for the compiler to parallelize a loop. Below are several situations that can prevent parallelization.

Using potential aliases as addresses of variables

In the following example, the code passes `&j` to `getval`; `getval` can use that address in any number of ways, including possibly assigning it to `iptr`. Even though `iptr` is not passed to `getval`, `getval` might still access it as a global variable or through another alias. This situation makes `j` a potential alias for `*iptr`.

```
void subex(iptr, n, j)
int *iptr, n, j;
{
   n = getval(&j,n);

   for (j--; j<n; j++)
      iptr[j] += 1;
}
```

This potential alias means that `j` and `iptr[j]` might occupy the same memory space for some value of `j`. The assignment to `iptr[j]` on that iteration would also change the value of `j` itself. The possible alteration of `j` prevents the compiler from safely parallelizing the loop. In this case, the Optimization Report says that no induction variable could be found for the loop, and the compiler does not parallelize the loop. (For information on Optimization Reports, see “Optimization Report” on page 155).

Avoid taking the address of any variable that is used as the iteration variable for a loop. To parallelize the loop in `subex`, use a temporary variable `i` as shown in the following code:

```
void subex(iptr, n, j)
int *iptr, n, j;
{
   int i;
   n = getval(&j,n);
   i=j;
   for (i--; i<n; i++)
      iptr[i] += 1;
}
```

Using hidden aliases as pointers

In the next example, `ialex` takes the address of `j` and assigns it to `*ip`. Thus, `j` becomes an alias for `*ip` and, potentially, for `*iptr`. Assigned values to `iptr[j]` within the loop could alter the value of `j`. As a result, the compiler cannot use `j` as an induction variable and, without an induction variable, it cannot count the iterations of the loop. When the compiler cannot find the loop's iteration count the compiler cannot parallelize the loop.

```
int *ip;
void ialex(iptr)
int *iptr;{
  int j;
  *ip = &j;{
  for (j=0; j<2048; j++)
     iptr[j] = 107;
}
```

To parallelize this loop, remove the line of code that takes the address of `j` or introduce a temporary variable.

Using a pointer as a loop counter

Compiling the following function, the compiler finds that `*j` is not an induction variable. This is because an assignment to `iptr[*j]` could alter the value of `*j` within the loop. The compiler does not parallelize the loop.

```
void ialex2(iptr, j, n)
int *iptr;
int *j, n;
{
```

```
    for (*j=0; *j<n; (*j)++)
       iptr[*j] = 107;
}
```

Again, this problem is solved by introducing a temporary iteration variable.

Aliasing stop variables

In the following code, the stop variable `n` becomes a possible alias for `*iptr` when `&n` is passed to `foo`. This means that `n` is altered during the execution of the loop. As a result, the compiler cannot count the number of iterations and cannot parallelize the loop.

```
void salex(int *iptr, int n)
{
   int i;
   foo(&n);
   for (i=0; i < n; i++)
      iptr[i] += iptr[i];
   return;
}
```

To parallelize the affected loop, eliminate the call to `foo`, move the call below the loop. In this case, flow-sensitive analysis takes care of the aliasing. You can also create a temporary variable as shown below:

```
void salex(int *iptr, int n)
{
   int i, tmp;
   foo(&n);
   tmp = n;
   for (i=0; i < tmp; i++)
      iptr[i] += iptr[i];
   return;
}
```

Because `tmp` is not aliased to `iptr`, the loop has a fixed stop value and the compiler parallelizes it.

Global variables

Potential aliases involving global variables cause optimization problems in many programs. The compiler cannot tell whether another function causes a global variable to become aliased.

The following code uses a global variable, n, as a stop value. Because n may have its address taken and assigned to ik outside the scope of the function, n must be considered a potential alias for *ik. The value of n, therefore, is altered on any iteration of the loop. The compiler cannot determine the stop value and cannot parallelize the loop.

```
int n, *ik;
void foo(int *ik)
{
   int i;

   for (i=0; i<n; i++)
      ik[i]=i;
}
```

Using a temporary local variable solves the problem.

```
int n;
void foo(int *ik)
{
   int i,stop = n;

   for (i=0; i<stop; ++i)
      ik[i]=i;
}
```

If ik is a global variable instead of a pointer, the problem does not occur. Global variables do not cause aliasing problems except when pointers are involved. The following code is parallelized:

```
int n, ik[1000];
void foo()
{
   int i;

   for (i=0; i<n; i++)
      ik[i] = i;
}
```

False cache line sharing

False cache line sharing is a form of cache thrashing. It occurs whenever two or more threads in a parallel program are assigning different data items in the same cache line. This section discusses how to avoid false cache line sharing by restructuring the data layout and controlling the distribution of loop iterations among threads.

Consider the following Fortran code:

```
REAL*4 A(8)
DO I = 1, 8
  A(I) = ...
  .
  .
  .
ENDDO
```

Assume there are eight threads, each executing one of the above iterations. `A(1)` is on a processor cache line boundary (32-byte boundary for V2250 servers) so that all eight elements are in the same cache line. Only one thread at a time can “own” the cache line, so not only is the above loop, in effect, run serially, but every assignment by a thread requires an invalidation of the line in the cache of its previous “owner.” These problems would likely eliminate any benefit of parallelization.

Taking all of the above into consideration, review the code:

```
REAL*4 B(100,100)
DO I = 1, 100
  DO J = 1, 100
    B(I,J) = ...B(I,J-1)...
  ENDDO
ENDDO
```

Assume there are eight threads working on the `I` loop in parallel. The `J` loop cannot be parallelized because of the dependence. *** 'HP compilers, by default, give each thread about the same number of iterations, assigning (if necessary) one extra iteration to some threads. This happens until all iterations are assigned to a thread. Table 14-2 shows the default distribution of the I loop across 8 threads.' on page 298 *** shows how the array maps to cache lines, assuming that `B(1,1)` is on

a cache line boundary. Array entries that fall on cache line boundaries are in shaded cells. Array entries that fall on cache line boundaries are noted by hashmarks.

Table 14-1 Initial mapping of array to cache lines

1, 1	1, 2	1, 3	1, 4	. . .	1, 99	1,100
2, 1	2, 2	2, 3	2, 4	. . .	2, 99	2,100
3, 1	3, 2	3, 3	3, 4	. . .	3, 99	3,100
4, 1	4, 2	4, 3	4, 4	. . .	4, 99	4,100
5, 1	5, 2	5, 3	5, 4	. . .	5, 99	5,100
6, 1	6, 2	6, 3	6, 4	. . .	6, 99	6,100
7, 1	7, 2	7, 3	7, 4	. . .	7, 99	7,100
8, 1	8, 2	8, 3	8, 4	. . .	8, 99	8,100
9, 1	9, 2	9, 3	9, 4	. . .	9, 99	9,100
10, 1	10, 2	10, 3	10, 4	. . .	10, 99	10,100
11, 1	11, 2	11, 3	11, 4	. . .	11, 99	11,100
12, 1	12, 2	12, 3	12, 4	. . .	12, 99	12,100
13, 1	13, 2	13, 3	13, 4	. . .	13, 99	13, 100
. . .	. . .	. . .	. . .	. . .	. . .	. . .
97, 1	97, 2	97, 3	97, 4	. . .	97, 99	97,100
98, 1	98, 2	98, 3	98, 4	. . .	98, 99	98,100
99, 1	99, 2	99, 3	99, 4	. . .	99, 99	99,100
100, 1	100, 2	100, 3	100, 4	. . .	100, 99	100,100

Array entries surrounded by hashmarks(#) are on cache line boundaries.

HP compilers, by default, give each thread about the same number of iterations, assigning (if necessary) one extra iteration to some threads. This happens until all iterations are assigned to a thread. Table 14-2 shows the default distribution of the `I` loop across 8 threads.

Table 14-2 Default distribution of the `I` loop

Thread ID	Iteration range	Number of iterations
0	1-12	12
1	13-25	13
2	26-37	12
3	38-50	13
4	51-62	12
5	63-75	13
6	76-87	12
7	88-100	13

This distribution of iterations causes threads to share cache lines. For example, thread 0 assigns the elements `B(9:12,1)`, and thread 1 assigns elements `B(13:16,1)` in the same cache line. In fact, every thread shares cache lines with at least one other thread. Most share cache lines with two other threads. This type of sharing is called false because it is a result of the data layout and the compiler's distribution of iterations. It is not inherent in the algorithm itself. Therefore, it is reduced or even removed by:

1. Restructuring the data layout by aligning data on cache line boundaries
2. Controlling the iteration distribution.

Aligning data to avoid false sharing

Because false cache line sharing is partially due to the layout of the data, one step in avoiding it is to adjust the layout. Adjustments are typically made by aligning data on cache line boundaries. Aligning arrays generally improves performance. However, it can occasionally decrease performance.

The second step in avoiding false cache line sharing is to adjust the distribution of loop iterations. This is covered in “Distributing iterations on cache line boundaries” on page 299.

Aligning arrays on cache line boundaries

Note the assumption that in the previous example, array `B` starts on a cache line boundary. The methods below force arrays in Fortran to start on cache line boundaries:

- Using uninitialized `COMMON` blocks (blocks with no `DATA` statements). These blocks start on 64-byte boundaries.
- Using `ALLOCATE` statements. These statements return addresses on 64-byte boundaries. This only applies to parallel executables.

The methods below force arrays in C to start on cache line boundaries:

- Using the functions `malloc` or `memory_class_malloc`. These functions return pointers on 64-byte boundaries.
- Using uninitialized global arrays or structs that are at least 32 bytes. Such arrays and structs are aligned on 64-byte boundaries.
- Using uninitialized data of the `external` storage class in C that is at least 32 bytes. Data is aligned on 64-byte boundaries.

Distributing iterations on cache line boundaries

Recall that the default iteration distribution causes thread 0 to work on iterations 1-12 and thread 1 to work on iterations 13-25, and so on. Even though the cache lines are aligned across the columns of the array (see *** 'HP compilers, by default, give each thread about the same number of iterations, assigning (if necessary) one extra iteration to some threads. This happens until all iterations are assigned to a thread. Table 14-2 shows the default distribution of the I loop across 8 threads.' on page 298 ***), the iteration distribution still needs to be changed. Use the `CHUNK_SIZE` attribute to change the distribution:

```
      REAL*4 B(112,100)
      COMMON /ALIGNED/ B
C$DIR PREFER_PARALLEL (CHUNK_SIZE=16)
      DO I = 1, 100
        DO J = 1, 100
          B(I,J) = ...B(I,J-1)...
        ENDDO
      ENDDO
```

You must specify a constant CHUNK_SIZE attribute. However, the ideal is to distribute work so that all but one thread works on the same number of whole cache lines, and the remaining thread works on any partial cache line. For example, given the following:

NITS = number of iterations

NTHDS = number of threads

LSIZE = line size in words (8 for 4-byte data, 4 for 8-byte data, 2 for 16-byte data) size in words (8 for 4-byte data

the ideal CHUNK_SIZE would be:

```
CHUNK_SIZE = LSIZE * (1 + ( (1 + (NITS - 1) / LSIZE ) - 1
)/NTHDS)
```

For the code above, these numbers are:

NITS = 100

LSIZE = 8 (aligns on V2250 boundaries for 4-byte data)

NTHDS =8

```
CHUNK_SIZE = 8 * (1 + ( (1 + (100 - 1) / 8 ) - 1) / 8)
           = 8 * (1 + ( (1 +  12           ) - 1) / 8)
           = 8 * (1 + ( 12                    ) / 8)
           = 8 * (1 + 1                          )
           = 16
```

CHUNK_SIZE = 16 causes threads 0, 1, ..., 6 to execute iterations 1-16, 17-32, ..., 81-96, respectively. Thread 7 executes iterations 97-100. As a result there is no false cache line sharing, and parallel performance is greatly improved.

You cannot specify the ideal CHUNK_SIZE for every loop. However, using

CHUNK_SIZE = *x*

where *x* times the data size (in bytes) is an integral multiple of 32, eliminates false cache line sharing. This is only if the following two conditions below are met:

- The arrays are already properly aligned (as discussed earlier in this section).
- The first iteration accesses the first element of each array being assigned. For example, in a loop `DO I = 2, N`, because the loop starts at `I = 2`, the first iteration does not access the first element of the array. Consequently, the iteration distribution does not match the cache line alignment.

The number 32 is used because the cache line size is 32 bytes for V2250 servers.

Thread-specific array elements

Sometimes a parallel loop has each thread update a unique element of a shared array, which is further processed by thread 0 outside the loop.

Consider the following Fortran code in which false sharing occurs:

```
      REAL*4 S(8)
C$DIR LOOP_PARALLEL
      DO I = 1, N
        .
        .
        .
       S(MY_THREAD()+1) = ... ! EACH THREAD ASSIGNS ONE
ELEMENT OF S
        .
        .
        .
      ENDDO
C$DIR NO_PARALLEL
      DO J = 1, NUM_THREADS()
       = ...S(J)              ! THREAD 0 POST-PROCESSES S
      ENDDO
```

The problem here is that potentially all the elements of `S` are in a single cache line, so the assignments cause false sharing. One approach is to change the code to force the unique elements into different cache lines, as indicated in the following code:

```
      REAL*4 S(8,8)
C$DIR LOOP_PARALLEL
      DO I = 1, N
        .
        .
        .
        S(1,MY_THREAD()+1) = ... ! EACH THREAD ASSIGNS
ONE ELEMENT OF S
        .
        .
        .
      ENDDO
C$DIR NO_PARALLEL
      DO J = 1, NUM_THREADS()
       = ...S(1,J)             ! THREAD 0 POST-PROCESSES
S
      ENDDO
```

Scalars sharing a cache line

Sometimes parallel tasks assign unique scalar variables that are in the same cache line, as in the following code:

```
      COMMON /RESULTS/ SUM, PRODUCT
C$DIR BEGIN_TASKS
      DO I = 1, N
        .
        .
        .
        SUM = SUM + ...
        .
        .
        .
      ENDDO
C$DIR NEXT_TASK
      DO J = 1, M
        .
        .
        .
        PRODUCT = PRODUCT * ...
        .
        .
```

```
        .
      ENDDO
C$DIR END_TASKS
```

Working with unaligned arrays

The most common cache-thrashing complication using arrays and loops occurs when arrays assigned within a loop are unaligned with each other. There are several possible causes for this:

- Arrays that are local to a routine are allocated on the stack.
- Array dummy arguments might be passed an element other than the first in the actual argument.
- Array elements might be assigned with different offset indexes.

Consider the following Fortran code:

```
COMMON /OKAY/ X(112,100)
        ...
CALL UNALIGNED (X(I,J))
        ...
SUBROUTINE UNALIGNED (Y)
REAL*4 Y(*)
    ! Y(1) PROBABLY NOT ON A CACHE LINE BOUNDARY
```

The address of `Y(1)` is unknown. However, if elements of `Y` are heavily assigned in this routine, it may be worthwhile to compute an alignment, given by the following formula:

```
LREM = LSIZE - ( (
( LOC(Y(1))-4, LSIZE*x) + 4) /x)
```

where

`LSIZE`	is the appropriate cache line size in words
x	is the data size for elements of `Y`

For this case, `LSIZE` on V2250 servers is 32 bytes in single precision words (8 words). Note that:

```
( ( MOD ( LOC(Y(1))-4, LSIZE*4) + 4) /4)
```

returns a value in the set 1, 2, 3, ..., `LSIZE`, so `LREM` is in the range 0 to 7.

Then a loop such as:

```
DO I = 1, N
  Y(I) = ...
ENDDO
```

is transformed to:

```
C$DIR NO_PARALLEL
      DO I = 1, MIN (LREM, N) ! 0 <= LREM < 8
        Y(I) = ...
      ENDDO
C$DIR PREFER_PARALLEL (CHUNK_SIZE = 16)
      DO I = LREM+1, N
         ! Y(LREM+1) IS ON A CACHE LINE BOUNDARY
        Y(I) = ...
      ENDDO
```

The first loop takes care of elements from the first (if any) partial cache line of data. The second loop begins on a cache line boundary, and is controlled with `CHUNK_SIZE` to avoid false sharing among the threads.

Working with dependences

Data dependences in loops may prevent parallelization and prevent the elimination of false cache line sharing. If certain conditions are met, some performance gains are achieved.

For example, consider the following code:

```
COMMON /ALIGNED / P(128,128), Q(128,128), R(128,128)
REAL*4 P, Q, R
DO J =  2, 128
  DO I = 2, 127
    P(I-1,J) = SQRT (P(I-1,J-1) + 1./3.)
    Q(I  ,J) = SQRT (Q(I  ,J-1) + 1./3.)
    R(I+1,J) = SQRT (R(I+1,J-1) + 1./3.)
  ENDDO
ENDDO
```

Only the `I` loop is parallelized, due to the loop-carried dependences in the `J` loop. It is impossible to distribute the iterations so that there is no false cache line sharing in the above loop. If all loops that refer to these arrays always use the same offsets (which is unlikely) then you could make dimension adjustments that would allow a better iteration distribution.

For example, the following would work well for 8 threads:

```
      COMMON /ADJUSTED/ P(128,128), PAD1(15), Q(128,128),
     > PAD2(15), R(128,128)

       DO J =  2, 128
C$DIR    PREFER_PARALLEL (CHUNK_SIZE=16)
         DO I = 2, 127
           P(I-1,J) = SQRT (P(I-1,J-1) + 1./3.)
           Q(I  ,J) = SQRT (Q(I  ,J-1) + 1./3.)
           R(I+1,J) = SQRT (R(I+1,J-1) + 1./3.)
         ENDDO
       ENDDO
```

Padding 60 bytes before the declarations of both `Q` and `R` causes the `P(1,J)`, `Q(2,J)`, and `R(3,J)` to be aligned on 64-byte boundaries for all `J`. Combined with a `CHUNK_SIZE` of 16, this causes threads to assign data to unique whole cache lines.

You can usually find a mix of all the above problems in some CPU-intensive loops. You cannot avoid all false cache line sharing, but by careful inspection of the problems and careful application of some of the workarounds shown here, you can significantly enhance the performance of your parallel loops.

Floating-point imprecision

The compiler applies normal arithmetic rules to real numbers. It assumes that two arithmetically equivalent expressions produce the same numerical result.

Most real numbers cannot be represented exactly in digital computers. Instead, these numbers are rounded to a floating-point value that is represented. When optimization changes the evaluation order of a floating-point expression, the results can change. Possible consequences of floating-point roundoff include program aborts, division by zero, address errors, and incorrect results.

In any parallel program, the execution order of the instructions differs from the serial version of the same program. This can cause noticeable roundoff differences between the two versions. Running a parallel code under different machine configurations or conditions can also yield roundoff differences, because the execution order can differ under differing machine conditions, causing roundoff errors to propagate in different orders between executions. Accumulator variables (reductions) are especially susceptible to these problems.

Consider the following Fortran example:

```
C$DIR GATE(ACCUM_LOCK)
      LK = ALLOC_GATE(ACCUM_LOCK)
      .
      .
      .
      LK = UNLOCK_GATE(ACCUM_LOCK)
C$DIR BEGIN_TASKS, TASK_PRIVATE(I)
      CALL COMPUTE(A)
C$DIR CRITICAL_SECTION(ACCUM_LOCK)
      ACCUM = ACCUM + A
C$DIR END_CRITICAL_SECTION
C$DIR NEXT_TASK

      DO I = 1, 10000
        B(I) = FUNC(I)
C$DIR   CRITICAL_SECTION(ACCUM_LOCK)
        ACCUM = ACCUM + B(I)
C$DIR   END_CRITICAL_SECTION
```

```
          .
          .
          .
        ENDDO


C$DIR NEXT_TASK
        DO I = 1, 10000
          X = X + C(I) + D(I)
        ENDDO
C$DIR CRITICAL_SECTION(ACCUM_LOCK)
        ACCUM = ACCUM/X
C$DIR END_CRITICAL_SECTION
C$DIR END_TASKS
```

Here, three parallel tasks are all manipulating the real variable `ACCUM`, using real variables which have themselves been manipulated. Each manipulation is subject to roundoff error, so the total roundoff error here might be substantial.

When the program runs in serial, the tasks execute in their written order, and the roundoff errors accumulate in that order. However, if the tasks run in parallel, there is no guarantee as to what order the tasks run in. This means that the roundoff error accumulates in a different order than it does during the serial run.

Depending on machine conditions, the tasks may run in different orders during different parallel runs also, potentially accumulating roundoff errors differently and yielding different answers.

Problems with floating-point precision can also occur when a program tests the value of a variable without allowing enough tolerance for roundoff errors. To solve the problem, adjust the tolerances to allow for greater roundoff errors or declare the variables to be of a higher precision (use the `double` type instead of `float` in C and C++, or `REAL*8` rather than `REAL*4` in Fortran). Testing floating-point numbers for exact equality is strongly discouraged.

Enabling sudden underflow

By default, PA-RISC processor hardware represents a floating point number in denormalized format when the number is tiny. A floating point number is considered tiny if its exponent field is zero but its mantissa is nonzero. This practice is extremely costly in terms of execution time and seldom provides any benefit.

You can enable sudden underflow (flush to zero) of denormalized values by passing the `+FPD` flag to the linker. This is done using the `-W` compiler option.

For more information, refer to the *HP-UX Floating-Point Guide*.

The following example shows an `f90` command line issuing this command:

```
%f90 -Wl,+FPD prog.f
```

This command line compiles the program `prog.f` and instructs the linker to enable sudden underflow.

Invalid subscripts

An array reference in which any subscript falls outside declared bounds for that dimension is called an invalid subscript. Invalid subscripts are a common cause of answers that vary between optimization levels and programs that abort and result in a core dump.

Use the command-line option `-C` (check subscripts) with `f90` to check that each subscript is within its array bounds. See the f90(1) man page for more information. The C and aC++ compilers do not have an option corresponding to the Fortran compiler's `-C` option.

Misused directives and pragmas

Misused directives and pragmas are a common cause of wrong answers. Some of the more common misuses of directives and pragmas involve the following:

- Loop-carried dependences
- Reductions
- Nondeterminism of parallel execution

Descriptions of and methods for avoiding the items listed above are described in the sections below.

Loop-carried dependences

Forcing parallelization of a loop containing a call is safe only if the called routine contains no dependences.

Do not assume that it is always safe to parallelize a loop whose data is safe to localize. You can safely localize loop data in loops that do not contain a loop-carried dependence (LCD) of the form shown in the following Fortran loop:

```
DO I = 2, M
  DO J = 1, N
    A(I,J) = A(I+IADD,J+JADD) + B(I,J)
  ENDDO
ENDDO
```

where one of `IADD` and `JADD` is negative and the other is positive. This is explained in detail in the section “Conditions that inhibit data localization” on page 62.

You cannot safely parallelize a loop that contains any kind of LCD, except by using ordered sections around the LCDs as described in the section “Ordered sections” on page 267. Also see the section “Inhibiting parallelization” on page 111.

The `MAIN` section of the Fortran program below initializes `A`, calls `CALC`, and outputs the new array values. In subroutine `CALC`, the indirect index used in `A(IN(I))` introduces a potential dependence that prevents the compiler from parallelizing `CALC`’s `I` loop.

```
PROGRAM MAIN
REAL A(1025)
INTEGER IN(1025)
COMMON /DATA/ A
DO I = 1, 1025
  IN(I) = I
ENDDO
CALL CALC(IN)
CALL OUTPUT(A)
END


SUBROUTINE CALC(IN)
INTEGER IN(1025)
REAL A(1025)
COMMON /DATA/ A
DO I = 1, 1025
  A(I) = A(IN(I))
ENDDO
RETURN
END
```

Because you know that `IN(I) = I`, you can use the `NO_LOOP_DEPENDENCE` directive, as shown below. This directive allows the compiler to ignore the apparent dependence and parallelize the loop, when compiling with `+O3 +Oparallel`.

```
      SUBROUTINE CALC(IN)
      INTEGER IN(1025)
      REAL A(1025)
      COMMON /DATA/ A
C$DIR NO_LOOP_DEPENDENCE(A)
      DO I = 1, 1025
         A(I) = A(IN(I))
      ENDDO
      RETURN
      END
```

Reductions

Reductions are a special class of dependence that the compiler can parallelize. An apparent LCD can prevent the compiler from parallelizing a loop containing a reduction.

The loop in the following Fortran example is not parallelized because of an apparent dependence between the references to A(I) on line 6 and the assignment to A(JA(J)) on line 7. The compiler does not realize that the values of the elements of JA never coincide with the values of I. Assuming that they might collide, the compiler conservatively avoids parallelizing the loop.

```
DO I = 1,100
  JA(I) = I + 10
ENDDO
DO I = 1, 100
  DO J = I, 100
      A(I) = A(I) + B(J) * C(J)    !LINE 6
      A(JA(J)) = B(J) + C(J)       !LINE 7
  ENDDO
ENDDO
```

NOTE In this example, as well as the examples that follow, the apparent dependence becomes real if any of the values of the elements of JA are equal to the values iterated over by I.

A no_loop_dependence directive or pragma placed before the J loop tells the compiler that the indirect subscript does not cause a true dependence. Because reductions are a form of dependence, this directive also tells the compiler to ignore the reduction on A(I), which it would normally handle. Ignoring this reduction causes the compiler to generate incorrect code for the assignment on line 6. The apparent dependence on line 7 is properly handled because of the directive. The resulting code runs fast but produces incorrect answers.

To solve this problem, distribute the J loop, isolating the reduction from the other statements, as shown in the following Fortran example:

```
      DO I = 1, 100
        DO J = I, 100
          A(I) = A(I) + B(J) * C(J)
        ENDDO
      ENDDO
C$DIR NO_LOOP_DEPENDENCE(A)
      DO I = 1, 100
        DO J = I, 100
```

```
        A(JA(J)) = B(J) + C(J)
      ENDDO
    ENDDO
```

The apparent dependence is removed, and both loops are optimized.

Nondeterminism of parallel execution

In a parallel program, threads do not execute in a predictable or determined order. If you force the compiler to parallelize a loop when a dependence exists, the results are unpredictable and can vary from one execution to the next.

Consider the following Fortran code:

```
DO I = 1, N-1
  A(I) = A(I+1) * B(I)
  .
  .
  .
ENDDO
```

The compiler does not parallelize this code as written because of the dependence on `A(I)`. This dependence requires that the original value of `A(I+1)` be available for the computation of `A(I)`.

If this code was parallelized, some values of `A` would be assigned by some processors before they were used by others, resulting in incorrect assignments.

Because the results depend on the order in which statements execute, the errors are nondeterministic. The loop must therefore execute in iteration order to ensure that all values of `A` are computed correctly.

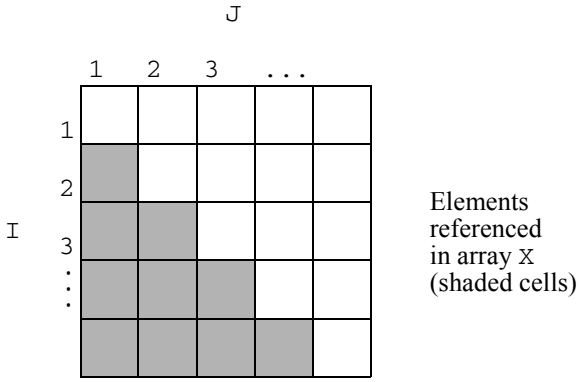
Loops containing dependences can sometimes be manually parallelized using the `LOOP_PARALLEL(ORDERED)` directive as described in “Parallel synchronization” on page 253. Unless you are sure that no loop-carried dependence exists, it is safest to let the compiler choose which loops to parallelize.

Triangular loops

A triangular loop is a loop nest with an inner loop whose upper or lower bound (but not both) is a function of the outer loop's index. Examples of a lower triangular loop and an upper triangular loop are given below. To simplify explanations, only Fortran examples are provided in this section.

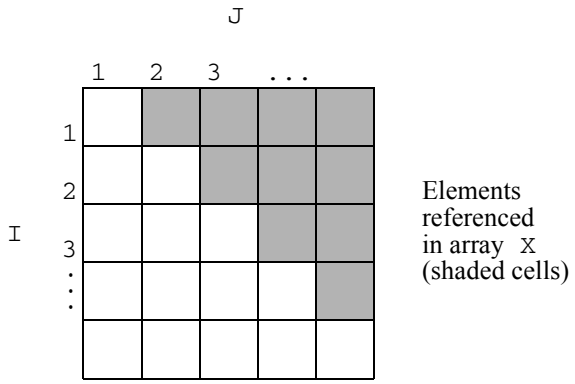
Lower triangular loop

```
DO J = 1, N
  DO I = J+1, N
    F(I) = F(I) + ... + X(I,J) + ...
```



Upper triangular loop

```
DO J = 1, N
  DO I = 1, J-1
    F(I) = F(I) + ... + X(I,J) + ...
```



While the compiler can usually auto-parallelize one of the outer or inner loops, there are typically performance problems in either case:

- If the outer loop is parallelized by assigning contiguous chunks of iterations to each of the threads, the load is severely unbalanced. For example, in the lower triangular example above, the thread doing the last chunk of iterations does far less work than the thread doing the first chunk.
- If the inner loop is auto-parallelized, then on each outer iteration in the `J` loop, the threads are assigned to work on a different set of iterations in the `I` loop, thus losing access to some of their previously encached elements of `F` and thrashing each other's caches in the process.

By manually controlling the parallelization, you can greatly improve the performance of a triangular loop. Parallelizing the outer loop is generally more beneficial than parallelizing the inner loop. The next two sections explain how to achieve the enhanced performance.

Parallelizing the outer loop

Certain directives allow you to control the parallelization of the outer loop in a triangular loop to optimize the performance of the loop nest.

For the outer loop, assign iterations to threads in a balanced manner. The simplest method is to assign the threads one at a time using the `CHUNK_SIZE attribute`:

```
C$DIR PREFER_PARALLEL (CHUNK_SIZE = 1)
      DO J = 1, N
        DO I = J+1, N
          Y(I,J) = Y(I,J) + ...X(I,J)...
```

This causes each thread to execute in the following manner:

```
      DO J = MY_THREAD() + 1, N, NUM_THREADS()
        DO I = J+1, N
          Y(I,J) = Y(I,J) + ...X(I,J)...
```

where 0 <= `MY_THREAD()` < `NUM_THREADS()`

In this case, the first thread still does more work than the last, but the imbalance is greatly reduced. For example, assume `N` = 128 and there are 8 threads. Then the default parallel compilation would cause thread 0 to do `J` = 1 to 16, resulting in 1912 inner iterations, whereas thread 7 does `J` = 113 to 128, resulting in 120 inner iterations. With `chunk_size = 1`, thread 0 does 1072 inner iterations, and thread 7 does 1023.

Parallelizing the inner loop

If the outer loop cannot be parallelized, it is recommended that you parallelize the inner loop if possible. There are two issues to be aware of when parallelizing the inner loop:

- Cache thrashing

  Consider the parallelization of the following inner loop:

  ```
   DO J = I+1, N
  F(J) = F(J) + SQRT(A(J)**2 - B(I)**2)
  ```

  where `I` varies in the outer loop iteration.

  The default iteration distribution has each thread processing a contiguous chunk of iterations of approximately the same number as every other thread. The amount of work per thread is about the same; however, from one outer iteration to the next, threads work on different elements in `F`, resulting in cache thrashing.

- The overhead of parallelization

  If the loop cannot be interchanged to be outermost (or at least outermore), then the overhead of parallelization is compounded by the number of outer loop iterations.

The scheme below assigns “ownership” of elements to threads on a cache line basis so that threads always work on the same cache lines and retain data locality from one iteration to the next. In addition, the `parallel` directive is used to spawn threads just once. The outer, nonparallel loop is replicated on all processors, and the inner loop iterations are manually distributed to the threads.

```
C F IS KNOWN TO BEGIN ON A CACHE LINE BOUNDARY
      NTHD = NUM_THREADS()
      CHUNK = 8                ! CHUNK * DATA SIZE (4
BYTES)
                               !    EQUALS PROCESSOR CACHE
LINE SIZE;
                                !    A SINGLE THREAD WORKS
ON CHUNK = 8
                                !    ITERATIONS AT A TIME
     NTCHUNK = NTHD * CHUNK  ! A CHUNK TO BE SPLIT AMONG
THE THREADS
       ...
C$DIR PARALLEL,PARALLEL_PRIVATE(ID,JS,JJ,J,I)
      ID = MY_THREAD() + 1   ! UNIQUE THREAD ID
      DO I = 1, N
        JS = ((I+1 + NTCHUNK-1 - ID*CHUNK ) / NTCHUNK) *
NTCHUNK
     >         + (ID-1) * CHUNK + 1
         DO JJ = JS, N, NTCHUNK
           DO J = MAX (JJ, I+1), MIN (N, JJ+CHUNK-1)
             F(J) = F(J) + SQRT(A(J)**2 - B(I)**2)
           ENDDO
         ENDDO
       ENDDO
C$DIR END_PARALLEL
```

The idea is to assign a fixed ownership of cache lines of `F` and to assign a distribution of those cache lines to threads that keeps as many threads busy computing whole cache lines for as long as possible. Using `CHUNK = 8` for 4-byte data makes each thread work on 8 iterations covering a total of 32 bytes—the processor cache line size for V2250 servers.

In general, set `CHUNK` equal to the smallest value that multiplies by the data size to give a multiple of 32 (the processor cache line size on V2250 servers). Smaller values of `CHUNK` keep most threads busy most of the time.

Because of the ever-decreasing work in the triangular loop, there are fewer cache lines left to compute than there are threads. Consequently, threads drop out until there is only one thread left to compute those iterations associated with the last cache line. Compare this distribution to the default distribution that causes false cache line sharing and consequent thrashing when all threads attempt to compute data into a few cache lines. See “False cache line sharing” on page 296 in this chapter.

The scheme above maps a sequence of NTCHUNK-sized blocks over the F array. Within each block, each thread owns a specific cache line of data. The relationship between data, threads, and blocks of size NTCHUNK is shown in Figure 14-1 on page 319.

Figure 14-1 Data ownership by CHUNK and NTCHUNK blocks

NTCHUNK 1

CHUNKs of F	Associated thread
F(1) ... F(8)	thread 0
F(9) ... F(16)	thread 1
F(17) ... F(24)	thread 2
F(33) ... F(40)	thread 3
F(41) ... F(48)	thread 4
F(25) ... F(32)	thread 5
F(49) ... F(56)	thread 6
F(57) ... F(64)	thread 7

NTCHUNK 2

CHUNKs of F	Associated thread
F(65) ... F(72)	thread 0
F(73) ... F(80)	thread 1
F(81) ...	...

CHUNK is the number of iterations a thread works on at one time. The idea is to make a thread work on the same elements of F from one iteration of I to the next (except for those that are already complete).

The scheme above causes thread 0 to do all work associated with the cache lines starting at `F(1)`, `F(1+NTCHUNK)`, `F(1+2*NTCHUNK)`, and so on. Likewise, thread 1 does the work associated with the cache lines starting at `F(9)`, `F(9+NTCHUNK)`, `F(9+2*NTCHUNK)`, and so on.

If a thread assigns certain elements of `F` for `I = 2`, then it is certain that the same thread encached those elements of `F` in iteration `I = 1`. This eliminates cache thrashing among the threads.

Examining the code

Having established the idea of assigning cache line ownership, consider the following Fortran code in more detail:

```
C$DIR PARALLEL,PARALLEL_PRIVATE(ID,JS,JJ,J,I)
        ID = MY_THREAD() + 1    ! UNIQUE THREAD ID
        DO I = 1, N
          JS = ((I+1 + NTCHUNK-1 - ID*CHUNK ) / NTCHUNK)
* NTCHUNK
     >           + (ID-1) * CHUNK + 1
           DO JJ = JS, N, NTCHUNK
             DO J = MAX (JJ, I+1), MIN (N, JJ+CHUNK-1)
               F(J) = F(J) + SQRT(A(J)**2 - B(I)**2)
             ENDDO
           ENDDO
        ENDDO
C$DIR END_PARALLEL
```

```
C$DIR PARALLEL, PARALLEL_PRIVATE(ID,JS,JJ,J,I)
```

Spawns threads, each of which begins executing the statements in the parallel region. Each thread has a private version of the variables `ID`, `JS`, `JJ`, `J`, and `I`.

```
ID = MY_THREAD() + 1 ! UNIQUE THREAD ID
```

Establishes a unique `ID` for each thread, in the range 1 to `num_threads()`.

```
DO I = 1, N
```

Executes all threads of the `I` loop redundantly (instead of thread 0 executing it alone).

```
JS = ((I+1 + NTCHUNK-1 - ID*CHUNK ) / NTCHUNK) * NTCHUNK
      + (ID-1) * CHUNK + 1
```

Determines, for a given value of I+1, which NTCHUNK the value I+1 falls then. Then it assigns a unique CHUNK of it to each thread ID. Suppose that there are *ntc* NTCHUNKs, where *ntc* is approximately N/NTCHUNK. Then the expression:

```
(I+1 + NTCHUNK-1 - ID*CHUNK ) / NTCHUNK)
```

returns a value in the range 1 to *ntc* for a given value of I+1. Then the expression:

```
((I+1 + NTCHUNK-1 - ID*CHUNK ) / NTCHUNK) * NTCHUNK
```

identifies the start of an NTCHUNK that contains I+1 or is immediately above I+1 for a given value of ID.

For the NTCHUNK that contains I+1, if the cache lines owned by a thread either contain I+1 or are above I+1 in memory, this expression returns this NTCHUNK. If the cache lines owned by a thread are below I+1 in this NTCHUNK, this expression returns the next highest NTCHUNK. In other words, if there is no work for a particular thread to do in this NTCHUNK, then start working in the next one.

```
(ID-1) * CHUNK + 1
```

identifies the start of the particular cache line for the thread to compute within this NTCHUNK.

```
DO JJ = JS, N, NTCHUNK
```

runs a unique set of cache lines starting at its specific JS and continuing into succeeding NTCHUNKs until all the work is done.

```
DO J = MAX (JJ, I+1), MIN (N, JJ+CHUNK-1)
```

performs the work within a single cache line. If the starting index (I+1) is greater than the first element in the cache line (JS) then start with I+1. If the ending index (N) is less than the last element in the cache line, then finish with N.

The following are observations of the preceding loops:

- Most of the “complicated” arithmetic is an outer loop iterations.

- You can replace divides with shift instructions because they involve powers of two.
- If this application were to be run on an V2250 single-node machine, it would be appropriate to choose a chunk size of 8 for 4-byte data.

Compiler assumptions

Compiler assumptions can produce faulty optimized code when the source code contains:

- Iterations by zero
- Trip counts that may overflow at optimization levels +O2 and above

Descriptions of, and methods for, avoiding the items listed above are in the following sections.

Incrementing by zero

The compiler assumes that whenever a variable is being incremented on each iteration of a loop, the variable is being incremented by a loop-invariant amount other than zero. If the compiler parallelizes a loop that increments a variable by zero on each trip, the loop can produce incorrect answers or cause the program to abort. This error can occur when a variable used as an incrementation value is accidentally set to zero. If the compiler detects that the variable has been set to zero, the compiler does not parallelize the loop. If the compiler cannot detect the assignment, however, the symptoms described below occur.

The following Fortran code shows two loops that increment by zero:

```
CALL SUB1(0)
.
.
.
SUBROUTINE SUB1(IZR)
DIMENSION A(100), B(100), C(100)
J = 1
DO I = 1, 100, IZR ! INCREMENT VALUE OF 0 IS
                   ! NON-STANDARD
   A(I) = B(I)
ENDDO
PRINT *, A(11)
DO I = 1, 100
   J = J + IZR
   B(I) = A(J)
   A(J) = C(I)
```

```
ENDDO
PRINT *, A(1)
PRINT *, B(11)
END
```

Because IZR is an argument passed to SUB1, the compiler does not detect that IZR has been set to zero. Both loops parallelize at +O3 +Oparallel +Onodynsel.

The loops compile at +O3, but the first loop, which specifies the step as part of the DO statement (or as part of the for statement in C), attempts to parcel out loop iterations by a step of IZR. At runtime, this loop is infinite.

Due to dependences, the second loop would not behave predictably when parallelized—if it were ever reached at runtime. The compiler does not detect the dependences because it assumes J is an induction variable.

Trip counts that may overflow

Some loop optimizations at +O2 and above may cause the variable on which the trip count is based to overflow. A loop's trip count is the number of times the loop executes. The compiler assumes that each induction variable is increasing (or decreasing) without overflow during the loop. Any overflowing induction variable may be used by the compiler as a basis for the trip count. The following sections discuss when this overflow may occur and how to avoid it.

Linear test replacement

When optimizing loops, the compiler often disregards the original induction variable, using instead a variable or value that better indicates the actual stride of the loop. A loop's stride is the value by which the iteration variable increases on each iteration. By picking the largest possible stride, the compiler reduces the execution time of the loop by reducing the number of arithmetic operations within each iteration.

The Fortran code below contains an example of a loop in which the induction variable may be replaced by the compiler:

```
ICONST = 64
ITOT = 0
DO IND = 1,N
  IPACK = (IND*1024)*ICONST**2
  IF(IPACK .LE. (N/2)*1024*ICONST**2)
```

```
>     ITOT = ITOT + IPACK
      .
      .
      .
 ENDDO
 END
```

Executing this loop using `IND` as the induction variable with a stride of 1 would be extremely inefficient. Therefore, the compiler picks `IPACK` as the induction variable and uses the amount by which it increases on each iteration, $1024*64^2$ or 2^{22}, as the stride.

The *trip count* (`N` in the example), or just *trip*, is the number of times the loop executes, and the *start* value is the initial value of the induction variable.

Linear test replacement, a standard optimization at levels `+O2` and above, normally does not cause problems. However, when the loop stride is very large a large trip count can cause the loop limit value (*start*+((*trip*-1)***stride*)) to overflow.

In the code above, the induction variable is a 4-byte integer, which occupies 32 bits in memory. That means if *start*+((*trip*-1)***stride*) (1+((`N`-1)*2^{22})) is greater than 2^{31}-1, the value overflows into the sign bit and is treated as a negative number. If the stride value is negative, the absolute value of *start*+((*trip*-1)***stride*) must be not exceed 2^{31}. When a loop has a positive stride and the trip count overflows, the loop stops executing when the overflow occurs because the limit becomes negative—assuming a positive stride—and the termination test fails.

Because the largest allowable value for start+((*trip*-1)***stride*) is 2^{31}-1, the start value is 1, and the stride is 2^{22}, the maximum trip count for the loop is found.

The stride, trip, and start values for a loop must satisfy the following inequality:

$$start + ((trip - 1) * stride) \leq 2^{31}$$

The start value is 1, so trip is solved as follows:

$$start + ((trip - 1) * stride) \leq 2^{31}$$

$$1 + (trip - 1) * 2^{22} \leq 2^{31}$$

$$(trip - 1) * 2^{22} \leq 2^{31} - 1$$

$$trip - 1 \leq 2^{9} - 2^{-22}$$

$$trip \leq 2^{9} - 2^{-22} + 1$$

$$trip \leq 512$$

The maximum value for `n` in the given loop, then, is 512.

NOTE If you find that certain loops give wrong answers at optimization levels `+O2` or higher, the problem may be test replacement. If you still want to optimize these loops at `+O2` or above, restructure them to force the compiler to choose a different induction variable.

Large trip counts at +O2 and above

When a loop is optimized at level `+O2` or above, its trip count must occupy no more than a signed 32-bit storage location. The largest positive value that can fit in this space is $2^{31} - 1$ (2,147,483,647). Loops with trip counts that cannot be determined at compile time but that exceed $2^{31} - 1$ at runtime yield wrong answers.

This limitation only applies at optimization levels `+O2` and above.

A loop with a trip count that overflows 32 bits is optimized by manually strip mining the loop.

A Porting CPSlib functions to pthreads

Introduction

The Compiler Parallel Support Library (CPSlib) is a library of thread management and synchronization routines that was initially developed to control parallelism on HP's legacy multinode systems. Most programs fully exploited their parallelism using higher-level devices such as automatic parallelization, compiler directives, and message-passing. CPSlib, however, provides a lower-level interface for the few cases that required it.

With the introduction of the V2250 series server, HP recommends the use of POSIX threads (pthreads) for purposes of thread management and parallelism. Pthreads provide portability for programmers who want to use their applications on multiple platforms.

This appendix describes how CPSlib functions map to pthread functions, and how to write a pthread program to perform the same tasks as CPSlib functions. Topics included in this chapter include:

- Accessing pthreads
- Symmetric parallelism
- Asymmetric parallelism
- Synchronization using high-level functions
- Synchronization using low-level functions

Accessing pthreads

When you use pthreads routines, your program must include the `<pthread.h>` header file and the pthreads library must be explicitly linked to your program.

For example, assume the program prog.c contains calls to pthreads routines. To compile the program so that it links in the pthreads library, issue the following command:

```
% cc -D_POSIX_C_SOURCE=199506L prog.c -lpthread
```

The `-D_POSIX_C_SOURCE=199506L` string indicates the appropriate POSIX revision level. In the example above, the level is indicated as 199506L.

Mapping CPSlib functions to pthreads

Table A-1 shows the mapping of the CPSlib functions to pthread functions. Where applicable, a pthread function is listed as corresponding to the appropriate CPSlib function. For instances where there is no corresponding pthread function, pthread examples that mimic CPSlib functionality are provided.

The CPSlib functions are grouped by type: barriers, informational, low-level locks, low-level counter semaphores, symmetrics and asymmetrics, and mutexes.

Table A-1 CPSlib library functions to pthreads mapping

CPSlib function	Maps to pthread function
Symmetric parallel functions	
`cps_nsthreads`	N/A See “Symmetric parallelism” on page 336 for more information.
`cps_ppcall`	N/A See “Symmetric parallelism” on page 336 for more information. Nesting is not supported in this example.
`cps_ppcalln`	N/A See “Symmetric parallelism” on page 336 for more information.
`cps_ppcallv`	N/A No example provided.
`cps_stid`	N/A See “Symmetric parallelism” on page 336 for more information.

Table A-1 CPSlib library functions to pthreads mapping (Continued)

CPSlib function	Maps to pthread function
cps_wait_attr	N/A See “Symmetric parallelism” on page 336 for more information.
Asymmetric parallel functions	
cps_thread_create	pthread_create See “Asymmetric parallelism” on page 351 for more information.
cps_thread_createn	pthread_create Only supports passing of one argument. See “Asymmetric parallelism” on page 351 for more information.
cps_thread_exit	pthread_exit See “Asymmetric parallelism” on page 351 for more information.
cps_thread_register_lock	This function was formerly used in conjunction with m_lock. It is now obsolete, and is replaced with one call to pthread_join. See “Asymmetric parallelism” on page 351 for more information.
cps_thread_wait	N/A No example available.
Informational	
cps_complex_cpus	pthread_num_processors_np The HP pthread_num_processors_np function returns the number of processors on the machine.

Table A-1 CPSlib library functions to pthreads mapping (Continued)

CPSlib function	Maps to pthread function
cps_complex_nodes	N/A This functionality can be added using the appropriate calls in your ppcall code.
cps_complex_nthreads	N/A This functionality can be added using the appropriate calls in your ppcall code.
cps_is_parallel	N/A See the ppcall.c example page 336 for more information.
cps_plevel	Because pthreads have no concept of levels, this function is obsolete.
cps_set_threads	N/A See the ppcall.c example page 336 for more information.
cps_topology	Use pthread_num_processors_np() to set up your configuration as a single-node machine.
Synchronization using high-level barriers	
cps_barrier	N/A See the my_barrier.c example in page 354 for more information.
cps_barrier_alloc	N/A See the my_barrier.c example in page 354 for more information.
cps_barrier_free	N/A See the my_barrier.c example in page 354 for more information.

Table A-1 CPSlib library functions to pthreads mapping (Continued)

CPSlib function	Maps to pthread function
Synchronization using high-level mutexes	
cps_limited_spin_mutex_alloc	pthread_mutex_init The CPS mutex allocate functions allocated memory and initialized the mutex. When you use pthread mutexes, you must use pthread_mutex_init to allocate the memory and initialize it. See pth_mutex.c page 354 for a description of using pthreads.
cps_mutex_alloc	pthread_mutex_init The CPS mutex allocate functions allocated memory and initialized the mutex. When you use pthread mutexes, you must use pthread_mutex_init to allocate the memory and initialize it. See pth_mutex.c page 354 for a description of using pthreads.
cps_mutex_free	pthread_mutex_destroy cps_mutex_free formerly uninitalized the mutex, and called free to release memory. When using pthread mutexes, you must first call pthread_mutex_destroy. See pth_mutex.c page 354 for a description of using pthreads.
cps_mutex_lock	pthread_mutex_lock See pth_mutex.c page 354 for a description of using pthreads.
cps_mutex_trylock	pthread_mutex_trylock See pth_mutex.c page 354 for a description of using pthreads.

Table A-1 CPSlib library functions to pthreads mapping (Continued)

CPSlib function	Maps to pthread function
cps_mutex_unlock	pthread_mutex_unlock See pth_mutex.c page 354 for a description of using pthreads.
Synchronization using low-level locks	
[mc]_cond_lock	pthread_mutex_trylock
[mc]_free32	pthread_mutex_destroy cps_mutex_free formerly uninitalized the mutex, and called free to release memory. When using pthread mutexes, you must call pthread_mutex_destroy.
[mc]_init32	pthread_mutex_init
[mc]_lock	pthread_mutex_lock
[mc]_unlock	pthread_mutex_unlock
Synchronization using low-level counter semaphores	
[mc]_fetch32	N/A See fetch_and_inc.c example page 361 for a description of using pthreads.
[mc]_fetch_and_add32	N/A See fetch_and_inc.c example page 361 for a description of using pthreads.
[mc]_fetch_and_clear32	N/A See fetch_and_inc.c example page 361 for a description of using pthreads.

Table A-1 CPSlib library functions to pthreads mapping (Continued)

CPSlib function	Maps to pthread function
[mc]_fetch_and_dec32	N/A See fetch_and_inc.c example page 361 for a description of using pthreads.
[mc]_fetch_and_inc32	N/A See fetch_and_inc.c example page 361 for a description of using pthreads.
[mc]_fetch_and_set32	N/A See fetch_and_inc.c example page 361 for a description of using pthreads.
[mc]_init32	N/A See fetch_and_inc.c example page 361 for a description of using pthreads.

Environment variables

Unlike CPSlib, pthreads does not use environment variables to establish thread attributes. pthreads implements function calls to achieve the same results. However, when using the HP compiler set, the environment variables below must be set to define attributes.

The table below describes the environment variables and how pthreads handles the same or similar tasks.

The environment variables below must be set for use with the HP compilers if you are not explicitly using pthreads.

Table A-2 CPSlib environment variables

Environment variable	Description	How handled by pthreads
`MP_NUMBER_OF_THREADS`	Sets the number of threads that the compiler allocates at startup time.	By default, under HP-UX you can create more threads than you have processors for.
`MP_IDLE_THREADS_WAIT`	Indicates how idle compiler threads should wait.	The values can be: -1 - spin wait; 0 - suspend wait; N - spin suspend where N > 0.
`CPS_STACK_SIZE`	Tells the compiler what size stack to allocate for all it's child threads. The default stacksize is 80 Mbyte.	Pthreads allow you to set the stack size using attributes. The attribute call is `pthread_attr_setstacksize`. The value of `CPS_STACK_SIZE` is specified in Kbytes.

Using pthreads

Some CPSlib functions map directly to existing pthread functions, as shown in Table A-1 on page 329. However, certain CPSlib functions, such as `cps_plevel`, are obsolete in the scope of pthreads. While about half of the CPSlib functions do not map to pthreads, their tasks can be simulated by the programmer.

The examples presented in the following sections demonstrate various constructs that can be programmed to mimic unmappable CPSlib functions in pthreads. The examples shown here are provided as a first step in replacing previous functionality provided by CPSlib with POSIX thread standard calls.

This is not a tutorial in pthreads, nor do these examples describe complex pthreads operations, such as nesting. For a definitive description of how to use pthreads functions, see the book *Threadtime* by Scott Norton and Mark D. Dipasquale.

Symmetric parallelism

Symmetric parallel threads are spawned in CPSlib using `cps_ppcall()` or `cps_ppcalln()`. There is no logical mapping of these CPSlib functions to pthread functions. However you can create a program, similar to the one shown in the `ppcall.c` example below, to achieve the same results.

This example also includes the following CPSlib thread information functions:

- `my_nsthreads` (a map created for `cps_nthreads`) returns the number of threads in the current spawn context.
- `my_stid` (a map created for `cps_stid`) returns the spawn thread ID of the calling thread.

The `ppcall.c` example performs other tasks associated with symmetrical thread processing, including the following:

- Allocates a cell barrier data structure based upon the number of threads in the current process by calling `my_barrier_alloc`

- Provides a barrier for threads to “join” or synchronize after parallel work is completed by calling `my_join_barrier`
- Creates data structures for threads created using `pthread_create`
- Uses the `CPS_STACK_SIZE` environment variable to determine the stacksize
- Determines the number of threads to create by calling `pthread_num_processors_np()`
- Returns the number of threads by calling `my_nsthreads()`
- Returns the `is_parallel` flag by calling `my_is_parallel()`

ppcall.c

```
/*
 * ppcall.c
 * function
 * Symmetric parallel interface to using pthreads
 * called my_thread package.
 *
 */

#ifndef _HPUX_SOURCE
#define _HPUX_SOURCE
#endif

#include <spp_prog_model.h>
#include <pthread.h>
#include <stdlib.h>
#include <errno.h>
#include "my_ppcall.h"

#define K        1024
#define MB        K*K

struct thread_data {
        int     stid;
        int     nsthreads;
        int      release_flag; r};
};

typedef struct thread_data thread_t;
```

```
typedef struct thread_data *thread_p;

#define WAIT_UNKNOWN0
#define WAIT_SPIN1
#define WAIT_SUSPEND2

#define MAX_THREADS64

#define W_CACHE_SIZE    8
#define B_CACHE_SIZE    32

typedef struct {
        int volatile    c_cell;
     int             c_pad[W_CACHE_SIZE-1];
} cell_t;

#define ICELL_SZ        (sizeof(int)*3+sizeof(char *))

struct cell_barrier {
     int               br_c_magic;
     int volatile      br_c_release;
     char *            br_c_free_ptr;
     int               br_c_cell_cnt;
     char              br_c_pad[B_CACHE_SIZE-ICELL_SZ];
     cell_t            br_c_cells[1];
};

#define BR_CELL_T_SIZE(x) (sizeof(struct cell_barrier) +
 (sizeof(cell_t)*x))

/*
 * ALIGN - to align objects on specific alignments
(usually on
 * cache line boundaries.
 *
 * arguments
 *       obj- pointer object to align
 *       alignment- alignment to align obj on
 *
 * Notes:
 *      We cast obj to a long, so that this code will
work in
```

```
 *      either narrow or wide modes of the compilers.
 */
#define ALIGN(obj, alignment)\
   ((((long) obj) + alignment - 1) & ~(alignment - 1))

typedef struct cell_barrier * cell_barrier_t;

/*
 * File Variable Dictionary:
 *
 * my_thread_mutex- mutex to control access to the
following:
 *   my_func, idle_release_flag, my_arg,
 *   my_call_thread_max, my_threads_are_init,
 *     my_threads_are_parallel.
 *
 *     idle_release_flag        - flag to release
spinning
 *                                idle threads
 *     my_func                 - user specified function
to call
 *     my_arg                    - argument to pass to
my_func
 *     my_call_thread_max        - maximum number of
threads
 *                                  needed on this ppcall
 *     my_threads_are_init      - my thread package init
flag
 *     my_threads_are_parallel  - we are executing
parallel
 *                                code flag
 *     my_thread_ids           - list of child thread ids
 *     my_barrier             - barrier used by the join
 *     my_thread_ptr          - the current thread thread
                              - pointer in thread-private
 *                              memory.
 */

static pthread_mutex_tmy_thread_mutex =
PTHREAD_MUTEX_INITIALIZER;
static int volatile         idle_release_flag = 0;
static void                 (*my_func)(void *);
```

```
static void                 *my_arg;
static int                  my_call_thread_max;
static int                  my_stacksize = 8*MB;
static int                  thread_count = 1;
static int                  my_threads_are_init = 0;
static int volatile         my_threads_are_parallel = 0;
static pthread_t            my_thread_ids[MAX_THREADS];
static cell_barrier_t       my_barrier;

static thread_p thread_private my_thread_ptr;

/*
 * my_barrier_alloc
 *   Allocate cell barrier data structure based upon the
 *   number of threads that are in the current process.
 *
 * arguments
 *   brc  - pointer pointer to the user cell barrier
 *   n    - number of threads that will use this barrier
 *
 * return
 *   0- success
 *   -1- failed to allocate cell barrier
 */

static int
my_barrier_alloc(cell_barrier_t *brc, int n)
{
   cell_barrier_t b;
   char *p;
   int i;

/*
 * Allocate cell barrier for 'n' threads
 */
if ( (p = (char *) malloc(BR_CELL_T_SIZE(n))) == 0 )
return -1;

/*
 * Align the barrier on a cache line for maximum
   performance.
*/
```

```
   b = (cell_barrier_t) ALIGN(p, B_CACHE_SIZE);
   b->br_c_magic = 0x4200beef;
   b->br_c_cell_cnt = n;    /* keep track of the # of
threads */
   b->br_c_release = 0;     /* initialize release flag */
   b->br_c_free_ptr = p;    /* keep track of orginal
malloc ptr */

   for(i = 0; i < n; i++ )
      b->br_c_cells[i].c_cell = 0;/* zero the cell flags
*/

   *brc = b;

    return 0;
}
/*
 * my_join_barrier
 *   Provide a barrier for all threads to sync up at,
after
 *   they have finished performing parallel work.
 *
 * arguments
 *    b       - pointer to cell barrier
 *    id      - id of the thread (need to be in the
 *  range of 0 - (N-1), where N is the
 *number of threads).


 * return
 *none
 */

static void
my_join_barrier(cell_barrier_t b, int id)
{
int i, key;

/*
```

```
 * Get the release flag value, before we signal that we
 * are at the barrier.
 */
key = b->br_c_release;

if ( id == 0 ) {
/*
 * make thread 0 (i.e. parent thread) wait for the child
 * threads to show up.
 */
for( i = 1; i < thread_count; i++ ) {
/*
 * wait on the Nth cell
 */
while ( b->br_c_cells[i].c_cell == 0 )
/* spin */;

/*
 * We can reset the Nth cell now,
 * because it is not being used anymore
 * until the next barrier.
/*
b->br_c_cells[i].c_cell = 0;
}

/*
 * signal all of the child threads to leave the barrier.
 */
++b->br_c_release;
} else {
/*
 * signal that the Nth thread has arrived at the barrier.
 */
b->br_c_cells[id].c_cell = -1;

while ( key == b->br_c_release )
/* spin */;
}
}

/*
 * idle_threads
```

```
 *   All of the process child threads will execute this
 *   code. It is the idle loop where the child threads
wait
 *   for parallel work.
 * arguments
 *   thr- thread pointer
 *
 * algorithm:
 *   Initialize some thread specific data structures.
 *   Loop forever on the following:
 *      Wait until we have work.
 *      Get global values on what work needs to be done.
 *      Call user specified function with argument.
 *      Call barrier code to sync up all threads.
 */static void
idle_threads(thread_p thr)
{
/*
 * initialized the thread thread-private memory pointer.
 */
my_thread_ptr = thr;

   for(;;) {
      /*
       * threads spin here waiting for work to be assign
       * to them.
       */
       while( thr->release_flag == idle_release_flag )
         /* spin until idle_release_flag changes */;

       thr->release_flag = idle_release_flag;
       thr->nsthreads = my_call_thread_max;

      /*
       * call user function with their specified
argument.
       */
      if ( thr->stid < my_call_thread_max )
         (*my_func)(my_arg);
      /*
       * make all threads join before they were to the
idle
```

```
        loop.
 */
my_join_barrier(my_barrier, thr->stid);
   }
}
/** create_threads
 *   This routine creates all of the MY THREADS package
data
 *   structures and child threads.
 *
 *   arguments:
 *     none
 *
 *   return:
 *     none
 *
 * algorithm:
 *   Allocate data structures for a thread
 *   Create the thread via the pthread_create call.
 *   If the create call is successful, repeat until the
 *   number of threads equal the number of processors.
 *
 */

static void
create_threads()
{
   pthread_attr_t attr;
   char *env_val;
   int i, rv, cpus, processors;
   thread_p thr;

   /*
    * allocate and initialize the thread structure for
the
    * parent thread.
    */
   if ( (thr = (thread_p) malloc(sizeof(thread_t))) ==
NULL ) {
      fprintf(stderr,"my_threads: Fatal error: can not
      allocate memory for main thread\n");
```

```
      abort();
   }
   my_thread_ptr = thr;

   thr->stid = 0;
   thr->release_flag = 0;

  /*
   * initialize attribute structure
   */
   (void) pthread_attr_init(&attr);

  /*
   * Check to see if the CPS_STACK_SIZE env variable is
defined.
   * If it is, then use that as the stacksize.
   */
  if ( (env_val = getenv("CPS_STACK_SIZE")) != NULL ) {
     int val;
      val = atoi(env_val);
      if ( val > 128 )
         my_stacksize = val * K;
}

(void) pthread_attr_setstacksize(&attr,my_stacksize);

/*
 * determine how many threads we will create.
 */
processors = cpus = pthread_num_processors_np();
if ( (env_val = getenv("MP_NUMBER_OF_THREADS")) != NULL
) {
   int val;

   val = atoi(env_val);
   if ( val >= 1 )
      cpus = val;
}

for(i = 1; i < cpus && i < MAX_THREADS; i++ ) {
    /*
     * allocate and initialize thread data structure.
```

```
     */
    if ( (thr = (thread_p) malloc(sizeof(thread_t))) ==
NULL )
       break;

    thr->stid = i;
    thr->release_flag = 0;

    rv = pthread_create(&my_thread_ids[i-1], &attr,
         (void *(*)(void *))idle_threads, (void *) thr);
    if ( rv != 0 ) {
       free(thr);
       break;
    }
    thread_count++;
    }

    my_threads_are_init = 1;

    my_barrier_alloc(&my_barrier, thread_count);

    /*
     * since we are done with this attribute, get rid of
it.
     */
    (void) pthread_attr_destroy(&attr);
}

/*
 * my_ppcall
 *   Call user specified routine in parallel.
 *
 * arguments:
 *   max- maximum number of threads that are needed.
 *   func- user specified function to call
 *   arg- user specified argument to pass to func
 *
 * return:
 *   0- success
 *   -1- error
 *
 * algorithm:
```

```
 *   If we are already parallel, then return with an
error
 *   code. Allocate threads and internal data structures,
 *    if this is the first call.
 *    Determine how many threads we need.
 *    Set global variables.
 *    Signal the child threads that they have parallel
work.
 *   At this point we signal all of the child threads and
 *    let them determine if they need to take part in the
 *    parallel call. Call the user specified function.
 *    Barrier call will sync up all threads.
 */

int
my_ppcall(int max, void (*func)(void *), void *arg)
{
    thread_p thr;
    int i, suspend;

    /*
     * check for error conditions
      */
    if ( max <= 0 || func == NULL )
       return EINVAL;

    if ( my_threads_are_parallel )
       return EAGAIN;

    (void) pthread_mutex_lock(&my_thread_mutex);
     if ( my_threads_are_parallel ) {
        (void) pthread_mutex_unlock(&my_thread_mutex);
        return EAGAIN;
    }

    /*
     * create the child threads, if they are not already
created.
     */
    if ( !my_threads_are_init )
       create_threads();
```

```
    /*
     * set global variables to communicate to child
threads.
     */
    if ( max > thread_count )
       my_call_thread_max = thread_count;
    else
       my_call_thread_max = max;

    my_func = func;
    my_arg = arg;

     my_thread_ptr->nsthreads = my_call_thread_max;

     ++my_threads_are_parallel;

     /*
      * signal all of the child threads to exit the spin
loop
      */
     ++idle_release_flag;

     (void) pthread_mutex_unlock(&my_thread_mutex);

     /*
      * call user func with user specified argument
      */
     (*my_func)(my_arg);

     /*
      * call join to make sure all of the threads are
done doing
      * there work.
      */
     my_join_barrier(my_barrier, my_thread_ptr->stid);

     (void) pthread_mutex_lock(&my_thread_mutex);

     /*
      * reset the parallel flag
      */
     my_threads_are_parallel = 0;
```

```
     (void) pthread_mutex_unlock(&my_thread_mutex);

     return 0;
}

/*

* my_stid
 *   Return thread spawn thread id. This will be in the
range
 *   of 0 to N-1, where N is the number of threads in the
 *   process.
 * arguments:
 *   none
 *
 * return
 *   spawn thread id
 */

int
my_stid(void)
{
return my_thread_ptr->stid;
}

/*
 * my_nsthreads
 *   Return the number of threads in the current spawn.
 *
 * arguments:
 *   none
 *
 * return
 *   number of threads in the current spawn
 */

int
my_nsthreads(void)
{
   return my_thread_ptr->nsthreads;
}
```

```
/*
 * my_is_parallel
 *   Return the is parallel flag
 *
 * arguments:
 *   none
 *
 * return
 *   1- if we are parallel
 *   0- otherwise
 */

int
my_is_parallel(void)
{
   int rv;

   /*
    * if my_threads_are_init is set, then we are
parallel,
    * otherwise we not.
    */
   (void) pthread_mutex_lock(&my_thread_mutex);
    rv = my_threads_are_init;
   (void) pthread_mutex_unlock(&my_thread_mutex);

    return rv;
}

/*
 * my_complex_cpus
 *   Return the number of threads in the current process.
 *
 * arguments:
 *   none
 *
 * return
 *   number of threads created by this process
 */

int
```

```
my_complex_cpus(void)
{
    int rv;

    /*
     * Return the number of threads that we current have.
     */
   (void) pthread_mutex_lock(&my_thread_mutex);
    rv = thread_count;
   (void) pthread_mutex_unlock(&my_thread_mutex);

    return rv;
}
```

Asymmetric parallelism

Asymmetric parallelism is used when each thread executes a different, independent instruction stream. Asymmetric threads are analogous to the Unix `fork` system call construct in that the threads are disjoined.

Some of the asymmetric CPSlib functions map to pthread functions, while others are no longer used, as noted below:

- `cps_thread_create()` spawned asymmetric threads and now maps to the pthread function `pthread_create()`.
- `cps_thread_createn()`, which spawned asymmetric threads with multiple arguments, also maps to `pthread_create()`. However, `pthread_create()` only supports the passing of one argument.
- CPSlib terminated asymmetric threads using `cps_thread_exit()`, which now maps to the pthread function `pthread_exit()`.
- `cps_thread_register_lock` has no corresponding pthread function. It was formerly used in conjunction with `m_lock`, both of which have been replaced with one call to `pthread_join`.
- `cps_plevel()`, the CPSlib function which determined the current level of parallelism, does not have a corresponding pthread function, because levels do not mean anything to pthreads.

The first example in this section `cps_create.c`, provides an example of the above CPSlib functions being used to create asymmetric parallelism.

create.c

```
/*
 * create.c
 *         Show how to use all of the cps asymmetric
functions.
 *
 */

#include <cps.h>

mem_sema_t wait_lock;

void
tfunc(void *arg)
{
            int i;

            /*
             * Register the wait_lock, so that the parent
thread
             * can wait on us to exit.
             */
             (void) cps_thread_register_lock(&wait_lock);

             for( i = 0; i < 100000; i++ )
                  /* spin for a spell */;

             printf("tfunc: ktid = %d\n", cps_ktid());
             cps_thread_exit();
}

main()
{
             int node = 0;
             ktid_t ktid;

             /*
              * Initialize and lock the wait_lock.
              */
             m_init32(&wait_lock, &node);
             m_cond_lock(&wait_lock);
```

```
            ktid = cps_thread_create(&node, tfunc, NULL);

             /*
              * We wait for the wait_lock to be release.
That is
              * how we know that the child thread
              * has terminated.
              */
             m_lock(&wait_lock);

             exit(0);
}
```

pth_create.c

The example below shows how to use the `pth_create.c` function to map to asymmetric functions provided by the CPSlib example.

```
/*
 * pth_create.c
 *          Show how to use all of the pthread functions
that
             map to cps asymmetric functions.
 *
 *
 */
#include <pthread.h>

void
tfunc(void *arg)
{
             int i;

             for( i = 0; i < 100000; i++ )
                          /* spin for a spell */;

            printf("tfunc: ktid = %d\n", pthread_self());
             pthread_exit(0);
}

main()
{
```

```
            pthread_t ktid;
            int status;

            (void) pthread_create(&ktid, NULL, (void
*(*)(void *)
               tfunc, NULL);

            /*
             * Wait for the child to terminate.
             */
           (void) pthread_join(ktid, NULL);

           exit(0);
}
```

Synchronization using high-level functions

This section demonstrates how to use barriers and mutexes to synchronize symmetrically parallel code.

Barriers

Implicit barriers are operations in a program where threads are restricted from completion based upon the status of the other threads. For example, in the `ppcall.c` example (page 337), a join operation occurs after all spawned threads terminate and before the function returns. This type of implicit barrier is often the only type of barrier required.

The `my_barrier.c` example shown below provides a pthreads implementation of CPSlib barrier routines. This includes the following example functions:

- `my_init_barrier` is similar to the `cps_barrier_alloc` function in that it allocates the barrier (`br`) and sets its associated memory counter to zero.
- `my_barrier`, like the CPSlib function `cps_barrier`, operates as barrier wait routine. When the value of the shared counter is equal to the argument *n* (number of threads), the counter is set to zero.
- `my_barrier-destroy`, like `cps_barrier_free`, releases the barrier.

my_barrier.c

```
/*
 * my_barrier.c
 *Code to support a fetch and increment type barrier.
 */

#ifndef _HPUX_SOURCE
#define _HPUX_SOURCE
#endif

#include <pthread.h>
#include <errno.h>

/*
 * barrier
 *    magic          barrier valid flag
 *    counter        shared counter between threads
 *    release       shared release flag, used to signal
waiting
 *                   threads to stop waiting.
 *    lock           binary semaphore use to control
read/write
 *                  access to counter and write access to
 *                   release.
 */

struct barrier {
   int               magic;
   int volatile      counter;
   int volatile      release;
   pthread_mutex_t   lock;
};

#define VALID_BARRIER        0x4242beef
#define INVALID_BARRIER      0xdeadbeef

typedef struct barrier barrier_t;
typedef struct barrier *barrier_p;

/*
 * my_barrier_init
 *    Initialized a barrier for use.
```

```
 *
 * arguments
 *    br- pointer to the barrier to be initialize.
 *
 * return
 *    0- success
 *    >0- error code of failure.
 */

int
my_barrier_init(barrier_p *br)
{
   barrier_p b, n;
   int rv;

   b = (barrier_p) *br;

   if ( b != NULL )
      return EINVAL;

   if ( (n = (barrier_p) malloc(sizeof(*n))) == NULL )
      return ENOMEM;

   if ( (rv = pthread_mutex_init(&n->lock, NULL)) != 0 )
      return rv;

   n->magic = VALID_BARRIER;
   n->counter = 0;
   n->release = 0;

   *br = n;

   return 0;
}

/*
 * my_barrier
 *    barrier wait routine.
 *
 * arguments
 *   br          - barrier to wait on
 *   n           - number of threads to wait on
```

```
 *
 * return
 *   0          - success
 *   EINVAL     - invalid arguments
 */
int
my_barrier(barrier_p br, int n)
{
     int rv;
     int key;

     if ( br == NULL || br->magic != VALID_BARRIER )
     return EINVAL;

     pthread_mutex_lock(&br->lock);

     key = br->release;/* get release flag */
     rv = br->counter++;/* fetch and inc shared counter
*/

     /*
      * See if we are the last thread into the barrier
      */
if ( rv == n-1 ) {
/*
 * We are the last thread, so clear the counter

 * and signal the other threads by changing the
 * release flag.
 */
br->counter = 0;
++br->release;
pthread_mutex_unlock(&br->lock);
} else {
pthread_mutex_unlock(&br->lock);

/*
 * We are not the last thread, so wait
 * until the release flag changes.
 */
while( key == br->release )
/* spin */;
```

```
}

return 0;
}

/*
 * my_barrier_destroy
 *destroy a barrier
 *
 * arguments
 *b- barrier to destory
 *
 * return
 *0- success
 *> 0 - error code for why can not destroy barrier
 */

int
my_barrier_destroy(barrier_p *b)
{
barrier_p br = (barrier_p) *b;
int rv;

if ( br == NULL || br->magic != VALID_BARRIER )
return EINVAL;

if ( (rv = pthread_mutex_destroy(&br->lock)) != 0 )
return rv;

br->magic = INVALID_BARRIER;
br->counter = 0;
br->release = 0;

*b = NULL;

return 0;
}
```

Mutexes

Mutexes (binary semaphores) allow threads to control access to shared data and resources. The CPSlib mutex functions map directly to existing pthread mutex functions as shown in Table on page 329. The example

below, pth_mutex.c, shows a basic pthread mutex program using the pthread_mutex_init, pthread_mutex_lock, pthread_mutex_trylock, and pthread_mutex_unlock.

There are some differences between the behavior of CPSlib mutex functions and low-level locks (cache semaphores and memory semaphores) and the behavior of pthread mutex functions, as described below:

- CPS cache and memory semaphores do not perform deadlock detection.
- The default pthread mutex does not perform deadlock detection under HP-UX. This may be different from other operating systems. pthread_mutex_lock will only detect deadlock if the mutex is of the type PTHREAD_MUTEX_ERRORCHECK.
- All of the CPSlib unlock routines allow other threads to release a lock that they do not own. This is not true with pthread_mutex_unlock. If you do this with pthread_mutex_unlock, it will result in undesirable behavior.

pth_mutex.c

```
/*
 * pth_mutex.c
 * Demostrate pthread mutex calls.
 *
 * Notes when switching from cps mutex, cache semaphore
or
 * memory semaphores to pthread mutex:
 *
 *1) Cps cache and memory semaphores did no checking.
 *2) All of the cps semaphore unlock routines allow
 *   other threads to release a lock that they do not
 *   own. This is not the case with
 *   pthread_mutex_unlock. It is either a error or a
 *   undefinedbehavior.
 *3) The default pthread mutex does not do deadlock
 *   detection under HP-UX (this can be different on
     other operation systems).
 */

#ifndef _HPUX_SOURCE
#define _HPUX_SOURCE
```

```
#endif

#include <pthread.h>
#include <errno.h>

pthread_mutex_t counter_lock;
int volatile counter = 0;

void
tfunc()
{
   (void) pthread_mutex_lock(&counter_lock);
   ++counter;
   (void) pthread_mutex_unlock(&counter_lock);
}

main()
{
   pthread_t tid;

   if ( (errno = pthread_mutex_init(&counter_lock,
NULL)) != 0 ) {
     perror("pth_mutex: pthread_mutex_init failed");
     abort();
}

   if ( (errno = pthread_create(&tid, NULL, (void
*(*)(void *))
     tfunc, NULL)) != 0 ) {
        perror("pth_mutex: pthread_create failed");
        abort();
}

tfunc();

(void) pthread_join(tid, NULL);

   if ( (errno = pthread_mutex_destroy(&counter_lock))
!= 0 ) {
      perror("pth_mutex: pthread_mutex_destroy failed");
      abort();
}
```

```
    if ( counter != 2 ) {
        errno = EINVAL;
        perror("pth_mutex: counter value is wrong");
        abort();
}
    printf("PASSED\n");
    exit(0);
}
```

Synchronization using low-level functions

This section demonstrates how to use semaphores to synchronize symmetrically parallel code. This includes functions, such as low-level locks, for which there are pthread mappings, and low-level counter semaphores for which there are no pthread mappings. In this instance, an example is provided so that you can create a program to emulate CPSlib functions, using pthreads.

Low-level locks

The disposition of CPSlib's low-level locking functions is handled by the pthread mutex functions (as described in Table on page 329). See "Mutexes" on page 358 for an example of how to use pthread mutexes.

Low-level counter semaphores

The CPSlib `[mc]_init32` routines allocate and set the low-level CPSlib semaphores to be used as counters. There are no pthread mappings for these functions. However, a pthread example is provided below.

This example, `fetch_and_inc.c`, documents the following tasks:

- `my_init` allocates a counter semaphore and initializes the counter associated with it (p) to a value.
- `my_fetch_and_clear` returns the current value of the counter associated with the semaphore and clears the counter.
- `my_fetch_and_inc` increments the value of the counter associated with the semaphore and returns the old value.
- `my_fetch_and_dec` decrements the value of the counter associated with the semaphore and returns the old value.

- `my_fetch_and_add` adds a value (int val) to the counter associated with the semaphore and returns the old value of the integer.
- `my_fetch_and_set` returns the current value of the counter associated with the semaphore, and sets the semaphore to the new value contained in `int val`.

The `[mc]_init32` routines allocate and set the low-level cps semaphores to be used as either counters or locks. An example for counters provides pthread implementation in the place of the following CPSlib functions:

- `[mc]fetch32`
- `[mc]_fetch_and_clear32`
- `[mc]_fetch_and_inc32`
- `[mc]_fetch_and_dec32`
- `[mc]_fetch_and_add32`
- `[mc]_fetch_and_set32`

fetch_and_inc.c

```
/*
 * fetch_and_inc
 *    How to support fetch_and_inc type semaphores using
pthreads
 *
 */

#ifndef _HPUX_SOURCE
#define _HPUX_SOURCE
#endif

#include <pthread.h>
#include <errno.h>

struct fetch_and_inc {
   int volatilevalue;
   pthread_mutex_tlock;
};

typedef struct fetch_and_inc fetch_and_inc_t;
typedef struct fetch_and_inc *fetch_and_inc_p;
```

```
int
my_init(fetch_and_inc_p *counter, int val)
{
   fetch_and_inc_p p;
   int rv;

   if ( (p = (fetch_and_inc_p) malloc(sizeof(*p))) ==
NULL )
       return ENOMEM;

   if ( (rv = pthread_mutex_init(&p->lock, NULL)) != 0 )
       return rv;

   p->value = val;

   *counter = p;

   return 0;
}

int
my_fetch(fetch_and_inc_p counter)
{
   int rv;

   pthread_mutex_lock(&counter->lock);

   rv = counter->value;

   pthread_mutex_unlock(&counter->lock);

   return rv;
}

int
my_fetch_and_clear(fetch_and_inc_p counter)
{
   int rv;

   pthread_mutex_lock(&counter->lock);
```

```
    rv = counter->value;
    counter->value = 0;

    pthread_mutex_unlock(&counter->lock);

    return rv;
}

int
my_fetch_and_inc(fetch_and_inc_p counter)
{
    int rv;

    pthread_mutex_lock(&counter->lock);

    rv = counter->value++;

    pthread_mutex_unlock(&counter->lock);

    return rv;
}

int
my_fetch_and_dec(fetch_and_inc_p counter)
{
    int rv;

    pthread_mutex_lock(&counter->lock);

    rv = counter->value--;

    pthread_mutex_unlock(&counter->lock);

    return rv;
}

int
my_fetch_and_add(fetch_and_inc_p counter, int val)
{
    int rv;

    pthread_mutex_lock(&counter->lock);
```

```
    rv = counter->value;
    counter->value += val;

    pthread_mutex_unlock(&counter->lock);

    return rv;
}

int
my_fetch_and_set(fetch_and_inc_p counter, int val)
{
    int rv;

    pthread_mutex_lock(&counter->lock);

    rv = counter->value;
    counter->value = val;

    pthread_mutex_unlock(&counter->lock);

    return rv;
}
```

Glossary

absolute address An address that does not undergo virtual-to-physical address translation when used to reference memory or the
I/O register area.

accumulator A variable used to accumulate value. Accumulators are typically assigned a function of themselves, which can create dependences when done in loops.

actual argument In Fortran, a value that is passed by a call to a procedure (function or subroutine). The actual argument appears in the source of the calling procedure; the argument that appears in the source of the called procedure is a *dummy argument*. C and C++ conventions refer to actual arguments as *actual parameters*.

actual parameter In C and C++, a value that is passed by a call to a procedure (function). The actual parameter appears in the source of the calling procedure; the parameter that appears in the source of the called procedure is a *formal parameter*. Fortran conventions refer to actual parameters as *actual arguments*.

address A number used by the operating system to identify a storage location.

address space Memory space, either physical or virtual, available to a process.

alias An alternative name for some object, especially an alternative variable name that refers to a memory location. Aliases can cause data dependences, which prevent the compiler from parallelizing parts of a program.

alignment A condition in which the address, in memory, of a given data item is integrally divisible by a particular integer value, often the size of the data item itself. Alignment simplifies the addressing of such data items.

allocatable array In Fortran 90, a named array whose rank is specified at compile time, but whose bounds are determined at run time.

allocate An action performed by a program at runtime in which memory is reserved to hold data of a given type. In Fortran 90, this is done through the creation of *allocatable arrays*. In C, it is done through the dynamic creation of memory blocks using `malloc`. In C++, it is done through the dynamic creation of memory blocks using `malloc` or `new`.

ALU Arithmetic logic unit. A basic element of the central processing unit (CPU) where arithmetic and logical operations are performed.

Amdahl's law A statement that the ultimate performance of a computer system is limited by the slowest component. In the context of HP servers this is interpreted to mean that the serial component of the application code will restrict the maximum speed-up that is achievable.

American National Standards Institute (ANSI) A repository and coordinating agency for standards implemented in the U.S. Its activities include the production of Federal Information Processing (FIPS) standards for the Department of Defense (DoD).

ANSI See *American National Standards Institute*.

apparent recurrence A condition or construct that fails to provide the compiler with sufficient information to determine whether or not a recurrence exists. Also called a *potential recurrence*.

argument In Fortran, either a variable declared in the argument list of a procedure (function or subroutine) that receives a value when the procedure is called (*dummy argument*) or the variable or constant that is passed by a call to a procedure (*actual argument*). C and C++ conventions refer to arguments as *parameters*.

arithmetic logic unit (ALU) A basic element of the central processing unit (CPU) where arithmetic and logical operations are performed.

array An ordered structure of operands of the same data type. The structure of an array is defined by its rank, shape, and data type.

array section A Fortran 90 construct that defines a subset of an array by providing starting and ending elements and strides for each dimension. For an array `A(4,4)`, `A(2:4:2,2:4:2)` is an array section containing only the evenly indexed elements `A(2,2)`, `A(4,2)`, `A(2,4)`, and `A(4,4)`.

array-valued argument In Fortran 90, an *array section* that is an actual argument to a subprogram.

ASCII American Standard Code for Information Interchange. This encodes printable and non-printable characters into a range of integers.

assembler A program that converts assembly language programs into executable machine code.

assembly language A programming language whose executable statements can each be translated directly into a corresponding machine instruction of a particular computer system.

automatic array In Fortran, an array of explicit rank that is not a dummy argument and is declared in a subprogram.

bandwidth A measure of the rate at which data can be moved through a device or circuit. Bandwidth is usually measured in millions of bytes per second (Mbytes/sec) or millions of bits per second (Mbits/sec).

bank conflict An attempt to access a particular memory bank before a previous access to the bank is complete, or when the bank is not yet finished recycling (i.e., refreshing).

barrier A structure used by the compiler in barrier synchronization. Also sometimes used to refer to the construct used to implement barrier synchronization. See also *barrier synchronization*.

barrier synchronization A control mechanism used in parallel programming that ensures all threads have completed an operation before continuing execution past the barrier in sequential mode. On HP

servers, barrier synchronization can be automated by certain CPSlib routines and compiler directives. See also *barrier*.

basic block A linear sequence of machine instructions with a single entry and a single exit.

bit A binary digit.

blocking factor Integer representing the stride of the outer strip of a pair of loops created by blocking.

branch A class of instructions which change the value of the program counter to a value other than that of the next sequential instruction.

byte A group of contiguous bits starting on an addressable boundary. A byte is 8 bits in length.

cache A small, high-speed buffer memory used in modern computer systems to hold temporarily those portions of the contents of the memory that are, or are believed to be, currently in use. Cache memory is physically separate from main memory and can be accessed with substantially less latency. HP servers employ separate data and instruction cache memories.

cache, direct mapped A form of cache memory that addresses encached data by a function of the data's virtual address. On V2250 servers, the processor cache address is identical to the least-significant 21 bits of the data's virtual address. This means cache thrashing can occur when the virtual addresses of two data items are an exact multiple of 2 Mbyte (21 bits) apart.

cache hit A *cache hit* occurs if data to be loaded is residing in the cache.

cache line A chunk of contiguous data that is copied into a cache in one operation. On V2250 servers, processor cache lines are 32 bytes

cache memory A small, high-speed buffer memory used in modern computer systems to hold temporarily those portions of the contents of the memory that are, or are believed to be, currently in use. Cache memory is physically separate from main memory and can be accessed with substantially less latency. V2250 servers employ separate data and instruction caches.

cache miss A *cache miss* occurs if data to be loaded is not residing in the cache.

cache purge The act of invalidating or removing entries in a cache memory.

cache thrashing *Cache thrashing* occurs when two or more data items that are frequently needed by the program map to the same cache address. In this case, each time one of the items is encached it overwrites another needed item, causing constant cache misses and impairing data reuse. Cache thrashing also occurs when two or more threads are simultaneously writing to the same cache line.

central processing unit (CPU) The central processing unit (CPU) is that portion of a computer that recognizes and executes the instruction set.

clock cycle The duration of the square wave pulse sent throughout a computer system to synchronize operations.

clone A compiler-generated copy of a loop or procedure. When the HP compilers generate code for a parallelizable loop, they generate two versions: a serial clone and a parallel clone. See also *dynamic selection*.

code A computer program, either in source form or in the form of an executable image on a machine.

coherency A term frequently applied to caches. If a data item is referenced by a particular processor on a multiprocessor system, the data is copied into that processor's cache and is updated there if the processor modifies the data. If another processor references the data while a copy is still in the first processor's cache, a mechanism is needed to ensure that the second processor does not use an outdated copy of the data from memory. The state that is achieved when both processors' caches always have the latest value for the data is called cache coherency. On multiprocessor servers an item of data may reside concurrently in several processors' caches.

column-major order Memory representation of an array such that the columns are stored contiguously. For example, given a two-dimensional array `A(3,4)`, the array element `A(3,1)` immediately precedes element `A(1,2)` in memory. This is the default storage method for arrays in Fortran.

compiler A computer program that translates computer code written in a high-level programming language, such as Fortran, into equivalent machine language.

concurrent In parallel processing, threads that can execute at the same time are called concurrent threads.

conditional induction variable A loop induction variable that is not necessarily incremented on every iteration.

constant folding Replacement of an operation on constant operands with the result of the operation.

constant propagation The automatic compile-time replacement of variable references with a constant value previously assigned to that variable. Constant propagation is performed within a single procedure by conventional compilers.

conventional compiler A compiler that cannot perform interprocedural optimization.

counter A variable that is used to count the number of times an operation occurs.

CPA CPU Agent. The gate array on V2250 servers that provides a high-speed interface between pairs of PA-RISC processors and the *crossbar*. Also called the *CPU Agent* and the *agent*.

CPU Central processing unit. The central processing unit (CPU) is that portion of a computer that recognizes and executes the instruction set.

CPU Agent The gate array on V2250 servers that provides a high-speed interface between pairs of PA-RISC processors and the *crossbar*.

CPU-private memory Data that is accessible by a single thread only (not shared among the threads constituting a process). A thread-private data object has a unique virtual address which maps to a unique physical address. Threads access the physical copies of thread-private data residing on their own hypernode when they access thread-private virtual addresses.

CPU time The amount of time the CPU requires to execute a program. Because programs share access to a CPU, the wall-clock time of a program may not be the same as its CPU time. If a program can use multiple processors, the CPU time may be greater than the wall-clock time. (See *wall-clock time*.)

critical section A portion of a parallel program that can be executed by only one thread at a time.

crossbar A switching device that connects the CPUs, banks of memory, and I/O controller on a single hypernode of a V2250 server. Because the crossbar is nonblocking, all ports can run at full bandwidth simultaneously, provided there is not contention for a particular port.

CSR Control/Status Register. A CSR is a software-addressable hardware register used to hold control information or state.

data cache (Dcache) A small cache memory with a fast access time. This cache holds prefetched and current data. On V2250 servers, processors have 2-Mbyte off-chip caches. See also *cache, direct mapped*.

data dependence A relationship between two statements in a program, such that one statement must precede the other to produce the intended result. (See also *loop-carried dependence (LCD)* and loop-independent dependence (LID).)

data localization Optimizations designed to keep frequently used data in the processor data cache, thus eliminating the need for more costly memory accesses.

data type A property of a data item that determines how its bits are grouped and interpreted. For processor instructions, the data type identifies the size of the operand and the significance of the bits in the operand. Some example data types include `INTEGER`, `int`, `REAL`, and `float`.

Dcache Data cache. A small cache memory with a one clock cycle access time under pipelined conditions. This cache holds prefetched and current data.On V2250 servers, this cache is 2 Mbytes.

deadlock A condition in which a thread waits indefinitely for some condition or action that cannot, or will not, occur.

direct memory access (DMA) A method for gaining direct access to memory and achieving data transfers without involving the CPU.

distributed memory A memory architecture used in multi-CPU systems, in which the system's memory is physically divided among the processors. In most distributed-memory architectures, memory is accessible from the single processor that owns it. Sharing of data requires explicit message passing.

distributed part A loop generated by the compiler in the process of loop distribution.

DMA Direct memory access. A method for gaining direct access to memory and achieving data transfers without involving the CPU.

double A double-precision floating-point number that is stored in 64 bits in C and C++.

doubleword A primitive data operand which is 8 bytes (64 bits) in length. Also called a *longword*. See also *word*.

dummy argument In Fortran, a variable declared in the argument list of a procedure (function or subroutine) that receives a value when the procedure is called. The dummy argument appears in the source of the called procedure; the parameter that appears in the source of the calling procedure is an *actual argument*. C and C++ conventions refer to dummy arguments as *formal parameters*.

dynamic selection The process by which the compiler chooses the appropriate runtime clone of a loop. See also *clone*.

encache To copy data or instructions into a cache.

exception A hardware-detected event that interrupts the running of a program, process, or system. See also *fault*.

execution stream A series of instructions executed by a CPU.

fault A type of *interruption* caused by an instruction requesting a legitimate action that cannot be carried out immediately due to a system problem.

floating-point A numerical representation of a real number. On V2250 servers, a floating point operand has a sign (positive or negative) part, an exponent part, and a fraction part. The fraction is a fractional representation. The exponent is the value used to produce a power of two scale factor (or portion) that is subsequently used to multiply the fraction to produce an unsigned value.

FLOPS Floating-point operations per second. A standard measure of computer processing power in the scientific community.

formal parameter In C and C++, a variable declared in the parameter list of a procedure (function) that receives a value when the procedure is called. The formal parameter appears in the source of the called procedure; the parameter that appears in the source of the calling procedure is an actual parameter. Fortran conventions refer to formal parameters as dummy arguments.

Fortran A high-level software language used mainly for scientific applications.

Fortran 90 The international standard for Fortran adopted in 1991.

function A procedure whose call can be imbedded within another statement, such as an assignment or test. Any procedure in C or C++ or a procedure defined as a FUNCTION in Fortran.

functional unit (FU) A part of a CPU that performs a set of operations on quantities stored in *registers*.

gate A construct that restricts execution of a block of code to a single thread. A thread locks a gate on entering the gated block of code and unlocks the gate on exiting the block. When the gate is locked, no other threads can enter. Compiler directives can be used to automate gate constructs; gates can also be implemented using *semaphores*.

Gbyte See *gigabyte*.

gigabyte 1073741824 (2^{30}) bytes.

global optimization A restructuring of program statements that is not confined to a single basic block. Global optimization, unlike interprocedural optimization, is confined to a single procedure. Global optimization is done by HP compilers at optimization level `+O2` and above.

global register allocation (GRA) A method by which the compiler attempts to store commonly-referenced scalar variables in registers throughout the code in which they are most frequently accessed.

global variable A variable whose scope is greater than a single procedure. In C and C++ programs, a global variable is a variable that is defined outside of any one procedure. Fortran has no global variables per se, but `COMMON` blocks can be used to make certain memory locations globally accessible.

granularity In the context of parallelism, a measure of the relative size of the computation done by a thread or parallel construct. Performance is generally an increasing function of the granularity. In higher-level language programs, possible sizes are routine, loop, block, statement, and expression. Fine granularity can be exhibited by parallel loops, tasks and expressions, Coarse granularity can be exhibited by parallel processes.

hand-rolled loop A loop, more common in Fortran than C or C++, that is constructed using `IF` tests and `GOTO` statements rather than a language-provided loop structure such as `DO`.

hidden alias An alias that, because of the structure of a program or the standards of the language, goes undetected by the compiler. Hidden aliases can result in undetected *data dependences*, which may result in wrong answers.

High Performance Fortran (HPF) An ad-hoc language extension of Fortran 90 that provides user-directed data distribution and alignment. HPF is not a standard, but rather a set of features desirable for parallel programming.

hoist An optimization process that moves a memory load operation from within a loop to the basic block preceding the loop.

HP Hewlett-Packard, the manufacturer of the PA-RISC chips used as processors in V2250 servers.

HP-UX Hewlett-Packard's Unix-based operating system for its PA-RISC workstations and servers.

hypercube A topology used in some massively parallel processing systems. Each processor is connected to its binary neighbors. The number of processors in the system is always a power of two; that power is referred to as the dimension of the hypercube. For example, a 10-dimensional hypercube has 2^{10}, or 1,024 processors.

hypernode A set of processors and physical memory organized as a symmetric multiprocessor (SMP) running a single image of the operating system. Nonscalable servers and V2250 servers consist of one hypernode. When discussing multidimensional parallelism or memory classes, hypernodes are generally called nodes.

Icache Instruction cache. This cache holds prefetched instructions and permits the simultaneous decoding of one instruction with the execution of a previous instruction. On V2250 servers, this cache is 2 Mbytes.

IEEE Institute for Electrical and Electronic Engineers. An international professional organization and a member of ANSI and ISO.

induction variable A variable that changes linearly within the loop, that is, whose value is incremented by a constant amount on every iteration. For example, in the following Fortran loop, `I`, `J` and `K` are induction variables, but `L` is not.

```
DO I = 1, N
   J = J + 2
   K = K + N
   L = L + I
ENDDO
```

inlining The replacement of a procedure (function or subroutine) call, within the source of a calling procedure, by a copy of the called procedure's code.

Institute for Electrical and Electronic Engineers (IEEE) An international professional organization and a member of ANSI and ISO.

instruction One of the basic operations performed by a CPU.

instruction cache (Icache) This cache holds prefetched instructions and permits the simultaneous decoding of one instruction with the execution of a previous instruction. On V2250 servers, this cache is 2 Mbytes.

instruction mnemonic A symbolic name for a machine instruction.

integral division Division that results in a whole number solution with no remainder. For example, 10 is integrally divisible by 2, but not by 3.

interface A logical path between any two modules or systems.

interleaved memory Memory that is divided into multiple banks to permit concurrent memory accesses. The number of separate memory banks is referred to as the memory stride.

interprocedural optimization Automatic analysis of relationships and interfaces between all subroutines and data structures within a program. Traditional compilers analyze only the relationships within the procedure being compiled.

interprocessor communication The process of moving or sharing data, and synchronizing operations between processors on a multiprocessor system.

intrinsic A function or subroutine that is an inherent part of a computer language. For example, `SIN` is a Fortran intrinsic.

job scheduler That portion of the operating system that schedules and manages the execution of all processes.

join The synchronized termination of parallel execution by spawned tasks or threads.

jump Departure from normal one-step incrementing of the program counter.

kbyte See *kilobyte*.

kernel The core of the operating system where basic system facilities, such as file access and memory management functions, are performed.

kernel thread identifier (ktid) A unique integer identifier (not necessarily sequential) assigned when a thread is created.

kilobyte 1024 (2^{10}) bytes.

latency The time delay between the issuing of an instruction and the completion of the operation. A common benchmark used for comparing systems is the latency of coherent memory access instructions. This particular latency measurement is believed to be a good indication of the *scalability* of a system; low latency equates to low system overhead as system size increases.

linker A software tool that combines separate object code modules into a single object code module or executable program.

load An instruction used to move the contents of a memory location into a register.

locality of reference An attribute of a memory reference pattern that refers to the likelihood of an address of a memory reference being physically close to the CPU making the reference.

local optimization Restructuring of program statements within the scope of a basic block. Local optimization is done by HP compilers at optimization level `+O1` and above.

localization Data localization. Optimizations designed to keep frequently used data in the processor data cache, thus eliminating the need for more costly memory accesses.

logical address Logical address space is that address as seen by the application program.

logical memory Virtual memory. The memory space as seen by the program, which may be larger than the available physical memory. The virtual memory of a V2250 server can be up to 16 Tbytes. HP-UX can map this virtual memory to a smaller set of physical memory, using disk space to make up the difference if necessary. Also called *virtual memory*.

longword (l) Doubleword. A primitive data operand which is 8 bytes (64 bits) in length. See also *word*.

loop blocking A loop transformation that strip mines and interchanges a loop to provide optimal reuse of the encachable loop data.

loop-carried dependence (LCD) A dependence between two operations executed on different iterations of a given loop and on the same iteration of all enclosing loops. A loop carries a dependence from an indexed assignment to an indexed use if, for some iteration of the loop, the assignment stores into an address that is referred to on a different iteration of the loop.

loop constant A constant or expression whose value does not change within a loop.

loop distribution The restructuring of a loop nest to create simple loop nests. Loop distribution creates two or more loops, called distributed parts, which can serve to make parallelization more efficient by increasing the opportunities for loop interchange and isolating code that must run serially from parallelizable code. It can also improve data localization and other optimizations.

loop-independent dependence (LID) A dependence between two operations executed on the same iteration of all enclosing loops such that one operation must precede the other to produce correct results.

loop induction variable See *induction variable*.

loop interchange The reordering of nested loops. Loop interchange is generally done to increase the granularity of the parallelizable loop(s) present or to allow more efficient access to loop data.

loop invariant Loop constant. A constant or expression whose value does not change within a loop.

loop invariant computation An operation that yields the same result on every iteration of a loop.

loop replication The process of transforming one loop into more than one loop to facilitate an optimization. The optimizations that replicate loops are `IF-DO` and `if-for` optimizations, dynamic selection, loop unrolling, and loop blocking.

machine exception A fatal error in the system that cannot be handled by the operating system. See also *exception*.

main memory Physical memory other than what the processor caches.

main procedure A procedure invoked by the operating system when an application program starts up. The main procedure is the main program in Fortran; in C and C++, it is the function main().

main program In a Fortran program, the program section invoked by the operating system when the program starts up.

Mbyte See megabyte (Mbyte).

megabyte (Mbyte) 1048576 (2^{20}) bytes.

megaflops (MFLOPS) One million floating-point operations per second.

memory bank conflict An attempt to access a particular memory bank before a previous access to the bank is complete, or when the bank is not yet finished recycling (i.e., refreshing).

memory management The hardware and software that control memory page mapping and memory protection.

message Data copied from one process to another (or the same) process. The copy is initiated by the sending process, which specifies the receiving process. The sending and receiving processes need not share a common address space. (Note: depending on the context, a process may be a *thread*.)

Message-Passing Interface (MPI) A message-passing and process control library. For information on the Hewlett-Packard implementation of MPI, refer to the *HP MPI User's Guide* (B6011-90001).

message passing A type of programming in which program modules (often running on different processors or different hosts) communicate with each other by means of system library calls that package, transmit, and receive data. All message-passing library calls must be explicitly coded by the programmer.

MIMD (multiple instruction stream multiple data stream) A computer architecture that uses multiple processors, each processing its own set of instructions simultaneously and independently of others. MIMD also describes when processes are performing different operations on different data. Compare with SIMD.

multiprocessing The creation and scheduling of processes on any subset of CPUs in a system configuration.

mutex A variable used to construct an area (region of code) of *mutual exclusion*. When a mutex is locked, entry to the area is prohibited; when the mutex is free, entry is allowed.

mutual exclusion A protocol that prevents access to a given resource by more than one thread at a time.

negate An instruction that changes the sign of a number.

network A system of interconnected computers that enables machines and their users to exchange information and share resources.

node On HP scalable and nonscalable servers, a node is equivalent to a *hypernode*. The term “node” is generally used in place of hypernode.

non-uniform memory access (NUMA)

This term describes memory access times in systems in which accessing different types of memory (for example, memory local to the current hypernode or memory remote to the current hypernode) results in non-uniform access times.

nonblocking crossbar A switching device that connects the CPUs, banks of memory, and I/O controller on a single hypernode. Because the crossbar is nonblocking, all ports can run at full bandwidth simultaneously provided there is not contention for a particular port.

NUMA Non-uniform memory access. This term describes memory access times in systems in which accessing different types of memory (for example, memory local to the current hypernode or memory remote to the current hypernode) results in non-uniform access times.

offset In the context of a process address space, an integer value that is added to a base address to calculate a memory address. Offsets in V2250 servers are 64-bit values, and must keep address values within a single 16-Tbyte memory space.

opcode A predefined sequence of bits in an instruction that specifies the operation to be performed.

operating system The program that manages the resources of a computer system. V2250 servers use the HP-UX operating system.

optimization The refining of application software programs to minimize processing time. Optimization takes maximum advantage of a computer’s hardware features and minimizes idle processor time.

optimization level The degree to which source code is optimized by the compiler. The HP compilers offer five levels of optimization: level `+O0`, `+O1`, `+O2`, `+O3`, and `+O4`. The `+O4` option is not available in Fortran 90.

oversubscript An array reference that falls outside declared bounds.

oversubscription In the context of parallel threads, a process attribute that permits the creation of more threads within a process than the number of processors available to the process.

PA-RISC The Hewlett-Packard Precision Architecture reduced instruction set.

packet A group of related items. A packet may refer to the arguments of a subroutine or to a group of bytes that is transmitted over a network.

page A page is the unit of virtual or physical memory controlled by the memory management hardware and software. On HP-UX servers, the default page size is 4 K (4,096) contiguous bytes. Valid page sizes

are: 4 K, 16 K, 64 K, 256 K, 1 Mbyte, 4 Mbytes, 16 Mbytes, 64 Mbytes, and 256 Mbytes. See also *virtual memory*.

page fault A page fault occurs when a process requests data that is not currently in memory. This requires the operating system to retrieve the page containing the requested data from disk.

page frame A page frame is the unit of physical memory in which pages are placed. Referenced and modified bits associated with each page frame aid in memory management.

parallel optimization The transformation of source code into parallel code (parallelization) and restructuring of code to enhance parallel performance.

parallelization The process of transforming serial code to a form of code that can run simultaneously on multiple CPUs while preserving semantics. When `+O3 +Oparallel` is specified, the HP compilers automatically parallelize loops in your program and recognize compiler directives and pragmas with which you can manually specify parallelization of loops, tasks, and regions.

parallelization, loop The process of splitting a loop into several smaller loops, each of which operates on a subset of the data of the original loop, and generating code to run these loops on separate processors in parallel.

parallelization, ordered The process of splitting a loop into several smaller loops, each of which iterates over a subset of the original data with a stride equal to the number of loops created, and generating code to run these loops on separate processors. Each iteration in an ordered parallel loop begins execution in the original iteration order, allowing dependences within the loop to be synchronized to yield correct results via gate constructs.

parallelization, stride-based The process of splitting up a loop into several smaller loops, each of which iterates over several discontiguous chunks of data, and generating code to run these loops on separate processors in parallel. Stride-based parallelism can only be achieved manually by using compiler directives.

parallelization, strip-based The process of splitting up a loop into several smaller loops, each of which iterates over a single contiguous subset of the data of the original loop, and generating code to run these loops on separate processors in parallel. Strip-based parallelism is the default for automatic parallelism and for directive-initiated loop parallelism in absence of the `chunk_size = n` or `ordered` attributes.

parallelization, task The process of splitting up source code into independent sections which can safely be run in parallel on available processors. HP programming languages provide compiler directives and pragmas that allow you to identify parallel tasks in source code.

parameter In C and C++, either a variable declared in the parameter list of a procedure (function) that receives a value when the procedure is called (*formal parameter*) or the

variable or constant that is passed by a call to a procedure (*actual parameter*). In Fortran, a symbolic name for a constant.

path An environment variable that you set within your shell that allows you to access commands in various directories without having to specify a complete path name.

physical address A unique identifier that selects a particular location in the computer's memory. Because HP-UX supports virtual memory, programs address data by its virtual address; HP-UX then maps this address to the appropriate physical address. See also *virtual address*.

physical address space The set of possible addresses for a particular physical memory.

physical memory Computer hardware that stores data. V2250 servers can contain up to 16 Gbytes of physical memory on a 16-processor hypernode.

pipeline An overlapping operating cycle function that is used to increase the speed of computers. Pipelining provides a means by which multiple operations occur concurrently by beginning one instruction sequence before another has completed. Maximum efficiency is achieved when the pipeline is "full," that is, when all stages are operating on separate instructions.

pipelining Issuing instructions in an order that best uses the pipeline.

procedure A unit of program code. In Fortran, a function, subroutine, or main program; in C and C++, a function.

process A collection of one or more execution streams within a single logical address space; an executable program. A process is made up of one or more threads.

process memory The portion of system memory that is used by an executing process.

programming model A description of the features available to efficiently program a certain computer architecture.

program unit A procedure or main section of a program.

queue A data structure in which entries are made at one end and deletions at the other. Often referred to as first-in, first-out (FIFO).

rank The number of dimensions of an array.

read A memory operation in which the contents of a memory location are copied and passed to another part of the system.

recurrence A cycle of dependences among the operations within a loop in which an operation in one iteration depends on the result of a following operation that executes in a previous iteration.

recursion An operation that is defined, at least in part, by a repeated application of itself.

recursive call A condition in which the sequence of instructions in a procedure causes the procedure itself to be invoked again. Such a procedure must be compiled for reentrancy.

reduced instruction set computer (RISC) An architectural concept that applies to the definition of the instruction set of a processor. A RISC instruction set is an orthogonal instruction set that is easy to decode in hardware and for which a compiler can generate highly optimized code. The PA-RISC processor used in V2250 servers employ a RISC architecture.

reduction An arithmetic operation that performs a transformation on an array to produce a scalar result.

reentrancy The ability of a program unit to be executed by multiple threads at the same time. Each invocation maintains a private copy of its local data and a private stack to store compiler-generated temporary variables. Procedures must be compiled for reentrancy in order to be invoked in parallel or to be used for recursive calls. HP compilers compile for reentrancy by default.

reference Any operation that requires a cache line to be encached; this includes load as well as store operations, because writing to any element in a cache line requires the entire cache line to be encached.

register A hardware entity that contains an address, operand, or instruction status information.

reuse, data In the context of a loop, the ability to use data fetched for one loop operation in another operation. In the context of a cache, reusing data that was encached for a previous operation; because data is fetched as part of a cache line, if any of the other items in the cache line are used before the line is flushed to memory, reuse has occurred.

reuse, spatial Reusing data that resides in the cache as a result of the fetching of another piece of data from memory. Typically, this involves using array elements that are contiguous to (and therefore part of the cache line of) an element that has already been used, and therefore is already encached.

reuse, temporal Reusing a data item that has been used previously.

RISC Reduced instruction set computer. An architectural concept that applies to the definition of the instruction set of a processor. A RISC instruction set is an orthogonal instruction set that is easy to decode in hardware and for which a compiler can generate highly optimized code. The PA-RISC processor used in V2250 servers employs a RISC architecture.

rounding A method of obtaining a representation of a number that has less precision than the original in which the closest number representable under the lower precision system is used.

row-major order Memory representation of an array such that the rows of an array are stored contiguously. For example, given a two-dimensional array `A[3][4]`, array element `A[0][3]` immediately precedes `A[1][0]` in memory. This is the default storage method for arrays in C.

scope The domain in which a variable is visible in source code. The rules that determine scope are different for Fortran and C/C++.

semaphore An integer variable assigned one of two values: one value to indicate that it is "locked," and another to indicate that it is "free." Semaphores can be used to synchronize parallel threads. Pthreads provides a set of manipulation functions to facilitate this.

shape The number of elements in each dimension of an array.

shared virtual memory A memory architecture in which memory can be accessed by all processors in the system. This architecture can also support virtual memory.

shell An interactive command interpreter that is the interface between the user and the Unix operating system.

SIMD (single instruction stream multiple data stream) A computer architecture that performs one operation on multiple sets of data. A processor (separate from the SMP array) is used for the control logic, and the processors in the SMP array perform the instruction on the data. Compare with *MIMD (multiple instruction stream multiple data stream)*.

single A single-precision floating-point number stored in 32 bits. See also *double*.

SMP Symmetric multiprocessor. A multiprocessor computer in which all the processors have equal access to all machine resources. Symmetric multiprocessors have no manager or worker processors; the operating system runs on any or all of the processors.

socket An endpoint used for interprocess communication.

socket pair Bidirectional pipes that enable application programs to set up two-way communication between processes that share a common ancestor.

source code The uncompiled version of a program, written in a high-level language such as Fortran or C.

source file A file that contains program source code.

space A contiguous range of virtual addresses within the system-wide virtual address space. Spaces are 16 Tbytes in the V2250 servers.

spatial reference An attribute of a memory reference pattern that pertains to the likelihood of a subsequent memory reference address being numerically close to a previously referenced address.

spawn To activate existing threads.

spawn context A parallel loop, task list, or region that initiates the spawning of threads and defines the structure within which the threads' spawn thread IDs are valid.

spawn thread identifier (stid) A sequential integer identifier associated with a particular thread that has been spawned. stids are only assigned to spawned threads,

and they are assigned within a spawn context; therefore, duplicate stids may be present amongst the threads of a program, but stids are always unique within the scope of their spawn context. stids are assigned sequentially and run from 0 to one less than the number of threads spawned in a particular spawn context.

SPMD Single program multiple data. A single program executing simultaneously on several processors. This is usually taken to mean that there is redundant execution of sequential scalar code on all processors.

stack A data structure in which the last item entered is the first to be removed. Also referred to as last-in, first-out (LIFO). HP-UX provides every thread with a stack which is used to pass arguments to functions and subroutines and for local variable storage.

store An instruction used to move the contents of a register to memory.

strip length, parallel In strip-based parallelism, the amount by which the induction variable of a parallel inner loop is advanced on each iteration of the (conceptual) controlling outer loop.

strip mining The transformation of a single loop into two nested loops. Conceptually, this is how parallel loops are created by default. A conceptual outer loop advances the initial value of the inner loop's induction variable by the parallel strip length. The parallel strip length is based on the trip count of the loop and the amount of code in the loop body. Strip mining is also used by the data localization optimization.

subroutine A software module that can be invoked from anywhere in a program.

superscalar A class of *RISC* processors that allow multiple instructions to be issued in each clock period.

Symmetric Multiprocessor (SMP) A multiprocessor computer in which all the processors have equal access to all machine resources. Symmetric multiprocessors have no manager or worker processors; the operating system runs on any or all of the processors.

synchronization A method of coordinating the actions of multiple threads so that operations occur in the right sequence. When manually optimizing code, you can synchronize programs using compiler directives, calls to library routines, or assembly-language instructions. You do so, however, at the cost of additional overhead; synchronization may cause at least one CPU to wait for another.

system administrator (sysadmin) The person responsible for managing the administration of a system.

system manager The person responsible for the management and operation of a computer system. Also called the system administrator and the sysadmin.

Tbyte See terabyte (Tbyte).

terabyte (Tbyte) 1099511627776 (2^{40}) bytes.

term A constant or symbolic name that is part of an *expression*.

thread An independent execution stream that is executed by a CPU. One or more threads, each of which can execute on a different CPU, make up each process. Memory, files, signals, and other process attributes are generally shared among threads in a given process, enabling the threads to cooperate in solving the common problem. Threads are created and terminated by instructions that can be automatically generated by HP compilers, inserted by adding compiler directives to source code, or coded explicitly using library calls or assembly-language.

thread create To activate existing threads.

thread identifier An integer identifier associated with a particular thread. See *thread identifier, kernel (ktid)* and *thread identifier, spawn (stid)*.

thread identifier, kernel (ktid) A unique integer identifier (not necessarily sequential) assigned when a thread is created.

thread identifier, spawn (stid) A sequential integer identifier associated with a particular thread that has been spawned. stids are only assigned to spawned threads, and they are assigned within a spawn context; therefore, duplicate stids may be present amongst the threads of a program, but stids are always unique within the scope of their spawn context. stids are assigned sequentially and run from 0 to one less than the number of threads spawned in a particular spawn context.

thread-private memory Data that is accessible by a single thread only (not shared among the threads constituting a process).

translation lookaside buffer A hardware entity that contains information necessary to translate a virtual memory reference to the corresponding physical page and to validate memory accesses.

TLB See *translation lookaside buffer*.

trip count The number of iterations a loop executes.

unsigned A value that is always positive.

user interface The portion of a computer program that processes input entered by a human and provides output for human users.

utility A software tool designed to perform a frequently used support function.

vector An ordered list of items in a computer's memory, contained within an array. A simple vector is defined as having a starting address, a length, and a stride. An indirect address vector is defined as having a relative base address and a vector of values to be applied as offsets to the base.

vector processor A processor whose instruction set includes instructions that perform operations on a *vector* of data (such as a row or column of an array) in an optimized fashion.

virtual address The address by which programs access their data. HP-UX maps this address to the appropriate physical memory address. See also *space*.

virtual aliases Two different virtual addresses that map to the same physical memory address.

virtual machine A collection of computing resources configured so that a user or process can access any of the resources, regardless of their physical location or operating system, from a single interface.

virtual memory The memory space as seen by the program, which is typically larger than the available physical memory. The virtual memory of a V2250 server can be up to 16 Tbytes. The operating system maps this virtual memory to a smaller set of physical memory, using disk space to make up the difference if necessary. Also called *logical memory*.

wall-clock time The chronological time an application requires to complete its processing. If an application starts running at 1:00 p.m. and finishes at 5:00 a.m. the following morning, its wall-clock time is sixteen hours. Compare with *CPU time*.

word A contiguous group of bytes that make up a primitive data operand and start on an addressable boundary. In V2250 servers a word is four bytes (32 bits) in length. See also *doubleword*.

workstation A stand-alone computer that has its own processor, memory, and possibly a disk drive and can typically sit on a user's desk.

write A memory operation in which a memory location is updated with new data.

zero In floating-point number representations, zero is represented by the sign bit with a value of zero and the exponent with a value of zero.

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